Ultra Deep Water Discharge of Produced Water and/or Solids at the Seabed

09121-3100-01

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Revision No.	Date	Description	Originator's Name & Initials	Reviewed / Checked By Name & Initials	Pages
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1.0 EXECUTIVE SUMMARY

Produced water consists of formation water (the water present naturally in the reservoir), flood water previously injected into the formation to maintain pressure, and/or, in the case of some gas production, condensed water.(ANL, 2004)

In 2005, nearly 107 Million Barrels of water were produced daily in offshore operations worldwide together with the 120 million barrels of oil equivalent. About forty percent of the daily water production (44 million barrels of water) was discharged offshore.(OGP, 2005)

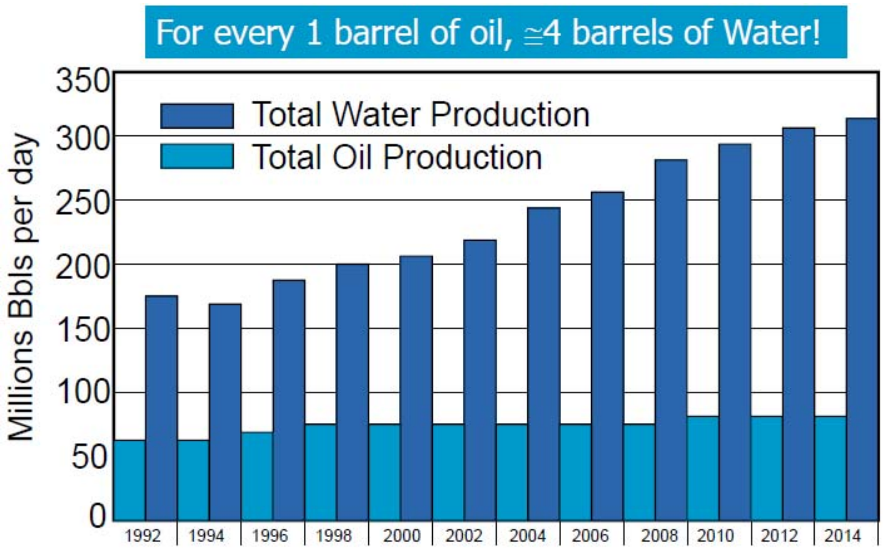

Figure 1: Global Oil and Water Production History and Forecast (TUV-NEL, 2010)

The above figure highlights a major issue for the oil and gas industry. As the forecast oil production remains consistent, the produced water from this production continues to increase. The handling of produced water will become increasingly more important and appears to be a problem that will not go away.

1.1 Offshore Handling of Produced Water

Current discharge of produced treated water from offshore development is only done through topsides facilities.

According to the International Association of Oil and Gas Producers 2005 study, the produced water industry has shown results that looked at the discharge in the world's oceans over the past 30 years. The results given showed that no abnormal effects to the marine life have taken place and it suggested the current regulation levels set forth in the industry are safe for the environment. (OGP, 2005)

Gas wells tend to produce low volumes of water with relatively high concentrations of organic contaminants. Oil wells in contrast, generally produce higher volumes of produced water. These volumes increase with time, and can, for mature fields, reach over 10 times the volume of oil produced. (ANL, 2004)

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The composition of produced water is complex and varies widely. It is determined by the characteristics of the reservoir and by the maturity of production. One of its major constituents is inorganic salts, which make it similar to seawater, although salinity can range from almost fresh to fully saturated. (ANL, 2004)

Produced water from oil fields, offshore platforms and onshore platforms as well as wastewater from the refineries can and does contain fair amounts of free and floating oil. It must be removed before biological treatment and or discharged to the environment. At present the available technology uses several steps to remove this free and floating oil and there are numerous current methods. Oil water separation is a commonly performed task in most oil production and processing facilities, and there are numerous current methods. (ANL, 2004)

Typically, the industry uses 3 different devices or stages of the process but their combined use may not be required due to the water quality to be processed. The industry is using an API separator using the difference in specific gravity of the oil, water and suspended solids in a process that is based on the principles of Stokes law. It often requires a secondary treatment device as the separation efficiency is less than ideal. Secondary separation devices can include hydrocyclones or compact floatation units and is used to enhance coalescence of the oil phase and settlement of the suspended solids. For the final stage where the amount of oil and suspended solids is relatively low, induced gas floatation (IGF) and dissolved gas flotation (DGF) devices can be employed to enhance flotation and separation of the oil and suspended solids, as well as the use of advanced filtration systems with advance coalescence components.

1.2 Topside Technologies

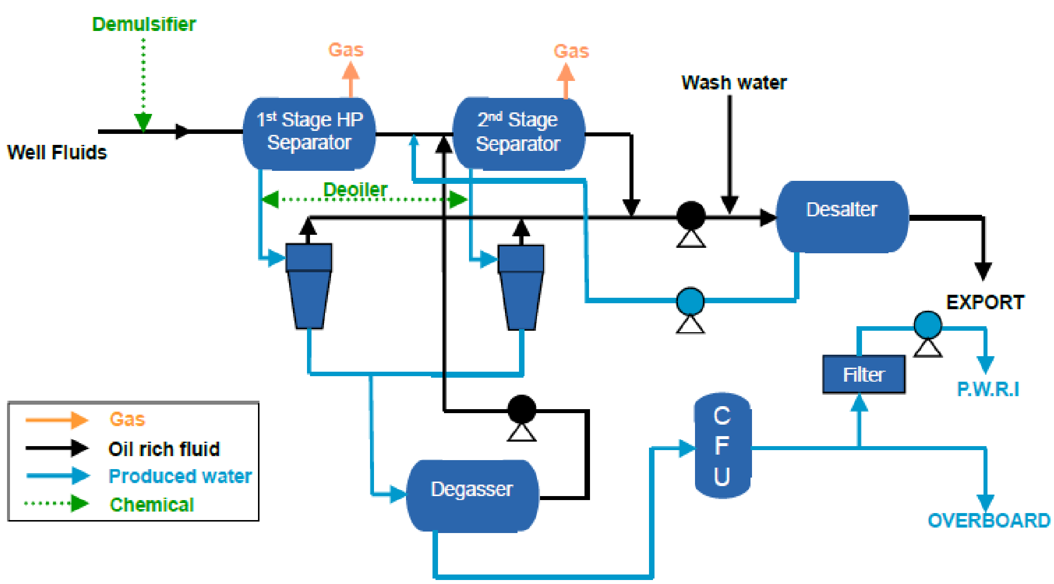

Figure 2: Block Diagram showing typical produced water treatment system.

(Courtesy of TUV/NEL, 2010)

There are many topside treatment technologies available for removing dispersed and dissolved oil and reducing toxicity from produced water. These technologies include:

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- Mechanical (gravity, enhanced gravity, gas flotation, filtration, membrane etc)
- Absorption / adsorption / extraction (Granular Activated Carbons – GAC, Macro Porous Polymer Extraction – MPPE; C-tour etc)
- Advanced Oxidation Process (AOP)
- Biological (bio reactors)
- Hybrid (combination of various technologies, e.g. Compact Flotation Units – CFUs)

Most of the mechanical methods are now well established. Technologies such as hydrocyclones and gas flotation units with and without the use of chemicals are well applied offshore for produced water treatment to meet typical produced water discharge standards.

Electrodialysis and reverse osmosis have been commonly used for sea water desalination purposes. They are now by far the two technologies that have been considered for removing salts from produced water. However for both technologies, it is extremely important to remove oil and solids as a pre-treatment.

In reviewing all these technologies, none have been deployed in a subsea production system. Only subsea separation and reinjection techniques have been used. There is no known successful subsea produced water treatment system as of today.

1.3 State of the Art Technologies

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 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.

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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.

1.4 US Regulatory Issues

On October 1, 2011, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service (MMS), was replaced by the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) as part of a major reorganization. Below is the organization chart for BOEM as of March 2012.

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Bureau of Ocean Energy Management (BOEM)

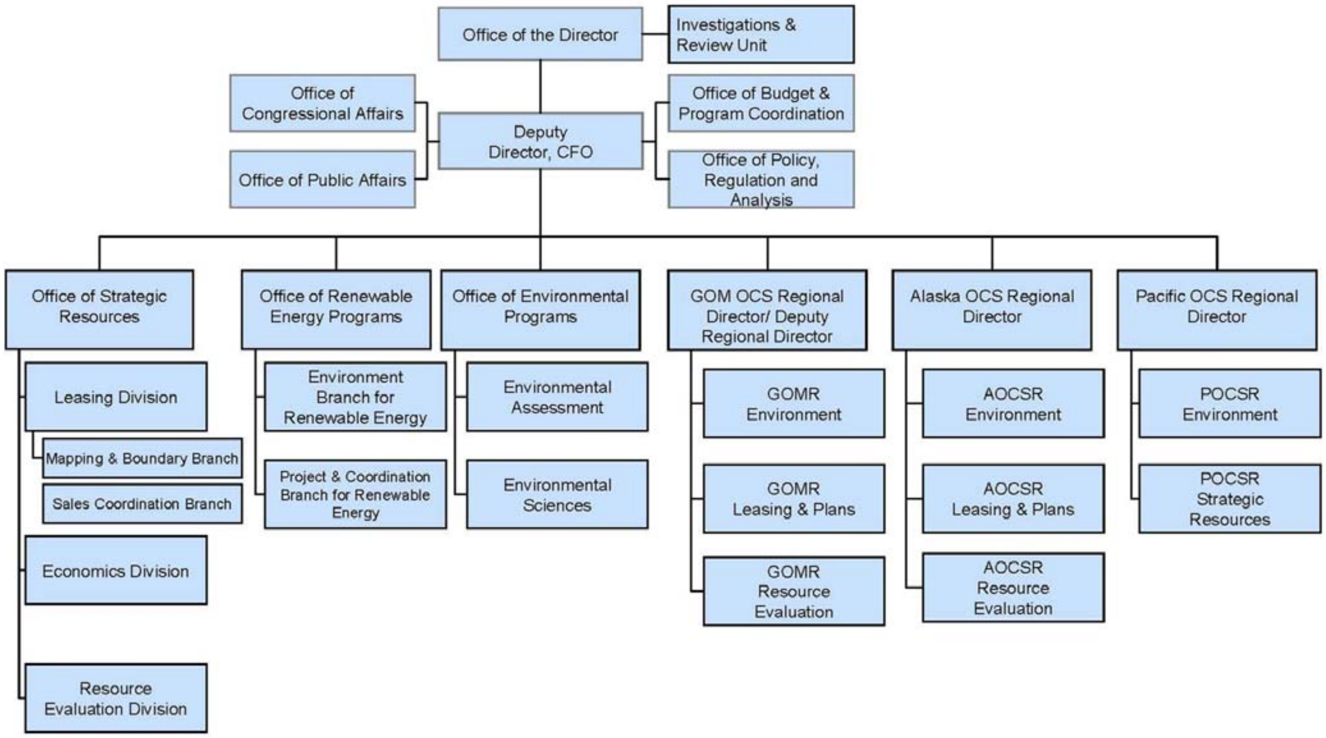

Figure 3: Bureau of Ocean Energy Management (BOEM)

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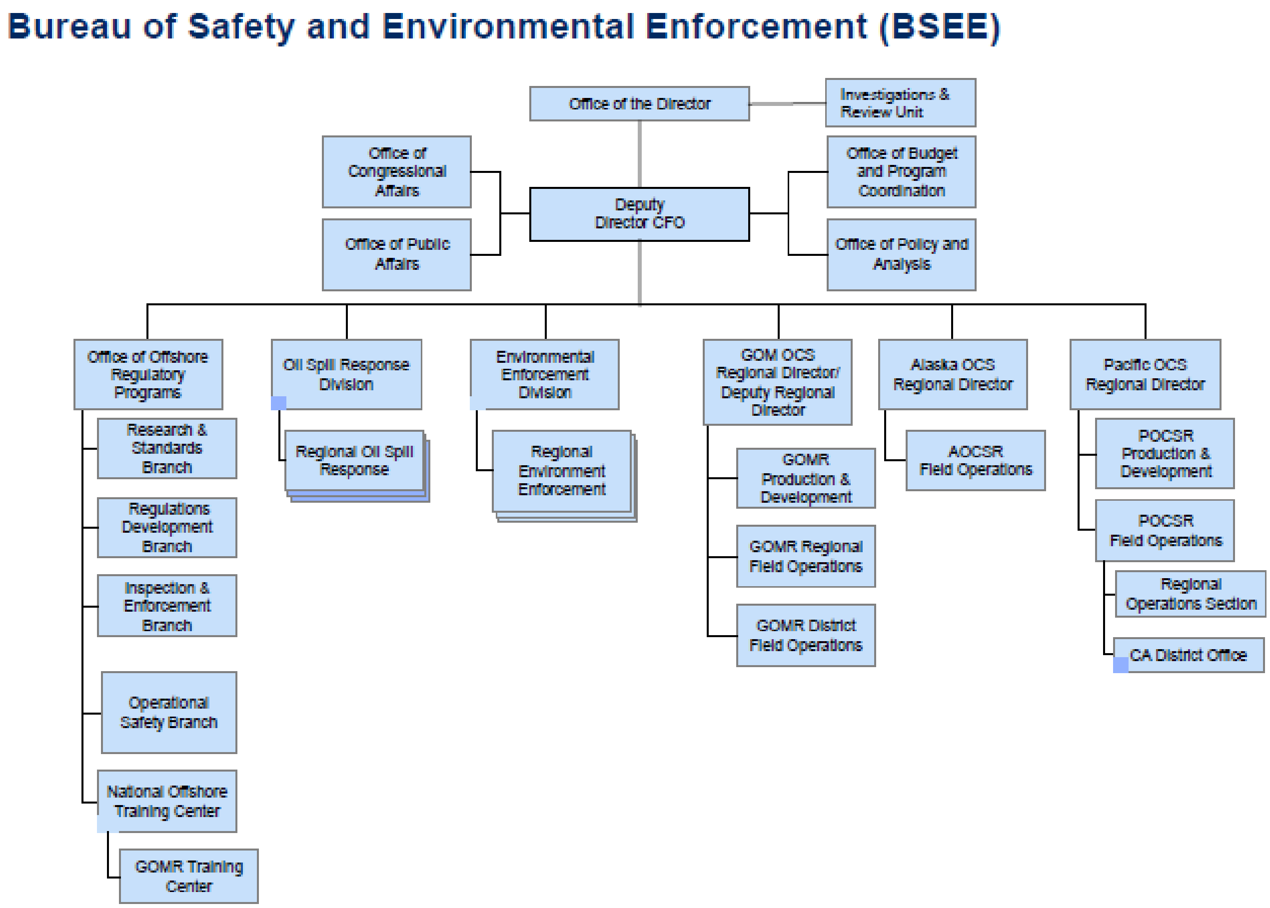

Figure 4: Organization Chart for BSEE as of March 2012.

Today, the BOEM and BSEE focus on the 3 regions of Alaska, the Gulf of Mexico and the Pacific.

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Figure 5: BOEM Alaska Region

BOEM Gulf of Mexico OCS Region
Blocks and Active Leases by Planning Area
March 1, 2012

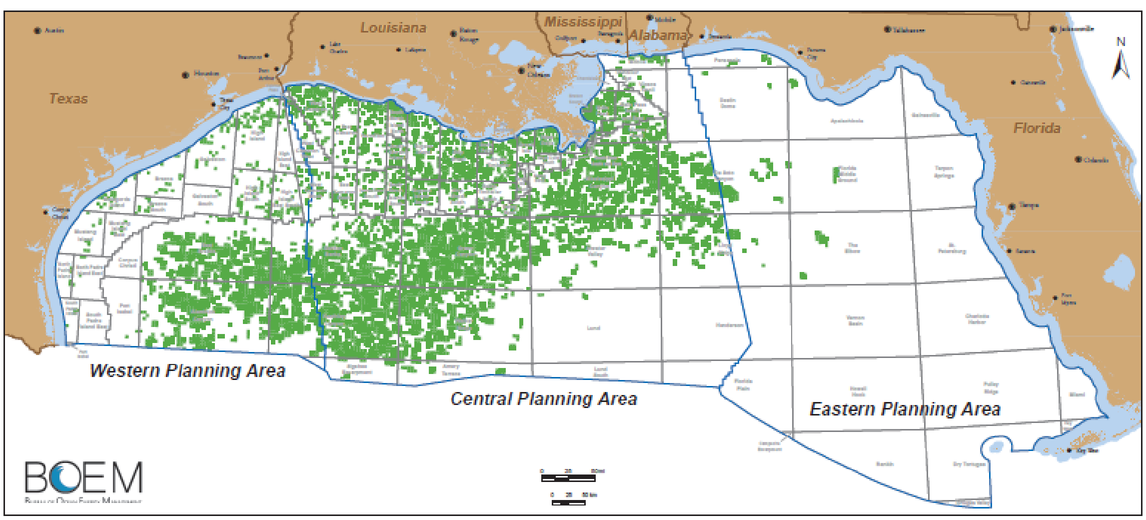

Figure 6: BOEM Gulf of Mexico Region

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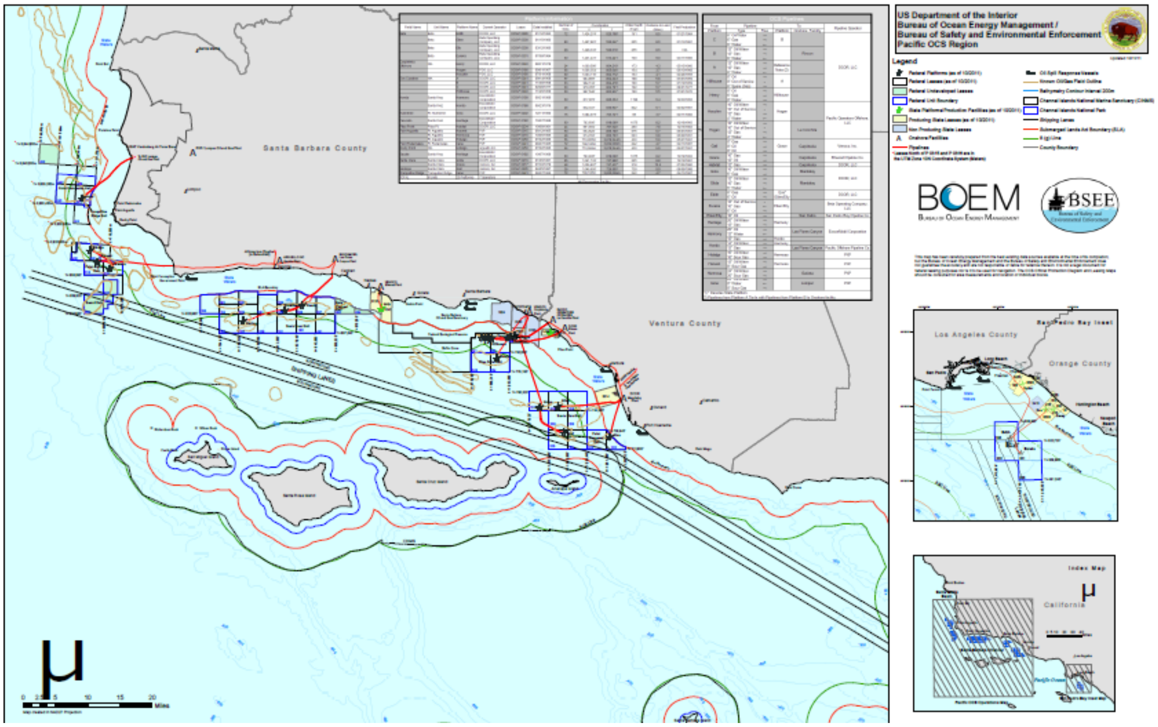

Figure 7: BOEM Pacific Region

Each of the above regions follow the Clean Water Act and the guidelines from the Environmental Protection Agency (EPA). The EPA sets the standards for water quality discharge requirements and BSEE handles the enforcement.

The Clean Water Act prohibits all discharges of pollutants unless they are authorized by National Pollutant Discharge Elimination System (NPDES) permits. The Act also requires that NPDES permits first limit pollutants based on economically achievable treatment technologies and then include additional limits as needed to protect water quality.(EPA, 2011)

Regulations are changing today. New point sources and existing point sources of pollutants have different NPDES regulations. New sources are subject to more rigorous effluent limits than existing sources based on the idea that it is cheaper to minimize effluent pollutants if environmental controls are considered during plant design than if an existing facility is retrofitted. New source discharges must comply with standards based on the performance of demonstrated technology with the greatest degree of effluent reduction. These new source performance standards (NSPS) should represent the most stringent numerical values attainable. NSPS are based upon the best available demonstrated control technology and are at least as stringent as best available technology.(EPA, 2011)

The NPDES guidelines define a new source as any area in which significant site preparation work is done. EPA interprets “significant site preparation” for offshore effluent guidelines as “the process of clearing and preparing an area of the ocean floor for purposes of constructing or placing a development or production facility on or over the site.” Thus, development and production facilities at a new site would be new sources. Development and production facilities are existing sources if significant site preparation work took place before NSPS became effective. Exploratory wells are not considered new sources because site preparation is not considered significant.(EPA, 2011)

Currently, there are no regulations governing produced water disposal at the seabed and the discharge of sand is prohibited in the Gulf of Mexico.

1.5 Worldwide Regulations

The oil in water content serves as the primary target for worldwide regulations, and toxicity is commonly addressed with dilutions of seawater. Measurement, monitoring and reporting requirements vary by region, but all require sampling and measuring/testing of the samples. A single method of measuring is specified in the US regulations

The following are some of the regulatory impacts on seabed discharge of produced water and/or solids:

- Sand cannot be discharged in US projects.
- There is no current regulation on suspended solids. However, suspended solids tend to have oil adhering onto them. Excessive amount of suspended solids in produced water can make the discharge exceed the oil in water content. Therefore, some measure of suspended solids removal should be included in the water treatment equipment.
- The current approved methods for oil and grease monitoring are based on laboratory testing of water samples. With the US regulations, the minimum sampling and testing frequency is once per month which makes monitoring feasible with available technology such as ROV access, although it can be expensive. The US regulation does not provide means of using online monitoring to substitute for laboratory measurements.
- The US regulations allow the toxicity criteria to be met through dilution.
- The US regulations require daily visual sheen monitoring. For the developments that will potentially discharge produced water at seabed, which are typically subsea tieback developments and maybe with long offset, daily observation of visual sheen may be challenging. Additionally, the water sampling requirement after observing sheen (within 2 hours after a visual sheen is observed) may also be challenging to meet.

1.6 Marine Life Issues

Many studies have been done to test the effects of produced water on marine life. The process that produced water goes through upon discharge is important in determining how it will affect the surrounding marine life.

First, the discharged treated produced water goes through two phases of dilution. The first phase of dilution happens within the first few tens of meters where it dilutes by a 30 to 100-fold factor. The second phase happens 500 to 1000 meters away from the discharge point where the produced water dilutes by a 1000 to 100000-fold factor.(OGP,2005) Secondly low molecular weight hydrocarbons volatilize into the air or are degraded by photolytic or biological processes. Also, the produced water constituents are exposed to several chemical processes including precipitation, hydrolysis, oxidation, and complexation upon discharge. Next, the constituents adsorb on the suspended solids. The rate of adsorption depends on the amount of suspended solids and the adsorptive tendencies of the constituents.(OGP,2005) Finally the constituents begin to biodegrade. The rate of biodegradation depends on each constituent’s chemical structure. Naturally occurring bacteria in marine environments also control biodegradation of produced water constituents. (ANL, 2004)

Field studies were done near Norway in a region with a high density of produced water discharge, which accounts for nearly 70% of all the discharge of water in the North Sea. At a distance of 10

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km from the discharge point, aromatic hydrocarbons could be detected; however it was only within 500m that the concentrations of hydrocarbons would cause a rise in biological effects. Fish were also tested in this study and results show that produced water at current regulation poses only a minor risk to marine life. Dilution models are often used today to understand this process better in specific regions.(OGP,2005)

In the early 1990's a study was done in the Gulf of Mexico which compared the bioaccumulation of target chemicals in edible tissue of fish collected at GOM platforms discharging >4600 bbl/d to that of fish collected at platforms with no produced water discharges. It also targeted to evaluate the ecological and human health considerations of observed concentration of target chemicals in edible tissues of fishes collected near offshore platforms in the GOM. As a result, none of the target chemicals were present in edible tissues at concentrations that might be harmful to the fish or to human health. Also, there were no major differences in tissues collected from discharging sites as opposed to non-discharging sites. The few observed elevated concentrations were distributed equally between the discharging and non-discharging sites, suggesting that produced water discharge was not the source of the elevations.(OGP,2005)

After performing this study, it is clear there is a need to better understand the deepwater marine life and how it will react to the discharge criteria that is defined in the basis of design for the study.

1.7 Subsea Produced Water Treatment Concepts

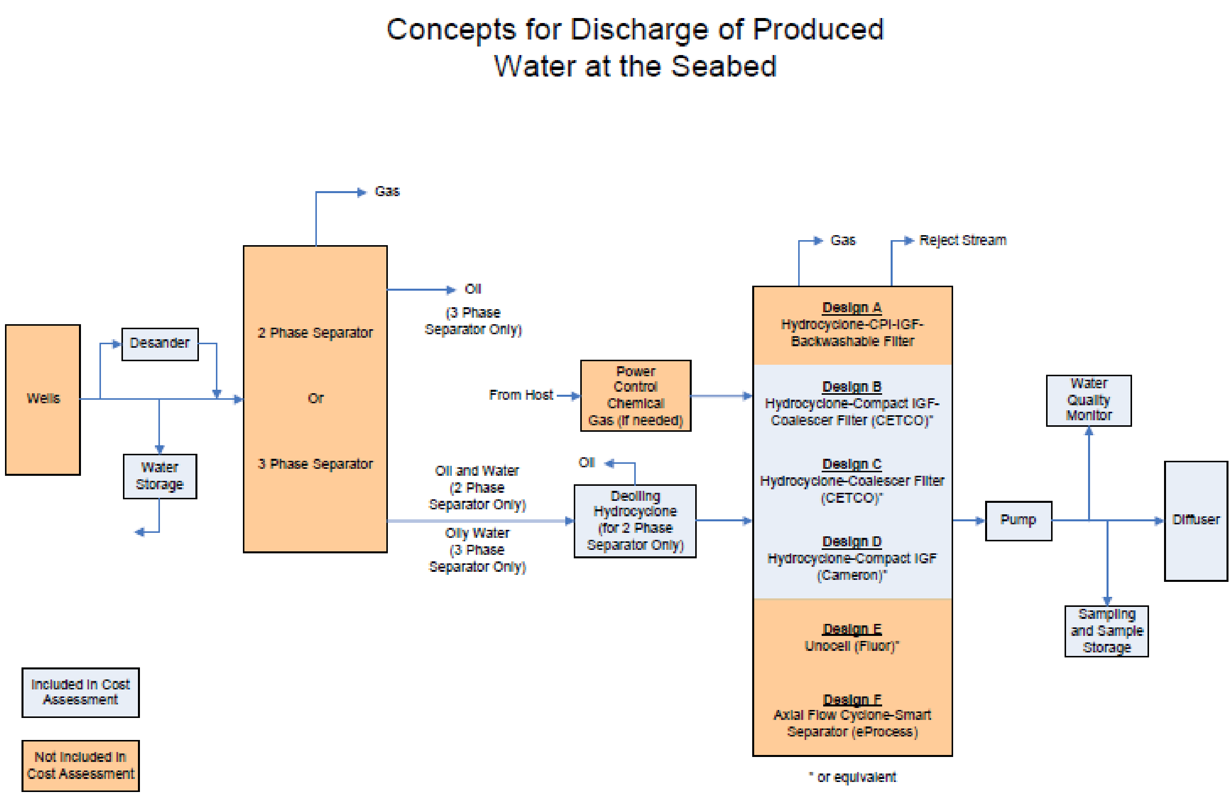

Figure 8: Subsea Produced Water Treatment and Discharge Concepts

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The above flow diagram is shown to illustrate how a subsea processing system will look with a subsea produced water treatment system.

Design A is mostly a straightforward migration of topsides water treatment technology to subsea, as such is not considered a feasible design for subsea but is provided only as a reference point to start with. The key factor making this design not feasible is the corrugated plate interceptors for which we have not found compact versions suitable for subsea applications in 5000 – 8000 ft water depth.

We consider that Designs B, C and D are designs for which additional work on the technology gaps (Section 8) have the good potential of progressing the technology for these designs to project ready status in the next 3-5 years. Therefore these designs are selected for further assessment in the current study.

While the key technologies for Designs E and F are also likely to progress to project ready status in the next 3-5 years, they are more focused on a single supplier/vendor proprietary technology than Designs C, D and E, and therefore not further assessed in the current study.

1.8 Technology Gaps and Roadmap

The following are the technology gaps for subsea discharge of produced water:

System Component or Technology Need	Current Technology Readiness Level (TRL)	Estimated Time to TRL 5 (Project Ready)
Inline Desanders	TRL 3	Q3 2014
Solids Filter	TRL 0	Q4 2017
Coalescing Oil Filter	TRL 2	Q2 2015
Solids Handling and Storage	TRL 3	Q1 2015
Ceramic Membrane Filters	TRL 2	Q2 2015
Filter Maintenance	TRL 4	Q3 2014
Liquid/Liquid Subsea Hydrocyclones	TRL 2	Q2 2015
Fast Acting Valves	TRL 2	Q2 2015
Electrical Power Actuators	TRL 2	Q2 2015
Large Vessel Integrity	TRL 2	Q2 2014
Compact Floatation Units (CFU)	TRL 2	Q2 2015
Subsea Produced Water Quality Sampling	TRL 4	Q3 2014

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System Component or Technology Need	Current Technology Readiness Level (TRL)	Estimated Time to TRL 5 (Project Ready)
Subsea Produced Water Quality Monitoring	TRL 1	Q3 2014
Subsea Sample Storage	TRL 3	Q1 2015

1.9 Summary

Although discharging produced water to the ambient seawater from topside is standard practice in the industry and with proven technology, several obstacles must be overcome to do this subsea at the seabed. Today's topside technologies are meeting discharge criteria set forth by the toughest regulators around the world and studies show that the marine life is not adversely affected by these practices.

No known subsea production system has ever used any form of the typical produced water treatment technologies on topside offshore facilities, anywhere, throughout the world.

However, after a long review of the top processes and technologies being used in the industry today, subsea processing of produce water and discharge to the seabed should be achievable with development and qualification of technology in the next 3-5 years.

It is estimated that, with a continuously funded technology development program, the timing for the conceptual design to become project ready is

- Design B (hydrocyclones, Compact Flotation and Coalescing Filters): 2017
- Design C (hydrocyclones and Coalescing Filters): 2017
- Design D (Compact Flotation): 2015

REFERENCES

1.) OGP, International Association of Oil and Gas Producers, Fate and Effects of Naturally Occurring Substances in Produced Water on the Marine Environment, Report No. 364, February 2005.

2.) TUV-NEL, Figure 1 data chart courtesy of TUV-NEL Produced Water Group Workshop 2010.

3.) BOEM, http://www.boemre.gov/eppd/ – The Bureau of Ocean Energy Management, Regulations and Enforcement website, 2012

4.) EPA-NPDES, http://cfpub.epa.gov/npdes/ – The Environmental Protection Agencies National Pollutant Discharge Elimination System website, 2011

5.) ANL - Argonne National Laboratory, A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas and Coal Bed Methane, Jan. 2004

6.) David W. Fisher and Detlof von Winterfeldt, Setting Standards for Chronic Oil Discharges in the North Sea., Jan. 1978

INTRODUCTION TO STUDY

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INTRODUCTION TO STUDY

2.0 INTRODUCTION

This Report summarizes the information gathered and defined for the Research Partnership to Secure Energy for America (RPSEA) Project, Seabed Discharge of Produced Water and/or Solids – 09121-3100-01.

Fluor was awarded a contract with the objective to clearly define the challenges facing the subsea processing industry to understand what would be required to discharge produced water and or solids at the seabed. This is part of RPSEA's prime contract DE-AC26-07NT42677 that has been issued by the Department of Energy.

The work was completed with the collaboration of

- Fluor project team conducting the research, concept development and evaluation, technology gap analysis, technology development roadmap creation, and the other detailed tasks for the study
- RPSEA, providing overall project supervision
- A Working Committee, with representatives from Anadarko, BP, Chevron, ConocoPhillips, ExxonMobil, Shell, Statoil and Total, providing guidance to the study
- Experts from universities and industry (Texas A&M University Galveston, Louisiana State University, Entergy and TUV-NEL) participating in discussions in their areas of expertise such as marine life, water production statistics, and laboratory testing of produced water samples for regulatory compliance
- Technology suppliers, providing experience on their installed systems, discussion on their emerging technologies, and their understanding of the water treatment requirements. These include Aker Solutions, Borneman, Advance Sensors, ASCOM, CALTEC, Cameron, CETCO, ClearFlow Solutions, Champion, Clean H2O Services, Enhydra, DPS Global Technologies, Enerscope Systems, Envirotech, FMC Technologies, Emerson Process, eProcess Technologies, Framo, GE, JM Canty, Jorin, NIMTech, Roxar, Seimens, Nalco Veolia, ProSep, Halliburton Water Services, Schlumberger Water Services, MI Swaco, WS Tech, Turner Designs, Tracerco, Veil Environmental and Vigilant Environmental,
- The project management personnel for the study, university and industry experts, and technology supplier representatives who provided guidance or input to the study are listed in Tables 2.1 and 2.2.

The project team researched many different sources to properly address the challenges facing seabed discharge of produced water and/or solids. The goals of this project were to: (a) identify worldwide regulations, standards and HSE requirements governing produced water disposal; (b) identify constituents of produced water (PW) and quantify their adverse contribution in satisfying the current regulations; (c) estimate their relevance to an environmental situation; (d) understand and summarize the seabed conditions and aquatic life with regard to their potential impact of discharging PW; (e) review cost and impact assessments of individual components and hypothetical systems, and the combination there of and reference their technical readiness level (TRL 1 – 7); (f) define with subsea processors (SSP) developers an initial conceptual SSP design incorporating discharge of produced water and/or solids.

Using that basis of design, a thorough assessment was done on the regulations for discharging produced water throughout the industry. The seabed and marine life was studied at the target water depths of 5000 to 8000 feet depths. Then, a state of the art review into the produced water treatment process and analytical requirements was made. Using that information, the group of subject matter experts within Fluor completed a series of conceptual design workshops to produce an initial conceptual design for treating and discharging produced water at the seabed.

Lastly, the completed workshop helped to identify the gaps in the technology and was used to establish a roadmap and conclusion of this first of its kind study.

Table 2.1. Project Management Personnel for the Study

Name	Organization	Role	Phone	Email
Don Richardson	RPSEA	Project Manager	281-690-5514	drichardson@rpsea.org
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Table 2.2. Working Committee Members

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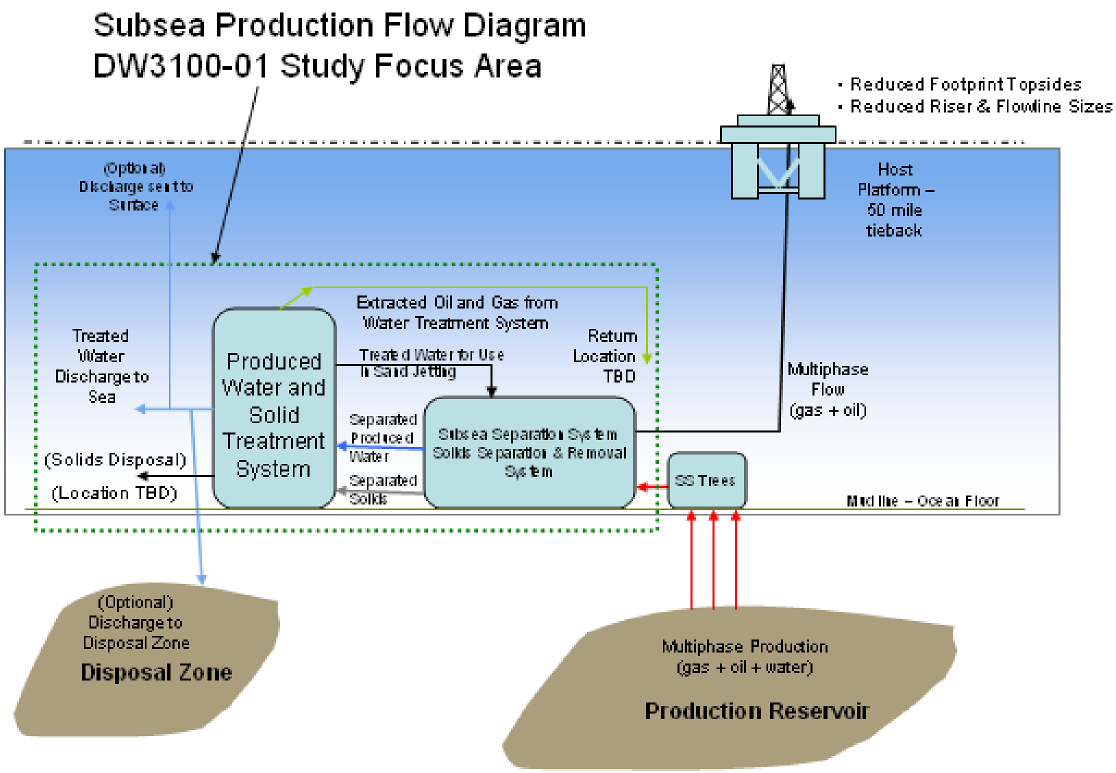
2.1 Basis of Design for Study

A Basis of Design was developed to provide a framework for the study.

One can derive many different types of scenarios for a field development plan or field layout. In this case, the produced water treatment system must be used with a subsea separation system. The host to the system will be a 50 mile tieback. The subsea processing system will separate the full well streams into oil, gas and water with solids and the produced water treatment system will consider an inlet of separated produced water and solids. The max oil concentration may be as high as 5000 ppm oil in water. The facility will include reliable inlet and outlet real time monitoring. The Discharge Zone needs to minimize the environmental impact. It should be required to have a height of 10 – 15 feet from the seafloor and placed in a geometric location away from the subsea equipment at a distance that allows for effective dispersal. Another method of discharge may be to send the treated produced water to the surface for surface dispersion, but this method will not be studied in this project.



The study will also identify operational challenges of handling upsets, restarts and commissioning start up.

2.2 Basis of Design Inputs and Production Conditions

The following table lists the general field design parameters and comments regarding the choice of these input parameters:

Table 2.3 Field Inputs

Design Parameter	Value	Comments
Seawater Temperature	38 °F	The Seawater Temperature, Field Water Depth, Remote Host Water Depth, and the Tieback Distance used in the study were suggested as typical values that operating companies expect to encounter as they develop Canopy-type fields in the Gulf of
Field Water Depth	8,000 feet	
Remote Host Water	5,000 feet	

Design Parameter	Value	Comments
Depth		Mexico.
Tieback Distance	50 miles	
System Design Pressure (shut in tubing head pressure)	7,500 psia	This is the system design pressure for shut in conditions.
Flowing Wellhead Pressure[1]	1000 psia	This is an estimated flow pressure at working conditions. It would be less or more depending on the flowing conditions.
Flowing Wellhead Temperature	250 °F	This temperature reflects the typical temperature of a Palogene production field used for the flowing wellhead temperature.
Liquid Rate	Up to 80,000 barrels / day	The Liquid Rate for the study was selected to be high enough to support the need for subsea processing field developments.
Water Cut	0 - 80%	Typical for the industry and recommended from RPSEA working committee member to consider a longer life cycle of the well.

[1]To reduce the complexity of the design basis, the separation system operating pressure, boosting system inlet pressures, and produced water treatment system inlet pressure are assumed to be equal to the flowing wellhead pressure (1000psia)

2.3 Basis of Design Fluid Properties from the Producing Wells

The following table lists the fluid properties used for the study (Low GOR and High GOR) and comments regarding the choice of the fluid properties:

Table 2.4, Fluid Properties from the Producing Wells.

Design Parameter	Low GOR	High GOR	Comments
Gas-Oil Ratio	250 scf/bbl	2000 scf/bbl	The Gas-Oil Ratio and API Gravity were based upon the Early Production System Study (CTR 9902).
API Gravity, °API	17	28	
Solid Concentration, ppm[1]	100	100	The solid concentration selected for the study was purposefully higher than any operating company expects to see during normal operations. The main purpose for selecting this value was to identify

Design Parameter	Low GOR	High GOR	Comments
			potential gaps related to high inlet solid concentrations
Bubble Point, psia	1500	4000	The single bubble point pressure specified at the beginning of the study was inadvertently dropped from the subsequent design basis presentation and discussion (when the remaining fluid properties were defined). Future studies should consider using a lower bubble point pressure for the Low GOR fluid property cases (~1200 psia).

[1] Parts per million (volumetric basis) solid particles distributed in the liquid phase (oil + water).

The following stock tank oil viscosity data is needed to provide a typical viscosity of the oil at different temperatures throughout the subsea production system.

Table 2.5, Stock Tank Oil Viscosity Data[2]

Temperature, °F	Low GOR viscosity, cP	High GOR viscosity, cP
40		178
41	3300	
50	2100	95
68	900	53
86	200	
104		19
122	70	
140		10

Temperature, °F	Low GOR viscosity, cP	High GOR viscosity, cP
158	30	
194	20	
266	8	1

[2] Typical viscosity values for 17 and 28 °API oil (data provided by a RPSEA working committee member).

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Table 2.6, Actual Flow Rates

Design Parameter	Low GOR = 250 scf/bbl		High GOR = 2000 scf/bb	
Water Cut, %	0	80	0	80
Oil, barrels / day	80,000	16,000	80,000	16,000
Water, barrels / day	0	64,000	0	64,000
Gas, cubic feet / day	20 MM	4 MM	160 MM	32 MM
Gas Volume Fraction, %	98.3	98.3	99.7	99.7

Note: Both scenarios were evaluated using the Low GOR and the High GOR fluid cases to ensure the broadest range of design parameters were considered. Actual subsea processing systems will typically not be designed for this broad range of fluid properties.

2.4 Basis of Design Produced Water Treatment System

The following table lists the overall technical specifications for the produced water treatment system.

Table 2.7, Produced Water Treatment System Technical Specifications

Design Parameter	Value
Water Depth	8,000 feet
Design Pressure	7,500 psia
Design Temperature	250 °F max
Water Rate	Up to 64,000 barrels / day
Water Disposal	Seabed Discharge
Inlet oil concentration Upset potential concentration	1000 ppm 5000 ppm
Target Outlet Oil Concentration (Current Gulf of Mexico requirement is 29 ppm for discharging overboard, Gabon is 20 ppm, North Sea is 30 ppm.)	15 ppm average per month (recommendations for 10 ppm) No more than 62 tons per year.
Target Inlet solid concentration	100 ppm
Target Outlet Solid Production	~ 700 lbs per day max

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Table 2.8, Basis of Design for Typical Cations and Anions in Produced Water Compositions

Properties		**Low**	**High**	**Typical Design Values**
Specific Gravity	g/cm^3	1.08	1.15	1.1482
pH		6.1	7.8	6.12
Resistivity	Moh m	0.037	0.061	0.05
Cations				
Calcium (Ca)	mg/L	3080	6300	6300
Magnesium (Mg)	mg/L	171	3294	1090
Barium (Ba)	mg/L	38	405	405
Strontium (Sr)	mg/L	53	295	295
Sodium (Na)	mg/L	30348	80470	80470
Potassium (K)	mg/L	455	455	455
Iron (Fe)	mg/L	2	46	46
Manganese (Mn)	mg/L	2	26	6
Lithium (Li)	mg/L	3	7	6.6
Aluminum (Al)	mg/L	0	0	
Ammonia (NH_3)	mg/L	0	0	
Cadmium (Cd)	mg/L	0	0	<0.006
Chromium (Cr)	mg/L	0	0	<0.007
Cobalt (Co)	mg/L	0	0	<0.01
Copper (Cu)	mg/L	0	0	<0.009
Molybdenum (Mo)	mg/L	0	0	<0.044
Nickel (Ni)	mg/L	0	0	<0.02
Phosphorus (P)	mg/L	0	0	<0.17
Silicon (Si)	mg/L	27	27	27
Vanadium (V)	mg/L	0	0	<0.01
Anions				
Chloride (Cl)	mg/L	58540	136550	136550
Sulfate (SO_4)	mg/L	1	250	25
Dissolved CO_2	mg/L	50	110	
Bicarbonate (HCO_3)	mg/L	73	1270	1270
H_2S	mg/L	0	0	
Phosphate (PO_4)	mg/L	0	0	<1.0
Silica (SiO_2)	mg/L	0	0	
Fluoride (F)	mg/L	79	79	79
Nitrate (NO_3)	mg/L	0	0	<1.0
Lead (Pb)	mg/L	0	0	<2.2
Zinc (Zn)	mg/L	1	1	0.5
Bromine (Br)	mg/L	0	0	
Boron (B)	mg/L	0	0	

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Properties		Low	High	Typical Design Values
Borate ($B(OH)_4$)	mg/L	36	36	36
Bromide (Br)	mg/L	185	185	185
Carbonate (CO_3)	mg/L	26	26	
Iodide (I)	mg/L	39	39	39
Nitrite (NO_2)	mg/L	0	0	<1.0
Sulfide (S)	mg/L	0	0	
TDS	**mg/L**			**227285**

(The above compositions were taken from multiple samples, component by component. They don't coexist in the same sample. Also, the typical solid composition will have to be characterized later in the project in terms of oil concentration and other pollutants.)

Discussions on produced water components are provided in Section 3.

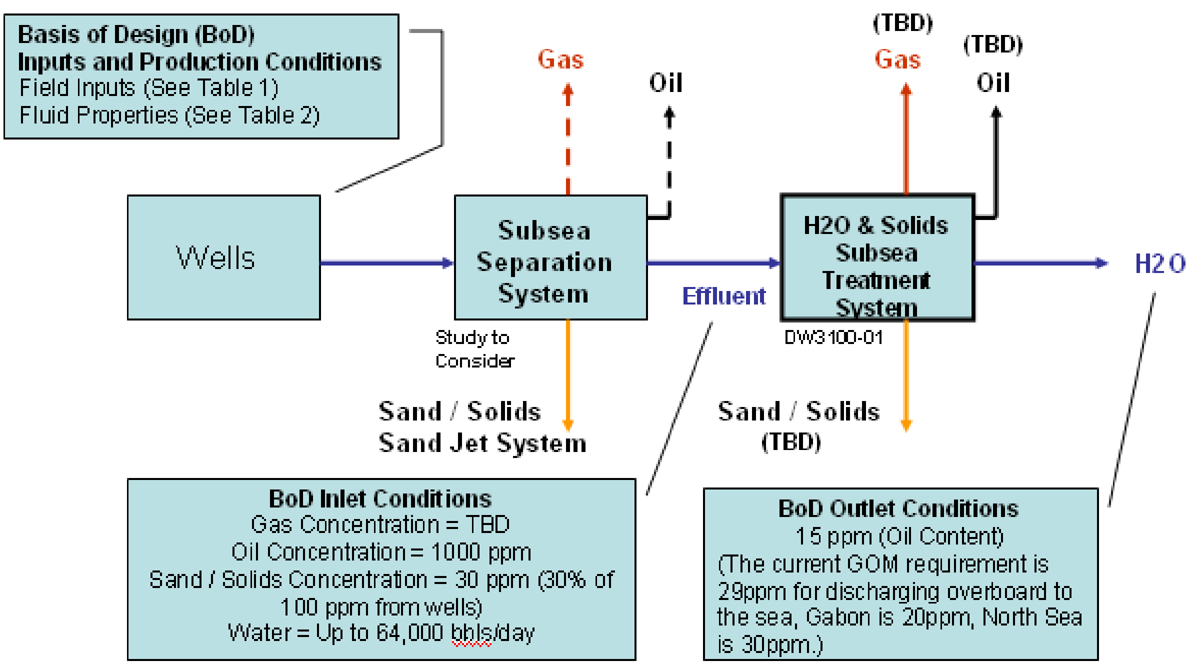
2.5 Basis of Design for Typical Seawater Composition

(Reference below taken from the OCS Report MMS 2006-018 for the Gulf of Mexico)

Major dissolved constituents in seawater with a chlorinity of 19 ‰ and a salinity of 34.32 ‰.			
Dissolved substance	Ion or compound	Concentration (grams per kilogram)	Percent by weight
Chloride	Cl^-	18.980	55.04
Sodium	Na^+	10.556	30.61
Sulfate	SO_4^{2-}	2.649	7.68
Magnesium	Mg^{2+}	1.272	3.69
Calcium	Ca^{2+}	0.400	1.16
Potassium	K^+	0.380	1.10
Bicarbonate	HCO_3^-	0.14	0.41
Bromide	Br^-	0.065	0.19
Boric Acid	H_3BO_3	0.026	0.07
Strontium	Sr^{2+}	0.013	0.04
Fluoride	F^-	0.001	0.0
Totals		34.482	99.99

2.6 Flow Diagram for BOD

The following flow diagram is given to help highlight the basis of design constraints and requirements.



The question of what is good enough quality will most likely be addressed through water quality based limits. The best available technology economically achievable (BAT) oil and grease limits for Offshore Subcategory produced water were established under the Effluent Limitations Guidelines based on the dissolved gas floatation technology. Those produced water discharges are limited a monthly average of 29 mg/l and a daily maximum of 42 mg/l. The oil and grease limits have been difficult to achieve in some cases where dissolved oil is present in the produced water. In many cases operators have resolved that issue by adjusting the pH of produced water prior to treatment.(EPA, 2011)

Currently, there are no regulations governing produced water disposal at the seabed and the discharge of sand is prohibited in the Gulf of Mexico.

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

SECTION 3 TABLE OF CONTENTS

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

3.0 PRODUCED WATER COMPOSITIONS AND PRODUCTION ADDITIVES

Produced water is the total water generated from the oil and gas extraction process (EPA 1993). It includes the formation water brought from the reservoir by the production process and the water injected into the reservoir for secondary recovery. The produced water is a complex mixture of water, dissolved inorganic and organic components, droplets of hydrocarbon and non-hydrocarbon organic materials, and suspended solids of silt, clay and sand. Additionally, produced water may contain elevated concentration of radionuclides. The compositions are mostly dependent on the nature of the oil and gas reservoir, and also to some extent on the processing of the well stream fluids and treatment of the produced water. The produced water compositions are also affected by the production additives used.

A number of studies have been performed in the past several decades to characterize the produced water. Some of the studies are:

- A study the US Environmental Protection Agency (EPA) conducted in the 1980's (EPA 1993) which includes a study of 30 Gulf of Mexico platforms, a California sampling program, and an Alaska sampling program. These studies formed the basis for produced water in the EPA development document for offshore effluent discharge limitation guidelines.
- A study conducted by US Department of Interior, Minerals Management Service (MMS), on the fate and effects of nearshore discharges of outer continental shelf produced water from seven platforms (MMS 1991)
- A study by the Offshore Operators Committee on the bioaccumulation due to US Gulf of Mexico produced water (OOC 1997)
- A characterization of offshore versus onshore produced water by Oak Ridge National Laboratory funded by US Department of Energy and the Petroleum Energy Research Forum (McFarlane 2004)
- A study of Gulf of Mexico produced water with and without treatment with silica gel (Brown 1992)
- A detailed analysis of produced water from wells on the Louisiana shelf (Neff 1992)
- A number of studies on the produced water from North Sea (OGP 2005, OGP 2002, OGP 1994, Utvik 1999, Utvik 2002, Barth 1987, Brendehaug 1992)

The compositions discussed below are based on discharges from platforms, which are treated produced water. The influent to a subsea water treatment system before seafloor discharge is dependent upon the separation system used as well as other production system configuration or parameters.

3.1 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)

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

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

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.

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

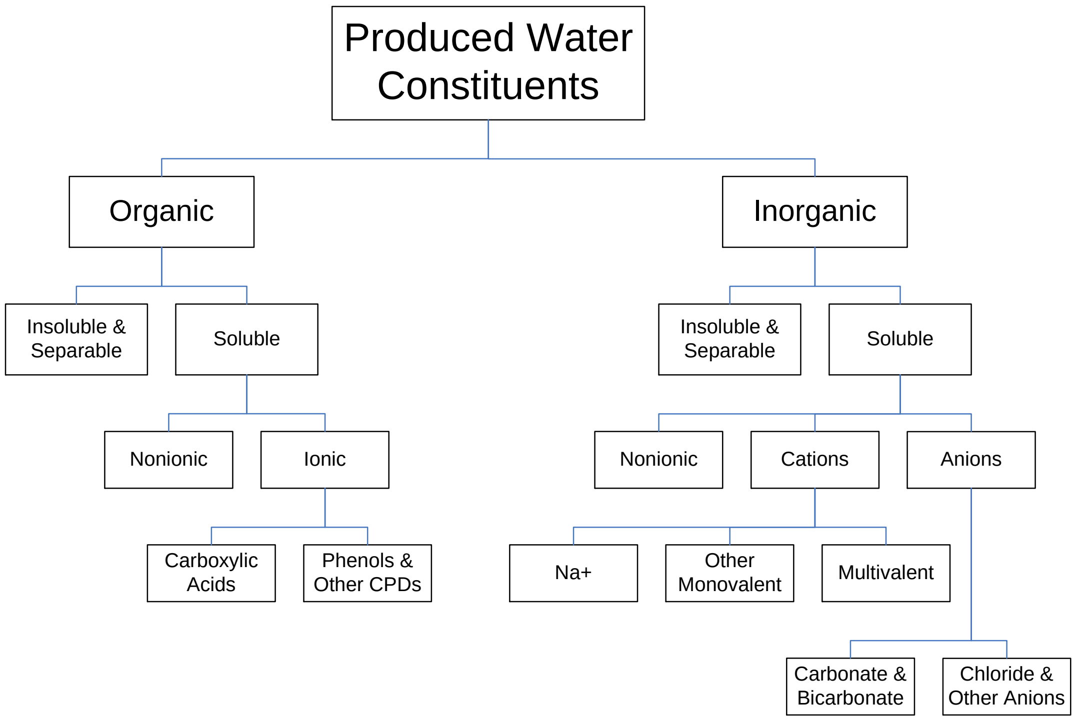


Figure 9 - Produced Water Constituents (Hayes, 2004)

3.2 Produced Water Compositions

3.2.1 Dissolved Solids

For fields without water injection, the produced water is composed of formation water as the primary part and condensed water from gas as the small remaining part. Exceptions are gas fields in early production years when there is virtually no formation water produced and the produced water is essentially all condensed water. Formation water generally has lower pH and higher salinity than sea water. For fields with water injection, the produced water compositions will approach that of the injected water over time. The salinity of the produced water can vary from almost fresh, to close that of seawater, or saturated depending on the nature of the reservoir and the production process.

The major inorganic constituents of produced water are dissolved salts of sodium, calcium, magnesium, potassium, barium, iron, strontium, and manganese. There is also small amount of other cations of other metals. The primary anionic constituents are chloride, bicarbonate, sulphate and nitrate. For the current study, the formation water analysis results for six deepwater US Gulf of Mexico producing facilities were collected, as shown in Table 1. These values represent the typical produced water compositions from deepwater Gulf of Mexico.

The 30 platform study by US EPA (EPA 1993) observed the baseline characteristics in produced water (Best Practicable Technology effluent) as shown in Table 2. For the produced water characteristics from the California and Alaska sampling program, see the reference (EPA 1993).

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

The salinity and sulfide content of the nearshore discharges of US Gulf of Mexico outer continental shelf produced waters were measured in the 1991 MMS study (MMS 1991a, b, c). The salinity ranged 43 – 192 ppt (part per thousand). The sulfide content ranged from not detectable to 143 □g-at S.l^{-1}. The study observed that, “The produced water effluent generally had barium (Ba), vanadium (V) and nickel (Ni) in highest concentrations. Zinc (Zn), copper (Cu) and chromium (Cr) were also found in high concentrations in most of the discharges. Cadmium (Cd), mercury (Hg) and lead (Pb) were also detected in various effluents. [The data for aluminum (Al) and arsenic (As) were not reported, because the high salt background caused interference with the analysis.]”. Similar conclusion on metal concentration can also be drawn from the study by Neff et al (1992).

The dissolved solids characteristics in North Sea produced water were summarized by the International Association of Oil & Gas Producers study (OGP 2005). The largest component is chloride, with an average of 44,630 mg/l, followed by sulphate (814 mg/l), bicarbonate (615 mg/l), and nitrade (1 mg/l). The study also found the produced water contained trace metals of Fe, Hg, Cd, Pb, Zn, Cu, Cr, As, and Ni. The concentration varies considerably across fields. Produced water from gas fields usually has higher values of heavy metals than oil fields. Early production produces significantly higher trace metal content than that from mature fields.

Produced water may also contain a small amount of Naturally Occurring Radioactive Material (NORM). NORM originates in geological formation and is brought to surface as dissolved solids in produced water. NORM may precipitate into scale or sludge when the water temperature reduces as it reaches the surface. The most abundant NORM compounds are Ra-226 and Ra-228 (Veil 2004), which are both shown in Table 2.

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

Table 1. Formation Water Analysis Results for Some Deepwater US Gulf of Mexico Oil Producing Facilities

Properties		Facility 1	Facility 2	Facility 3	Facility 4	Facility 5	Facility 6
Specific Gravity	g/cm^3	1.076	1.123	1.106	1.082		1.1482
pH		6.8	7	6.2	6.93	7.8	6.12
Resistivity	Mohm	0.0607	0.0371	0.0377			0.05
Cations							
Calcium (Ca)	mg/L	4880	5800	3080	3360	5120	6300
Magnesium (Mg)	mg/L	170.8	366	3294	437	972	1090
Barium (Ba)	mg/L	173.42	38.19	195.4	42		405
Strontium (Sr)	mg/L				53		295
Sodium (Na)	mg/L	35234	58710	56456	44868	30348	80470
Potassium (K)	mg/L						455
Iron (Fe)	mg/L	17.64	30	39.09	2	4	46
Manganese (Mn)	mg/L	3.76	26	8.55	2.1		6
Lithium (Li)	mg/L		2.53				6.6
Aluminum (Al)	mg/L						
Ammonia (NH_3)	mg/L						
Cadmium (Cd)	mg/L						<0.006
Chromium (Cr)	mg/L						<0.007
Cobalt (Co)	mg/L						<0.01
Copper (Cu)	mg/L						<0.009
Molybdenum (Mo)	mg/L						<0.044
Nickel (Ni)	mg/L						<0.02
Silicon (Si)	mg/L						27
Vanadium (V)	mg/L						<0.01
Phosphorus (P)	mg/L						<0.17
Anions							
Chloride (Cl)	mg/L	67000	113000	111000	76000	58539.5	136550
Sulfate (SO_4)	mg/L	1	1	1	250	200	25
Dissolved CO_2	mg/L	50		110	70		
Bicarbonate (HCO_3)	mg/L	1220	102	854	488	73.2	1270
H_2S	mg/L						
Phosphate (PO_4)	mg/L						<1.0
Silica (SiO_2)	mg/L						
Fluoride (F)	mg/L						79
Nitrate (NO_3)	mg/L						<1.0
Lead (Pb)	mg/L						<2.2
Zinc (Zn)	mg/L						0.5

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

Properties		Facility 1	Facility 2	Facility 3	Facility 4	Facility 5	Facility 6
Borate ($B(OH)_4$)	mg/L						36
Bromide (Br)	mg/L						185
Carbonate (CO_3)	mg/L					26.4	
Iodide (I)	mg/L						39
Nitrite (NO_2)	mg/L						<1.0
Sulfide (S)	mg/L						
TDS	mg/L	108751	178076	175038	125572	95283	227285

Table 2. Effluent Metal Pollutant Concentration in US Offshore Discharges of Produced Water (EPA 1993)

Constituent	Concentration after BPT Level Treatment (mg/l)	Concentration after BAT Level Treatment (mg/l) – Gas Flotation Treatment
Aluminum	0.078	0.050
Arsenic	0.11	0.073
Barium	55.6	35.6
Boron	25.7	16.5
Cadmium	0.023	0.014
Copper	0.45	0.28
Iron	4.9	3.1
Lead	0.19	0.12
Manganese	0.12	0.074
Nickel	1.7	1.1
Titanium	0.007	0.004
Zinc	1.2	0.13
Radium 226 (in pCi/L)	0.00023	0.00020
Radium 228 (in pCi/L)	0.00028	0.00025

3.2.2 Suspended Solids

Produced water contains a small amount of suspended solids, which can be silt, clay, sand, precipitated solids, or organic materials. Suspended solids can also come from proppant, corrosion products, and other types from wellbore operations (Veil 2004). Studies found that US Gulf of Mexico and North Sea discharges of produced water contain 3 – 249 mg/L of total suspended solids (OGP 1994, Jackson 1981). As shown in Table 2, the EPA study determined a baseline effluent characteristic of 67.5 mg/l in total suspended solids with Best Practicable Technology. The EPA study also determined 30.0 mg/l to be the Best Available Technology (Improved Gas Flotation) concentration.

3.2.3 Organic Constituents

The organic constituents of produced water fall into the three general categories (OGP 2005):

- Dispersed hydrocarbons
- Dissolved hydrocarbons
- Dissolved non-hydrocarbons

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

Additionally, the suspended solids may be coated with organic materials. Dissolved non-hydrocarbon organic compounds form the bulk of the organic contents of the produced water.

Table 3 shows the typical concentrations of organic constituents in produced water from US offshore production. Table 4 shows a compilation of the analyses from several studies of Norwegian produced water from 1995 onward (McFarlene 2004, Utvik 2002). Another set of North Sea data is presented in Table 5.

The dispersed oil is the primary contributor to the oil and grease amount measurements. Its environmental impacts are the contamination and accumulation on ocean sediments which can disturb the benthic community, and sheening on the ocean surface and increasing biological oxygen demand near the mixing zone (Veil 2004, Stephenson 1992).

Due to their solubility properties, compounds such as aliphatic hydrocarbons are mainly found in dispersed phases while others such as carboxylic acids are mainly found in the water phase (OGP 2005). Hydrocarbons that occur naturally in produced water due to solubility or semi-solubility include organic acids, polycyclic aromatic hydrocarbons (PAHs), phenols, and volatiles. These hydrocarbons contribute to water toxicity, and their toxicities are additive (Veil 2004, Glickman 1998).

Tables 3 and 4 show that carboxylic acids are the largest fraction of organic materials in produced water. Due to the high solubility of low molecular weight carboxylic acids (fatty acids), ketones, and alcohols,, the organic solvents used in oil and grease analysis (such as Freon and hexane) extracts virtually none of them, therefore they do not contribute to the oil and grease measurements (Veil 2004, Ali 1999).

Phenols and aromatic compounds have varying solubility in water. Aromatic compounds in produced water can be subdivided into three main categories (OGP 2005):

- Mono-aromatic highly volatile compounds - benzene, toluene, ethylbenzene and xylene (BTEX)
- 2 ring compounds - naphthalene, phenanthrene, and dibenzothiophene (NPD)
- Compounds with 3 or more rings – Polycyclic Aromatic Hydrocarbons (PAH)

Aromatics in produced water are predominantly BTEX, with benzene and toluene being the major component of BTEX, as can be seen from Tables 3 and 4. PAH components are less than 0.2% of the aromatic content of produced water.

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

Table 3. Typical Concentrations of Organic Constituents in Produced Water from US Offshore Production (EPA 1993).

Constituent	Concentration after BPT Level Treatment (mg/l)	Concentration after BAT Level Treatment (mg/l) – Gas Flotation Treatment
Oil and grease	25	23.5
2-Butanone	1.03	0.41
2,4-Dimethylphenol	0.32	0.25
Anthracene	0.018	0.007
Benzene	2.98	1.22
Benzo(a)pyrene	0.012	0.005
Chlorobenzene	0.019	0.008
Di-n-butylphthalate	0.016	0.006
Ethylbenzene	0.32	0.062
n-Alkanes	1.64	0.66
Naphthalene	0.24	0.092
p-Chloro-m-cresol	0.25	0.010
Phenol	1.54	0.54
Steranes	0.077	0.033
Toluene	1.901	0.83
Triterpanes	0.078	0.031
Total xylenes	0.70	0.38

Table 4. North Sea Produced Water Contamination (Utvik 2002)

Compound	Low Concentration ($mg \cdot L^{-1}$)	High Concentration ($mg \cdot L^{-1}$)
Dispersed oil	10	40
BTEX	1	40
NPD	0.9	10
PAH	0.01	0.13
Organic Acids	55	760
Phenol	0.1	6
C1-C4 alkylated phenols	0.17	11.3
C4-C7 alkylated phenols	0.1	0.8

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Table 5. Typical North Sea Produced Water Constituents (Brendehaug 1992)

Wells	Gullfaks A Flotation Cell	Gullfaks B Flotation Cell	Statfjord B Flotation Cell	Statfjord B Degas Tank	Statfjord B Flotation Cell	Statfjord B Degas Tank
Main fractions	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Aliphatic	2.45	5.81	0.0254	1.65	0.316	0.888
Aromatic	1.04	3.99	1.5	1.63	1.05	2.12
Polar	6.77	15.7	72.4	31.8	27.5	65.3
Fatty acids	36.7	53.5	690	790	543	lost
Total Organic	47	79	763	825	575	lost
Aromatic	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L
BTEX	582	533	168	130	145	159
Napthalenes	49.3	2160	622	942	708	845
Phenanthrenes	12.5	90	23	41.7	36.8	21-3
Dibenzothiophenes	3.17	22.7	8.16	10.8	10.2	5.07
Acenaphthene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Acenaphthylene	0.047	1.53	1.11	1.04	0.666	0.787
Fluorene	0.254	11.3	12	12	8.89	9.5
Anthracene	<0.001	<0.001	0.032	0.046	0.0341	0.0396
Fluoranthene	0.0269	0.195	0.0415	0.0892	0.0854	0.0458
Pyrene	0.0291	0.194	0.0559	0.121	0.118	0.0669
Benzo(a)anthracene	<0.001	0.0311	0.0045	0.0193	0.0151	0.012
Chrysene/triphenylene	0.329	0.3398	0.0403	0.203	0.226	0.112
Benzo(bjk)fluroranthene	<0.001		<0.001		<0.001	<0.001
Benzo(a)pyrene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Benzo(ghi)perylene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Phenols	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Phenol	0.262	0.152	4.86	2.59	2.84	2.3
C1	0.209	0.375	2.84	3.09	2.92	2.51
C2	0.0603	0.107	1.26	0.72	0.771	0.884
C3	0.054	0.725	0.634	0.253	0.322	0.603
C4	0.0117	0.237	0.0658	0.0217	0.0279	0.0805
C5	0.0124	0.0946	0.0235	0.0048	0.0081	0.0352
C6	0.006	0.0243	0.0073	<.001	0.0016	0.0127
C7	0.0026	0.0062	<.001	<.001	<.001	<.001
Total	0.618	1.72	9.69	6.69	6.89	6.43

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

3.3 Production Additives Summary

In addition to the natural constituents, produced water also contains production additives which are chemicals added to the production stream for purposes of flow assurance, reservoir flow performance, production system integrity management, bacteria control, separation enhancement, etc. The production additives may be added to the reservoir through periodical batch treatment, bullheading into the tubing during production shutdown, or continuous injection at various locations such as bottom of tubing, upstream of production chokes, downstream of production chokes, and in topsides separation or treatment equipment. The concentration of the production additives in produced water depend on many factors including the dosage of chemical used and partitioning of the chemicals into oil and water phases.

The following are the primary production additives used in deepwater developments:

- Gas hydrate inhibitors
- Corrosion inhibitors
- Scale inhibitors
- Asphaltene dispersands
- Paraffin inhibitors
- Defoamers
- Demulsifiers
- Biocides and other additives

Gas hydrate inhibitors and corrosions are the most frequently used chemicals for deepwater developments. Subsea defoamer injection has been critical to some of the recent deepwater projects with subsea separation. Table 6 summarizes the chemicals, their dosages, and typical concentration in water.

In some cases, there may also be some amount of drilling and completion fluid residues in the initial period of production.

Table 6. Production Additives in Deepwater Developments and Typical Concentrations

Production Additive	Typical Injection Point	Typical Dosage	Typical Concentration in Produced Water
Gas Hydrate Inhibitor – Methanol and Ethanol	Upstream of production chokes	20 – 50% by weight of produced water	10-30% by weight
Gas Hydrate Inhibitor – MEG	Upstream of production chokes	25 – 150% by weight of produced water	20 – 60% by weight
Gas Hydrate Inhibitor – Kinetic Inhibitor	pstream of production chokes	0.75% - 2% of produced water volume	0.75% - 2% of produced water volume
Gas Hydrate Inhibitor – Anti-Agglomerates	Upstream of production chokes	0.5% - 2% of produced water volume	0.5% - 2% of produced water volume
Corrosion Inhibitors	Pipeline. Also used in downhole tubing.	10-50 ppm in water, up to 500 ppm in special cases	Almost all partitioned to water

PRODUCED WATER COMPOSITIONS PRODUCTION ADDITIVES

Production Additive	Typical Injection Point	Typical Dosage	Typical Concentration in Produced Water
Scale Inhibitors	Downhole squeeze and/or continuous injection to tubing	10-50 ppm in water	Almost all partitions to water
Asphaltene Dispersants	Downhole injection to tubing	250 ppm in oil	Almost none
Paraffin Inhibitors	Downstream of production chokes for deepwater developments.	500 ppm in oil	Almost none
Defoamers	Subsea separators	100 ppm of liquid	Little
Emulsion Breakers	Downstream of production chokes for deepwater developments.	25 – 100 ppm of oil	Some partitions to water
Biocides and other additives	Varies	100 ppm	Varies

* Typical rates according to Nalco (Nalco 2011).

3.3.1 Gas Hydrate Inhibitors

There are currently three types of gas hydrate inhibitors: thermodynamic inhibitors (methanol, ethanol or glycol), kinetic hydrate inhibitors, and anti-agglomerates. The latter two require substantially lower dosage than thermodynamic inhibitors and therefore are referred to as low-dosage hydrate inhibitors (LDHI).

Methanol and Ethanol

Methanol inhibits hydrate formation by shifting the thermodynamic equilibrium of the fluid mixture it is added to, so that the hydrate formation temperature at the local pressure is lower than the expected fluid temperature. Methanol readily dissolves in water however it is volatile so partitions into gas, and it also partitions into liquid hydrocarbon. The required dosage rate depending on the hydrate subcooling, salinity of the produced water, gas liquid ratio, water cut etc. Typical methanol concentration in the produced water for deepwater development is 10 – 30% by weight.

Ethanol is used instead of methanol in regions of high ethanol availability, such as Brazil. Slightly higher weight percentage of ethanol is required to achieve the same inhibition level.

Glycol

Mono-Ethylene Glycol (MEG) is the most common form of glycol used. Diethylene glycol (DEG) and Tri-Ethylene Glycol (TEG) have also been used in some special cases. Glycol inhibits hydrate formation by shifting the thermodynamic equilibrium, similar to methanol. Glycol almost entirely partitions into water. Typical glycol concentration in the produced water for deepwater development is 20 – 60% by weight.

Kinetic Hydrate Inhibitors

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Instead of reducing the hydrate formation temperature, kinetic hydrate inhibitors (KHIs) function by delaying nucleation and reducing growth of hydrates so that the total amount of hydrate in the system during the KHI's effective period is less than the threshold to cause hydrate blockage. KHI's are generally alkylated ammonium, phosphonium, or sulfonium compounds, such as tetrabutylammonium bromide, amino acids and amino alcohols (Fink 2003). The two main classes of polymers used in KHI formulations in oil and gas field operations are: (1) homopolymers and copolymers of vinyl caprolactam; (2) hyperbranched poly(ester amide)s (Villano 2009).

The time period of effectiveness is affected by KHI, its dosage rate, and the subcooling. At present the subcooling limit for KHI is generally 10 – 11^{o}C. According to Nalco, one of suppliers of hydrate inhibitors and other oil field chemicals, typical dosage of the formulated KHI products is 0.75% - 2% of produced water volume (Nalco 2011).

Anti-Agglomerates

Anti-agglomerates (AA) are another type of low dosage hydrate inhibitor, with typical dosage of anti-agglomerates is 0.5% - 2% of produced water volume (Nalco 2011). AAs allow the formation of hydrate particles but prevent their agglomeration to larger pieces and blockage of flow conduits. AAs are typically surfactants. The most common AAs are quaternary ammonium compounds. The mechanism of inhibition is to attach the surfactant to the surface of hydrate crystal surface. The "hydratephilic" head of the surfactant attaching to the surface disrupts the growth, while the hydrophobic tail of the surfactant makes the crystals oil wet making them easily dispersed in the liquid hydrocarbon phase (Webber 2010, Kelland 2006). Another mechanism of anti-agglomeration is using a special type of polymeric emulsifier to confirm the hydrate formation in the water droplets in the water-in-oil emulsion (Kelland 2006).

Challenges in applying AAs are typically emulsion formation and phase partitioning (Webber 2010), leading to potential discharge water problems. The challenges can be addressed in most cases by selection of the proper formulation.

3.3.2 Corrosion Inhibitors

Corrosion inhibitors are among the most common chemicals used in oil and gas developments. The majority used in oil production systems are nitrogenous and have been classified into the following broad groupings (Fink 2003):

- Amides and imidazolines
- Salts of nitrogenous molecules with carboxylic acids (fatty acids, naphthenic acids)
- Nitrogen quaternaries
- Polyoxylated amines, amides, and imidazolines
- Nitrogen heterocyclics

In the Gulf of Mexico deepwater developments, amides/imidazolines, amines & amine salts are used as corrosion inhibitors (Boehm 2001).

Corrosion inhibitors can have a side effect of stabilizing emulsions, which leads to challenges in oil water separation efficiency and increases in oil and grease amount in the discharged water. Some corrosion inhibitor may increase the toxicity of produced water.

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Typical dosage of corrosion inhibitors is 10-50 ppm in water, and can be as high as 500 ppm in special cases.

3.3.3 Scale Inhibitors

Scales can form in the reservoir or production system. Scales form when the solubility of scale forming materials (such as calcium carbonate and gypsum) decreases due to temperature change, or when water from different sources meet and create low solubility materials such as barium sulfate. Conventional scale inhibitors are thermodynamic inhibitors which are hydrophilic, and oil-soluble scale inhibitors have been developed for downhole squeezing operations (Fink 2003). Coated inhibitors are also available. Scale inhibitors are not applied in combination with corrosion inhibitors.

Thermodynamic inhibitors are scale-specific complexing and chelating agents (Fink 2003). Common scale inhibitors of barium sulfate are ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid. Calcicum carbonate scale can be inhibited by varying the pH (adding acid) or the partial pressure of carbon dioxide. Another mechanism of scale inhibition is based on adherence inhibitors. Some chemicals simply suppress the adherence of crystals to the metal surfaces.

Typical dosage of scale inhibitors is 10-50 ppm in water.

3.3.4 Asphaltene Dispersants

Asphaltene deposition in production system components such as downhole tubing is removed by aromatic solvents such as xylene and toluene. Asphaltene problems are commonly prevented by continuous injection of asphaltene dispersants at downhole locations. The dispersants are polymeric chemicals that have strong association with asphaltenes therefore have stronger peptizing effect than natural resins (Kokal 2005). The dispersants are resins or amphiphilic compounds such as alkylphenol-formaldehyde resins with hydrophilic-lipophilic vinyl polymers, dodecylbenzenesulfonic acid (Chang 1993, Bout 1995, Goual 2004), Ethercarboxylic acids (Miller 2000). For deepwater applications, the product formulation also contains high flash point aromatic solvents (Dunlop 2003).

Typical asphaltene dispersant dosage is 250 ppm. The dispersants partition almost completely in the oil phase (Nalco 2011).

3.3.5 Paraffin Inhibitors

When applied in subsea oil and gas developments, paraffin inhibitors are typically injected downstream of subsea chokes to reduce the paraffin deposition rate in the pipelines transporting the produced fluids to host locations. Paraffin inhibitors are frequently copolymers of ethylene with vinylacetate or polymers from p-nonylphenyl methacrylate and p-dodecylphenyl methacrylate, and other paraffin inhibitors are polyacrylamide and wastes from the production of glycerol (Fink 2003).

Typical dosage of paraffin inhibitors is up to 500 ppm in oil. The inhibitors partition mostly to the oil phase and very little to the water phase (Nalco 2011).

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3.3.6 Defoamers

Foams may occur when pressure is reduced and dissolved gas in the oil comes out of solution. Historically defoamers are used in topsides separators to eliminate separation difficulties due to foaming. In recent developments with subsea separation systems, continuous defoamer injection is critical to the performance of the separation system and hence critical to the continued production (Deuel 2011). In many deepwater projects, silicone defoamer has been used on the platforms and has worked well on low to medium gravity oil. For the recent Shell Parque das Conchas BC-10 project in Brazil, a fluorsilicone defoamer was used in the subsea separator. The conventional silicone defoamer was not effective because the production included moderate viscosity oil and low viscosity condensate (Hera 2010). Typical defoamer dosage is about 100 ppm of the liquid volume produced.

3.3.7 Demulsifiers

Emulsions of water and oil occur from the natural emulsifiers in the crude oil and the agitations the oil and water experiences during the production process. The natural emulsifiers contained in crude oils have a complex chemical structure, so demulsifiers must be selectively developed to overcome their effect, leading a wide variety of demulsifiers as listed below (Fink 2003). Demulsifiers are typically injected at 25-100 ppm of oil volume, with some partitioning into the water phase (Nalco 2011).

Demulsifier	Type
Blends containing (1) tannin or amino methylated tannin, (2) a cationic polymer, (3) polyfunctional amines	WiO
Copolymer of diallyldimethyl ammonium chloride and quaternized amino alkylmethacrylates and (meth)acrylic esters (e.g., 2-ethylhexylacrylate)	OiW
Amphoteric acrylic acid copolymer	OiW
Branched polyoxyalkylene copolyesters	OiW
Copolymer of esters of acrylic acid and the respective acids, methacrylic acid	WiO
Copolymer of polyglycol acrylate or methacrylate esters	OiW
Poly(1-aeryloyl-4-methyl piperazine and copolymers of 1-aeryloyl-4-methyl piperazine quaternary salts with acrylamide quaternary salts)	OiW
Copolymers of acrylamidopropyltrimethyl ammonium chloride with acrylamide	OiW
Vinyl phenol polymers	OiW
Ethoxylated or epoxidized polyalkylene glycol	WiO
Polymers from dimethylaminoethyl methacrylate,	OiW

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dimethylaminopropyl methacrylamide	
Polymer of monoallylamine Copolymers of allyl-polyoxyalkylenes with acrylics	OiW
Copolymer of diallyldimethyl ammonium chloride and vinyl trimethoxysilane	WiO
Cationic amide-ester compositions	OiW
Polyalkylenepolyamides-amines	OiW,
Fatty acid N,N-dialkylamides	OiW
Diamides from fatty amines	WiO
Polycondensates of oxalkylated fatty amine	OiW
Poly(diallyldimethyl ammonium chloride) Alkoxylated fatty oil	OiW
Oxalkylated polyalkylene polyamines	WiO
Crosslinked oxalkylated polyalkylene polyamines Phenol-formaldehyde resins, modified with benzylamine	OiW
Alkoxylated alkylphenol-formaldehyde resins	WiO
Phenol-formaldehyde polymer modified with ethylene carbonate Modified phenol-formaldehyde resins	WiO
Polyalkylene polyamine salts	OiW
Dithiocarbamate of bis-hexamethylenetriamine Di- and tri-dithiocarbamic acid compounds	OiW
Polythioalkyloxides	WiO
Polyether/polyurethanes	WiO
Polyurea-modified polyetherurethanes	WiO
Sulfonated polystyrenes	OiW

3.3.8 Biocides and Other Additives

Both seawater and produced water have been widely injected into the reservoir for pressure maintenance or secondary recovery. Reservoir souring can occur from the bacteria that exist in seawater. Biocides are injected into the seawater on the topsides to control the reservoir souring. Additionally, H_2S scavengers are injected to mitigate against the microbiologically induced corrosion.

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The dosages for biocides and H_2S scavengers are similar to the other production additives such as corrosion and scale inhibitors.

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4.0 WORLDWIDE OFFSHORE PRODUCED WATER REGULATIONS

Most countries and regions in the world regulate the produced water and solids discharges offshore through three primary criteria: Oil and grease concentration, toxicity, and produced sand/solids. However there are many differences in the details of the regulations across countries/regions of the world regarding produced water regulations. This section discusses the regulations that are relevant to the current study of seabed discharge of produced water and/or solids.

4.1 US Regulatory Structure

Today in the United States, the BOEMRE (Bureau of Ocean Energy Management, Regulation and Enforcement) has started a new focus of offshore regulations by 4 primary regions. These are Region 4 (Eastern Gulf of Mexico), Region 6 (Western Gulf of Mexico), Region 9 (Offshore California) and Region 10 (Arctic Waters of Alaska). (BOEMRE Website 2011)

Regions 4 and 6 are the most relevant to the current study of the seabed discharge of produced water and/or solids.

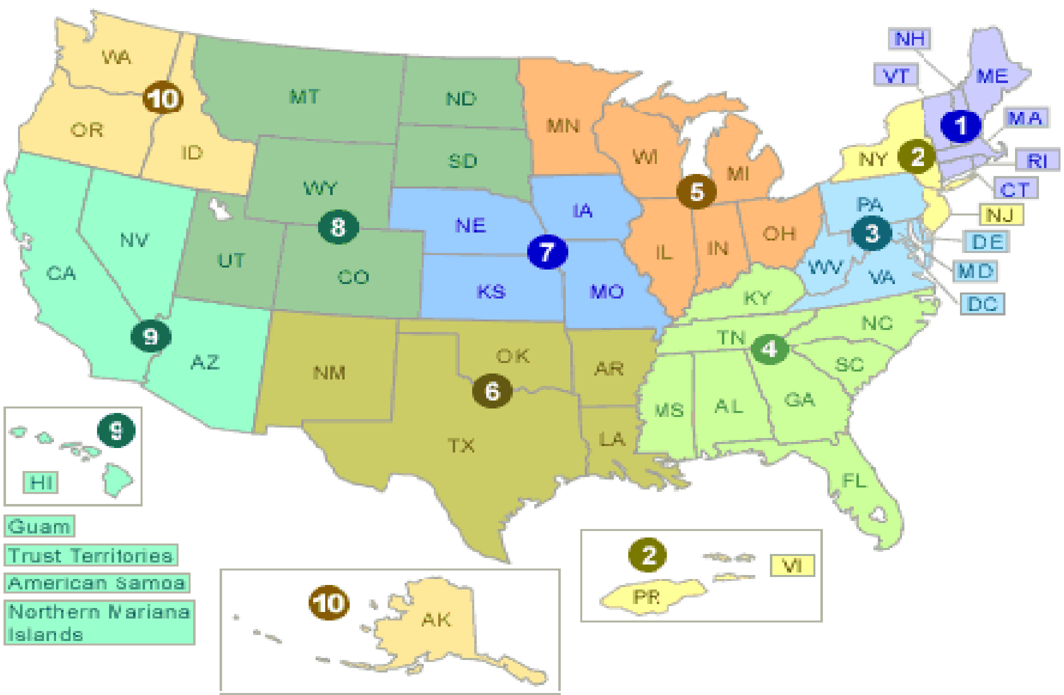

Figure 1 – Map of EPA regions. (Source: US EPA)

The Clean Water Act of 2009 prohibits all discharges of pollutants unless they are authorized by National Pollutant Discharge Elimination System (NPDES) permits. The Act also requires that NPDES permits first limit pollutants based on economically achievable treatment technologies and then include additional limits as needed to protect water quality. (EPA NPDES Website 2011)

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New point sources and existing point sources of pollutants have different NPDES regulations. New sources are subject to more rigorous effluent limits than existing sources based on the idea that it is cheaper to minimize effluent pollutants if environmental controls are considered during plant design than if an existing facility is retrofitted. New source discharges must comply with standards based on the performance of demonstrated technology with the greatest degree of effluent reduction. These new source performance standards (NSPS) should represent the most stringent numerical values attainable. NSPS are based upon the best available demonstrated control technology and are at least as stringent as best available technology. (EPA NPDES Website 2011)

The NPDES guidelines define a new source as any area in which significant site preparation work is done. EPA interprets “significant site preparation” for offshore effluent guidelines as “the process of clearing and preparing an area of the ocean floor for purposes of constructing or placing a development or production facility on or over the site.” Thus, development and production facilities at a new site would be new sources. Development and production facilities are existing sources if significant site preparation work took place before NSPS became effective. Exploratory wells are not considered new sources because site preparation is not considered significant. (EPA NPDES Website 2011)

The US offshore regulations govern the quality of the produced water by the oil and grease concentration, toxicity limitation, and prohibition of offshore discharges of produced sand. Those produced water discharges are limited to a monthly average of 29 mg/l and a daily maximum of 42 mg/l. The oil and grease limits have been difficult to achieve in some cases where dissolved oil is present in the produced water. In many cases operators have resolved that issue by adjusting the pH of produced water prior to treatment. (EPA NPDES Website 2011). There is also a toxicity requirement which will be addressed later in this section.

Worldwide Regional Agreements

Among the different regulations around the world, a few regions have formal agreements between countries in a specific area. Before their creation, these areas suffered from effects of pollution and waste, where the environmental damage was considered extreme. These agreements have helped to correct that problem and are contributing to a healthier ecosystem in that respective area. (Argonne Water Paper, 2004)

The one unique component to these regional agreements is that they insist on the use of best technologies and practices that are available to support the monitoring programs and discharge criteria for produced water treatment. Most of the oil in water limits range from 30 to 40 mg/liter, but some like the HELCOM standards target 15 mg/liter oil in water limits.

The table below highlights the oil in water limits set for those agreement areas.

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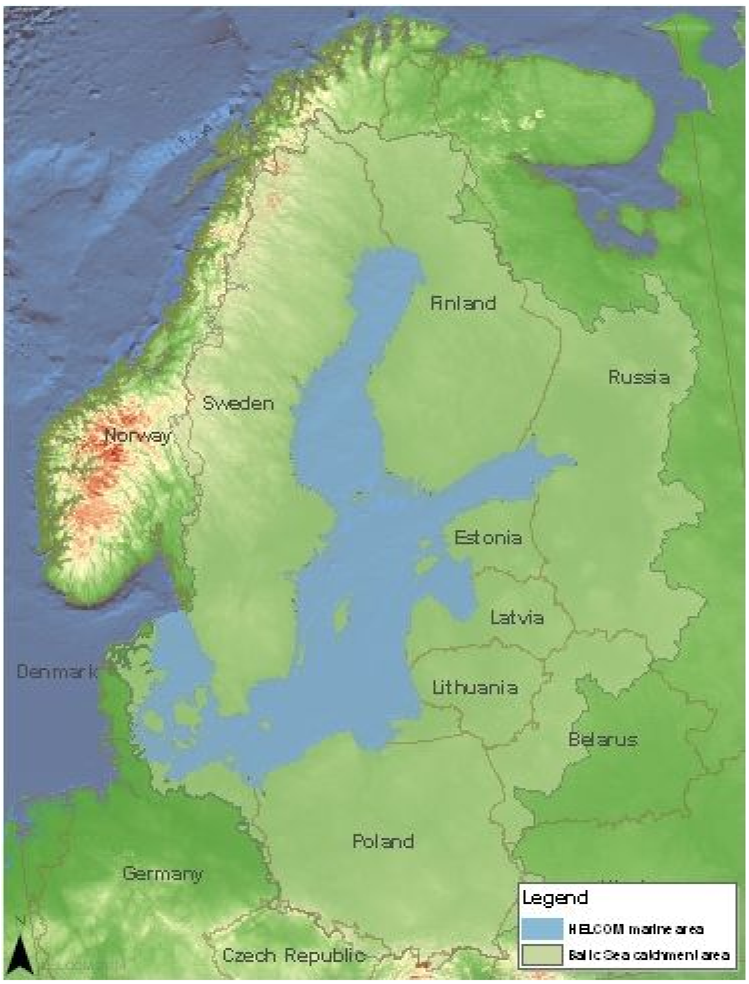
Table A. Summary of regional agreements between certain countries.

Agreement	Oil in Water Limit	Other Requirements
Baltic Sea Convention and HELCOM standards	15 mg/l in 2000, 40 mg/l if BAT can not be achieved	Pre-Approval of Chemical Additives
Barcelona Convention and Protocols (Mediterranean Countries)	40 mg/l in 2000 100 mg/l max.	
Kuwait Convention and Protocols (Red Sea Region)	40 mg/l in 2000 100 mg/l max.	
OSPARCOM (North Sea Countries)	30 mg/l	Pre-Approval of Chemical Additives

4.2.1 Baltic Sea Convention and HELCOM standards



http://www.helcom.fi/helcom/en_GB/aboutus/

FLUOR

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The Helsinki Commission, or HELCOM, works to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental co-operation between Denmark, Estonia, the European community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. (Argonne Water Paper, 2004)

HELCOM is the governing body of the "Convention on the Protection of the Marine Environment of the Baltic Sea Area" – more usually known as the Helsinki Convention. Since 1972, HELCOM has been working to protect the marine environment of the Baltic Sea. This work has been driven by the specific environmental, economic and social situation in the Baltic region and the specific sensitivity of the Baltic Sea. (Argonne Water Paper, 2004). In the light of political changes, and developments in international environmental and maritime law, a new Convention was signed in 1992 by all the states bordering on the Baltic Sea, and the European Community. After ratification the Convention entered into force on 17 January 2000. The Convention covers the whole of the Baltic Sea area, including inland waters as well as the water of the sea itself and the sea-bed. Measures are also taken in the whole catchment area of the Baltic Sea to reduce land-based pollution. (HELCOM 2011).

They will use the Best Environmental Practices and Best Available Technologies will be promoted by the contracting parties to prevent the pollution of the Baltic Sea. Additional measures shall be taken if the consequent reductions of inputs do not lead to acceptable results. Since the beginning of the 1980s the Helsinki Commission has been working to improve the Baltic marine environment, largely through some 200 HELCOM recommendations. The Baltic Sea has seen a dramatic improvement in water. (Argonne Water Paper, 2004)

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4.2.2 Barcelona Convention and Protocols (Mediterranean Countries)

In 1975, 16 Mediterranean countries and the European community adopted the Mediterranean Action Plan (MAP), the first-ever regional seas program under the United Nations Environment Program (UNEP) umbrella and in 1976 they adopted the Convention for the Protection of the Mediterranean Sea against Pollution (Barcelona Convention). (Mediterranean Convention 2005)

Today, 35 years later, the contracting parties are now 22, and they are determined to protect the Mediterranean marine and coastal environment while boosting regional and national plans to achieve sustainable development. (Mediterranean Convention 2005). The contracting countries are Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, European Union, Egypt, France
Greece, Israel, Italy, Lebanon, Libya, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Syria, Tunisia, Turkey

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The Convention's main objectives are to assess and control marine pollution, to ensure sustainable management of natural marine and coastal resources, to integrate the environment in social and economic development, to protect the marine environment and coastal zones through prevention and reduction of pollution, and as far as possible, elimination of pollution, whether land or sea-based. It is also used to protect the natural and cultural heritage of the area, to strengthen solidarity among Mediterranean coastal states and to contribute to the improvement of the quality of life. (Mediterranean Convention 2005)

4.2.3 Kuwait Convention and Protocols (Red Sea Region)

The Kuwait Regional Convention for Co-operation on the Protection of the Marine Environment from Pollution was adopted in 1978 and came into force in 1979. An action plan was adopted in 1978. The objective of the Convention is to prevent, abate, and combat pollution of the marine environment in the region. (Kuwait Convention 2004). The contracting countries are Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates.

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In 1982, in connection with the adoption of the protocol concerning co-operation in combating pollution by oil and other harmful substances in cases of emergency, the Marine Emergency Mutual Aid Centre (MEMAC) was established within the framework of the Convention. UNEP is also cooperating with ROPME/MEMAC on the development of guidelines for environmental damage assessment and preparation of compensation claims in cases of oil spills. (Kuwait Convention 2004)

It establishes a high priority on combating oil and hydrocarbon pollution and is reflected also in the protocol on land-based sources for ballast water, slops, bilges and other oily water discharges generated by land-based reception facilities and ports through loading and repair operations. It also focuses on brine water and mud discharges from oil and gas drilling and extraction activities from land-based sources, oily and toxic sludges from crude oil and refined products storage facilities, effluents and emissions from petroleum refineries, petrochemical and fertilizer plants and Emissions from natural gas flaring and desulfurization plants. (Kuwait Convention 2004)

4.2.4 OSPARCOM (North Sea Countries)

Source : http://www.ospar.org/

The treaties of Paris and Oslo (OSPAR) were signed in 1992 and regulate the protection of the marine environment in the northeast Atlantic region. They went into effect in 1998. The treaties are binding for all the participating countries. An international committee (mostly referred to as OSPARCOM) is responsible for working out these treaties. (OSPAR Convention 2006)

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OSPAR is the mechanism by which fifteen Governments of the western coasts and catchments of Europe, together with the European Community, cooperate to protect the marine environment of the North-East Atlantic. It started in 1972 with the Oslo Convention against dumping. It was broadened to cover land-based sources and the offshore industry by the Paris Convention of 1974. These two conventions were unified, up-dated and extended by the 1992 OSPAR Convention. The new annex on biodiversity and ecosystems was adopted in 1998 to cover non-polluting human activities that can adversely affect the sea.

The fifteen Governments are Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom. Finland is not on the western coasts of Europe, but some of its rivers flow to the Barents Sea, and historically it was involved in the efforts to control the dumping of hazardous waste in the Atlantic and the North Sea. Luxembourg and Switzerland are Contracting Parties due to their location within the catchments of the River Rhine. (OSPAR 2011)

Oil discharges with produced water have fallen on average by 20% in the OSPAR area and most countries have met the latest OSPAR 15% reduction target, even though volumes of produced water are expected to increase. Pollution from drilling fluids and cuttings piles has been considerably reduced. Impacts of offshore oil and gas activities have reduced around some installations, but the evidence base for the environmental impacts is limited. (OSPAR Convention 2006)

OSPAR strategy objectives for hazardous substances move towards the cessation of discharges, emissions and losses of hazardous substances by 2020. The ultimate aim is to achieve concentrations of hazardous substances in the marine environment near background values for naturally occurring substances and close to zero for man-made substances. (OSPAR Convention 2006)

The current OSPAR requirement for produced water quality is stated in Recommendations 2001/1 and 2006/4 which is an amendment of 2001/1 (OSPAR 2001, 2006).

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Worldwide Regulation on Oil and Grease Concentration

Table B. Summary of worldwide regulations by country (Jones 2002 with updates)

Country	Legal Basis	Oil in Water Limit
Albania	Barcelona Convention	40 mg/L 100 mg/L max
Algeria	Barcelona Convention	40 mg/L 100 mg/L max
Angola		
Argentina	Resolution No. 105/92	
Australia (Western)	More info required	30 mg/L 50 mg/L max
Azerbaijan	More info required	More info required
Bahrain	KUWAIT Convention	40 mg/L 100 mg/L max
Belgium	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Brazil		20 mg/L max.
Canada	Act RSC 1987	40 mg/L avg. 80 mg/L max
China	GB 4914-85	30-50 mg/L avg. 75 mg/L max.
Colombia	SEPC	Removal of 80% of oil
Denmark (North Sea)	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Denmark (Baltic Sea)	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Ecuador	SEPC	More info required
Egypt	Decree No. 338/95	15 mg/L max. 40 mg/L max. (Alternative)
Estonia	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Finland (Baltic Sea)	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
France (Mediterranean Sea)	Barcelona Convention	40 mg/L 100 mg/L max

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Country	Legal Basis	Oil in Water Limit
France (North Sea)	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Germany (Baltic Sea)	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Germany (North Sea)	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Greece	Barcelona Convention	40 mg/L avg. 100 mg/L max
Indonesia	MD KEP 3/91; 42/97	75 mg/L avg.
Iran	KUWAIT Convention	40 mg/L avg. 100 mg/L max
Iraq	KUWAIT Convention	40 mg/L avg. 100 mg/L max
Ireland (North Sea)	Rules and Procedures for Offshore Petroleum Exploration Operations. OSPAR Convention	30 mg/L
Israel	Barcelona Convention	40 mg/L avg. 100 mg/L max
Italy	Dm of 28.7 1994	40 mg/L avg.
Kuwait	KUWAIT Convention	40 mg/L avg. 100 mg/L max
Lebanon	Barcelona Convention	40 mg/L 100 mg/L max
Libya	Barcelona Convention	40 mg/L 100 mg/L max
Lithuania	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Monaco	Barcelona Convention	40 mg/L 100 mg/L max
Morocco	Barcelona Convention	40 mg/L 100 mg/L max
Netherlands	Mining reg. 1996. Reg. 687/ 1224, 1987; OSPAR Convention	40 mg/L avg. 100 mg/L max.
Nigeria	Act No. 34/68: Regs 1992	40 mg/L avg. 72 mg/L max.
Norway	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Poland	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Portugal	OSPAR Convention	30 mg/L (Recommendation 2001/1)

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Country	Legal Basis	Oil in Water Limit
Qatar	KUWAIT Convention	40 mg/L avg. 100 mg/L max.
Oman	Decree No. 10/82 KUWAIT Convention	40 mg/L avg. 100 mg/L max.
Russia	The requirement to produced water for reinjection is determined by Industry Standard OST 39-225-88 Sea water requirement is in Federal Fishery Agency Order No. 20 dated 18-Jan-2010	Up to 50 mg/L max. 0.05 mg/L MPC
Russia (Baltic Sea)	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Saudi Arabia	KUWAIT Convention	40 mg/L 100 mg/L max
Spain (Mediterranean Sea)	Barcelona Convention	40 mg/L 100 mg/L max
Spain (North Sea)	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Sweden (Baltic Sea)	HELCOM Convention	15 mg/L max. 40 mg/L (Alternative)
Sweden (North Sea)	OSPAR Convention	30 mg/L (Recommendation 2001/1)
Syria	Barcelona Convention	40 mg/L 100 mg/L max
Thailand	NEQA 1992: Gov. Reg. 20/90	100 mg/L max.
Trinidad		40 mg/L max.
Tunisia	Order of 1989	10 mg/L max
Turkey (Mediterranean Convention)	Barcelona Convention	40 mg/L 100 mg/L max
United Arab Emirates	KUWAIT Convention	40 mg/L avg. 100 mg/L max.
United Kingdom	OSPAR Convention	30 mg/L (Recommendation 2001/1)
United States	40 CFR 435 EPA NPDES Permit	29 mg/L monthly average 42 mg/L daily max
Venezuela	Decree No. 833/1995	20 mg/L

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Country	Legal Basis	Oil in Water Limit
Vietnam	Decision No. 333/QB 1990	40 mg/L
Yugoslavia	Barcelona Convention	40 mg/L 100 mg/L max

4.4 Regulations on Toxicity

The approach to how toxicity is handled varies by region. For instance, the European approach is based on "single substance", to control the use of chemicals because of their potential to be environmentally toxic. The American approach however is more concerned with controlling the final emissions (actual environmental toxicity of effluents.) There are different methods used which cater to the different goals of the regions. The regulations appear to undergo changes every 5 years. The latest regulations were adopted in the US EPA office on October 2007 and will expire on September 30, 2012.

4.4.1 US Toxicity Regulations

As mentioned above the EPA regulations in the US continue to evolve and change. As of October 2007, the latest requirements have been provided to industry through EPA general permits. The Gulf of Mexico discharge requirements from new sources, existing sources and new dischargers in the Offshore Subcategory (40 CFR Part 435, Subpart A) are the same. The general permit authorizes discharges from exploration, development and production facilities located in and discharging to Federal waters of the Gulf of Mexico. (EPA 2007)

The EPA permit (EPA 2007) requires the following toxicity tests:

"The permittee shall utilize the Mysidopsis bahia (Mysid shrimp) chronic static renewal 7-day survival and growth test using Method 1007.0. A minimum of eight (8) replicates with five (5) organisms per replicate must be used in the control and in each effluent dilution of this test.
[I.D.3.b.]

The permittee shall utilize the Menidia beryllina (Inland Silverside minnow) chronic static renewal 7-day larval survival and growth test (Method 1006.0). A minimum of five (5) replicates with eight (8) organisms per replicate must be used in the control and in each effluent dilution of this test.

The NOEC (No Observed Effect Concentration) is defined as the greatest effluent dilution which does not result in a lethal or sub-lethal effect that is statistically different from the control (0% effluent) at the 95% confidence level. In the case of a test that exhibits a non-monotonic concentration response, determination of the NOEC will rely on the procedures described in Method Guidance and Recommendations for Whole Effluent Toxicity (WET) Testing (40 CFR Part 136), July 2000, EPA 821-B-00-004. "

"If the effluent fails the survival endpoint (or the sub-lethal endpoint, after two years from
the effective date of this permit) at the critical dilution, the permittee shall be considered in violation of this permit limit.".

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The EPA permit also provided tables of critical dilution concentrations which the No Observable Effect Concentration (NOEC) must be equal to or greater than. The critical dilution is based on the highest monthly average discharge rate for the three months prior to the month in which the test sample is collected, the size of the pipe diameter discharging the effluent and the water depth between the discharge pipe and the bottom of the seafloor. Operators must comply with this requirement within two years after the effective date of the permit. To meet the requirements, operators can increase mixing using a diffuser, add seawater, or install multiple discharge ports. Alternatively, operators wanting to reduce the critical dilution of the discharge may make operational changes that reduce the flow rate, such as, shutting-in wells. (EPA 2007)

All changes must be provided to the EPA with a description of the specific changes that were made and the resultant flow rates of the discharge, along with a certification that the flow rate will not change, unless a new certification is made. Operators discharging produced water at a rate greater than 75,000 barrels per day shall determine the critical dilution using special EPA approved software. When seawater is added to the treated produced water prior to discharge, the total produced water flow, including the added seawater, shall be used in determining the critical dilution from the above dilution table. (EPA 2007)

Table I. Effluent Limitations, Prohibitions and Monitoring Requirements

Discharge	Regulated & Monitored Parameter	Discharge Limitation/ Prohibition	Measurement Frequency	Monitoring Requirement	
				Sample Type/ Method	Recorded Value(s)
Produced Water	Oil and grease	42 mg/l daily maximum, 29 mg/l monthly average	Once/month	Grab(*20)	Daily maximum, monthly average
	Toxicity	7-day minimum NOEC(*21) and monthly average min NOEC(*21)	Rate Dependent(*28)	Grab	Lowest NOEC for either species
	Free Oil	Monitor	Once/day (*19,*29)	Visual sheen	Number of days sheen observed
	Flow (MGD)	Monitor	Once/month	Estimate	Monthly Average
Produced Sand	No Discharge				

To help clarify the above table comments, the below footnote references can be used:

- 19 – When discharging and the facility is manned, monitoring shall be accomplished during times when observation of a visual sheen on the surface of the receiving water is possible in the vicinity of the discharge.
- 20 – May be based on either a grab sample or a composite which consists of the arithmetic average of the results of grab samples collected at even intervals during a period of 24 hours or less.
- 21 – See the above dilution rate in the previous list of tables.
- 28 – Once per annual discharge monitoring report (DMR) monitoring period for discharges from 0 barrels per day to 4599 barrels per day, once per calendar quarter for discharges of 4,600 barrels per day and greater.

4.4.2 North Sea Toxicity Regulations

Toxicity regulations in the North Sea area follow the OSPAR convention recommendations and agreements. Unlike the US regulations, OSPAR does not impose a single toxicity criteria, but instead using a combination of approaches toward the goal of zero environmental harm discharges:

- Reduce discharge volumes (OSPAR Recommendation 2001/1 as amended by Recommendations 2006/4 and 2011/8)
- Control chemical use by harmonized screening and using more chemicals with less toxicity (OSPAR Recommendation 2008/1 Amending OSPAR Recommendation 2000/4 on a Harmonised Pre screening Scheme for Offshore Chemicals)
- Assess toxicity of chemicals with a "single substance approach", with guidelines for toxicity testing (OSPAR Guidelines for Toxicity Testing of Substances and Preparations Used and Discharged Offshore, Reference number: 2005-12)
- Use risk assessment methods to evaluate the risk of chemicals to the environment (OSPAR Decision 2000/2 on a Harmonised Mandatory Control System for the Use and Reduction of the Discharge of Offshore Chemicals, as amended by OSPAR Decision 2005/1). The OSPAR sanctioned risk assessment method is CHARM, which means the Chemical Hazard Assessment and Risk Management model developed by authorities and offshore industry within the Convention area.

The CHARM model calculate the PEC/PNEC ratio (ratio between the predicted environmental concentration PEC and the predicted no effect concentration PNEC) of offshore chemicals. Additional models have been developed and used by different countries, such as (De Vries 2009):

- DREAM / EIF. Both the Dose-related Risk and Effect Assessment Model (DREAM) and the Environmental Impact Factor (EIF) are implemented in Norway by SINTEF.
- PROTEUS, which is a modeling tool developed in the UK by BMT-Cordah which also expresses risk based on either body burdens or PEC:PNEC ratios.
- MIKE is a Danish product developed by the DHI (Danish Hydraulic Institute) group, again expressing risk as PEC:PNEC ratios.
- Delft3D, a Dutch product developed by WLDelft Hydraulics (currently known as Deltares) is used for dispersion calculation. By combining it with PNEC values, it can be used as a risk assessment tool.
- CHU (Chemical Hazard Unit) is a methodology based on the CHARM model in which risk is expressed as PEC:PNEC ratios.

The chemicals are ranked based on the predicted risks and screened with the rankings.

It is increasingly recognized that, although the single substance approach to toxicity has been effective, it has some shortcomings. These are primarily that there are many substances (out of the over 50,000 substances which exist in the world) that lack sufficient data, and that this approach may miss some harmful substances in the effluent especially if the effluent composition is complex. To overcome these shortcomings, some countries have started using Whole Effluent Assessment (OSPAR 2007), which assesses the toxicity of the effluent as a whole when bioassays are exposed to them.

WEA and the Whole Effluent Testing (WET) method used in the US both aim to assess the toxicity of the effluent as a whole, although with differences on the bioassays used, details of the tests, and the procedures to reach conclusion on the measurements. The WET method is described in Method

Guidance and Recommendations for Whole Effluent Toxicity (WET) Testing (40 CFR Part 136), July 2000, EPA 821-B-00-004.

4.5 Comparison of Produced Water Discharge Regulations in the United States and Norway

In the U.S. and Norway, government policies encourage the responsible development of domestic energy sources. Petroleum exploration and development is closely regulated in each nation to protect public health and the environment. U.S. and Norway regulations strictly limit offshore petroleum industry discharges including drilling fluids or muds, drill cuttings, and produced water. This information sheet compares how the U.S. and Norway manage wastewater discharges from petroleum exploration, development and production in coastal and offshore waters. Comparisons here are generally focused on each nation's current wastewater discharge regulations.

4.5.1 U.S. Regulations

In the U.S., the Clean Water Act was enacted "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The Clean Water Act prohibits the discharge of any pollutant into U.S. waters from petroleum activities or other sources, unless the discharge complies with specific requirements.

Section 402 of the Clean Water Act authorizes the U.S. Environmental Protection Agency (EPA) to regulate industry discharges through National Pollutant Discharge Elimination System (NPDES) permits. NPDES permits must contain: numeric limits based on the technology available to control pollutants, without reference to the effect on the receiving water; and if needed, more stringent limits to control pollutants to meet the water quality standards of the receiving waters.

EPA's NPDES regulations for the petroleum industry limit discharges into marine waters, with different restrictions for "coastal" and "offshore" waters. Coastal waters are landward of the inner boundary of the U.S. territorial seas. Offshore waters are seaward of the inner boundary of the U.S. territorial seas. Coastal discharge requirements are generally more stringent than offshore requirements.

Section 403 of the Clean Water Act requires that NPDES permits in offshore waters comply with EPA's Ocean Discharge Criteria guidelines. EPA will issue an NPDES permit only if the Ocean Discharge Criteria Evaluation finds that the discharge will not cause unreasonable degradation of the marine environment. (EPA Jan 2011)

4.5.2 Norway Regulations

In Norway, the Pollution Control Act regulations require petroleum activities to be carried out with the least possible risk of pollution. The Norway Climate and Pollution Agency regulates petroleum industry use of drilling fluids and muds, produced water, and chemicals, with water discharge permits.

To further protect marine waters, Norway first introduced a "zero discharge" goal for petroleum activities. (White Paper 58, 1996-1997) This goal was later refined to mean zero discharge of environmentally hazardous substances, using Best Available Techniques, and following the precautionary principle. (White Paper 25, 2002/2003) (EPA Jan 2011)

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An advisory cooperative group composed of government and industry representatives developed a common definition that identified relevant technologies to achieve zero discharge, and created a standard manner to report discharges. This advisory group found that a literal interpretation of the zero discharge goal was not economically feasible or environmentally beneficial.

Norway defines zero environmentally harmful discharges as:

• Zero discharge of all added environmentally hazardous chemicals classified as "red" or "black" in the national classification system;

• Zero harmful discharges from natural compounds and chemicals classified as "yellow" or "green".

Norway established stricter requirements for drilling operations and produced water in areas north of the 68th parallel in the Barents Sea and Lofoten area. (White Paper 38, 2003-2004) (EPA Jan 2011)

4.5.3 U.S. and Norway Comparison Summary

Direct comparisons of the U.S. and Norway offshore discharge regulations are difficult and complex. Both nations have robust and thorough regulatory regimes that aim to balance environmental protection with economic considerations in developing domestic energy. U.S. and Norway regulations continue to be refined based on environmental concerns, economics, and innovations in science and technology.

Norway's "zero discharge" goal is not a numeric standard or a discharge level, but is instead a goal based on the precautionary principle and available technology. This is comparable to the U.S. goal to prevent unreasonable degradation of ocean waters.

In the U.S., oil and gas NPDES permits limit discharges using both technology and water quality-based controls. NPDES permits must meet the requirements in the code of federal regulations (40 CFR Part 435). In addition, all permits for discharges in the territorial sea, contiguous zone, and oceans must comply with the Ocean Discharge Criteria. (EPA Jan 2011)

4.5.4 Notes on Comparisons

Norway follows the Oslo-Paris Convention of the Marine Environment of the North-East Atlantic (OSPAR) offshore screening chemical guidelines. This means that the components in the chemicals are tested for toxicity (on algae, shrimp, and juvenile fish), biodegradation and bioaccumulation.

Based on this testing, Norway requires operators on the Norwegian Continental Shelf to classify chemicals used offshore as "green", "yellow", "red", or "black." Norway requires zero discharge of all added environmentally hazardous chemicals classified as "red" or "black". However, "red" chemicals may be discharged if an operator demonstrates no other options are available and an active search is underway for a replacement or substitution.

This classification system is a risk assessment approach to help operators determine the chemicals and additives they are allowed to use offshore, based on ecotoxicological data in the OSPAR Harmonized Offshore Chemical Notification Format and hazardous chemicals on the priority list

i.e., a discharge at a concentration of 3% or more should kill no more than half a test population of marine organisms continuously exposed 96 hours.

Chemicals on Norway's "green" list are those that Pose Little or No Risk ("PLONOR") to the marine environment, based on the Convention for the Protection of the Marine Environment of the North-East Atlantic. (EPA Jan 2011)

4.6 Regulations on Offshore Discharge of Solids, Heavy Metals, and NORM

The discharge of solids throughout the world is similar to the discharge criteria for produced water in that it varies from place to place and no specific format is followed. The below table helps to illustrate the differences found in this study. Table J summarizes the worldwide regulations on offshore discharge of produced sand, suspended solids, heavy metals, and Naturally Occurring Radioactive Materials (NORM).

Produced Sand - Produced sand regulations range from no regulation to the prohibition of discharge (US). Ship to shore or re-inject is preferred by many countries. In countries where offshore discharge of produced sand is allowed, a frequent requirement is that the oil adhered to the sand is limited to 1% by weight on dry sand (produced sand is typically covered with oil). This requirement is also used by the World Bank's Internal Financial Corporation. In countries adopting the OSPAR convention (Norway, UK etc), the same requirement applies, however an additional requirement is that the selected method represents the Best Available Technology (BAT) and Best Environmental Practices (BEP). Comparison of ship to shore, re-injection, and discharge offshore is needed to fulfill the BAP/BEP requirement.

Suspended Solids – There is no specific regulation on the concentration of suspended solids in produced water discharged offshore. Since the suspended solids has significant organic components (see discussion below on US regulations), the concentration of suspended solids is inherently limited by the oil in water content limit.

Heavy Metals – There is no specific regulation on the concentration to heavy metals in the produced water discharged offshore. However the concentration is inherently by the toxicity limit since the heavy metals are toxic.

NORM – NORM is typically regulated by the overall regulations/guidelines in the country on radioactive material. The amount of NORM in the produced water is typically too low for regulation. NORM regulations mostly apply to scales formed in the production and processing systems since scales tend to accumulate the materials.

Below are additional discussions on the regulations in selected countries and World Bank.

4.6.1 USA

The EPA believes that limitations on oil and grease contained in the Offshore Guidelines effectively controls levels of certain toxic and nonconventional pollutants (EPA 1993). Therefore, the oil and grease limit is used as a "surrogate" for other pollutants in U.S. offshore produced water standards (Veil, 2006) meaning when oil and grease are controlled, other pollutants will also be controlled. Heavy metal may be inherently regulated by toxicity requirement.

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Discharge of produced sand is prohibited due to concern on NORM and the control of other pollutants (EPA 1993, Federal Circuits 1996). All sand collected from production, separation, and treatment equipment must be collected and shipped to shore for further treatment and disposal. The EPA's position is that sand washing reduces only oil content, leaving radionuclides in the sand. Therefore, even washed sand that still contains NORM must be transported to shore for disposal. However, the EPA does not regulate radio nuclides in produced water "because inadequate information existed to issue rules regarding the radionuclides, Radium 226 and Radium 228". The EPA is "continuing to gather information on radionuclides and could issue regulations in the future if the compiled information shows a need for such regulation." The EPA stated its intent to require radium monitoring as part of the permitting process for offshore oil and gas producers.

Excerpts from EPA (1993) on produced sand:

"In the offshore Oil and Gas Effluent Guidelines, EPA is controlling all pollutants found in the produced sand waste stream by a zero discharge limitation. This limitation represents the appropriate level of control under BAT, BCT and NSPS.

Produced sand consists of the slurried particles used in hydraulic fracturing and the accumulated formation sands and other particles (including scale) generated during production. This waste stream also includes sludges generated by a chemical polymer used in the flotation or filtration (or other portions) of the produced water treatment system. Produced sand is generally contaminated with crude oil from oil production or condensate for gas production. In addition, some produced sand contains elevated levels of naturally occurring radioactive materials (NORM).

The specific conventional, toxic and nonconventional pollutants found to be present in produced sand are summarized in Table X-2, Average Oil Content in Produced Sand, Tables X-3 and X-4, Summary of Radioactivity Data for Produced Sand from OOC Survey and Average Radioactivity Levels in Produced Sand, respectively, and Table XIII-2, Produced Sand Characteristics. The specific pollutants constituents of oil including those described previously in this section. In addition, radium 226 and radium 228, which are NORM and considered to be nonconventional pollutants are controlled with the elimination of discharges of produced sand that contain elevated levels of NORM."

The Total Suspended Solids (TSS) concentration and heavy metals for Offshore Subcategory of GoM is not specifically regulated (EPA 2007). A study of 10 Louisiana platforms found 3 – 249 mg/L of Total Suspended Solids in daily samples of discharged produced water (Jackson 1981). The TSS concentration tests followed the ASTM D1888-67 and EPA Storet No. 00530 procedures which were essentially the same. However the report commented that the test results for TSS were questionable and discussed the nature of the problem. The oil and grease contents in the discharged produced water were 15 – 106 mg/L based on infrared tests, out of which 17 – 92% are soluble oil (Table 207 EPA 2007).

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4.6.2 Angola

According to SAIEA (2009), Clause 2, Article 19 of the Environment Framework Act allows for the promulgation of pollution control legislation to address the production, discharge, deposit, transport and management of gaseous, liquid and solid pollutants. Clause 4 prohibits the importation of hazardous waste except through specific legislation, approved by the National Assembly. However, specific pollution control legislation and environmental standards for Angola have not yet been developed. The standards established by the World Bank and World Health Organization are applied, and most foreign companies or aid agencies apply these or the pollution control standards from their home countries.

4.6.3 Australia

Chevron Wheatstone project discharge water to limit TSS < 250 mg/L in discharged water (Chevron 2010). Inpex Ichthys project plans to discharge produced sand offshore, but to be kept "to a minimum and will only be so disposed of with the approval of the relevant regulatory authorities". (Inpex 2010)

4.6.4 Canada

The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB), the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) and the National Energy Board (NEB) regulate the discharge of produced water for the Canadian offshore oil and gas industry. The Offshore Waste Treatment Guidelines require operators to closely monitor the concentration of oil and gas in produced water, through laboratory analysis, to confirm that residual oil and gas content is within regulatory limits to ensure protection of the environment. Samples are taken on a regular basis and the laboratory results are reported to the applicable regulator.

4.6.5 Nigeria

A study of the produced water discharges in shallow water near Chevron's Escravos Tank Farm found 58 mg/L of TSS in treated produced water during late dry season and 63 mg/L in late wet season. (Okoro, 2010)

Disposal of wastes and monitoring requirements are governed by Environmental Guidelines and Standards for Petroleum Industry in Nigeria (EGASPIN), ref. Kusamotu:

Chemical /Hazardous Wastes/LSA or Norm – Encapsulation in abandoned well bores or injection into the depleted reservoirs on a case -by - case basis (as appropriate) shall be the preferred options.

Treatment and Disposal of Wastes from Production Operations – Wastes from production operations shall be treated to the satisfaction of the Director of Petroleum Resources before any disposal. Method of disposal of produced sand and oily sludges must not endanger human life, living organism or cause pollution to ground and surface waters. Approved methods are recycling (resource recovery), incineration, solidification, land farming and land filling. Any other method(s) acceptable to the Director of Petroleum Resources can be used after an approval has been sought for and given.

Monitoring of Wastes – The recipient water bodies of all facilities that discharge produced formation/oily water offshore and oily waste (inland/near shore) shall be monitored (sampling and analysis) once every month. Low Specific Activity (LSA) or Naturally Occurring Radio – active Material (NORM) shall be monitored in production tubing, vessels, pumps, valves, sulphate and carbonate scales, sands and sludges.

4.6.7 Norway

Section 68 of the Activities Regulation (Norway states "Cuttings from drilling and well activities, sand and other solid particles shall not be discharged to sea if the content of formation oil, other oil or base fluid in organic drilling fluid exceeds ten grams per kilo of dry mass". However, Statoil recommended (Statoil, 2004) an alternative strategy (including sand control and monitoring) for Statfjord late life modifications instead of sand cleaning due to the low environmental benefit of the latter.

OGP Study (1994) of northern North Sea found 3-85 mg/L of Total Suspended Solids in discharged produced water.

The discharge of radioactive material is governed by OSPAR. In PARCOM Recommendation 91/4 on Radioactive Discharges, the contracting parties agreed "to apply the Best Available Technology to minimize and, as appropriate, eliminate any pollution caused by radioactive discharges from all nuclear industries". Although the offshore production platforms are not nuclear facilities, the discharges of produced water with NORM follows this recommendation. Further, the Bergen Statement (Meeting of the OSPAR Commision, September 2010) reaffirmed "commitment to ensure that discharges, emissions and loses of radioactive substances are reduced by 2020 to levels where the additional concentrations in the marine environment above historic levels are close to zero. We will continue to improve the evidence base and assessment tools for indicator radionuclides from the nuclear and non-nuclear sectors."

4.6.8 United Kingdom

Key legislations regarding UK offshore discharge of produced water are:

- Offshore Petroleum Activities (Oil Pollution Prevention and Control) Regulations 2005
- Offshore Petroleum Activities (Oil Pollution Prevention and Control) (Amendment) Regulations 2011

Supporting legislations are:

- Convention on the Protection of the Marine Environment of the North East Atlantic 1992 (OSPAR Convention)
- PARCOM Recommendation 86/1 of a 40 mg/l Emission Standard for Platforms
- OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations as amended by OSPAR Recommendation 2006/4

The discharge of produced water with NORM follows the OSPAR convention, as discussed in the above subsection for Norway.

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4.6.9 World Bank

Internal Financial Corporation's Environmental, Health, and Safety Guidelines for Offshore Oil and Gas Development states that:

"Whenever practical, produced sand removed from process equipment should be transported to shore for treatment and disposal, or routed to an offshore injection disposal well if available. Discharge to sea is not considered to be current good practice. If discharge to sea is the only demonstrable feasible option then the discharge should meet the guideline values of oil concentration lower than 1% by weight on dry sand."

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Table J. Summary of worldwide regulations on offshore discharge of solids, heavy metals, and NORM.

Country / Organization	Produced Sand / Suspended Solids	Heavy Metals	Naturally Occurring Radioactive Material (NORM)
USA	No discharge of produced sand is permitted No specific regulation on amount of suspended solids in the discharged produced water	No specific regulation	No specific EPA regulation on amount in discharged produced water NORM regulation by states (radiation level control)
Angola	No specific regulation. 1% oil on sand (World Bank standard)	No specific regulation	No specific regulation
Australia	No specific regulation	No specific regulation	No specific regulation, however *Guidelines for Naturally Occurring Radioactive Materials* published by Australian Petroleum Production & Exploration Association (2002) is followed.

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Country / Organization	Produced Sand / Suspended Solids	Heavy Metals	Naturally Occurring Radioactive Material (NORM)
Canada	Monitor and report volume of produced sand recovered during production operations Acceptability of discharge depends on the concentration of oil in the sand and its aromatic content In all cases, the sand should be treated to reduce oil concentrations to the lowest level practicable	No specific regulation	Regulated by Canadian Guidelines for the Management of Naturally Occurring Radioactive Materials (NORM) The Guidelines recommend that NORM may be re leased with no radiological restrictions when the associated dose is no more than 0.3 mSv in a year. Derived Re lease Limits are provided in the Guideline NORM quantities in excess of the Unconditional Derived Release Limits may, after a specific site review, be released without further consideration. In such in stances, the basic premise is that the material, in its final disposition, will not con tribute a dose to an individual that is greater than 0.3 mSv/a. Outside those situations or conditions, the material falls within a more restrictive NORM classification.

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Country / Organization	Produced Sand / Suspended Solids	Heavy Metals	Naturally Occurring Radioactive Material (NORM)
Ghana	Ship-to-shore or re-inject. No discharge to sea except when oil concentration lower than 1% by weight on dry sand. Discharge of produced water follows OSPAR	No specific regulation	No specific regulation
International Atomic Energy Agency			In the case of radium-226 the annual release rate limit is 410,000 GBq (IAEA, 1986)
Nigeria	Discharge offshore is not listed as one of the approved methods. The approved methods for disposal are: recycling (resource recovery), incineration, solidification, land farming and land filling. Any other method(s) – presumably including discharging offshore – acceptable to the Director of Petroleum Resources can be used after an approval has been sought for and given.	No specific regulation	Disposal and monitoring required per Egaspin Article 4.2.1.
Norway	OSPAR – Best Available Technology (BAT) and Best Environmental Practices (BEP) Sand discharge allowed if meeting environmental standards (oil content on sand less than 1%). Goal is "Zero environmentally harmful discharges"		NORM discharge follows OSPAR recommendations

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Country / Organization	Produced Sand / Suspended Solids	Heavy Metals	Naturally Occurring Radioactive Material (NORM)
Russia	Discharge is not allowed MPC of suspended soils in produced water for reinjection is 50 mg/L max MPC for suspended solids in sea water is 10 mg/L to be determined by gravimetric analyses	For sea water: Hg is prohibited (MPC 0.00001 mg/L) Other heavy metals (including As, Cd, Pb, Zn) have MPC 0.01 mg/L For the produced water heavy metal MPCs are not determined	No specific regulation for NORM in produced water Radiation safety is governed by NRB 99/2009
UK	Offshore discharge possible if other methods (such as onshore disposal) not representing Best Environmental Practices (BEP) At present there are no specific regulatory limits for the concentration of oil on sand/scale or total weight of oil on sand/scale that may be discharged from offshore installations. Department of Energy and Climate Change (DECC) are aware that by utilizing BAT and BEP some cleaning methods can achieve concentrations of oil on sand/scale to below 1%, therefore BAT and BEP must be utilized when determining methods used for the treatment and subsequent discharge of oil on sand/scale.		Covered by Radioactive Substances Act The authorized annual discharges of scale from production platforms are between 5 and 30 GBq of radium (E&P Forum, 1988). NORM discharge follows OSPAR recommendations

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Country / Organization	Produced Sand / Suspended Solids	Heavy Metals	Naturally Occurring Radioactive Material (NORM)
World Bank	Ship-to-shore or reinjection is preferred. No discharge to sea except when oil concentration lower than 1% by weight on dry sand.		

4.7 Visual Sheen

In US regulations on produced water, no free oil shall be discharged as determined by the visual sheen method on the surface of the receiving water. Monitoring is to be done daily when discharging. If a sheen is observed it must be recorded on the NPDES permit. Additional measures on sampling must also be taken, which will be discussed in the later subsection on sampling.

There is no regulation on visual sheen in other countries regulations. However the visual sheen producing free oil content may be indirectly regulated by the requirement of best available techniques and best environmental practice.

4.8 Measurement of Oil and Grease Concentration

In the oil and gas industry, oil and grease in produced water is defined by the method in which it is measured. Because the methods used to measure oil in water for regulatory purposes vary throughout the world, it is very difficult to compare oil in water analyses.

The measurement methods can be grouped into two categories; direct and indirect. The direct method measures the mass per unit volume of oil directly. The US EPA Method 1664 uses a direct measurement method in which "oil and grease" is defined as "a mixture of those components of produced water that are extractable in hexane at pH 2 or lower and remain after vaporization of the hexane". (Tyrie, 2007) That "oil" which is remaining from a 1 liter sample of produced water is weighed and the concentration of oil-in-water is directly reported in mg/l. This method is advantageous because it is straightforward and does not require a standard to compare to; however it is limited by what components are actually extractable. (EPA Method 1664) Any dispersed hydrocarbons that are not extracted are not "legally" considered oil by this method. Also, this procedure must be done in an accredited lab by trained technicians. Since this method cannot be used in the field, operators rely on indirect methods that use instruments that are calibrated with the oil produced by the facility. This gives a good estimate of what the 1664 method concentration will be so that discharges can be kept in compliance.

Indirect or instrumental methods measure other characteristics of the sample, and then relate that measurement to a standard to determine the mass of the oil. Prior to 2007 OSPAR required an indirect method using infrared (IR) analysis. In this method tetrachloroethylene is used to extract the oil from the sample, and then IR absorption instruments use spectrophotometry to quantify the oil by targeting carbon hydrogen (C-H) bonds which absorbs IR energy at a 3.41 micron wavelength. (Tyrie, 2007) Since indirect methods do not measure the actual weight of the oil, instrument calibrations must be done to create a relationship between the characteristic measured, such as IR absorption, and the oil concentration. When the IR absorption is plotted against the known concentration of a standard sample, the relationship must be linear, or else a lower standard concentration must be used. (OSPAR 2005-15) Calibrations have many issues, one being that the composition of the standard needs to be the same as the sample being analyzed. This is rarely the case since the standard usually uses only crude oil and the oil in produced water includes not only crude oil, but dissolved oil from the formation water and treatment chemicals that may measure as oil. (Tyrie, 2007)

As of 2007 OSPAR uses another indirect method of measurement in which a capillary gas chromatographer with a non-polar column and a flame ionization detector (FID) is used to analyze the water. The gas chromatographer produces a graph and "the total peak area between n-heptanes and n-tetracontane is measured. The peak areas of the aromatic hydrocarbons toluene, ethyl benzene and three isomers of xylene are subtracted from the total peak area, and the concentration of dispersed oil is quantified against an external standard consisting of a mixture of two specified mineral oils, and the content of dispersed oil is calculated". (OPSAR 2005-15)

It is difficult to compare the final mg/l concentration result of a direct method analysis with the result of an indirect analysis because they do not measure the same thing, and "oil" is defined differently for each procedure. Even various indirect methods that measure different characteristics of the sample have different definitions; therefore the same sample would give different results. Because of this, produced water should be analyzed using the procedure specified for the regulatory requirements of the region and the mg/l oil in water concentration of one region should not be compared to the concentration of another in which a different measurement method is used. (Tyrie, 2007)

4.9 Sampling and Testing Frequency

4.9.1 US EPA

The US EPA requires that samples of produced water to be discharged be collected from all facilities and analyzed at a minimum of once per month to verify that it meets oil-in-water concentration regulations (EPA 2007). A sample must also be taken within two hours of an observable sheen, as well as after the startup of a system that was shutdown due to a sheen.
A visual sheen test is required once per day. Two types of samples are acceptable. A grab sample can be used as long as it is collected within 15 minutes of observing a sheen; otherwise a composite sample is necessary. A composite sample is an arithmetic average of multiple grab samples collected at even intervals over 24 hours or less. Samples used for oil and grease monitoring are analyzed using the US EPA Method 1664 prior to any addition of seawater. This method uses extraction by n-hexane.

Toxicity testing of produced water must be done once per year for facilities discharging less than 4600 barrels per day, while those discharging more must be tested once per quarter. If those facilities discharging more than 4600 barrels per day of produced water are compliant for a year of quarterly testing, the frequency may be reduced to annually. The produced water samples being tested for toxicity are analyzed after the addition of any substances, including seawater, and before the flow is split into multiple ports.

4.9.2 North Sea

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OSPAR governs produced discharge regulations in the North Sea and requires that on manned facilities, 16 samples of produced water per month be analyzed for compliance verification (OSPAR 2001). The reporting requirements for unmanned facilities is slightly less stringent stating only that the timing of samples should ensure that the samples are representative of the effluent and that operational aspects and logistics should be taken into consideration.

OSPAR member countries may have stricter requirement on sampling than the OSPAR recommendation. Although the United Kingdom Continental Shelf (UKCS) is governed by OSPAR, the UK has added additional requirements for frequency of sampling on their facilities. Any facility that is manned and discharges more than 2 tonnes of dispersed oil per year shall take at least two samples per day. Unmanned facilities with greater than 2 tonnes of discharge should have a sample taken every time it is visited. Manned facilities discharging under 2 tonnes of dispersed oil per year are to be sampled once per month, and those that are unmanned also require testing once per month, even if visited more frequently.

All OSPAR samples are analyzed for oil-in-water concentration using the OSPAR Reference Method outlined in Recommendation 2005-15. OSPAR accepts alternative methods that have been correlated against the OSPAR Reference Method. Criteria for alternative methods are explained in Recommendation 2006-6.

4.9.3 Determine Agency Enforcement Methods and Penalty Arrangements

Inspections

Enforcement of BOEMRE regulations begins with inspections. The Potential Incidents of Noncompliance (PINC) list is the backbone of the Bureau Inspection Program. The PINC list acts as a guide for inspectors, giving them a specific item-by-item checklist of what to look for during inspections. It also informs the operators and contractors about exactly what the inspectors are watching for (BOEMRE website). The actual PINC list for pollution can be found at http://www.boemre.gov/regcompliance/PDFs/PINC/GLE.pdf

BOEMRE's Gulf of Mexico inspection program is directed out of the Regional Office in New Orleans, Louisiana and also includes five district offices. There are 55 inspectors that go offshore daily, weather permitting. Each district inspector inspects one to three drilling rigs or platforms per day. Aerial surveillance is conducted en route. "During FY 2009, the Gulf of Mexico Region conducted 614 drilling inspections, 3,862 production inspections, 296 work over and completion inspections, 7,201 meter inspections, 63 abandonment inspections, and 4,765 pipeline inspections" (BOEMRE website).

Initial inspections are done to ensure proper installation of mobile units or structures and associated equipment. Announced and unannounced inspections are conducted after production begins. The purpose of unannounced inspections is to foster a climate of safe operations, maintain a BOEMRE presence, and to focus on operators with a poor performance record. Surprise inspections are also done after a critical safety feature which was defective is fixed (BOEMRE website).

Enforcement Action

If a noncompliance with a checklist requirement is found, a prescribed enforcement action will occur depending on the violation. This could include a written warning, denoted as (W) on the PINC list, a shut-in of a component such as a piece of equipment, a pipeline, a zone or a well, denoted as (C), or a shut-in of the entire platform or facility, denoted as (S). An operator is given 14 days to mitigate a violation of a safety or environmental requirement before monetary penalties are incurred (BOEMRE website).

Penalties

"Under 43 U.S.C. 1350(b) of OCSLA, as amended, and regulations appearing at 30CFR 250.200-250.206, civil penalties can be assessed for failure to comply with responsibilities under the law, a license, a permit, or any regulation or order issued pursuant to the Act." (BOEMRE website) If a corrective action is not taken within a reasonable amount of time, there will be a penalty of no more than $40,000 a day for each day that the failure continues. If the failure is considered "a threat of serious, irreparable, or immediate harm or damage to life (including fish and other aquatic life), property, any mineral deposit, or the marine, coastal, or human environment, a civil penalty may be assessed without regard to the requirement or expiration of a period allowed for corrective action." No penalties will be assessed until the violator has been given an opportunity for a hearing. "The Secretary shall, by regulation at least every 3 years, adjust the penalty specified in this paragraph to reflect any increases in the Consumer Price Index (all items, United States city average) as prepared by the Department of Labor" (43 U.S.C. 1350(b)). "The Oil Production Act of 1990 changed the way BOEMRE will address civil penalties and remedies. Civil penalties are now issued for serious violations.

The following tables taken from the Notice to Lessees No 2011-N06 categorizes the civil penalties.

GENERALIZED TABLE FOR CIVIL PENALTY ASSESSEMENTS IN $/DAY/VIOLATION			
Enforcement Code	**Category A**	**Category B**	**Category C**
W	$5,000-**$40,000** ($15,000)*	$10,000-**$40,000** ($20,000)*	$20,000-**$40,000** ($25,000)*
C	$10,000-**$40,000** ($20,000)*	$15,000-**$40,000** ($25,000)*	$30,000-**$40,000** ($35,000)*
S	$15,000-**$40,000** ($25,000)*	$20,000-**$40,000** ($30,000)*	$35,000-**$40,000** ($37,000)*

Note: W = Warning, C = Component Shut-in, and S = Facility Shut-in;
* = Starting Point for Assessment

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Category A	**Category B**	**Category C**
Threat of injury to humans. Threat of harm or damage to the marine or coastal environment, including mammals, fish, and other aquatic life (threat may or may not involve endangered/threatened species). Threat of pollution. Threat of damage to any mineral deposit or property.	Injury to humans that result in 1-3 days away from work or 1-3 days on restricted work or job transfer. Minor harm or damage to the marine or coastal environment, including mammals, fish, and other aquatic life (harm to aquatic life did not involve an endangered/threatened species.) Pollution caused by liquid hydrocarbon spillage of up to 50bbl. Minor damage to any mineral deposit. Minor property damage equal to or less than $25,000. Additional incidents required to be reported under 30 CFR 250.188, except a(6), (b)(1), and b(4).	Loss of human life. Injury to humans that result in more than 3 days away from work or more than 3 days on restricted work or job transfer. Serious harm or damage to the marine or coastal environment, including mammals, fish, and other aquatic life (harm to aquatic life involved numerous individuals <u>or</u> involved one or more members of an endangered/threatened species.) Pollution caused by liquid hydrocarbon spillage of more than 50 bbl. Serious damage to any mineral deposit. Serious property damage greater than $25,000.

If the violation is serious enough and is found to be a knowing and willful violation, BOEMRE may recommend that the matter be referred to the Department of Justice for criminal prosecution." These criminal penalties will include a fine of no more than $100,000, imprisonment of no more than ten years, or both. Each day that a serious violation continues will constitute a separate violation (43U.S.C. 1350(c)) "The issuance and continuance in effect of any lease or of any assignment or other transfer of any lease shall be conditioned upon compliance with regulations issued under the OCSLA" (BOEMRE website).

4.10 Section Summary

Worldwide regulations do appear to be well adopted throughout the world, but it has a wide difference of area regulations governing all the different parts of the world. These differences have come about through decades of research and development and regulation creation and enforcement.

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The oil in water content serves as the primary target for worldwide regulations, and toxicity is commonly addressed with dilutions of seawater. Measurement, monitoring and reporting requirements vary by region, but all require sampling and measuring/testing of the samples. A single method of measuring is specified in the US regulations. The OSPAR convention allows for alternate methods if they are satisfactorily calibrated against the reference method.

Proper assessment of the area standards and regulations are critical for new discharge implementations, but most of the information is readily available through the global produced water industry.

There are currently no regulations governing produced water disposal at the seabed. This study will attempt to identify the framework for creating effective seabed produced water and/or solids disposal and discharge.

The following are some of the regulatory impacts on seabed discharge of produced water and/or solids:

- Sand cannot be discharged in US projects. In these projects, sand must be collected for retrieval to shore, or send to platform. In other countries, sand discharge is not prohibited but would require additional seabed equipment to wash the sand to less than 1% oil content based on dry weight before discharge. This will bring in additional complexity in monitoring of oil content in sand. Additionally, radioactivity monitoring of the sand and the produced water may be required.
- There is no current regulation on suspended solids. However, suspended solids tend to have oil adhering onto them. Excessive amount of suspended solids in produced water can make the discharge exceed the oil in water content. Therefore, some measure of suspended solids removal should be included in the water treatment equipment.
- There are challenges to overcome regarding monitoring and reporting. The current approved methods for oil and grease monitoring are based on laboratory testing of water samples. With the US regulations, the minimum sampling and testing frequency is once per month which makes monitoring feasible with available technology such as ROV access, although it can be expensive. The US regulation does not provide means of using online monitoring to substitute for laboratory measurements. OSPAR rules differentiate between manned and unmanned facilities with the former require much more frequent sampling. The OSPAR rules allow alternate methods to be used if they be calibrated satisfactorily against the reference method, but the rules were developed to address alternate laboratory methods which were legacy methods used on existing installations. It is unclear how online methods can be calibrated. There are gaps in the current regulations regarding monitoring and reporting of the oil and grease content. Toxicity is currently monitored by periodical sampling and testing, but at much longer period (quarterly etc) than oil and grease monitoring, so the currently available technology (ROV access) may be feasible for toxicity monitoring of seabed discharges.
- The US regulations allow the toxicity criteria to be met through dilution. Dilution can be achieved by adding seawater, using diffuser, or using multiple ports. Specific software to use (CORMIX/CORMIX2) if diffuser is used to increase dilution. However, since the critical dilution tables and the software were developed to address shallow water and near surface discharge. It remains to be determined on whether they are applicable to seabed discharge, where there is much less seawater motion (currents or wave induced). In the case that they are not, a methodology needs to be developed to assess the dilution effect.

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- The US regulations require daily visual sheen monitoring. For the developments that will potentially discharge produced water at seabed, which are typically subsea tieback developments and maybe with long offset, daily observation of visual sheen may be challenging. Additionally, the water sampling requirement after observing sheen (within 2 hours after a visual sheen is observed) may also be challenging to meet.
- Currently there is no direct regulation on total dissolved solids. However they are indirectly regulated through toxicity. If the dissolved solids cause the toxicity to exceed the allowable limit, either additional equipment to remove the solids, or dilution can be used. The latter may be a more feasible approach due to the potentially large amount of dissolved solids in produced water, particularly that from deepwater fields.

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5.1 Surface Discharge Effects on Marine Life

Various references and sources were discovered in this research study to better understand the seabed and marine life from 5000 to 8000 feet of water depths. Information was collected from various sources including academia and survey companies.

Many studies have been done to test the effects of produced water on marine life. The process that produced water goes through upon discharge is important in determining how it will affect the surrounding marine life.

First, the discharged treated produced water goes through two phases of dilution. The first phase of dilution happens within the first few tens of meters where it dilutes by a 30 to 100-fold factor. The second phase happens 500 to 1000 meters away from the discharge point where the produced water dilutes by a 1000 to 100000-fold factor (OGP, 2005). Secondly low molecular weight hydrocarbons volatilize into the air or are degraded by photolytic or biological processes. Also, the produced water constituents are exposed to several chemical processes including precipitation, hydrolysis, oxidation, and complexation upon discharge. Next, the constituents adsorb on the suspended solids. The rate of adsorption depends on the amount of suspended solids and the adsorptive tendencies of the constituents (OGP, 2005). Finally the constituents begin to biodegrade. The rate of biodegradation depends on each constituent's chemical structure. Naturally occurring bacteria in marine environments also control biodegradation of produced water constituents (Argonne National Lab, 2004).

Field studies were done near Norway in a region with a high density of produced water discharge, which accounts for nearly 70% of all the discharge of water in the North Sea. At a distance of 10 km from the discharge point, aromatic hydrocarbons could be detected; however it was only within 500m that the concentrations of hydrocarbons would cause a rise in biological effects. Fish were also tested in this study and results show that produced water at current regulation poses only a minor risk to marine life. Dilution models are often used today to understand this process better in specific regions (OGP, 2005).

In the early 1990's a study was done in the Gulf of Mexico which compared the bioaccumulation of target chemicals in edible tissue of fish collected at GOM platforms discharging >4600 bbl/d to that of fish collected at platforms with no produced water discharges. It also targeted to evaluate the ecological and human health considerations of observed concentration of target chemicals in edible tissues of fishes collected near offshore platforms in the GOM. As a result, none of the target chemicals were present in edible tissues at concentrations that might be harmful to the fish or to human health. Also, there were no major differences in tissues collected from discharging sites as opposed to non-discharging sites.
The few observed elevated concentrations were distributed equally between the discharging and non-discharging sites, suggesting that produced water discharge was not the source of the elevations (OGP, 2005).

For the DW3100 study, there is a need to better understand the ultra deepwater marine life and how it will react to the discharge criteria that is defined in the basis of design for the study.

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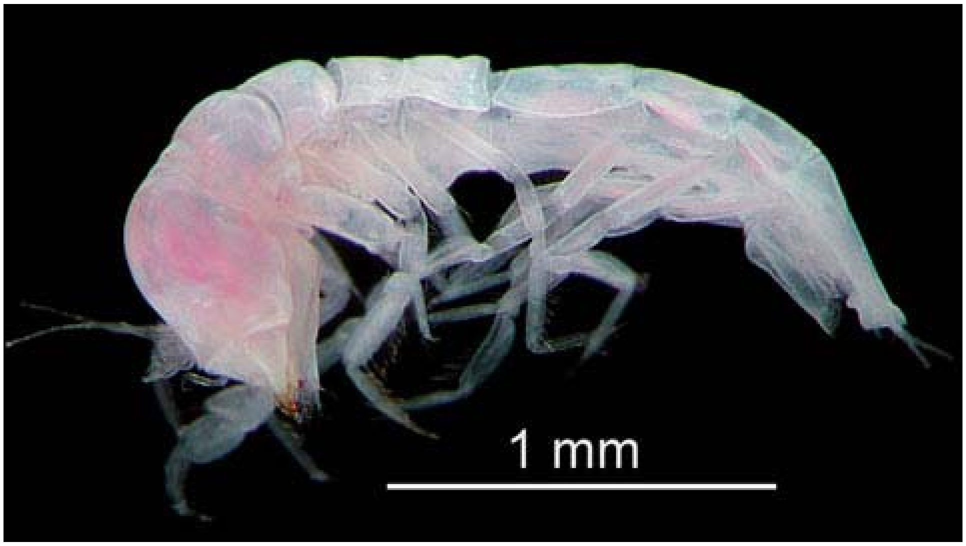
5.2 US Gulf of Mexico Characteristics

The US Gulf of Mexico is home to an abundance of mammals, turtles, coastal and marine birds, fishes, and invertebrates. In fact there are 29 known mammal species living in the Gulf of Mexico, 8 of which are listed as either endangered or threatened, as well as 5 species of sea turtles, all of which are endangered or threatened. Benthic invertebrates are found at water depths greater than 650 feet and are the most likely to be affected by subsea processing activities (Grieb, 2008). "Benthic invertebrates are organisms that live on the bottom of a water body (or in the sediment) and have no backbone. The size of benthic invertebrates spans 6-7 orders of magnitude (Heip, 1995). They range from microscopic (*e.g.* microinvertebrates, <10 microns) to a few tens of centimetres or more in length (*e.g.* macroinvertebrates, >50 cm). Benthic invertebrates live either on the surface of bedforms (*e.g.* rock, coral or sediment - epibenthos) or within sedimentary deposits (infauna), and comprise several types of feeding groups *e.g.* deposit-feeders, filter-feeders, grazers and predators. The abundance, diversity, biomass and species composition of benthic invertebrates can be used as indicators of changing environmental conditions."(OzCoast 2011)

The environmental and biological conditions of the deep Gulf of Mexico can be defined as having high pressures, low temperatures, and an absence of light, all which limit the types of organisms that can survive there. The deep Gulf also has low organic matter (or food) inputs, which affects "the overall abundance and biomass of the organisms that are present. However, unique communities (i.e., chemosynthetic organisms) are associated with the presence of conditions that provide nutrient subsidies such as methane hydrates or hydrocarbon seeps." (Grieb, 2008)



Thaumastasoma species 521 (Crustacea; Isopoda; Nannoniscidae), A typical species of the lower continental slope.
Photo: George D. F. Wilson, Reference paper from Marine Ecology Process Series, Bathemetric Zonation of Deep Sea Macrofauna in relation to export of surface phytoplankton production.

Some major features of the Gulf of Mexico are the continental shelves, which range from a width of 10 miles near the mouth of the Mississippi River to 217 miles near west Florida; the Florida and Yucatan Straits, the continental slopes and rises, and the abyssal plains which reach a depth of nearly 12,000 feet. The northwestern region of the Gulf of Mexico has a huge salt formation covered with sediment from the Mississippi river. In some places, the salt formation pushes up through the sediment causing salt domes and associated faults. Hydrocarbon seeps are common along these faults.

The geography of the Gulf of Mexico causes it to have a Loop Current which is made by water entering through the Yucatan Strait and exiting through the Florida Strait. This Loop Current mainly affects the eastern region of the Gulf of Mexico, however the Loop Current causes eddies that travel westward and southward and affect the western region. The Loop Current and resulting eddies affect the deep waters of the gulf by generating topographic Rossby waves (TRWs). "TRWs are low-frequency deep-sea currents. These deepwater currents propagate westward in the lower 1,000-2,000 meters (3,280-6,560 feet) of the water column, and have been measured at up to 9km per day (0.2 kn) These bottom currents are strong enough to cause bottom scour." (Grieb, 2008)

Although temperature, salinity, dissolved oxygen, pressure, light, and nutrient concentrations change rapidly with depth in the Gulf of Mexico, below 1,000 meters (3,280 feet) these characteristics stay relatively constant. This steady state environment causes the organisms living there to be extremely sensitive to change in any of these characteristics. In the deep Gulf, the temperature is about 4°C (39°F), and the salinity is less than 35 ssu. Dissolved oxygen concentrations reach a minimum of 2.5 to 3.4 ml/L at 1,150 - 1,940 feet and rise to 4.6ml/L below 3,940 feet. Pressure rises one atmosphere of pressure (0.1 MPa) every 10 meters (33feet) of depth, making pressure in the deep Gulf extremely high. There is only limited amounts of available light between 600 – 3,280 feet, and it is completely absent below 3,280 feet. "The absence of light precludes photosynthesis and primary production in the deep-sea. As a result of the absence of light and limited surface productivity, the deep Gulf of Mexico is nutrient limited and organisms must rely on particulate organic carbon (POC) falling from surface waters and transported vertically." (Grieb, 2008)

5.3 Deep Sea Marine Life in the US Gulf of Mexico

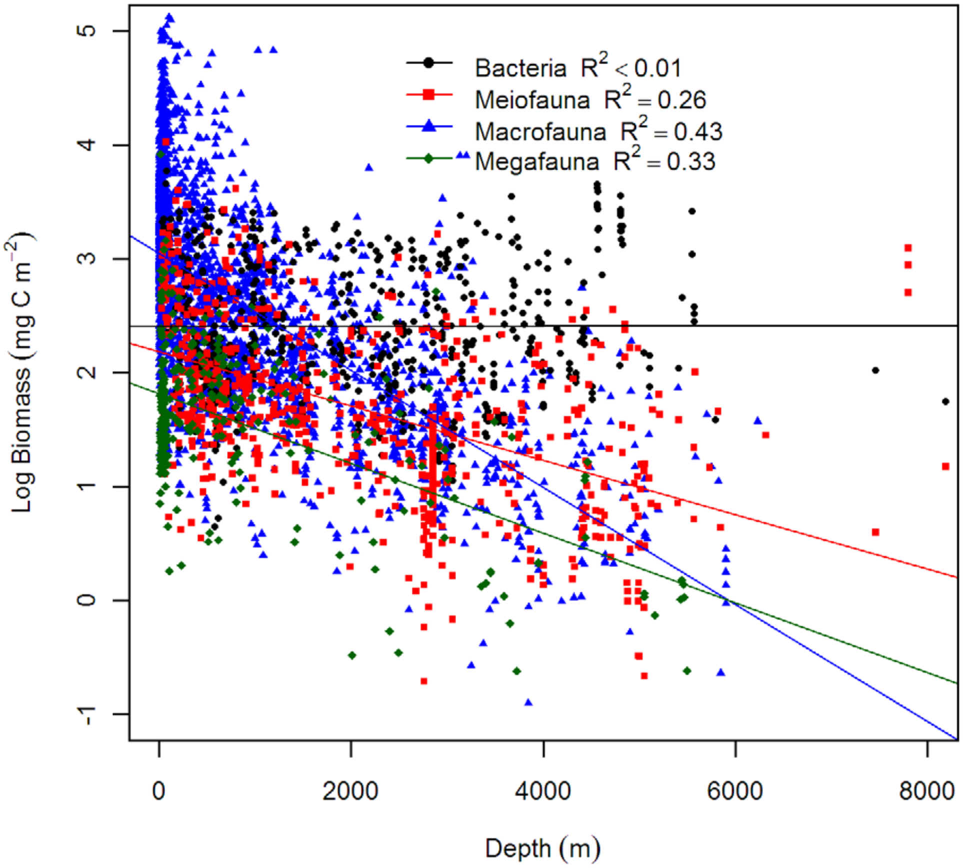
5.3.1 Benthic Communities

The Gulf of Mexico can be divided into four zones by depth. The upper zone is located on the continental shelf and upper slope. The next zone is between 3,280 and 7, 500 feet, the mesoabyssal zone is located between 7,550 and 10,580 feet and the lower abyssal zone is anything greater than 10,660 feet (Wei and Rowe, 2006). Since the target depth for this study is 5,000-8,000 feet, only those organisms that exist in those parameters will be discussed.

In the 3,280-7,500 foot zone, both shallow and deepwater species are present (Gallaway, 2001; Wei and Rowe, 2006). The Loop Current causes there to be great differences in species composition between the eastern and western regions of the Gulf. The mesoabyssal zone contains "true" deep-sea fauna (USDOI, MMS 2007c).

Organisms can be classified by their size as meiofauna (between 40 and 300 μm), macrofauna (> 300 μm), and megafauna (animals that can be seen with the naked eye). The diversity versus depth of these different classifications reaches a maximum at 4,900 feet and steadily declines with depth, as seen in the figure below (Grieb, 2008).

MARINE LIFE



Biomass is shown as a function of depth for bacteria, meiofauna, macrofauna, and mega fauna. Biomass was log10 transformed and the effects of latitude and longitude were removed by partial regression. Reference taken from (Wei and Rowe, 2006)

The above figure highlights the levels of bacteria throughout the world's oceans and at all depths is constant. The reference study found that the abundance of marine organisms is directly related to nutrient levels (Wei and Rowe, 2006). The source of nutrients in the Gulf is primarily from pelagic detritus from plankton (Biggs).

5.3.2 Chemosynthetic Communities

Hydrocarbon seeps are the most common place to find chemosynthetic communities in the Gulf of Mexico because these communities are able to utilize dissolved gasses as an energy source (Grieb, 2008). "Chemosynthesis occurs due to the presence of free-living or symbiotic sulfate-reducing bacteria. At least 60 of these communities have been located to date. These chemosynthetic communities are complex, with high abundances and organism densities (Paull, 1984; Kennicutt, 1985). They may be dominated by a single species or a combination of vestimentiferan tubeworms, seep (mytilid) mussels, large vesicomyid clams, small lucinid clams, and polychaete ice worms." (MacDonald, 2002)

MARINE LIFE

A small bush of tubeworms. When tubeworm bushes are young, only endemic species of animals can colonize them. The presence of the mussels *(Bathymodiolis childressi)* in the center of the bush means that methane is seeping just below. *Image courtesy of Gulf of Mexico 2002, NOAA/OER.*

5.4 Section Summary

From current knowledge, we can understand what effect surface discharges of produced water within the latest regulation levels have on marine life on the surface. We are also aware of the types of organisms that exist at deepwater levels that would be affected by seabed discharge. There is a knowledge gap in knowing how exactly those deepwater organisms will be effected by seabed discharge of produced water and what standards must be met to ensure there are no harmful effects. One way to gain this information may be to do a pilot study with seabed discharge and study the deepwater marine life to determine what appropriate discharge criteria is needed to ensure their safety.

MARINE LIFE

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STATE OF THE ART REVIEW OF PRODUCED WATER TREATMENT TECHNOLOGIES

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6.0 STATE OF THE ART REVIEW OF PRODUCED WATER TREATMENT TECHNOLOGIES

This section discusses the current produced water treatment technologies, along with their respective vendors and 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.

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:

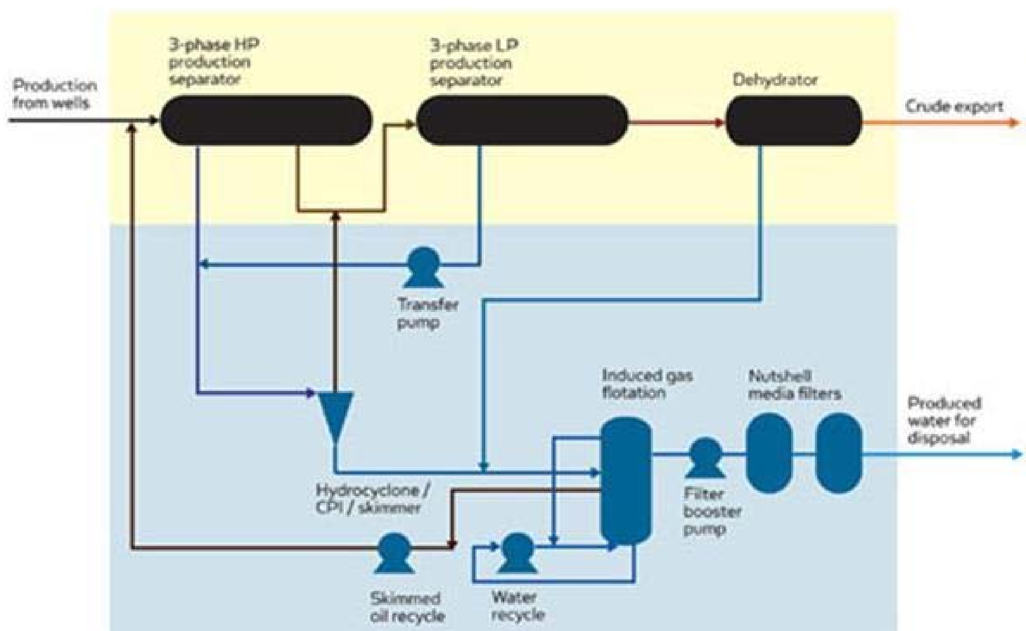

Figure 1 - Typical Produced Water Treatment Package (Courtesy of Prosep)

Additional information on the ProSep solutions can be found in **Appendix 03**.

6.1 Conventional Oil and Grease Removal

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

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- 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 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, 2003; www.netl.doe.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)

UNIT PROCESS	TECHNOLOGY DESCRIPTION	STATE OF DEVELOPMENT	STRENGTH	LIMITATION
Separator	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.	Very well established treatment process used in the oil and gas industry.	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).	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.

UNIT PROCESS	TECHNOLOGY DESCRIPTION	STATE OF DEVELOPMENT	STRENGTH	LIMITATION

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UNIT PROCESS	TECHNOLOGY DESCRIPTION	STATE OF DEVELOPMENT	STRENGTH	LIMITATION
Filtration	A bed of sand or walnut shell granular media that is at least four feet deep in a vertical tank.	Well known and established technology in the oil and gas industry.	Able to remove small diameter oil droplets from produced water. Useful for polishing the effluent.	Soluble TPH components are not removed; not recommended for influent oil concentrations over 100 ppm.
Hydrocyclone	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.	Well know and established technology in the oil and gas industry.	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.	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.
Induced Gas Flotation	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.	Well known and established technology in the oil and gas industry.	Oil removals of greater than 93% have been demonstrated with chemical additions.	Does not remove soluble oil components.
Membrane Filtration	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.	Widely practiced on a large scale in industry. Developmental for O&G applications. Micelle-enhanced version of this process is an emerging technology.	Compact. Removes about 85-99% of total oil. Effluent oil & grease can consistently be reduced to below 14 ppm.	Iron fouling can be a problem. Effective cleaning is critical to preventing membrane fouling and reduction in permeate flux

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

6.1.1 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 viscosity (Stokes Law). **Appendix 5** discusses Stokes Law in detail. 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)

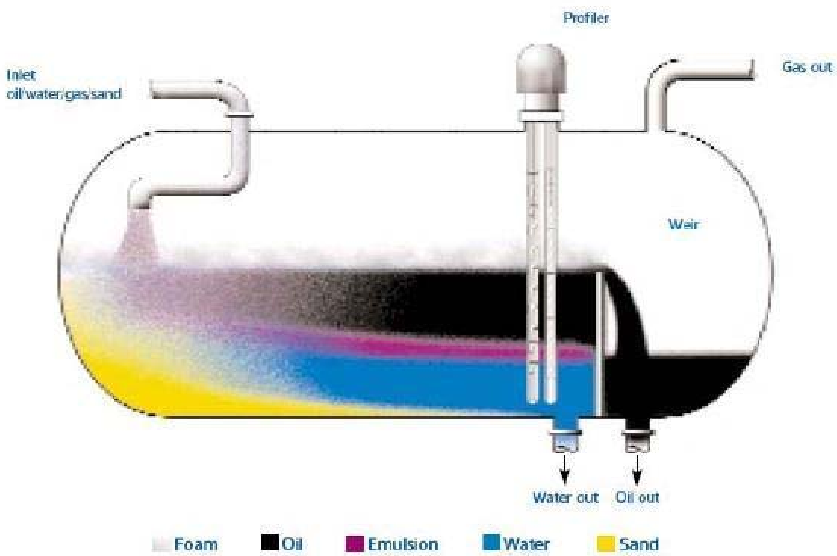

Figure 2 - Typical Production Separator and Profile (Courtesy of Produced Water Society)

6.1.2 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) The 2009 RPSEA study is a good reference for more details in produced water treatment technologies and can be referenced in **Appendix 17**.

Figure 3 - Modern Walnut Shell Filtration Package (Courtesy of Produced Water Society)

Figure 4 - Pilot Compact Walnut Shell Filter Package (Courtesy of Produced Water Society)

Coalescing Filters are currently in wide use throughout the offshore facilities. These filters can be backwashed several times before their efficiency is used up, in which case they would then require replacing. Typical replacement times run from once a month to once every 6 months. Many different vendors are supplying these filters today. They typically allow for the entire flow of produced water to enter from the bottom and travel up through a vertical flow pattern towards a filter interface where oil droplets break out and accumulate. The accumulate oil coalesces into larger droplets and are taken of the top of the unit. Any gas that may breakout will also be collected with the oil.

Appendix 1 – CETCO Water Treatment, offers a complete write up on the coalescing filters used by Cetco Oilfield Service Company and can help illustrate further their benefits and typical use in the industry today.

6.1.3 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.

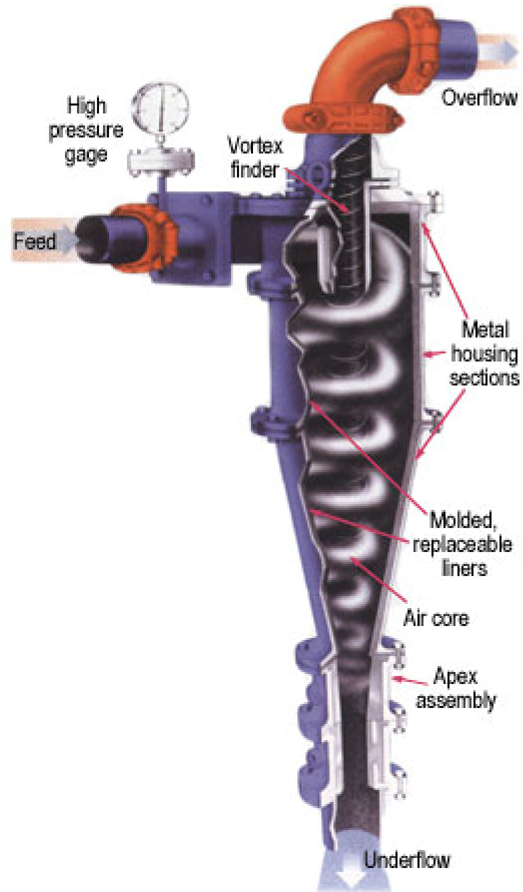

Figure 5 - Basic Concept of a Hydrocyclone (Courtesy of www.cronin-cook.com)

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. Refer to Appendix 9 for more details on Hydrocyclones.

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 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)

6.1.4 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.

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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. Refer to **Appendix 10** for details on the Cameron WEMCO IGF system.

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) Details on the Envirotech flotation cells can be referenced in **Appendix 11**.

6.1.5 Membrane Filtration

Membrane filtration systems operate under Micro Filtration (MF) and Ultra Filtration (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, 2003)

Ceramic membranes are an important membrane category that is of particular interest in applications requiring high chemical or thermal stability. It is considered the most recent type of filter technology that is gaining more support and use throughout the offshore industry. They are composed of tubular ceramic membranes formed by a porous support of one or more layers of decreasing pore diameter and an active or separating layer usually made of alumina or zirconia and covering the internal surface of the tube. The ceramic membranes are always housed in stainless steel housings. Depending on the requirements of each particular application, a wide range of ceramic membrane designs and stainless steel membrane housing are commercially available. The use of ceramic membranes for micro filtration and ultra filtration solutions is of great interest due to the potential to remediate fouling problems associated with those processes and solutions (adsorption or deposition of macromolecules on the membrane pores/surface) that strongly reduce volume flow and make the use of hard chemical and high temperatures in cleaning procedures necessary, which in turn causes damage to polymeric membranes. (Ashaghi, 2007)

Ceramic membranes have been investigated for produced water treatment and have been found to be successful in reducing total suspended solids and suspended oil. However, the technologies use is limited as of today. One challenge in adoption of ceramic membranes for produced water treatment has been the high operating cost. While operators can accept the relative high capital cost of ceramic membranes, the high cross flow recycle rates that has been shown to be required to manage fouling, contribute substantial operating costs. One ceramic membrane system under investigation uses a back-pulse to reduce the fouling potential, and thereby reduce the cross flow recycle rates, which may warrant further investigation. (Bishop, 1995) Refer to **Appendix 12** for more details on ceramic membranes.

Advantage of Membrane Filtration

• Narrow and well-defined pore size distribution, in comparison with their polymeric counterparts allows membranes to achieve a high degree of particulate removal at high flux as demanded by applications as the removal of emulsified oils from waste waters. (Ashaghi, 2007)
• Material stability in harsh environments can provide cost-efficient high temperature deashing of spent lubricants and the removal of submicron suspended/dissolved solids from industrial solvents. (Bishop, 1995)
• Membrane cleaning with harsh chemicals (if necessary) does not reduce membrane performance stability, which is critical in dealing with waste streams that constantly vary or display a high propensity for membrane fouling. (Ashaghi, 2007)

6.1.6 Summary of Primary Technologies for Oil Removal

The oil in water removal capabilities of offshore separation methods are shown in Table 2. The concentration level in the outlet stream is given based on interviews with different vendors providing the various technologies outlined. These levels should be considered average and in many cases, more attention given their operation and maintenance can yield even lower output concentration results.

Table 2 - Particle Size Removal Capabilities

TECHNOLOGY	Removes Particles Greater Than Size Indicated (in microns) Ref. Hayes, 2004	Typical Oil in Water Concentration in Outlet Stream
API Gravity Separator	150	5000 - 1000 ppm
Corrugated Plate Separator	30	100 - 40 ppm
Induced Gas Flotation	25	30 - 20 ppm
Induced Gas Flotation with Chemical Addition	3-5	10 – 2 ppm

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TECHNOLOGY	Removes Particles Greater Than Size Indicated (in microns) Ref. Hayes, 2004	Typical Oil in Water Concentration in Outlet Stream
Hydrocyclone – 35mm	10-15	200 – 100 ppm
Media Filter	5	40 - 15 ppm
Membrane Filter	0.01	15- 5 ppm
Coalescing Filter	[HOLD]	[HOLD]

6.1.7 Other De-Oiling Technologies

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

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

TECHNOLOGY		
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.		
Weighted (or Ballasted) Flocculation	***Description***	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.
	Commercial Availability	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.
	Uses and Strengths	The proprietary ballasted flocculation system has gained popularity in the domestic water and wastewater industries. Its main advantages are a small foot print relative to gravity or air flotation clarifiers, and a very good quality effluent (turbidities of about 0.1 NTU are possible).
	Weaknesses	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.
	R&D Needed	Technology is well understood for normal applications. Has potential for removal of low to moderate concentrations of hydrocarbons in water, perhaps including asphalthenes. 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&D work would consist of both laboratory and pilot studies.

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TECHNOLOGY		
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.

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TECHNOLOGY		
Adsorptive Filtration	***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.
	R&D Needed	The technology, in its many variations, is well understood and requires little if any R&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.
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).		
Evaporation / Condensation	***Description***	The process consists in evaporating the water, leaving non-volatile contaminants in the liquid phase. The vapors arethen 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.

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TECHNOLOGY		
Evaporation / Condensation	***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.
	Uses and Strengths	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.

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TECHNOLOGY		
Evaporation / Condensation	***Weaknesses***	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.
	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.
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.		
Other Chemicals	***Description***	Many chemical may be added for different water treatment needs. Usually, they are used to enhance or enable the performance of various separation processes.
	Commercial Availability	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.

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TECHNOLOGY		
Other Chemicals	***Uses and Strengths***	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 bio-fouling problem.
	Weaknesses	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.
	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.		
Electro-Flocculation	***Description***	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.
	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.

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TECHNOLOGY		
Electro-Flocculation	***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.
	Weaknesses	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.
	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.

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TECHNOLOGY		
Adsorptive Bubble (Foam Fractionation)	***Description***	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.
	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	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.
	Weaknesses	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.

TECHNOLOGY		
	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. 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.

6.2 Best Available Technology for 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).

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.

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

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

6.2.1 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.

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Table 5 - Treatment Technologies for Identified Constituents (PTAC, 2007)

TECHNOLOGY		
Cake Filtration	**Description**	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.
	Commercial Availability	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.
	Uses and Strengths	Widely used in most industries, they are an efficient and cost effective means of separating solids from water.
	Weaknesses	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.
	R&D Needed	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.
Media Filters	**Description**	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.
	Commercial Availability	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.

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TECHNOLOGY		
Media Filters	**Uses and Strengths**	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.
	Weaknesses	Concentration of solids in the feed should be < 10 mg/L - ideally < 1 mg/L. Media filters clog rapidly even with small concentrations of free oil. Filters require large foot print, 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. One technology to address this issue can be the use of self cleaning filters as described in **Appendix 6**.
	R&D Needed	Pilot plant studies are done to determine performance, design criteria, and effect of filtration aids, such as coagulants and polymers.
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.

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TECHNOLOGY		
Adsorptive Filtration	**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.
	R&D Needed	The technology, in its many variations, is well understood and requires little if any R&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. Appendix 7 can be referenced for a product called **Osorb** with promising developments that has a potential use subsea.

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6.2.2 New Advanced Technologies

In recent years, the produced water industry has seen a number of new technologies for produced water treatment and handling. Below is a list of some of the most significant and successful technologies to be included in this state of the art review.

Macro Porous Polymer Extraction

MPPE (Macro Porous Polymer Extraction) systems remove dissolved and dispersed hydrocarbons such as aliphatic, aromatic, polyaromatic and halogenated compounds.

Figure 6 -Operating MPPE System (Image taken from MPP Paper)

The technology is robust and compact, particularly adapted to shale gas operations. MPPE was listed by OSPAR as Best Available Technology (BAT). Experiences published in SPE Conference (TOTAL & Akzo Nobel) and Offshore Technology Conference (Shell/Exxon & Akzo Nobel). Commercial units running at TOTAL, NAM (Shell/Exxon), Statoil, and Hydro/Shell with over 25 years accumulated experience. OSPAR: Oslo Paris Convention for the Protection of the Marine Environment of the Northeast Atlantic. Hydrocarbon-contaminated water is passed through a column packed with MPPE particles. The particles are porous polymer beads, which contain a specific extraction liquid. The immobilized extraction liquid removes the hydrocarbons from the water. Only the hydrocarbons, which have a high affinity for the extraction liquid, are removed. The purified water can either be reused or discharged. Periodical insitu regeneration of the extraction liquid is accomplished by stripping the hydrocarbons with low-pressure steam.

The stripped hydrocarbons are condensed and then separated from the water phase by gravity. The almost 100% pure hydrocarbon phase is recovered, removed from the system and ready to use/reuse or disposal. The condensed aqueous phase is recycled within the system. The application of two columns allows continuous operation with simultaneous extraction and regeneration. A typical cycle is one hour of extraction and one hour of regeneration. The subsea challenge for this technology is to apply the regeneration technique using steam. That process would not be impossible, but it is not a typical technique in ultra deep water application

Obsorb

Osorb is a hydrophobic glass like material that will not absorb water. It works at temperatures up to 210 degree Celcuis and pH up to 10. The material adsorbs up to 8 its own weight in target compounds by swelling up to 8 times its original size. Osorb can capture a wide range of dissolved and dispersed organics from water. These include volatile organic compounds (VOCs), hydrocarbons, pharmaceuticals, pesticides, herbicides, chlorinated solvents, endocrine disruptors, and other contaminants.
The material can be regenerated over 100 times. Absorbed compounds can be removed with mild thermal treatment or rinsing. Any absorbed organics can then be properly disposed, recycled, or further refined. Hydrophobic meaning not compatible with water: not dissolving in, absorbing, or mixing easily with water.

At the bench scale, Osorb is working effectively on all produced water samples provided. ISO9377 appears to be an accurate method for assessing hydrocarbon content, but other analytical techniques such as TOC are also being explored. The PW Unit #1 pilot scale unit has proven effective at using Osorb to treat Clinton produced water. Upcoming field tests in Wamsutter, WY will be useful to further
study the ability of Osorb to remove BTEX, oil and grease, and other organic species from produced waters at 1.5 bbl/min. These tests will provide more quantitative data regarding the reduction in contaminant concentrations in produced water from over 11 locations. The unit will continue to be
refined as a continuous process system, working towards a system capable of operating at 5 bbl/min. Skid Unit #1 has provided valuable data regarding the performance of Osorb in a fixed bed system, and its upcoming field pilots in south Texas and the Marcellus will provide additional quantitative data.

Compact Flotation Units – CFU

Over the last 10 years, the Oil and Gas Industry has seen a large increase in the number of companies manufacturing and testing compact flotation units. Robust vessels fitted with vortex inducing vanes, flow conditioning and fixed inlet piping arrangements, these units offer fewer moving parts and higher separation efficiency. They provide a high quality performance for produced water treatment. CFU are discussed further in the section 7.0 for conceptual designs.

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Vendors of Compact Flotation Units
Cameron – TST CFU
Veolia Water Services - CoPhase
MI Swaco - EPCON
Opus - Maxim
Seimens - Vorsep
Wiser CFU
ProSep - CTour

The below diagram shows the typical installation point of a compact flotation unit. Notice the use of hydrocyclones in line with the CFU for desanding and deoiling.

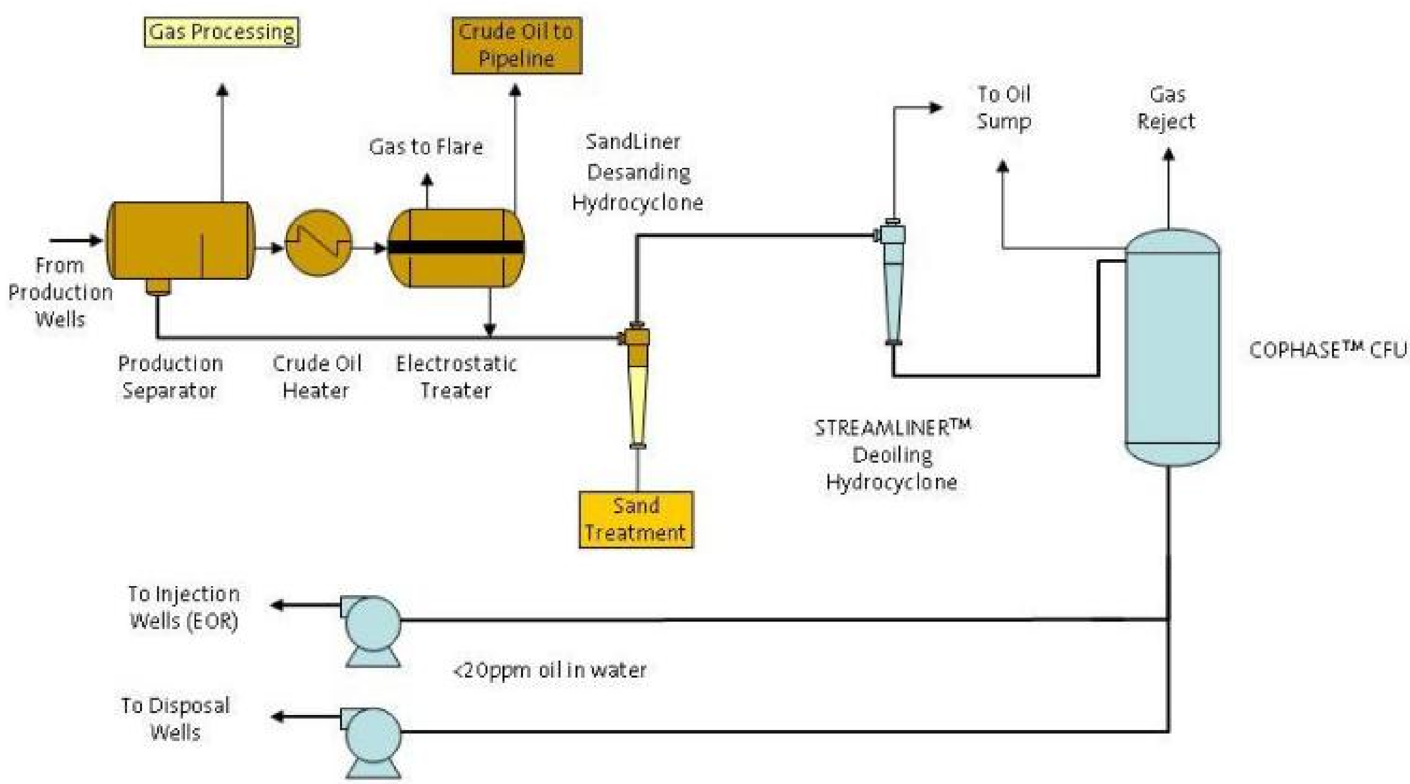

Figure 7 - Diagram of the CoPhase CFU Installation Point – Courtesy of Veolia

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The graphic below shows a flow diagram of a single train for a surface Produced Water Treatment System based on their Cameron's TST Compact Flotation Unit. From this start point, a sketch shows the CFU technology inserted into a subsea processing train. After the wellhead desander, well start-up storage tank and flowline mounted separator the flow stream would be diverted into one of these water processing trains.

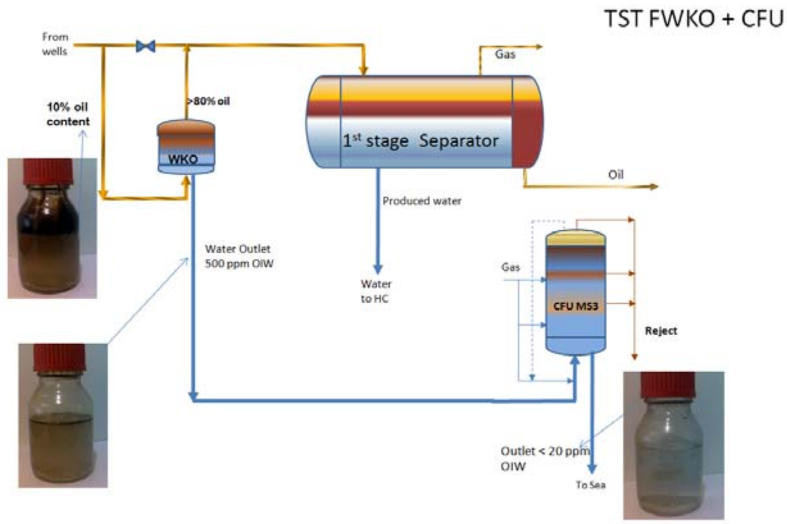

Figure 8: Cameron Compact Flotation Unit – Water Purities

Compact Flotation Unit – Cameron TST CFU Technology

The technology is based on both induced and dissolved gas flotation. External gas injection and special internals for mixing of gas and oil have been developed to achieve easy separation of this mixture from the water. The water can be treated through several stages and up to 4 stages can be housed in one vessel. The numbers of stages needed depend on the application. Multiple stages within one vessel bring lower fabrication cost and require less space. Each stage has multiple input pipes that create better internal mixing and contact between the gas bubbles and oil droplets without any moving parts. The design is claimed to have higher performance than existing CFU's with less equipment, lower weight and to be less dependent on chemicals than the first generation of CFU's.

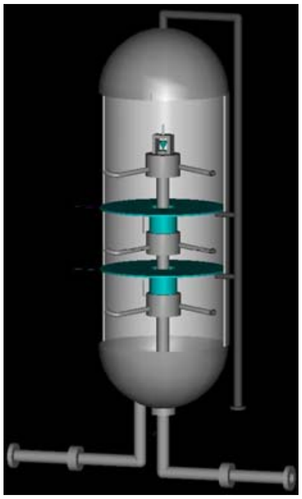

Figure 9: Cameron - CFU MS3 (Three stage vessel)

The performance has been verified topside offshore at different places in the process train with up to 90% water cut. It was able to remove oil droplets down to 1 micron.

However, some fluid properties will decrease the CFU performance for example dissolved gas in the feed and low salinity <1.5 %. Oil droplet from 50 < 5 micron diameter and upstream use of chemicals decrease performance while flocculent very often increase it.

CFU have tested 18 API oil and higher Flow rates to 100,000 bpd. The high internal velocity in the unit will not allow for solids to settle, solids will exit without accumulating inside the vessel. Solids up to 30 - 40μ particles will be separated by flotation, larger will follow the water. A four stage CFU with a capacity of 32,000 bpd might be 3 ft dia x 15 ft tall and weigh 10 tons. A surface installation was able to reduce 50 ppm inlet contamination down to 10 ppm outlet levels.

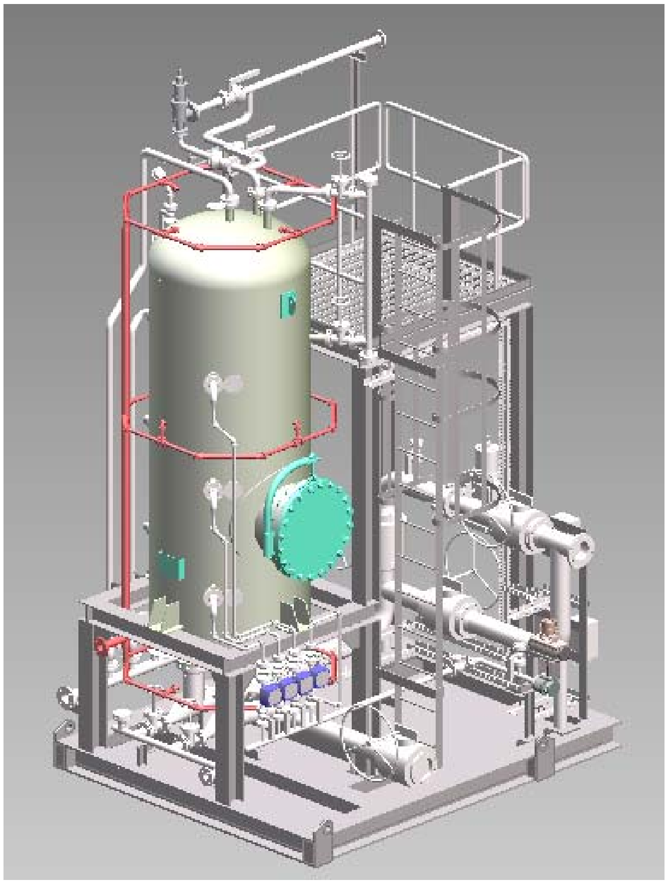

Figure 10: Cameron Four stage CFU - Capacity 32,000 bpd – Platform Base & Overall Height: 2.6 x 2.5 x 5.0 meter

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Magnetic Flocculation Removal

This processing technology removes oil and suspended solids from produced water by a process of adding a magnetic powder in combination with an inorganic and high polymer based coagulant. Once mixed, the process fluid enters a magnetic skimmer which removes the coagulated extractant leaving behind a very clean treated water.

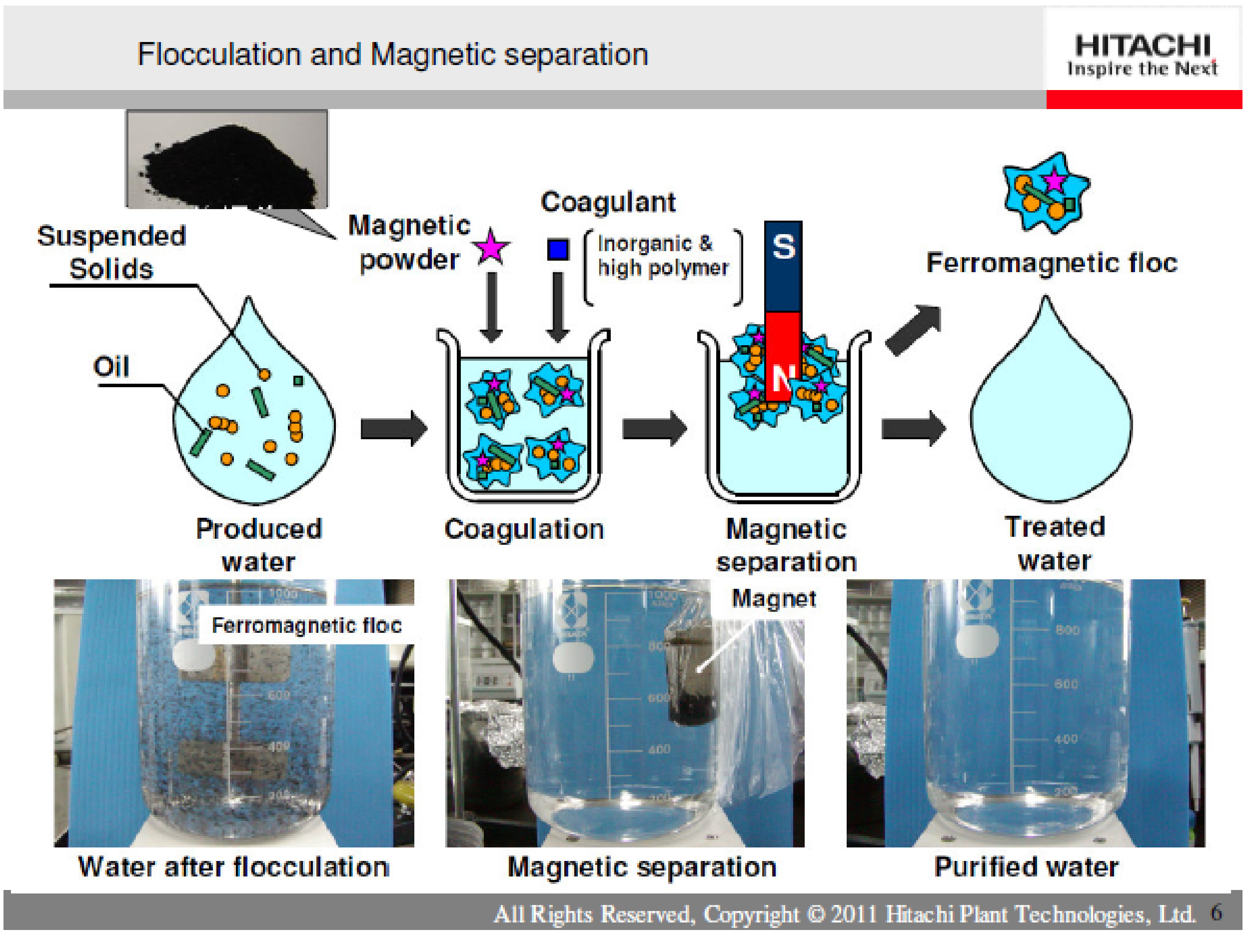

Figure 11 - Magnetic Flocculation Technique (Courtesy of Hitachi)

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6.2.3 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

PRACTICE	VENDOR
Hydrocyclone	Cameron – refer to **Appendix 8** Siemens Veolia FL Smith EnerScope – refer to **Appendix 16**
Centrifuge	EVTN Alpha Laval
Filtration	Cameron New Logic Siemens Veolia Ecodyne
Coalescence	ACS Industries Inc Siemens Veolia ProSep Technologies Coalesense BV – refer to **Appendix 15**
Flotation	Enviro-Tech Siemens Veolia IDI
Combined processes	MI-Swaco ProSep Technologies – refer to **Appendix 3**. Cameron Siemens Veolia CALTEC
Solvent Extraction	VWS MPP Systems B.V. Veolia Ecodyne
Adsorption	CETCO MyClex - Refer to **Appendix 13**
Oxidation	Ecosphere Technologies

Additional information can be referred to in the recent DeepStar Project ES015477, Jules Verne Study. Due to confidentiality issues, that information could not be shared in this study.

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6.3 Oil In Water Monitoring Techniques For Produced Water Treatment Systems

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.

6.3.1 Typical Measurement Techniques for Oil-in-Water Monitoring

6.3.1.1 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 in included in the **Appendix 02 – Hach Colorimeter** 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 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 it is through the measurement system, it 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 12 - 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.

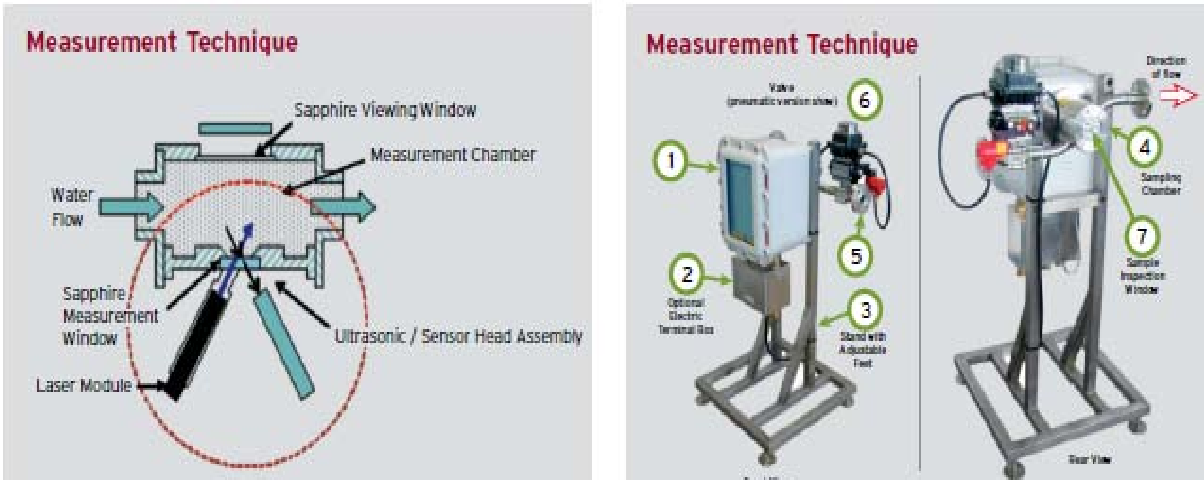

Figure 13 - Side Stream Technique And Equipment Design (Courtesy Of Advanced Sensors)

Additional information can be review in Appendix 04 on the Advance Sensor Technology.

Figure 14 - Advanced Sensors Inline Probe Measurement (courtesy of Advanced Sensors)

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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 15 -Proanalysis Installation Illustration (Courtesy Of Proanalysis)

Particle-Counting Method

The particle counting method can be further broken down into three techniques: measuring turbidity, Coulder 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.

Figure 16 - Laser Particle Counter (courtesy of Spectrex website)

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The Coulder counter shown above 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 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.

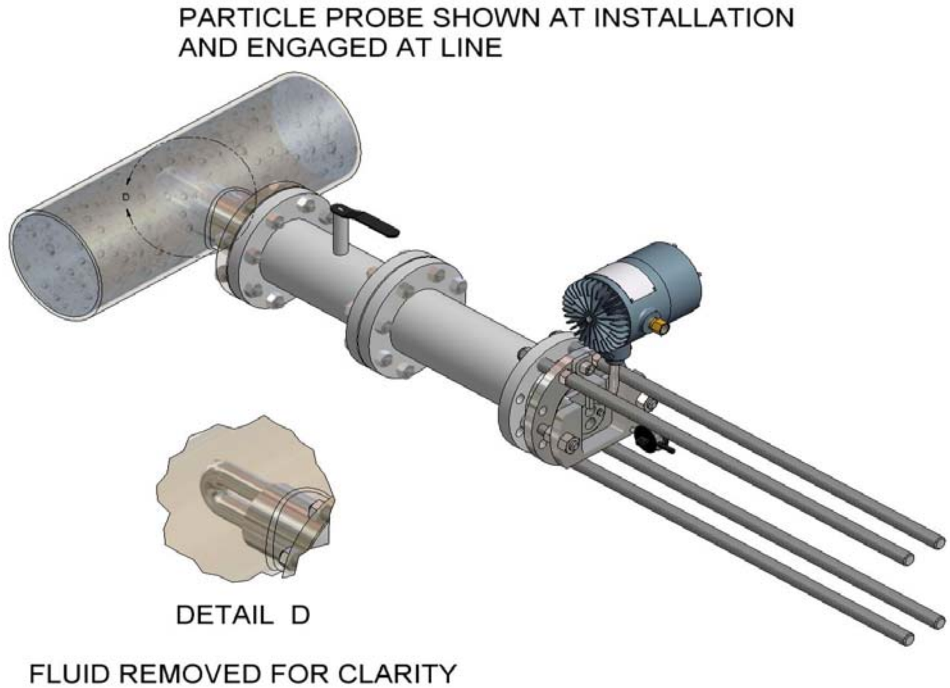

Figure 17 - JM Canty initial subsea inline concept (courtesy of JM Canty)

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).

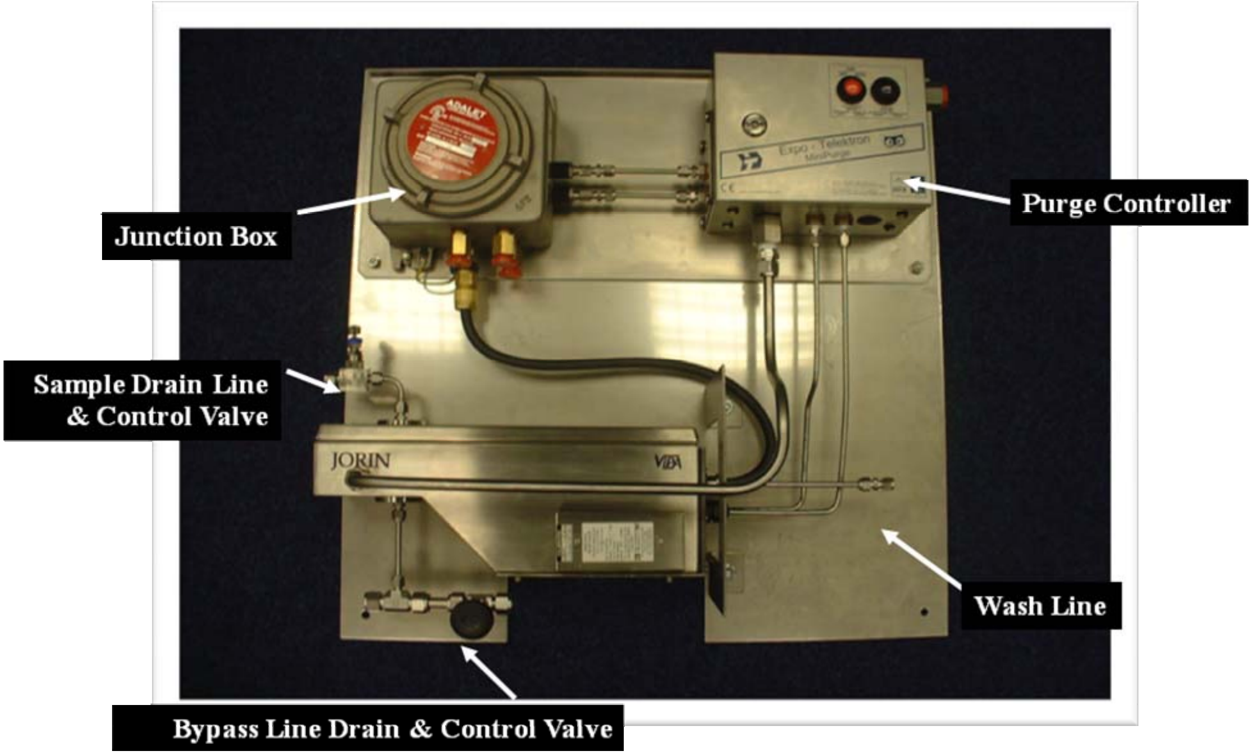

Figure 18 - Image Of Jorin Meter Components (Courtesy Of Jorin)

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.

6.4 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.

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.

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6.5 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.

6.5.1 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.

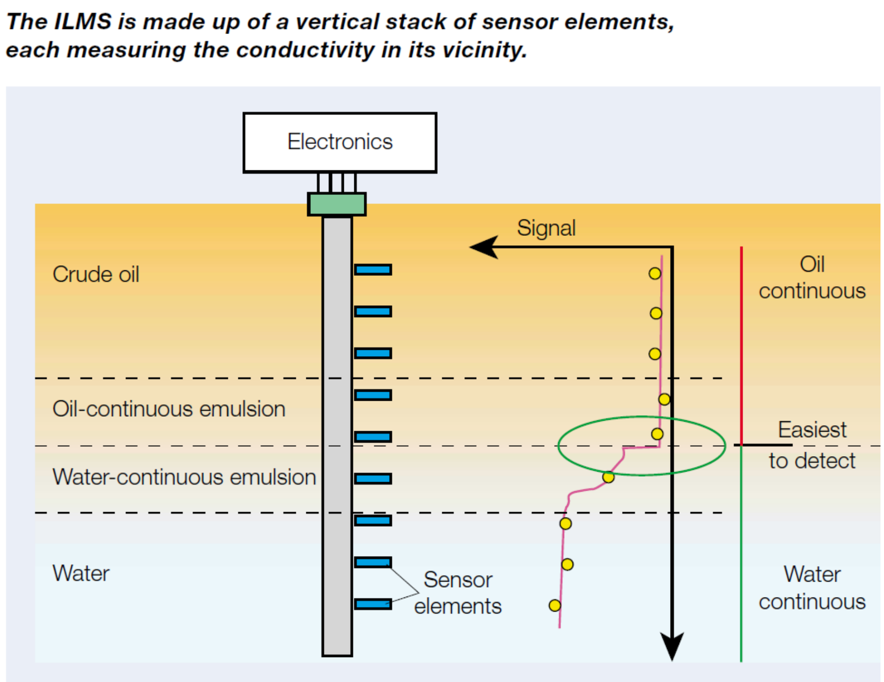

Figure 19 - Illustration of the ABB Inductance Level Monitoring System used for Tordis (courtesy ABB Sensors)

6.5.2 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 20 -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.

6.5.3 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. Weatherford is working on a subsea version of the Red Eye Water Cut Meter.

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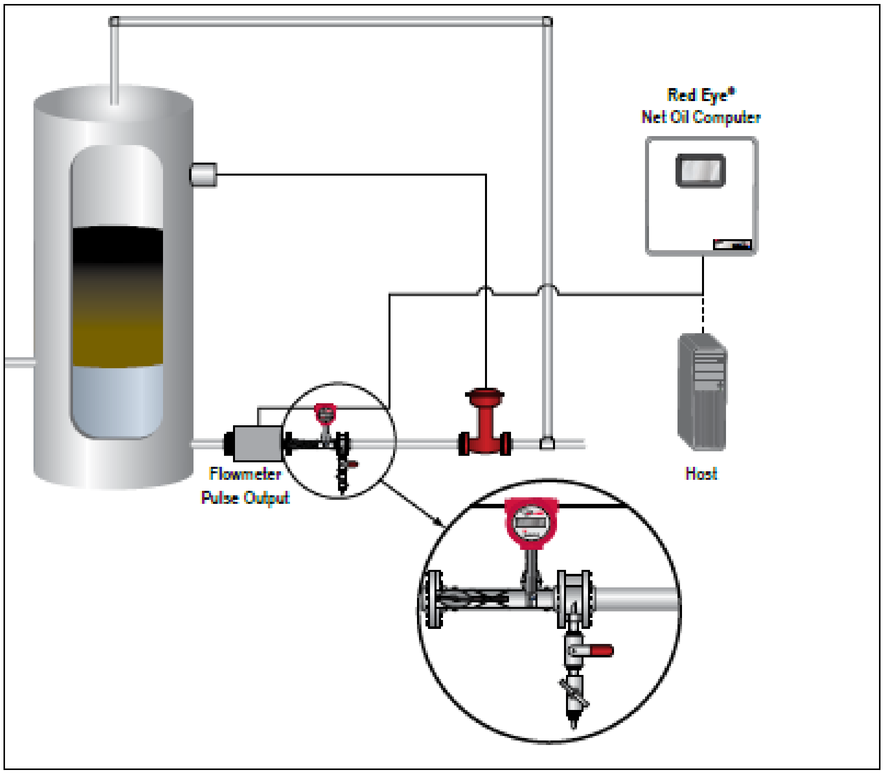

Figure 21 - Typical Installation Points for the Red Eye Water Cut Meter (courtesy of Weatherford)

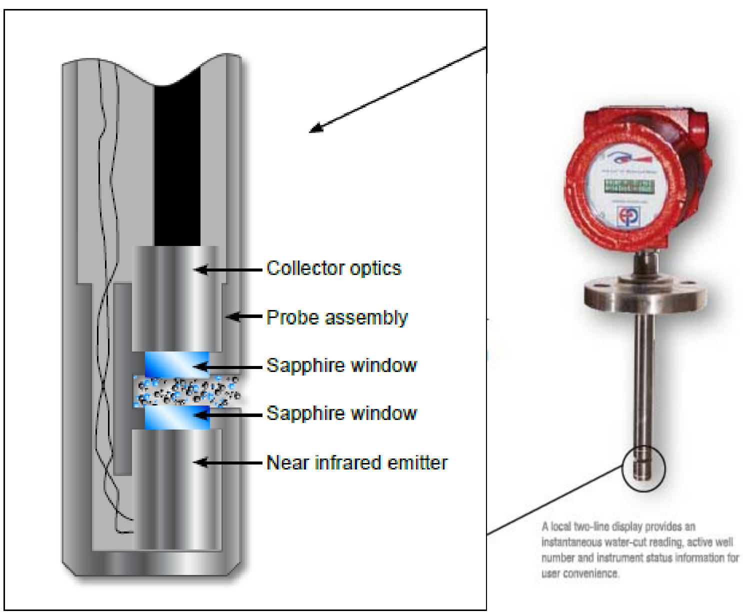

Figure 22 - Cut away of the Red Eye Water Cut Meter (courtesy of Weatherford)-

6.5.4 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 (absorptive or extinction coefficient)

Figure 23 - Optek Photometer (courtesy Optek)

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.

6.5.5 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.

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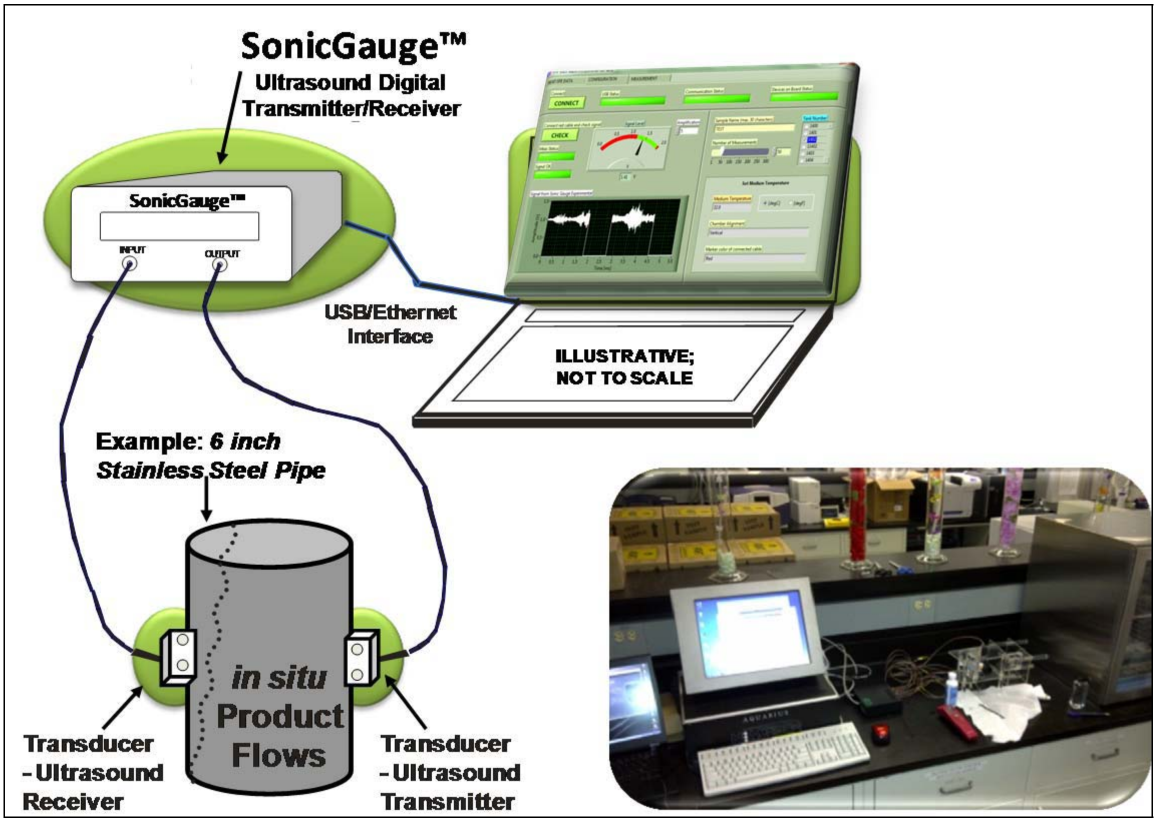

Figure 24 - SonicGauge Illustrated (Courtesy of NIMTech)

6.6 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.

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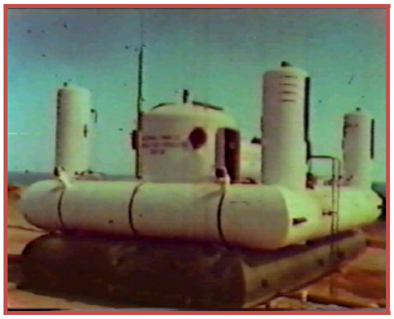
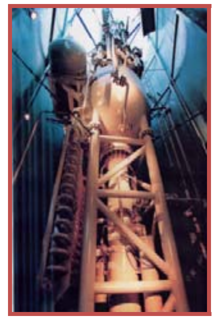
6.7 Pictorial History of Seabed Processing



BP Zakum (1969 – 1972)



Kvaerner Booster Station (Mid 80's)

Argyll - British Offshore Engineering Technology (BOET) (1986 – 1989)

Petrobras VASPS Technology (2000 – Ongoing)

Texaco Highlander Subsea Slug Catcher and Vertical Separator (1985)

Alpha Thames -AESOP (1999 – 2000 Successfully Tested)

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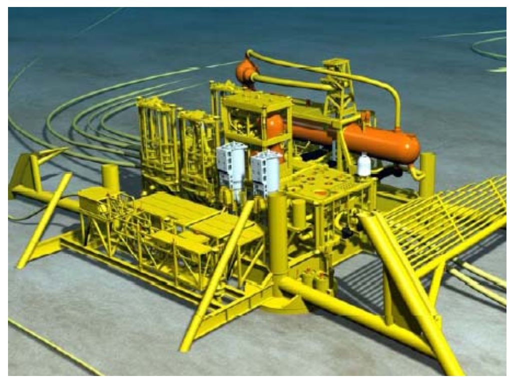
Good-fellow Assocs. subsea production (GASP) project

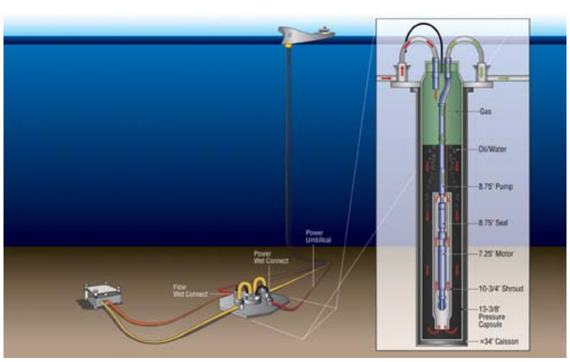
(1986 – 1990 Successfully tested)

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

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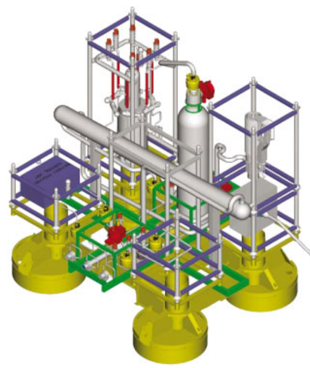
Petrobras Marlim – InLine Separator 2011

Total Pazflor Vertical Subsea Separator - 2011

Petrobras Congro, Malhado & Corvina - VASPS with Horizontal ESP - 2012



Petrobras Canapu with Twister In-line Supersonic – Year TBA

Figure 25 - Pictorial History Of Seabed Processing

6.8 Installed and Planned Subsea Separation Systems

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 (Subsea Processing Gamechanger 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.

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

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

6.8.1 Troll C Subsea Separation System

(Offshore Magazine, Nov 1, 2002)

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 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

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Figure 26 - 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.

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 (~ 38,000 b/d)
Oil capacity:	4,000 cu m/day (~ 25,000 b/d
Gas capacity:	800,000 cu m/day (~28 MMcf/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%

Figure 27 - Design Parameters for the Troll C Subsea Separation Station

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

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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.

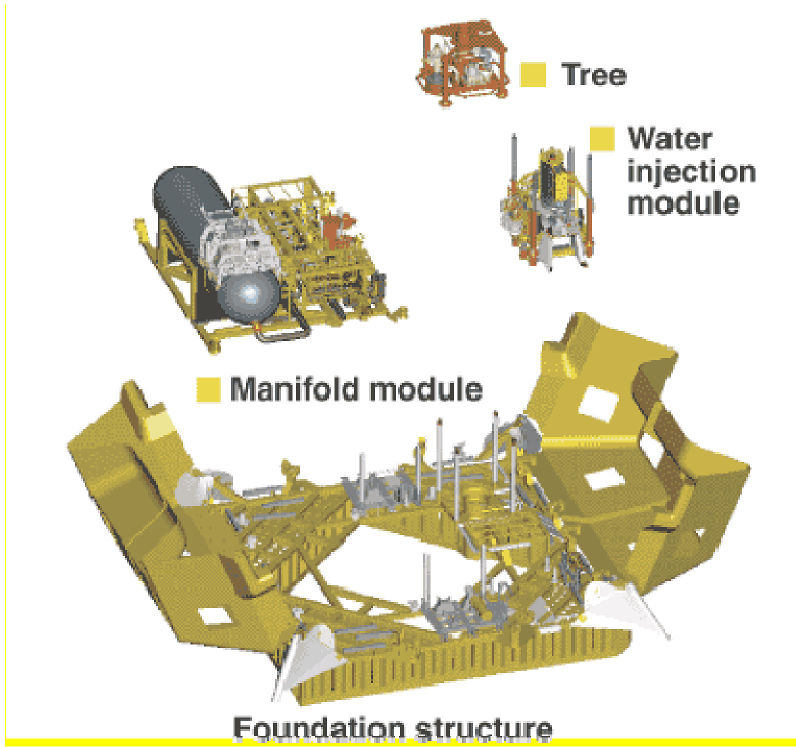

Figure 28 - Exploded view of Troll Pilot system

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 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%.

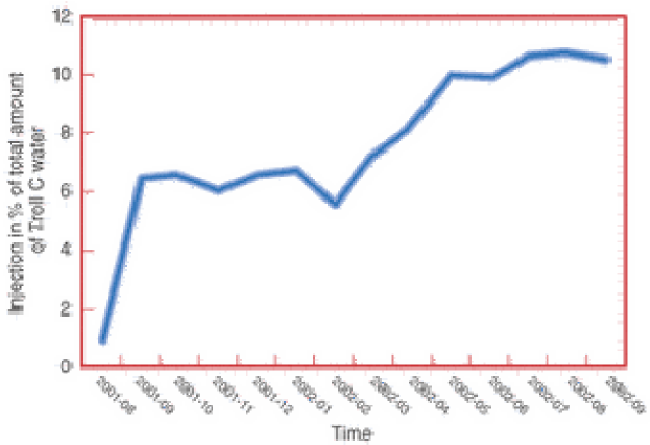

Figure 29 - The amount of produced water from the subsea separation station injected in percent of the total water handled through the Troll C topside and subsea.

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.

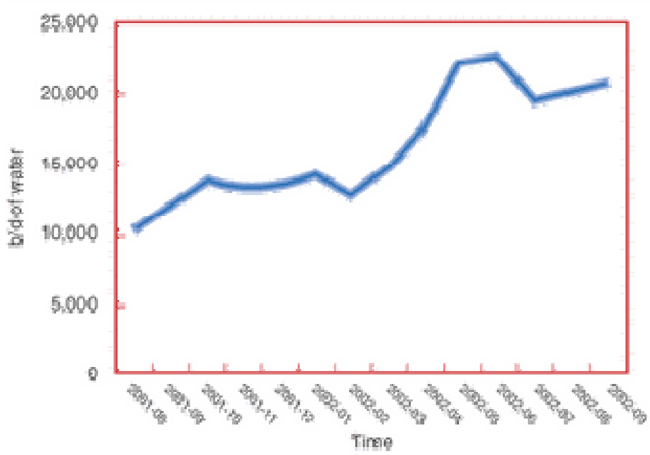

Figure 30 - The average monthly amount of water injected (B/D)

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.

6.8.2 Petrobras Marimba - VASPS Prototype

(SPE 95039, 2008)
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 m^3/d of fluid with 100,000 m^3/d of gas from gas lift. Wellhead pressure was 36 kg/cm^2. After VASPS installation, the subsea phase separation allowed the wellhead pressure to be reduced to 11 kg/cm^2. This resulted in a production increase of 1000 m^3/d without gas lift. The performance and operating stability of the subsea separator was proved.

- Gas-Liquid Separation
- Oil and Water Not Separated

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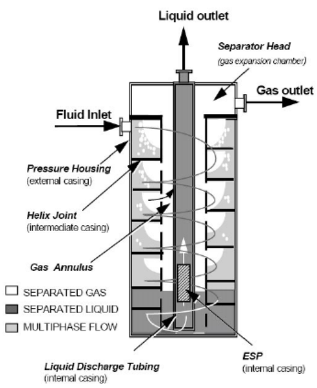
Vertical Annular Separation and Pumping System (VASPS) Installation Data

(1)

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 m3/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



(2)

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 31 -(1) VASPS - Installed In Marimba Field 2001 (OTC 18198), (2) VASPS Concept (OTC 18198)

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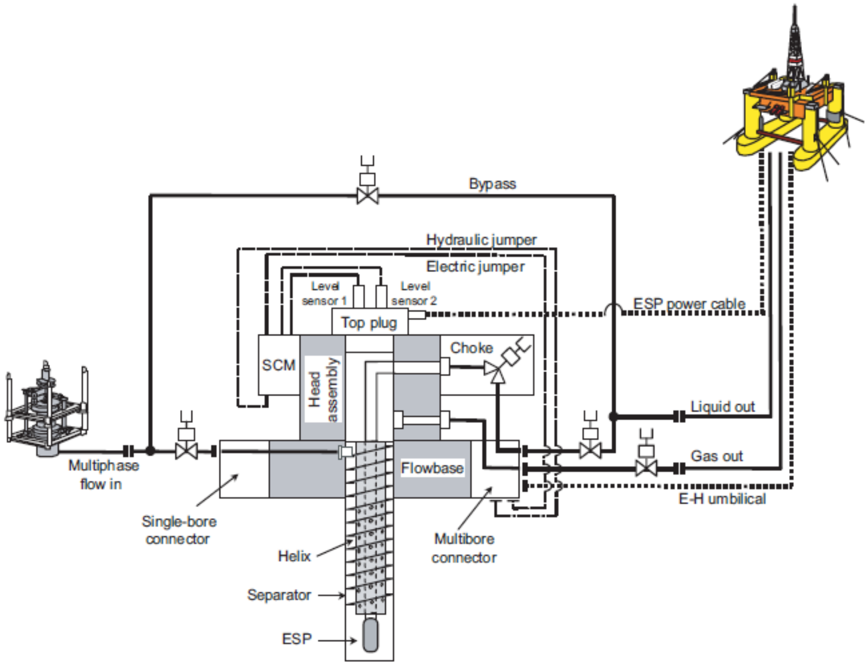

Figure 32 - VASP Layout

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.

(OTC 18198, 2007)

6.8.3 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.

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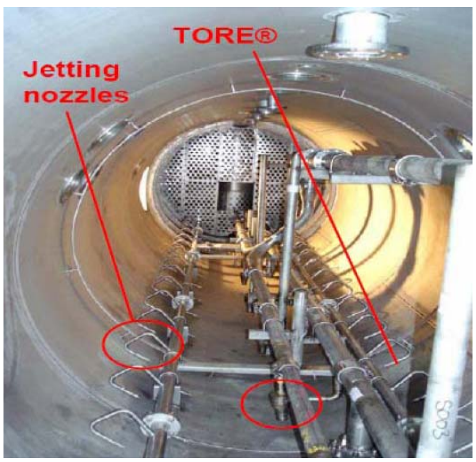
The water stream was designed to meet a maximum of 1,000 mg/l. At project start up, an ROV sampling system was used to confirm how well the separator was performing and it seemed to surpass the design specification with a water sample that contained about 500 ppm of the original oil.

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.



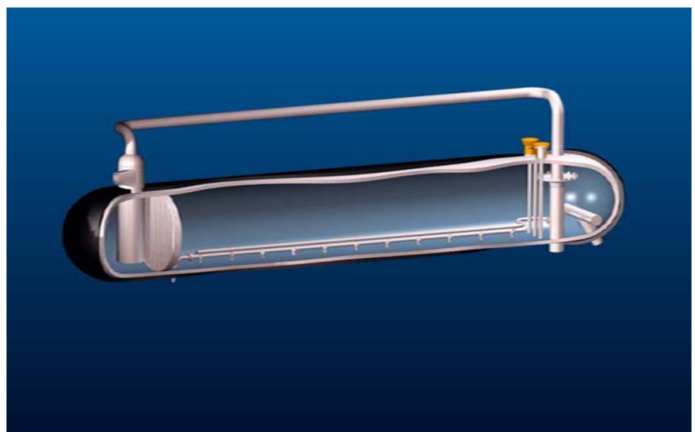


Figure 33 -CDS Sand Jetting System - Gravity Separator Internals

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.

(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.

http://www.fmctechnologies.com/en/SeparationSystems/Solutions/SolidsHandling/SandHandlingExperience.aspx

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Figure 34 - TORDIS SSBI - Subsea Separator (Courtesy Of Fmc Technologies)

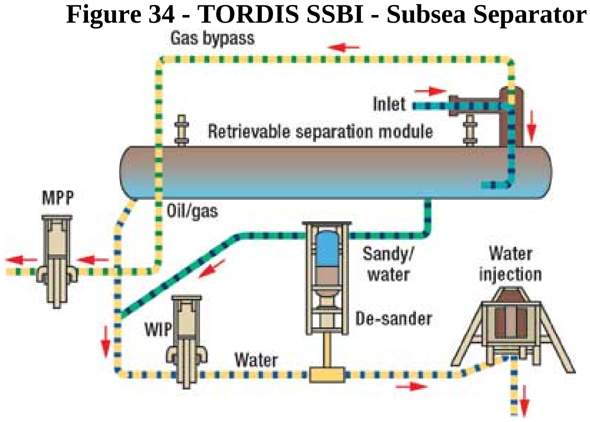

Figure 35 - Tordis Subsea Separator Flow Diagram (Courtesy FMC Technologies)

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.

6.8.4 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.

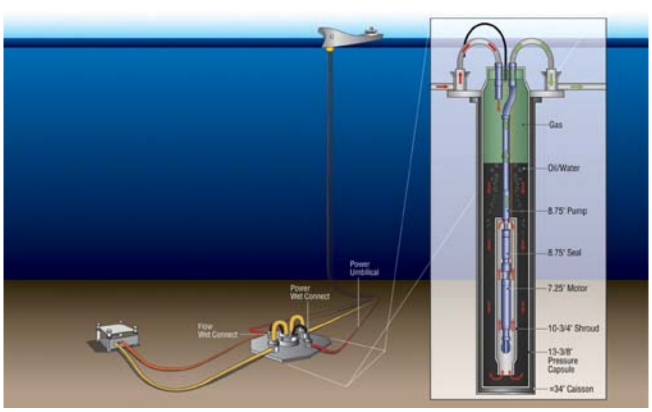

Figure 36 - Shell BC-10 Separation Caisson

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.

6.8.5 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. (Oil & Gas Financial Journal, 2010):

Figure 37 - Shell Perdio Subsea Caissson Separator

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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.

6.8.6 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.

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 38 - 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

6.8.7 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.

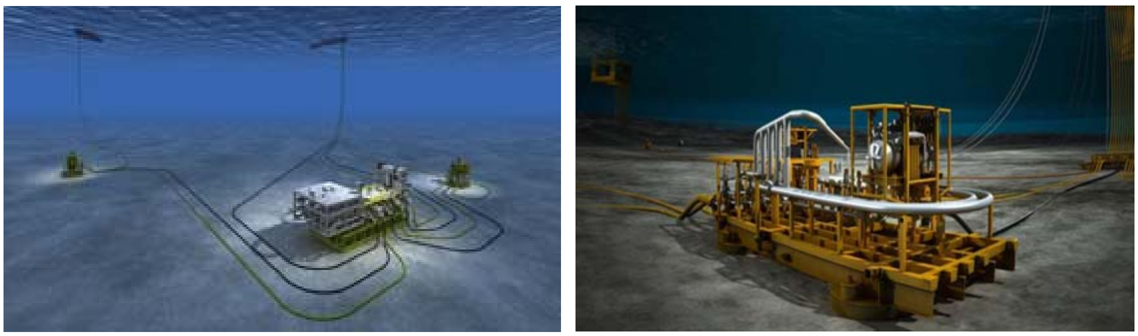

Figure 39 - FMC - 2 Phase Gas / Liquid Separation using InLine Technology

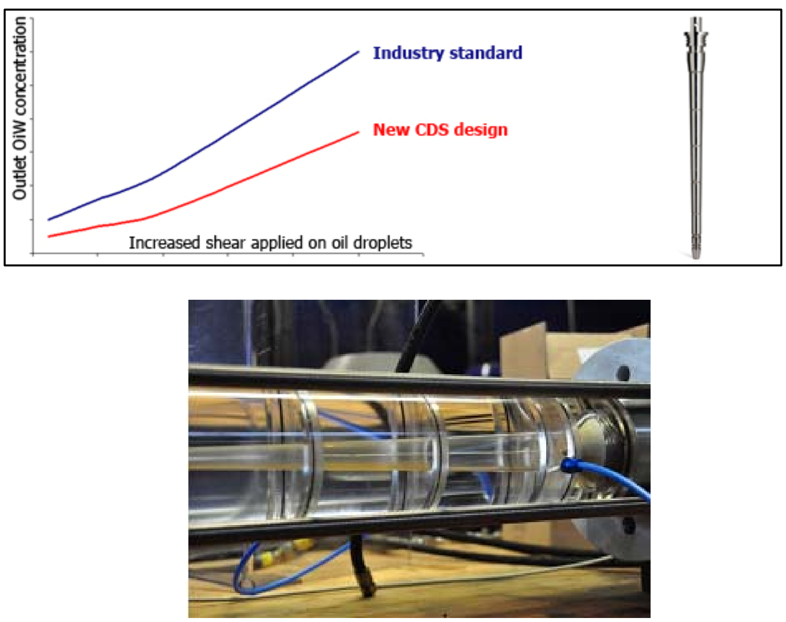

Figure 40 -Inline HydroCyclone

6.8.8 Petrobras Congro, Malhado & Corvina

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

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6.8.9 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

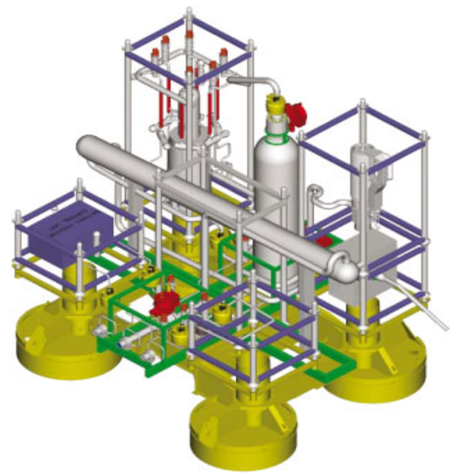


Figure 41 - Petrobras Canapu

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.

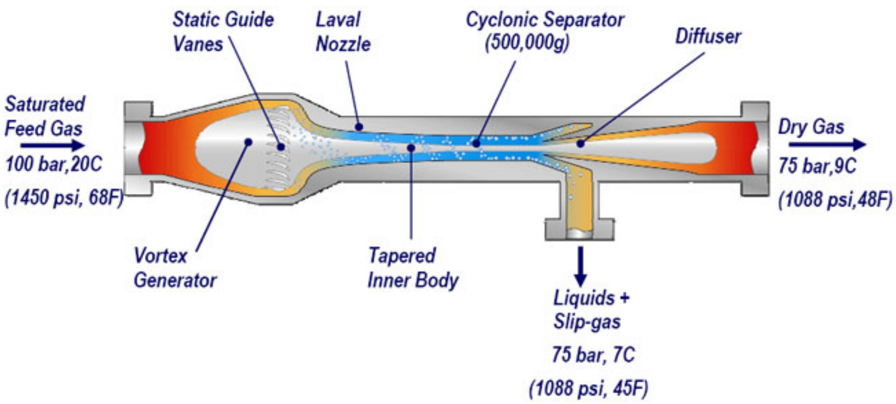


Figure 42 - Twister schematic (Courtesy Twister BV)

Simulations demonstrate that, when expanded through a Twister tube, H_2S and CO_2 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.

http://twisterbv.com/products-services/twister-supersonic-separator/how-it-works/

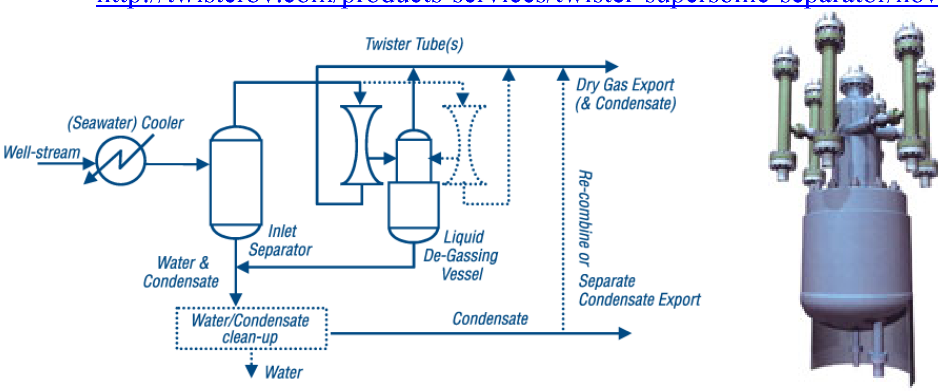
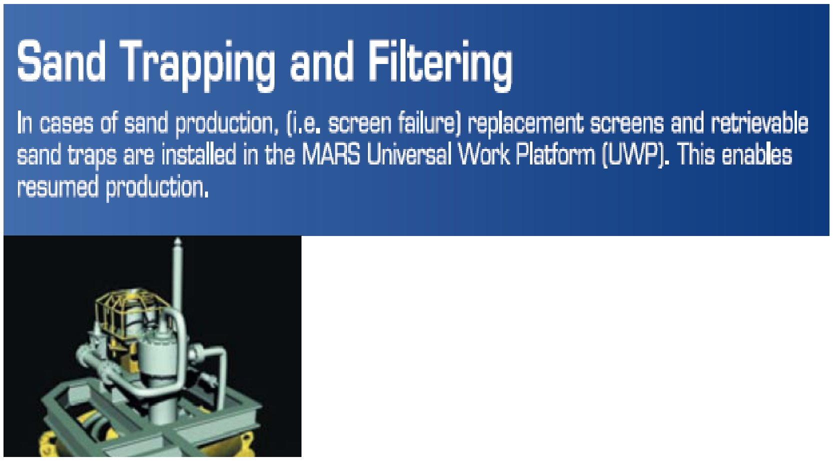


Figure 43 -Twister – Supersonic Separator

6.8.10 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.

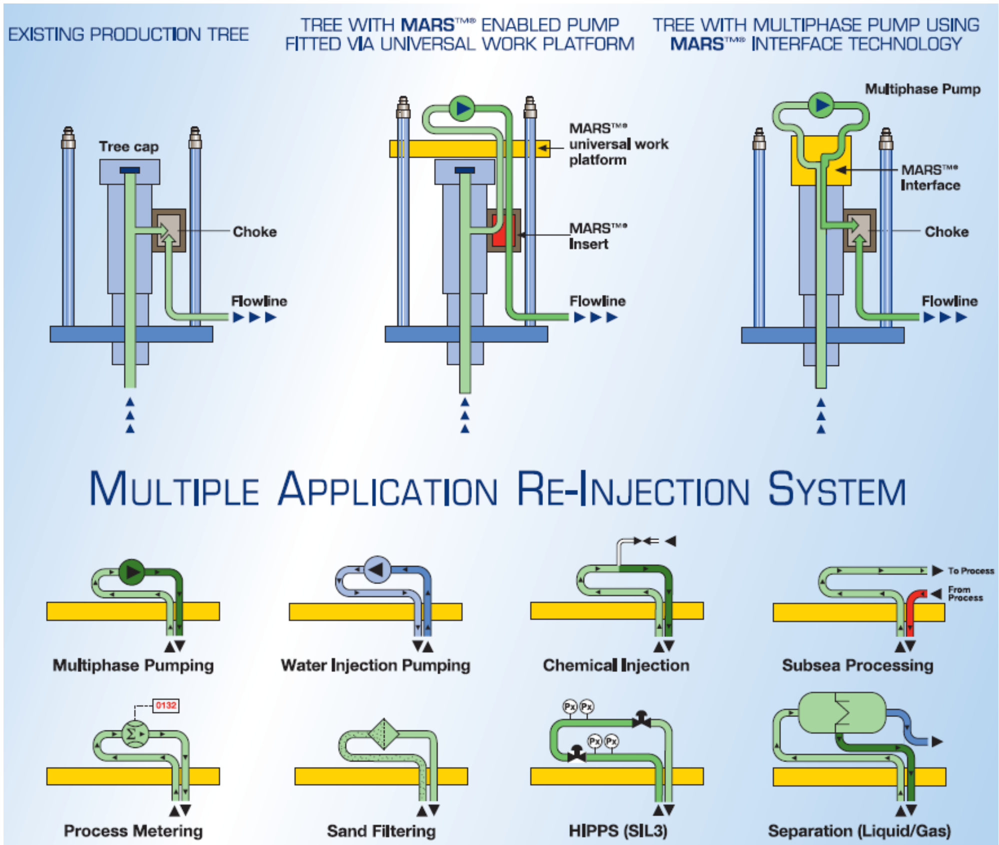


Figure 44 - Multi Application Re-Injection System-

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.

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

6.9.1 Aker Solutions DeepBooster with Subsea Separation

- Compact degassing and scrubbing as a first separation stage
- Compact Electrostatic Coalescer, CEC

- 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

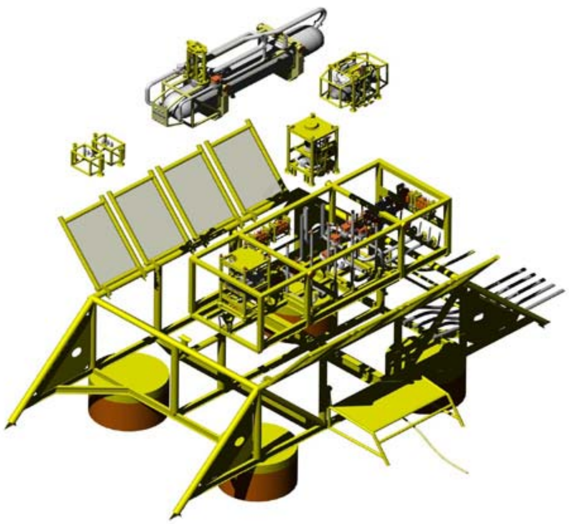


Figure 45 - Aker Solutions Deep Booster with Separation System FlexSep

6.9.2 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 46 -KeyMAN™ - Passive Manifold Base

Retrievable Modules

- Standardized Interface

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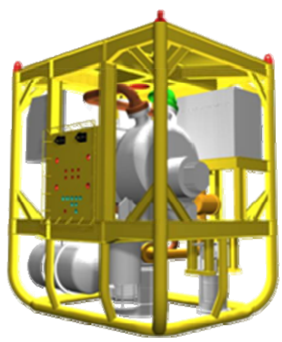
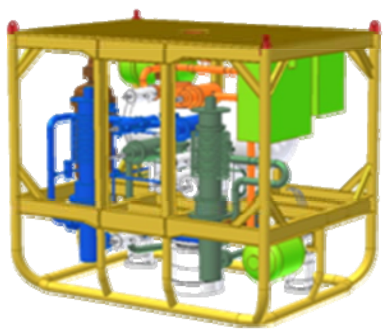
- Electric Operation
- Processing
- Boosting
- Water Injection
- Gas Compression
- Metering
- Can Include HIPPS

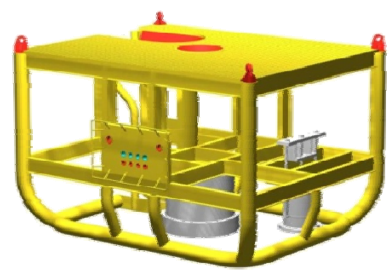


Boosting & Gas Compression

Processing & Water Injection



Metering & HIPPS



Dummy Module

Figure 47 - 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
- Transportation of heavy oils or the mitigation of emulsions, whist 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

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Table 8 – Listing of Alpha Thames Patents

Patented Solutions

AlphaPRIME™ Field Development			AlphaPRIME™ CPU			Individual Products		
Importance	**Strength**	**Patent** (Item no.)	**Importance**	**Strength**	**Patent** (Item no.)	**Importance**	**Strength**	**Patent** (Item no.)
III 5	S	Electrical Power Distribution Ring Main (2)	I 5	S	Modular System (1)	2	S	MATE 2 (17)
1	W	Pigging (3)	5	S	CPU Architecture (5)	1	S	MATE (18)
3	VS	Electric Trees -Power & Control (4)	2	M	Water Clean up & Disposal (11)	3	S	VMC (19)
1	M	Disposal of Well Test Line (6)	4	S	Slug Control (12)	2	VS	AB3 Valve (20)
4	S	Downhole Jet Pump (7)	V 5	S	Dynamic Separation Enhancement (13)	IV 5	VS	HWC (21)
4	VS	Fluid Transportation (8)	2	S	HIPPS System (26)	5	MS	ELEx (22)
3	MS	Sand Management (9)	4	VS	Gas Compressor Protection (27)	II 5	VS	REAct (23)
1	M	Low Pressure Water Injection Line (10)	1	M	Emulsions Avoidance (28)	5	M	REAct Mk2 (24)
1	M	Single Well Development (14)	3	M	Rawwater Injection Cleaning (29)	2	VS	CUSP (25)
1	W	Early Production (15)				3	VS	HeliC DisC (32)
1	M	Low Gas Injection Line (16)						
2	S	Nodal/Grid Development (30)						
2	M	Smart Control Development (31)						

6.9.3 Cameron Subsea Compact Electrostatic Separator

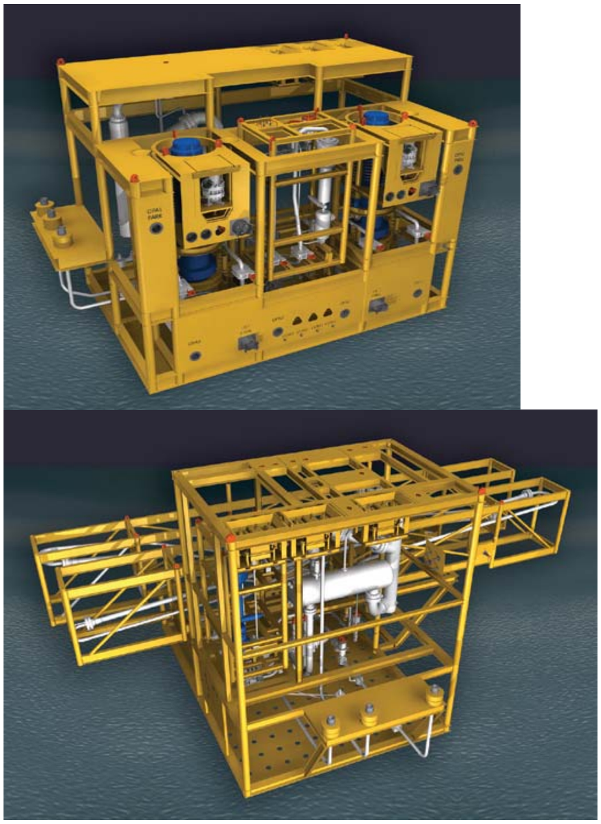
The Compact Electrostatic Separator allows rapid separation of oil from water in a subsea environment by reducing the entrained water. The skid consists of a 14” compact electrostatic separator capable of process 2,500 Bbl/day of oil and water. The skid is 10’ x 24’ and weighs approximately 27,500 lbs. 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.

CAMERON

Figure 48 - Cameron Subsea Compact Electrostatic Separator

6.9.4 Cameron Two-Phase and Three-Phase Compact Subsea Separators

- Without ESP
- With ESP
- Using Electrostatic Method



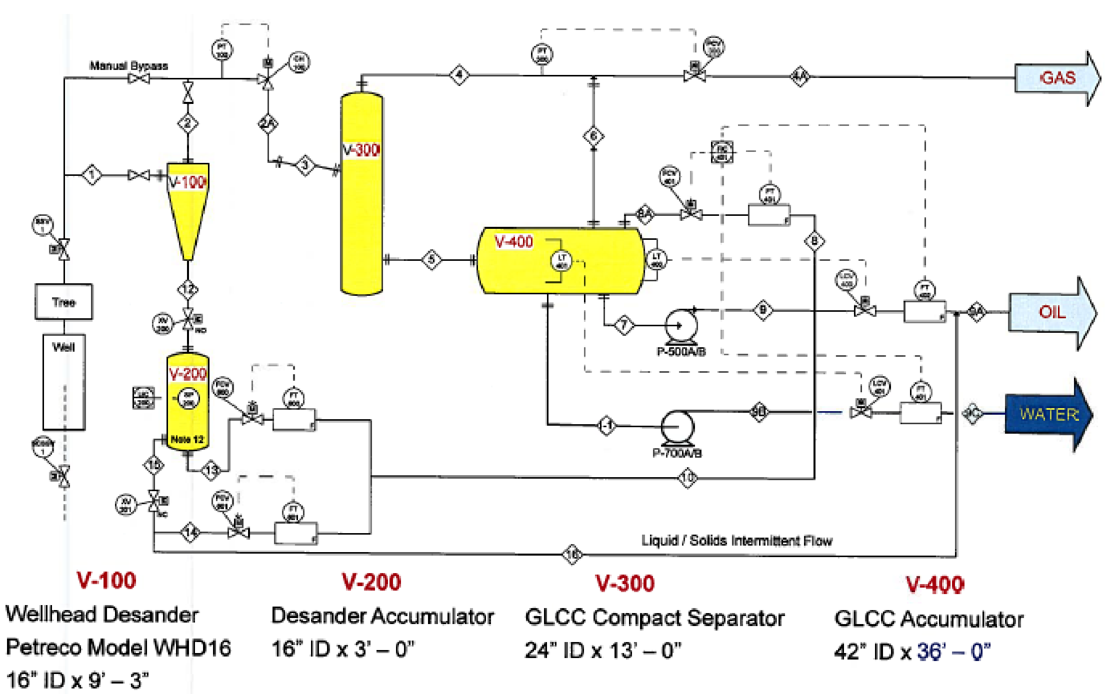


Figure 49 - Cameron Three Phase Subsea Separation Process

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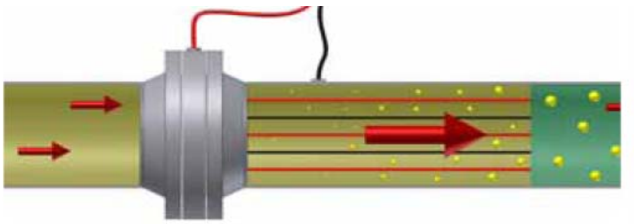
6.9.5 FMC InLine Electrocoalescer

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 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 conditions:

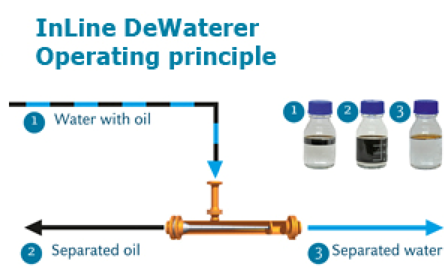
- 50 m^3/h through 4” unit
- Residence time: 0.14 s
- Crude oil
- 20% water cut

FMC Technologies

Figure 50 - FMC Testing Loop for ElectroCoalescer

6.9.6 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)



Criteria	Results
Oil in Water at inlet	1 - 50 %
Oil in Water after separation	200 - 2000 ppmv
Gas Volume Fraction at inlet	0 - 50 %
Total Flow rate at inlet	10 - 40 m^3/h
Water removal efficiency	< 95 %
Pressure Drop reject (from inlet to oil outlet)	0.3 - 2.5 Bar
Pressure Drop underflow (from inlet to water outlet)	0.1 - 2.0 Bar

Figure 51 - In Line Dewater Principle and Performance

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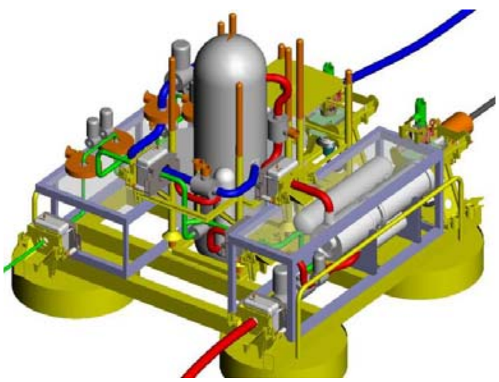
6.9.6.1 GE Nu-Proc Test Separator with Electrostatic Coalescer

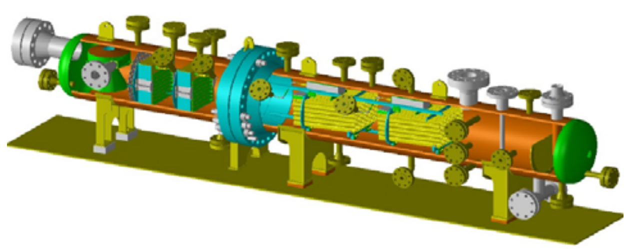
vetcogray

- 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)



NuProc Test Deep Water Separator
Volume 6 m3

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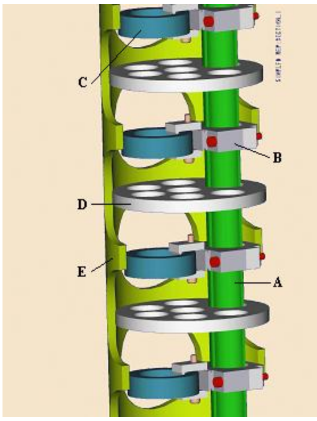

Inductive Level Profiler **Nucleonic Level Profiler**

Figure 52 - Advance Separation Techniques

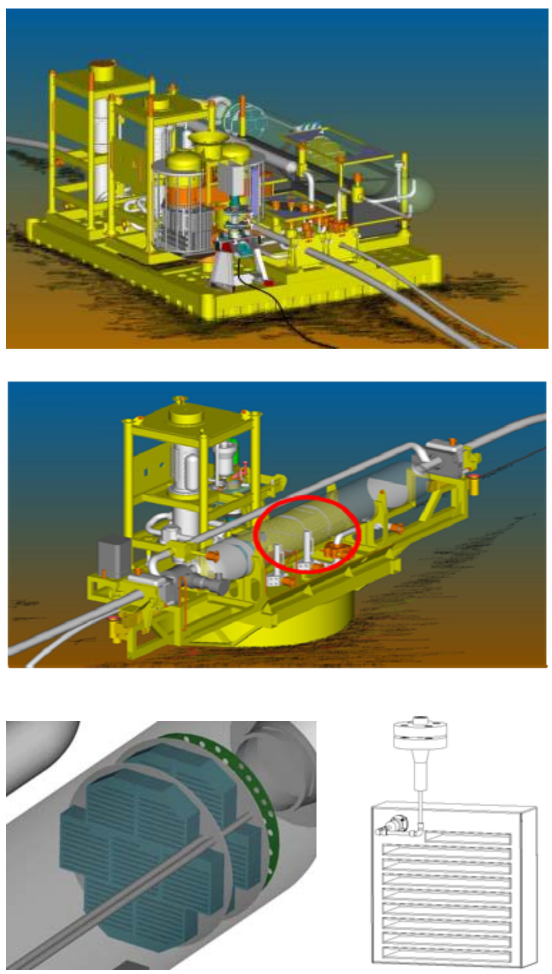

Figure 53 - Electrostatic Coalescence, Viec

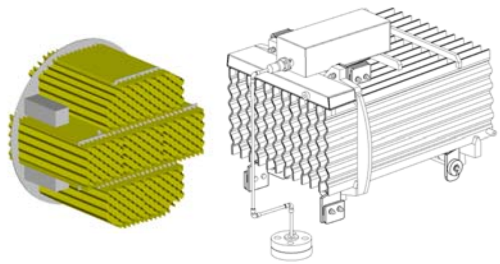

Figure 54 - Electrostatic Coalescence, Lowacc

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

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

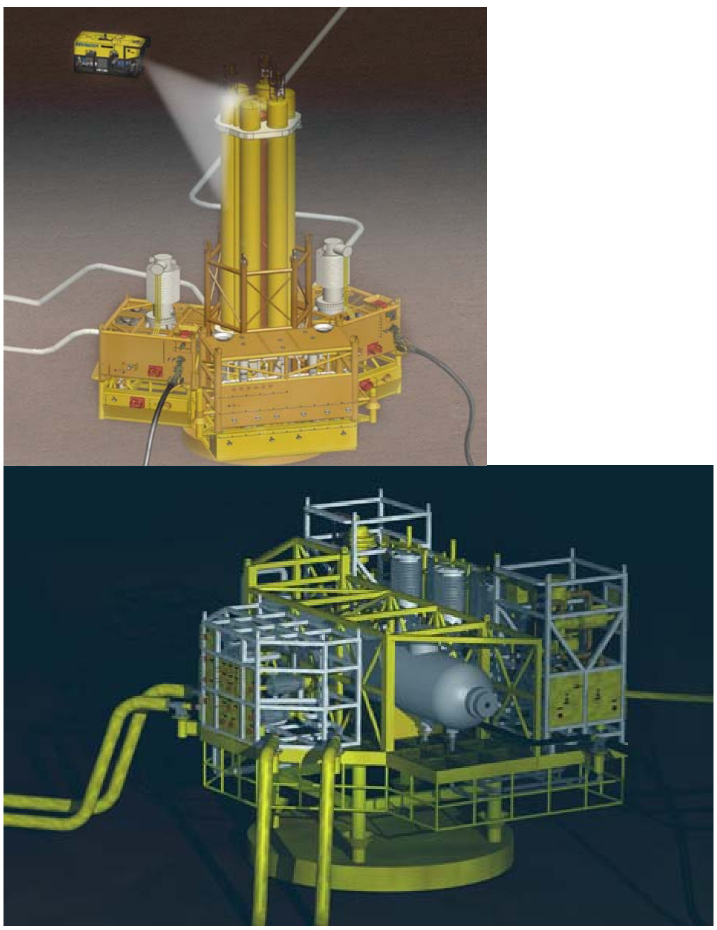

Figure 55 - Saipem Subsea Seperators Concepts – Vertical Multi-Pipe (VMP)

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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.(OTC 21394, 2011)

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

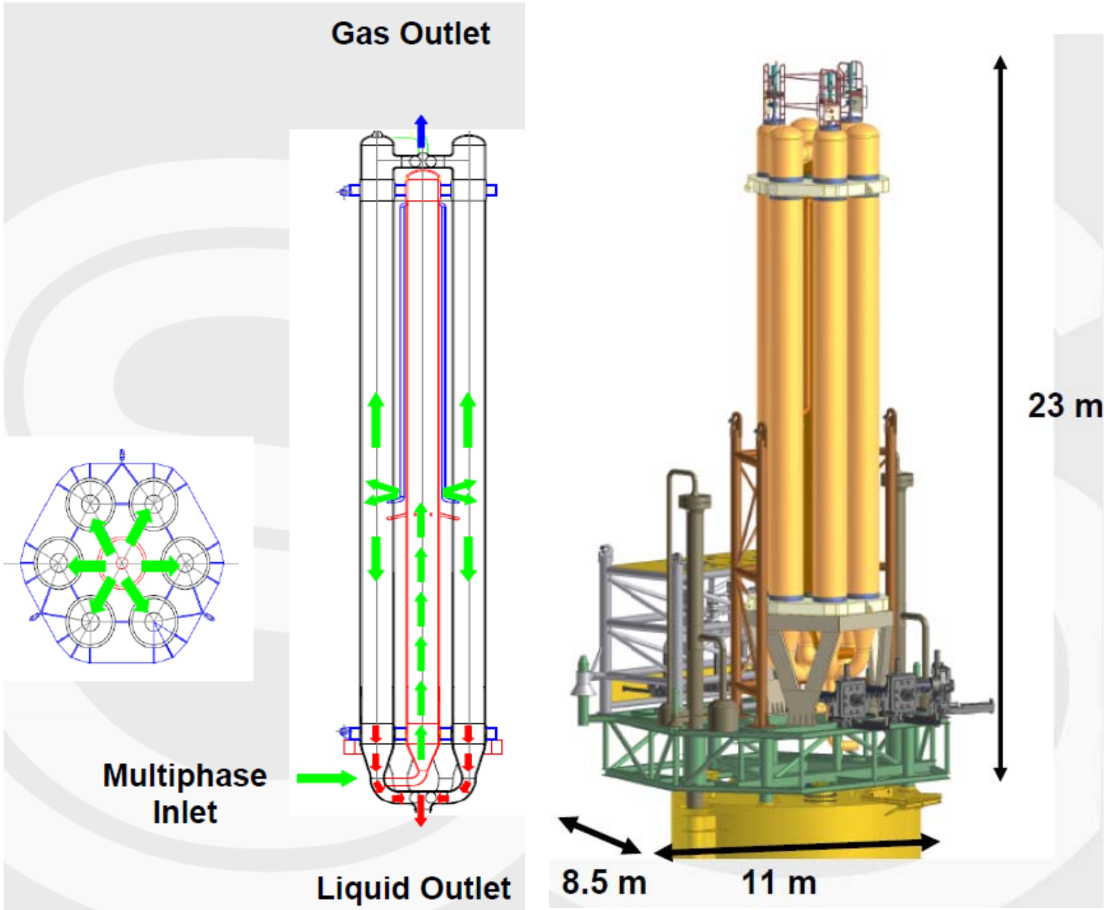

Figure 56 - Configurable Subsea Separation And Pumping System

- 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

6.10 In-Line Rotary Separator (IRIS)

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

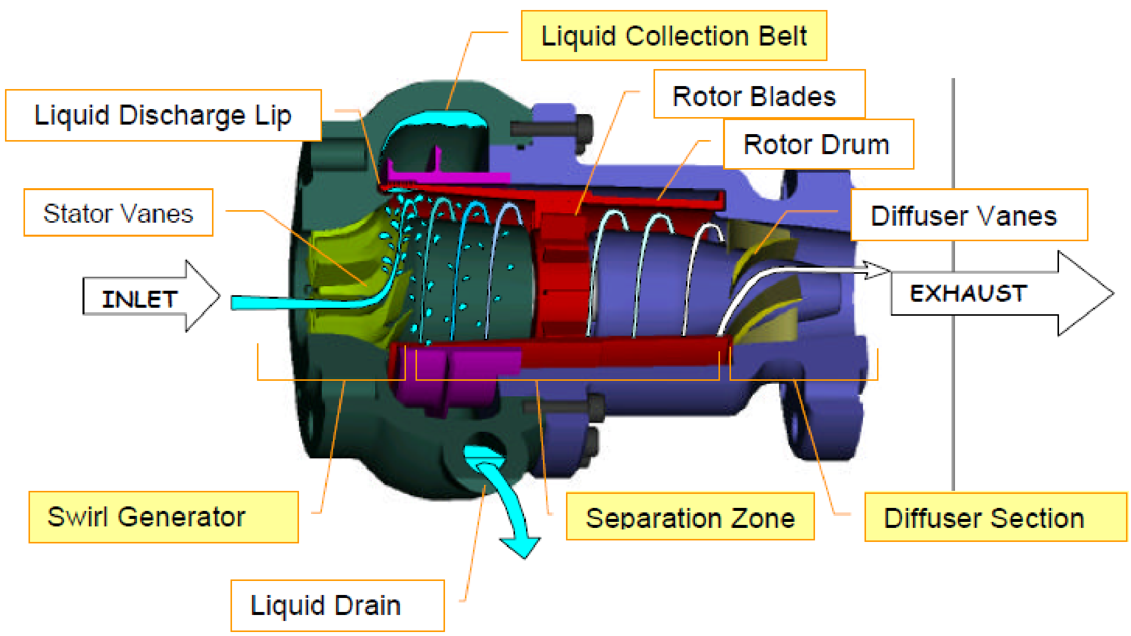

Figure 57 - IRIS cross-section showing components and flow path

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.

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

6.11 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-Simulinkmodel)

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)

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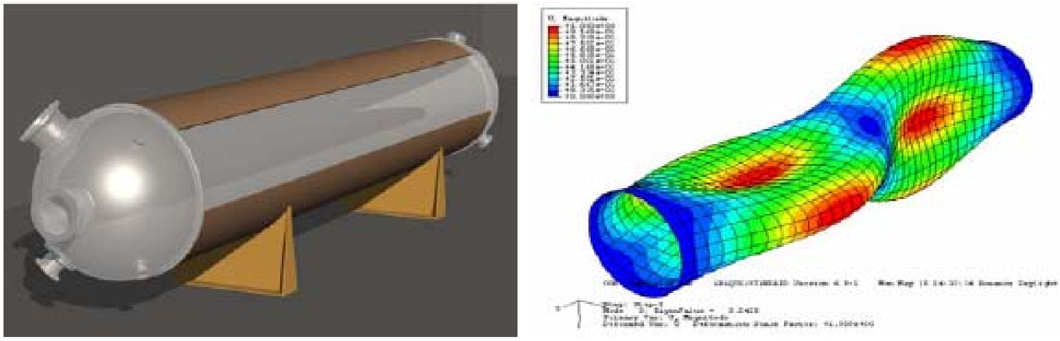

Figure 58 - Hybrid separator (steel + composite) for subsea system lightening

6.12 Additional Considerations for Subsea Processing and Water Treatment

6.12.1 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.

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)

6.12.2 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.

- 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 59 - Inline Cyclonic Separation Equipment - Clockwise: Liquid-Liquid Separation, Phase Splitter, De liquidizer, De-Sander (Ref. OTC 20080 paper, 2009)

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6.12.3 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.

FMC Technologies

http://www.fmctechnologies.com/en/SeparationSystems/Solutions/SolidsHandling.aspx

Figure 60 - FMC In Line Desander Operating Principle

6.12.4 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. Retrievability 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 band width 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)

6.12.5 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)

6.12.6 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)

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

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

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

CONCEPT	PROS	CONS	COMMENTS
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.**

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CONCEPT	PROS	CONS	COMMENTS
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.**
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**

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 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.

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7.0 CONCEPTUAL DESIGNS FOR SEABED DISCHARGE OF PRODUCED WATER AND/OR SOLIDS

7.1 Introduction

The purpose of this section is to present the FEED design concepts for subsea produced water process trains to meet the requirements of the Project Basis of Design and while doing so identify any technology gaps.

7.2 Method of Approach

The project team has reviewed the State of the Art for Waste Water Processing. Many vendors have been contacted for discussions and presentations and inclusion of their experience and equipment where appropriate. This has included onshore technology that has been taken topsides offshore and others that have been taken deeper than 3,000 feet to the seabed. Starting from this research and the knowledge and experience within the team and the steering committee a series of Concept Workshops have been held.

The sequence of process train drawings were created for discussion at the workshop meetings. Proven surface and shallow water process stages were assembled together into possible systems to review. The drawings included in **Appendix 18** form a record of what has been discussed but are not intended to be solutions. While the pros and cons of the early drawing were considered when creating the next in the sequence their purpose was to review other options.

Following this selection process two trains have been proposed below as worthy of further development towards the design objective.

A major purpose of this study is to identify Technology Gaps that will need to be addressed to enable ultra deep water processing to become a reality.

7.3 Selection considerations

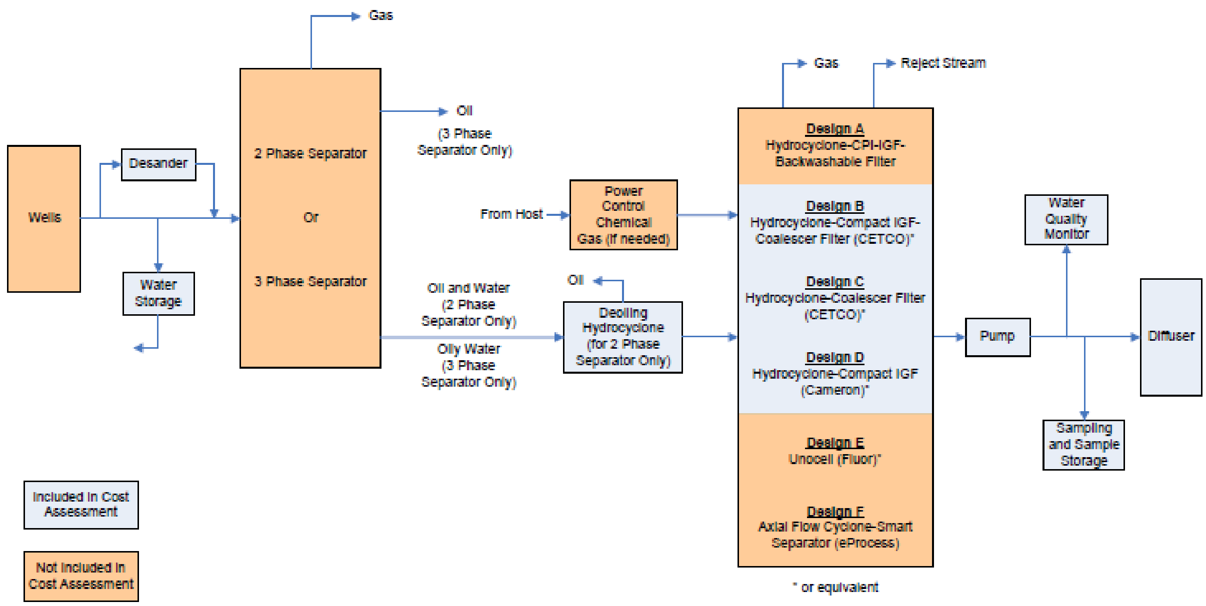
Starting with a ‘Typical’ offshore process train with multiple stages, the purpose and sequence of the stages were considered. An example of this was whether the desanding stage had to come first and as close as possible to the wellheads. Further selection criteria came from the need for a fully enclosed system, some stages working well above atmospheric pressure and others needing low atmospheric pressures to enable separation. All the systems will be subjected to external pressure from the head of 5,000 to 8,000 ft of water. At these depths the ambient temperature may be only 38 °F and many of the processes benefit from being as warm as possible. This would suggest a compact thermally insulated system would work better.

Issues of component size and weight must also be considered. Large thick walled pressure vessels may have to be installed individually without guidelines. Compact seabed template solutions will increase the potential hazards of Dropped Object. Safety Zones around the process train stages; associated pumps, switch gear, transformers; chemicals and controls equipment make for a large installation area on the seabed.

The design scenario is for a 50 mile tie-back. This and the 8,000 ft depth make this a remote installation for which the reliance on intervention and maintenance must be kept to a minimum for both safety and cost reasons.

The following is the overall conceptual options that have been created:

Concepts for Discharge of Produced Water at the Seabed



7.4 Assumptions

The following assumptions have been made for the development on top of the requirements of the Basis of Design:

1. The system may be included as part of the installation during the initial field development or
2. The system may be installed in stages as the existing field depletes
3. The system Design Life is 10 years with major intervention only after periods of 5 years
4. If only a single flowline is available it was sized for initial field flow rates
5. The flowline is piggable from the Drill Center to the Facility
6. Wellhead pressures have decreased as the water cut has increased
7. The shut in pressure used as the System Design Pressure is the current value and not the higher pressure that may have existed earlier in the field's life
8. The train should be designed to contain the wellhead shut in pressure
9. Booster pumping, desanding and gas/liquid separation may be installed before water processing is required
10. The booster pump installation is not within this study's scope
11. Gas and filtered water may be used to lift and drive the produced fluid within the train

12. Nitrogen will be supplied if natural gas would cause hydrates

13. For reservoir flow continuity considerations, a 100% redundancy in the process train is required (Further Sparing Policy is beyond study scope)

14. Planned testing, maintenance and sampling will not interrupt flow

15. Planned or emergency shutdown stages may go up to and include back flushing the system with seawater into the well bore to avoid environmental contamination

7.5 Table 1: List of Abbreviations Used in This Section

AFC	Axial Flow Cyclone
API	American Institute of Petroleum
ASME	American Society of Mechanical Engineers
AUV	Autonomous Underwater Vehicle
bbl/d	Barrels per day
BOD	Basis of Design
BOP	Blow Out Preventer
CFU	Compact Flotation Unit
CPI	Corrugated Plate Interceptors
DGI	Dissolved Gas Flotation
dia	diameter
GoM	Gulf of Mexico
gpm	gallons per minute
HIPPS	High Integrity Pressure Protection System
IGF	Induced Gas Flotation
K.O. Drum	Knock Out Drum
OIW	Oil In Water
PFD	Process Flow Diagram
ppm	parts per million
psig	pound force per square inch gauge
PVC	Polyvinyl Chloride
PWT	Produced Water Treatment
R&D	Research & Development
ROV	Remotely Operated Vehicle
SDU	Subsea Distribution Unit
UDW	Ultra Deep Water
VSD	Variable Speed Drives
WHD	Wellhead Desander

7.6 Typical Stages in a Surface PWT Process Train

In a typical surface treatment system, produced water exits the bulk separators (i.e. free water knockout) with 1000 - 2000 ppm oil-in-water content. The water will be near wellhead temperature and from ambient to near wellhead pressure. For offshore installations the primary treatment step is a deoiler hydrocyclone, which reduces the OIW to the range of 29 -100 ppm followed by a secondary treatment stage using a hydraulic flotation cell to meet overboard discharge requirements of <29 ppm OIW.

Onshore facilities may use a corrugated plate interceptor separator or American Petroleum Institute separator as the primary treatment, possibly followed by mechanical flotation cells as the secondary treatment.

The following design boundary conditions are given for a generic walnut shell filter used in an oilfield installation. These values can vary widely but these represent values for surface process.

- Water flow rate: 5,000 - 75,000 bpd (145 -2190 gpm) for a single vessel
- Water temperature: Ambient to 150°F
- Operating pressure: Atmospheric to 50 psig
- OIW content: <50 ppm inlet (from deoiler/flotation outlet), <5 ppm outlet (injection quality)
- Solids content: <25 ppm inlet, <5 ppm outlet (injection quality)
- Particle size inlet: <20 micron oil droplets, <10 micron solids
- Particle size outlet: <2 microns oil and solids

Brief Description of Reference Drawing Number: SK-RPSEA -1

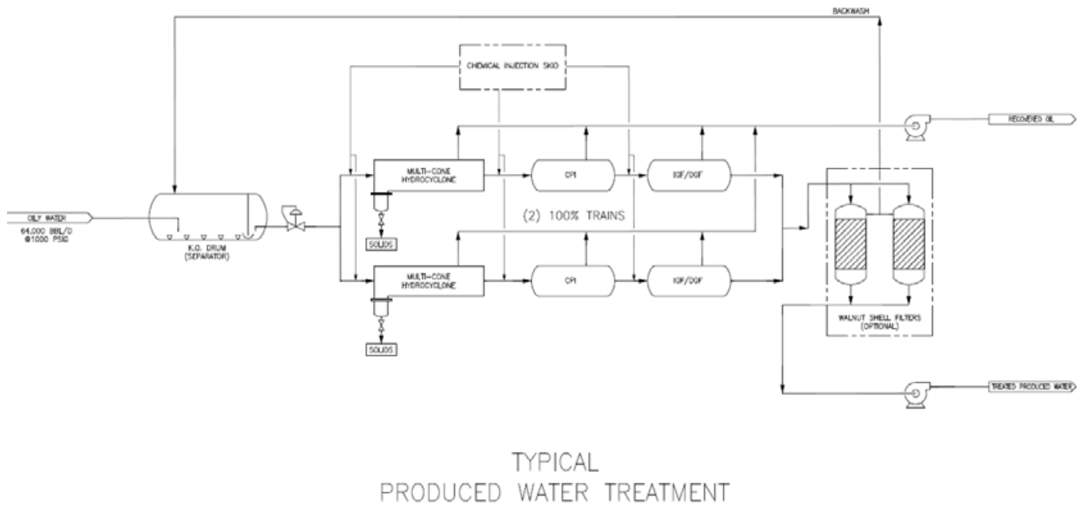


Figure 1: Typical Produced Water Stage in a Surface System

(Presented to steering committee 8/8/2011)

The sketch shows a flow diagram of a typical topside Produced Water Treatment System with the following stages:

- Knock Out Drum Separator
- Multi-Cone Hydrocyclone with solids removal
- Corrugated Plate Interceptors
- Induced Gas Flotation / Dissolved Gas Flotation

7.7.1 Knock Out Drum Separator

This horizontal pressure vessel may be 10 ft dia x 25 ft long. It accepts the oily water at 1,000 psi and 1,000 ppm solids. Backwash from later filtration is also flushed into this separator. The sand at 100 ppm and other particles above 150 microns, which settle in the separator, will be jetted and removed from the bottom of the vessel.

7.7.2 Multi-Cone Hydrocyclone

The process train splits into two parallel trains to provide 100% redundancy in the system. This pressure vessel may be mounted vertically or horizontally. It accepts input pressures in the range of 150 to 2,600 psi and its first stage is a desanding cyclone that ejects the remainder of the 700 lbs/day entrained sand from the flow path.

The remaining hydrocyclones require 2 to 3 seconds residence time to separate more oil and gas to the oil stream so that the oily water leaves the vessel with impurities at 5 to 15 micron sizes and 50 to 200 ppm.

7.7.3 Corrugated Plate Interceptors

These pressure vessels function more efficiently when mounted vertically and on the surface may be 6 ft dia x 40 ft in length or 8 ft dia x 22 ft length. The chamber is packed with corrugated plates to create a honeycomb of 'off vertical' channels. The oil droplets attach to the plate surface and coalesce together until the pull of buoyancy takes over and the oil floats to the top of the tank for extraction and the water is drained from below. The plate design is reported to be sensitive to the properties of the fluid input. Some users would only use CPI on the surface for deck spillage clean up and feel that considerable intervention for manual cleaning of the plates is required. The above needs further investigation but sheds doubt on this technology's viability.

7.7.4 Induced Gas Flotation / Dissolved Gas Flotation

These pressure vessels function more efficiently when mounted vertically and on the surface may be 6 ft dia x 30 ft in length or 8 ft dia x 15 ft length. Recycled gas is mixed as fine bubbles with the oily water as it enters the bottom of the vessel. As the gas floats upward it collects oil droplets that coagulate together with other droplets and the combination floats to the top of the vessel where the gas exits from the top and the oil is drained to the oil stream from just below. This can remove particles down to a range of 3 to 5 microns.

7.7.5 Discussion on the Typical Stages in a Surface PWT Process Train

Onshore process trains can be sized solely to optimize their process function. Vessels can be large and fixed to concrete foundations with connections to the vessel bolted, screwed or welded. Sand and solids can be collected in porous sacks for the liquids to drain through and the output water can flow by gravity into an open topped tank to be lab tested before release. Operators can read gauges, set valves and pump speeds, view the fluids and draw samples from many locations along the train. Electrical power is drawn from the overhead grid. If the filters need changing then the vessel can be opened and the exchange made. If the granules need backwashing they can be flushed into another tank then returned and topped up as needed. Operations & Maintenance staff can be on-hand 24/7 so the system needs minimum automation.

None of the above will happen when the process train is installed 1½ miles underwater with approaching 2 tons / in^2 ambient pressure and 50 miles from the workstation. When the technology gaps are bridged to enable ultra deep water processing, tying back to onshore will make it safer and more efficient. When the technology gaps are bridged and ultra deep water processing is able to tie back to onshore facilities, this will make it safer and more efficient to implement.

7.8 DESIGN OPTION A – UDW MARINIZATION OF A TYPICAL SURFACE PWT PROCESS TRAIN

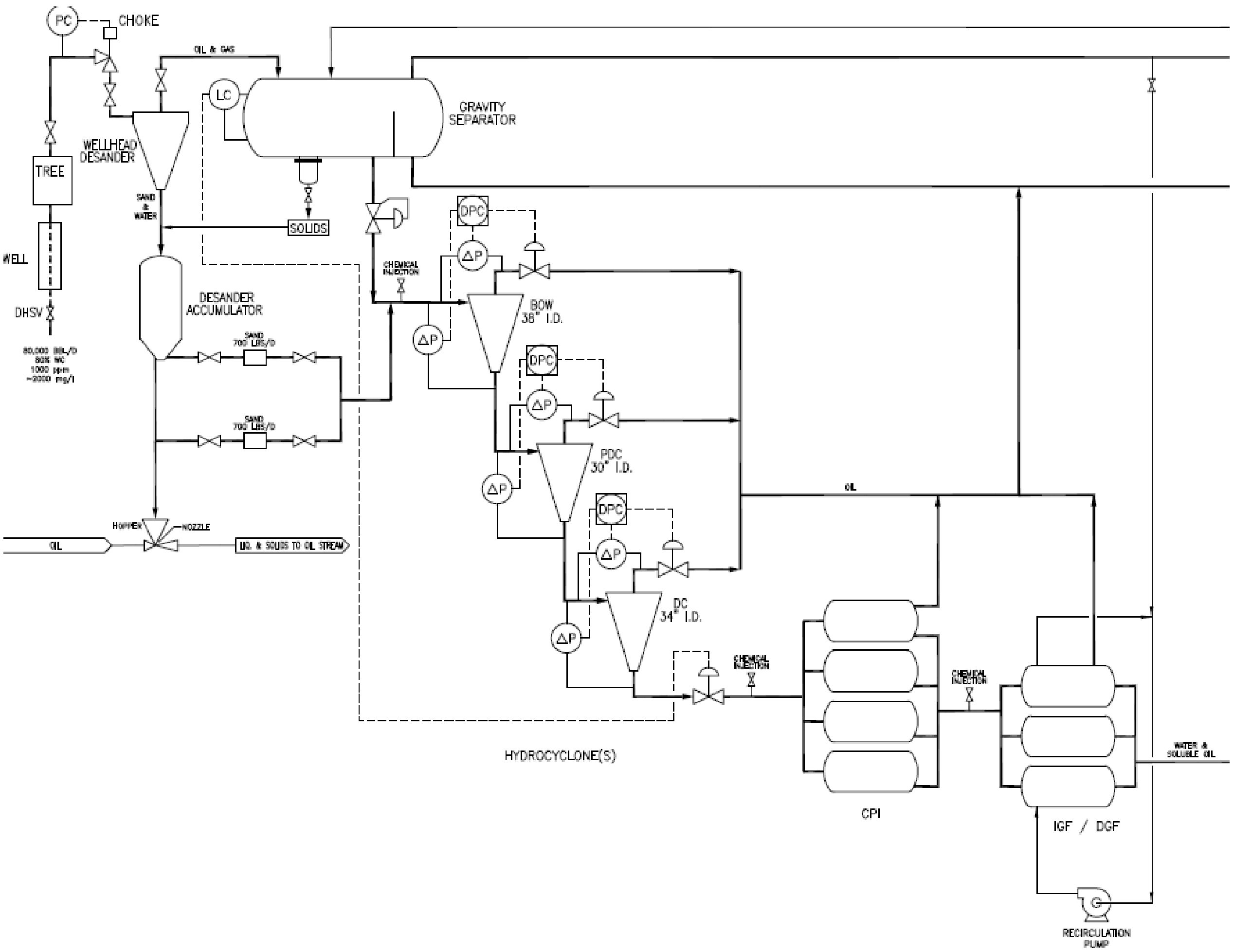


Figure 2: Design A

Brief Description of Reference Drawing Number: PFD-RPSEA – 6
(Presented to steering committee 9/28/2011)

The sketch shows a single train of the flow diagram for a marinized typical topside Produced Water Treatment System with the following stages:

- Desanding Cyclone & Desanding Accumulator
- Gravity Separator
- Multi-Cone Hydrocyclone
- Corrugated Plate Interceptors, Settling Tanks or Coalescing Filters
- Induced Gas Flotation / Dissolved Gas Flotation
- Pump Transfer to Sea & Flowline Pressure Boosting

7.8.1 Subsea Wellheads, Trees and Shut-In Pressures

The wellhead and tree have been included in the schematic as flow control devices on the process input. However, the tree choke is not normally under Process System control. Many filtering stages control their flow at the output and should back pressures build up or the system be Shut-In, the train must be able to withstand the full wellhead Shut-In pressure. Flow control valves will have to be rated to the full differential pressure of 7,500 psi while consideration may be allowed for the external pressure of up to 3,450 psi on the vessels. The system may actually see its highest pressure loadings during surface testing. The impact on component weights and costs must be considered. Brief calculations indicate that to achieve a compromise between vessel weight, diameter and wall thickness while controlling cost and manufacturability, vessels should be limited to a maximum of 3 ft diameter and a minimum wall thickness of 1.5 inches.

More detailed vessel designs will have to allow access for assembly and maintenance while avoiding openings in the cylindrical surface which are weak points under collapse pressures. FMC have split their compact separator in half length wise and connected the halves with a flange. This allows the best access and the flange is a radial stiffener. Collapse can start as a local depression in the cylindrical wall or changes in cross section to lobed or rosette shapes so internal and external hoops can help resist this by stiffening the wall. Axial stiffening can also be needed to avoid a concertina type collapse. Like an aircraft fuselage the attachments to the vessel's surfaces will have to tolerate the vessel‘s expansion and contraction.

The South Stream project in the Black Sea calls for 32 in pipe in depths up to 7,200 ft. The success of this project relies on the manufacturability of the line pipe with the required wall thickness.

Using the current DNV F101 formulation, most mills indicate that they are able to produce pipe with a significantly improved fabrication factor, incorporating strength recovery through thermal aging. The thermal aging effect is the ability of steel to recover its strength due to strain aging. This is the largest contribution to wall thickness. Pipe collapse resistance is linked to the pipe hoop compressive strength. Many studies indicate that a significant recovery in collapse strength can be gained for DNV SAWL 450 steel (in the order of 30%). Test results suggest the collapse resistance is recovered and even increases beyond the original value.

7.8.2 Pressure Vessel Shape

The pressure hull can consist of spherical or cylindrical shapes in various combinations. Table 2 illustrates the advantages and disadvantages of various pressure hull shapes.

Table 2 - Advantages and Disadvantages of Submersible Pressure Hull Shapes

Shape	**Advantages**	**Disadvantages**
Sphere	1. Most favorable weight to displacement ratio 2. Thru-hull penetrations easily made 3. Stress analyses more accurate and less complex	1. Difficult and inefficient interior arrangements 2. Large hydrodynamic drag
Shape	**Advantages**	**Disadvantages**
Ellipse	1. Moderate weight to displacement ratio 2. More efficient interior arrangements than in *Sphere* 3. Thru-hull penetrations easily incorporated	1. Expensive to construct 2. Difficult to perform accurate structural analysis

Shape	Advantages	Disadvantages
Cylinder	1. Inexpensive to construct 2. More efficient interior arrangements than in *Ellipse* 3. Low hydrodynamic drag	1. Least efficient weight to displacement ratio 2. Interior frames required to increase strength

7.8.3 Desanding Cyclone & Desanding Accumulator

The wellhead desander is used to remove the 700 lbs/day of sand and solids from the well stream as early as possible. It is at the front of the process train allowing solids to be removed at higher pressure and therefore lower velocity. The well flow is directed tangentially into the cyclone resulting in a spinning effect that forces the heavier solids to the wall of the vessel. As the solids lose energy they fall due to the effects of gravity and are collected below in a desanding accumulator.

The solids free liquid is extracted from the top of the cyclone. The vessel can be isolated from the incoming flow and the accumulated solids flushed out of the vessel by pumping water into the vessel flush connection and recovering the solids from retrievable containers. The units would be deployed in at least tandem configuration and used on a stand-bye / duty regime to allow continuous solids removal.

7.8.4 Gravity Separator

The gravity separation stage will require a large volume horizontal pressure vessel. To meet the diameter limitations for collapse strength of 3 ft this may become a long pipe or several parallel cylinders. The 'Pipe' solution could be straight and represent part of the flowline while 'Cylinders' could be divided into 2 phase separations sets. Some solids control will still be required. The process train splits into two parallel trains after the separator to provide 100 % redundancy in the system.

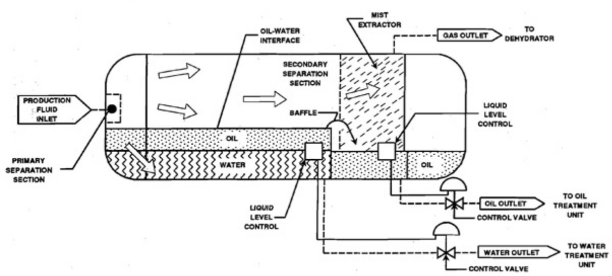


Figure 3: Diagram of a 3 Phase Gravity Separator

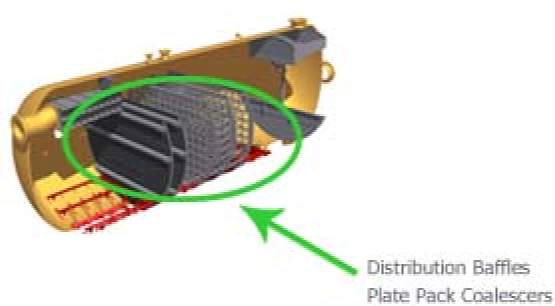


Figure 4: FMC's CDS – Gravity Separator

CDS Adds the following internals to the separator; a mesh agglomerater, perforated baffles and parallel plate that ensure good flow distribution and enhanced separation. The separator performs at higher efficiencies that result in a maximum performance in minimum dimensions.

This pressure vessel may be mounted vertically or horizontally. It accepts input pressures in the range of 150 to 2,600 psi and its first stage is a desanding cyclone that ejects the remainder of the 700 lbs/day entrained sand from the flow path.

7.8.5 Multi-Cone Hydrocyclone

Hydrocyclones should be installed immediately downstream of the separators. To maintain interface control within the separator, a level control valve is used on the clean water "underflow" outlet from the hydrocyclones. These control valves may be combined with pumps between the hydrocyclones to maintain optimum pressure drops and flow rates through them.

Figure 5: Aker Solutions Multi Core Hydrocyclone

7.8.6 Induced Gas Flotation / Dissolved Gas Flotation

These pressure vessels also function more efficiently when mounted vertically and 3 x 60 ft or perhaps 5 x 40 ft vessels would be required. There may be issues with the taller vessels controlling the bubble size and upward acceleration while attracting the oil particles. This would still remove particles down to a range of 3 to 5 microns.

7.8.7 Pump Transfer to Sea & Flowline Pressure Boosting

The process train starts at the 1,000 psi wellhead flowing pressure and declines through the process train. For the clean water discharge to flow into the sea the pressure will have to exceed the ambient sea pressure of 3,500 psi. Booster pumping is required.

The oil and gas flows will also need pressure boosting to overcome the head and flow losses for the 50 mile tie-back to the surface facility. This could be carried out separately and co-mingled down stream or handled by a multiphase pump. This could change as the field depletes.

The system should also include the possibility of reinjecting the gas into the well for gas lift.

7.8.8 Discussion on the Typical Stages in a Surface Process Train

The sketch shows a single train of the PFD for a marinized typical topside Produced Water Treatment System.

Desanding Cyclone & Desanding Accumulator

Sand production will be avoided if possible because of the erosion damage and obstruction it can cause and then the need to dispose of it in an environmentally safe way. The forward planning should allow for a desander to be incorporated when required and the equipment should be specified for sandy service.

Multiple desanders should be mounted as close to the wellhead as possible and the need for an accumulator considered against the alternative of continuous eduction of the sand to a longer term storage container or into the oil flow to the surface facility. The oil flow rate and the 50 mile tie-back distance may make the later impractical.

The nature of the oil and whether it can largely be removed from the sand at this stage or remains with the sand in sufficient quantity to make a conglomerated mass must also be considered.

Gravity Separator

The separator vessel size is a rather arbitrary but must provide a residence time compatible with the other stages. A reduction in the diameter to 36 inches would reduce the residence time to maybe 15 seconds. But it may need to be moved downstream of the Hydrocyclones to achieve this.

Multi-Cone Hydrocyclone

Multiple Hydrocyclones are shown in series. They have different insert sizes to deal with different particle sizes. Most users question how effective this would be and some would not use more than two cyclones on series. Flow control with booster pumps and exit flow modulation possibly combined with bypass loops could adjust the system to suit the current oil properties.

They are a compact device that lends itself to incorporation into a pressure vessel design able to withstand the collapse pressures applied.

The pressure vessels required will be large and heavy requiring a substantial seabed platform and probably would be individually installed onto it.

Whether horizontal or vertical, resting on saddles or plugged into a receptacle many connections and holding clamps will be required. Manufacturing and pressure testing such large vessels will be challenging and installation will bring hazards both on the surface and on landing.

Induced Gas Flotation / Dissolved Gas Flotation

These gas flotation cells are simple devices with little potential for collecting produced fluid deposits on its internal surfaces. It may have been simplistic to scale the vessel volumes to a similar size to those required for this flow on the surface. A move towards better efficiency and smaller vessels is indicated and below a vessel that combines the benefits of CPI and IGF to achieve this is presented.

Pump Transfer to Sea & Flowline Pressure Boosting

The possibility of boosting the pressure earlier in the process train should be considered with particular interest on the effect on the filtering process. Boosting upstream should be done for the total inlet fluids and if possible with as much ‘distance’ between pump discharge and wellhead desander inlet as possible. This will allow any detrimental pump action on the fluids to ‘settle’ out, and allow the fluids the opportunity for coalescence again before separation occurs. However, boosting after the separation processes would ensure that the fluids are not handled / mixed / emulsified beforehand. Separating the ‘untouched’ fluids will result in a better performance outcome.

Note that Design A was just performed to understand how the basic typical topside applications would look subsea. It is not considered practical due to the use of the corrugated plate inteceptors.

7.9 DESIGN OPTION B – SIMPLIFIED UDW SUBSEA PWT PROCESS TRAIN

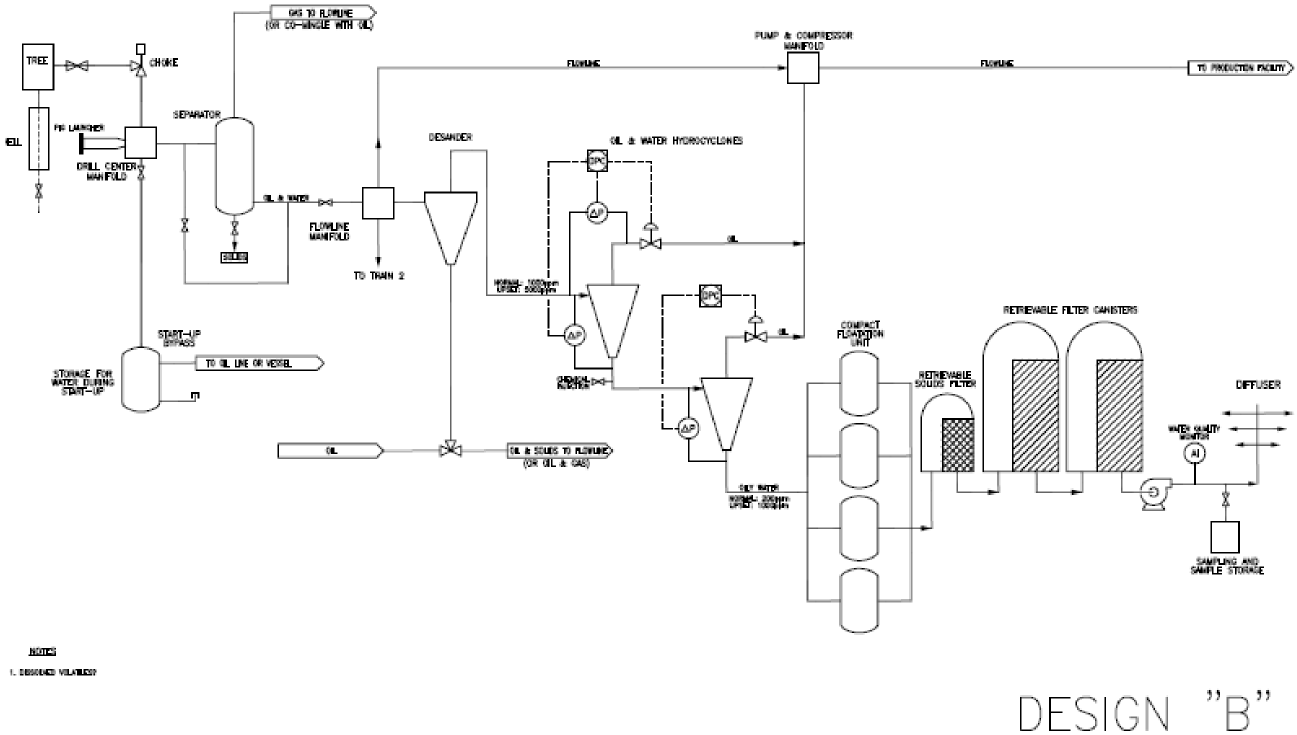


Figure 6: Design B

Brief Description of Reference Drawing Number: PFD-RPSEA – 7

(Presented to steering committee 9/28/2011)

The sketch shows a single train of the flow diagram for a simplified Produced Water Treatment System with the following stages:

- Desanding Cyclone & Desanding Accumulator
- Gravity Separator
- Multi-Cone Hydrocyclone
- Induced Gas Flotation / Compact Flotation Unit
- Retrievable Solids Filter
- Retrievable Filter Canisters
- Coalescer

7.9.1 Train Simplification

Option A has several stages in its process train that overlap or duplicate other stages. This simplified train removes the CPI, leaving the IGF and introducing a Coalescing stage. Only the changes from option A will be presented and discussed below.

7.9.2 Induced Gas Flotation

As before, multiple vertical IGF vessels are required. They will probably be interconnected in a combined series / parallel array, with more capacity available for connection to cover upset flow conditions and maintenance. This stage can also use Compact Flotation Units which has been discussed in section 6 and further in this section below.

7.9.3 Retrievable Solids Filters and Filter Canisters for Polymer based filters and Ceramic Membranes

This design uses the solids filter and filters canisters with the requirement of their use being retrievable, due to the servicing requirement needed by filters. Since the intervention of subsea equipment and the retrievability of subsea equipment has become a standard in the industry today, the retrievability of a filter should see a rapid development

7.9.4 Coalescers Oil/water Separators

Coalescers contain special oleophilic media packs that attract oil and repel water. They claim to be at least ten times more efficient for oil removal than simple API separation tanks. Oily water with relatively low total suspended solids can be separated in a coalescer. High temperature alkaline cleaners can be processed through the coalescer for free oil removal and reuse.

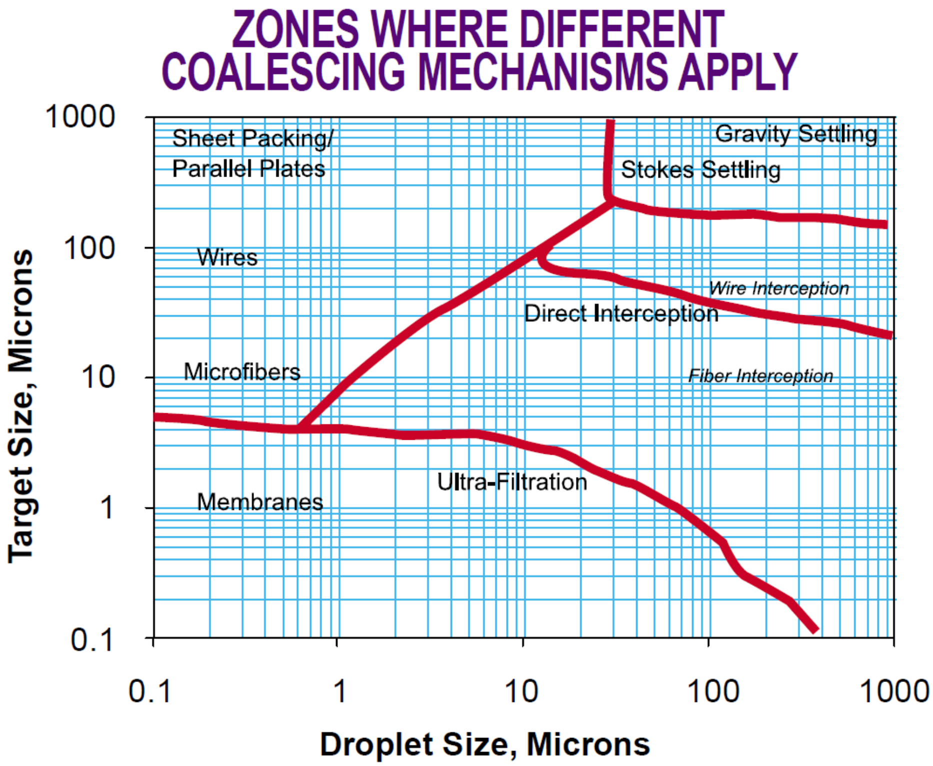


Figure 7: Coalescing Oil Droplet Size Mechanisms

7.9.5 Discussion on the Simplified UDW Subsea PWT Process Train

The Filter technology offers a number of benefits to the user, including:

- Improved quality of produced water discharged without the need for deoiling chemicals
- Enhances the performance of other water treatment technology
- Extends the turndown of deoiling hydrocyclones by greatly improving their efficiency at low flow rates
- Back washable and cost effective

Coalescers offer the following features:

- Flows rates up to 3,000 gpm
- Effluent quality to less than 10 mg/l free, non-emulsified oil remaining
- Removal of oil droplets to 20 microns or less (droplet size limit of emulsion)
- Recovered oil typically less than 1% water
- Can handle up to 100% influent oil on a continuous basis
- Cleaned via a bottom hopper to that allow solids to settle out of the oily water
- Special media available - corrugated PVC, vertical perforated polypropylene tubes
- Compact size, minimum ground space

7.10 DESIGN Option C – UDW Subsea PWT Process Train with Filter Canisters

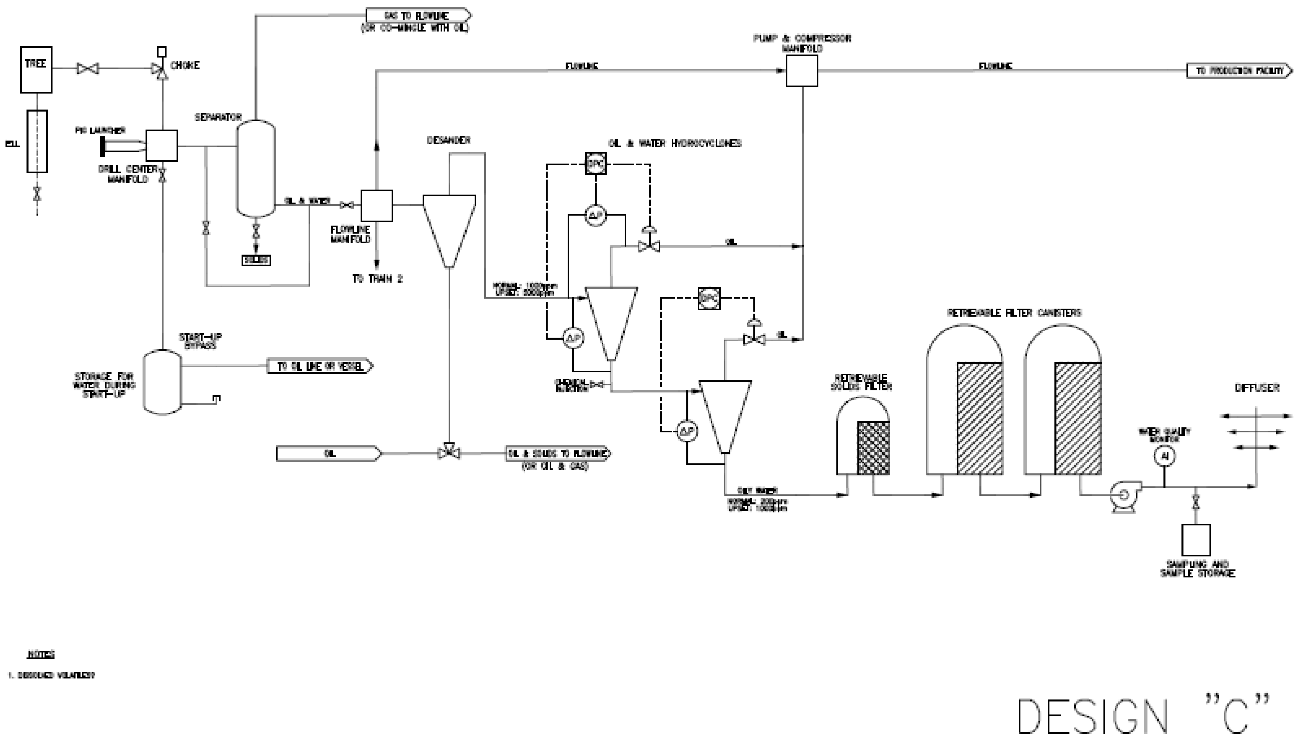


Figure 8: Design C

Brief Description of Reference Drawing Number: PFD-RPSEA – 4

(Presented to steering committee 9/28/2011)

The sketch shows a single train of the flow diagram for a Produced Water Treatment System. It includes a pig launcher and two additional manifolds to bring in field architecture requirements. These would be installed with the flowline to allow future equipment plug-ins.

The sketch presents a process train with the following stages:

- Separator
- Solids Filter, Desanding Cyclone & Sand Eductor
- Multi-Cone Hydrocyclone
- Storage for Start-Up Water & Methanol
- Solids Filter, Retrievable Filter Canisters
- Boosting, Monitoring
- Sampling & Storage
- Diffuser

7.10.1 Separator

The separator has moved upstream of the division in the flow path at the Flowline Manifold. It is actually installed on a flowline bypass to allow pigging. It would be installed when the produced fluid starts to need processing or boosting. It could separate the 2 phases for pumping and compression while extracting the solids / sand for introduction back into the flowline after the streams have been comingled. At this stage the flowrate in the flowline may be still high enough to carry the sand and solids back to the surface.

7.10.2 Solids Filter, Desanding Cyclone & Sand Eductor

The Desanding Cyclone is now shown as the first stage of the ‘Hydrocyclone’ package. The Accumulator has been removed to avoid concern of the oily sand solidifying in the vessel by keeping it moving. An eductor beneath the desander is fed with oil to carry the mixture into the down stream oil line. The desander can remove over 80% of the solids from the fluid but it may be prudent to include a Solids Filter to further improve the fluid entering the hydrocyclones. This could be a retrievable cartridge or preferably a mesh that can be back washed into the oil stream to extend its service, but could ultimately be recovered for maintenance or replacement.

7.10.3 Storage for Start-Up Water & Methanol

During Start-Up of wells, water and methanol will flow into the flowline from the well. If this cannot be allowed to flow back to the facility then it will be directed to a subsea storage facility. Each well can produce so many barrels for storage and this will need several tanks. Volume compensation becomes a challenge. If sea water is used it becomes contaminated and cannot be discharged back to sea. However, oil or gas could be temporarily diverted back to fill the tanks from the flowline. The tanks would be on a service loop that individual wells could be diverted to as necessary. Incoming water and methanol would push the oil & gas back into the flowline and then be shut-in before it could follow.

When a surface vessel comes to drain the storage tanks, flowline gas & oil can be used to fill the void. Given that the flowline pressure has to be sufficient to lift the oil to the surface after a 50 mile flowline transit, the working pressure of the flowline booster pump should be also able to boost the water and methanol to the surface vessel.

7.10.4 Multi-Cone Hydrocyclone

Only two Hydrocyclones are represented but it could have several stages with pumps and exit flow control to optimize their performance. Stages would be switched in and out as flow and back wash issues require.

7.10.5 Solids Filter, Retrievable Filter Canisters

The final polishing stage starts with a solids filter to protect the filter cartridges in the retrievable filter canisters. Again this could be a retrievable cartridge or preferably a mesh that can be back washed into the oil stream to extend its service but could ultimately be recovered for maintenance or replacement.

The filter canisters have several vertical feeder pipes with perforated walls. The cylindrical filter elements are threaded in stacks onto these pipes to the top of the canister. As the oily water flows radially outward the oil particles coalesce on the filters’ outside surface, become buoyant and flow to the top of the canister for extraction to the flowline. The polished water exits through the bottom of the canister.

7.10.6 Boosting, Monitoring

The polished water is at the end of a process train that started at the wellhead flowing pressure of 1,000 psi. However, as oil and gas is separated and fed to the flowline it will have to be boosted to perhaps 5,000 psi to flow the 50 miles to the facility. Pumps may also be needed to optimize the hydrocyclones’ flows / pressure drops which will increase the filtrate output pressures entering the flowline stream feeding to the flowline pump / compressor.

Cetco, the company who manufactures the type of filter cartridges that could be used in the polishing stage, advise that the cartridges are not sensitive to being crushed by the pressure levels but just need a pressure differential to flow. The water pressure will eventually have to exceed 3,500 psi to overcome ambient sea pressure and flow to sea.

Pressure monitoring and boosting throughout the process to maintain the flowrate is required. This is needed to optimize separation processes. It is also necessary to avoid back flow of oil and gas and backwash that would boost separator pressure and back-pressure the well.

To optimize the processes, entry and exit fluid condition monitoring will be used to adjust pressure and flow controls. Two and three phase flow meters will be located throughout the process train.

7.10.7 Sampling & Storage

At the point of water discharge to sea, continuous water quality monitoring to a level acceptable to the certifying authorities is required to confirm that discharge can continue or trigger an immediate but controlled shut-in. The trees would shut in the wells and the pumps would switch to closed loops while they wind down.

In addition to the continuous discharge flow stream, monitoring physical samples are required of the stream for laboratory analysis. A sample handling cartridge system, working at ambient pressures, is required to extract and seal samples for recovery to the surface. This would require monthly visits to the monitor station by an ROV or autonomous underwater vehicle.

7.10.8 Diffuser

This will be a vertical tube standing at the end of the discharge line from the process train. Ten to fifteen feet above mudline it will have horizontally directed non return nozzles to diffuse and disperse the water and acceptable solids in all directions. The solids will be approximately 62 tons / year. If there is a seabed current it will help this dispersion but the diffuser(s) would ideally be positioned downstream of the trains. If two trains are installed for handling upsets and maintenance down time the solids would be dispersed even further as each train takes its turn to operate.

Diffusers suffer from reduced hydraulic capacity and dilution efficiency caused by salt water, sediment, and marine organisms occupying a portion of the outfall pipe.

The open ports in the diffuser cannot prevent backflow, and therefore allow intrusion during periods of low flow and hydraulic instabilities.

The cost of evacuating the sediment from the outfall and restoring it to service can be significant. Variable orifice duckbill valves prevent intrusion of salt water and sediment giving savings in operation and maintenance over the life of the diffuser. The variable orifice inherently produces significant hydraulic advantages by minimizing head loss at peak flow, and generating enhanced initial dilution at lower flows.

Ref. Use of Elastomeric “Duckbill” Valves for Long-Term Hydraulic and Dilution Efficiency of Marine Diffusers - Michael J. Duer, P.E

7.10.9 Discussion on UDW Subsea PWT Process Train with Filter Canisters

This sketch allowed the workshop to perform a ‘System Check’ that starts at the Drill Center and extends to the Diffuser discharging to sea. In doing so it allowed consideration like Pig Launching and Start-Up water handling to be identified, recognized as ‘Out with the Studies Scope’ and recorded for others to resolve.

The change to the train configuration is the introduction of Retrievable Filter Canisters, filled with filter cartridges, preceded upstream by a solids filter and possibly followed downstream with a charcoal filter. These filters are very effective at reducing the contaminants to acceptable levels. The unknown is their serviceable working life. They will be periodically back flushed to remove caking but will eventually have to be recovered to the surface for replacement. Sub-Modules from the seabed mounting would be recycled to a surface vessel for maintenance and reinstallation.

These operations are possible. They would be costly for Time & Materials as well as vessel availability. Weather conditions limiting access must also be considered. At least two trains will be installed and some process stages will have additional reserve capacity. While this may not be a Technology Gap it could result in limited functionality and be commercially unacceptable.

Fluid quality monitoring will be required throughout the process train. It will therefore be dealing with different levels and qualities of different fluids. Many monitoring methods are offered for surface applications. Some may be more appropriate at different stages than others. All this data must be processed and fed back into the train's flow controls. This will have to be a computer controlled system to handle the interactions and achieve the required speed of response.

A comparison should be made between the control systems required for the process train and the control system for a subsea pipeline High Integrity Pressure Protection System (HIPPS). The later basically has two valves inline that are triggered to close quickly to prevent over pressuring the flowline or excessive flow indicating a flowline failure. The pressure surge can travel a mile down the flowline past the valves before they can shut off the flow. This can cause hydraulic hammer loads and pump flow issues.

The sensitivity of the monitoring causes the valve actuation to 'flutter' and regulations where they are used in other parts of the world require frequent testing which range from partial closure to complete closure.
The train controls must add fluid quality to pressure monitoring and flow control to simple shut-off and do it interactively at and between several points in the train. Frequent regulatory testing should also be anticipated.

7.11 DESIGN OPTION D – COMPACT FLOTATION UNIT (CFU)

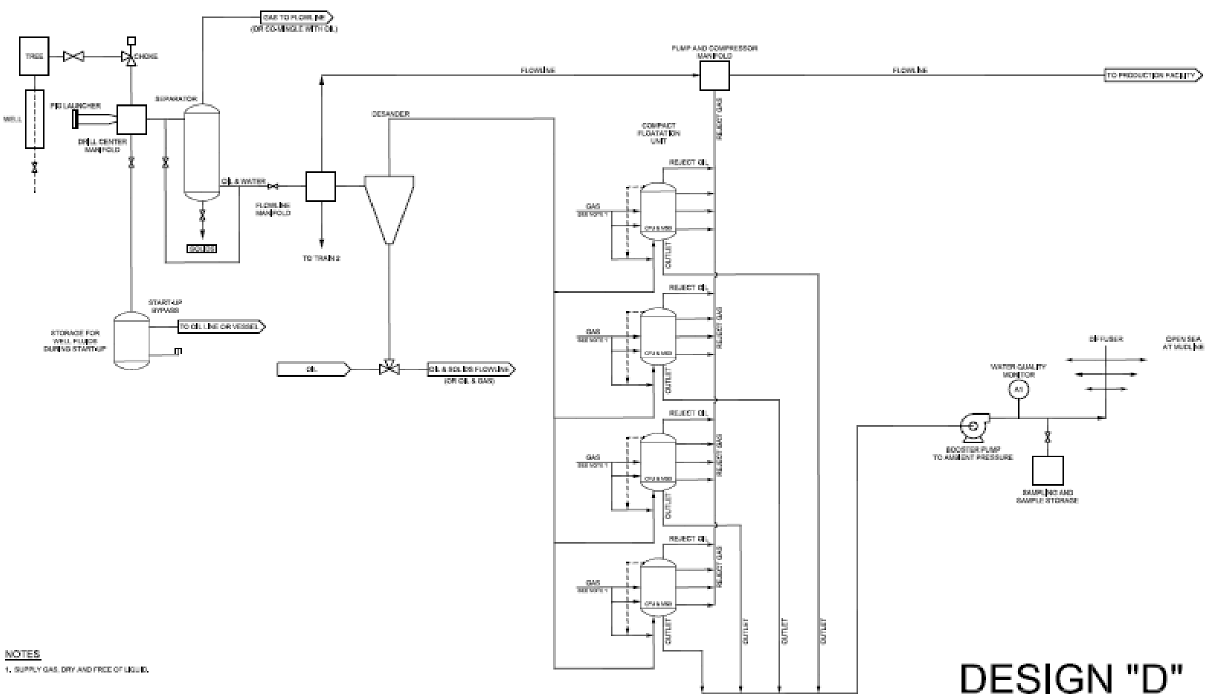


Figure 9: Design D

Brief Description of Reference Drawing Number: PFD-RPSEA – 8

This design uses the desander, hydrocyclone, and compact flotation units. The drawing presents a process train with the following stages:

- Solids Filter, Desanding Cyclone & Sand Eductor
- Compact Flotation Unit – Water Knock-Out Drum
- Gravity Separator (Optional)
- Compact Flotation Unit – 3 Stage Unit
- Storage for Start-Up Water & Methanol
- Solids Filter, Retrievable Filter Canisters
- Boosting, Monitoring
- Sampling & Storage
- Diffuser

Only the CFU units will be discussed as all the others have been addressed previously.

7.11.1 Compact Floatation Unit Technology

This next generation Compact Flotation Technology (CFT) is relatively new to the North American region but has been well proven with more than 50 installations world wide on offshore platforms. Many different compact floatation units exist today and they are units that uses gas flotation and additional centrifugal forces to separate and remove hydrocarbons as liquid and gas, aromatic compounds, hydrophobic substances and small solid particles from produced water. The technology uses special internals for mixing of gas and oil through several stages within one vessel. These internals are designed to achieve effective separation of this gas and oil from the water. The technology has performed well under high OIW concentrations and small oil droplet size distributions.

Ideally, Compact Flotation Units (CFU) are capable of handling higher inlet oil concentrations, over 1,000 ppm and providing lower outlet OIW concentrations of less than 10 ppm. The Cameron TST CFU system requires less equipment, has a lower weight, smaller footprint, is less dependent on chemicals and can potentially replace multiple produced water treatment stages.

7.11.2 Discussion on the Compact Flotation Unit (CFU)

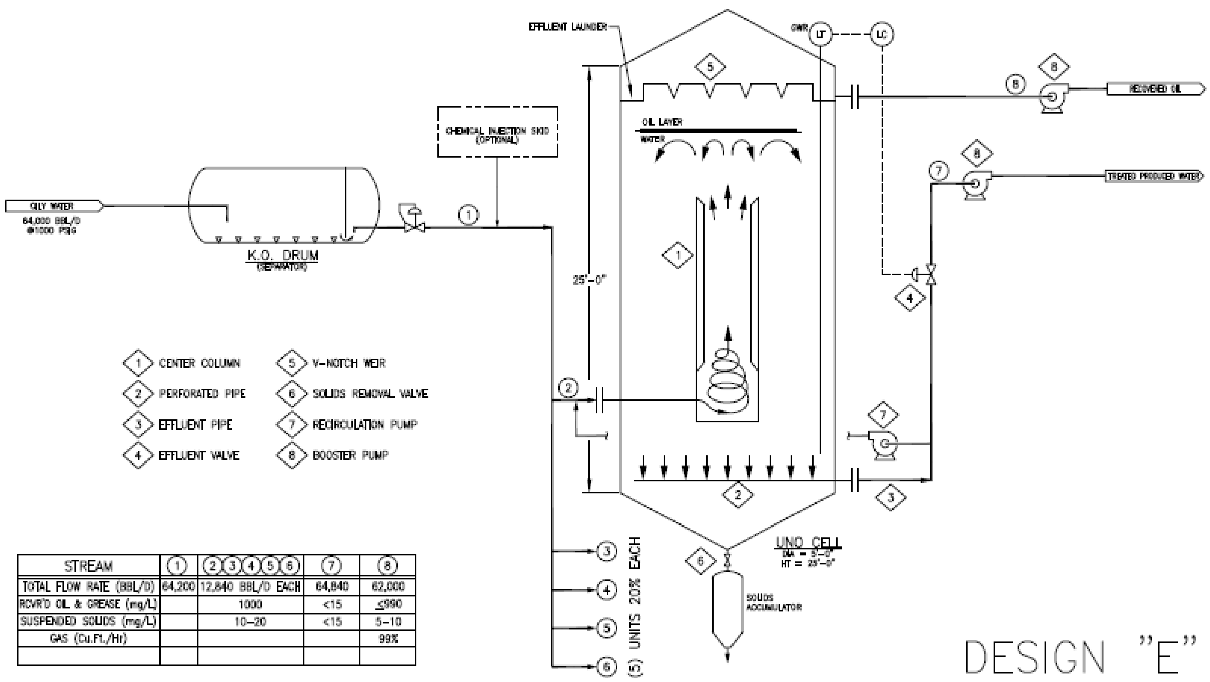
The system as shown includes a gravity separator and hydrocyclone stage to help handle slugs and upsets. It has been extensively used on the surface and the unit could be plugged into the middle of the marinated trains considered above. Cameron advises that limiting the vessel diameter to 3 ft for collapse resistance can be accepted by the design. The access port in the vessel would have to change and it may finish up with the main body flanged in the middle. Attachments to the vessel like the internal guide strakes will have to consider vessel wall deflections due to pressure changes. The number and size of the units would still have to be worked out but pictures of surface units that handle the study’s flowrates look promising.

Fewer stages in the train simplify the installation and controls. No moving parts and the use of corrosion resistant materials will minimize maintenance, at least for this larger component. External pumps and manifolds could be modularized for recovery to the surface to receive repair or maintenance.

Siapam and Veolia teamed up and reported results in OTC 22667 paper which is very similar to this design "D", but adds the use of a ceramine membrane filter. The paper offers supporting comments to the advantages of using produced water treatment technologies in a subsea processing system.

They have initiated a design and qualification program to enhance the performance of the reservoir and not have to accommodate the traditional limitations of a production separation system.(OTC 22667, 2011)

7.12 DESIGN OPTION E – UNO-CELL PWT PROCESS TRAIN



STREAM	1	2 3 4 5 6	7	8
TOTAL FLOW RATE (BBL/D)	64,200	12,840 BBL/D EACH	64,840	62,000
RCVR'D OIL & GREASE (mg/L)		1000	<15	≤990
SUSPENDED SOLIDS (mg/L)		10–20	<15	5–10
GAS (Cu.Ft./Hr)				99%

Figure 10: Design E

Brief Description of Reference Drawing Number: PFD-RPSEA – 5 Unocell
(Presented to steering committee 9/28/2011)

The drawing, referenced above, shows the Uno-Cell technology inserted into a subsea processing train. After the wellhead desander and flowline mounted knock out separator the flow stream would be diverted into one of these water processing trains.

The drawing presents a process train with the following stages:

- Solids Filter, Desanding Cyclone & Sand Eductor
- Gravity Separator (Optional)
- Unocell Separator
- Storage for Start-Up Water & Methanol
- Solids Filter, Retrievable Filter Canisters
- Boosting, Monitoring

- Sampling & Storage
- Diffuser

Only the Uno-Cell will be discussed as all the others components have been addressed previously.

7.12.1 Uno-Cell Separator Operation Sequence

The chemically treated underflow from the FWKO drum enters tangentially into the center column. Then the mass flow spins and rises at a controlled optimum velocity through the center column enhancing the coalescence of oil particles. The flow exits upward into the established pool of oil and water and is forced to turn uniformly downward in the opposite direction to the center column.

The downward flow velocity is considerably lower than the rising velocity in the center column, and the free oil in the incoming water is trapped in the oil pool at the oil-water interface level. Large oil droplets and the difference between the oil & water's specific gravity helps to float away any entrapped oil in the downward travelling water before it exits the Uno-Cell.

Recovered oil accumulates at the top of the vessel and its level begins to rise. At the predetermined set point, the effluent valve starts to slowly close. The water level in the Uno-Cell starts to rise and it pushes the accumulated oil through the v-notch weir into the effluent launder and out via the exits line.

At a pre-determined level, as the recovered oil is being removed, the effluent valve starts to open and lower the water level to the normal operating level and this operating scenario repeats itself continuously.

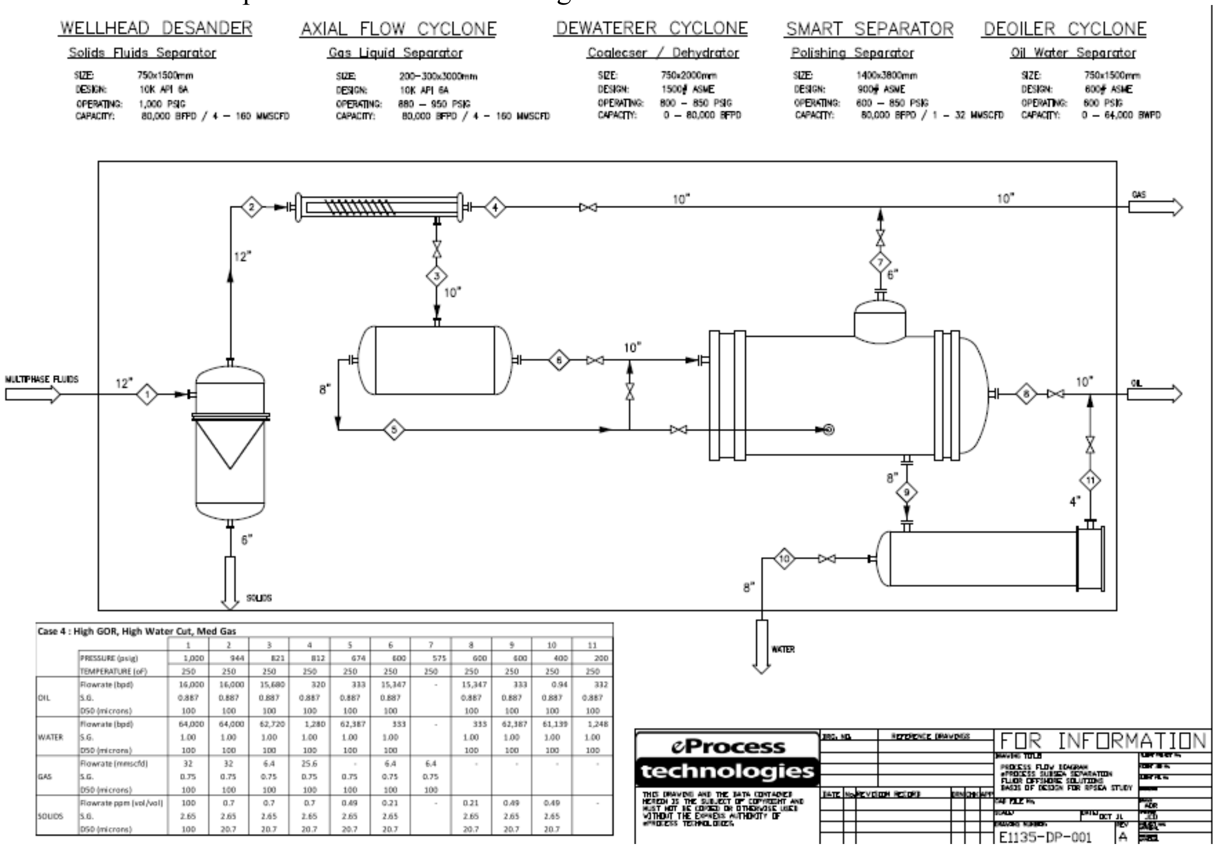
Any settable suspended solids will accumulate at the bottom of Uno-Cell and will be flushed out via the valve at the bottom of the vessel into a solids accumulator for disposal.

The recirculation pump outside the vessel ensures the optimum chemical process by constantly introducing treated water with the incoming untreated produced water. This maintains a constant flow rate through the center column for consistent higher oil removal operation.

The Uno-Cell has no moving parts; its controls are very simple, it enhances oil coalescence, improves oil recovery, produces no process waste streams, prevents flow short circuiting and can be readily marinized for deep water application.

7.13 DESIGN Option F – eProcess PWT Process Train

Brief Description of Reference Drawing Number: E1135-DP-001



Case 4 : High GOR, High Water Cut, Med Gas

		1	2	3	4	5	6	7	8	9	10	11
	PRESSURE (psig)	1,000	944	821	812	674	600	575	600	600	400	200
	TEMPERATURE (oF)	250	250	250	250	250	250	250	250	250	250	250
OIL	Flowrate (bpd)	16,000	16,000	15,680	320	333	15,347	-	15,347	333	0.94	332
	S.G.	0.887	0.887	0.887	0.887	0.887	0.887		0.887	0.887	0.887	0.887
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
WATER	Flowrate (bpd)	64,000	64,000	62,720	1,280	62,387	333	-	333	62,387	61,139	1,248
	S.G.	1.00	1.00	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
GAS	Flowrate (mmscfd)	32	32	6.4	25.6	-	6.4	6.4	-	-	-	-
	S.G.	0.75	0.75	0.75	0.75	0.75	0.75	0.75				
	D50 (microns)	100	100	100	100	100	100	100				
SOLIDS	Flowrate ppm (vol/vol)	100	0.7	0.7	0.7	0.49	0.21	-	0.21	0.49	0.49	-
	S.G.	2.65	2.65	2.65	2.65	2.65	2.65		2.65	2.65	2.65	
	D50 (microns)	100	20.7	20.7	20.7	20.7	20.7		20.7	20.7	20.7	

7.13.1 Introduction

eProcess Technologies provided a proposal for a Subsea Separation system using their technology and based on the study 'Basis of Design' (BOD) document in Section 1. They are Compact Separation Specialists with a range of equipment based on cyclonic equipment that is used comprehensively in Topsides applications, either upstream (API) or downstream (ASME) of the choke. The following is an edited version of the information they provided which is included in full in **Appendix 14.**

The drawing presents a process train with the following stages:

- Wellhead Desander for Solids – Fluid Separation
- Axial Flow Cyclone for Gas – Liquid Separation
- Dewaterer Cyclone – Coalescer & Dehydrator
- Smart Separator
- Deoiler Cyclone

7.13.2 Wellhead Desander

The Wellhead Desander (WHD) is a robust, simple and effective solids removal separatorwith a 2-3 second retention time, and no moving parts.

The WHD is based on a single 20 inch insert. This is a particularly large sized cyclone for a typical oil & gas application, but given the high inlet flowrate requirements, this size is required. An alternative would be the provision of a number of smaller sized units housing smaller inserts. For example 2 -16 inch insert units, or 3 or 4 - 10 inch insert units.

The smaller units would separate smaller sized solids and therefore would be more efficient. They would also allow for a level of operating redundancy.

For the range of process conditions, the WHD provided a recovery of between 11 to 35 microns sized solids in the outlet stream corresponding to 99.9 to 95.9% separation efficiency, at an operating pressure drop between 44 – 113 psig.

7.13.3 Axial Flow Cyclone

An Axial Flow Cyclone (AFC) provides cost effective and efficient compact gas liquid separation. Multiphase fluids enter the base of an AFC and rotate from the action of centrifugal forces. Stationary helical vanes force the heavier liquids to the wall of the cyclone, and the lighter gas phase migrates to the center. Dry gas is separated and directed to the outlet stream, and the remaining partially degassed multiphase stream continues axially through the separator.

Due to the nature of the separation process, individually sized AFC’s are required for such a large variable gas flowrate. AFC sizes of 8, 10, and 12 inches are required to cover the operating range. These AFC’s would be bundled together and synchronized to operate over the required range of inlet gas conditions.

For the study’s process conditions the AFC will provide a gas separation efficiency of approximately 80% actual gas volume, with less than 2.5% entrained liquids. The units would have an operating pressure drop of between 80 – 155 psig.

7.13.4 Dewaterer Cyclone

The Dewaterer Cyclone provides efficient and cost-effective solutions for the bulk oil water coalescing and separation for crude dehydration applications. Typically Dehydration applications can decrease BS&W from 40% to the export specification and Pre-separation can debottleneck high water cut production facilities from 80 – 90% water cut down to below 10%

Dewaterer cyclones are pressure drop dependant, where fluids are directed into the Dewaterer inlet causing the fluids to spin under a centrifugal force. These strong forces cause the two immiscible liquids (oil and water) to separate. The heavier water phase is forced outward toward the cyclone wall and the lighter oil phase migrates toward the center core.

In the cases where water is present and needs to be processed, the Dewaterer can reduce the water in the oil phase significantly so that it can be separated and sent directly to the low residence time water section of the Smart Separator for treatment by the Deoiler Cyclone.

For the study’s process conditions, the Dewaterer operated at say an oil separation pressure of 500 psig, which equates to approximately 34 large sized Dewaterer liners which would be housed in a nominal 30 inch vessel.

7.13.5 Smart Separator

The process may require the residence time provided by a gravity based separator as part of the Subsea Separation System. The basis of design for such separators are built around field proven correlations based on Stokes Law, and published mechanistic principles to generate inlet momentum versus shear relationships (gas and liquid shear), gas carry under, liquid carryover, liquid-liquid separation, and equipment sizing.

The separator for the study is based on a very short residence time as it is assumed little to no separation of any of the phases is required. The study assumes that the flow conditions are steady state in nature and that no upset flow conditions exist or need to be addressed.

7.13.6 Deoiler Cyclone

Hydrocyclone based systems, are one of the most cost-effective solutions for tough produced water treatment clean up. Located directly downstream on the water outlet of the production separator and upstream of the water level control valve, these systems operate in a proportional "pressure ratio" control manner.

Deoiler hydrocyclones are pressure drop dependant. By accurately controlling the pressures across the hydrocyclone, the water phase is sent in one direction to the underflow, and the oil phase is sent in the opposite direction to the overflow. The process is a simple and effective separator, with a 2-3 second retention time, and no moving parts.

In the cases where water is present and needs to be processed, the Deoiler can clean the resultant produced water to less than 15 ppm. This is due to the very high temperature of the water at 250°F, a level not seen in typical topsides applications. The higher the water temperature the more efficient the separation will be.

For the study process conditions, the Deoiler would operate at say an oil separation pressure of 200 psig, which equates to approximately 90 small sized Deoiler liners which would be housed in a nominal 30 inch vessel.

7.13.7 Process Package

The resultant Process Package is shown in our attached PFD referenced above. The PFD and resultant information provides approximate equipment sizes based on the range of process. A simple material balance on the PFD for the oil, water, gas, and solid components is presented.

An optimization of this system would be the consolidation of the Dewaterer, Separator, and Deoiler vessels into a single integrated unit. This would have significant savings in the size and weight of the package.

7.13.8 Discussion of the eProcess PWT Process Train

This option provides a compact processing system and eProcess has developed the detail to a level to provide basic component size information. The process methods selected appear to have no moving parts and can be packaged for subsea operation within the pressure vessel limitation. No further attempt has been made to marinize the system but these have been extensively covered in the text above and need not be repeated here.

Their staff includes the principal oil & gas process engineer involved with the development of the multiphase turbine technology. This technology was developed through a joint-venture between Dresser-Rand and Kvaerner Process Systems, and included the two & three-phase turbine and

IRIS technologies. He spent extensive time in the field with Shell, Chevron, and Marathon to manage the field test programs for each of these devices.

The three-phase turbine (oil-water-gas) was tested at Marathon. It provided excellent separation under steady-state operations, but its drawbacks were in handling raw well fluids which inherently have dynamic gas, liquid, and solid flows and delivery pressure. The design is on hold but they feel that they have the path required to provide a solution.

Without having had the chance to review this design the initial reaction is concern at how reliable a subsea turbine driven centrifuge might be. But the industry is installing large powerful electric motors at the study's target depth and beyond. The design should be investigated further.

7.14 Schematic Field Layouts

7.14.1 Introduction

Three sketches of possible field layouts have been made. These are at a high level, without significant infrastructure. The purpose is to present where the main components of the process train could be laid out and then to discuss when and how they might be installed.

The Project Design Basis considers a field approaching the end of its productive life with a high water cut. However, the flowline would have been sized for its earlier oil production rates and not just the 20% that the oil and gas flow has dropped to. The oil flow rate will be low and may present a problem if the sand and solids are returned to this line to be carried by the oil the 50 miles to the surface.

7.14.2 Hardware

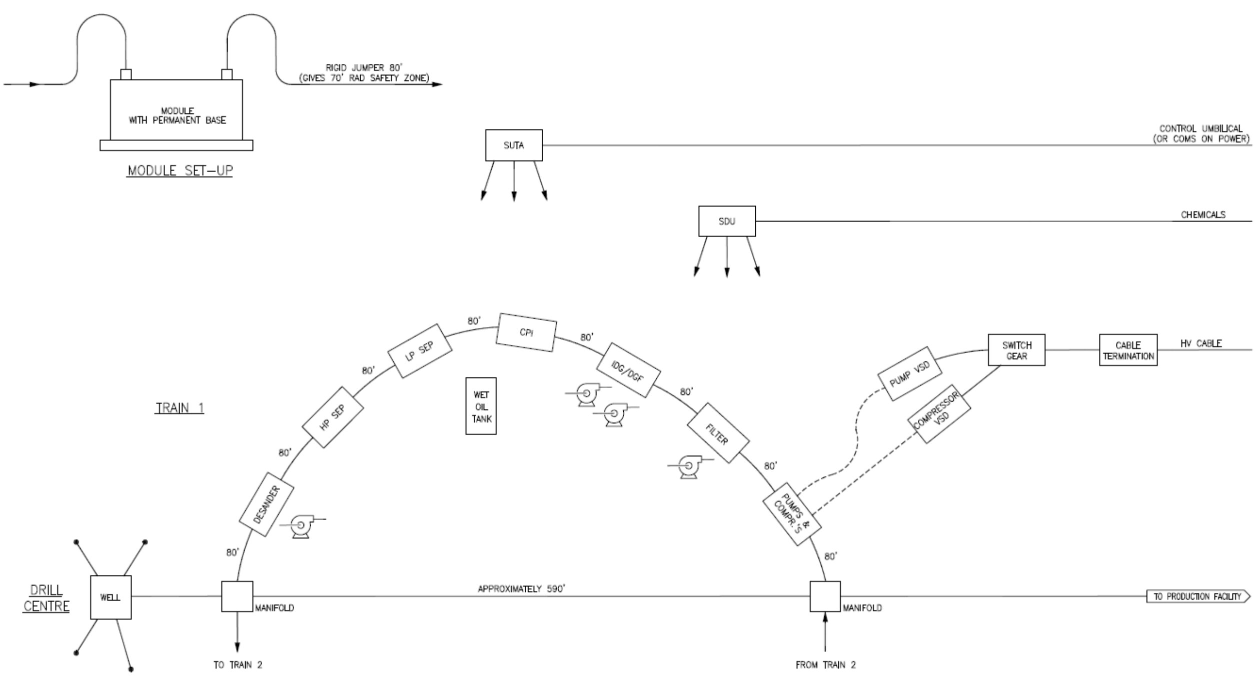


Figure 11: Ref. Drawing Number: SK-SEABED -1

When the wells have been drilled and the drill center manifold installed, the flowline could be laid with one or two in-line manifolds to allow future process train assemblies to be plugged in. Seabed foundations and receptacles for these assemblies could be installed at the same time as these manifolds or later when the process needs are better defined and the latest and most suitable techniques can be selected. The flow path from the drill center will remain piggable.

7.14.3 Pumps & Power

If the wellhead flowing pressure is low it may be necessary at this early stage to install pumps to boost the flow for the 50 mile tie-back and 8,000 ft rise to the surface facility. High capacity pumps are already being installed in the Gulf for this task so this is not a technology gap but a source to be employed when designing and installing similar equipment at a later stage for within the process train. However, currently while the pumps are on the seabed the Variable Speed Drives (VSD) control modules and switch gear are at the other end of the 50 mile cable on the surface. The process system will have many motors that have to be individually controlled. Electrical power distribution and individual VSD modules will have to be local.

The booster pump will have been specified for the fluid flow quality and quantity from a more productive time in the field life. The pump may change from single to multi phase or separation could be introduced to allow separate liquid and gas boosting to be followed by co-mingling into the single flowline.

7.14.3.1 Location of Desander & Separator

A separator module would be plugged into the first manifold or between the drill center and first flowline manifold.

If the wells start producing sand it is prudent to remove it before fluid separation and pumping to avoid clogging and damaging the system. The intent is to reinsert the sand downstream of the pumps and compressors at the co-mingling stage.

7.14.3.2 Daisy Chain Modules & Controls

When the water cut reaches the level that water needs to be discharged at the seabed the appropriate process modules would be installed as a daisy chain. This approach allows considerable future flexibility to adjust for fluid needs and accept future technology. A second process train could be installed on the other side of the flowline to provide 100 % redundancy maintenance down time.

The controls, chemicals and additional electrical power could be integrated with other field needs or stand alone. The number of fluid lines and control functions will probably require that they are stand alone and that a second set would be required for the second process train.

Control Fluid and chemicals in a 50 mile umbilical will have their own issues outside of the study's scope but it will probably lead to a Subsea Distribution Unit (SDU). These will need metering, manifolds, controls, pumps, storage tanks and power.

7.14.3.3 Process Modules

Ideally the modules could be landed on dumb iron seabed platforms with a mat or pile foundation as seabed conditions require. Most of the modules will have thick walled pressure vessels that, depending on the selected technology, from now or the future could be 3 ft in diameter, 60 ft long and in batches. Some of the vessels will be horizontal and some vertical. Installation and maintenance considerations for size and weight might lead to the larger vessels being installed individually with appropriate isolation valves, connectors and lock down mechanisms. The vessels may be gas filled at some stages of handling / service and some like the water storage tanks may become buoyant enough to rise if not locked down.

The Daisy Chain's semi circular layout is to create a better space for flying lead paths and connections rather than a corridor like space between the train and the flowline. Note that the modules may in reality be several units assembled on the seabed in series or parallel configuration for reasons of weight, size, access, function. The intent here is to present the drivers that lead to this configuration.

Rigid jumpers and flying lead technology would then interconnect the modules with controls, chemicals and power. The rigid jumpers are shown to be 80 ft spans. This is with concern to provide safety zones around each module for dropped objects. At 8,000 ft the installation will be guidelineless and guide funnel type technology will be used. When the modules are recovered it is difficult to ensure a simple vertical lift. Even if the surface lift vessel is on station subsea currents can drag the module in any direction. As a pendulum mass on a long cable it can swing long distances over the seabed at a shallow angle. Heavy BOPs have been known the travel 120 ft across the seabed. Some of the process train cylinders could stand over 70 ft high. A tether system may be needed to avoid this hazard.

7.14.3.4 ROV Assistance

With the complexity of any subsea processing and the need for high levels of reliability monitoring, maintenance and intervention must be planned for in the design. The preference would be to perform the majority of this in situ by ROV or with ROV assistance. The modules should be open structures with ROV access on all sides and equipped with ROV docking and Interface points. The Daisy Chain train configuration provides the best module access.

It is a good principle to be able to recover to surface as much of the installation as possible. It can also help if complex tasks are relocated to the ROV rather than installing all the automated function on the modules. The ROV can be recovered to the surface for repair or reconfiguration perhaps with different skid packages. The ROV could plug its umbilical into the subsea system and detach from its launch vessel. It could stay working or be available onsite 24/7.

7.14.3.5 Simplified Process Train

Ref. Drawing Number: SK-SEABED -2

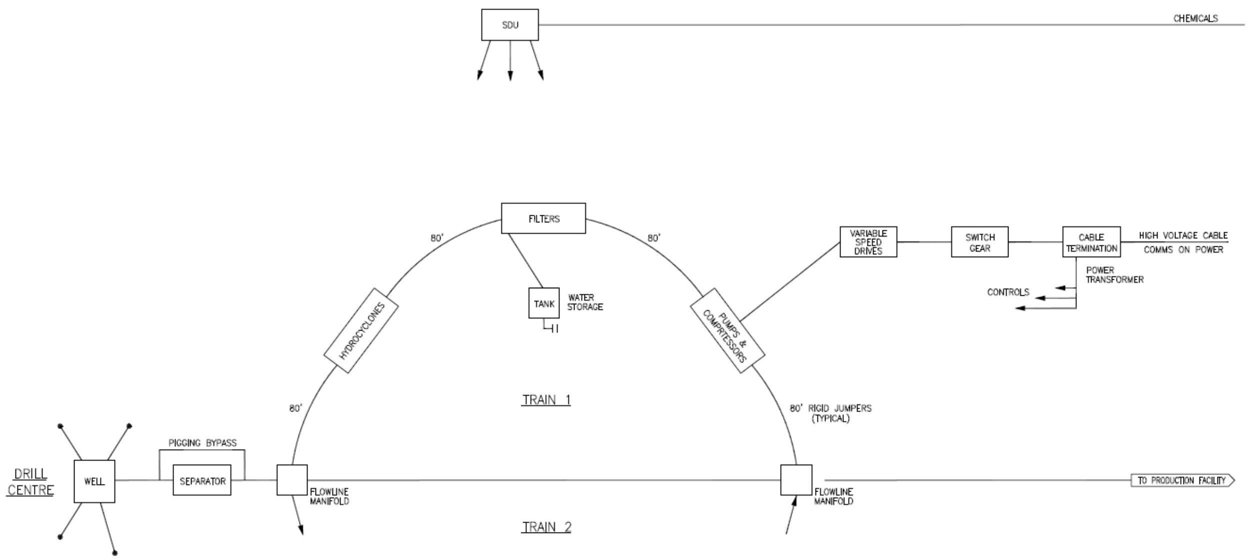


Figure 12: Ref. Drawing Number: SK-SEABED -2

The first drawing showed many modules for a first pass at a marinized process train. It makes the point that there is little limitation of layout space on the seabed. But some shown will be difficult to insert into thick walled pressure vessels. Others like the CPI may need too much maintenance to be remote installation friendly. Also from their filtering performance ranges is considerable duplication.

The second drawing, referred to above has moved the desander as close as possible to the wellhead and inserted the separator in the flowline. This makes them common to both trains and probably in service before the water cut has risen to a level needing extraction from the flowpath. The storage tank to hold the start-up water & methanol has also been moved closer to the drill center to keep the chemicals away from the process train. These three modules are not considered part of the study scope.

The number of modules in the daisy chain has been reduced. Multiple stages can be compacted into single modules. This would reduce the number of connections and isolation valves and therefore leak points, but caution has to be exercised on having the ability to handle up-sets and slugs.

7.14.4 Plug – In Modules

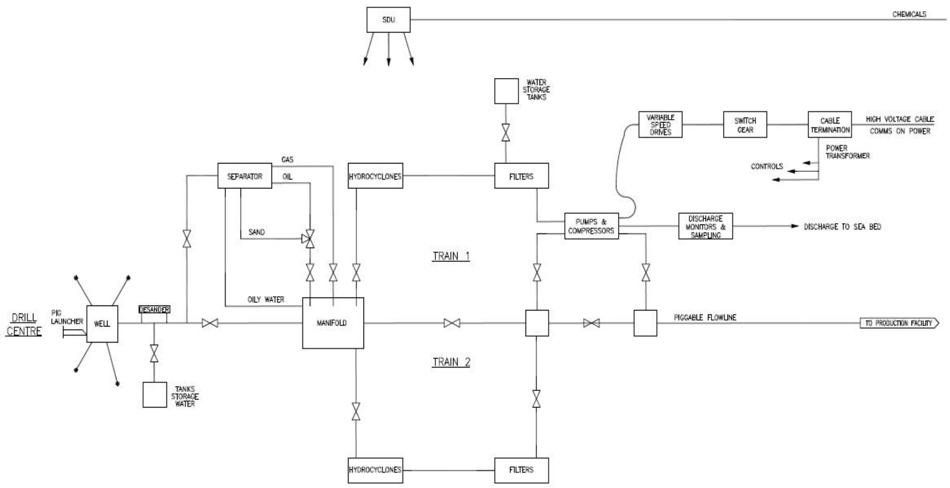


Figure 13: Ref. Drawing Number: SK-SEABED -3

This drawing presents how the installation can be plug & play. Forward planning at the installation design stage can allow the introduction of modules tailored to the needs of the production fluid. Valves indicate how the flow can be shunted through the separator module and back to the flowline. The same could happen with the pump & compressor module or the flow could be routed from the separator through the water treatment train and straight into the pump module.

8.0 TECHNOLOGY GAPS IDENTIFIED

The following potential gaps have been identified. To help set a basic understanding of what a technology gap is, the following definition should be kept in mind when reviewing this section. A technology gap is to be considered an area of attention needing further development where the technology does not exist or is not promoted, or is not seen as a reliable commercial application.

Some gaps have been created because the technology has not been developed or adapted to this application. An example would be comprehensive, on-site fluid monitoring. Other gaps show that the technology to solve them does not currently exist. Theoretical solutions will have to be subjected to the careful R&D process and field trials before they can reliably fill some of the gaps identified below.

System Component or Technology Need	**Gap Description and Details**	**Status**
Inline Desanders	The implementation and reliability of inline de-sanders and their handling of sand accumulation and removal of sand in the ultra deep water subsea processing system has not been done. They are used topside and limited subsea to 2881 ft of water on the Marlim project for Petrobras.	Tordis qualified technology in 2005 at 689 ft of water depth. 3 additional commercial projects plan to use the technology from projects commenced in 2009. Section 6.8.3 of this report gives an overview of this technology. Section 6.6.8 discusses the technologies use in the Marlim project that has just been commissioned in 2012.
Solids Filter	The implementation and reliability of a solids filter in the ultra deep water subsea processing system. They are used topside but not subsea. With all types of solids filters, there is a need to make them back washable and clog free. A subsea seawater injection filter with back washing capabilities has been produced in a Pilot with Shell, but needs proving for oily solids.	Table 5 of Section 6.0 in this report details issues with the media filters used for solid filtering. The subsea back washable filter for seawater injection needs to be proven and commercialized for PW use.

System Component or Technology Need	Gap Description and Details	Status
Coalescing Oil Filter	The implementation and reliability of coalescing oil filters and their use in the ultra deep water subsea processing system. Containment for coalescing filter use has not been widely tested and methods for intervention and replacement do not exist subsea.	They are used on topsides primarily, and have been used for temporary clean ups and short flow backs and clean ups in the Gulf of Mexico. Subsea use needs a full scale development plan. Section 6.3.2 in this report discusses this technology further.
Solids Handling and Storage	The implementation and reliability of solids handling with sand accumulation and removal of sand in the ultra deep water subsea processing system.	At 689 ft of water, Tordis qualified the sand accumulator in 2005 but had challenges removing the sand. Even though the Subsea projects of Pazflor, Marlim and Tordis worked with handling solids and storage, consistency has not been established. Section 6.8.1 – 6.8.3 discuss the issues with solids handling and storage.
Ceramic Membrane Filters	The implementation and reliability of ceramic membrane filters and their use in the ultra deep water subsea processing system. This technology will be used for final water polishing in the subsea system.	Section 6.3.5 of this report details ceramic membranes and their benefits. The technology is used only on topsides and not subsea.
Filter Maintenance	Filters need reliable, well designed housings to allow maintenance and access to filters for replacement if needed and provide flushing and pressure monitoring for change outs once a filter is past its useable back washable status.	Filter maintenance is commonly done, frequently offshore on topside facilities. No filter maintenance has ever been performed subsea.
Liquid/Liquid Subsea Hydrocyclones	Current subsea hydrocyclones are only being used to handle solids and are not being used for oil in water separation. They are used topside but not subsea.	Primarily used offshore on topside facilities, development and testing for subsea needs attention.
Fast Acting Valves	Large and small valves used subsea in the produced water treatment system will require fast acting open and close capabilities able to operate many times a day for many years.	Fast acting valves are required in each of the Conceptual Designs, but they do not yet exist for subsea.

System Component or Technology Need	**Gap Description and Details**	**Status**
Electrical Power Actuators	Electrically powered actuators for active control without control fluid management issues.	Electronic actuators for subsea use have been implemented, but needs further attention to improve reliability and performance.
Large Vessel Integrity	Collapse proof vessels will be required for ultra deep water operations and thus will require minimum diameters. Optimization of pressure vessel designs for UDW use for separation and storage need to be addressed. What is the limit to their size used? How can the needed technologies utilize smaller vessels?	Studies and design development work needs to be done for this technology need. The highlighted projects in section 6.5 should be reviewed to understand the latest subsea designs using large vessels. Section 7.2.3 addresses the vessels shapes commonly used today.
Compact Floatation Units (CFU)	This technology has been used topside but not subsea. Studies need to be done to test if the technology can work under pressure conditions in the Ultra Deep Waters.	Section 7.5 of this report discusses the use of this technology. Subsea development needs attention.
Subsea Produced Water Quality Sampling	Representative subsea produced water sampling, sample locations and reliable sampling systems for produced water quality determination, needs to be developed and made reliable. Subsea water quality sampling has not been performed subsea and does not have quality procedures approved for use by the regulatory agencies. An effort needs to be made with this technology development to prove effectiveness and concept design location points for sampling.	Subsea 7 and Framo have created a Subsea water sampling device that is deployed via a remotely operated vehicle. (ROV) Shell has recently designed a subsea sampling system, but no one has ultra deep water experience with subsea sampling of produced water.
Subsea Produced Water Quality Monitoring	Representative subsea water quality monitoring has not been performed and suitable measurement systems have not been developed. Quality procedures approved for use by the regulatory agencies has not been created. Various technologies may qualify for use, but a complete effort needs to be implemented and methods and standards need to be developed by the industry and by regulators.	Water Quality Monitoring is done topside offshore, but not subsea. Section 6.4.3 highlights to various water quality monitoring devices used in the industry today.
Subsea Sample Storage	Storage of subsea samples needs to be developed that includes integrity assurance to remain representative.	No subsea sample storage exists today and needs development.

The above gaps represent a major challenge the industry needs to focus on in order to implement the discharge of subsea treated produced water and the processing system to assure its effectiveness.

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9.0 COST SUMMARY AND COMPARISONS

9.1 Introduction

A cost analysis was performed on the conceptual designs that were chosen to be the most preferred options, Design B,C and D. Each design was estimated for the individual components to be used in the final subsea architecture. A material take off was performed on each of these designs and the items were sized and given an expected weight and design criteria to be used in the expected subsea cost. Keep in mind each design uses 2 trains, so components are doubled in many areas.

9.2 Component Costs

The following table shows the estimated item costs:

Subsea Equipment Item	Suggested Size	Estimated Cost per Item
Well head Desander	.75 m x 1.5 m	$ 1,000,000
Subsea Hydrocyclone	6 m x 4m x 1.6 m	$ 3,000,000
Wet Oil Tank - start up	1 m x 7 m	$ 437,500
Compact Flotation Unit	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	$ 1,500,000
Coalescing Filter System	1 - 1.5 m x 7m vessels with piping and valving	$ 250,000
Diffuser	5m x 20 m	$ 150,000
Isolation Valves	8" x 1 m x 2 m	$ 75,000
Control Valves	1 m x 2 m	$ 200,000
Chemical Injection Valve	.5m x .5 m	$ 150,000
Actuated Valves	1.5m x 1.0 m	$ 200,000
Double Block and Bleed Combo Valve	3 m x 2 m	$ 500,000
Connectors	8" subsea ROV type	$ 125,000
Subsea Control Modules	1 m x 2 m	$ 2,000,000
Booster Pump	1 m x 3 m	$ 500,000
Small Manifold	10 m x 10 m	$ 1,000,000
Multiphase Booster Pump	Subsea Twin Screw Standard pump	$2,500,000
Piggable Y	3 m x 7.5 m x 8"	$ 250,000
Retrievable Solids Filter	1 - 1.5 m x 3 m vessel with piping/valving	$ 200,000
Eductor	3 way 1m x 3m	$ 200,000
Flexible Jumpers	60 ft. x .3 m	$ 250,000
Water quality monitoring	1 m x 1 m	$1,000,000
Sample storage unit	3 m x 60 m	$ 750,000
Structural Steel framing supports and anodes	Estimate 25k per ton	$ 25,000

9.3 Material Take off for Conceptual Designs

The following tables highlight the total material required and used in the estimate for each of the relevant designs that have been assessed for costs. The items for Design B are:

Design B - Hydrocyclone/CFU/Filter (Cameron and CETCO)				
Equipment Type	**Size (meters)**	**Unit Wt. (tons)**	**Items Qty.**	**Total Wt. (tons)**
Well head Desander	.75 m x 1.5 m	5	2	10
Subsea Hydrocyclone 1	6 m x 4m x 1.6 m	20	2	40
Subsea Hydrocyclone 2	6 m x 4m x 1.6 m	20	2	40
Wet Oil Tank - start up	1 m x 7 m	20	1	20
Compact Flotation Unit 1	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 2	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 3	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 4	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Coalescing Filter System	1 - 1.5 m x 7m vessels with piping and valving	2	12	24
Diffuser	5m x 20 m	2	2	4
Isolation Valves	8" x 1 m x 2 m	0.25	100	25
Control Valves	1 m x 2 m	0.5	42	21
Chemical Injection Valve	.5m x .5 m	0.2	2	0.4
Actuated Valves	1.5m x 1.0 m	0.5	3	1.5
Double Block and Bleed Valve	3 m x 2 m	1	3	3
Connectors		0.2	124	24.8
Subsea Control Modules	1 m x 2 m	0.5	10	5
Booster Pump	1 m x 3 m	1.5	2	3
Small Manifold	10 m x 10 m	30	4	120
Multiphase Booster Pump		2	2	4
Piggable Y	3 m x 7.5 m x 8"	8	1	8
Retrievable Solids Filter	1 - 1.5 m x 3 m vessel with piping/valving	1	6	6
Eductor	3 way 1m x 3m	1	2	2
Flexible Jumpers	60 ft. x .3 m	2.5	40	100
Water quality monitoring	1 m x 1 m	0.25	2	0.5
Sample storage unit	3 m x 60 m	30	2	60
Structural Steel framing, supports and anodes	Estimate 25k per ton			
Estimated 33 days for installation	11 skids, 3 days for each skid with jumper connections			
	Total Weight of system	602.2 tons		

The items for Design C are:

Design C - Hydrocyclone/Filter (CETCO)				
Equipment Type	**Size (meters)**	**Unit Wt. (tons)**	**Items Qty.**	**Total Wt. (tons)**
Well head Desander	.75 m x 1.5 m	5	2	10
Subsea Hydrocyclone 1	6 m x 4m x 1.6 m	20	2	40
Subsea Hydrocyclone 2	6 m x 4m x 1.6 m	20	2	40
Wet Oil Tank - start up	1 m x 7 m	20	1	20
Coalescing Filter System	1 - 1.5 m x 7m vessels with piping and valving,	2	12	24
Diffuser	5m x 20 m	2	2	4
Isolation Valves	8" x 1 m x 2 m	0.25	60	15
Control Valves	1 m x 2 m	0.5	18	9
Chemical Injection Valve	.5m x .5 m	0.2	2	0.4
Actuated Valves	1.5m x 1.0 m	0.5	3	1.5
Double Block and Bleed Combo Valve	3 m x 2 m	1	3	3
Connectors		0.2	100	20
Subsea Control Modules	1 m x 2 m	0.5	8	4
Booster Pump	1 m x 3 m	1.5	2	3
Small Manifold	10 m x 10 m	30	4	120
Multiphase Booster Pump		2	2	4
Piggable Y	3 m x 7.5 m x 8"	8	1	8
Retrievable Solids Filter	1 - 1.5 m x 3 m vessel with piping/valving	1	6	6
Eductor	3 way 1m x 3m	1	2	2
Flexible Jumpers	60 ft. x .3 m	2.5	36	90
Water quality monitoring	1 m x 1 m	0.25	2	0.5
Sample storage unit	3 m x 60 m	30	2	60
Structural Steel framing and supports and anodes	Estimate 25k per ton			
Estimated 27 days for installation	9 skids, 3 days for each skid with jumper connections			
	Total Weight of system		484.4 tons	

The items for Design D are:

Design D - CFU Cameron				
Equipment Type	**Size (meters)**	**Unit Wt. (tons)**	**Items Qty.**	**Total Wt. (tons)**
Well head Desander	.75 m x 1.5 m	5	2	10
Wet Oil Tank - start up	1 m x 7 m	20	1	20
Compact Flotation Unit 1	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 2	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 3	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Compact Flotation Unit 4	5.2 m x 4 m x 5.2 m skid, vessel 1.5 m x 1.5 x 5.2 m	10	2	20
Diffuser	5m x 20 m	2	2	4
Isolation Valves	8" x 1 m x 2 m	0.25	84	21
Control Valves	1 m x 2 m	0.5	26	13
Chemical Injection Valve	.5m x .5 m	0.2	0	0
Actuated Valves	1.5m x 1.0 m	0.5	3	1.5
Double Block and Bleed Combo Valve	3 m x 2 m	1	3	3
Connectors		0.2	86	17.2
Subsea Control Modules	1 m x 2 m	0.5	6	3
Booster Pump	1 m x 3 m	1.5	2	3
Small Manifold	10 m x 10 m	30	4	120
Multiphase Booster Pump		2	2	4
Piggable Y	3 m x 7.5 m x 8"	8	1	8
Eductor	3 way 1m x 3m	1	2	2
Flexible Jumpers	60 ft. x .3 m	2.5	32	80
Water quality monitoring	1 m x 1 m	0.25	2	0.5
Sample storage unit	3 m x 60 m	30	2	60
Structural Steel framing and supports and anodes	Estimate 25k per ton			
Estimated 21 days for installation	7 skids, 3 days for each skid with jumper connections			
	Total Weight of system		450.2 tons	

An important note to make here is that each of the designs use a dual train to handle upsets. So in performing the material takeoff, many of the components where doubled to accommodate this need.

9.4 Design Option Cost Summary and Results

Once the estimated costs were made, an installation cost was determined by estimating the duration of time expected for each component to be installed by a typical day rate for an Ultra Deep Water Intervention Vessel. Using this method, each Design option is shown with an expected system cost and installation cost, along with the estimated installation duration and the estimated weight of the design. The table below shows the results of this cost analysis.

Design Option	Estimated System Cost	Estimated Days Duration of Installation	Estimated Installation Cost	Total Estimated Weight (tons)	Total Estimated Cost
Design B	$123,942,500	33	$43,522,500	602	$167,465,000
Design C	$93,197,500	27	$39,727,500	484	$132,925,000
Design D	$84,492,500	21	$35,932,500	450	$120,425,000

The study estimated a 30 day Site Integration Test for the entire system spread onshore at the fabrication yard. The mobilization and demobilization of 20 days was used for each design. And a 15% engineering supervision and management charge was added to each design as well. Each design cost does include the use of dual trains.

10.0 TECHNOLOGY ROADMAP FOR ULTRA DEEP WATER SEABED DISCHARGE OF PRODUCED WATER AND/OR SOLIDS

10.1 Introduction

The purpose of this section is to present the Roadmap for the Technology development needed to bring the Seabed Discharge of Produced Water and/or Solids in the Ultra Deep Water to commercialization. A schedule of the gaps identified in the previous section has been developed for this Roadmap. The current Technology Readiness Level was assessed for each technology gap. The effort required to bring the technology to the needed milestones, advancing the readiness level to the final stage of TRL 7, was then assessed. A schedule was developed based on this information to represent the Technology Roadmap.

Some technologies have a history of being stalled or derailed for one reason or the other and this roadmap assumes an aggressive, well funded development plan is adopted for each technology to proceed to the needed TRL 7 status. In many cases, an estimated 18 month duration was given to achieve a milestone. This is taken from experience where a test may be done for 12 months followed by a reporting period with the next 6 months to finalize the results and status of the test, allowing ample time for all required inputs and reviews. For rapid development needs, an emphasis can be made on the technologies roadmap to TRL 5 where they can meet requirement for full scale production tests in the environment conditions for a full scale production system.

Following the schedule of the Roadmap is a discussion section to help explain and clarify the decisions made in mapping the technology development. A copy of the Technology Roadmap for the Discharge of Produced Water and/or Solids at the Seabed can be found below and in Appendix XX.

10.2 Technology Readiness Level Definitions

(Ref API 17N for this table)

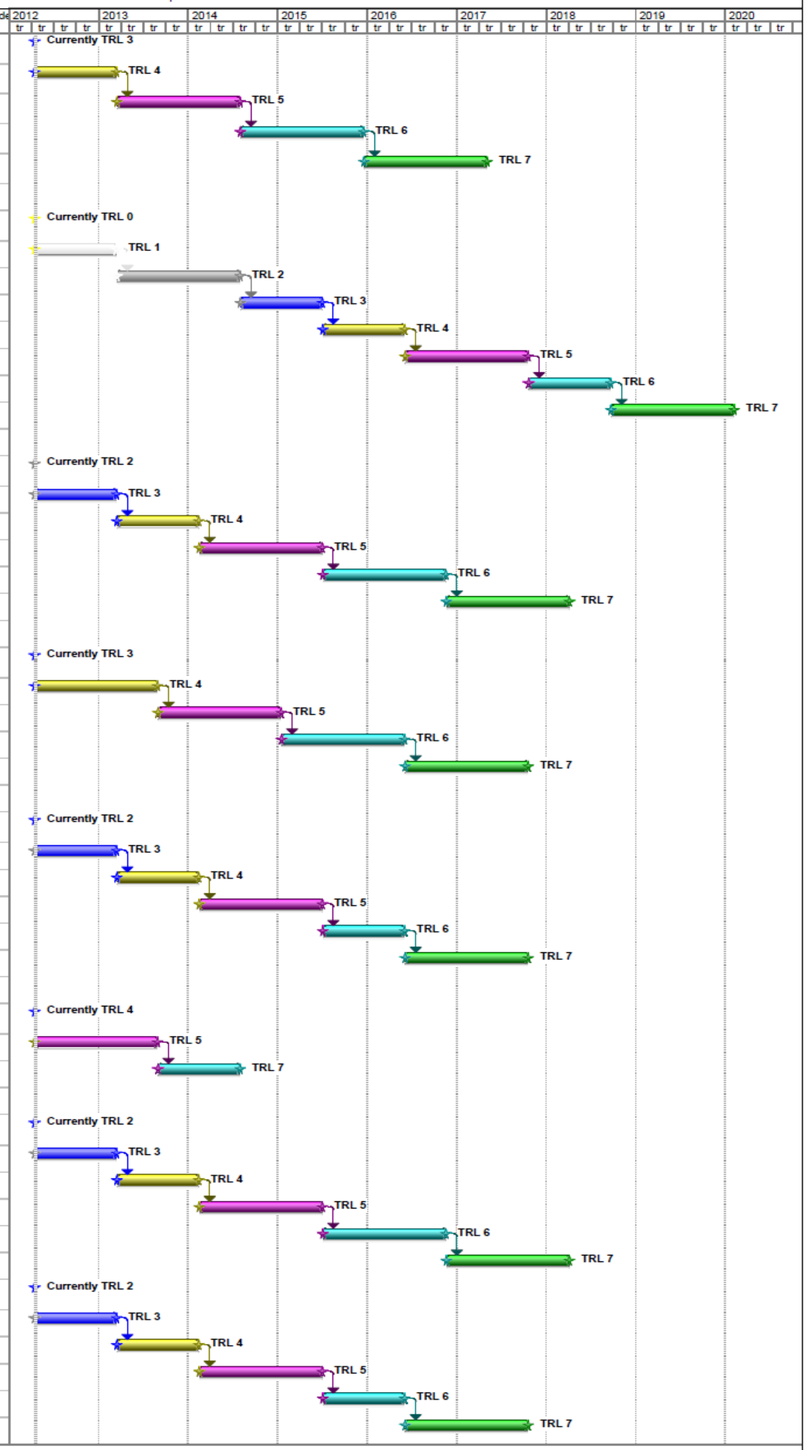
Technology Readiness Level	Milestone Stage Requirement	Idea for Concept	Physical Model Built	Prototype Built	Full Scale Prototype Production	Production Unit
TRL 0	Idea	0				
TRL 1	Proven concept	1				
TRL 2	Validated Concept		2			
TRL 3	Function/Performance Tested			3		
TRL 4	Environment Tested				4	4
TRL 5	System Tested				5	5
TRL 6	System Installed				6	6
TRL 7	Field Proven					7

This table was derived from the standard reference API 17N.

10.3 Technology Roadmap Schedule

RPSEA 09121-3101-01 Roadmap Schedule

ID	Task Name	Duration	Predecessors
1	**Inline Desanders**	1 day	
2	Full Scale Prototype Production	12 mons	
3	Production Unit System Tested	18 mons	2
4	Production System Installed	18 mons	3
5	Production Field Proven	18 mons	4
6			
7	**Solids Filter**	1 day	
8	Proven Concept	12 mons	
9	Validated Concept w/Physical Model	18 mons	8
10	Function Test Prototype	12 mons	9
11	Full Scale Prototype Production	12 mons	10
12	Production Unit System Tested	18 mons	11
13	Production System Installed	12 mons	12
14	Production Field Proven	18 mons	13
15			
16	**Coalescing Filter**	1 day	
17	Function Test Prototype	12 mons	
18	Full Scale Prototype Production	12 mons	17
19	Production Unit System Tested	18 mons	18
20	Production System Installed	18 mons	19
21	Production Field Proven	18 mons	20
22			
23	**Solids Handling and Storage**	1 day	
24	Full Scale Prototype Production	18 mons	
25	Production Unit System Tested	18 mons	24
26	Production System Installed	18 mons	25
27	Production Field Proven	18 mons	26
28			
29	**Ceramic Membrane Filters**	1 day	
30	Function Test Prototype	12 mons	
31	Full Scale Prototype Production	12 mons	30
32	Production Unit System Tested	18 mons	31
33	Production System Installed	12 mons	32
34	Production Field Proven	18 mons	33
35			
36	**SS Intervene Filter Maintenance**	1 day	
37	Intervention System Tested	18 mons	
38	Intervention Performed & Proven	12 mons	37
39			
40	**Liq/Liq SS Hydrocyclone**	1 day	
41	Function Test Prototype	12 mons	
42	Full Scale Prototype Production	12 mons	41
43	Production Unit System Tested	18 mons	42
44	Production System Installed	18 mons	43
45	Production Field Proven	18 mons	44
46	**Fast Acting Valves**	1 day	
47	Function Test Prototype	12 mons	
48	Full Scale Prototype Production	12 mons	47
49	Production Unit System Tested	18 mons	48
50	Production System Installed	12 mons	49
51	Production Field Proven	18 mons	50



Project: Roadmap Schedule
Date: Tue 4/17/12

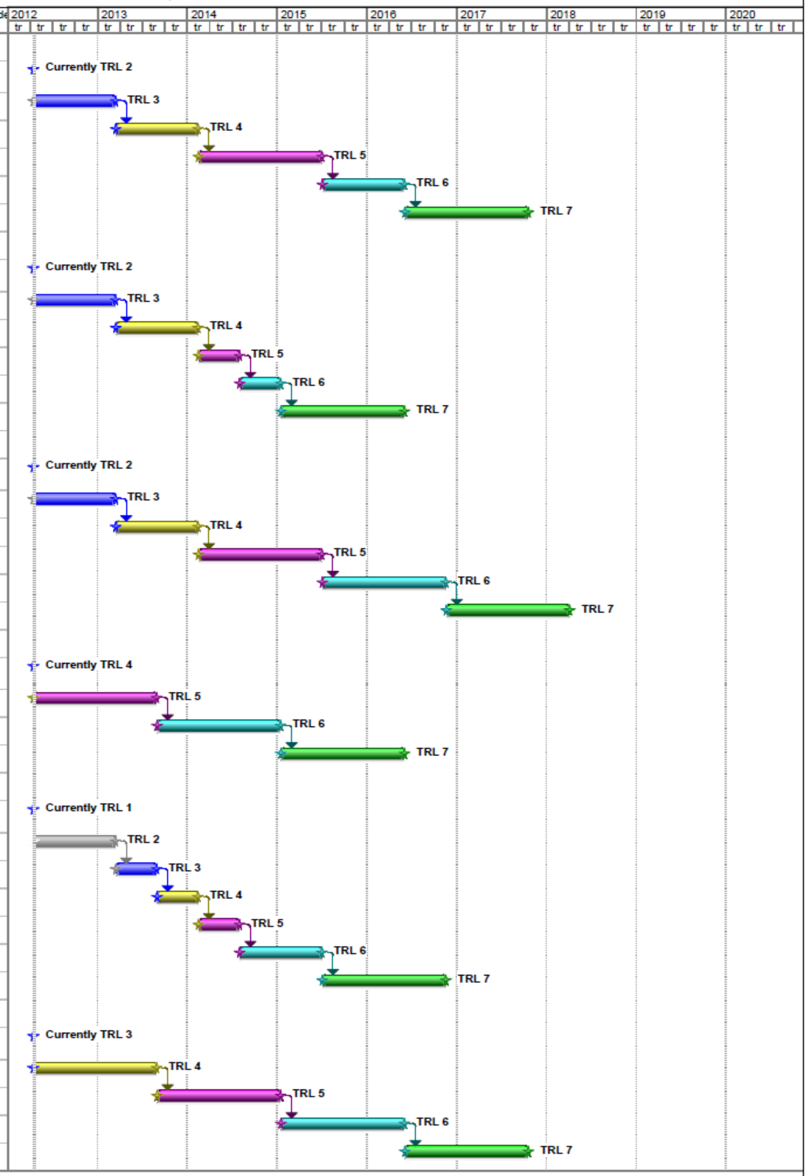
Task | Summary | Rolled Up Progress | Project Summary
Progress | Rolled Up Task | Split | Group By Summary
Milestone | Rolled Up Milestone | External Tasks | Deadline

Page 1

COST SUMMARY AND TECHNOLOGY ROADMAP

RPSEA 09121-3101-01 Roadmap Schedule

ID	Task Name	Duration	Predecessors
52			
53	**Electrical Power Actuators**	1 day	
54	Function Test Prototype	12 mons	
55	Full Scale Prototype Production	12 mons	54
56	Production Unit System Tested	18 mons	55
57	Production System Installed	12 mons	56
58	Production Field Proven	18 mons	57
59			
60	**Large Vessel Integrity**	1 day	
61	Function Test Prototype	12 mons	
62	Full Scale Prototype Production	12 mons	61
63	Production Unit System Tested	6 mons	62
64	Production System Installed	6 mons	63
65	Production Field Proven	18 mons	64
66			
67	**Compact Flotation Units**	1 day	
68	Function Test Prototype	12 mons	
69	Full Scale Prototype Production	12 mons	68
70	Production Unit System Tested	18 mons	69
71	Production System Installed	18 mons	70
72	Production Field Proven	18 mons	71
73			
74	**SS Produced Water Quality Sampling**	1 day	
75	Production Unit System Tested	18 mons	
76	Production System Installed	18 mons	75
77	Production Field Proven	18 mons	76
78			
79	**SS Produced Water Quality Monitoring**	1 day	
80	Validated Concept w/Physical Model	12 mons	
81	Function Test Prototype	6 mons	80
82	Full Scale Prototype Production	6 mons	81
83	Production Unit System Tested	6 mons	82
84	Production System Installed	12 mons	83
85	Production Field Proven	18 mons	84
86			
87	**Subsea Sample Storage**	1 day	
88	Full Scale Prototype Production	18 mons	
89	Production Unit System Tested	18 mons	88
90	Production System Installed	18 mons	89
91	Production Field Proven	18 mons	90



Project: Roadmap Schedule
Date: Tue 4/17/12

Task	Summary	Rolled Up Progress	Project Summary
Progress	Rolled Up Task	Split	Group By Summary
Milestone	Rolled Up Milestone	External Tasks	Deadline

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10.4 Roadmap considerations

In the evaluation process used for defining the technology roadmap, references were made to the original study basis of design conditions with the target depth, flow rates and hydrostatic pressures, as well as other relevant information that can be found in the basis of design for this study.
The following considerations were given to the technologies in the order they appear in the schedule:

- **Inline Desanders**

  Tordis, Pazlor and Marlim have used Inline Desanders successfully and due to the ultra deep water requirements in our basis of design, a new production unit will need to be tested for these conditions and thus the technology has been given a TRL 3 current status.

- **Solids Filter**

  The final polishing stage starts with a solids filter to protect the filter cartridges in the retrievable filter canisters. No proven concepts have been designed as of today. Temporary filters have been designed, but this type of filter should be considered a new concept. For this study, not all conceptual designs require the use of a solids filter. This consideration should be made when selecting concepts based on a required project timeline from an operator. This studies design B and C use the solids filter. The technology has been given a current TRL of 0.

- **Coalescing Filter**

  CETCO, the company who manufactures the type of filter cartridges that could be used in the polishing stage as a coalescing filter, advise that the cartridges are not sensitive to being crushed by the pressure levels but just need a pressure differential to flow. The water pressure will eventually have to exceed 3,500 psi to overcome ambient sea pressure and flow to sea, but the treated produced water can be stored and boosted to exit the diffuser. The temporary coalescing filter technology from CETCO called NEMOH helps establish a TRL 2 as a validated concept and the next stage is to build and test a prototype for long term use in the ultra deep water conditions.

- **Solids Handling and Storage**

  Tordis, Pazlor and Marlim have used solids handling technology and have implemented storage of solids which helps the TRL to Stage 3. To get to TRL 4, a full scale unit will need to be tested in the ultra deep water conditions in this studies basis of design.

- **Ceramic Membrane Filters**

  Ceramic filters are being implemented on topside installations to prove the concept and meet a TRL 2. For subsea, a prototype must be designed and tested successful to move to a TRL 3.

- **Subsea Intervene Filter Maintenance**

  Today, the Subsea Intervention services many different types of technologies subsea and thus intervening with the filter maintenance should be an easy transition. This puts the current TRL 4 and thus a specific filter maintenance operation needs to be designed and implemented to get to a TRL 5.

- **Liquid / Liquid Subsea Hydrocyclone**

  Marlim is using a subsea hydrocyclone, but for solids. The technology needs to be tested with a Liquid / Liquid interface. A current TRL 2 has been given, and a full scale prototype needs function testing to move to a TRL 3.

- **Fast Acting Valves**

  Operators are validating fast acting valves in 3000 meter water depths. Due to the limited information on this technology development, a TRL 2 has been given and the study acknowledges the readiness level may be higher.

- **Electrical Power Actuators**

  Operators are validating electrical power actuators in 3000 meter water depths, similar to the above fast acting valves. Due to the limited information on this technology development, a TRL 2 has been given and the study acknowledges the readiness level may be higher.

- **Large Vessel Integrity**

  Vessels can be large and fixed to concrete foundations with connections to the vessel bolted, screwed or welded. Tordis and Pazflor has used large vessels. Much testing will need to go into a large vessel design to meet the ultra deep water design criteria. The current status of TRL 2 has been given, and a full scale prototype will need to be function tested for the Ultra Deep Water conditions to move to a TRL 3.

- **Compact Flotation Units**

  The CFU is a proven concept and receives a TRL 2 and a full scale prototype needs to be function tested for the Ultra Deep Water conditions to move to a TRL 3.

- **Subsea Produced Water Quality Sampling**

  With the success of subsea sampling on Shell's BC-10 project, a TRL 4 has been given to this technology. A full scale production unit needs to be design and tested for the basis of design in this study to move to a TRL 5.

- **Subsea Produced Water Quality Monitoring**

  Proven concepts exist topside, but only models have been designed for subsea use to measure produced water quality. A current TRL 1 has been given for this technology and a validated conceptual design needs to be tested with a physical model to move to a TRL 2.

- **Subsea Sample Storage**

  The subsea sample storage has been given a TRL 3, as many different accumulators and chambers have been used at high pressure conditions for sample storage, both subsea and down hole. OceanWorks has recently developed a subsea chemical dispersant storage system for the well containment development work which should provide excellent support to this need. A full scale prototype needs to be design for the ultra deep water production conditions to move to a TRL 4.

10.5 Roadmap conclusion

The technology roadmap schedule can be reviewed to understand how the conceptual designs can be utilized for a fast development by the advancing of milestones through a TRL 5. The conceptual designs identified in the previous section having the needed technologies identified in this roadmap can be easily evaluate to help determine which concepts can be developed most rapidly.
The study concepts B, C and D have been chosen as the best designs to target development. If the roadmap is properly followed, the concepts could reach a TRL 5 milestone in the following years of development list below.

Concept	Description	Time to TRL 5
B	Hydrocyclone, Compact Flotation Unit, Coaleser Filters	Qtr 3 2017
C	Hydrocyclone, Coaleser Filters	Qtr 3 2017
D	Hydrocyclone, Compact Flotation Unit	Qtr 2 2015

Therefore, the conceptual Design "D" using a compact flotation unit, may be the best technology concept to target for the earliest development.

STUDY CONCLUSION

11.0 CONCLUSION

Current discharge of produced treated water is only done through topsides facilities. To establish a good benchmark, this study looked at the typical composition of the produced water from oil and gas wells. In addition, the study reviewed the state of the art technologies involved in treating the produced water. The study also reviewed regulations governing discharge throughout the world, with a primary focus on the requirements in the United States and the Gulf of Mexico.

The targeted environment is the Ultra Deep Waters of the Gulf of Mexico, and because of this, the study sought to understand the marine life at the seabed environment from 5000 to 8000 feet of water. Most of the seabed is comprised of a muddy bottom, but organisms of all types can be found in various areas throughout the Ultra Deep Waters. After performing this study, it is clear there is a need to better understand the deepwater marine life and how it will react to the discharge criteria that is defined in the basis of design for the study.

There are many topside treatment technologies available for removing dispersed and dissolved oil and reducing toxicity from produced water have been well identified and referenced. These technologies can be combined in many different ways to contribute to effect subsea processing concepts. Mechanical technologies for enhanced gravity, flotation and filtration using granular activated carbon, polymer filters and hybrid technologies like the Compact Flotation Units will help to make the following conceptual options successful and reliable.

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 tertiary systems which involve separator, CPI separator / hydrocyclones / skimmer, and Induced Gas Flotation. Filtration is sometimes 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 desanders 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.

STUDY CONCLUSION

- 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.

Treatment and discharging produced water to the ambient seawater from topside is standard practice in the industry and the technology is well proven. Today's topside technologies are meeting discharge criteria set forth by the toughest regulators around the world and studies show that the marine life is not adversely affected by these practices.

No known subsea production system has ever used any form of the typical produced water treatment technologies on topside offshore facilities, anywhere, throughout the world. A number of conceptual designs were developed, as discussed below.

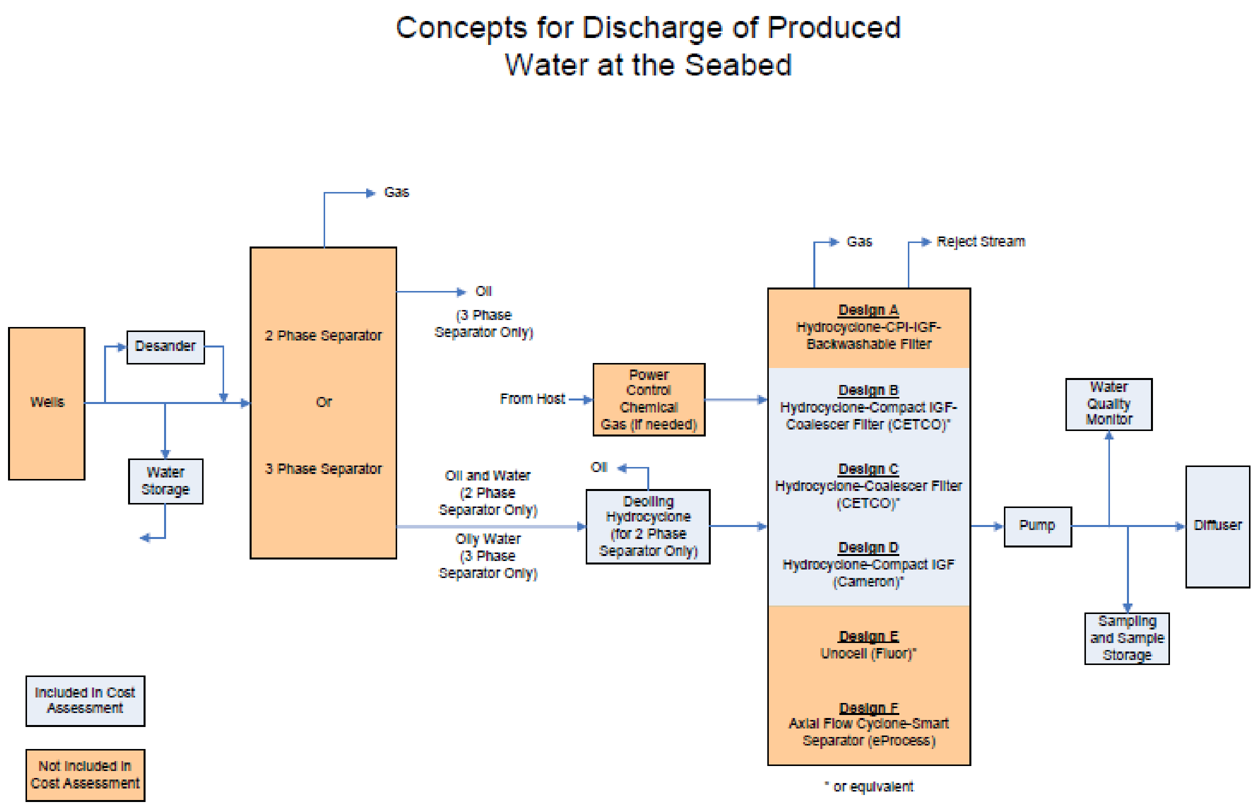


Figure 2: Block Diagram showing optional concepts for subsea produced water treatment system.

STUDY CONCLUSION

Design A is mostly a straightforward migration of topsides water treatment technology to subsea, as such is not considered a feasible design for subsea but is provided only as a reference point to start with. The key factor making this design not feasible is the corrugated plate interceptors for which we have not found compact versions suitable for subsea applications in 5000 – 8000 ft water depth.

We consider that Designs C, D and E are designs for which additional work on the technology gaps have the good potential of progressing the technology for these designs to project ready status in the next 3-5 years. Therefore these designs are selected for further assessment in the current study. While the key technologies for Designs E and F are also likely to progress to project ready status in the next 3-5 years, they are more focused on a single supplier/vendor proprietary technology than Designs C, D and E, and therefore not further assessed in the current study.

It is estimated that, with a continuous technology development program, the timing for the conceptual design to become project ready is

- Design B (hydrocyclones, Compact Flotation and Coalescing Filters): 2017
- Design C (hydrocyclones and Coalescing Filters): 2017
- Design D (Compact Flotation): 2015

System Component or Technology Need	Current Technology Readiness Level (TRL)	Estimated Time to TRL 5 (Project Ready)
Inline Desanders	TRL 3	Q3 2014
Solids Filter	TRL 0	Q4 2017
Coalescing Oil Filter	TRL 2	Q2 2015
Solids Handling and Storage	TRL 3	Q1 2015
Ceramic Membrane Filters	TRL 2	Q2 2015
Filter Maintenance	TRL 4	Q3 2014
Liquid/Liquid Subsea Hydrocyclones	TRL 2	Q2 2015
Fast Acting Valves	TRL 2	Q2 2015
Electrical Power Actuators	TRL 2	Q2 2015
Large Vessel Integrity	TRL 2	Q2 2014
Compact Floatation Units (CFU)	TRL 2	Q2 2015
Subsea Produced Water Quality Sampling	TRL 4	Q3 2014
Subsea Produced Water Quality Monitoring	TRL 1	Q3 2014
Subsea Sample Storage	TRL 3	Q1 2015

APPENDIX I – CETCO

PRODUCED WATER TREATMENT
COALESCING FILTERS
NEMOH

WATER TREATMENT

CETCO
OILFIELD
SERVICES
COMPANY

Water Treatment Applications

CETCO Oilfield Services provides water treatment services for all phases of oilfield production, from the well head to the refinery. Whether on a platform or in a tank farm, we can be found treating a variety of streams:

- **Heating/Cooling Medium Treatment**
- **Deck Drainage**
- **Drill Cuttings**
- **Brine Filtration and Recycling**
- **Methanol Filtration**
- **Produced Water Treatment and Polishing**
- **Workover Fluids and Coiled Tubing Jobs**
- **Initial Well Flow Backs/Completions**
- **Decommissioning Wastewaters**
- **Pipeline Maintenance**
- **Well Stimulations and Acid Flow Backs**

WATER TREATMENT

CrudeSorb® is packaged for quick media change outs – essential on temporary flow back applications or at remote locations.

Benefits of Using CETCO Water Treatment Services

- **Ensure overboard compliance**
- **Reduce waste by onsite treatment, cutting logistics and 3rd party processing**
- **Maximize production by isolating specific well work activities**
- **Ensure maximum asset return by treating online**
- **Avoid costly shut downs**

The CETCO Oilfield Services Process

CETCO Oilfield Services provides a unique and effective service to help customers manage unusual or temporary situations, such as off-spec discharges. Drawing on years of experience in water treatment, we have designed a rental fleet that meets a vast variety of flow rates, temperatures, and pressures. Our technical and service teams have extensive service and training and are often available at 24 hours notice. CETCO Oilfield Services Water Treatment Division specializes in the removal of hydrocarbons, solids, toxic materials, and other contaminants from oilfield wastewater streams produced during oil and gas operations, transportation, and storage.

CETCO's highly trained personnel optimize equipment and technologies to ensure our customers remain compliant with overboard water quality regulations while reducing waste disposal costs.

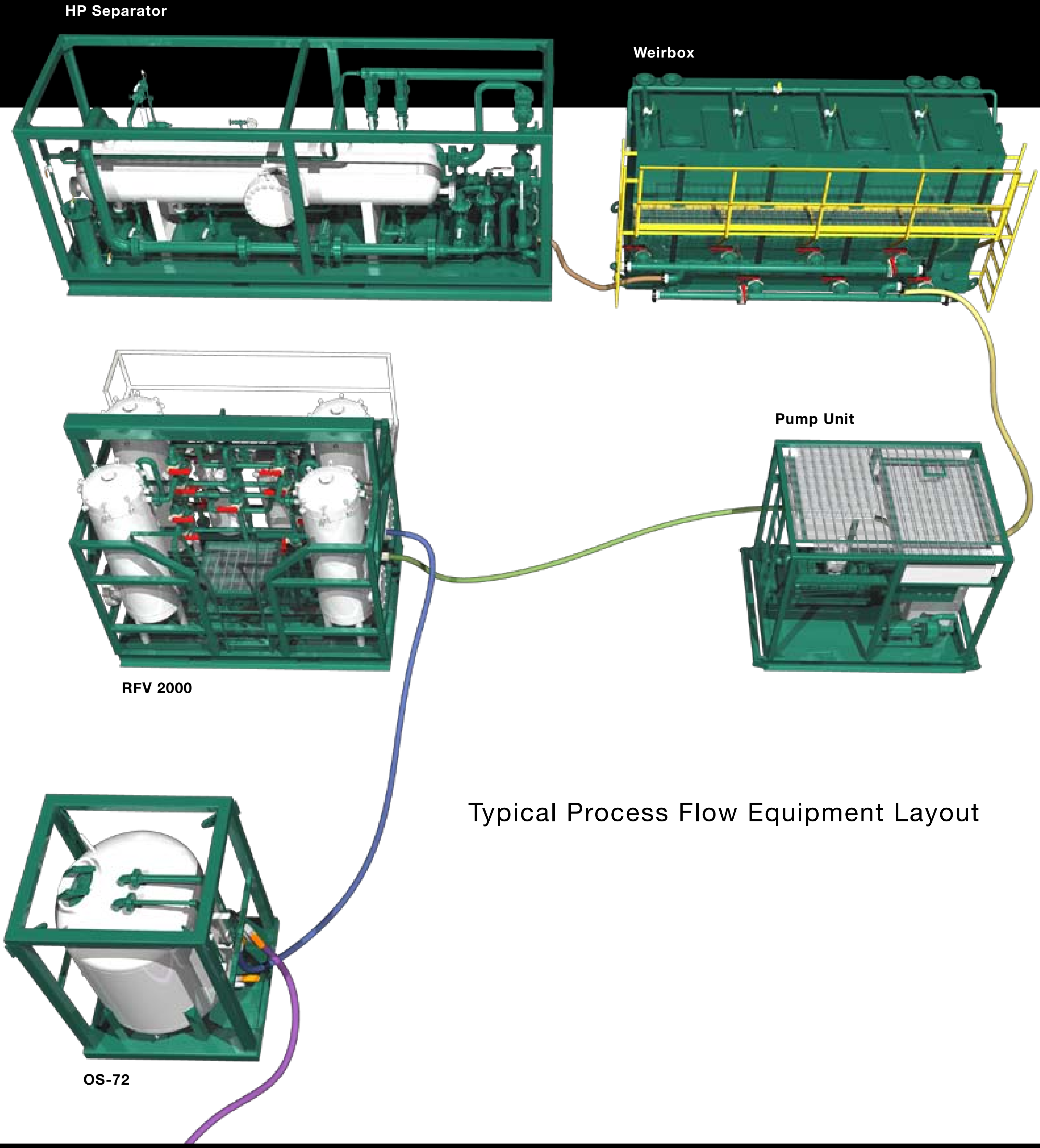
Patented Media Technology

CETCO Oilfield Services utilizes different technologies based on our customers' requirements. We utilize the appropriate technology design to remove oil, solids, and toxic materials from wastewater based streams.

CrudeSorb®

CrudeSorb is a proprietary adsorption media based on resin, polymer, and clay technology. It has been proven to be extremely efficient at removing oil, grease, and soluble organics from water.

CrudeSorb has been developed specifically for this purpose and is packaged in radial-flow, nonferrous canisters comprised of a cloth mesh and polycarbonate sealing caps at either end of the canister. Housing the CrudeSorb adsorption media in this way allows for quick media change outs – essential on temporary flow back applications or at remote locations.



Typical Process Flow Equipment Layout

CRUDESORB®

At each treatment stage our technology incrementally improves the water quality. This stepwise approach to processing provides assurances that the discharge specification is met or exceeded.

This conservative approach has also made CETCO Oilfield Services the most successful in online applications.

Stage 1

First, fluids enter the CETCO 120 barrel separation tank (weirbox) where fluids can be chemically treated for emulsions, gels can be broken, or toxic materials can be neutralized. Oil is recovered and solids are isolated.

Stage 2

Fluids are then pumped through sock filters to remove solids and coalesce additional oil.

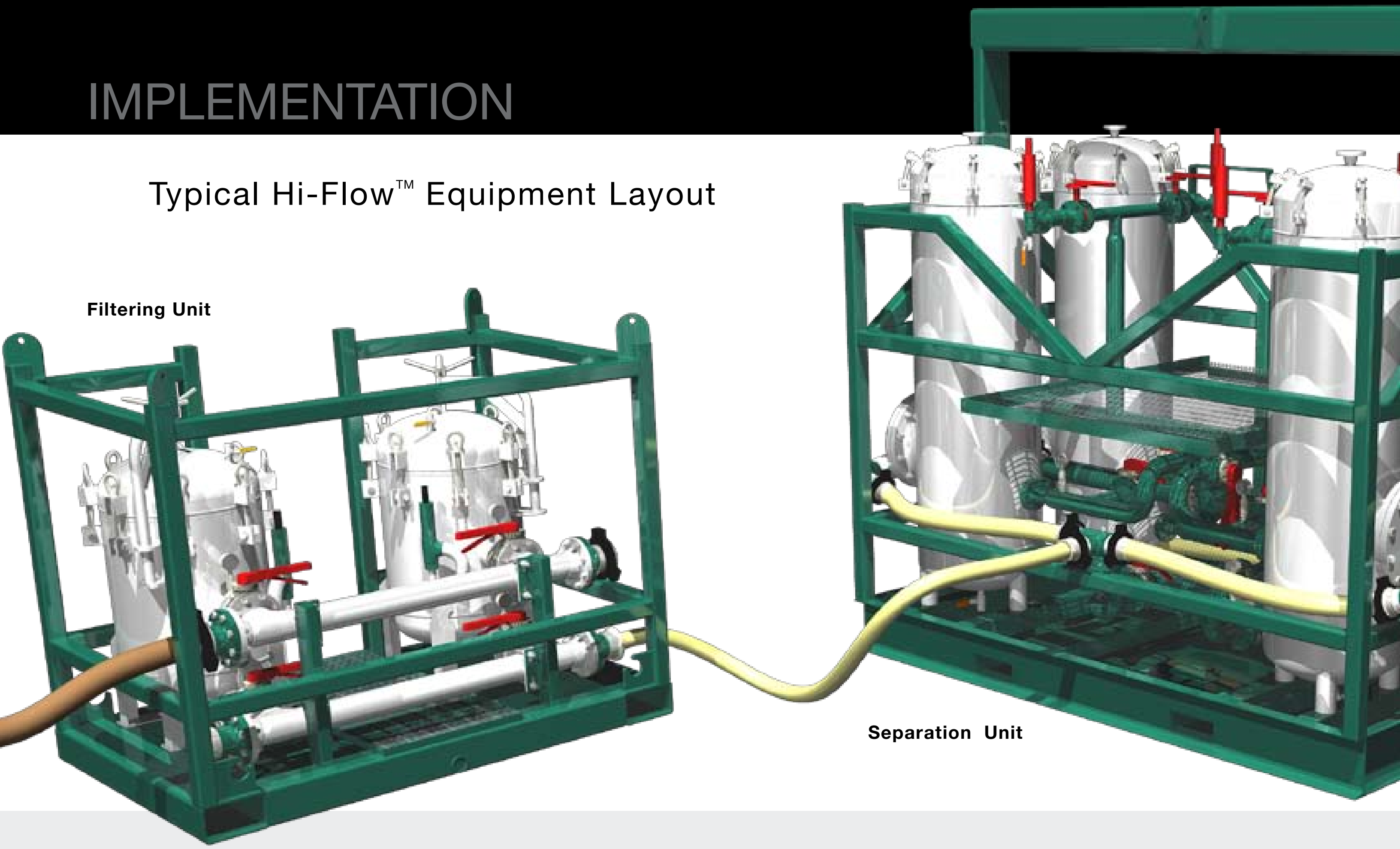
Stage 3

Water then flows through CETCO's patented CrudeSorb media in a specifically designed Radial Flow Vessel (RFV). Water flows through the canister fabric, media, and perforated core, and is routed downward through the stacked canister center cores through the CETCO patented vessel header. The fluids may be treated by a second vessel in series with additional CrudeSorb media, by a vessel with granulated activated carbon media, or routed overboard.

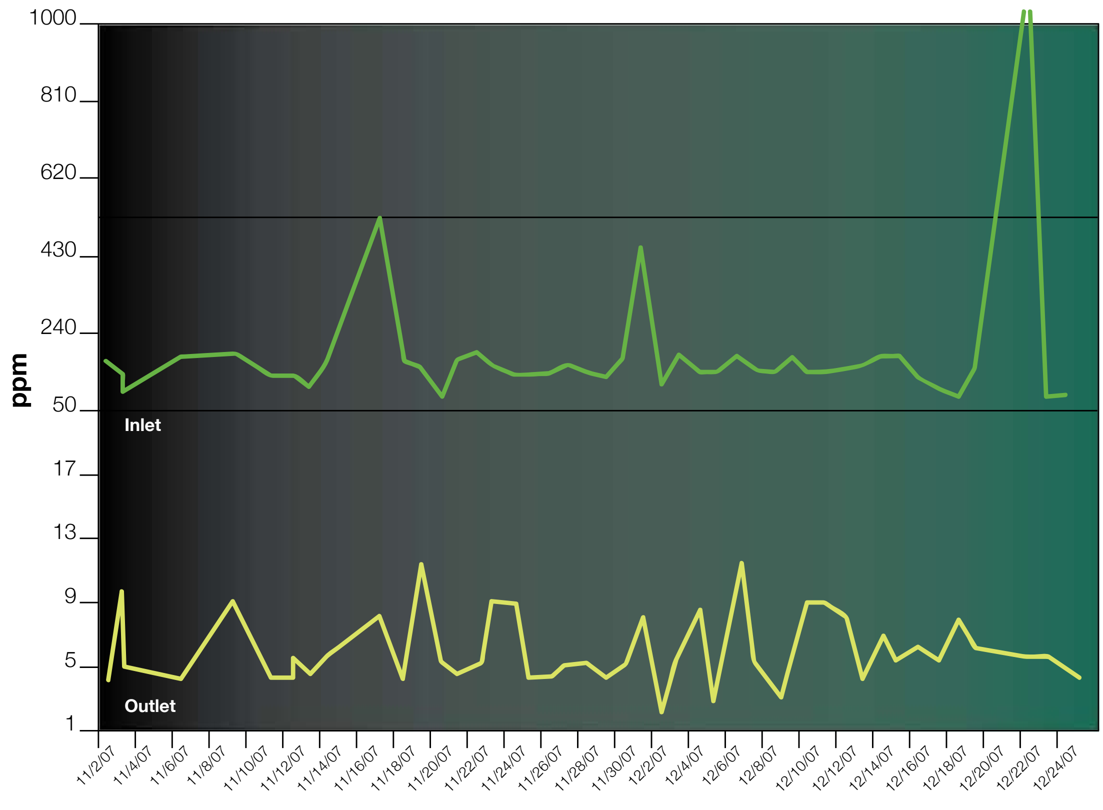
3 Stages of treatment

IMPLEMENTATION

Typical Hi-Flow™ Equipment Layout



Results from CETCO Oilfield Services Hi-Flow Process



FAST & SIMPLE

Hi-Flow Process Applications

- Permanent Produced Water Treatment and Polishing
- Diversion Skid
- System Upsets
- Increase Produced Water Handling Capacity

Hi-Flow Process Solutions

- Handles small to large volumes of liquid, from 1,000 BWPD to more than 40,000 BWPD
- Features a small footprint
- Performs well with large fluctuations in oil and grease inlets
- Ensures discharge compliance
- Allows flexibility – can be used on projects with short or long durations

Hi-Flow™ Process
CETCO Oilfield Services Hi-Flow Process can treat high rates of produced water, allowing the operator to return the produced water back into the environment in compliance with state and federal regulations. Our Hi-Flow Process gives you the flexibility you need in having one solution for many applications—the Hi-Flow process can handle small to large volumes of liquid, from 1,000 BWPD to more than 40,000 BWPD; it is not hindered by large fluctuations in oil and grease inlets; and it can be used on projects with short or long durations.

HI-FLOW™

CrudeSorb®MR Mercury Arsenic Removal Media
CrudeSorb MR is a new media material that can be packed in the canister similar to the CrudeSorb media. This new media is still based on organoclay technology but it has been heavily modified to enhance mercury and arsenic adsorption through both physical removal and chemical bonding. CrudeSorbMR is effective on all sources of mercury including the organic type of mercury, mercury element (zero valent), and mercury ions (both I and II valent). Additionally, CrudeSorbMR can also be as effective as the traditional CrudeSorb media to remove oil, grease, and other organic contaminant molecules when needed.

CRUDESORB®MR

CrudeSep®AF Produced Water Treatment System for high-efficiency removal of oil, gas, and solids

CrudeSep®AF Produced Water Treatment
CrudeSep AF is an unparalleled technology which separates oil, water, gas, and solids at variable flow ranges. Based on application of fluid dynamics, the CrudeSepAF is a novel technology which eliminates the dependency on gravitational separation prolific in traditional methods.

The inlet and outlet are located at the bottom of the vessel. The whole body of water is directed in a controlled vertical flow pattern towards a primary interface where droplets break out and accumulate. The return flow interacts with a series of specially engineered interfaces which encourage swirling eddies to form. These forced eddy currents propel the oil droplets towards additional gas interface surfaces for breakout and collection. Accumulated oil on these surfaces combines to form much larger oil droplets which join the main body of flow. These are now of a significantly larger size and interact with the initial interface at the top of the fluid column.

The vessel also works as a degassing unit as entrained gas will break out and be released with the separated oil particles. Solids and heavier particles will accumulate at the bottom of the vessel to be flushed out on an intermittent basis.

CRUDESEP® AF

CRUDESEP®AF

SOLIDS REMOVAL

Skids are designed to be operated and maintained on-line.

Additional Services

Bulk Oil and Chemical Treatment

CETCO Oilfield Services can remove bulk oil through gravity and flotation technology. The process stream enters the 120 barrel separation (weirbox) or sparging tank comprised of four individual compartments. Each compartment has chemical injection, sparging, and oil separation capabilities. The tank provides a great deal of flexibility in breaking emulsions, segregating solids, and recovering oil. Any unexpected surges of oil, solids, and undesirable waste can be isolated and treated independently. Oily water is progressively cleaned from one compartment to the next.

Solids Removal

CETCO can provide various solids filter skids depending on the rate desired. The skids are designed to be operated and maintained on-line. Various micron sizes and fabrics are available for specific applications.

Rental Fleet

Our rental fleet includes sparging tanks, sock filter skids, bulk and canisterized media skids. We also supply all the necessary fittings, hoses, and safety equipment.

Complete Solutions Provider

Our turnkey approach to the treatment of oilfield wastewater streams places personnel and safety first. Consistent results produce environmentally compliant assets with increased oil recovery and ultimate production maximizing your return on investment.

CETCO OILFIELD SERVICES COMPANY

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Broussard, Louisiana 800.432.0054
Houston, Texas 281.578.8911

www.cetcooilfieldservices.com

CETCO Oilfield Services Company is a wholly-owned subsidiary of AMCOL International Corporation

www.cetcooilfieldservices.com

CETCO OILFIELD SERVICES COMPANY

TREATS AND RELEASES FLUIDS AT SUBSEA LEVELS

NEMOH™

CETCO
OILFIELD
SERVICES

IMPLEMENTATION

Benefits of NEMOH™

- Treats and releases fluids at subsea levels
- Works at depths over 6,000 ft
- Ensures compliance
- Flexible and portable
- Treats a number of constituents since it can be operated with different media types

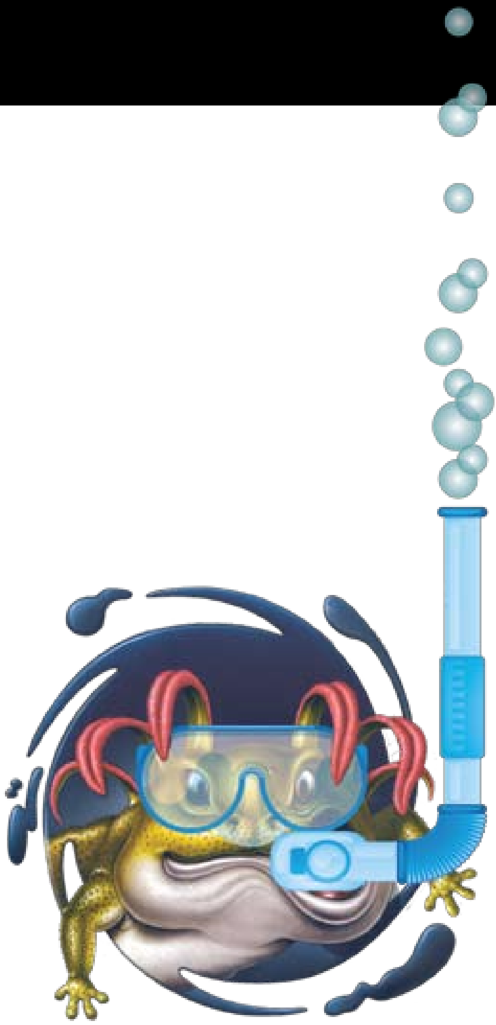
Applications

- Treating the de-pressurization fluids of a hydro test
- Treating the overflush of fluids from a chemical treatment
- Treating fluids from a de-oiling of difficult to flush lines
- Treating fluid for the addition of subsea architecture
- Treating fluids from repairs and abandonment of lines and wells

Nomadic Environmental

Subsea Fluid Treatment

- Helps ensure environmental compliance
- Allows operators to protect assets chemically
- Improves intervention efficiency of subsea architecture
- Removes oil, chemicals and other constituents
- Accommodates various media options



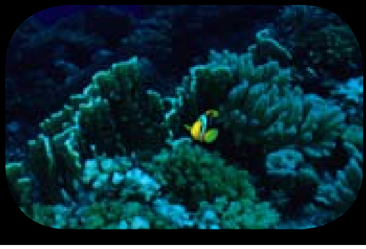
NEMOH™ (Nomadic Environmental Media Operated Host), is a novel, patent pending treatment vessel developed by CETCO Oilfield Services for processing and retaining fluid in a subsea environment. It is remotely operated and can operate at depths over 6,000 ft. NEMOH is an innovative solution for the problematic treatment of fluids at subsea levels and offers flexibility – it is able to be recovered in a reverse process, disconnected, or be guided by an ROV using a ship's winch, or it can be moved along the seabed to another location for another application. It is also extremely effective, since it can treat a number of constituents depending on whether the materials need to be oxidized, coalesced or neutralized because it can be operated with different media types. NEMOH may also be operated as a stand alone vessel (single pass) or in combination in series (multi-pass) with additional vessels utilized for processing fluid with higher levels or multiple constituents.

Media Operated Host

CASE HISTORY

CETCO Oilfield Services Pioneer New Technology for

Subsea Water Processing



PROBLEM:

A major deep water operator in the Gulf of Mexico had to find a way of treating water inhibited with chemicals in a subsea environment. Typically this work requires a topside facility or the use of multiple boats. However due to project delays, no topside equipment was available. This, coupled with the depth of the connections, called for an unconventional solution to treating the chemically contaminated fluids and releasing them at a subsea level.

At depths of up to 6,000 ft, subsea pipelines had been filled with water that contained a corrosion inhibitor and biocide which could be hazardous if released into the sea environment. The fluids needed to be treated in such a way that they would be safe to release into the surrounding marine environment.

The operator had to ensure compliance with local legislation regarding the release of a chemically treated discharge. To meet compliance, the water had to pass an acute toxicology test and have no visible sheen.

SOLUTION:

CETCO Oilfield Services was called in to assist on the project and responded with the deployment of a novel, patent pending treatment vessel that could operate at subsea levels of up to 6,000 ft.

NEMOH™, a Nomadic Environmental Media Operated Host, was designed by CETCO Oilfield Services as a hosting treatment vessel for processing and retaining fluid in a subsea environment.

An equalized underwater media vessel, NEMOH is designed to be flexible, portable, and can be used as a temporary installation. It is fitted with a protective cage and lifting frame and following it's immersion in water, is operated by underwater Remotely Operated Vehicles (ROVs). The technology can operate at varying sea levels and in all types of marine settings including fresh, salt, or brackish water.

Similarly, NEMOH enables CETCO Oilfield Services to treat a number of constituents depending on whether the materials need to be oxidized, coalesced or neutralized since it can be operated with different media types.

When the treatment process is complete, NEMOH can either be recovered in a reverse process, disconnected, or be guided by an ROV using a ship's winch, or it can be moved along the sea bed to another location for another application.

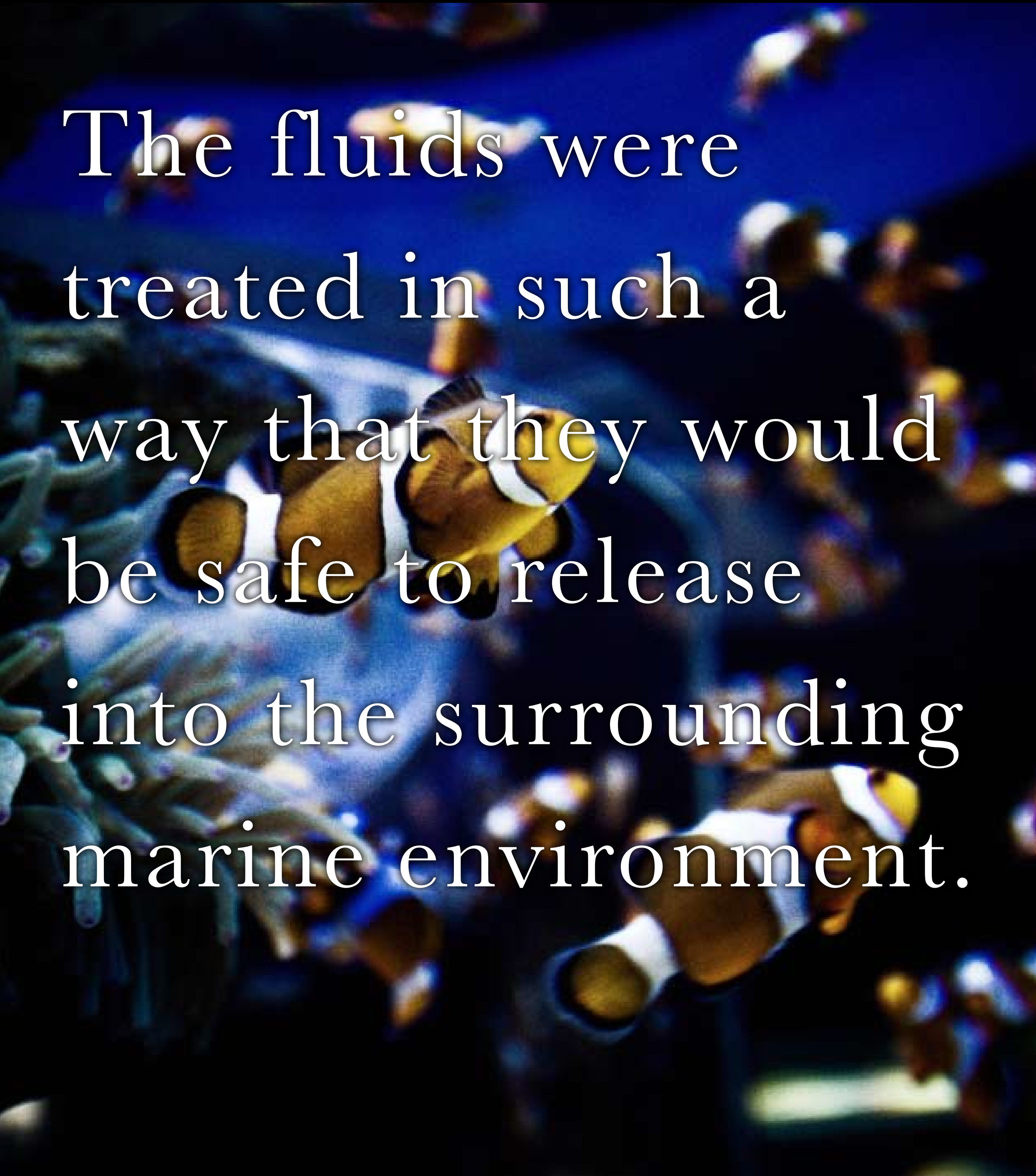
The technology can be used in a closed system to protect a formation for re-injection or as part of a process to protect down stream equipment or process stream. NEMOH may also be operated as a stand alone vessel (single pass) or in combination in series (multi-pass) with additional vessels utilized for processing fluid with higher levels or multiple constituents.

METHOD:

In order to effectively treat and discharge the fluid safely, CETCO Oilfield Services pioneered and deployed its NEMOH technology to the Gulf of Mexico.

NEMOH was immersed to depths of approximately 6,000 ft by a ship's crane that lowered it below deck until it was sighted by an ROV.

Once visualized, the operators of the ROV directed the winch and the movement of NEMOH to ensure that the skid had a safe landing on the bottom of the ocean. Once landed, the winch wire was disconnected and recovered to the surface.



The fluids were treated in such a way that they would be safe to release into the surrounding marine environment.

The ROV communicated with NEMOH by a device known as a hot stab or quick couple hose line into the inlet. The ROV then connected the other end of the line to the outlet, known as the Pipeline End Termination (PLET).

All NEMOH equalization valves were closed to ensure the path of flow was through the inlet and outlet of the vessel only. Valve positions on both the PLET and on NEMOH were checked for correct positioning. NEMOH was then ready to receive fluids.

The same process can be undertaken on the downstream of NEMOH if valves are installed for outlets going to further processing, sampling devices, or into other equipment or pipelines.

OUTCOME:
An innovative technology for processing water at subsea level, CETCO Oilfield Services utilized NEMOH to treat fluids where there were no permanent facilities. By performing operations quicker than traditional topside methods, CETCO Oilfield Services was able to enhance production and ensure the operator complied with discharge legislation.

Following the success of this project, the operator chose to employ NEMOH technology to treat the field's entire subsea system. The project also demonstrated how NEMOH can allow operators to use chemicals to protect valuable subsea equipment and ultimately enhance asset protection and management.

Since then, CETCO Oilfield Services has been able to deploy its NEMOH technology to assist in various niche operating markets.

NEMOH™

CETCO OILFIELD SERVICES

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Broussard, Louisiana 800.432.0054
Houston, Texas 281.578.8911

cetcooilfieldservices.com


NEMOH™
CETCO
OILFIELD
SERVICES

APPENDIX II

HACH Colorimeter

Brochure Details

DR/800 Series Colorimeters Multi-parameter analysis in the palm of your hand!

Features and Benefits

Choose from Three Models

Depending on your testing needs, you can select a DR/820, DR/850 or DR/890 Colorimeter, preprogrammed to test for at least 20, 50 or 90 parameters, respectively. All three models include the same convenient features: auto-wavelength selection, datalogging capabilities and user-generated calibrations. Refer to the table on pages 3-4 to select the colorimeter that tests the parameters you require.

These durable, hand-held, filter photometers are designed specifically for the rigors of on-site testing, with rugged components and waterproof, dustproof, chemical-resistant housings. DR/800 Series Colorimeters offer simple, push-button program selection and step-by-step prompts that guide users through the testing procedure. These instruments are equally appreciated by experienced analysts who value test efficiency and by operators who require ease of use with accurate results.

Advanced Features Add Value

- *Easy-to-use software offers push-button method selection, automatic wavelength selection and a preprogrammed method timer. Result, units, and parameter name are displayed immediately, with no countdown. The large digit display is very easy to read.*
- *The DR/800 retains the selected method until a new method is entered, even if it is turned off and then back on. This allows a series of analyses to be performed for the same parameter without reselecting the method.*
- *Datalogging capability includes push-button record management. Easily store data in the field for later access, with no delay in testing. The instrument stores up to 99 measurements in an internal, non-volatile memory. Data stored includes date/time, parameter, program number, concentration/absorbance/%T, sample number, and instrument serial number.*
- *Results are displayed directly in units of concentration, absorbance, or % transmittance. In many methods, concentration in alternate chemical forms is also available. For example, phosphate readings are available as P, PO_4 and P_2O_5. Displayed results can be changed from one form to the next at the touch of a button.*
- *User-program feature allows users to generate up to 10 custom procedures, with up to 12 data points each, and store them in a non-volatile instrument memory for later use.*
- *Advanced software includes automatic correction for reagent blanks and the option to fine-tune calibration curves with the standard adjust feature.*
- *Batteries provide self-contained power for field-testing.*

Hach DR/800 Series Colorimeters combine ease of use, multiple testing capabilities and field readiness. Analysis requires minimal time and preparation, with results displayed directly on the large liquid-crystal display in concentration, percent transmittance, or absorbance units.

DW WW PW IW E FB

Accessories Simplify Data Management

The Data Transfer Adapter (DTA) fits on the colorimeter and accepts data sent from the instrument's infrared LED transmitter. The DTA converts data to a standard RS-232 format and connects directly to a computer or printer. Data can be printed or downloaded conveniently, after storage or during collection.

DR/800 Series Colorimeters are compatible with HachLink™ Software, a Microsoft® Windows® compatible application that links instrument and computer, providing a convenient means of accessing and managing test data. Information including date/time, parameter, concentration/absorbance/%T, sample number, operator identity, and instrument serial number is accepted and stored in either text or tabular (spreadsheet) format, and can be easily transferred to popular spreadsheet or word-processing applications.

Easy Quality Control

DR/Check™ ABS Standards are the optional choice to verify the performance of your DR/800 Colorimeter in seconds. Standards are formulated with neutral density gel that produces similar absorbance readings at any wavelength. For all parameters at all wavelengths, running three secondary absorbance standards will verify your instrument's calibration easily, anytime.

DW = drinking water WW = wastewater municipal **PW = pure water / power**
IW = industrial water **E = environmental** C = collections **FB = food and beverage**

HACH®
Be Right™

Features and Benefits continued

Affordable COD Analysis

All three models include Hach's Manganese III COD procedure (mercury-free version). The DR/850 Colorimeter also performs our traditional USEPA-approved high-range COD procedure, and the DR/890 Colorimeter performs both low-range and high-range USEPA-approved COD procedures. An adapter suitable for COD vials and Test 'N Tube™ (TNT) vials is included with each instrument.

Push-Button Operation Speeds Analysis

Using Hach prepared reagents, testing is normally accomplished in just a few minutes, following this simple procedure:

1. When turned on, the instrument automatically recalls the last program used. To change programs, press the program key and enter the program number from the procedures manual. The instrument displays the program number, parameter, units, and the zero icon.
2. Prepare the blank (zero) according to the procedure, place it in the instrument, and press the zero key. The instrument displays the zero and the read icon.
3. Prepare the sample according to the procedure. (An internal timer is preprogrammed for methods that require a fixed reaction time. Timer duration is automatically displayed for the selected procedure; simply start the timer at the start of the reaction.) After reacting the sample, place the sample cell in the instrument and press the read key.
4. The instrument displays the result in concentration units. The user can also toggle the ABS %T key to display absorbance or % transmittance. Some results can be displayed in alternate chemical forms (e.g., Cr may be displayed as mg/L CrO_4 or Cr_2O_7). Scroll through available forms by pressing the CONC key.
5. Save the results by pressing the store key. The instrument will store up to 99 measurements in an internal, non-volatile memory. Results may be printed or transferred to a computer at any time using the Data Transfer Adapter.

Ergonomically designed instrument fits comfortably in the palm of your hand, with all functions easily accessible.

Instrument cap slides off and is used as a light shield during measurement.

All instrument setup and operation functions are accessible by the keypad. Following prompts provided on the instrument display, the user selects the appropriate program, zeroes the instrument, reacts the sample, and reads the results.

Large LCD display prompts user step by step through procedures. Separate areas of the display indicate program number, sample number, parameter, test results, units of measure, and other data.

Built-in timer is preprogrammed for methods requiring a fixed reaction time and can be set by the user.

Up to 99 individual readings can be stored and recalled with the touch of a button.

DR/800 Colorimeters Quick Reference Guide

Parameters marked "EPA" are EPA-approved, accepted, or equivalent for reporting purposes; sample pretreatment may be required on some procedures. If no reagent set is listed for a parameter, order needed reagents and supplies separately.

Test	EPA	Method	Number	DR/890	DR/850	DR/820	Product Number
Aluminum		Aluminon	8012	•	•	•	**2242000**
Ammonia, Nitrogen		Salicylate	8155	•	•		**2668000**
Ammonia, Nitrogen (Test 'N Tube), LR		Salicylate	10023	•	•		**2604545**
Ammonia, Nitrogen (Test 'N Tube), HR		Salicylate	10031	•	•		**2606945**
Ammonia, Free, Nitrogen		Indophenol	10200	•	•		**2879700**
Benzotriazole		UV Photolysis	8079	•			**2141299**
Bromine		DPD	8016	•	•	•	**2105669**
Bromine (AccuVac)		DPD	8016	•	•	•	**2503025**
Carbohydrazide		Iron Reduction	8140	•			**2446600**
Chloramine, Mono, LR		Indophenol	10171/10200	•	•		**2802246**
Chlorine, Free	•	DPD	8021	•	•	•	**2105569**
Chlorine, Free (AccuVac)	•	DPD	8021	•	•	•	**2502025**
Chlorine, Free (Test 'N Tube)		DPD	10102	•	•	•	**2105545**
Chlorine, Free, HR	•	DPD	10069	•	•	•	**1407099**
Chlorine, Total	•	DPD	8167	•	•	•	**2105669**
Chlorine, Total (AccuVac)	•	DPD	8167	•	•	•	**2503025**
Chlorine, Total (Test 'N Tube)		DPD	10101	•	•	•	**2105645**
Chlorine, Total, HR	•	DPD	10070	•	•	•	**1406499**
Chlorine Demand/Requirement		DPD	10223	•	•	•	—
Chlorine Dioxide, DPD	•	DPD/Glycine	10126	•	•	•	**2770900**
Chlorine Dioxide, DPD (AccuVac)	•	DPD/Glycine	10126	•	•	•	**2771000**
Chlorine Dioxide, MR		Direct Reading	8345	•			—
Chromium, Hexavalent	•	1,5 Diphenylcarbohydrazide	8023	•			**1271099**
Chromium, Hexavalent (AccuVac)	•	1,5 Diphenylcarbohydrazide	8023	•			**2505025**
Chromium, Total		Alkaline Hypobromite Oxidation	8024	•			**2242500**
COD, LR	•	Dichromate	8000	•			**2125825**
COD, HR	•	Dichromate	8000	•	•		**2125925**
COD, HR+		Dichromate	8000	•	•		**2415925**
COD		Manganese III	10067	•	•	•	**2623425**
Copper, LR		Porphyrin	8143	•			**2603300**
Copper	•	Bicinchoninate	8506	•			**2105869**
Copper (AccuVac)		Bicinchoninate	8026	•			**2504025**
Cyanide		Pyridine-Pyrazalone	8027	•	•		**2430200**
Cyanuric Acid		Turbidimetric	8139	•	•	•	**246066**
DEHA (Diethylhydroxylamine)		Iron Reduction	8140	•			**2446600**
Detergents (Surfactants)		Crystal Violet	8028	•	•		**2446800**
Dissolved Oxygen (AccuVac), LR		Indigo Carmine	8316	•	•		**2501025**
Dissolved Oxygen (AccuVac), HR		HRDO	8166	•	•	•	**2515025**
Erythorbic Acid (Isoascorbic Acid)		Iron Reduction	8140	•			**2446600**
Fluoride, Arsenic Free		SPADNS 2	10225	•	•		**2947549**
Fluoride, Arsenic Free (AccuVac)		SPADNS 2	10225	•	•		**2527025**
Fluoride		SPADNS	8029	•	•		**44449**
Fluoride (AccuVac)		SPADNS	8029	•	•		**2506025**
Hardness, Ca & Mg		Calmagite Colorimetric	8030	•	•	•	**2319900**
Hydrazine		p-Dimethylaminobenzaldehyde	8141	•			**179032**
Hydrazine (AccuVac)		p-Dimethylaminobenzaldehyde	8141	•			**2524025**
Hydroquinone		Iron Reduction	8140	•			**2446600**
Iron		FerroZine	8147	•			**230166**
Iron, Ferrous		1,10 Phenanthroline	8146	•	•	•	**103769**
Iron, Ferrous (AccuVac)		1,10 Phenanthroline	8146	•	•	•	**2514025**
Iron, Total		FerroMo	8365	•	•		**2544800**
Iron, Total		TPTZ	8112	•	•		**2608799**
Iron, Total (AccuVac)		TPTZ	8112	•	•		**2510025**
Iron, Total	•	FerroVer	8008	•	•	•	**2105769**
Iron, Total (AccuVac)	•	FerroVer	8008	•	•	•	**2507025**
Isoascorbic Acid (Erythorbic Acid) (ISA)		Iron Reduction	8140	•			**2446600**
Manganese, LR		PAN	8149	•			**2651700**

Continued on next page.

DR/800 Colorimeters Quick Reference Guide *continued*

Test	EPA	Method	Number	DR/890	DR/850	DR/820	Product Number
Manganese, HR	•	Periodate Oxidation	8034	•	•	•	**2430000**
Methylethylketoxime (MEKO)		Iron Reduction	8140	•			**2446600**
Molybdenum, Molybdate, LR		Ternary Complex	8169	•	•		**2449400**
Molybdenum, Molybdate, HR		Mercaptoacetic Acid	8036	•			**2604100**
Molybdenum, Molybdate (AccuVac), HR		Mercaptoacetic Acid	8036	•			**2522098**
Nickel		PAN	8150	•			**2242600**
Nitrate, Nitrogen, LR		Cadmium Reduction	8192	•	•	•	**2429800**
Nitrate, Nitrogen, MR		Cadmium Reduction	8171	•			**2106169**
Nitrate, Nitrogen (AccuVac), MR		Cadmium Reduction	8171	•			**2511025**
Nitrate, Nitrogen (Test ’N Tube), HR		Chromotropic Acid	10020	•			**2605345**
Nitrate, Nitrogen, HR		Cadmium Reduction	8039	•	•	•	**2106169**
Nitrate, Nitrogen (AccuVac), HR		Cadmium Reduction	8039	•	•	•	**2511025**
Nitrite, Nitrogen, LR	•	Diazotization	8507	•	•	•	**2107169**
Nitrite, Nitrogen (AccuVac), LR	•	Diazotization	8507	•	•	•	**2512025**
Nitrite, Nitrogen (Test ’N Tube), LR	•	Diazotization	10019	•	•	•	**2608345**
Nitrite, Nitrogen, HR		Ferrous Sulfate	8153	•			**2107569**
Nitrogen, Ammonia (See Ammonia, Nitrogen)							
Nitrogen, Total (Test ’N Tube), LR		Persulfate Digestion	10071	•			**2672245**
Nitrogen, Total (Test ’N Tube), HR		Persulfate Digestion	10072	•			**2714100**
Nitrogen, Total Inorganic (TIN) (Test ’N Tube)		Titanium Trichloride Reduction	10021	•	•		**2604945**
Nitrogen, Total Kjeldahl (TKN)		Nessler		•			**2495300**
Organic Carbon, Total (See TOC)							
Oxygen Demand, Chemical (See COD)							
Oxygen, Dissolved (See Dissolved Oxygen)							
Oxygen Scavengers (See specific compounds)							
Ozone (AccuVac), LR		Indigo	8311	•	•		**2516025**
Ozone (AccuVac), MR		Indigo	8311	•	•		**2517025**
Ozone (AccuVac), HR		Indigo	8311	•	•		**2518025**
pH		Colorimetric Phenol Red	10076	•	•	•	**2657512**
Phosphonates		Persulfate UV Oxidation	8007	•	•		**2429700**
Phosphorus, Reactive	•	PhosVer 3	8048	•	•		**2106069**
Phosphorus, Reactive (AccuVac)	•	PhosVer 3	8048	•	•		**2508025**
Phosphorus, Reactive (Test ’N Tube)	•	PhosVer 3	8048	•	•		**2742545**
Phosphorus, Reactive		Amino Acid	8178	•	•	•	**2244100**
Phosphorus, Reactive		Molybdovanadate	8114	•			**2076032**
Phosphorus, Reactive (AccuVac)		Molybdovanadate	8114	•			**2525025**
Phosphorus, Reactive (Test ’N Tube), HR		Molybdovanadate	8114	•			**2767345**
Phosphorus, Acid Hydrolyzable (Test ’N Tube)		PhosVer 3 with Acid Hydrolysis	8180	•	•		**2742645**
Phosphorus, Total (Test ’N Tube)	•	PhosVer 3 with Acid Persulfate Digestion	8190	•	•		**2742645**
Phosphorus, Total (Test ’N Tube), HR		Molybdovanadate with Acid Persulfate Digestion	10127	•			**2767245**
Silica, LR		Heteropoly Blue	8186	•	•		**2459300**
Silica, HR		Silicomolybdate	8185	•			**2429600**
Sulfate	•	SulfaVer 4	8051	•	•	•	**2106769**
Sulfate (AccuVac)	•	SulfaVer 4	8051	•	•	•	**2509025**
Sulfide	•	Methylene Blue	8131	•	•		**2244500**
Surfactants (See Detergents)							
Suspended Solids		Photometric	8006	•	•		—
Tannin & Lignin		Tyrosine	8193	•	•		**2244600**
TOC (Total Organic Carbon), LR		Direct Method	10129	•	•		**2760345**
TOC (Total Organic Carbon), MR		Direct Method	10173	•	•		**2815945**
TOC (Total Organic Carbon), HR		Direct Method	10128	•	•		**2760445**
Tolyltriazole		UV Photolysis	8079	•			**2141299**
Toxicity		ToxTrak	10017	•	•		**2597200**
Volatile Acids		Esterification	8196	•	•	•	**2244700**
Zinc	•	Zincon	8009	•	•		**2429300**

Specifications*

Wavelength Selection
Auto Select

Photometric Range
0 to 2 Abs

Operational Modes
Concentration, Abs, %T

External Outputs
Infrared to RS-232 Serial using the optional Data Transfer Adapter

Datalogging
99 sample readings (each reading includes date/time, parameter, program number, concentration, absorbance, % transmittance, sample number, instrument serial number)

User Programs
10 user-entered programs, 12 data points each

Display
Large liquid-crystal display (LCD) shows results, parameter name, program number and units

Dimensions
23.6 x 8.7 x 4.7 cm (9.3 x 3.4 x 1.9")

Weight
470 g (1 lb)

Power
4 AA alkaline or rechargeable alkaline batteries, nominal life of six months

Storage Temperature Range
-40 to 60ºC (-40 to 140ºF)

Operating Temperature Range
0 to 50ºC (32 to 122ºF)

Environmental
Meets IP67 standard, dustproof and waterproof to one meter for 30 minutes

Compliance
European CE Mark

**Specifications subject to change without notice.*

Ordering Information

DR/800 Series Colorimeters

Each DR/800 Series Colorimeter includes two 1-in. round sample cells marked at 10, 20 and 25 mL, two 1 cm sample cells, 16 mm COD/TNT adapter, batteries and illustrated instrument and procedure manuals.

4844000 DR/820 Colorimeter
4845000 DR/850 Colorimeter
4847000 DR/890 Colorimeter

Optional Instrumentation

8505900 **pH Starter Kit**
HQ11d pH meter, gel pH probe with 1 m cable, HQd meter stand, pH Buffer Kit (500 mL), pH storage solution (500 mL), and probe stand.

8506400 **pH Ultra Starter Kit**
HQ40d meter with A/C power and USB adapters, pH Ultra probe with 1 m cable, HQd meter stand, pH buffer kit (500 mL) and probe stand.

8506100 **Conductivity Starter Kit**
HQ14d conductivity meter, standard conductivity probe with 1 m cable, HQd meter stand, conductivity standard (1000 µS/cm, 100 mL), and probe stand.

8506000 **Complete Water Quality Lab Kit: DO/pH/Conductivity**
HQ40d meter with A/C power and USB adapters, refillable pH probe with 1 m cable, conductivity probe with 1 m cable, standard LDO probe with 1 m cable, HQd meter stand, pH Buffer Kit (500 mL), pH storage solution (500 mL), conductivity standard (1000 µS/cm, 100 mL), disposable BOD bottle and stopper for calibration, and probe stand.

LTV082.53.44001
DRB200 Reactor for digestion of up to 30 COD/TNT vials

4650000 2100P Portable Turbidimeter

1690001 Digital Titrator

Continued on next page.

Ordering Information *continued*

CEL/800 Series Portable Laboratories*

The heart of all CEL/800 Laboratories is a DR/800 Series Colorimeter with two sample cells, 16-mm COD/TNT adapter, and illustrated instrument and procedure manuals. Preconfigured labs also include complete reagent sets and all necessary apparatus. Many labs include additional instrumentation to expand your testing capabilities. CEL/800 Portable Labs are housed in durable carrying cases designed to accommodate all equipment comfortably, and to protect and organize the contents.

**Colorimeter Environmental Laboratory*

2688500 **CEL/890 Advanced Portable Laboratory**
Our most versatile portable laboratory, this fully configured system meets the most demanding needs. It includes a full complement of instruments and reagent sets for more than 20 parameters.The Advanced Portable Laboratory includes DR/890 Colorimeter, sensION1 pH Meter, sensION5 Conductivity/TDS Meter, Digital Titrator, illustrated instrument and procedures manuals, reagent sets, and all required apparatus in a rugged carrying case.

2690600 Replacement Reagent Set, complete

2687800 **CEL/850 Environmental Water Quality Laboratory**
Most important environmental tests can be performed using just one portable laboratory, with everything necessary for determining water quality in the field, and fast, on-the-spot results. The Environmental Water Quality Laboratory includes DR/850 Colorimeter, Digital Titrator, reagent sets, apparatus, and illustrated instrument and procedures manuals in a sturdy field case.

2690800 Replacement Reagent Set, complete

2688100 **CEL/890 Advanced Drinking Water Laboratory**
The CEL/890 Advanced Drinking Water Laboratory provides complete field capabilities, with instrumentation and tests that cover every major drinking water parameter. The Advanced Drinking Water Laboratory includes DR/890 Colorimeter, sensION1 pH Meter, sensION5 Conductivity/TDS Meter, Digital Titrator, reagent sets, apparatus, illustrated instrument and procedures manuals, and a sturdy field case.

2690200 Replacement Reagent Set, complete

2688000 **CEL/850 Basic Drinking Water Laboratory**
Designed to include the most commonly tested parameters for drinking water, the CEL/850 Basic Drinking Water Laboratory offers operators basic analytical capabilities in a single convenient package. Monitor influent, finished product, and distribution water quickly and easily. The Basic Drinking Water Laboratory includes DR/850 Colorimeter, sensION5 Conductivity/TDS Meter, reagent sets, apparatus, illustrated instrument and procedures manuals, and a sturdy field case.

2689800 Replacement Reagent Set, complete

2688300 **CEL/890 Advanced Wastewater Laboratory**
The CEL/890 Advanced Wastewater Laboratory includes the testing capabilities of the DR/890 Colorimeter, providing an analytical platform suited to a wide array of additional optional parameters. The Advanced Wastewater Laboratory includes DR/890 colorimeter, sensION1 pH Meter, reagent sets, apparatus, illustrated instrument and procedures manuals, and a sturdy field case.

2690400 Replacement Reagent Set, complete

CEL/890 Advanced Portable Laboratory

CEL/850 Basic Drinking Water Laboratory

Ordering Information *continued*

2688200 **CEL/820 Basic Wastewater Laboratory**
Offering broad analytical capabilities to meet the needs for basic wastewater analysis, the CEL/820 Basic Wastewater Laboratory provides accurate results, wherever you need them. The Basic Wastewater Lab includes DR/820 Colorimeter, Pocket Pal™ pH tester, reagent sets, apparatus, and illustrated instrument and procedures manuals in a sturdy field case.

2690000 Replacement Reagent Set, complete

2687700 **CEL/850 Professional Water Conditioning Laboratory**
The CEL/850 Professional Water Conditioning Laboratory features the DR/850 Colorimeter, affording extended testing capabilities with the option of adding more parameters for site or application-specific needs. The Professional Water Conditioning Laboratory includes DR/850 Colorimeter, sensION1 pH Meter, sensION5 Conductivity Meter, Digital Titrator, reagent sets, apparatus, a water softener, and illustrated instrument and procedures manuals in a sturdy field case.

2689600 Replacement Reagent Set, complete

2689100 **CEL/820 Water Conditioning Laboratory**
The CEL/820 Water Conditioning Laboratory offers the water quality improvement/purification professional a capable instrument and all equipment needed to accomplish fast, accurate testing on-site. The Water Conditioning Laboratory includes DR/820 Colorimeter, TDS Pocket Pal™ Tester, reagent sets, apparatus, a water softener, and illustrated instrument and procedures manuals in a sturdy field case.

2689400 Replacement Reagent Set, complete

2688400 **CEL/890 Professional Water Treatment Laboratory**
For boiler/cooling water applications. Offering quick, on-the-spot results, the CEL/890 Professional Water Treatment Laboratory covers parameters critical to effective treatment and corrosion prevention. The Professional Water Treatment Laboratory includes DR/890 Colorimeter, sensION1 pH Meter, sensION5 Conductivity/TDS Meter, Digital Titrator, BARTs™ for bacterial detection, reagent sets, apparatus, and illustrated instrument and procedures manuals in a sturdy field case.

2690900 Replacement Reagent Set, complete

2687600 **CEL/820 Water, Water Everywhere Education Laboratory**
The CEL/820 Water, Water Everywhere Education Laboratory offers one easy-to-store, easy-to-use portable system for a complete range of parameters. Students can easily follow the step-by-step instructions to obtain accurate, high-confidence results. The Water, Water Everywhere curriculum is available for download at www.hach.com. It covers the basics of water quality, the water cycle, and more. CEL/820 Water Water Everywhere Education Laboratory includes DR/820 Colorimeter, reagent sets, apparatus, and illustrated instrument and procedures manuals in a sturdy field case.

2723200 Replacement Reagent Set, complete

2687900 **CEL/850 Aquaculture Laboratory**
Maintain water quality easily with the portable CEL/850 Aquaculture Laboratory. Fast, on-the-spot results can identify problems early and help determine corrective action. The laboratory includes the sensION™1 pH Meter, Digital Titrator, TDS Pocket Pal™ Tester, reagent sets, apparatus, and illustrated instrument and procedure manuals in a sturdy field case.

2691700 Replacement Reagent Set, complete

2688800 **MEL/850 Potable Water Laboratory***
The MEL/850 Potable Water Laboratory offers field testing for the most common water-quality parameters, plus microbiological testing. The laboratory includes the DR/850 Colorimeter, a TDS Pocket Pal™ Tester, a pH Pocket Pal™ Tester, a pocket thermometer, a Portable Incubator, coliform presence/absence testing capabilities, and illustrated instrument and procedures manuals in a sturdy field case.

**Microbiological Environmental Laboratory*

Continued on next page.

Ordering Information *continued*

Accessories

4849000	Data Transfer Adapter, IR to RS-232, with cable
2763900	DR/Check™ Absorbance Standards for DR/800 verification
4942500	Instrument carrying case (hard sided)
2722000	Instrument carrying case with shoulder strap (soft sided)
4943000	CEL Portable Laboratory carrying case. Roomy field case includes space for the colorimeter, optional instrumentation, accessories, reagent sets and apparatus.
4966500	HachLink™ Software Package
1938004	Alkaline batteries size AA, pk/4

The optional carrying case provides room for the instrument, all accessories, and additional reagent sets.

Data Transfer Adapter converts infrared signals from the instrument to standard RS-232 protocol. The adapter fits over the instrument in place of the cap and connects directly to a printer or computer.

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At Hach, it's about learning from our customers and providing the right answers. It's more than ensuring the quality of water—it's about ensuring the quality of life. When it comes to the things that touch our lives...

Keep it pure.

Make it simple.

Be right.

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U.S.A.
Telephone: 800-227-4224
Fax: 970-669-2932
E-mail: orders@hach.com
www.hach.com

U.S. exporters and customers in Canada, Latin America, sub-Saharan Africa, Asia, and Australia/New Zealand, contact:

HACH COMPANY World Headquarters
P.O. Box 389
Loveland, Colorado 80539-0389
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Fax: 970-461-3939
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www.hach-lange.com

HACH®

Be Right™

APPENDIX III

ProSep Brochure

PRODUCED WATER TREATMENT SYSTEMS

ProSep

Together, creating pure oil, gas and water.

ProSep offers a full line of proven solutions for handling produced water while keeping installations in compliance and online. The line includes primary, secondary, and tertiary treatment solutions for onshore, fixed-offshore, and floating-offshore facilities. All of the offerings have been proven over a broad spectrum of applications and years of strong performance.

Whether the goal is to re-inject for disposal or pressure maintenance, discharge to the surface or go overboard, ProSep can help producers to effectively treat produced water in a timely, smooth and cost-efficient manner.

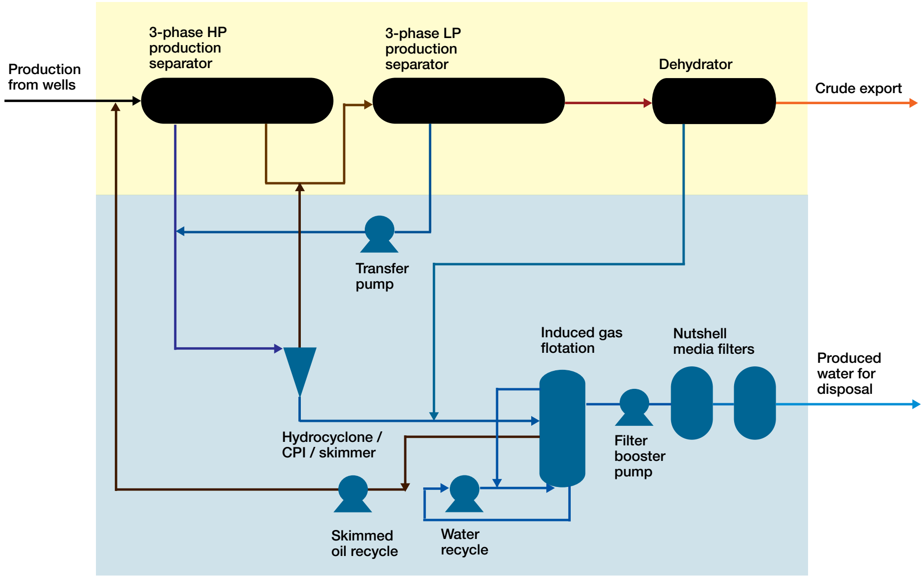
PROSEP'S OFFERING

- Complete line of produced water treatment solutions
- Decades of combined industry experience and packaging expertise
- Proven and accepted conventional equipment designs
- Next-generation technologies
- Quality manufacturing and assembly
- Client-focused, customized, solution-oriented approach

PRIMARY SEPARATION

In a typical process flow, production enters a three-phase high-pressure separator, from which the output is water with a 500-2000 mg/l oil-in-water concentration. Initial treatment of the produced water stream will be based on gravity separation principles to take the dispersed oil levels well below 500 mg/l.

TYPICAL PRODUCED WATER FLOW DIAGRAM



PROSPIN HYDROCYCLONE

The ProSpin Hydrocyclone is an excellent primary separation solution in most offshore applications where sufficient process pressure is available, since it has a small footprint and is highly efficient at separating free oil from water. ProSpin is unaffected by wave conditions and delivers typical removal efficiencies of 85-95% of all oil droplets >12-15 microns and typical effluent quality of 25-100 mg/l OiW.

PROPLATE CPI OR PROSKIM VERTICAL SKIMMER

Handle surges and high percentage oil volumes and still deliver a 50-150 mg/l OiW concentration with ProSep's ProPlate Corrugated Plate Interceptors (CPIs) and ProSkim Vertical Skimmers. Where available pressure is less than 50 psig, or high inlet oil concentrations are expected, ProPlate or ProSkim will often prove a better option for separation than hydrocyclones.

ProPlate CPIs are designed to provide the same removal efficiency as a traditional gravity separator in a much smaller vessel, making them ideal for fixed-platform as well as land-based installations. For floating applications with low pressure profiles, a CPI can be designed as a liquid-packed pressure vessel, mitigating the problems traditional atmospheric CPIs have with wave motions.

A ProSkim Vertical Skimmer can also serve as a motion-insensitive substitute for the CPI where process conditions warrant.

SECONDARY TREATMENT

After the first oil cut, the secondary stage of treatment conditions the produced water for overboard discharge, re-injection or further polishing through filtration. The secondary stage of treatment utilizes flotation principles to separate smaller and dispersed oil droplets. Discharge oil-in-water concentrations are typically below 25 ppmv.

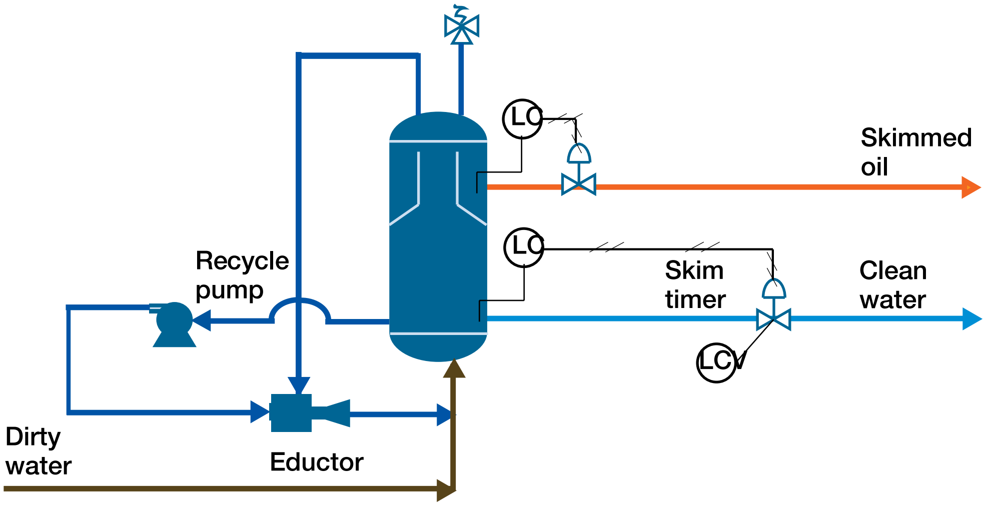
PROFLOAT INDUCED GAS FLOTATION

ProSep's ProFloat Flotation Systems deliver highly efficient removal of oil and solids (10,000 to 100,000 BPWD with a separation efficiency of up to 98%) while completely containing the process. ProFloat is ideal for secondary treatment of produced and wastewaters in refineries, petrochemical plants and in the oilfield. The solution can integrate into existing systems as standalone vessels or be fully skid-mounted as a turnkey package.

An IGF is often selected over dissolved gas flotation because of issues of solubility of inert and fuel gas at the high temperatures characteristic of produced water processes. The ProFloat IGF is also a proven performer with thousands of installations worldwide in diverse applications. A ProFloat IGF vessel can be either a horizontal multiple-cell or a vertical single-cell.

The ProFloat IGF is available in horizontal multiple-cell when higher separation efficiencies and flow rates are required. ProSep's multiple-cell IGFs are ideal for many onshore and fixed offshore applications because of their ability to consistently achieve OiW concentrations in the range of 15mg/l.

SINGLE-CELL INDUCED GAS FLOTATION VESSEL



TERTIARY TREATMENT

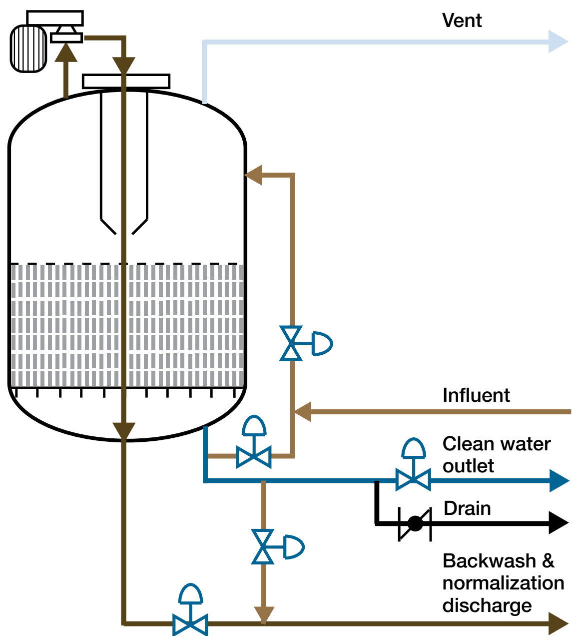
Primary and secondary treatment will keep 90% of operators worldwide within either regulatory or self-imposed discharge limits. Depending on the reservoir matrix or discharge requirements, a maximum of 15-25 mg/l of oil and/or solids may not be sufficient. The third-stage of produced water treatment utilizes filtration to "polish" the remaining oil droplets and solid particles from the stream.

PROSHELL NUTSHELL MEDIA FILTER

ProSep provides high-performance tertiary treatment equipment employing nutshell media filtration.

ProSep provides high-performance tertiary treatment equipment employing nutshell media filtration. The use of nutshell media provides the benefit of reducing or eliminating the need for large quantities of backwash water, scouring, and surfactants. The unique qualities of the pecan / walnut shell media blend make for an effective, hydrophilic bed, which is extremely hard and durable. Thus the ProShell Deep Bed Nutshell Filter media lasts longer than traditional media and remains highly effective throughout the filter life-cycle, typically requiring 5-10% makeup volume per year.

Under normal conditions represented by an inlet oil concentration of less than 50 mg/l and a comparable solids inlet concentration, nutshell filters will remove 95% of oil and solids larger than 5 microns. With the addition of chemicals, efficiencies can exceed 98% removal of particles greater than 3 microns.



NEAR-ZERO DISCHARGE OFFERINGS

CTOUR PROCESS

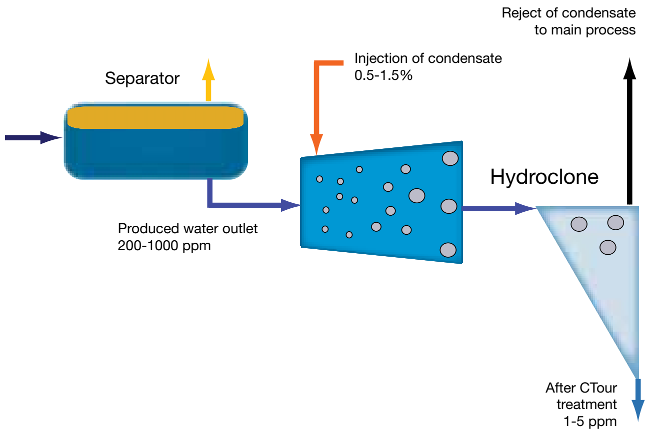
In response to increasing produced water volume combined with stricter discharge legislation, ProSep offers the CTour process. The process is one of the only technologies in the world that can cost-effectively remove both dispersed and dissolved hydrocarbons from large volumes of produced water.

It does this through injecting a condensate of light hydrocarbons into the produced water stream to extract the harmful components. In addition to environmental advantages, the CTour process provides improved separation efficiency for debottlenecking produced water treatment problems.

ProSep offers the following for CTour:

- Prediction of performance
- Process definition for implementation
- Configuration and specification of equipment for full-scale installation
- Project support
- Commissioning, start-up assistance, and project support
- Field testing

TYPICAL CTOUR PROCESS



The TORR™ de-oiling technology, with its small footprint and ability to replace less efficient de-oiling equipment, exceeds today's discharge regulations in the treatment of produced water for offshore producers and operators.

The TORR™ technology is an efficient oil/water separator that can treat produced water at high inlet oil concentrations at a faster rate, thus potentially restoring the residence time in the primary separation vessel and therefore lowering the water content in the dehydrated crude.

The scaleable technology addresses future increases in water cut.

TORR™ DE-OILING TECHNOLOGY

TORR™ INSTALLATION IN THE MIDDLE EAST

CONSIDERATIONS

- A properly designed chemical program will need to be in place to insure the proper functioning of the system and to possibly enhance performance beyond what the manufacturer can guarantee.
- When designing a produced water treatment system to handle substantial increase in water rates over the life of the field, remember that most control valves have an effective turndown ratio of 6:1 or less.
- Consider how the equipment performance will be affected over the life of the field and its changing process conditions.
- Assume there will always be more water than the reservoir engineers predicted; always build in some margin.

- If in doubt, pilot test. Non-conventional technologies are fine as long as their limitations and applicability are understood. Pilot-test any technologies unproven in a specific application.

REFERENCES

Available upon request.

FOR MORE INFORMATION

Contact your nearest ProSep office
www.prosep.com

About ProSep

ProSep is a technology-based process solutions provider for the upstream oil and gas industry.

The Company designs, develops, manufactures and commercializes technologies to separate oil, gas and water generated by oil and gas production.

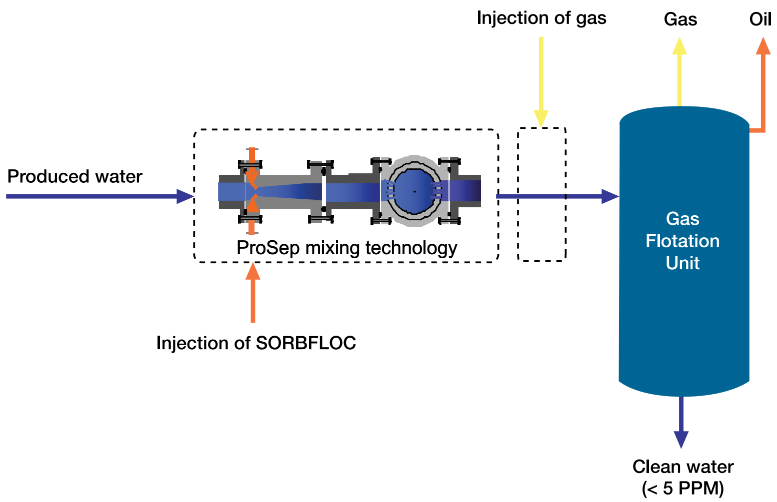
ProSep's innovative offerings have been awarded three Spotlight on New Technology Awards from the annual Offshore Technology Conference in Houston in 2005 and onwards, comprising the proprietary technologies ProScav, CTour and ProSalt.

GAS FLOTATION UNIT

ProSep

Together, creating pure oil, gas and water.

TYPICAL GFU CONFIGURATION



To treat produced water for overboard discharge or reinjection, the Gas Flotation Unit delivers a high degree of hydrocarbon removal. Combined with Sorbfloc®, the GFU removes dispersed and dissolved hydrocarbons, heavy metals, nano-particles, and aromatic components.

BENEFITS

- Up to 99% removal efficiency when combined with CTour® or Sorbfloc®
- High turndown
- Robust and simple design– No moving parts
- Minimal energy requirements
- Simple operation and low maintenance
- Small footprint
- Motion insensitive design

Designed by our business partner SorbWater Technology AS as a complement to Sorbfloc®, the GFU can be used as a stand-alone unit that meets strict requirements of oil-in-water content. When combined with CTour® or Sorbfloc®, its efficiency exceeds conventional induced gas flotation units by acheiving outlet oil-in-water content of <5 ppm.

REFERENCES

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PROFLOAT INDUCED GAS FLOTATION SYSTEMS

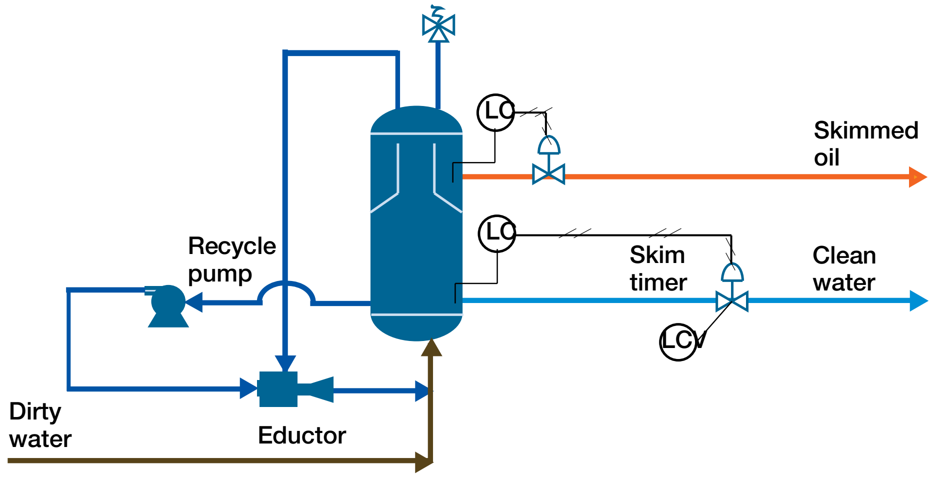
ProSep

Together, creating pure oil, gas and water.

To recover oil and to condition waters for overboard discharge, re-injection or further polishing through filtration, ProSep's ProFloat Flotation Systems deliver highly efficient removal of oil and solids (10,000 to 100,000 BPWD with a separation efficiency of up to 98%) while completely containing the process.

ProFloat is ideal for secondary treatment of produced and wastewaters in refineries, petrochemical plants and in the oilfield. The solution can integrate into existing systems as standalone vessels or be fully skid-mounted as a turnkey package.

SINGLE-CELL INDUCED GAS FLOTATION VESSEL



FEATURES

- Contained, gas-tight design
- Compact skid design
- Simple and reliable design and operation
- No internal moving parts, no specialty parts needed
- Availability of pressurized operation
- Low skim rates
- Operational and environmental safety
- Minimal energy requirements

INDUCED GAS FLOTATION

ProFloat employs induced gas flotation (IGF), as opposed to dissolved gas flotation (DGF), because of issues of solubility of inert and fuel gas at the high temperatures characteristic of produced water processes. The ProFloat IGF is available as either a vertical single-cell or a horizontal multiple-cell.

PRINCIPLES OF IGF

The highly efficient, motion-insensitive vertical induced gas flotation (IGF) process, with its small footprint, is ideal for space-limited installations, and especially for floating production applications. The process begins by providing a venturi-type eductor with pressurized water, which passes through and creates a vacuum at the gas suction port. The gas drawn from the vapor space in the IGF is induced into the recycle stream via an eductor. The gas is then thoroughly mixed with the water and contaminants through the aid of a static mixing device. This homogenous mixture is then released into a separation vessel. "Floated" oil and solids are skimmed from the surface of the vessel, and clarified effluent exits from the bottom of the vessel.

ProSep's IGF has a vertical design that uses Stokes law by reducing the apparent density of oils and solids by their attachment to the finely dispersed gas bubble population in the separation vessel, and by increased droplet size and buoyancy through coalescence.

Minimization of the liquid surface area susceptible to motion can be accomplished via the use of a compact and lightweight vertical single-cell or multiple vertical single-cell IGFs, as it is much easier to hold the liquid level control of a vertical vessel during operation due to its relatively small liquid surface area.

HORIZONTAL MULTIPLE-CELL IGFS

The IGF is also available in horizontal multiple-cell when higher separation efficiencies and flow rates are required. Multiple-cell units are also better at handling upsets. ProSep's multiple-cell IGFs are ideal for many onshore and fixed offshore applications because of their ability to consistently achieve OiW concentrations near the lower limit of 15 mg/l.

BENEFITS OF PROFLOAT IGF

- Energy-efficient code and non-code designs
- No hazardous off-gas emissions
- Minimal moving parts
- Single pumps (vs. multiple internal mixing mechanisms)
- Compact, customizable skid-mounted equipment
- Insensitive to FPSO and floating platform motions
- Low skimmed oil rates (typically 1-3%), minimizing downstream tankage
- Simple "set it and go" operation
- Low chemical consumption
- Low maintenance / operator intervention

REFERENCES

Available upon request.

FOR MORE INFORMATION

Contact your nearest ProSep office
www.prosep.com

PROPLATE CPI AND PROSKIM VERTICAL SKIMMER

ProSep

Together, creating pure oil, gas and water.

Handle surges and slugs of oil and still deliver a 50-150 mg/l OiW concentration with ProSep's ProPlate Corrugated Plate Interceptors (CPIs) and ProSkim Vertical Skimmers. Where available pressure is less than 50 psig, or high inlet oil concentrations are expected, ProPlate or ProSkim will often prove a better option for separation than hydrocyclones.

FEATURES AND BENEFITS

- High removal efficiencies
- Low CAPEX and OPEX
- Low installation costs
- No moving parts
- Low maintenance
- Relatively small vessel
- Adaptable design

APPLICATIONS

- Onshore and offshore production
- Refineries and industrial and petrochemical plants
- Produced water treatment
- Storm water / wash water treatment
- Ethylene quench water treatment

PROPLATE AND PROSKIM

ProPlate CPIs and ProSkim Skimmers are designed and built to meet customer specifications. ProSep has the equipment and the expertise to provide solutions for the toughest primary water treatment problems, available as code or non-code vessels, stand-alone vessels or turnkey skid packages.

PROPLATE CPI

ProPlate CPIs are designed to provide the same removal efficiency as a traditional gravity separator in a much smaller vessel, making them ideal for fixed-platform as well as land-based installations.

ProPlate CPIs are atmospheric tanks or pressurized vessels that are equipped with polypropylene or stainless steel packs designed to enhance coalescence and separation by decreasing the distance the oil droplet must travel to be removed from the continuous phase.

For floating applications with low pressure profiles, a CPI can be designed as a liquid-packed pressure vessel, mitigating the problems traditional atmospheric CPIs have with wave motions.

PROSKIM VERTICAL SKIMMER

A ProSkim vertical skimmer can also serve as a motion-insensitive substitute for the CPI. Though generally larger than a CPI based on residence times of 5-15 minutes, the ProSkim vertical skimmer provides an effective motion-insensitive option. They can be fitted with coalesciing packs to enhance efficiency and reduce residence time requirements, yet still achieve performance comparable to that of a CPI.

REFERENCES

Available upon request.

FOR MORE INFORMATION

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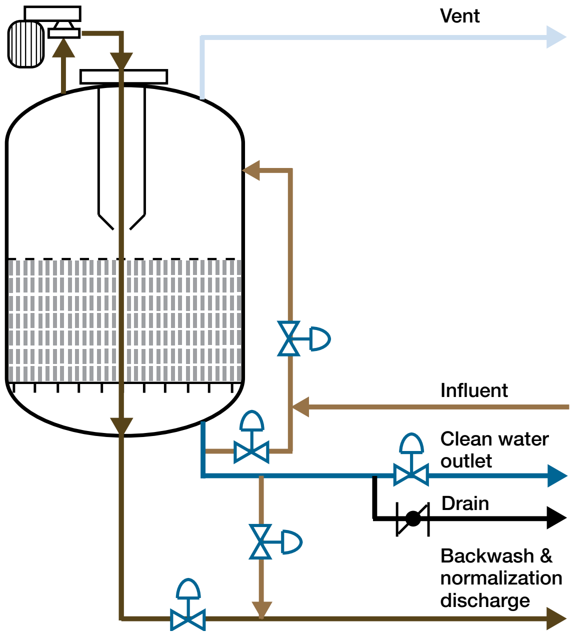
PROSHELL DEEP BED NUTSHELL FILTER

ProSep

Together, creating pure oil, gas and water.

When treatment of produced waters needs to go beyond the results of secondary treatment (typically 15-25 mg/l of oil and/or solids), ProSep provides high-performance tertiary treatment equipment. The ProShell Deep Bed Nutshell Filter can remove 98% of non-water soluble hydrocarbons and particulates greater than 5 microns in most cases, while significantly reducing or eliminating the need for large quantities of backwash water, scouring, and surfactants.



BENEFITS

- Deep bed design for contaminant retention reduces backwash frequency
- Influent stream utilization eliminates backwash water storage tanks and pumps
- System uses lowest backwash volume of available technologies
- Backwash cycle fully fluidizes and regenerates the media bed without additional air scouring
- “Green” technology aids in achieving “zero discharge”
- Nutshell media prevents the fouling / plugging typical of sand and multi-media filters
- Equipment has very low maintenance requirements
- Stainless steel internals and high-reliability backwash pump ensure >99% operational uptime
- Media attrition measures <5% annually

FEATURES

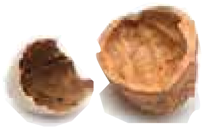
The unique qualities of crushed pecan / walnut shells make for a media that is oleophobic and elastic, yet extremely hard and durable. These characteristics of the ProShell Deep Bed Nutshell Filter lead to greatly diminished media attrition rates combined with maximum performance.

Under normal operating conditions, with a nominal inlet oil concentration of 50 mg/l or less and a comparable solids inlet concentration, nutshell filters will produce an effluent with less than 5 mg/l of dispersed oil and suspended solids without the addition of chemicals.

OPERATING PRINCIPLES

The ProShell Deep Bed Nutshell Filter System features a highly durable media screen supported at vessel bottom and an engineered fluidization path that successfully cleanses the media of oil and particles. The fluidization nozzle is strategically located to insure complete and rapid fluidization of the media bed, reducing backwash water volumes; the scrubber screen has been designed to retain the media within the filter vessel while efficiently drawing contaminants from the vessel. Raw feed water is used during all stages of the backwash cycle.

The nutshell filtration cycle begins when dirty fluid enters the vessel through a valve. As the contaminated fluid is forced through the media bed under pressure, oil and solids are trapped and accumulate within the bed. Clean, filtered water is discharged from the bottom of the vessel. The backwash process consists of 1) fluidizing the bed to dislodge contaminants, 2) discharging the contaminant-laden water, 3) delaying for one cycle which allows for the settling of the media bed, and 4) rinsing to remove any residual contaminants from the media bed prior to bring the filter back online.



MEDIA

The ProShell Deep Bed Nutshell Filter is filled with a blend of pecan and walnut shells which are specially conditioned and ground to a uniform size. The ratio of walnut to pecan shells maximizes contaminant retention while minimizing media attrition.

CARTRIDGE AND ABSOLUTE FILTERS

ProSep also offers cartridge filters with excellent removal efficiencies. As stand-alone tertiary treatment, they can become operator- and OPEX-intensive with frequent cartridge change-outs required to handle typically high contaminant loads. ProSep cartridge filters installed downstream of properly operated nutshell filters, however, offer an excellent produced water treatment solution that approaches “zero-discharge” requirements. In this scheme the ProSep nutshell filter removes the bulk of the suspended solids and dispersed oil, minimizing the load on the ProSep cartridge filters and maximizing the time between element replacements.

REFERENCES

Available upon request.

FOR MORE INFORMATION

Contact your nearest ProSep office
www.prosep.com

About ProSep

ProSep is a technology-based process solutions provider for the upstream oil and gas industry.

The Company designs, develops, manufactures and commercializes technologies to separate oil, gas and water generated by oil and gas production.

ProSep’s innovative offerings have been awarded three Spotlight on New Technology Awards from the annual Offshore Technology Conference in Houston in 2005 and onwards, comprising the proprietary technologies ProScav, CTour and ProSalt.

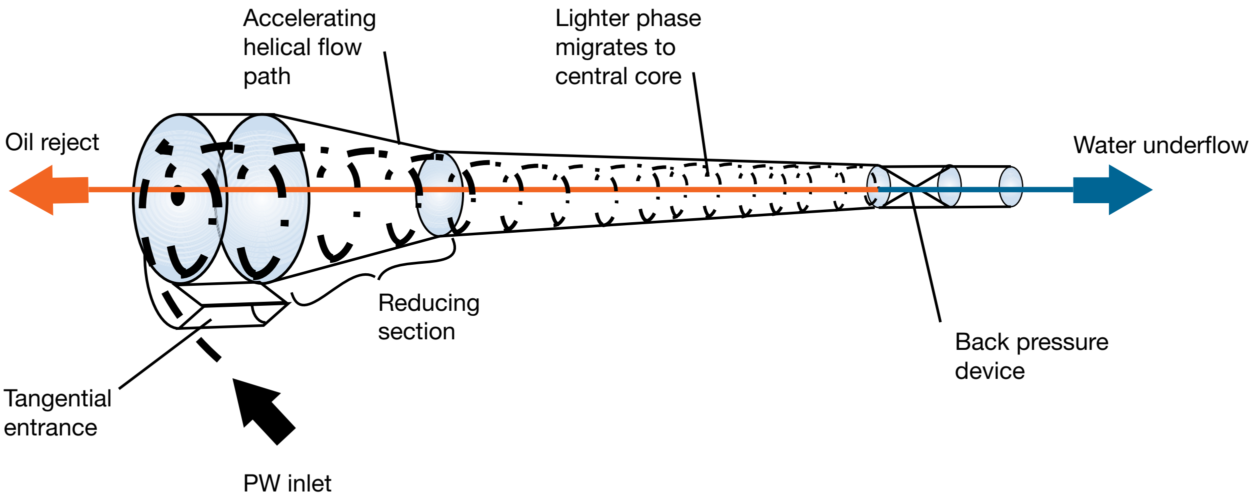
PROSPIN HYDROCYCLONES

ProSep

Together, creating pure oil, gas and water.

As part of effectively treating large volumes of produced water, the ProSpin hydrocyclone separates liquids that have different densities, especially oil and water, by taking advantage of gravity and centrifugal forces. The ProSpin hydrocyclone is an excellent primary separation solution in most offshore applications where sufficient process pressure is available, since it has a small footprint and is highly efficient at separating free oil from water.

PROSPIN FLOW PATH

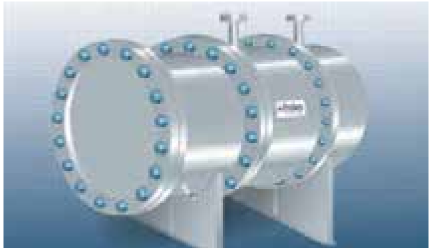


FEATURES

- Customizable size and materials
- Small footprint
- Good turndown
- No moving parts
- Simple controls
- Minimal maintenance
- No external utilities
- Quality construction
- Motion-insensitive
- No chemicals

OPERATING PRINCIPLES

With sufficient pressure from the separator or a pump to serve as a driver, the hydrocyclone takes in oily water at the tangential entrance and moves it through the reducing section. The fluid travels through the narrowing chamber, flowing along the walls and accelerating as it progresses, developing forces that are needed to separate the oil from the water.



The denser fluid moves to the walls of the hydrocyclone and is removed at the downstream fluid outlet (underflow). The less dense fluid is drawn into the low-pressure core and, by applying a back pressure to the outlet, flows back up the hydrocyclone to be removed at the upstream outlet orifice (overflow).

The ProSpin is unaffected by ship or platform motions and delivers typical removal efficiencies of 85-95% of all oil droplets >12-15 microns with effluent quality of 25-100 mg/l OiW.

APPLICATIONS

UPSTREAM PRODUCTION

- Produced water treatment for re-injection or disposal
- Bulk water removal
- Pre-separation ahead of an IGF or DGF

DOWNSTREAM REFINING AND PROCESSING

- Desalter water processing
- API separator replacement
- Ethylene quench water treatment

REFERENCES

Available upon request.

FOR MORE INFORMATION

Contact your nearest ProSep office
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TORR™ DE-OILING TECHNOLOGY

ProSep

Together, creating pure oil, gas and water.

The TORR™ de-oiling technology, with its small footprint and ability to replace less efficient de-oiling equipment, offers the best available process in the treatment of produced water for offshore producers and operators. The TORR™ technology exceeds today's discharge regulations and will address future regulations. The scaleable technology addresses future increases in water cut. Adding compact TORR™ vessels requires very little real estate when water cuts increase.

FEATURES

- Small footprint and low weight
- 1000 ppm down to discharge regulation
- Better polishing for reinjection applications
- Removes and recovers oil droplets larger than 2 microns
- Maximum flow rate per vessel of 60,000 BWPF
- Same high de-oiling efficiency during production start-up periods
- No additional treatment required for recovered oil
- Minimal pressure drop and maintenance and minimal operation costs
- Recovered hydrocarbons can be <0.5% BSW
- High flow rate turndown
- No moving internal parts
- No added heat or chemicals
- Operational temperatures up to 90˚C
- Solids handing capabilities
- Reduced process complexity

TECHNOLOGY

The TORR™ process consists of two inline pressure vessels, and an optional third vessel can be used as a standby.

Produced water enters the TORR™ unit for treatment and then passes through the core of multiple continuous coalescing elements. The continuous coalescing element adsorbs the small oil droplets, coalesces them to large oil globules and then desorbs them.

Gravity separation principles remove these large coalesced globules, which then rise to the top of the vessel. Any solution gas accumulating with the oil at the top of the vessel will be safely recovered. The oil and/or gas collected at the top of the vessel are recuperated and returned to a suitable collection unit.

The TORR™ technology treated produced water exceeds discharge regulations.

REFERENCES

Available upon request.

FOR MORE INFORMATION

Contact your nearest ProSep office
www.prosep.com

About ProSep

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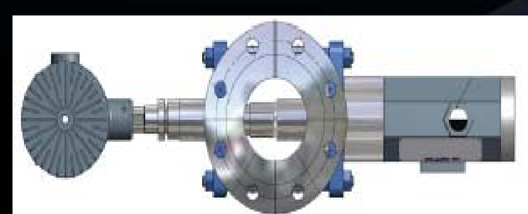
APPENDIX IV

Advanced Sensor Brochure

Advanced sensors

Techniques and Considerations when Measuring Oil in Water

Oil In Water Analysers



Oil In Water Analyser Techniques

Advanced sensors

1. Acoustic spectroscopy
2. Video Microscopy
3. Fluorescence
4. Infra Red Scatter, Absorption

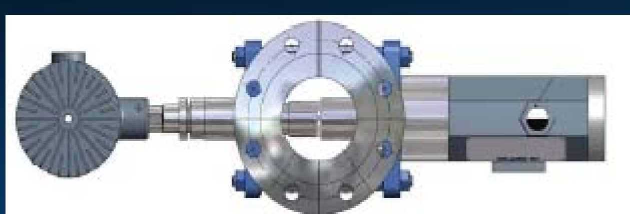
Oil In Water Analyser Techniques
The Challenges

	[illegible]	Video Microscopy	[illegible]	Fluorescence
Measurement Range	[illegible]	0-1000ppm	[illegible]	0-20,000ppm
Oil Droplet Size fluctuation	[illegible]	Oil droplet size does NOT affect measurement	[illegible]	[illegible]
Affects Of solids	[illegible]	Can differentiate and measure solids size. High concentrations can be problematic	[illegible]	Generally has no effect on fluorescence measurement
Affects Of Gas	[illegible]	Problematic, can be counted as oil droplets	[illegible]	Gas does not fluoresce
Affects Of Chemicals	[illegible]	problematic, can be counted as oil droplets	[illegible]	Some chemicals can fluoresce and be measured as oil
Pressure fluctuation	[illegible]	Generally has no effect on measurement	[illegible]	Generally has no effect on fluorescence measurement
Fouling	[illegible]	Although design limits fouling [illegible]	[illegible]	[illegible]

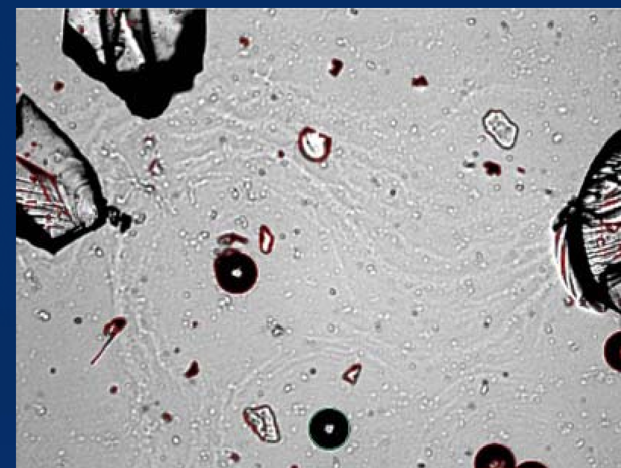
Video Microscopy

Advanced sensors

There is more to Produced Water than just oil.



Video Microscopy

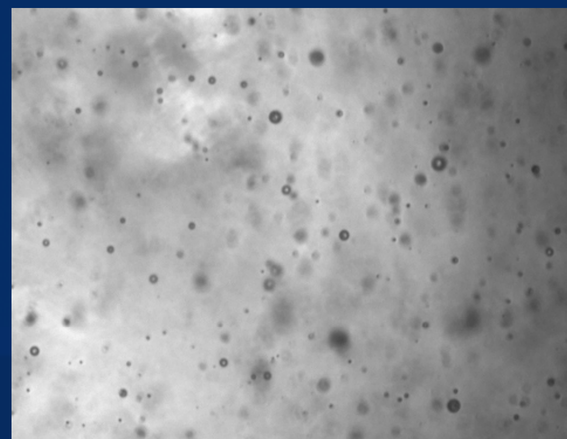


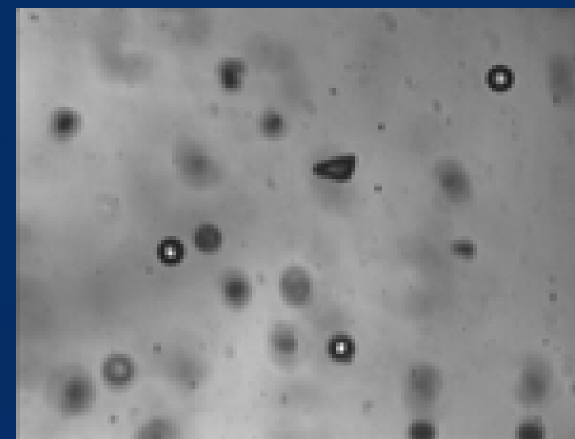
Measurement technique

1. Capture image of water sample.
2. Identification of objects is based on a roundness factor.
3. Objects above a roundness factor are **oil droplet** candidates.
4. Objects below a roundness factor are **solids/particulate** candidates.
5. Size distribution of both solids and droplets are measured.
6. Total area of round objects provide oil measurement.

Video Microscopy

Advanced sensors





1. Image quality, objects must be distinctly visible.
2. Isolation of oil droplets from solids and other oil droplets
3. Cleaning is critical to operation, current options available:
    1. Surfactants
    2. Ultrasonic's

Video Microscopy arguably is the best technique for droplet and particle sizing, but not oil content Measurement

Fluorescent OiW Analysers

Fluorescence

Advanced sensors

Fluorescence
0-20,000ppm
Oil droplet size will affect fluorescence and in turn measuremnt.
Generally has no effect on flourescence/measurement.
Gas does not fluoresce.
Some chemicals can fluoresce and be measured as oil.
Generally has no effect on flourescence/measurement
Cleaning critical to operation.

Fluorescence is arguably the best suited technique for field deployed Oil In Water Analysers

- **Oil Droplet Size**
- **Chemical Interference**
- **Fouling of Optics**

Two types of fluorescent analysers

Contact Type – Side Stream & Inline

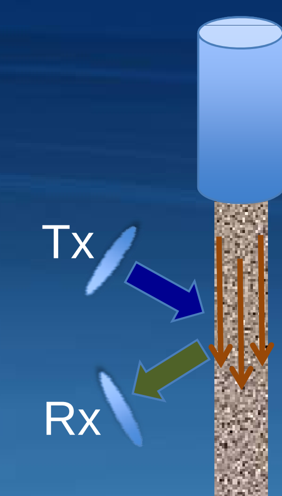
- Sensor in direct contact with water stream.
- Water stream requires no conditioning.
- **Cleaning techniques :**

  Ultrasonic, Surfactants, Manual

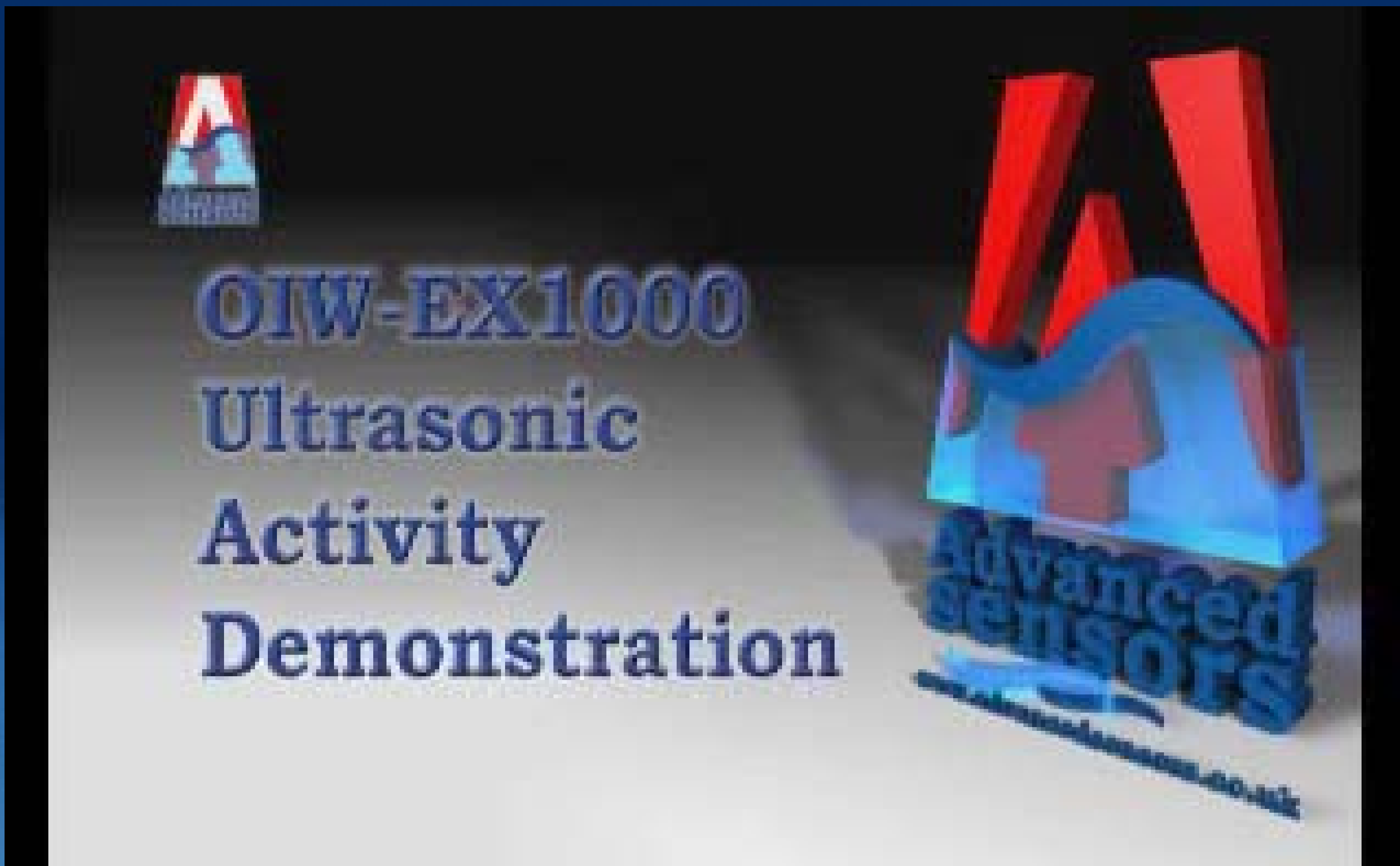
Non Contact Type – Side Stream

- **Sensors not in contact with water stream.**
- **Water stream requires pressure & flow regulation, degassing, & temp conditioning.**
- **Cleaning techniques :**

  Manual cleaning or replacement guards.



Ultrasonic Cleaning



The Maximum Measurement Range

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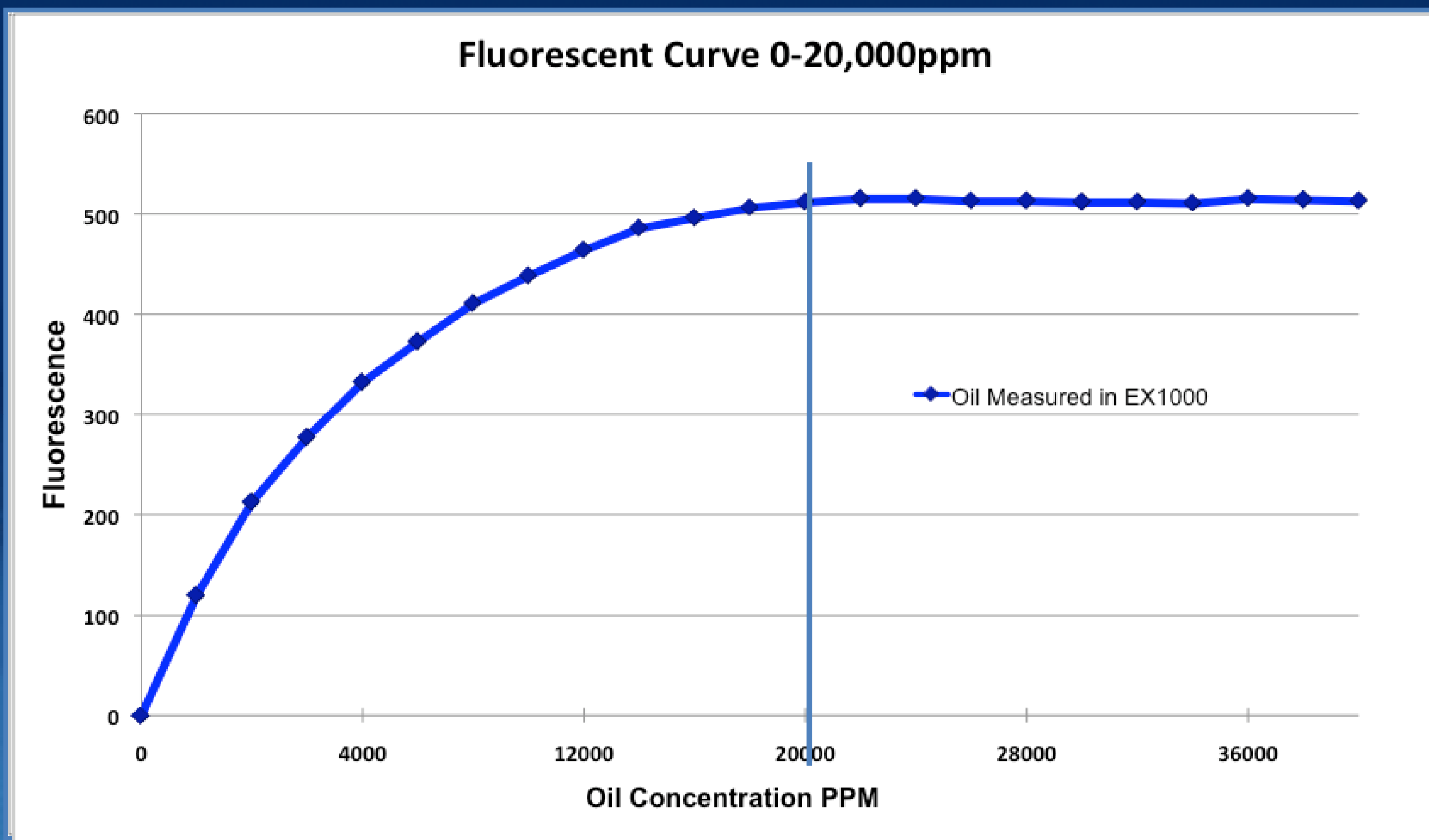
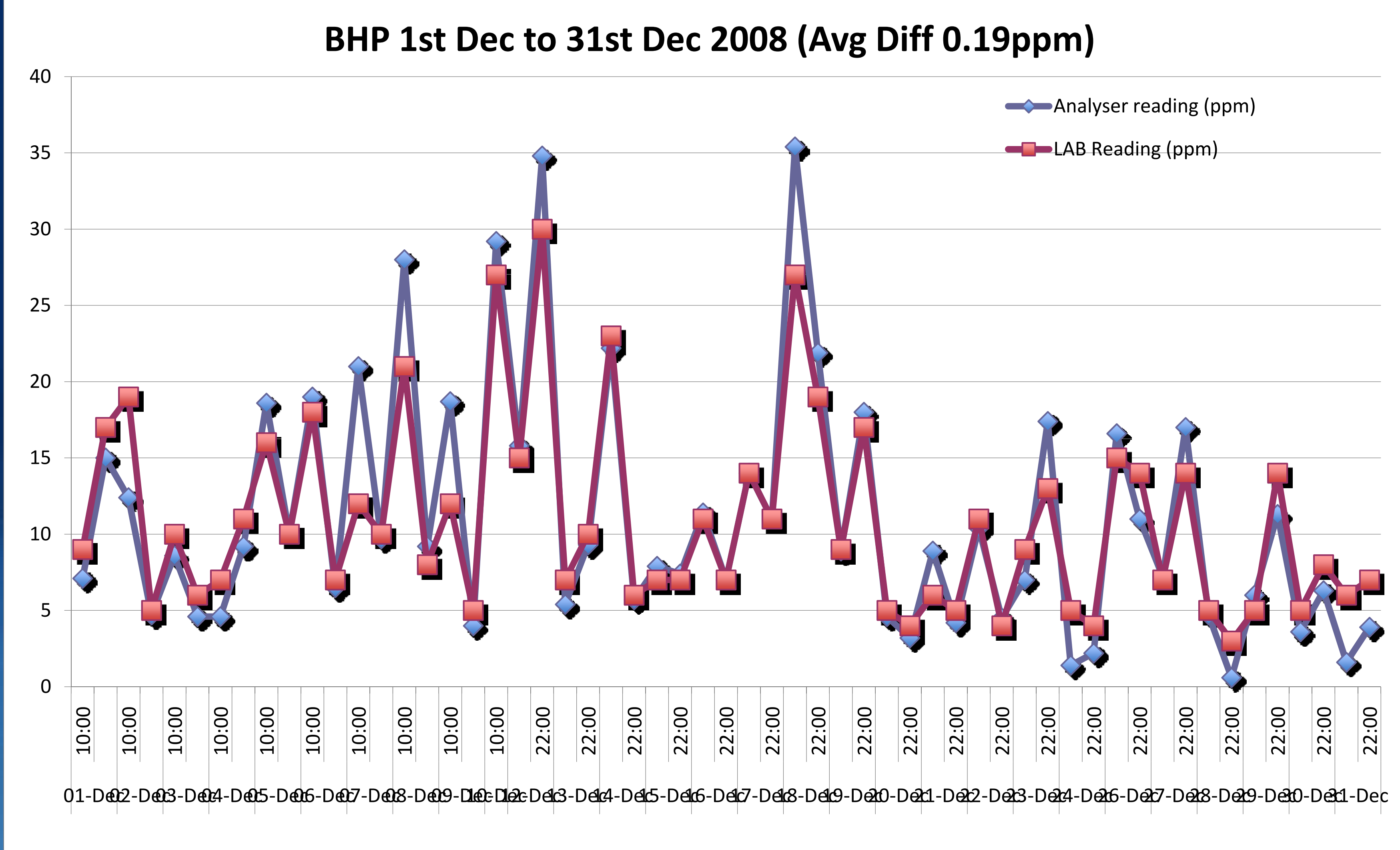


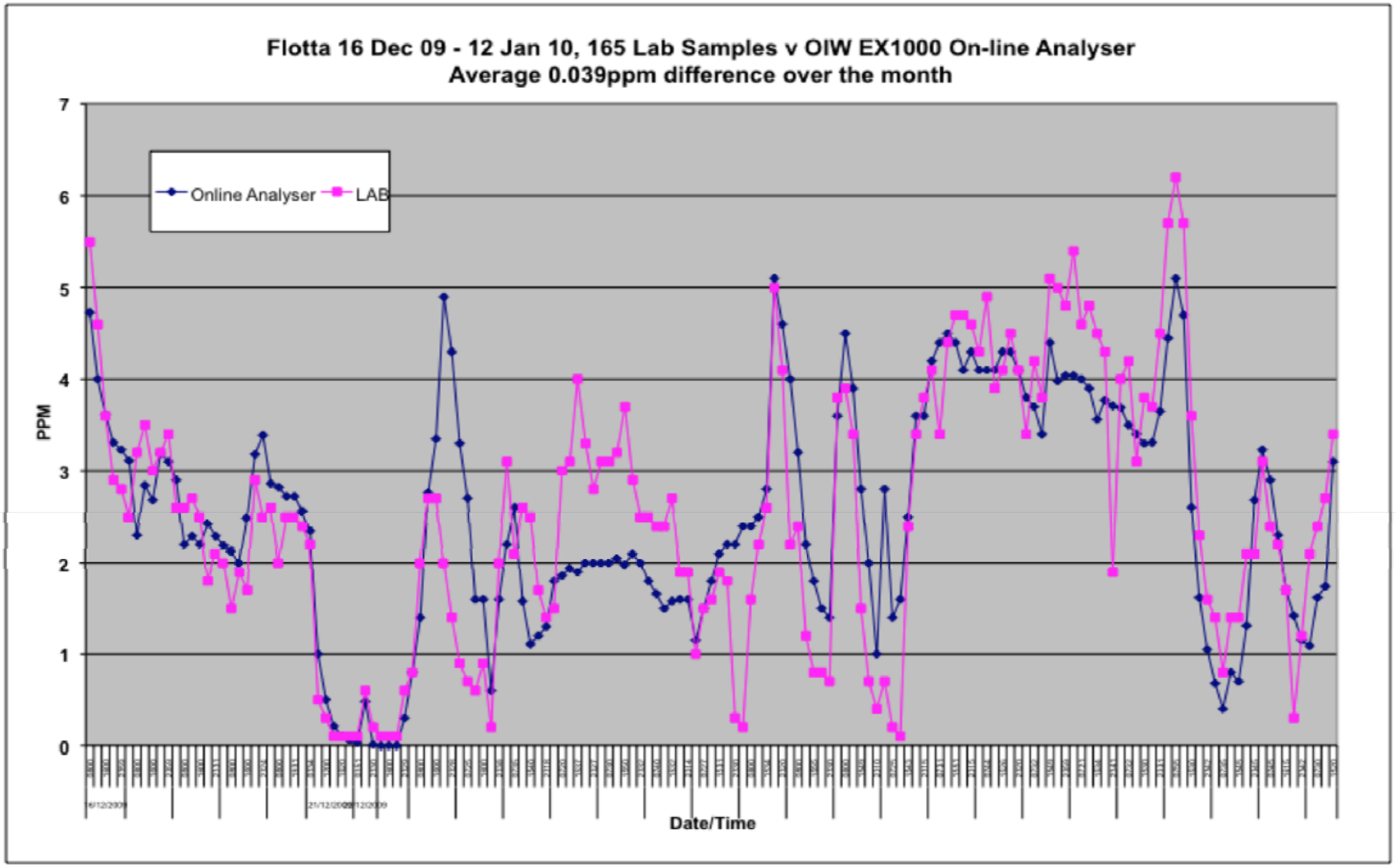
Example Field Results



Example Field Results

Talisman Flotta Results 12th Jan 2010

Analyser installed September 2006



Choosing A On-line OIW analyser

Advanced sensors

Video Microscopy Analyser

- Oil content measurement accuracy typically +/-20%
- Best suited for particle and droplet sizing.
- Not as accurate or reliable as Fluorescence for continuous Oil content measurement.

Side Stream Fluorescent Analyser

- Facilitates good sample representation, excellent for close lab correlation.
- Oil droplet size compensation possible.
- Subject to water conditions sample line may require periodic Flushing.
- Best suited for discharge management and reinjection, but can be used for process management.

Inline Fluorescent Analyser

- Difficulty obtaining representative sample, correlation to lab difficult.
- Oil droplet size compensation NOT possible.
- Best suited for process management

Caution: Determine Objective

Advanced sensors

- Reporting or Process Management
- Measurement Range:
- Maintenance or Cleaning Requirements: ⍰
- Sample Conditioning – Pressure, Gas, Solids, Flow, Pressure:
- Wetted Part Materials:
- Remote Connectivity and Support:
- Data logs:
- **Proof of Performance:**

Advanced sensors

END

APPENDIX V

Stokes Law

SEPARATING OIL FROM PRODUCED WATER

Oil droplets rise in water at a rate governed by Stokes Law

V = Velocity (mm/sec)
g = accel due to gravity
d_w = Water Phase Density
d_o = Oil Phase Density
D = Drop Diameter
μ = Viscosity of Water Phase (cP)

$$V = \frac{g\,(d_w - d_o)\,D^2}{18\,\mu}$$

Produced Water de-oiling techniques are governed by this law

- The limit on size where oil droplets rise in water is 1 to 5 µm
  - In gravity separators practical limit is 50 to 150µm
- Shear reduces the droplet size
  - Through valves, chokes, pipework bends or when gas is liberated
- The natural tendency for oil droplets to coalesce is reduced by :
  - Solids
  - Emulsifying agents (including some Production Chemicals)

Source: BP

APPENDIX VI

Self Cleaning Filters by Amiad

amiad FILTRATION SYSTEMS

EBS Filters

flow rates	filtration degrees	water for cleaning	min. operating pressure
up to **7200 m^3/h** (32000 US gpm)	**800-10** micron	less than **1%** of the total flow	**2** bar (30 psi)

The largest automatic self-cleaning filter for fine filtration

features:

- Large filtration area, reliable operating mechanism and simple construction make the EBS filter the ideal solution for filtration of high-flow and poor quality water to very fine filtration degrees
- Automatic flushing according to pressure differential and/or according to time
- No interruption of downstream flow during flushing
- Robust and reliable self-cleaning mechanism even on marginal operation conditions
- Minimal volume of reject water allows excellent operation during flush mode
- Applications: Water supply systems, Irrigation systems, Cooling Water, Waste Water Treatment, Industrial Pre-Filtration, etc.
- Industries: manufacturing, mining, water and waste water treatment plants, turf and agriculture, etc.

How the EBS Filters Work

General

The Amiad EBS Series are automatic filters, with an electric self-cleaning mechanism.
The "EBS" filters range in flow-rates of up to 7200 m³/h (32000 US gpm), with screens designed ranging from 800-10 micron filtration degree. Inlet/Outlet flanges are available from 8"-36" diameter.

The Filtering Process

Raw water enters from the filter inlet (1) and passes through the screen (2). Clean water flows through the filter outlet (3). The gradual dirt buildup on the inner screen surface causes a filter cake to develop, with a corresponding increase in the pressure differential across the screen. A pressure differential switch (4) senses the pressure differential and when it reaches a pre-set value, the cleaning process begins.

The Self-Cleaning Process

Cleaning of the filter is carried out by the suction scanner (5) which spirals across the screen, the open exhaust valves creates a high velocity suction stream at the nozzle tip which "vacuums" the filter cake from the screen. During the self-cleaning process, which takes approximately 30 seconds, filtered water continues to flow downstream.

The Control System

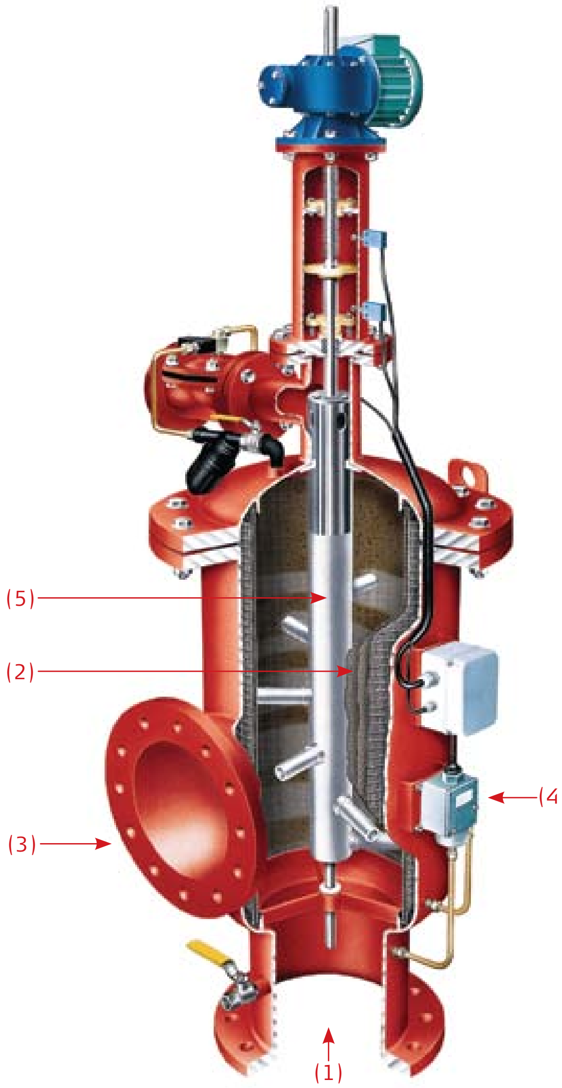
The "EBS" operation and cleaning cycle is controlled and monitored by a Programmable Logic Control (PLC).
The PLC allows maximum flexibility in control options and has many features that can be incorporated per customer's needs. During the self-cleaning cycle the PLC controls a solenoid that operates the exhaust valve by means of a hydraulic command or compressed air.

The self-cleaning cycle begins under any one of the following conditions:

1. Receiving a signal from the Pressure Differential Switch
2. Time interval parameter set at the control board
3. Manual Start

The control board also provides:

- Optional continuous flush mode
- Flush cycles counter
- Alarm output – may be used to open a bypass, shut-off a pump, etc.



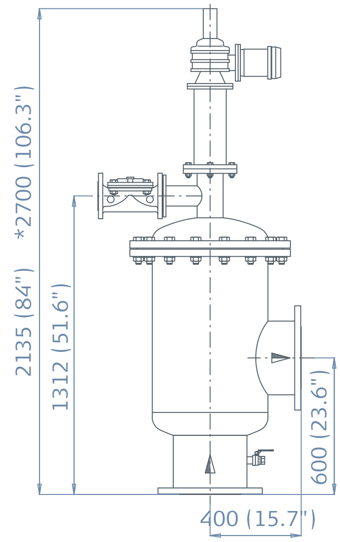
"EBS" Models

Amiad's "EBS" product-line consists of the following models:

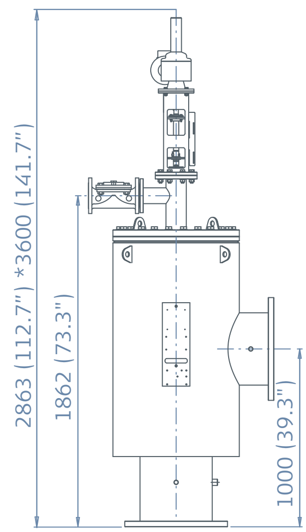
- EBS-10000 for up to 1200 m³/h (5300 US gpm)
- EBS-15000 for up to 1800 m³/h (8000 US gpm)
- Mega EBS 40000 which consists of four EBS-10000 screen elements for up to 4800 m³/h (21100 US gpm)
- Mega EBS 60000 which consists of four EBS-15000 screen elements for up to 7200 m³/h (32000 US gpm)

EBS 10000

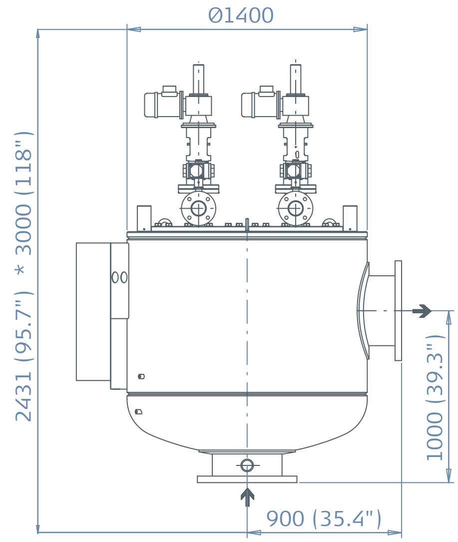
on-line



EBS 15000



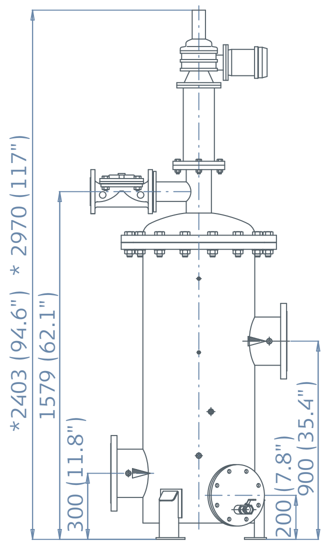
MEGA EBS 40000

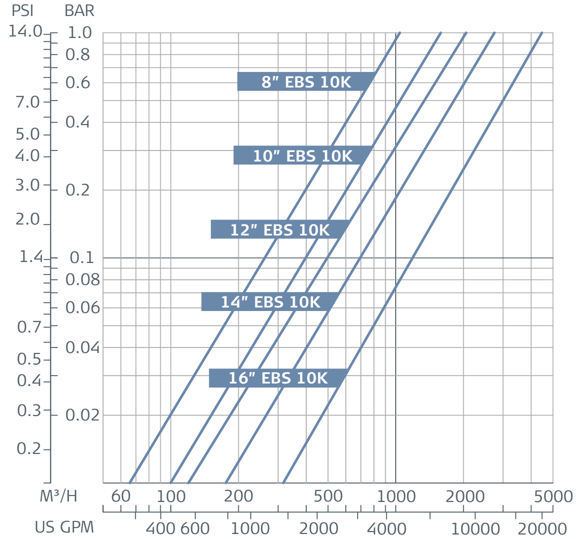


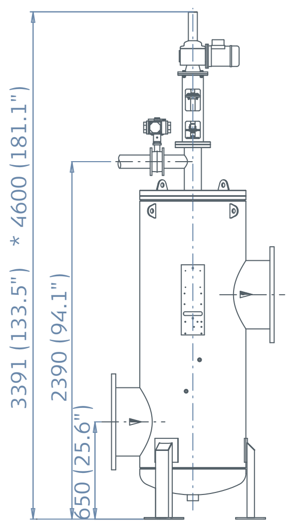
Dim. in mm (inch)
*Approx. length required for maintenance

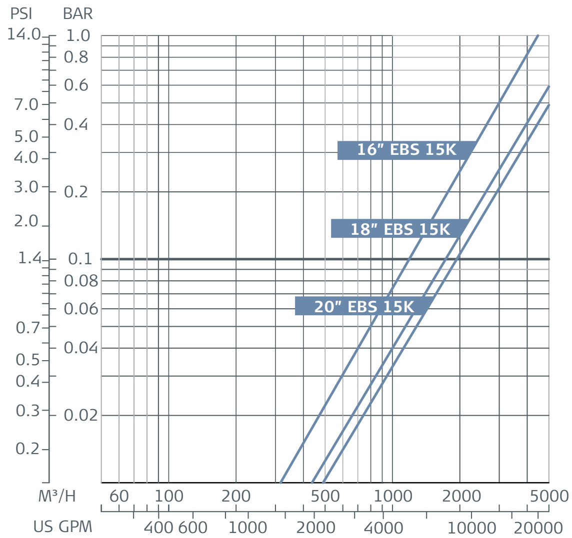
in-line

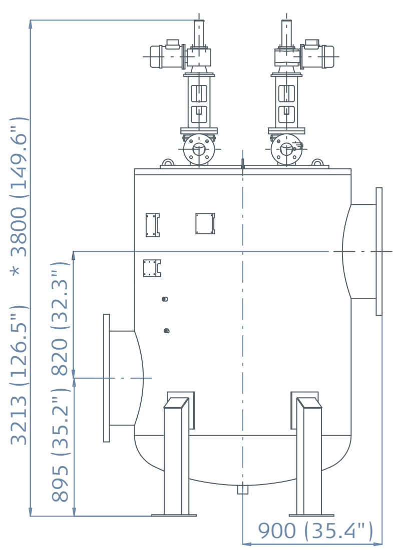
Pressure Loss Graphs

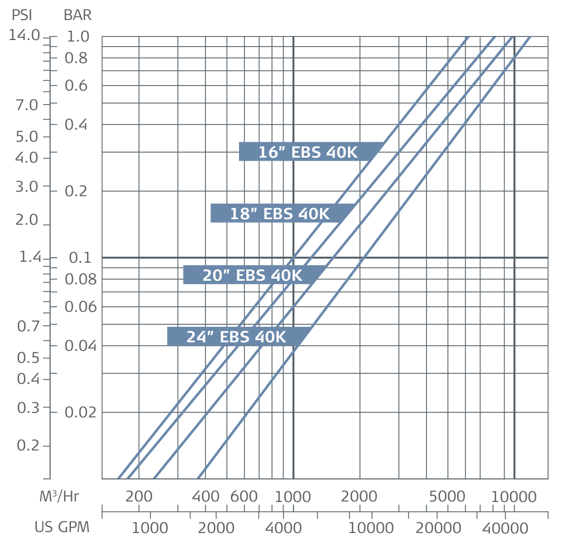












Dim. in mm (inch)
*Approx. length required for maintenance

Technical Specifications

Filter Type	EBS 10000	EBS 15000	Mega EBS 40000	Mega EBS 60000
General Data				
Maximum flow rate*	1200 m³/h (5300 US gpm)	1800 m³/h (8000 US gpm)	4800 m³/h (21100 US gpm)	7200 m³/h (32000 US gpm)
Inlet/Outlet diameter	8"-16" (200-400 mm)	10"-20" (250-500 mm)	16"-24" (400-600 mm)	20"–36" (500–900 mm)
Standard filtration degrees	Weave Wire Screen 800, 500, 300, 200, 130, 100, 80,50, 25, 10 micron			
Min. working pressure	2 bar (30 psi)			
Max. working pressure	10 bar (145 psi) 16 bar (232 psi) upon request			
Max. working temperature	60°C (140°F) 95°C (203°F) upon request			
Electrical Supply	3 phase, 220/380/440 VAC 50/60 Hz			
Weight (empty On-line models)	490 kg (1080 lb)	684 kg (1508 lb)	2250 kg (4960 lb)	6200 kg (13670 lb)

* Consult Amiad for optimum flow depending on filtration degree & water quality

Flushing Data				
Minimum flow for flushing (at 2 bar - 30 psi)	50 m³/h (220 US gpm)	50 m³/h (220 US gpm)	50 or 200 m³/h (220 or 880 US gpm)*	50 or 200 m³/h * (220 or X 880 US gpm) *
Reject water volume per flush cycle	420 liter (111 US gallon)	500 liter (132 US gallon)	1680 liter (444 US gallon)	2000 liter (528 US gallon)
Flushing cycle time	30 seconds	36 seconds	30 or 120 seconds*	144 or 36 seconds *
Exhaust valve	3" 80 mm	3" 80 mm	4 units of 3" 4 units of 80 mm	4 units of 3" 4 units of 80 mm
Flushing criteria	Differential pressure of 0.5 bar (7 psi), time intervals and manual operation			

* One by one or all four screens simultaneously

Screen Data				
Filter area	10000 cm² (1500 in²)	15000 cm² (2325 in²)	40000 cm² (6200 in²)	60000 cm² (9300 in²)
Screen types	Four-layer Weave Wire stainless steel 316L			

Control and Electricity				
Rated operation voltage	3 phase, 220/380/440 VAC 50/60 Hz			
Electric motor 20 / 24 Gear output RPM	½ HP	½ HP	4 x ½ HP	4 x ½ HP
Current consumption	1.5 Amp	1.5 Amp	5 Amp	5 Amp
Control voltage	24 VAC			

Construction Materials*	
Filter housing and lid	Epoxy or Polyester coated carbon steel 37-2
Cleaning mechanism	Stainless steel 316L, Acetal
Exhaust valve	Epoxy-coated cast iron, Natural rubber
Seals	Synthetic rubber, Teflon
Control	Aluminum, Brass, Stainless steel, PVC, Nylon

* Amiad offers a variety of construction materials and screens. Please consult us for specifications

industry

Automotive, Aviation, Ballast treatment, Electronics, Food & Beverage, Mining, Oil & Gas, Petrochemical, Power Generation, Pulp & Paper

municipal

Potable Water, Waste Water, Desalination, Brackish Water, High rise buildings, Pre-filtration to Membranes

irrigation

Agriculture, Golf & Turf, Aquaculture, Green Houses

Manufacturer & Headquarters
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NP.00958/11.2010

APPENDIX VII

Osorb

Osorb®: A Novel Technology in the Treatment of Produced Water
PW Unit #1 and Skid Unit #1

Jay Keener

Production Chemist and PW Unit #1 Program Manager
ABSMaterials, Inc. and PWA, LLC

Abstract

Osorb is a silica-based, swellable glass which can effectively capture 96-99.9% of organic compounds from a produced water stream. The glass is hydrophobic, allowing it to absorb up to eight times its own mass in hydrocarbons and VOCs without absorbing any water. After each use, the organics can be removed from the Osorb for recycling or disposal, and the glass can be reused hundreds of times. In bench testing, Osorb has been successfully used to treat samples of produced water from Wyoming, Canada, and the Gulf of Mexico. In testing the Wyoming produced water, the concentration of hydrocarbons was reduced up to 99.5% after treatment with Osorb. It was determined that this reduction remained effective when using as little as 1.25% w/v (kg glass/L water) Osorb and 60 seconds of contact time. Testing on the Wyoming produced water also indicated that sub-0° C temperatures do not inhibit the ability of Osorb to effectively absorb organic contaminants from the water. The treatment of the Alberta produced water resulted in a ~94.15% reduction in hydrocarbon concentration, though this treatment was carried out using 15% w/v Osorb. A pilot system, PW Unit #1, completed a successful field test in 2010, treating Clinton formation produced water. The use of Osorb in the system resulted in the successful reduction of the 277 ppm hydrocarbons in the Clinton water down to 0.1 ppm, a 99.9% reduction in hydrocarbon concentration. PW Unit #1 is undergoing final stages of development and fabrication and will be deployed in March 2011 to treat produced water in the gas fields in Wamsutter, WY. A second pilot system, Skid Unit #1, has completed two successful treatment tests on produced waters in Texas and Ohio, effectively targeting oil and grease, and BTEX compounds. Skid Unit #1 will be deployed to south Texas in February 2011.

Osorb glass is a new class of silica-based materials that have the capability of swelling and absorbing up to eight times their dried mass of neat, dissolved, or gaseous organic species. Osorb has been shown to possess the following attributes:

1. The rate of swelling is often mass transport limited.
2. Swelling is completely reversible if absorbed species are removed by evaporation or rinsing.
3. Absorption is non-selective and can be induced by non-ionic organic species.
4. The material is hydrophobic and does not swell in the presence of water or water vapor.
5. Swelling and absorption is driven by the release of stored tensile force rather than chemical reaction.

A formulation of Osorb which has proven very effective at treating highly contaminated produced water has been developed. Since much of the structure of Osorb is composed of aromatic rings, the glass has a particularly high affinity for the contaminants typically present in most produced waters: BTEX, VOC's, and hydrocarbons. Also, the high salinity of produced water increases the polarity of aqueous medium. Since the hydrocarbons and VOCs in the water are hydrophobic, this increased polarity causes the compounds to have a higher affinity for Osorb, which is also highly hydrophobic.

To date, multiple lab tests and initial field tests of the PW Unit #1 and Skid Unit #1 pilot scale systems have been completed. The lab tests examined the use of Osorb for the treatment of produced water. The field testing of PW Unit #1 was conducted to analyze a fluidized bed treatment system for larger scale produced water management. Field testing of Skid Unit #1 was conducted to analyze the ability of Osorb to treat produced water in a fixed bed treatment system.

Wyoming Produced Water Laboratory Testing

A sample of Wyoming produced water was collected for bench scale testing. Oil sheen was visible on top of the water sample, indicating the presence of high concentrations of hydrocarbon. A 20 mL aliquot of the water sample was agitated with 2 g Osorb (10% w/v) for 60 seconds. The removal of organics was immediately observable after the addition of Osorb. The Osorb particles, initially clear, swelled and turned brown. The treated produced water became clear and odorless. This physical observation indicates the transfer of organics from the water to the Osorb matrix. The produced water/Osorb solution was filtered to separate the Osorb from the resulting aqueous solution. The Osorb-treated and the untreated produced water were tested using a modified ISO 9377-2 method. The primary deviation from the ISO 9377 was the use of a mass spectrometer rather than a flame ionization detector. This was done so each organic component could be identified by comparison to a NIST98 mass spectral library.

Osorb was highly effective at removing the organic components from the produced water. Using 10% w/v Osorb (kg glass/L water) with a 60 seconds contact time resulted in ~98% extraction of organic species as measured by gas chromatography-mass spectrometry. As suggested by the visible sheen, most of the organic components were hydrocarbons. The post treated results showed some residual benzene and xylene compounds at 4 and 9 minutes.

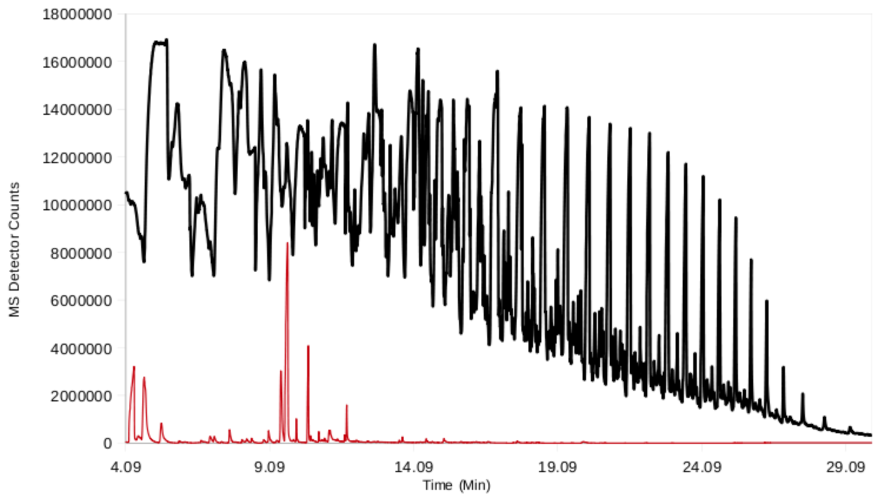


Figure 1. Gas chromatograph-mass spectrometry analyses of (black) untreated produced water and (red) water after 60 second treatment with 10% w/v Osorb.

After the initial analysis of the Wyoming produced water was complete, additional testing was conducted to analyze the effects of: variations in the exposure time of the water with Osorb, variations in the Osorb % w/v used to treat the water, and treatment at relatively low temperatures. To analyze variations in exposure time, three samples of the produced water were exposed to 2 g of Osorb for 30, 60, and 120 seconds, respectively. The results are shown below in Table 1.

Table 1. Correspondence between contact time of Osorb with the water and the % extraction.

Contact Time	% Extraction
30 s	96.0%
60 s	99.0%
120 s	39.5%

These results indicate that having the correct exposure time has a significant effect on the extraction of organic species from produced water, in part due to the surface interactions between the organic species and glass material. The chromatograms from these three tests are shown below in Figure 2. In order to quantify the reduction in contaminant concentration, mineral oil was used as a standard. Using this mineral oil standard, approximate concentrations were obtained for the untreated and treated produced water. The untreated produced water has an approximate total organic concentration of approximately 4.86 mg/L (4.86 ppm), while the sample treated for 60 seconds has a concentration of approximately 0.41 mg/L (0.41 ppm).

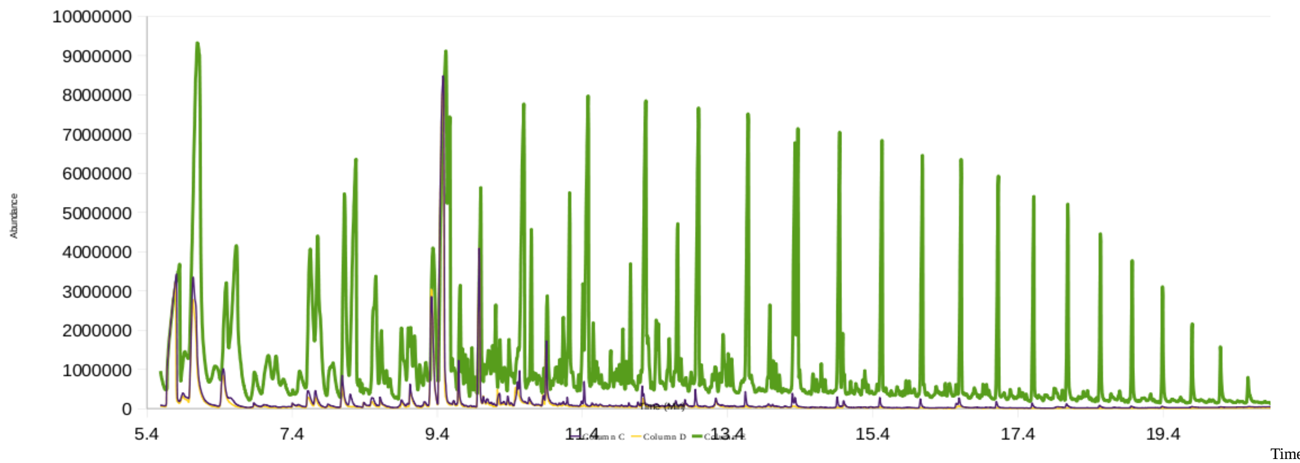


Figure 2. GC-MS chromatograms of produced water samples treated with Osorb for contact times of 30 seconds (blue), 60 seconds (yellow), and 120 seconds (green).

To gain a better understanding of the amount (% w/v) of Osorb required for remediation, 20 mL samples of Wyoming produced water were tested with 250 mg, 1 g, 1.5 g, and 3 g of Osorb, respectively. This testing was carried out with a contact time of 30 s. These extractions all yielded similar results (Table 2) to those obtained in the initial 2 g extraction test. The average extraction efficiency was 98.88%.

Table 2. Correspondence between amount of Osorb used and and the % extraction of the produced water. The contact time for all samples was 30 seconds.

Osorb (g)	Osorb (% w/v)	% Extraction
0.25	1.25%	99.54%
1.00	5.00%	98.93%
1.50	7.50%	98.54%
3.00	15.00%	98.22%

While this data indicates that 1.25 % w/v Osorb was effective at treating the Wyoming produced water, the results are not necessarily translatable to produced water samples from other locations. The amount of Osorb required to treat any contaminated water sample will depend on the identity and concentrations of the target species, as well as the formulation and quality of the Osorb.

To test the effectiveness of Osorb at decreased temperatures, a sample of Wyoming produced water was chilled to slightly above freezing (33.5 F). The standard 2 g of Osorb was used to treat 20mL of produced water with 30 seconds of contact time. The ISO 9377 method detailed earlier was used for extraction and analysis. The resulting spectra indicated an extraction efficiency of 99.18%, suggesting that cold temperatures do not inhibit the absorption of contaminants.

Alberta Produced Water Laboratory Tests

A sample of Alberta produced water was analyzed at the bench scale. A 20 mL sample of the water was treated with 3 g (15% w/v) Osorb for 30 seconds. The removal of organics was immediately observable after the addition of Osorb to the sample. The Osorb particles, initially clear and white, swelled and turned brown. At the same time, the treated produced water became a lighter brown and lost its odor. This physical observation indicates the transfer of organics from the water to the Osorb matrix.

After treatment, the sample was analyzed using the same modified ISO9377 method as previously discussed. GC-MS indicates that ~94.15% of the organic species in the sample was successfully extracted. Figure 3, below, depicts the GC chromatograms of both the untreated sample and the sample treated with 15% w/v Osorb.

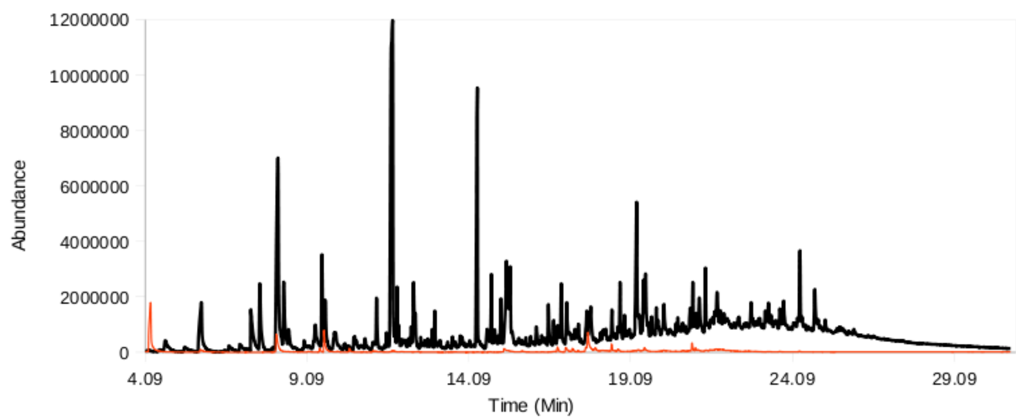


Figure 3. Gas chromatograph-mass spectrometry analysis of (black) untreated Alberta produced water and (red) water after a 30 seconds treatment with 3 g (15% w/v) Osorb.

Completed Clinton Produced Water Field Tests.

Produced water from the Clinton formation in Ohio was used to test PW Unit #1 at a well injection site near Wooster. A sample of untreated water and two samples of treated water were provided to the laboratory for testing. The untreated water was orange, cloudy, and smelled strongly of hydrocarbons. While the treated water was clear and had no odor, the samples did contain small amounts of fine, suspended solids, presumed to be fine Osorb. Therefore, the water samples were filtered through a 0.45 μm filter prior to GC analysis (ISO9377 method).

The analysis found that the untreated water contained 277 ppm hydrocarbons. The two water samples that had been treated with the PW1 system both contained only 0.1 ppm hydrocarbons, which is a 99.9% removal of contaminants. The GC chromatograms in Figure 4 depict this reduction in hydrocarbon concentrations.

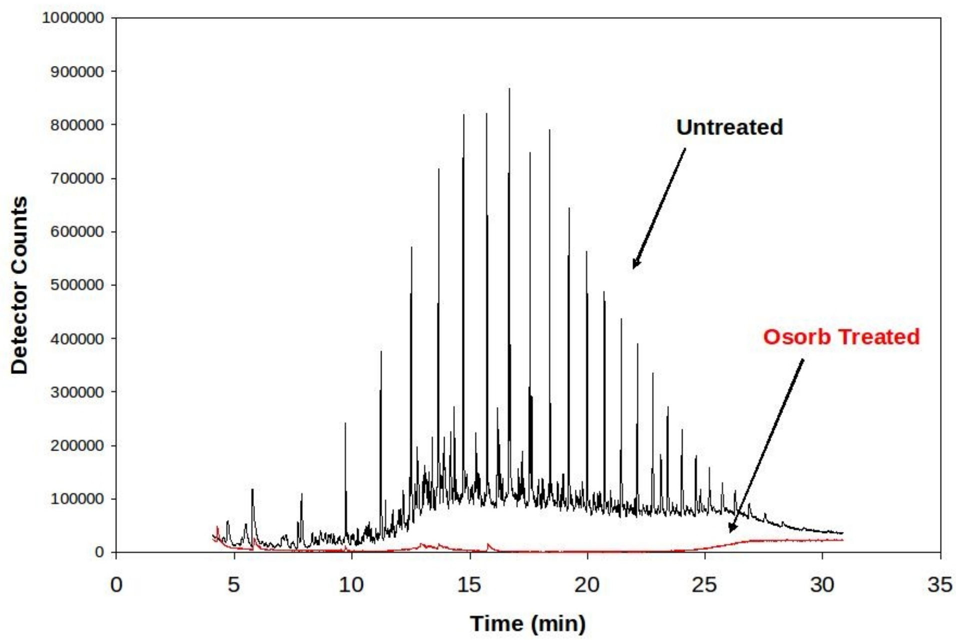


Figure 4. GC chromatograms of Clinton produced water before and after treatment by the PW Unit #1.

PW Unit #1 Development

PW Unit #1 has been extended from 1 trailer to 2 trailers: one for contaminant capture, and one for Osorb regeneration. The contaminant capture trailer includes extensive modifications and upgrades and is designed to treat contaminated water at a rate of 1.5 bbl/min. A high capacity, automatic media filtration system is being added to remove any sand and silt from the incoming water. Following this pre-filtration stage, the water will be pumped through an in-line mixing eductor. Osorb will be added into the top of this mixing eductor via a volumetric feeder, allowing the continuous addition of Osorb into the contaminated water stream. This feed system will allow our team to optimize the amount of Osorb to use as little as needed to meet client requirements. After the addition of Osorb, the water will be pumped into the mixing vessels through tank mixing eductors. These mixing eductors create the necessary turbulence that will result in sufficient contact between the Osorb and the organic species in the water. Following the contaminant capture inside the mixing vessel, the Osorb and clean water will be passed over a vibratory separator to collect the laden Osorb from the clean water discharge. Figure 5 depicts the preparation of the capture trailer during the Clinton produced water field pilot, prior to many of these aforementioned modifications.

Figure 5. Preparation of PW Unit #1 to treat Clinton gas-field produced water.

The complete Osorb regeneration trailer will include a double cone vacuum dryer, complete with thermal fluid system, vacuum pump, heat exchanger, and solvent collector. This system will allow for more rapid thermal regeneration of the Osorb, preparing the glass for reuse in the contaminant capture system.

Skid Unit #1 Development and Pilot Tests

A fixed bed, capture-only treatment system, Skid Unit #1, was developed to treat produced water at flow rates of 1-4 gpm. This system consists of two fixed beds of Osorb, which are contained in filter bags within two stainless steel vessels. The development of a fixed bed system for produced water treatment was important for comparison of fixed bed and fluidized bed (PW Unit #1) systems. Skid Unit #1, shown below in Figure 6, does not include an Osorb regeneration system.

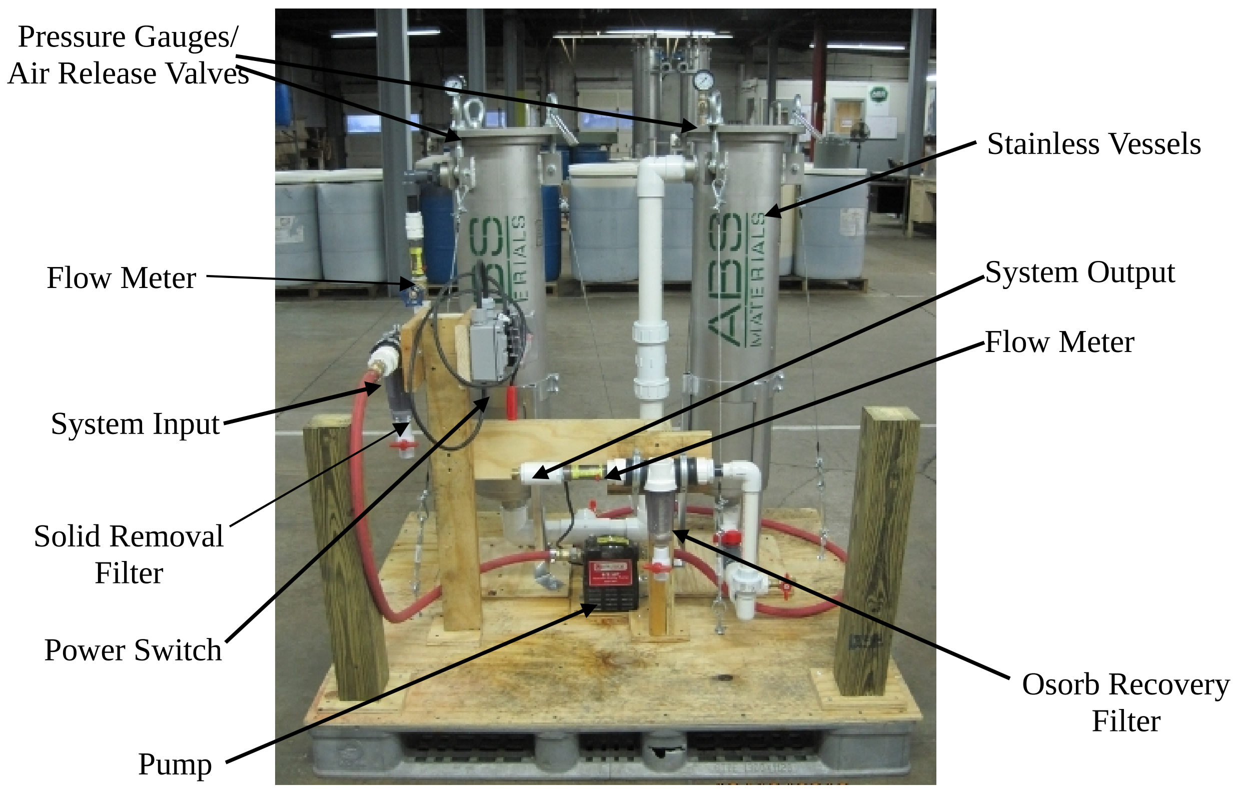


Figure 6. Skid Unit #1 is a capture only, fixed bed treatment systems designed to treat produced water at 1-4 gpm. The glass is regenerated using a separate system.

A pilot test of Skid Unit #1 was carried out in collaboration with the Global Petroleum Research Institute (GPRI) at Texas A&M University. During testing, 100 gal produced water was treated at a rate of 2 gpm. The results from this test are shown in Table 3. Most notably, the fixed bed system reduced Benzene concentrations from 4.24 ppm to 0.206 ppm and oil and grease from 11.5 ppm to no detect. This corresponds with reduction efficiencies of 95.14% and ~100.00%, respectively.

Table 3. Analytical data collected during pilot testing of Skid Unit #1 in collaboration with GPRI.

Analyte	Untreated Water (ppm)	25 gal (ppm)	50 gal (ppm)	75 gal (ppm)	100 gal (ppm)	% Reduction
Benzene	4.24	0.114	0.139	0.194	0.206	95.14%
Ethylbenzene	0.094	0.0016	0.0022	0.0025	0.0027	97.12%
Toluene	0.244	0.046	0.55	0.088	0.094	61.47%
1,2,4-Trimethylbenzene	0.01	0.0011	0.0014	0.0019	0.0019	61.47%
Total Xylenes	0.062	0.011	0.015	0.018	0.019	69.35%
Oil&Grease	11.5				0	100.00%

While the Osorb in the system was able to significantly reduce the concentrations of oil and grease and BTEX compounds in the produced water, analysis of the system indicated that the original design of the fixed bed columns (Figure 7a) could be improved. Due to the low density of Osorb, ~0.55 g/mL, it was determined that the Osorb was likely floating to the top of the filter bag once the columns were completely filled with water. This would have resulted in the formation of preferred paths for the water passing through the column (Figure 7b), reducing the contact time between the Osorb and the species in the water. In order to prevent the formation of these preferred paths, a porous filter disc and layer of sand pebbles were added to the column on top of the Osorb (Figure 7c). The sand pebbles and filter disc exert a downward force on the bed of Osorb, keeping the Osorb in a compact layer.

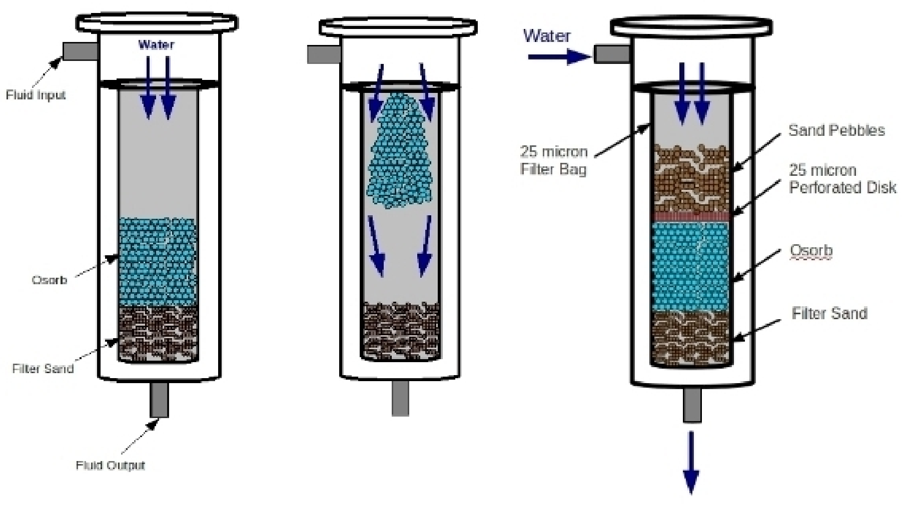


Figure 7. (a) The first generation fixed bed column design. (b) The preferred paths created during operation of the Skid Unit #1 when the columns are full of water. (c) The second generation fixed bed column design.

After modifying the design of the fixed bed columns, Skid Unit #1 completed a pilot treatment of 50 gal of Clinton produced water at 2 gpm. The data collected from this test is shown below in Table 4. The data indicates a reduction efficiency of >93% for BTEX compounds and >99% for oil and grease.

Table 4. Analytical data collected during the treatment of Clinton produced water with Skid Unit #1.

Analyte	Untreated Water (ppm)	50 gal (ppm)	% Reduction
Benzene	1.28	0	100.00%
Toluene	1.4	0.08	94.20%
p-Xylene	2.83	0.18	93.80%
Oil and Grease	290	2.48	99.10%

Conclusions and Future Work

At the bench scale, Osorb is working effectively on all produced water samples provided. ISO9377 appears to be an accurate method for assessing hydrocarbon content, but other analytical techniques such as TOC are also being explored. The PW Unit #1 pilot scale unit has proven effective at using Osorb to treat Clinton produced water. Upcoming field tests in Wamsutter, WY will be useful to further study the ability of Osorb to remove BTEX, oil and grease, and other organic species from produced waters at 1.5 bbl/min. These tests will provide more quantitative data regarding the reduction in contaminant concentrations in produced water from over 11 locations. The unit will continue to be refined as a continuous process system, working towards a system capable of operating at 5 bbl/min. Skid Unit #1 has provided valuable data regarding the performance of Osorb in a fixed bed system, and its upcoming field pilots in south Texas and the Marcellus will provide additional quantitative data.

APPENDIX VIII

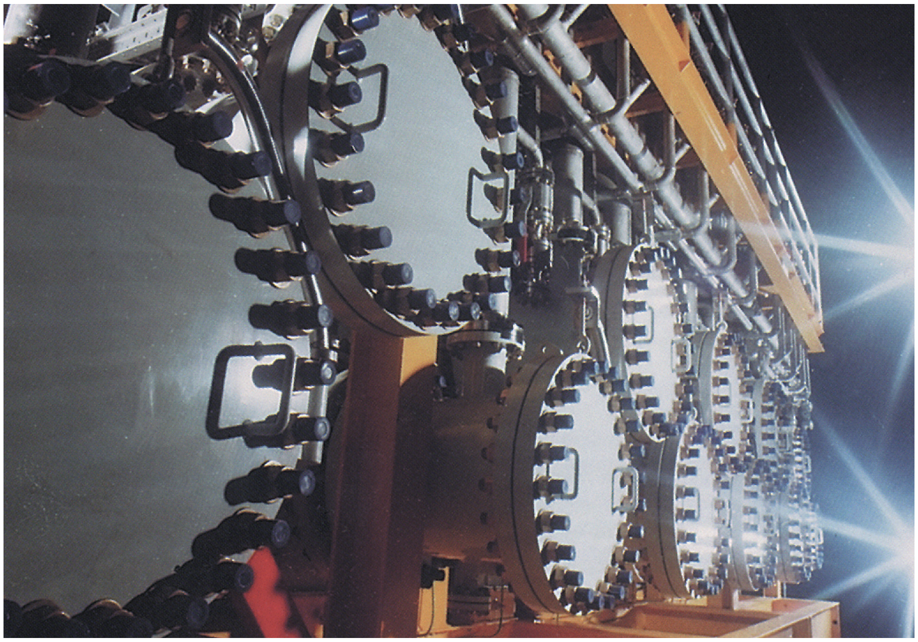
Vortoil by Cameron Deoiling Hydrocyclone

WATER

VORTOIL® Deoiling Hydrocyclones

Proven efficient separation systems

After more than 20 years of continuous development and operational experience, VORTOIL K&G Series deoiling hydrocyclones are widely recognized as being the most technologically advanced cyclones on the market.



Overview

VORTOIL Deoiling Hydrocyclones are utilized widely in offshore oil production for the efficient treatment of large volumes of produced water. Based on the physics of enhanced gravity separation and free vortex action, the hydrocyclone has a cylindrical inlet followed by a tapered tube with the liquids entering through tangential inlets. These forces, combined with differential pressures set up across the hydrocyclone, allow the heavy phase to exit at the underflow while the lighter phase falls into reverse flow and exits the overflow at the opposite end.

Operating Principle and Key Features

VORTOIL Deoiling Hydrocyclones are used to separate two liquids of differing densities, e.g. oil from water. Usually driven by process pressure, oily water enters the line through the inlet to the involute chamber and is directed to flow along the liner wall. Forced down the liner, the fluid accelerates in the narrowing cross-section and the forces required to separate the oil droplets are developed. Centrifugal forces acting upon the heavier water phase cause it to migrate to the wall of the tapered section. The lighter oil phase is displaced as a result and forms a central, low-pressure core which is removed via the reject. The outer clean water vortex exits via the underflow.

Performance

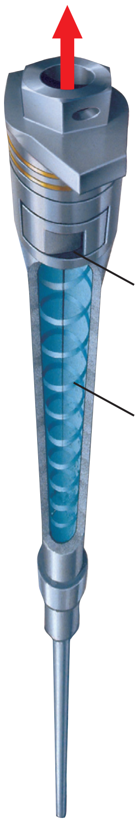
VORTOIL Deoiling Hydrocyclones offer a superior combination of high performance, small size, high capacity, light weight, high reliability, and low cost operation. We can improve your existing hydrocyclone system performance by retrofitting any existing hydrocyclone vessel with VORTOIL Deoiling Hydrocyclones that are more efficient and have higher capacity. Our hydrocyclone systems can also be packaged with other Cameron technologies to meet stringent environmental discharge limits.

Product Range

We have extensive experience on both conventional deoiling processes and pre-separation for concentrations of oil in water in excess of 2%.

Contact us to run a test before deciding what to do. We provide full testing services and will visit your installation with a range of our liners to undertake testing and ensure optimal selection.

While VORTOIL Deoiling Hydrocyclones are designed for liquid/liquid separation, it is recognized that many applications contain sand resulting in the highly abrasive wear of the liners. Cameron can address this problem through the use of a variety of special wear-resistant materials including tungsten carbide.



Benefits and Advantages

- Highest density hydrocyclone packing on the market giving the smallest package footprint and lowest weight.
- Ramped geometry maximizes flow and minimizes erosion.
- No moving parts, low maintenance, no external power required, minimal controls.
- Removable involute allows easy disassembly, cleaning, inspection and replacement.
- Range of material options to suit corrosive and erosive environments.
- Insensitive to motion, ideal for floating production systems.

Options and Types

- For high capacity applications choose the larger diameter VORTOIL G Series hydrocyclone which provides high throughput and performance with minimal footprint, weight and cost.
- For high efficiency choose the smaller diameter VORTOIL K Series hydrocyclone which makes it possible to handle the most difficult of separations. The K Series cyclone is recognized as the industry benchmark against which all other cyclones are compared.
- For large turndown applications, a single vessel divided into multi-compartments can be provided. This is ideal for variable flow rate systems, such as test separators. The vessel is segmented, allowing groups of liners to be turned on and off individually.
- To improve the operation and performance of existing hydrocyclone systems, we can retrofit any existing hydrocylone vessel with the more efficient/higher capacity latest VORTOIL hydrocyclones.
- Hydrocyclones can be packaged with other Cameron technologies to meet the stringent environmental discharge limits.

Installation Examples

Oil Production

- Shell, Fixed Platform, North Sea, UK
- ESSO Balder FPV, North Sea, Norway
- BP Schiehallion FPSO, Atlantic

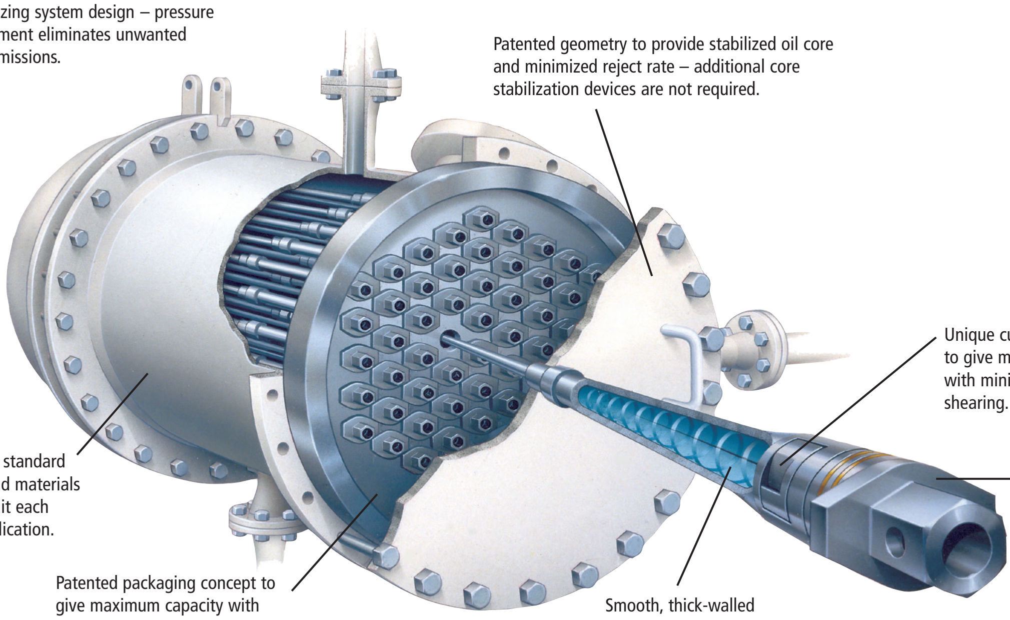
Applications

Oil Production

- Produced water treatment for discharge or reinjection
- Free Water Knock-Out pre-separation

Refining and Chemical Processing

- Deoiling feed to strippers
- API separator replacement
- Desalter water discharge



LOCATIONS

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OTHER LOCATIONS

Abu Dhabi
Australia
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Calgary
Colombia
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Japan
Mexico
Saudi Arabia
Russia

www.c-a-m.com

APPENDIX IX

Hydrocyclones

Cross Flow Filtration Hydrocyclones (CFFH):
Challenges and Opportunities for Cleaning Produced Water

Volodymyr Tarabara (CEE), Thomas Davis, Wenqian Shan
Charles Petty(CHEMS), Karuna Koppula, Satish Muthu
André Bénard (ME), Mark Gaustad, Ryan Rieck
Ram Mohan (ME & PE), Daniel Brito, Jesus Pacheco

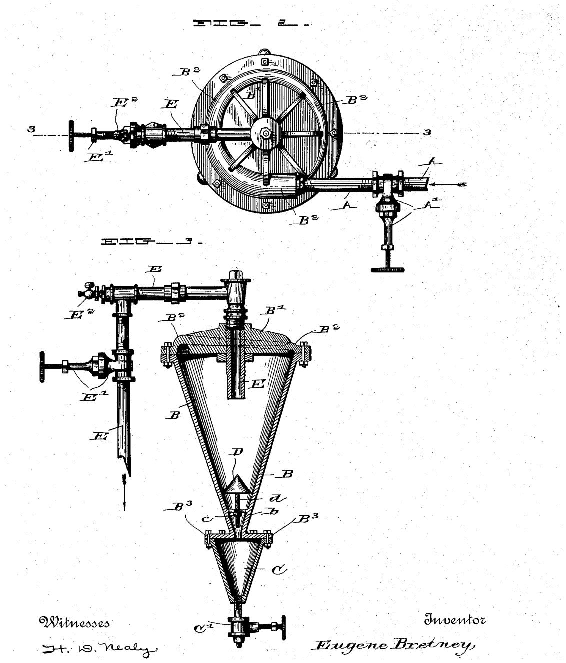
National Science Foundation
Industry/University Cooperative Research Center
for Multiphase Transport Phenomena

Michigan State University and The University of Tulsa

21st Annual Produced Water Seminar
Nassau Bay Hilton, Houston, Texas
January 19, 2011

Acknowledgments

“Water Purifier”,
Eugene Bretney, 1891
U.S. Patent 453,105



George Chase, The University of Akron
Duane Devall, Krebs/FLSmidth
Sean Meenan, Pall Corporation

I/UCRC-MTP Sponsors --- CFFH
Ansys, Bechtel, BP,
ConocoPhillips, MI-Swaco
U.S. Department of Interior - BOEMRE
National Science Foundation

NSF Partnership for International Research and Education: New generation synthetic membranes - Nanotechnology for drinking water safety

What Is Produced Water?

A multicomponent, multiphase fluid that may be toxic and radioactive.

- Produced with oil and gas
- Constituents ---

  Water

  Insoluble solids (sand, etc.)

  Soluble salts and inorganic chemicals (NaCl, etc.)

  Insoluble oil and grease

  Soluble hydrocarbons and other organic chemicals

  Biological species

Lots of Produced Water !
waste or opportunity?

About 6 stadiums/day in U.S. (600x600x150 ft^3)
About 22 stadiums/day worldwide

Spartan Football Stadium
MSU Campus
East Lansing , MI

Clark and Veil, 2009

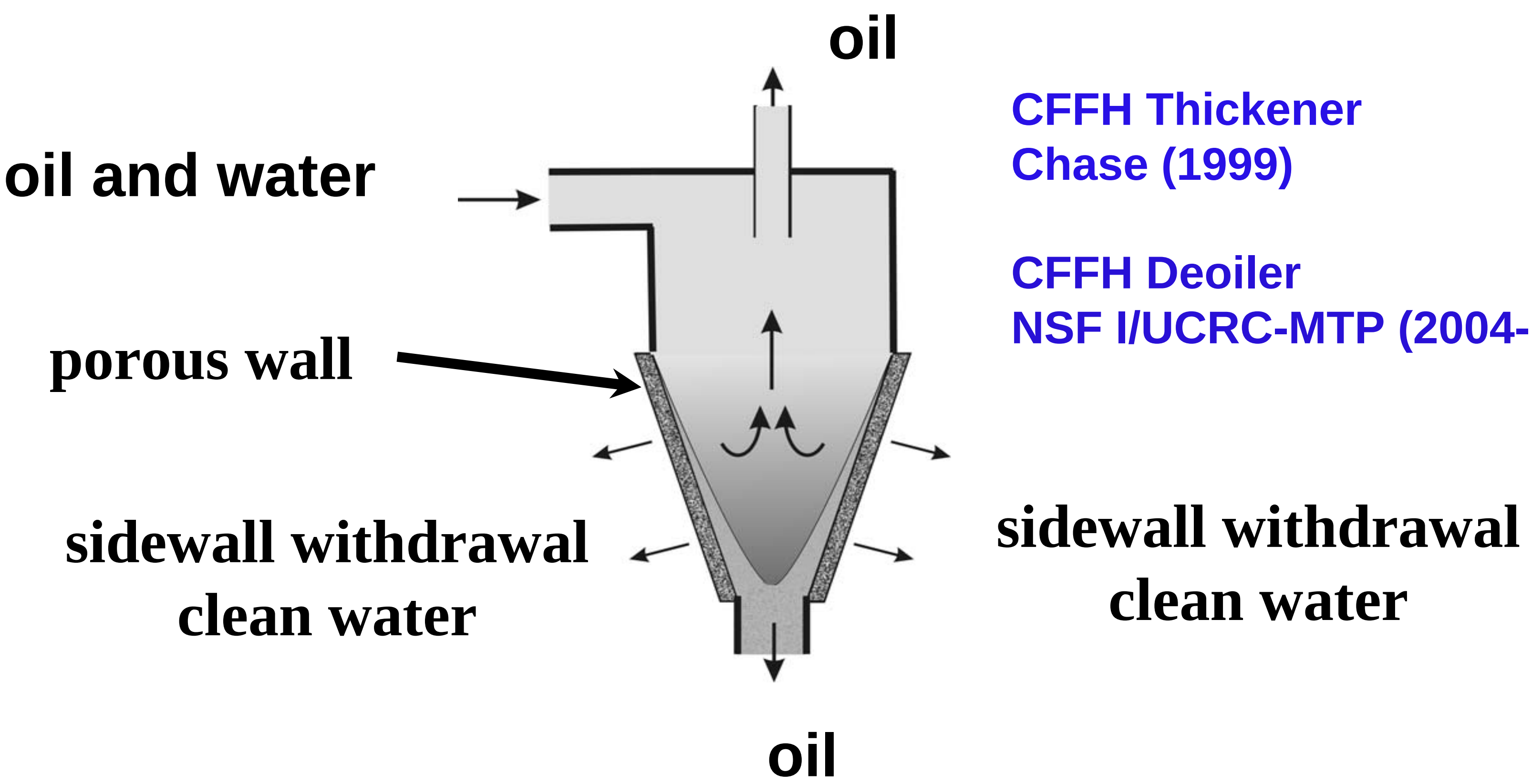
United States

2.4 billion gallons/day

Part I: Hydrocyclone --- physical principles
Charles Petty

Part II: Cross Flow Filtration --- membrane selection
Vlad Tarabara

Can a combination of centrifugal separation, cross flow filtration/coalescence improve oil/water separation?



CFFH Thickener
Chase (1999)

CFFH Deoiler
NSF I/UCRC-MTP (2004-present)

Separation Principles

$$\underline{e}_\theta \cdot < \underline{u}_c > = \underline{e}_\theta \cdot < \underline{u}_p >$$

$$\underline{e}_z \cdot < \underline{u}_c > = \underline{e}_z \cdot < \underline{u}_p >$$

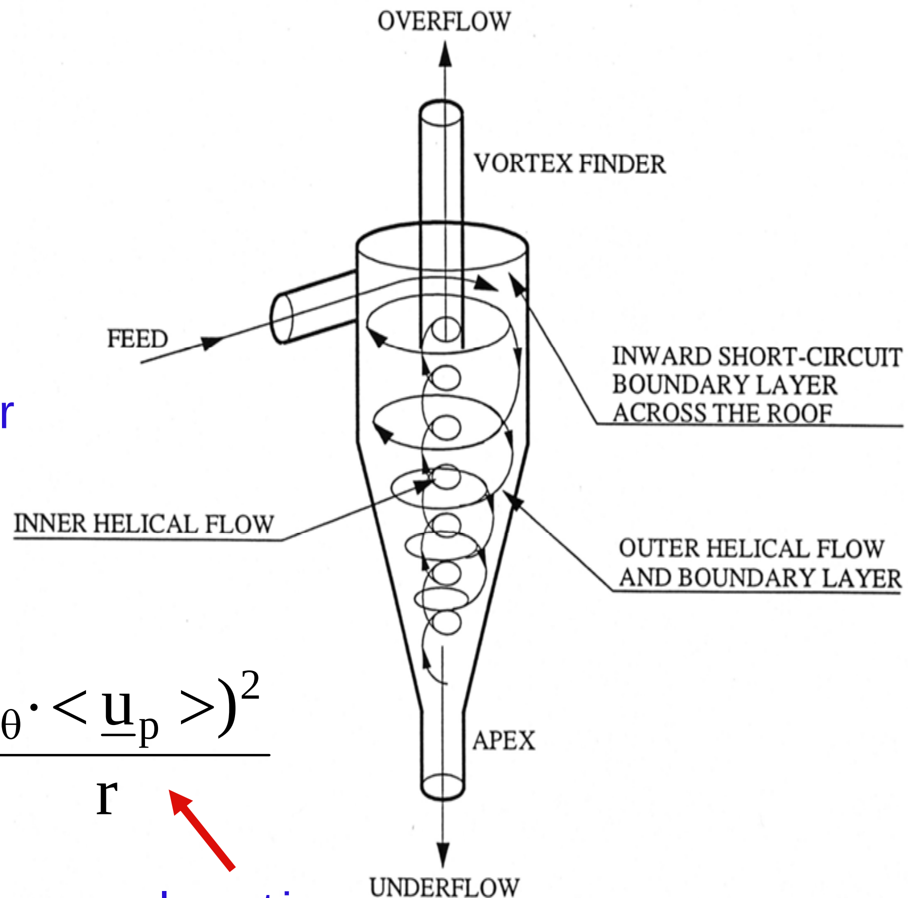
particle diameter

density difference

$$\underline{e}_r \cdot [< \underline{u}_p > - < \underline{u}_c >] = \frac{(\rho_p - \rho_c)\ell^2}{18\mu_c} \frac{(\underline{e}_\theta \cdot < \underline{u}_p >)^2}{r}$$

viscosity

acceleration



Flow Visualization

Klaus Weispfennig, 1991
Flow Visualization in a Confined Vortex Flow,
Hydrocyclone Development Consortium
Michigan State University

United States Patent [19]

McCarthy

[11] **Patent Number: 5,769,243**

[45] **Date of Patent: Jun. 23, 1998**

[54] **THROUGH-FLOW CLEANER WITH IMPROVED INLET SECTION**

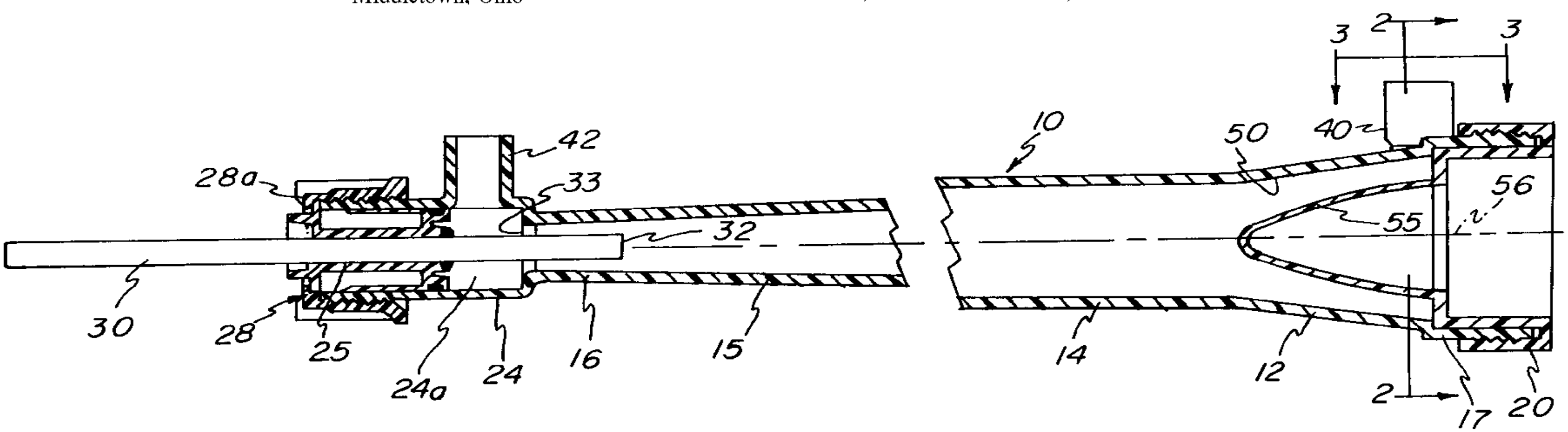
[75] Inventor: **Christopher E. McCarthy,** Middletown, Ohio

[73] Assignee: **Thermo Black Clawson Inc.,** Middletown, Ohio

0137084	4/1985	European Pat. Off. .	
348235	8/1972	U.S.S.R.	209/732
471905	5/1975	U.S.S.R.	209/732

OTHER PUBLICATIONS

3" *X–Clone Black Clawson Through Flow Centrifugal Cleaners*, Bulletin No. 75–SB, The Black Clawson Com-



Forward Flow Hydrocyclone

US005882530A

United States Patent [19]

Chase

[11] **Patent Number: 5,882,530**

[45] **Date of Patent: Mar. 16, 1999**

[54] **CROSSFLOW FILTER CYCLONE APPARATUS**

[75] Inventor: **George G. Chase**, Wadsworth, Ohio

[73] Assignee: **The University of Akron**, Akron, Ohio

4,597,871	7/1986	Okouchi et al.	210/456
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5,078,549	1/1992	Schweiss et al.	406/173
5,458,738	10/1995	Chamblee et al.	162/190

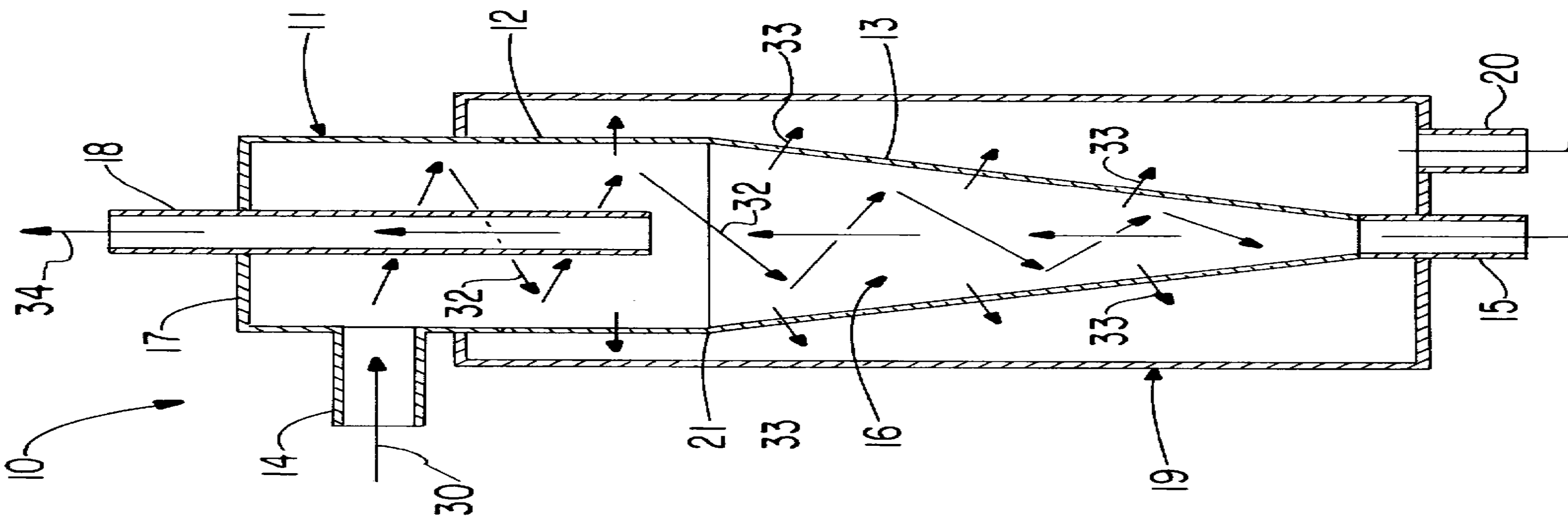
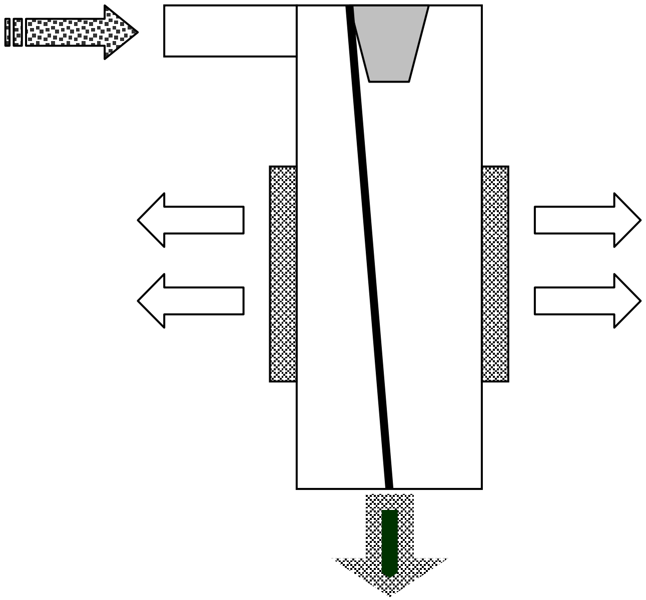


FIG.-2

CFFH for Thickening

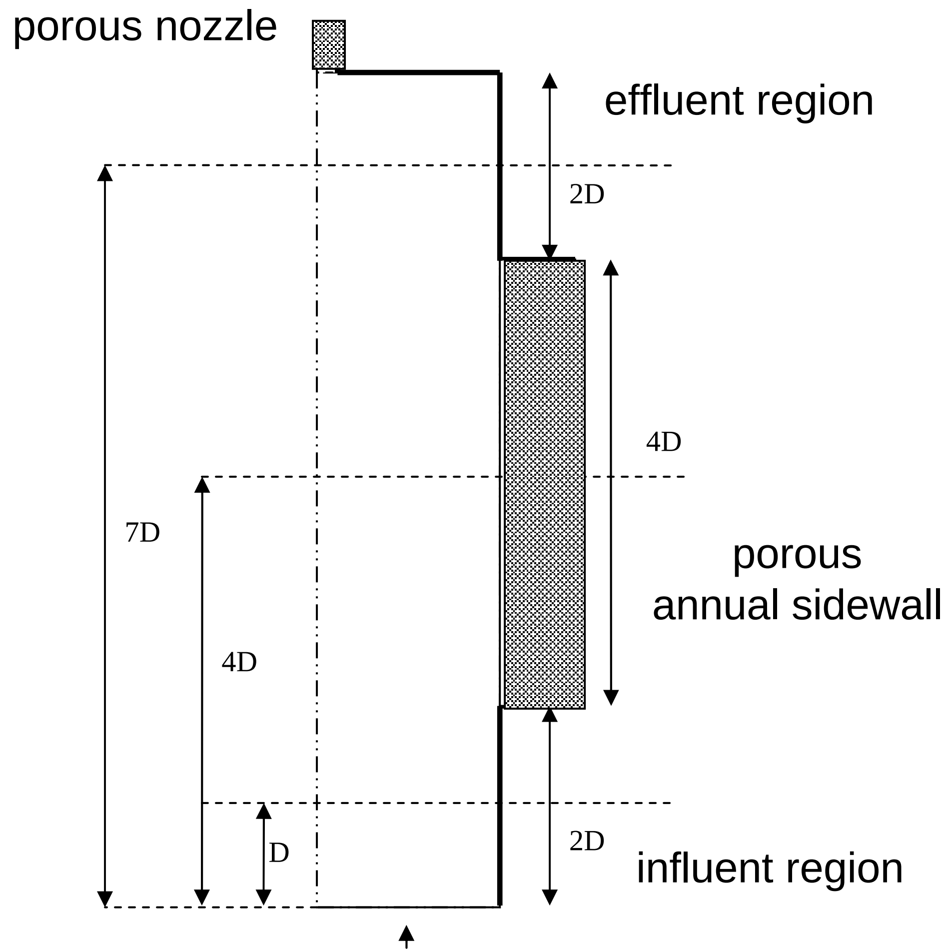
Forward Flow Cross Flow Filtration Hydrocyclone



Physical Properties		
Viscosity		$0.001\,kg/(m-s)$
Density		$1{,}000\,kg/m^3$
Mean Droplet Size		30 microns
Hydrophilic Porous Wall	Porosity	0.50
	Permeability	$10^{-10}\,m^2$
Oleophilic Porous Nozzle	Porosity	0.50
	Permeability	$10^{-8}\,m^2$

FF Geometry

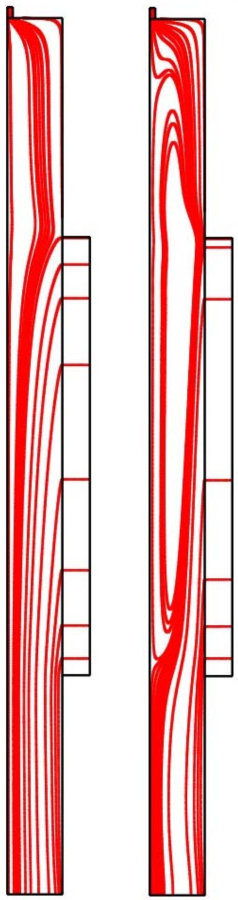
Vortex Tube Geometry, D = 20 mm	
Flow Domain	Length mm
20-mm diameter influent region	40
5mm -thick porous annular sidewall	80
20-mm diameter effluent region	40
2 mm-diameter porous overflow nozzle	2



$$u_z = u_F$$

$$u_\theta = u_F S \frac{r}{R}$$

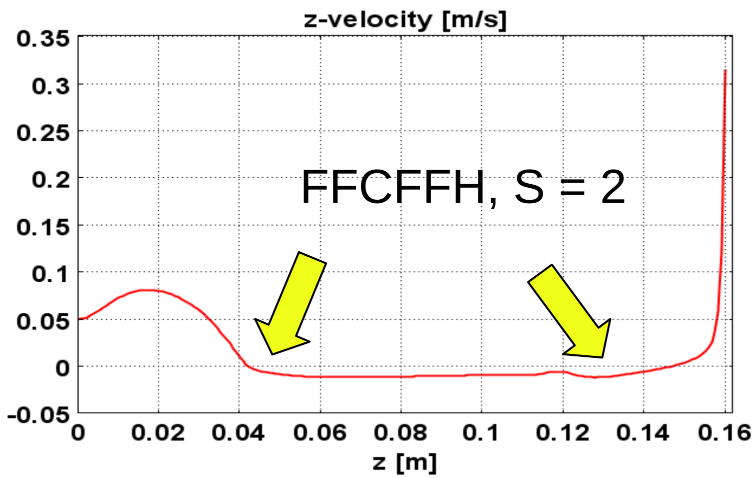
FFCFFH

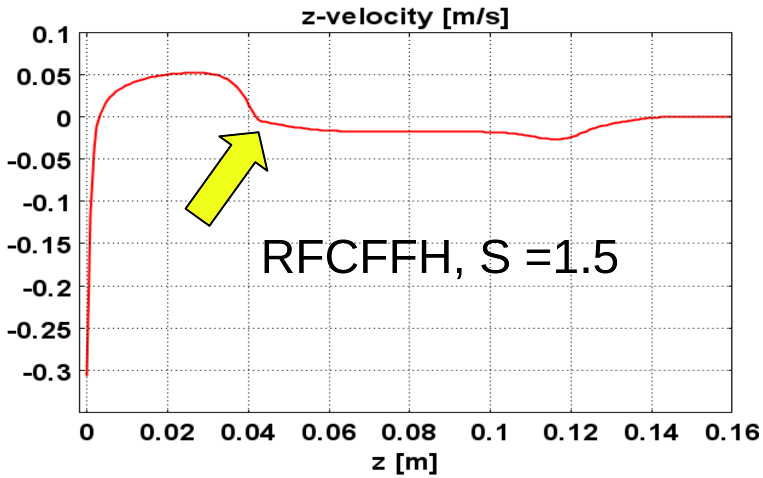


Re = 1,000

COMSOL Navier-Stokes solver

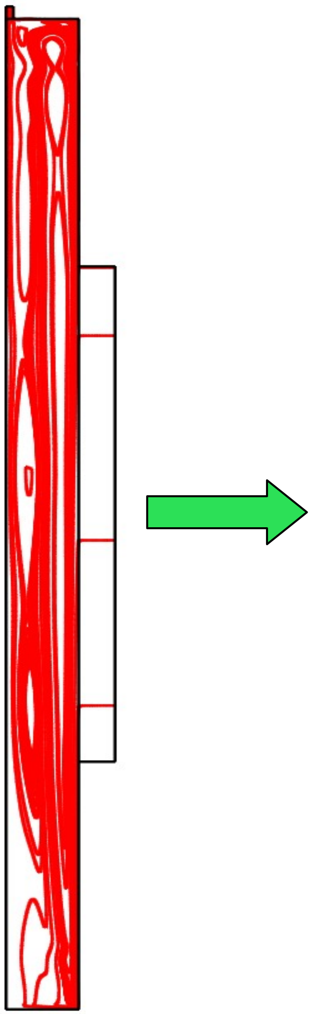
Axial Velocity
on the Axis of a FF- and a RF-CFFH

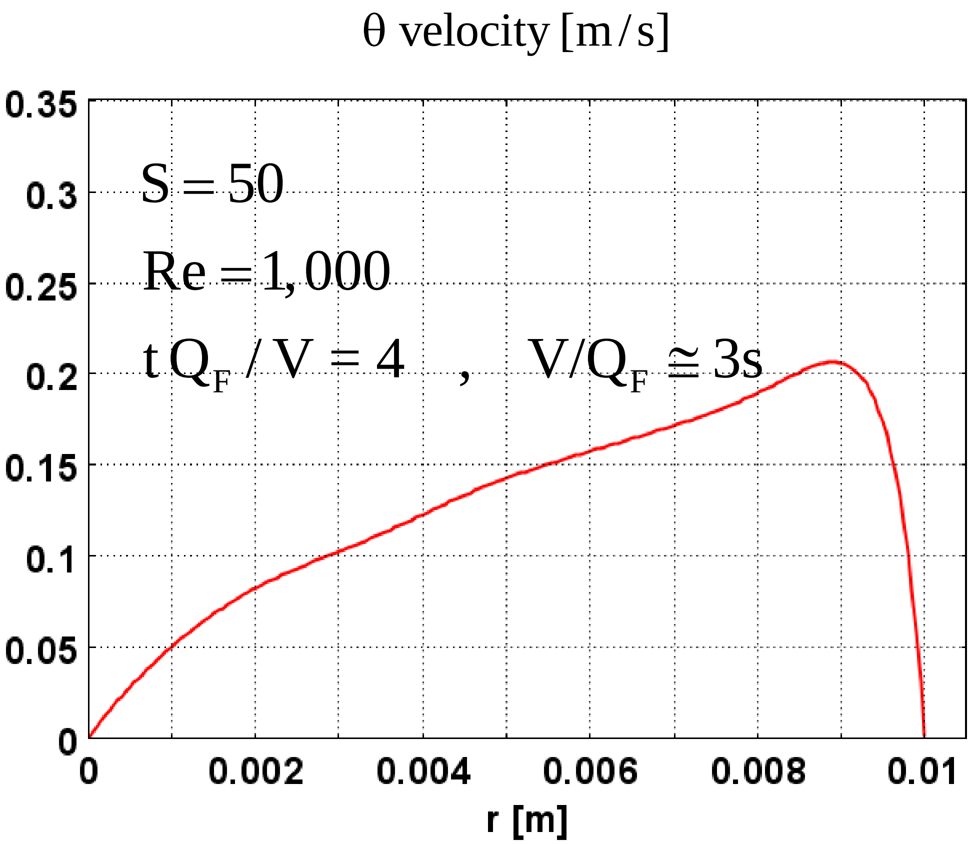




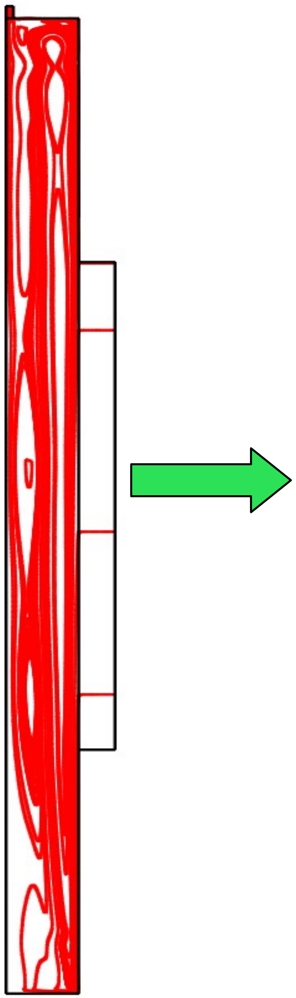
Note stagnation points near the overflow nozzles

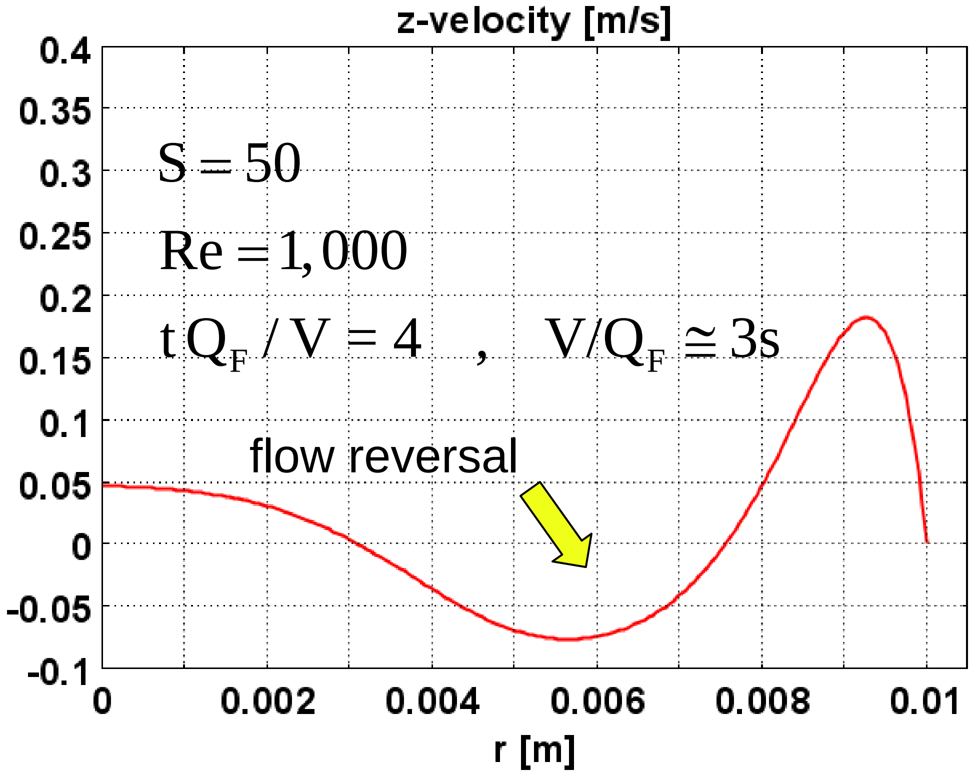
Tangential Velocity





Axial Velocity





Conclusions --- FFCFFH

- FFCFFH design may mitigate effluent nozzle flow reversal caused by recirculation flows.
- A low-capacity FFCFFH may provide sufficient centripetal acceleration to cause a light dispersed phase to drift into a recirculation zone
- A low capacity FFCFFH can support an overflow split of less than 10%

Influence of Swirl Number on the Pressure Drop and Split Ratio of a Cylindrical FFCFFH with Re = 1,000

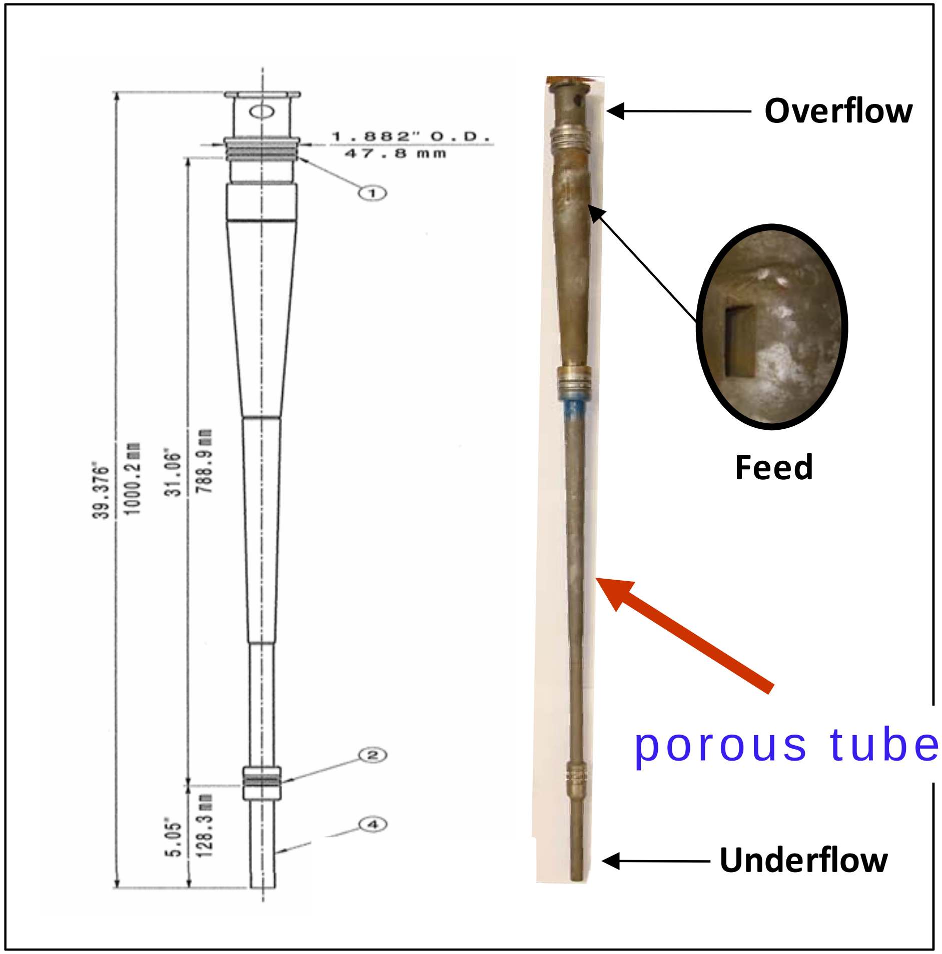
$(Q_F = 15.54\ cm^3/s \cong 0.93\ \ell pm \cong 0.25\ gpm)$

S	P_F , Pa	Q_U , cm^3/s	Q_O , cm^3/s	$(Q_U + Q_O)$, cm^3/s	$\frac{Q_U}{Q_U + Q_O}$
2	124	14.95	0.79	15.74	0.95
50	448	15.12	0.61	15.73	0.96

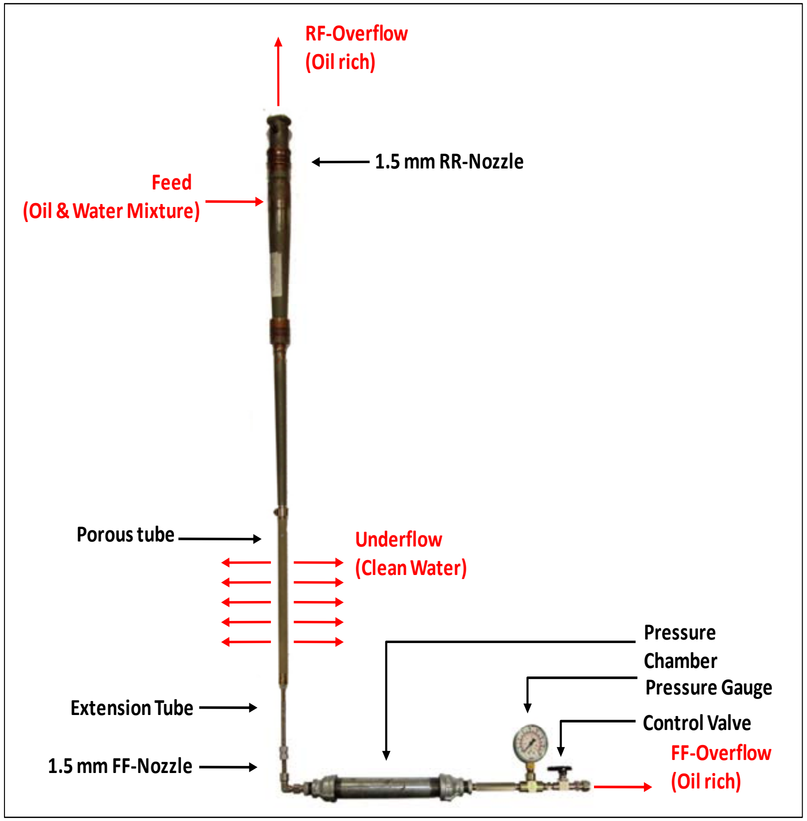
Cross Flow Filtration Hydrocyclone

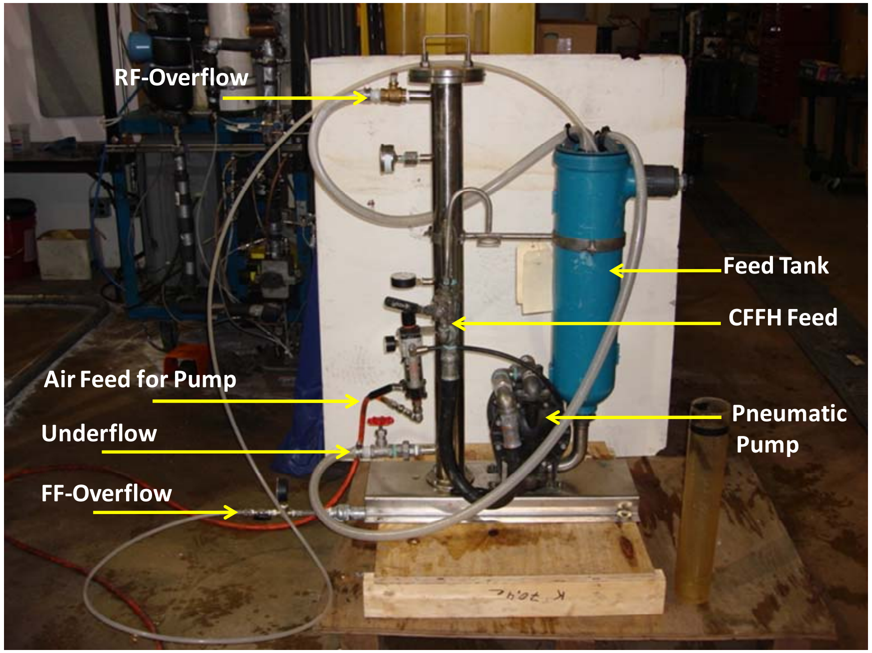
Krebs L40 Gmax swirl chamber

AccuSep porous metal tube (Pall)



Test Skid (prototype CFFH)





Part I: Hydrocyclone --- physical principles
Charles Petty

Part II: Cross Flow Filtration --- membrane selection
Vlad Tarabara

- Ceramic membranes as a barrier for oil
- Hydrocyclone-based hybrid processes
- Dual-affinity membrane system

Goals:

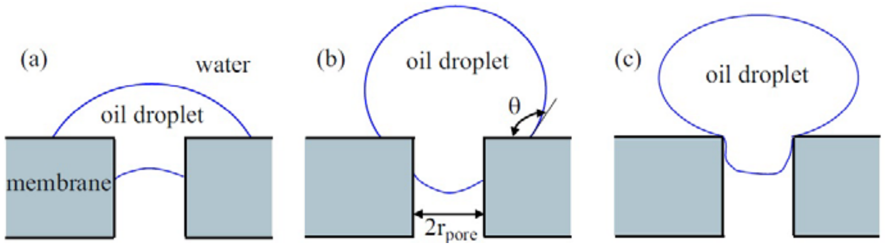
- **Engineer the porous wall (membrane) to improve performance**
- **Develop strategies for mitigating membrane fouling**

Oil-water separation technologies

Frankiewicz, T., 2001, 11th Produced Water Seminar, Houston, TX

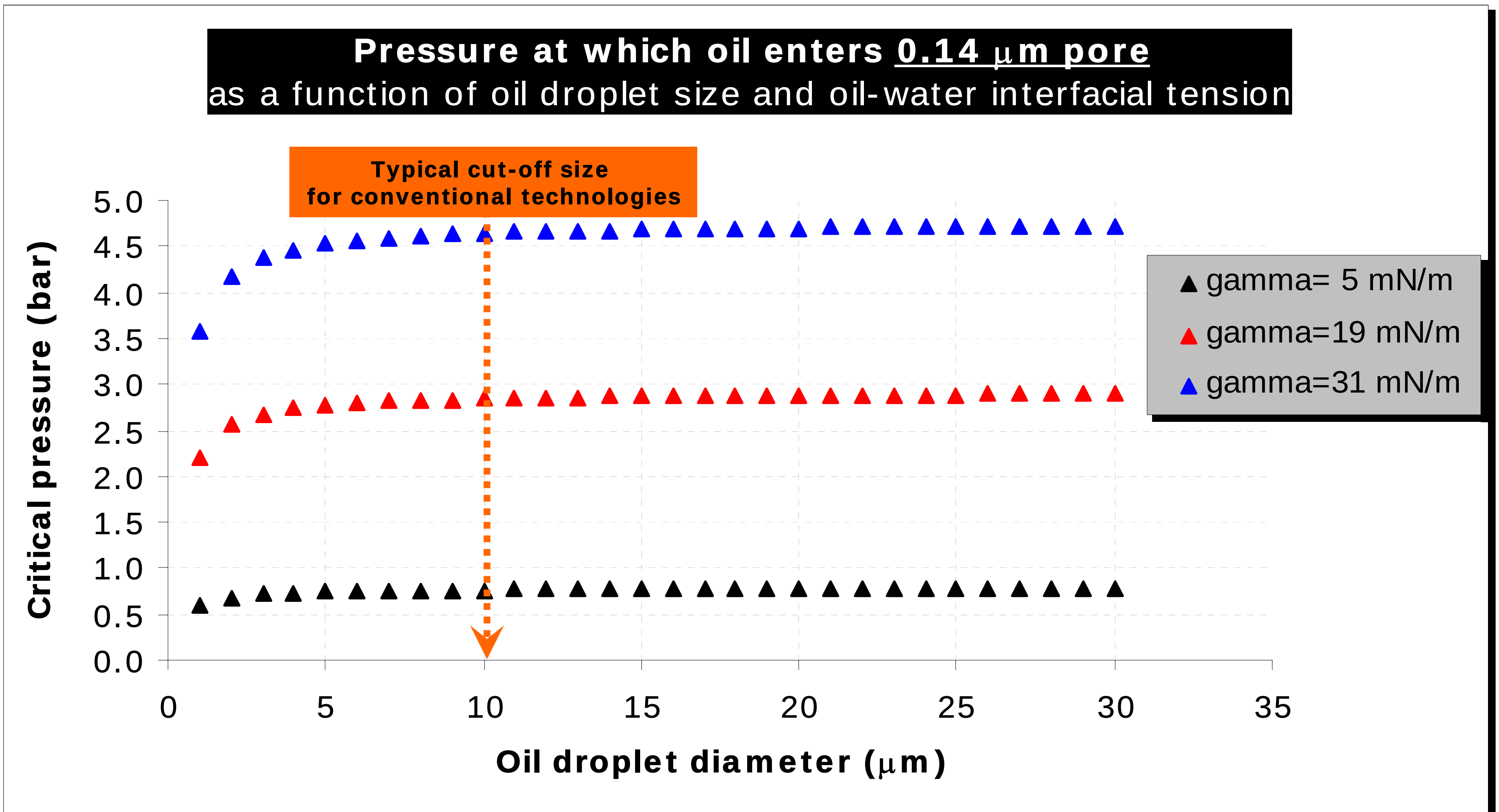
Technology	Removal Capacity by Particle Size (Units in Microns)
API gravity separator	150
Corrugated plate separator	40
Induced gas flotation without chemical addition	25
Induced gas flotation with chemical addition	3-5
Hydrocyclone	10-15
Mesh coalescer	5
Media filter	5
Centrifuge	2
Membrane filter	0.01

Main problem with membranes: fouling → flux decline



$$P_{crit} = \frac{2\sigma\cos\theta}{r_{pore}} \cdot \left[1 - \left(\frac{2 + 3\cos\theta - \cos^3\theta}{4\left(\frac{r_{drop}}{r_{pore}}\right)^3 \cos^3\theta - \left(2 - 3\sin\theta + \sin^3\theta\right)} \right)^{\frac{1}{3}} \right]$$

[Nazzal & Wiesner, 1996]



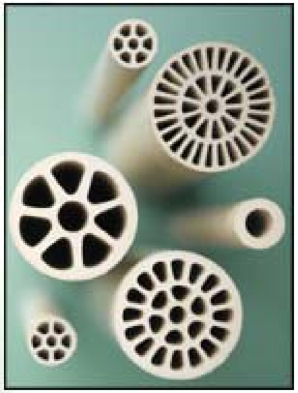
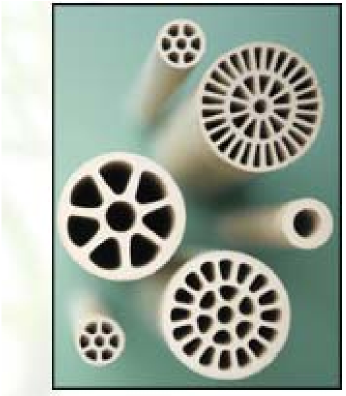


Image: http://www.tami-industries.com

Oil-water separation using ceramic membranes

Tubular ceramic membranes studied in cross-flow filtration	Pressure (bars)	Cross flow velocity (m/s)	Pore size (µm)	Droplet size (µm)	Feed oil concentration and type (ppm)	Oil rejection (%)	Steady state permeate flux (L/m2/hr)	Reference
Al_2O_3	0.7	0.24	0.2	1 – 10	1000, heavy crude oil + water	> 99	20 - 30	Mueller, J. 1997
Al_2O_3	0.7	0.24	0.8	1 – 10		> 98	20 - 30	
TiO_2	1	5 - 6	0.07	2.68	2000, synthesized bilge water	> 95	250	Peng, H. 2005
TiO_2	1	5 - 6	0.8	2.68		> 95	100	
Al_2O_3	1-1.5	3-5	0.2	1.5	5000, lubricant oil + surfactant + water	> 99	22	Yang, C. 1998
ZrO_2/Al_2O_3	1-1.5	3-5	0.2	1.5		> 99	93	



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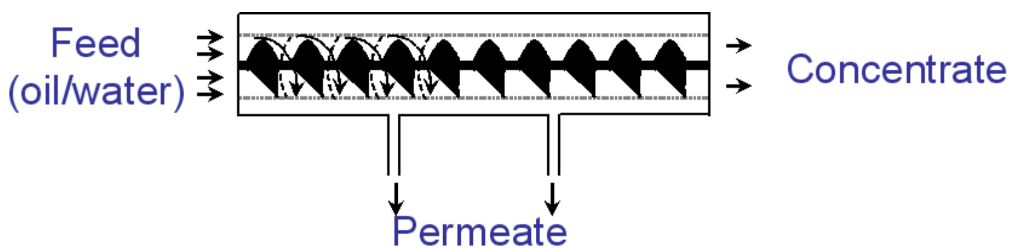
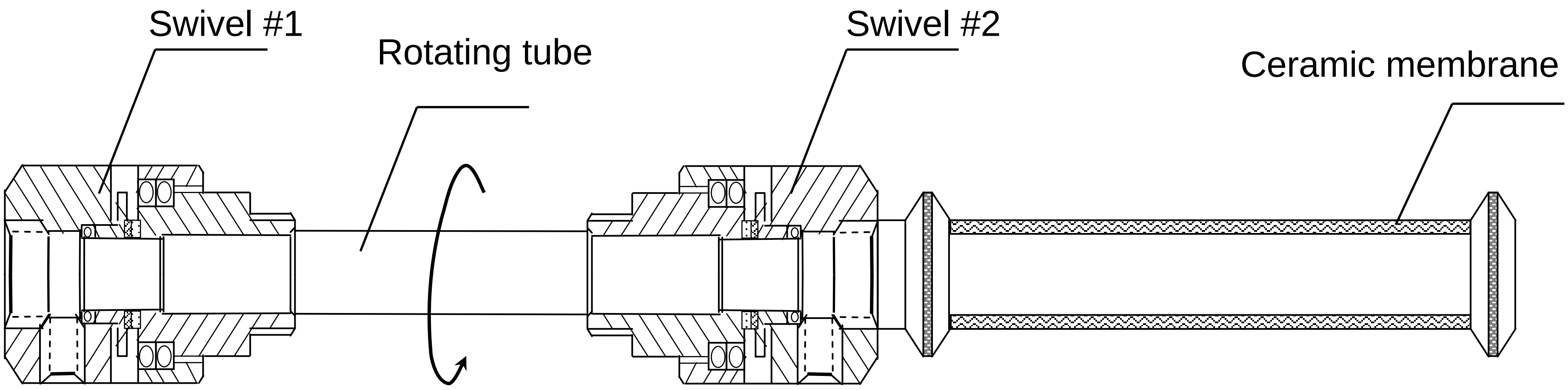
ZrO_2/Al_2O_3	1-1.5	3-5	0.2	1.5		> 99	93	
Nickel	0.1-0.3	0.32	3.3	1-40	1000, kerosene + surfactant + water	> 80	200	Cumming, I. W.,1999

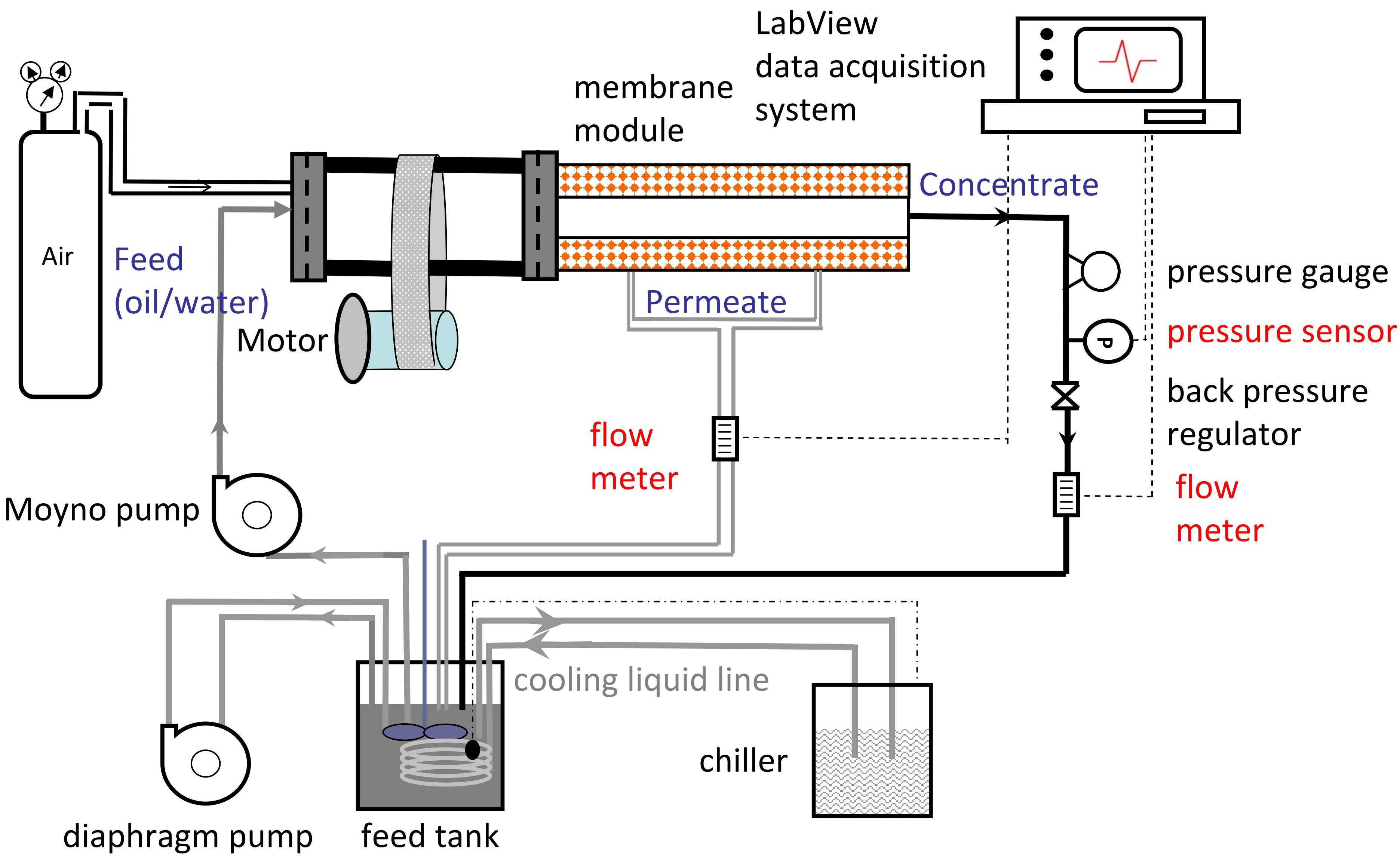




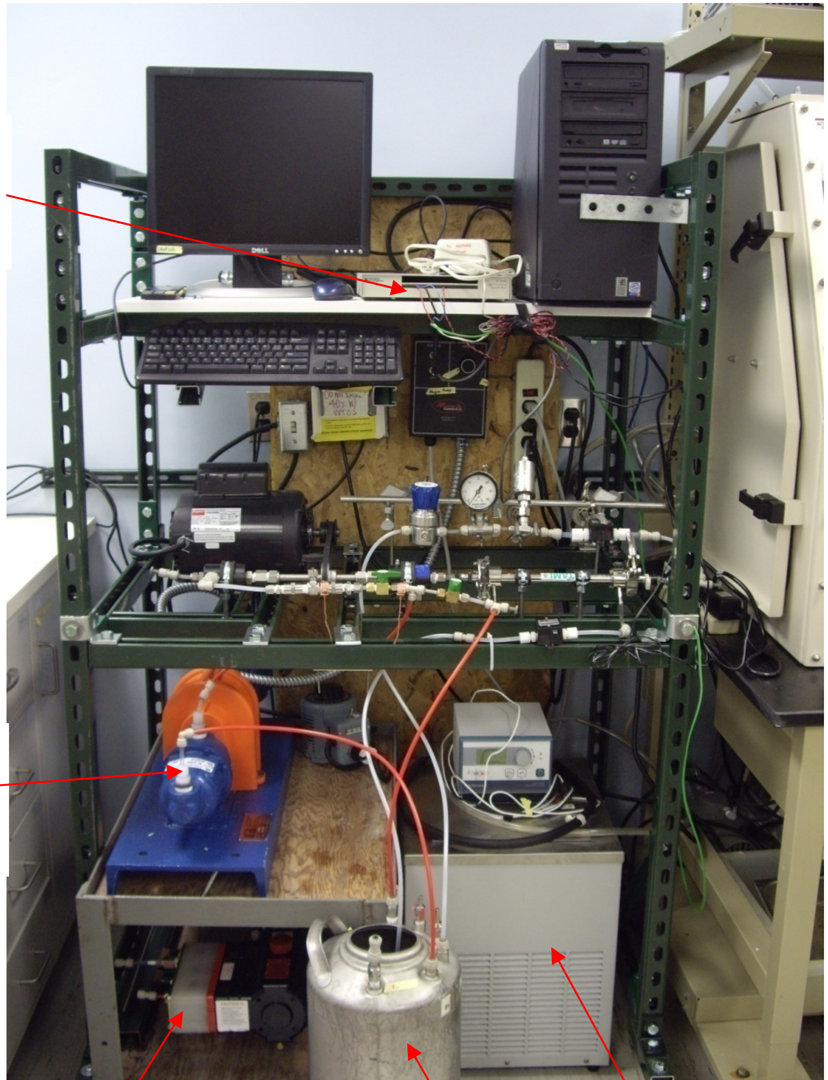
“Forced swirl” system

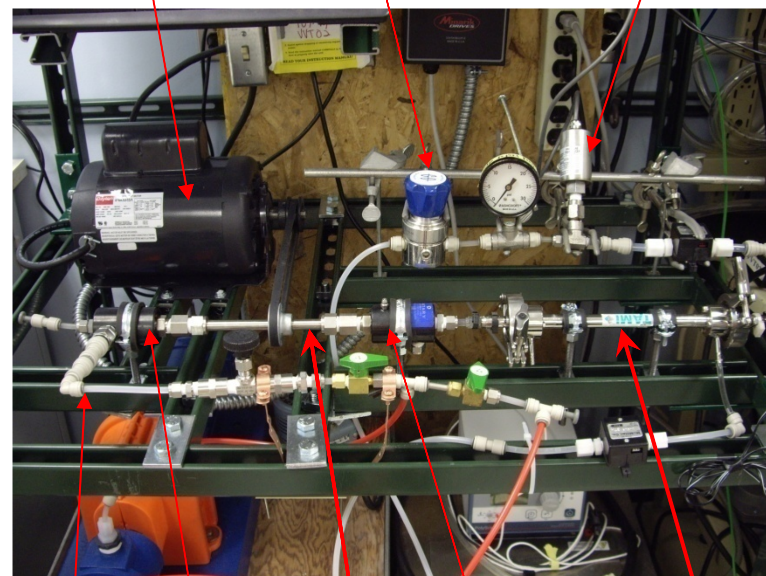
- can be used to independently control rotational and axial velocities of the flow

-- less resistance to flow than when inserts are used


LabView
data acquisition
system
membrane
module
Air
Feed
(oil/water)
Motor
Concentrate
Permeate
pressure gauge
pressure sensor
back pressure
regulator
flow
meter
flow
meter
Moyno pump
cooling liquid line
chiller
diaphragm pump
feed tank

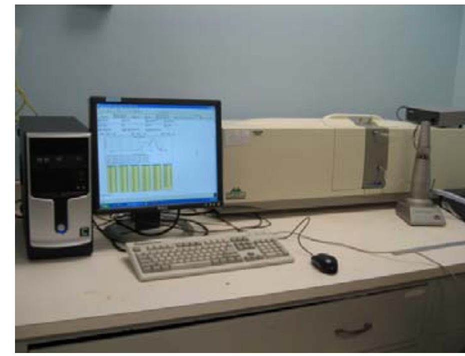
Sparged crossflow filtration hydrocyclone





Materials

- Model oil/water emulsion
  - Kerosene mixed in water
  - Polyvinyl alcohol (PVA) added as emulsifier
  - Oil concentration - by atomic absorption of chelated Cu
  - Oil droplet size – by light diffraction



- Ceramic membranes
  - Material: TiO_2
  - Pore sizes: 0.14, 1.4 and 3.5 μm
  - Dimensions: OD = 10 mm, ID = 6 mm,
  - Length = 250 mm, Surface area = 0.0047 m^2

Experimental protocol

1. Measure clean water flux for the ceramic membranes (TiO_2, 0.14, 1.4 and 3.5 µm pore size)

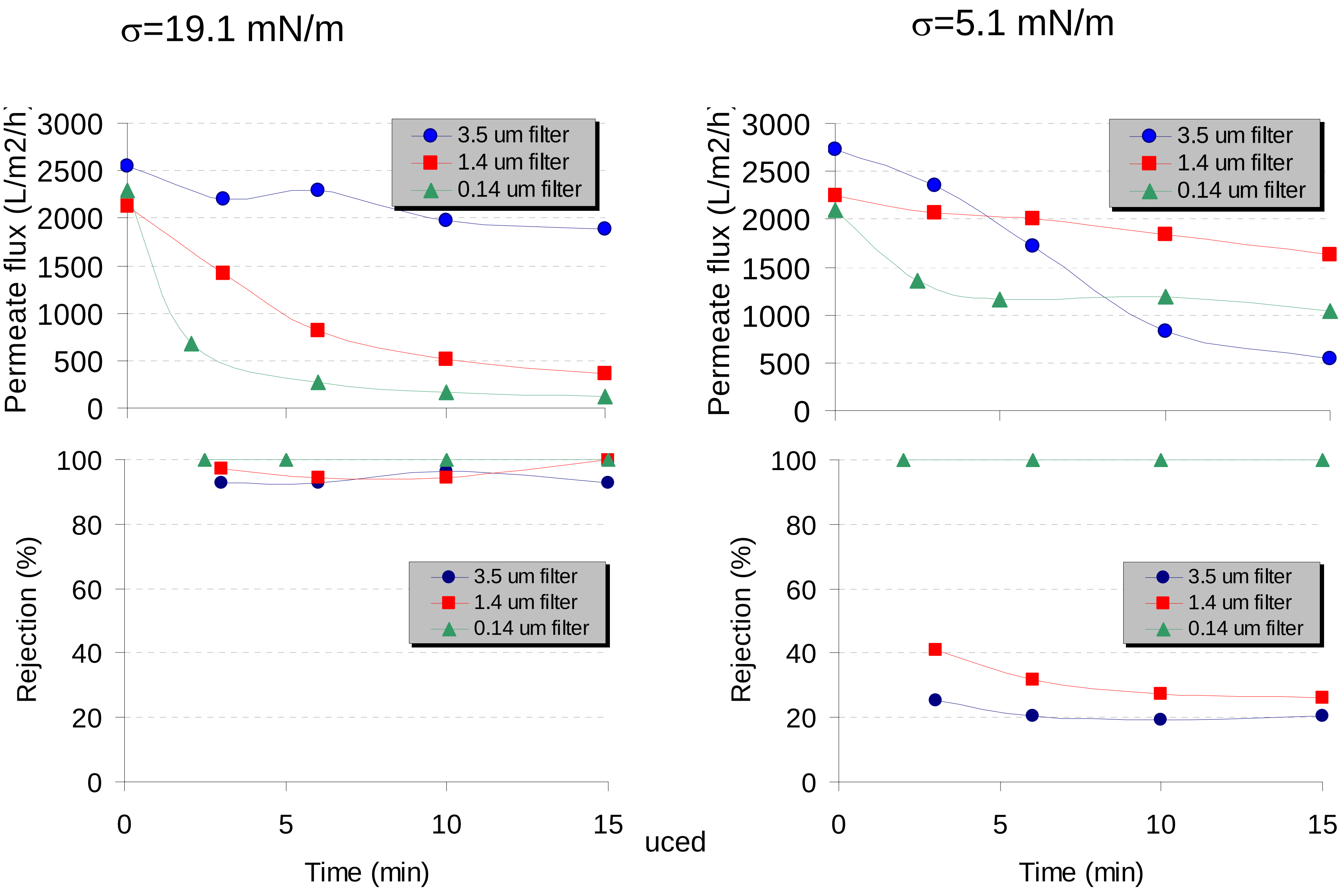
2. Prepare feed dispersion (kerosene in water)

3. During filtration, measure droplet size and oil concentration from the samples collected at different filtration times

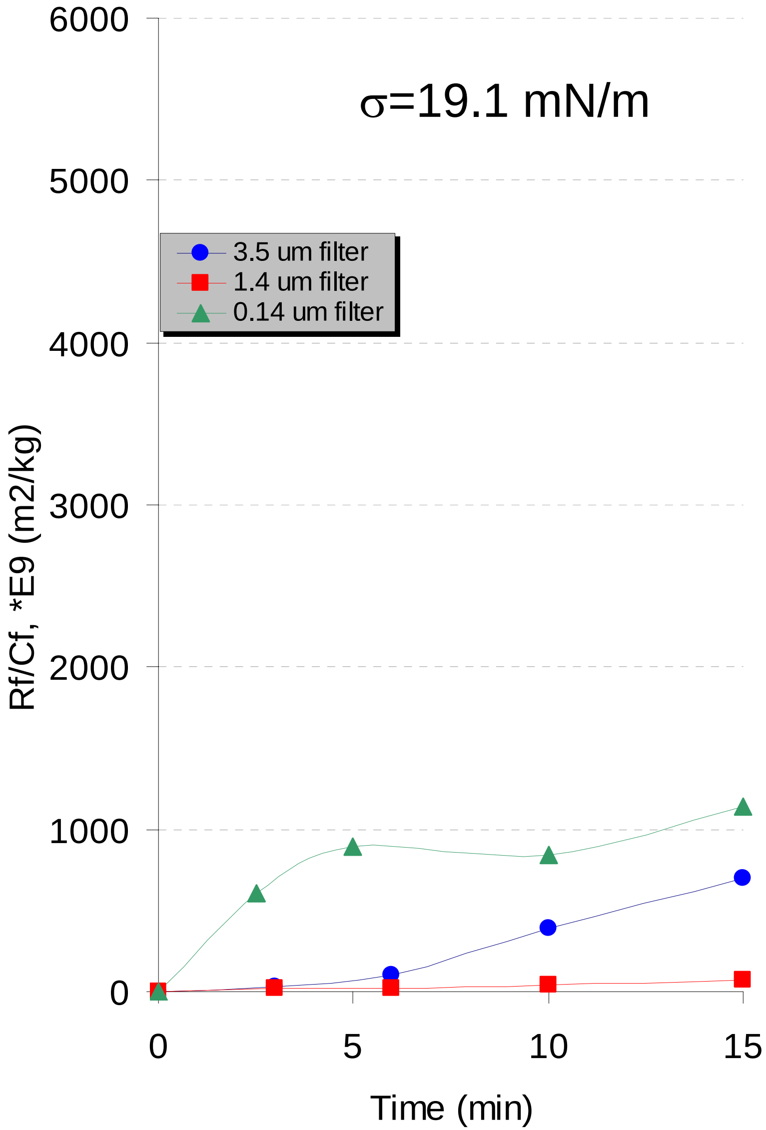
4. During filtration, measure permeate flux

5. Clean system and membrane

Flux and rejection performance



Added resistance due to fouling



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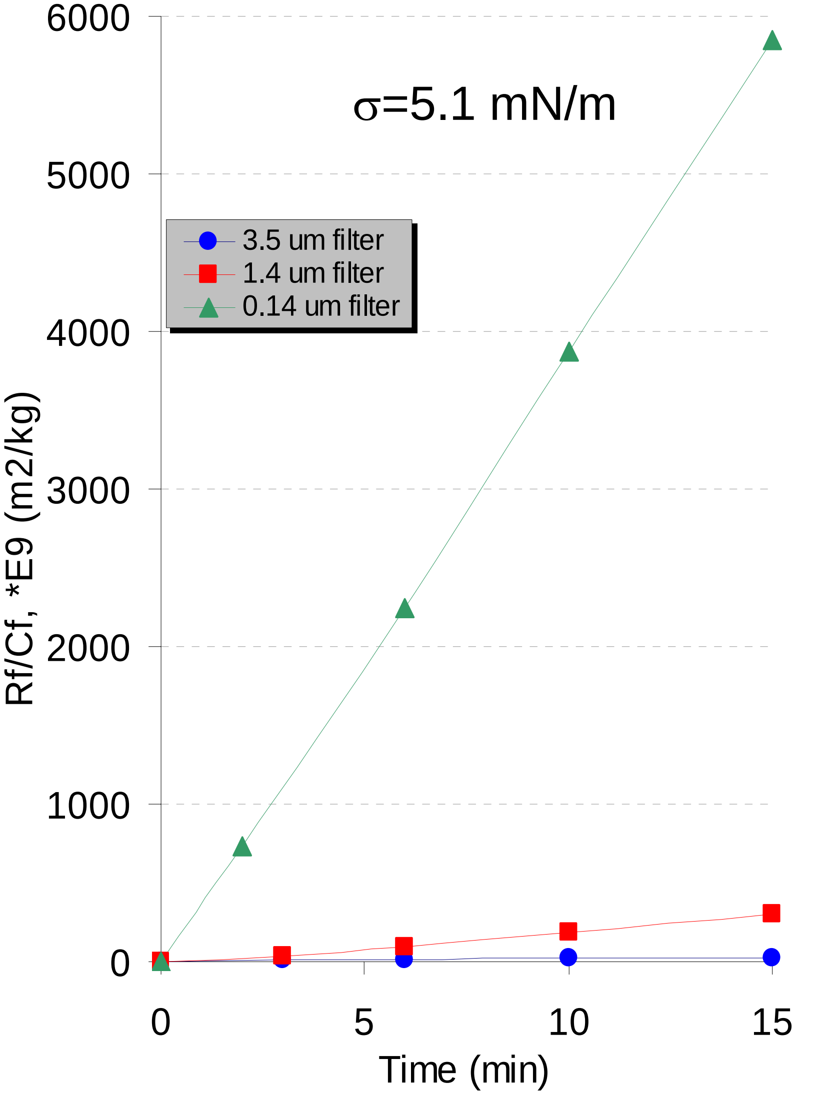


Figure of merit = Rejection*J/ΔP

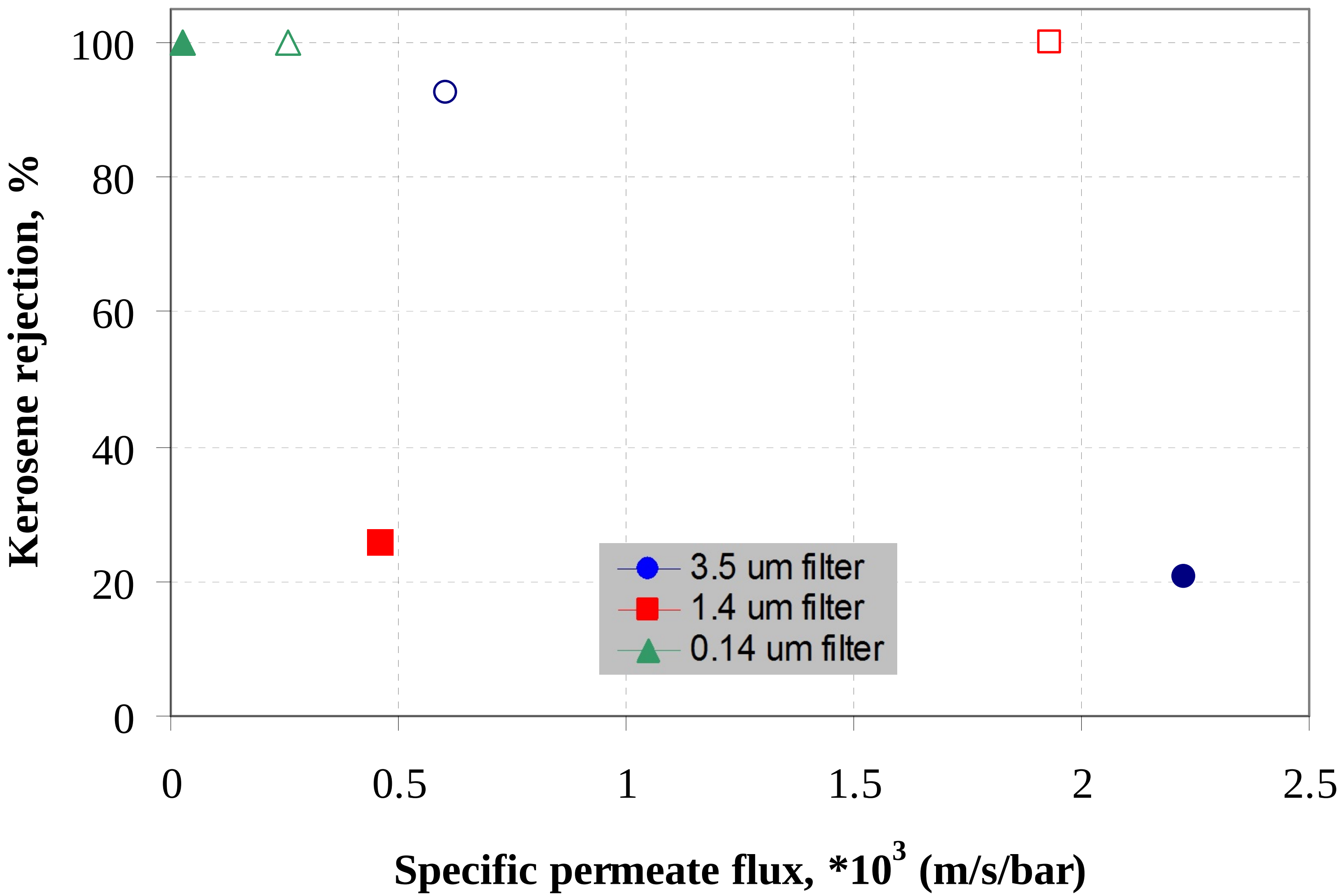


Figure of merit = Rejection*J/ΔP

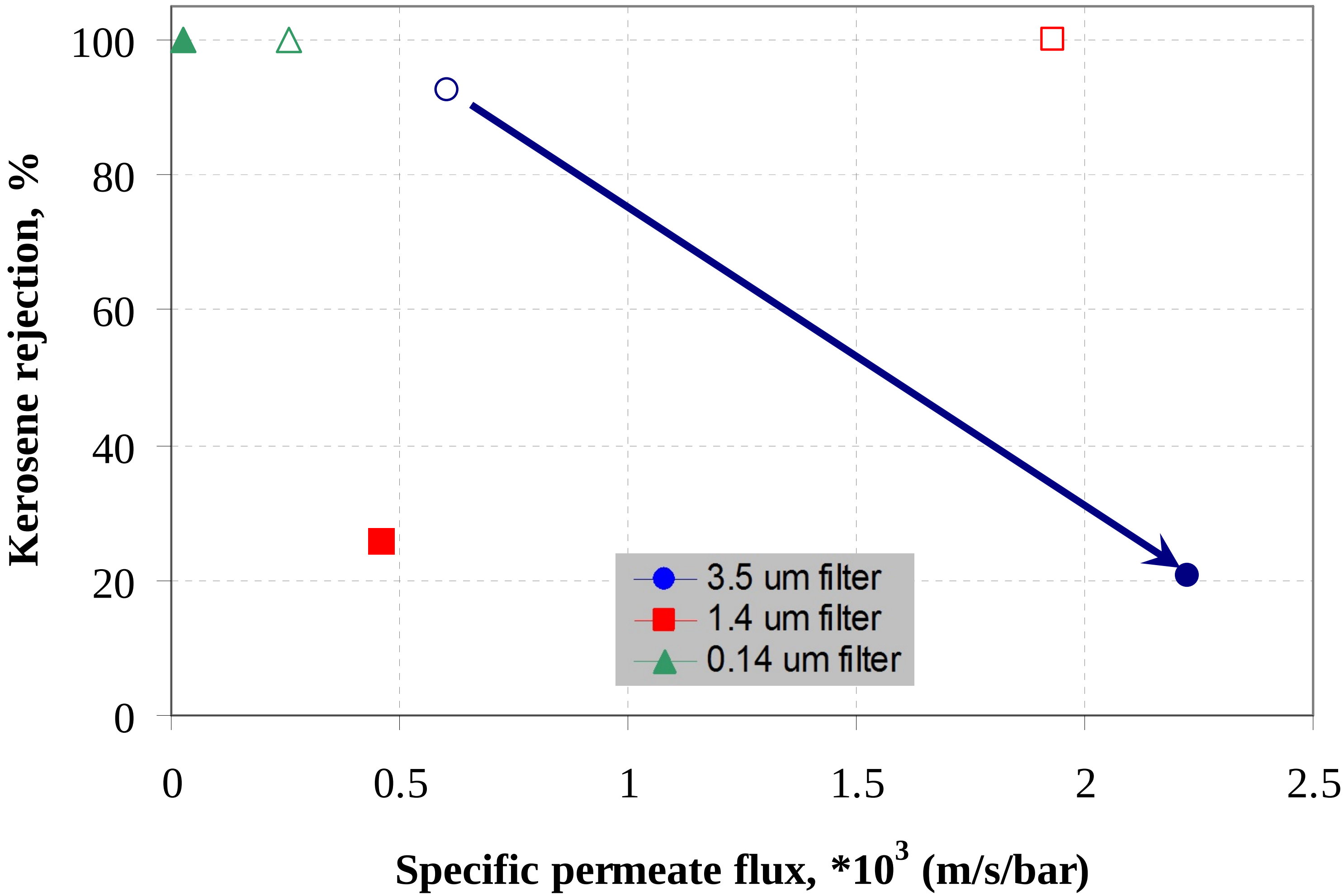
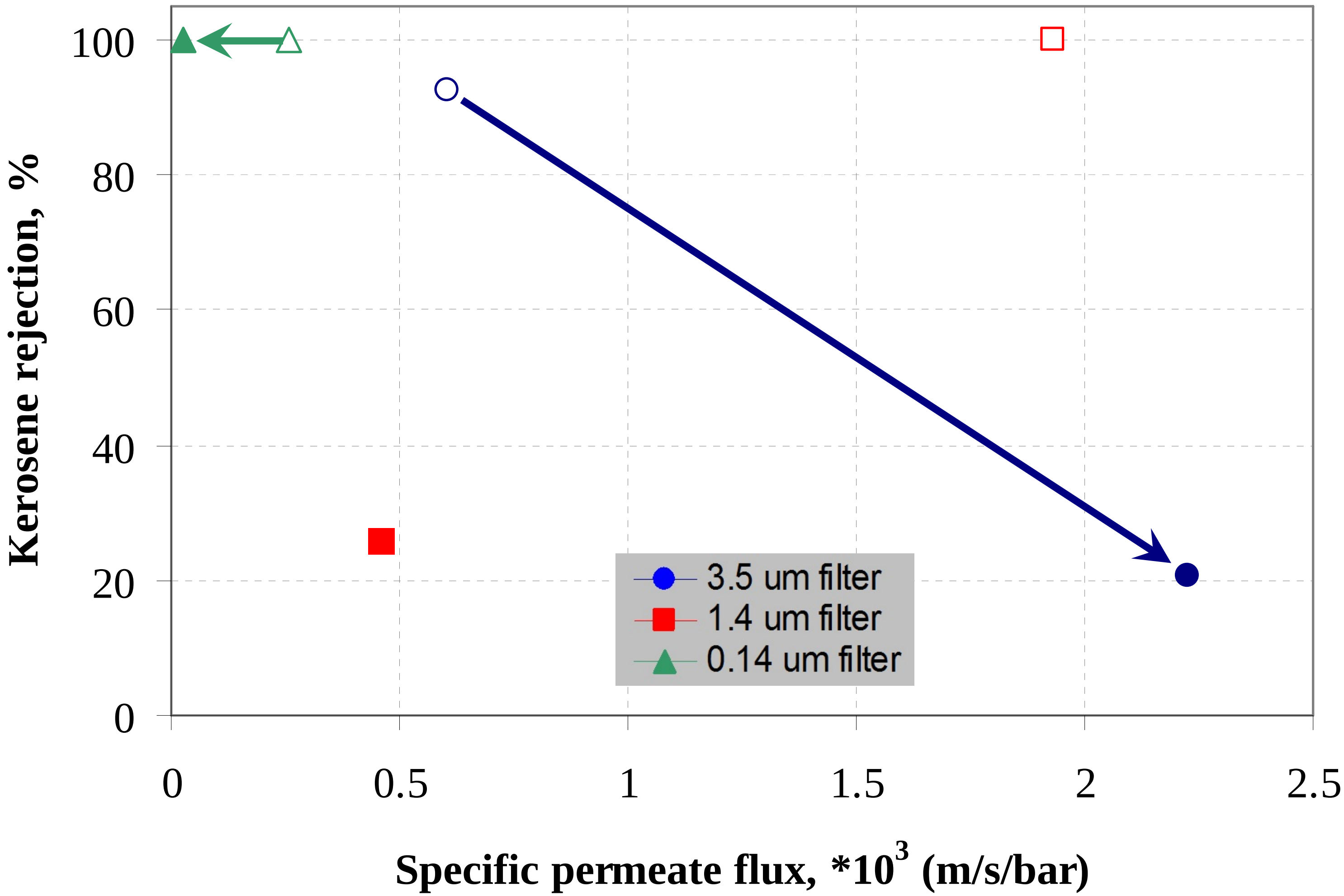


Figure of merit = Rejection*J/ΔP



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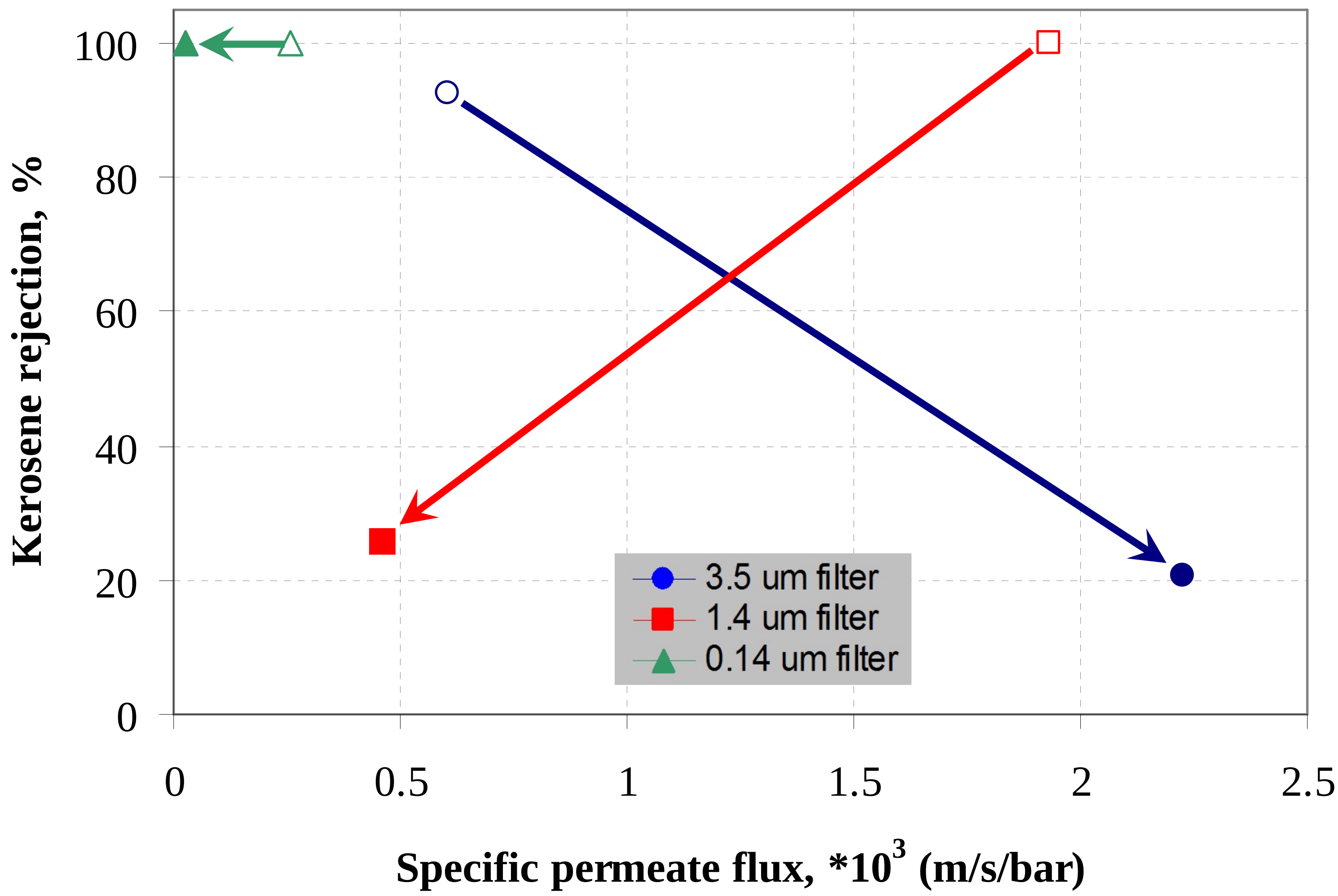
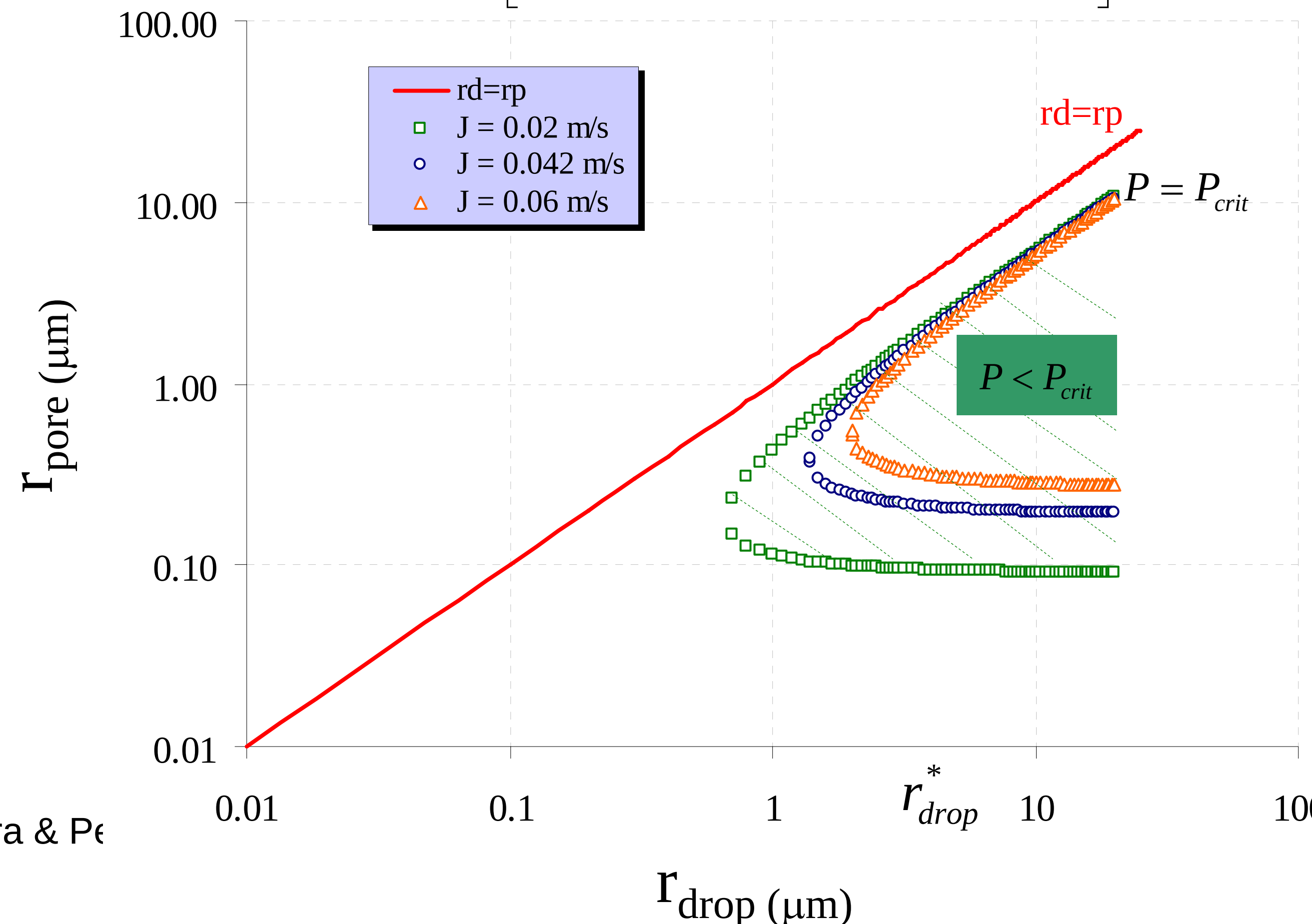


$P<P_{crit}$: operational domain

$$P_{crit} = \frac{2\sigma\cos\theta}{r_{pore}} \cdot \left[1 - \left(\frac{2+3\cos\theta-\cos^3\theta}{4\left(\frac{r_{drop}}{r_{pore}}\right)^3 \cos^3\theta - \left(2-\sin\theta+\sin^3\theta\right)} \right)^{\frac{1}{3}} \right]$$



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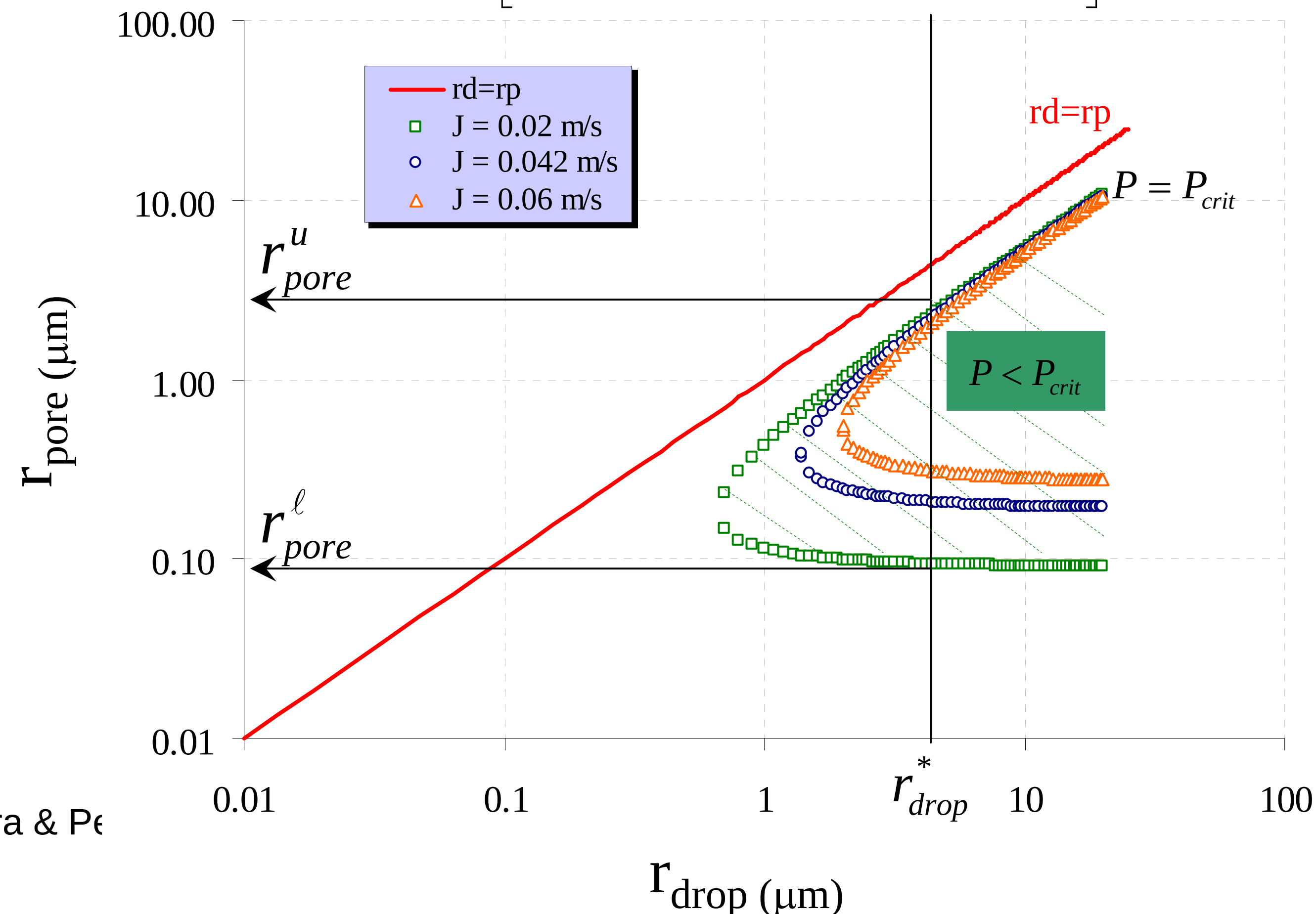

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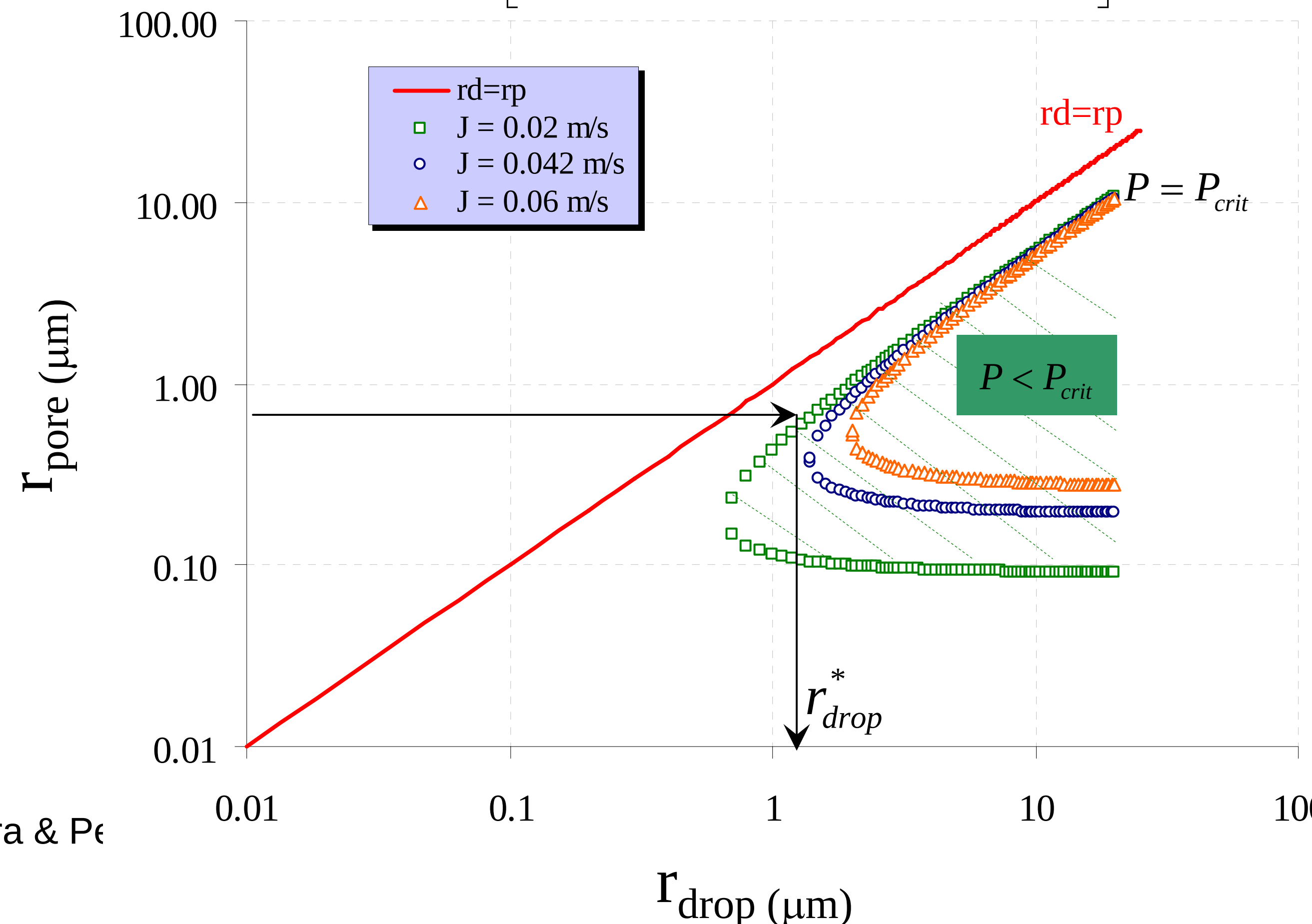
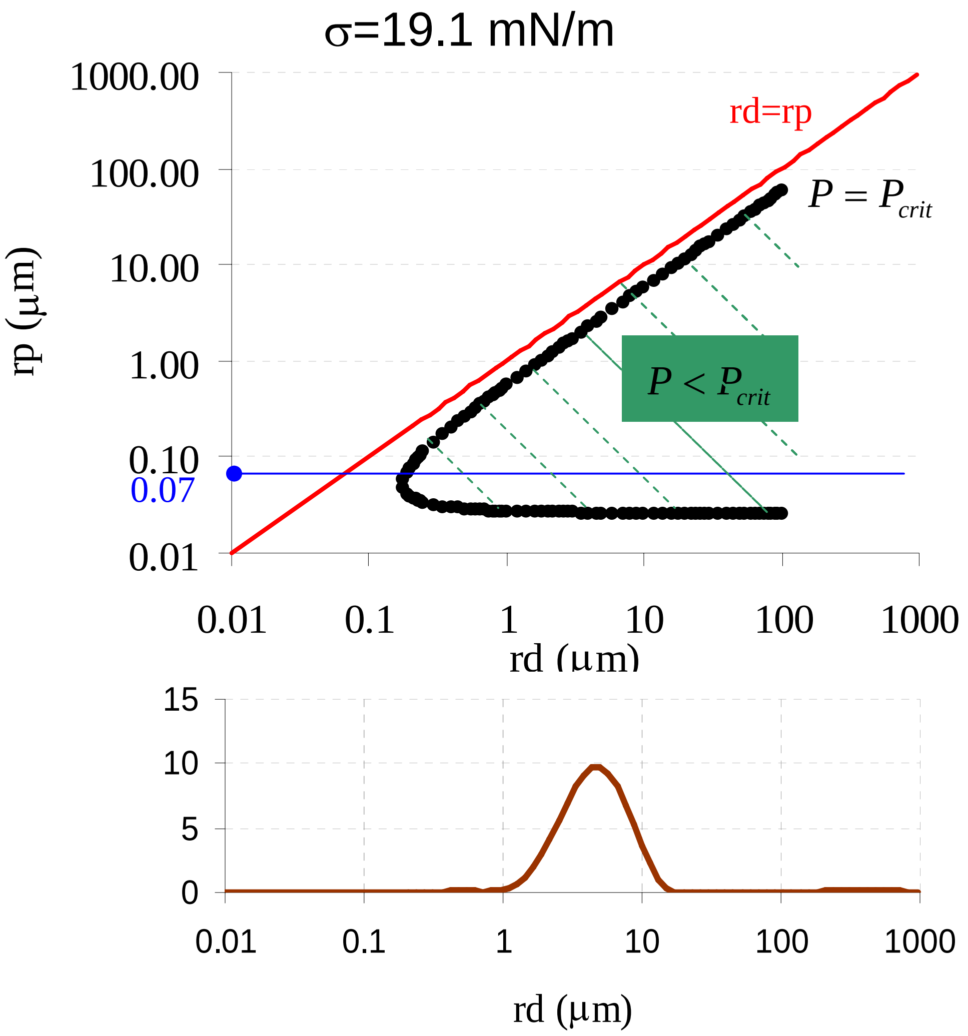
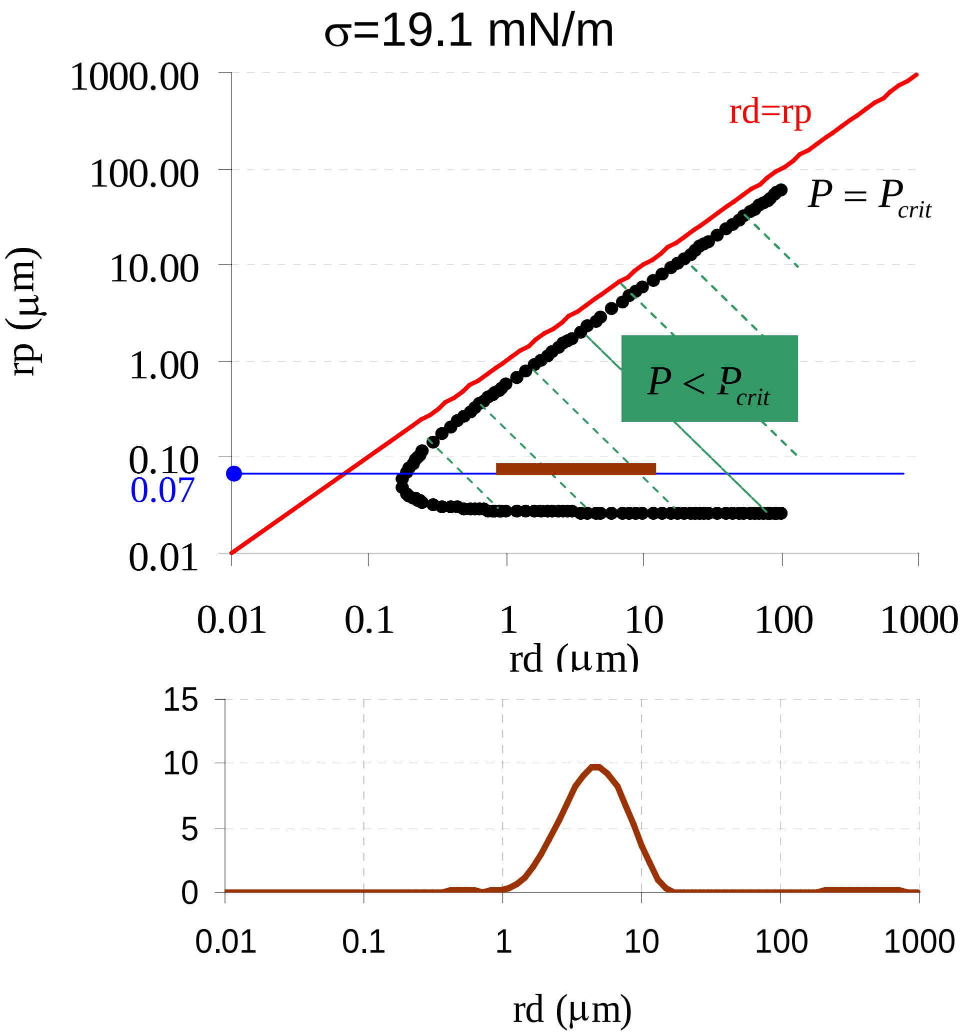


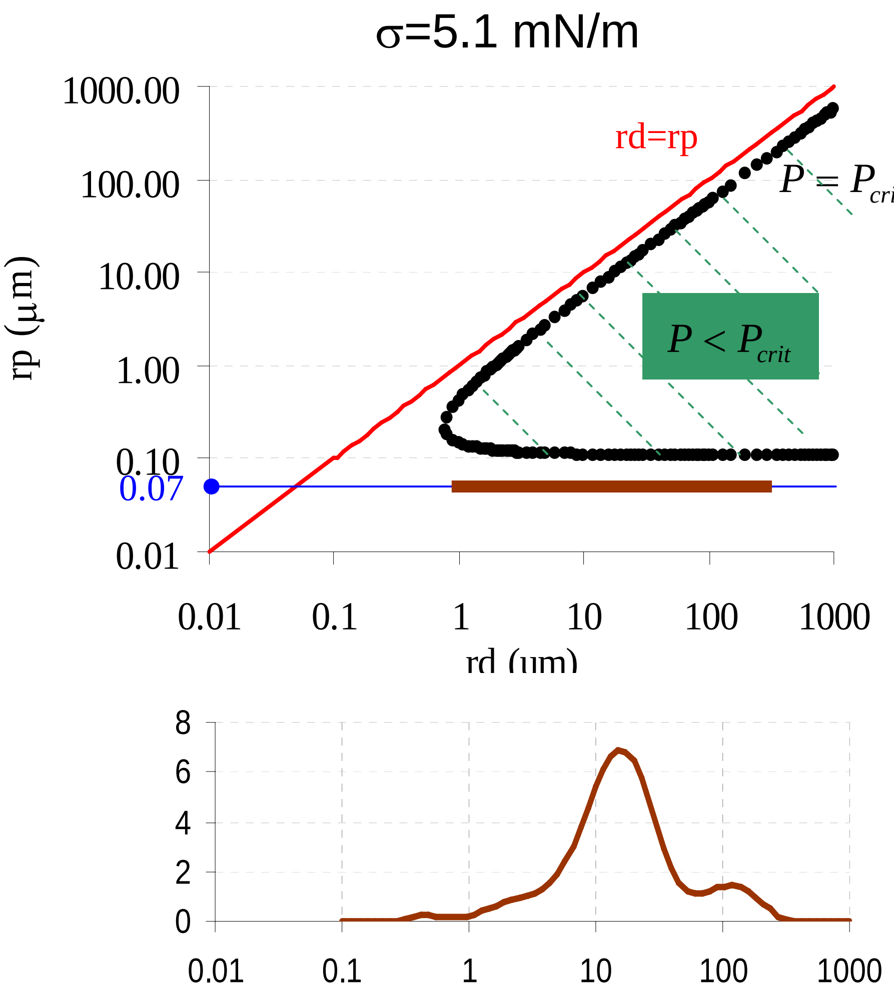
Operational domain - 0.14 μm filter

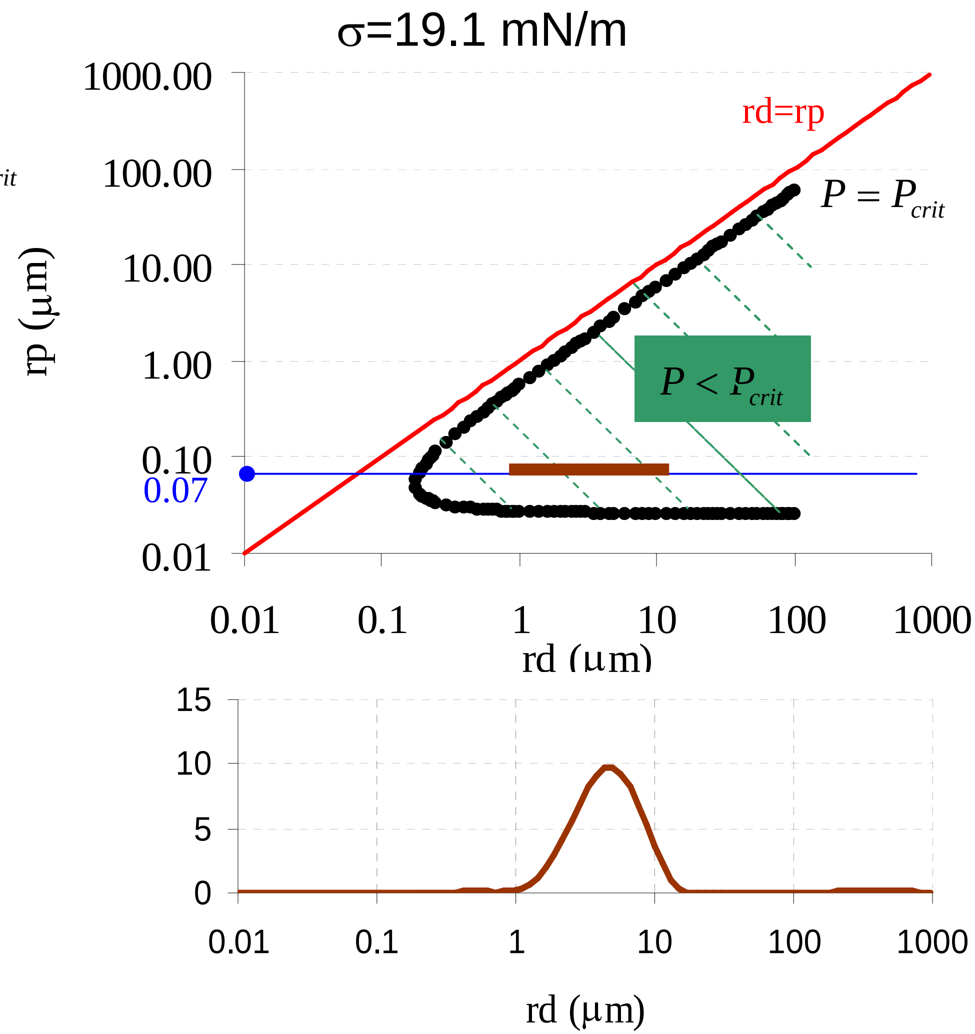


Operational domain - 0.14 μm filter



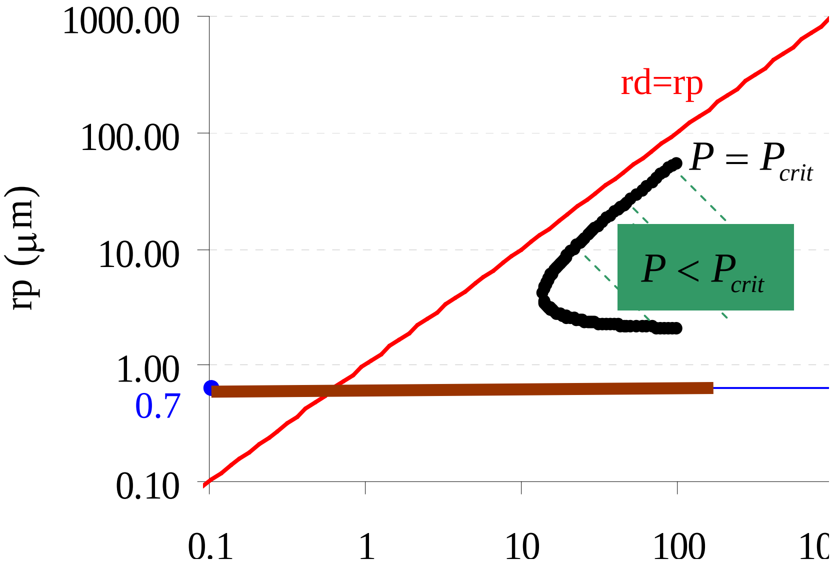
Operational domain - 0.14 μm filter



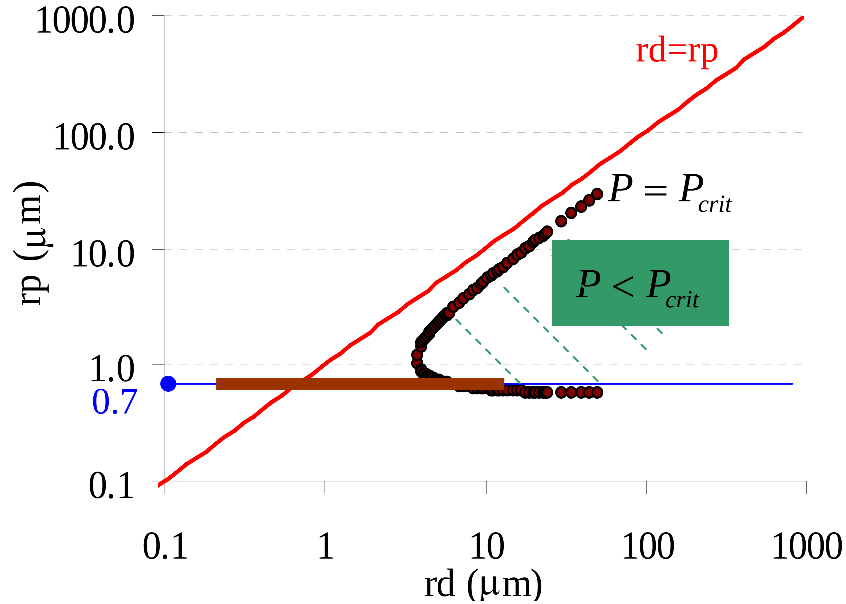


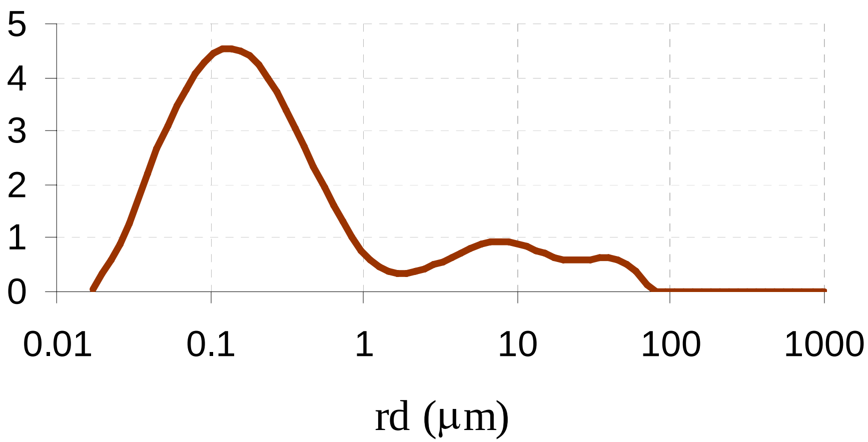
Operational domain - 1.4 μm filter

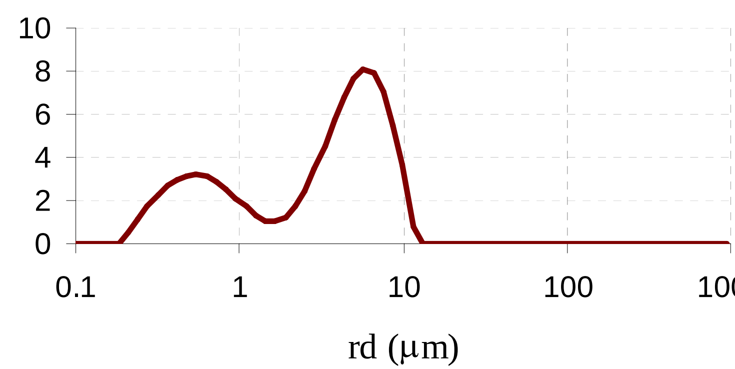
σ=5.1 mN/m



σ=19.1 mN/m

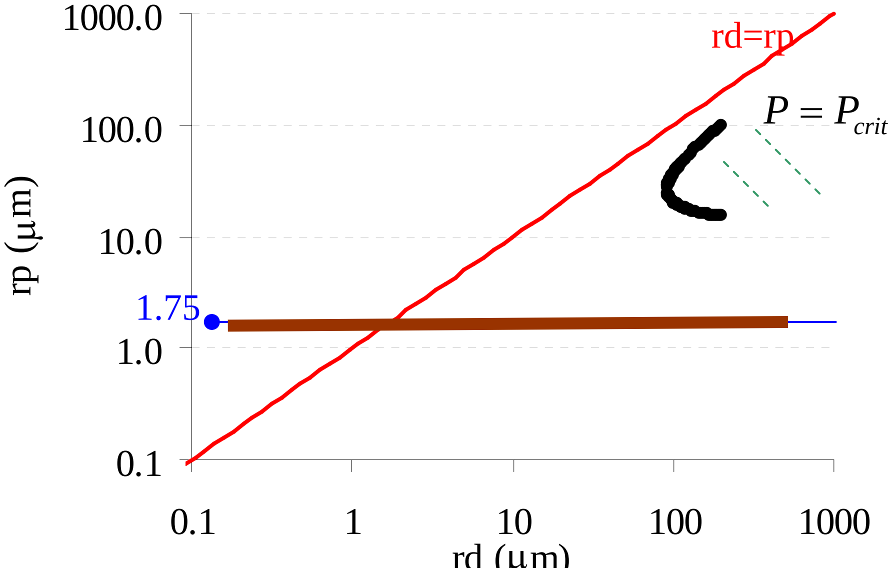




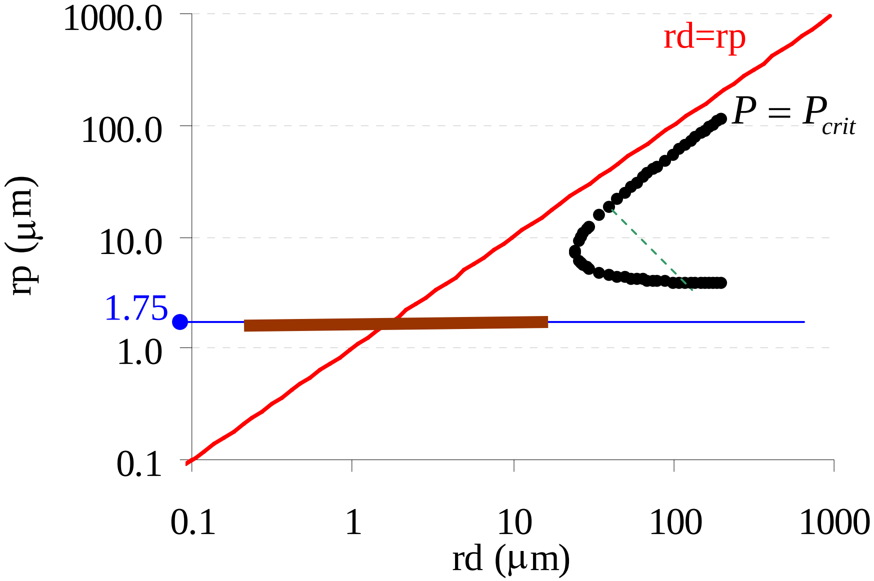


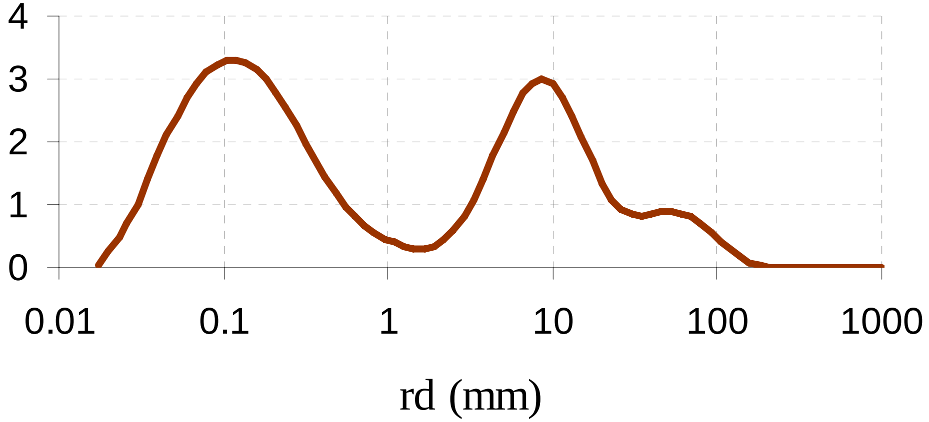
Operational domain – 3.5 μm filter

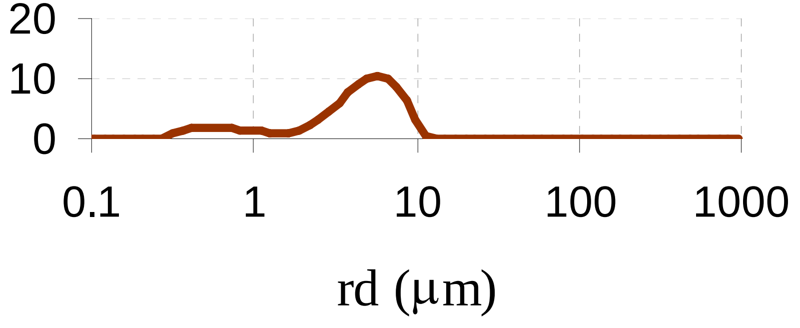
σ=5.1 mN/m



σ=19.1 mN/m

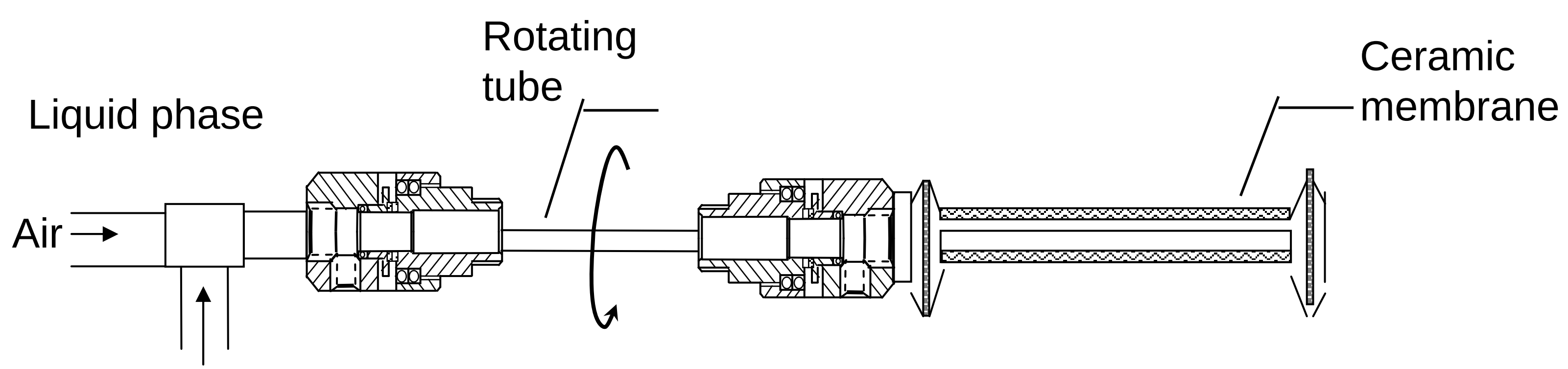




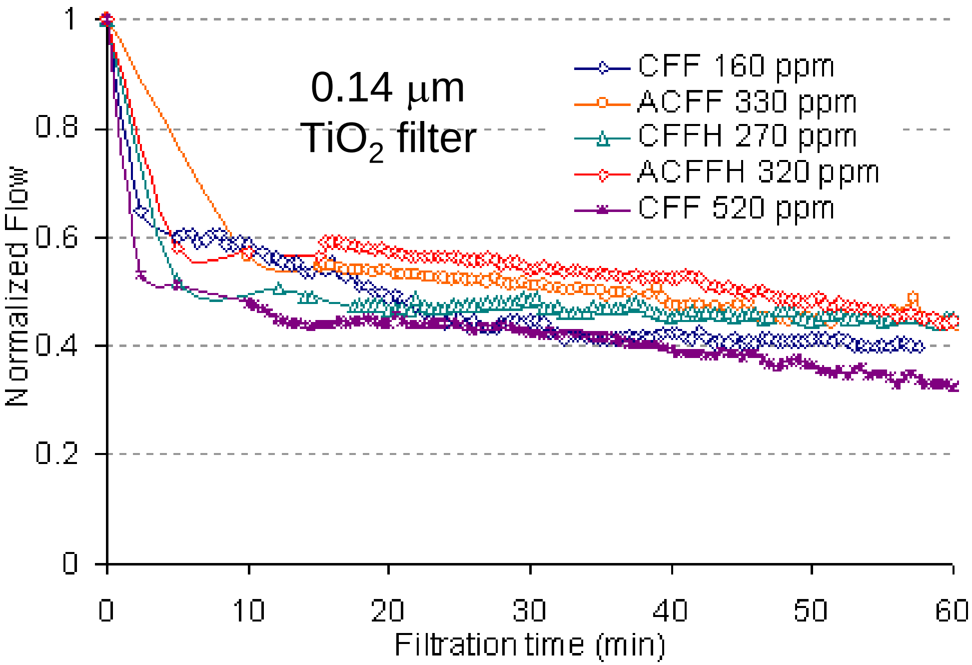


Combining --- (1) air sparging, (2) hydrocyclone, (3) membrane:possible hybrid separation processes

Fouling mitigation strategy / Flow type	Without air sparging	With air sparging
Without swirl	**Crossflow membrane filtration (CFF)**	**Air sparged crossflow membrane filtration (A-CFF)**
With swirl	**Crossflow membrane filtration hydrocyclone (CFF-H)**	**Air sparged crossflow membrane filtration hydrocyclone (A-CFF-H)**

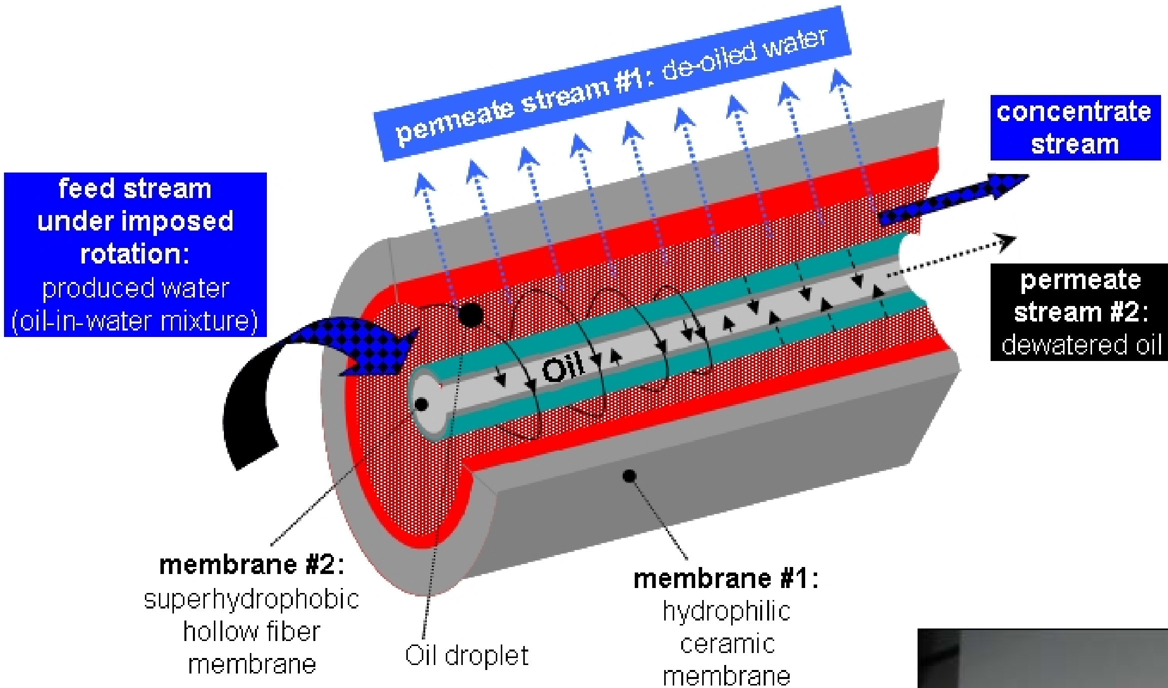


Hybrid separation processes – flux performance



Flow Type \ Fouling Mitigation Strategy	Without Air Sparging	With Air Sparging
Without Swirl	Crossflow Membrane Filtration (CFMF)	Air Sparged- Crossflow Membrane Filtration (AS-CFMF)
With Swirl	Crossflow Membrane Filtration Hydrocyclone (CFMFH)	Air Sparged- Crossflow Membrane Filtration Hydrocyclone (AS-CMFH)

Affinity-based hydrocyclonic separation



Membrane module consists of two membranes with opposite water affinities assembled in one crossflow filtration unit to simultaneously separate oil-water dispersions into oil and water phases.

"Water and Oil Separation System", V. V. Tarabara and W. Shan (inventors) , Provisional Patent 6550-000201-US-PS1 (MSU ID#TEC2010-0074-01)

Summary

- Membrane-based CFFH separation can afford sustained, complete rejections and smaller footprint
- Appropriate choice of membrane properties (pore size, surface chemistry) is critical
- Hybrid processes (swirl and air sparging) can be used to mitigate membrane fouling
- Affinity-based separation has potential for simultaneous oil recovery oil and water deoiling

Thank you

APPENDIX X

WATER

WEMCO® DEPURATOR® Systems

Proven efficient mechanical flotation systems

Highly effective mechanically induced gas flotation units for the secondary removal of oil and solids from produced water.

Overview

WEMCO DEPURATOR Systems use mechanically induced air/gas flotation (IGF) to remove oil and solids from produced water. After the produced water enters the depurator, motor driven rotors induce a re-circulating flow of air or blanket gas into the mixture. This disperses small bubbles throughout the tank volume and oil droplets and solids are carried to the surface in a rising gas froth where they are recovered by skimming. The original IGF design is still the standard for many applications, while the new pressurized version, available in two cell up to five cell designs, provides a real advantage for the oil and gas industry.

Operating Principle and Key Features

All WEMCO DEPURATORS use the froth flotation process to remove oil and solids from produced water. The key component is the mechanical aeration assembly that uses motor driven rotors to constantly disperse gas bubbles into the produced water. The oil and/or solids adhere to the bubbles and then rise with them to the surface of the cell, forming a froth. Because the contaminated water and the floating froth are constantly being subjected to re-introduced gas it is impossible for the floating materials to settle into the now cleaner water below.

Depending upon the type of depurator, the froth is removed either by mechanical skimmers or a hydraulic skimming process. The water then moves into the next cell where the process is repeated. In the final stage, the now cleaned water goes through a de-gassing discharge chamber and then exits the unit.

Performance

The overall removal efficiency of the motion application two cell design is 94% with a 2.5 minute residence time per cell. The four cell unit has approximately a 95% removal efficiency with only a 1.0 minute residence time per cell. The dual cell configuration is specifically suited to offshore applications where deck motion influences the liquid surface in the cells. This unit will operate satisfactorily during conditions of general motion and under pitch and roll conditions in particular.

Product Range

- Individual units for flow rates of 270 m^3/day to 28,160 m^3/day (1700 BPD to 177,000 BPD)
- Operating pressure from atmospheric to 1.05 Kg/cm^2 (15 PSIG)
- Separation efficiency up to 98% or more

Benefits and Advantages

- Proven reliable experience of more than 40 years and more than 5000 units operating worldwide in a wide variety of applications
- High mixing efficiency
- Wide operating flexibility
- Available from two cell up to five cell configurations
- Lower amounts of flotation chemicals required
- Suitable for onshore, offshore and motion sensitive applications
- Good retrofit capability

Options and Types

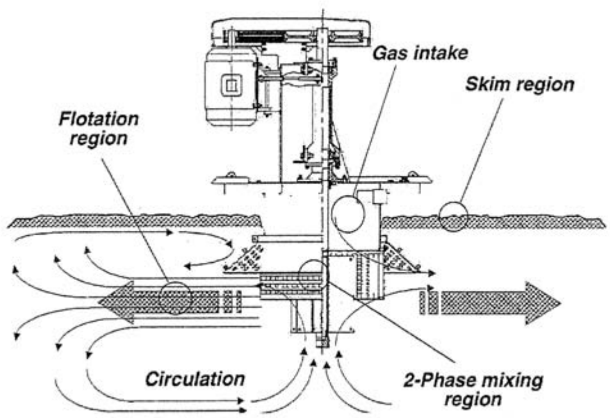
- IGF Original Tank Design
- Cylindrical Design
  – Dual cell design for motion sensitive applications
  – Two to five cell designs for fixed applications

Installation Examples

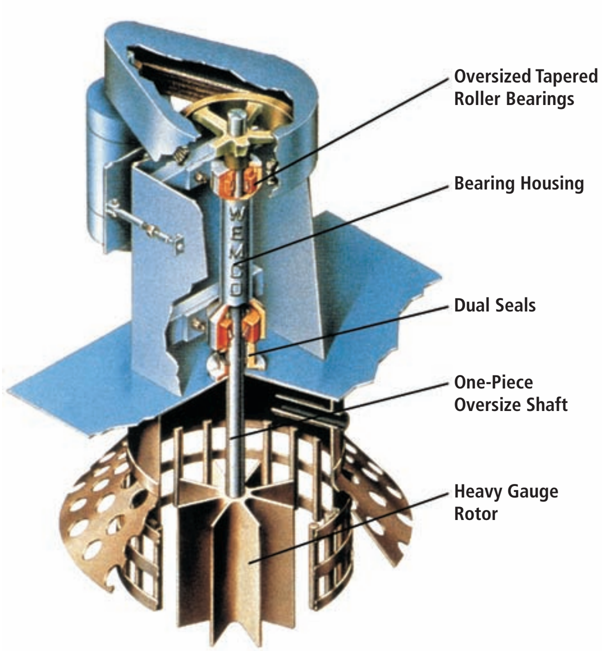
- Production: 158,990 m^3/day (1,000,000 BWPD) in twelve 144X Machines, Bakersfield, CA producing 0.8 - 2.0 PPM effluent in heavy oil
- Production: 270,280 m^3/day (1,700,000 BWPD) in ten 144X Machines, Nigeria Terminal
- Production: 20.5 Kg/cm^2 (290 PSIG) Design Pressure Dual Cell Machines for 20,670 m^3/day (130,000 BWPD)
- FPSO, Offshore Angola, mini-TLP, GOM
- Refining: 136,730 m^3/day (860,000 BWPD) Refinery Waste Water, Siberia, Russia
- Refining: Many units in continuous operation since 1970, USA, or earlier

Applications

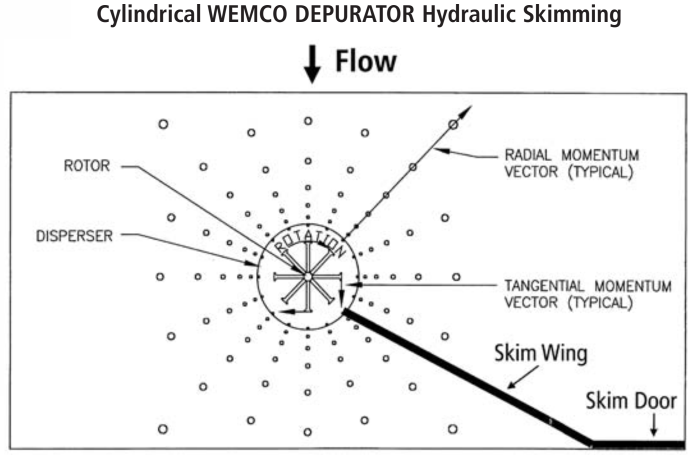
- Oil production
  - – Onshore
  - – Offshore (fixed and floating)
- Refinery and petrochemical waste water
- Metals casting and steel refining waste water



Schematic of flotation cell



Cylindrical WEMCO DEPURATOR Hydraulic Skimming



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Middlesex, UK TW16 7AH
TEL +44.1932.732000

Singapore
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TEL +65.6861.3355

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WEMCO® ISF® Systems

Proven efficient hydraulic flotation systems

A high-efficiency, hydraulic flotation machine for removing oil and suspended solids from produced and waste waters.

Overview

The WEMCO ISF (Induced Static Flotation) System is a leading technology for environmentally safe treatment of secondary produced waters. The ISF system is a simple, hydraulically operated gas flotation machine that delivers efficient oil/water separation with complete process containment. Effective oil recovery and water treatment are achieved simply and economically, with operator and environmental safety ensured by the completely enclosed flotation process. Units are available in either the horizontal standard four cell or vertical UNICEL® design which is well-suited for locations where space restrictions require a small footprint.

Operating Principle and Key Features

Streamlined for simple, efficient operation and maintenance, each ISF machine consists of a cylindrical vessel partitioned into several major components: floating, degassing, optional skim storage compartments, a recirculation pump and piping and a liquid level control system. All equipment is skid mounted for rapid installation and start-up.

The ISF is an induced gas flotation system through which a high-velocity stream of recycled clarified water enters the cells containing influent water through eductor nozzles in the bottom of the vessel. This induces a recirculating flow of air or gas from the vessel freeboard into the process water, and a unique eductor arrangement distributes small gas bubbles uniformly throughout the cell volume. These bubbles lift contaminants to the liquid surface forming a froth layer, which is then skimmed from the liquid surface by a simple collection trough. Gas and a small volume of treated water are continuously recycled from the degassing chamber into the treatment cells. The skim cycles are automatically initiated by a timer and the cycle interval, duration and level setpoints are all user-selectable and can be changed without interrupting operation or entering the vessel. The power requirements of the ISF are very low with the gas induction and mixing in the flotation cells being provided by a simple recirculating pump.

Performance

High-Efficiency Oil Removal - The separation efficiency of the unique ISF flotation cell design compares favorably to the industry standard depurator. At many installations, the ISF achieves effluent oil concentration in the range of 5 to 10 parts per million. Our ISF cells are designed to provide 90% or greater oil removal and 80% or greater removal of non-oil solids at full design capacity. This represents a major improvement over earlier hydraulic flotation systems which typically experienced performance degradation at only 40% of design capacity.

Product Range

- Individual units for flow rates of 380 m^3/day to 20,670 m^3/day (2400 BPD to 130,000 BPD)
- Separation efficiency up to 95%

Benefits and Advantages

- Compact, lightweight, horizontal or vertical installation
- Minimal footprint
- No internal moving parts, low maintenance
- Minimal power requirements, minimal controls
- Modular design, easy to expand, reduced installation costs
- Motion insensitive vertical UNICEL design is ideal for floating production systems
- Utilizes process or inherent feed pressure
- No environmental pollution
- All hazardous or toxic gases are contained
- Can be constructed to ASME code for pressurized operation

Options and Types

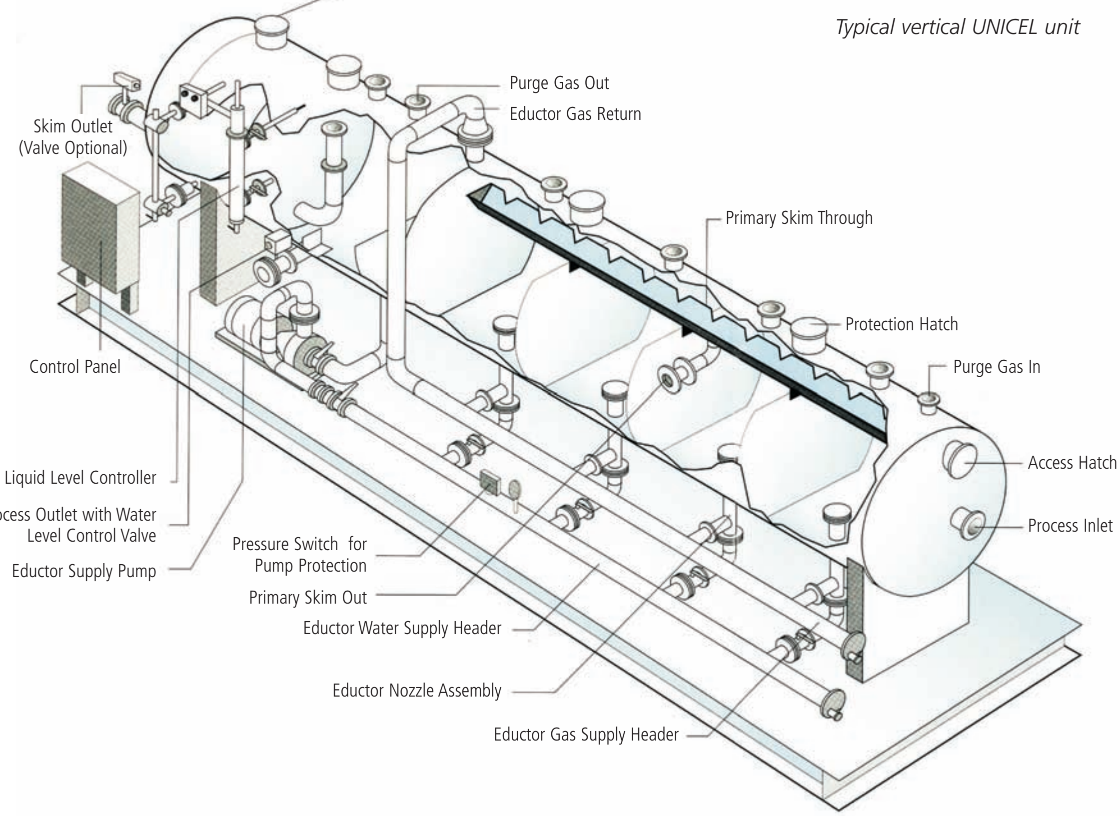
- Vertical UNICEL
- Four cell

Applications

The WEMCO ISF can be used wherever secondary treatment of oil-contaminated water or waste water is required.

- Oilfield produced waters
- Refinery waste waters
- Petrochemical waste waters

Typical vertical UNICEL unit



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Middlesex, UK TW16 7AH
TEL +44.1932.732000

Singapore
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TEL +65.6861.3355

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APPENDIX XI

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Clear Solutions to Oily Water Separation

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- and Technical Services.

ENVIRO-TECH SYSTEMS

Full Service Product Line

API 421

Skimmers

Enviro-Sep™ (CPI)

Hydro-Cyclone

Enviro-Cell™ (IGF)

Walnut Shell Filters

Sump Tanks

Skim Piles

Advances Sensor PPM Monitor

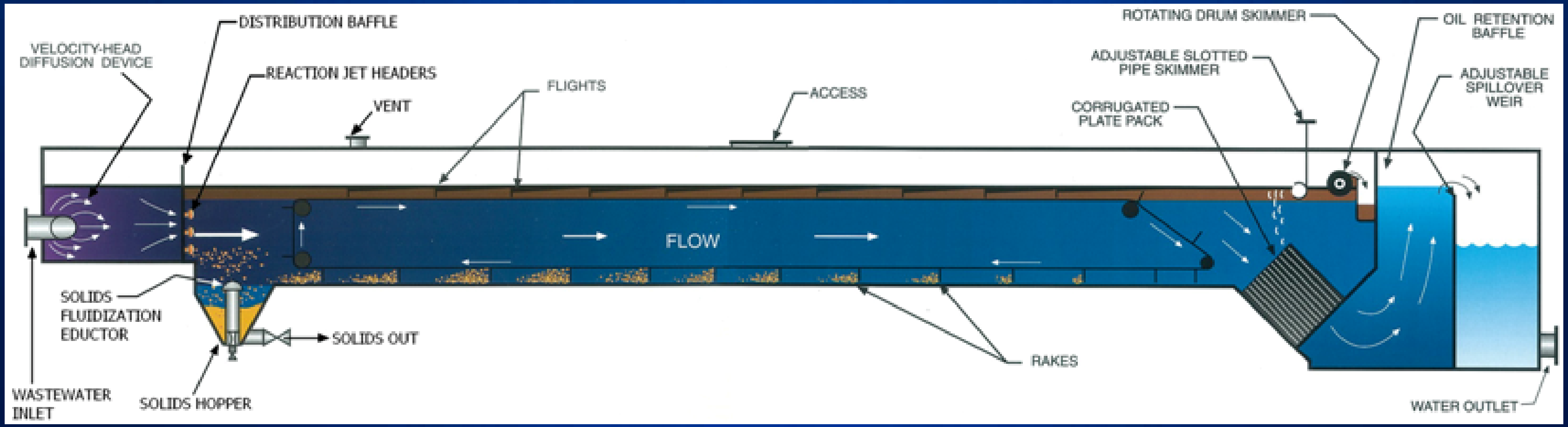
Retractable Sampler

Enerscope Desander

ENVIRO-TECH SYSTEMS

Skim-Sep API-421- Onshore Applications

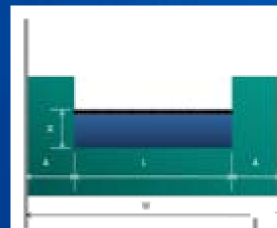
• **The API-421 Separator is generally the first step in the treatment of Produced or Processed Water. Its design allows for the removal of bulk oil and solids along with some organics.**

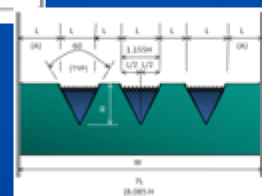


ENVIRO-TECH SYSTEMS

API-421 Optional Features

Weir System

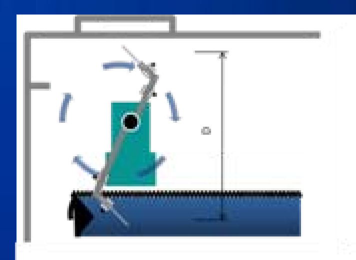


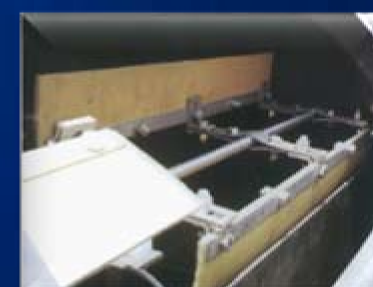


Rotating Drum Skimmer

Slotted Pipe Skimmer

Rotating Wiper for Floating Sludge Removal



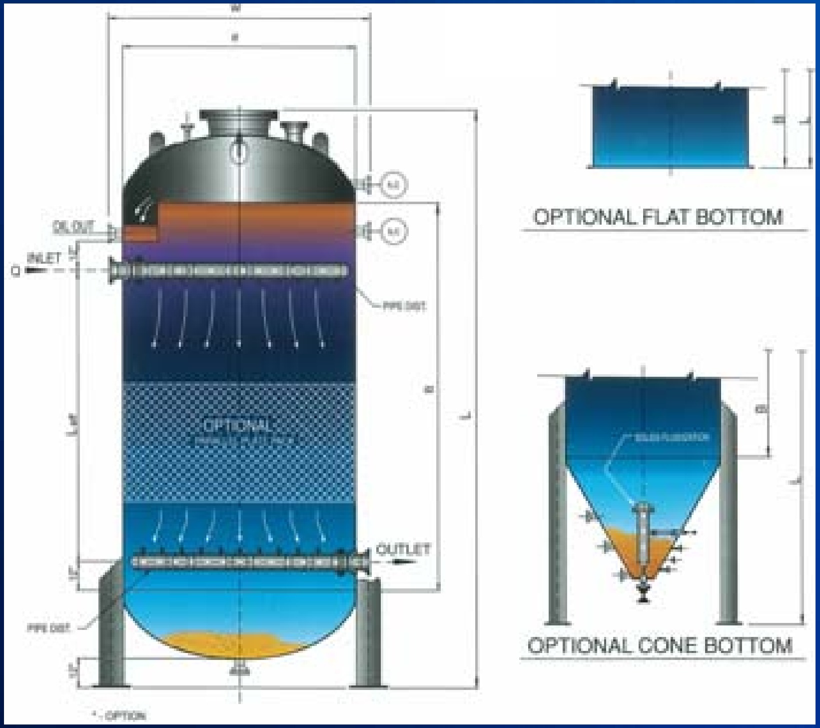


ENVIRO-TECH SYSTEMS

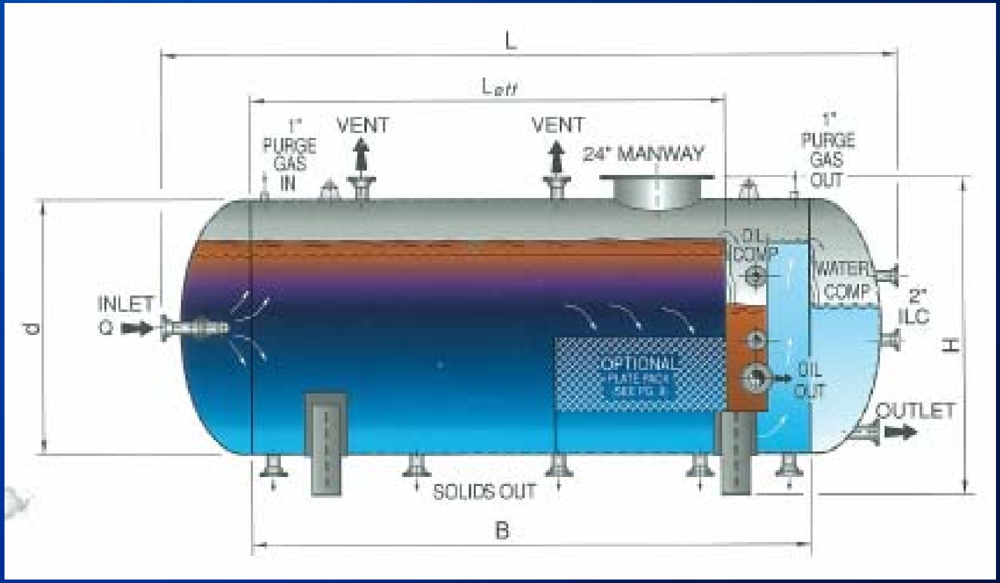
Skim-Sep Skimmers

Removes 150—50 micron size particles and is able to clean oily sands and solids

Vertical Cylindrical Skimmer



Horizontal Cylindrical Skimmer



ENVIRO-TECH SYSTEMS

Enviro-Sep™

CPI Features and Benefits

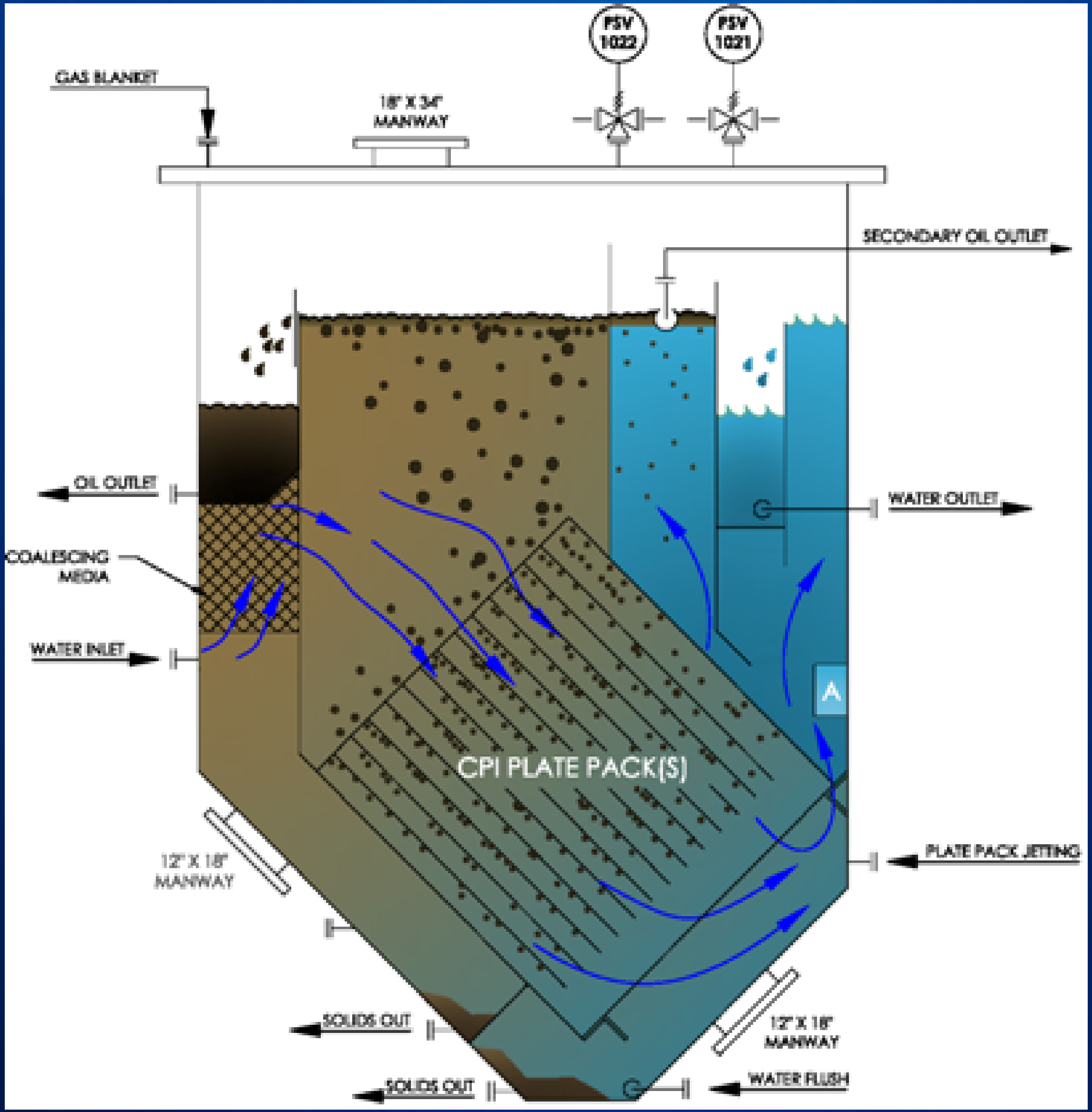
- Enlarged Inlet Compartment for Free Oil removal
- Primary and Secondary Solids with sloped bottom for solids removal
- Removalble Distribution Plate
- Design pressure up to 5 psig
- Man-way in each solids compartment
- Adjustable Oil Weir
- Stokes Law and Laminar Flow design
- Quick Release hatch doors
- Fiberglass (FPR) Plate Packs

Optional Features

- Rotatable Oil Skimmer Eliminating Vessel entry for weir Adjustment
- Plate Pack Jetting Allowing Continuous On-Line Pack Cleaning
- Solids cleaning Eductor
- Coalesing Pack
- Gas Sparging
- Induced Gas Flotation
- Plate Pack Construction of Stainless Steel

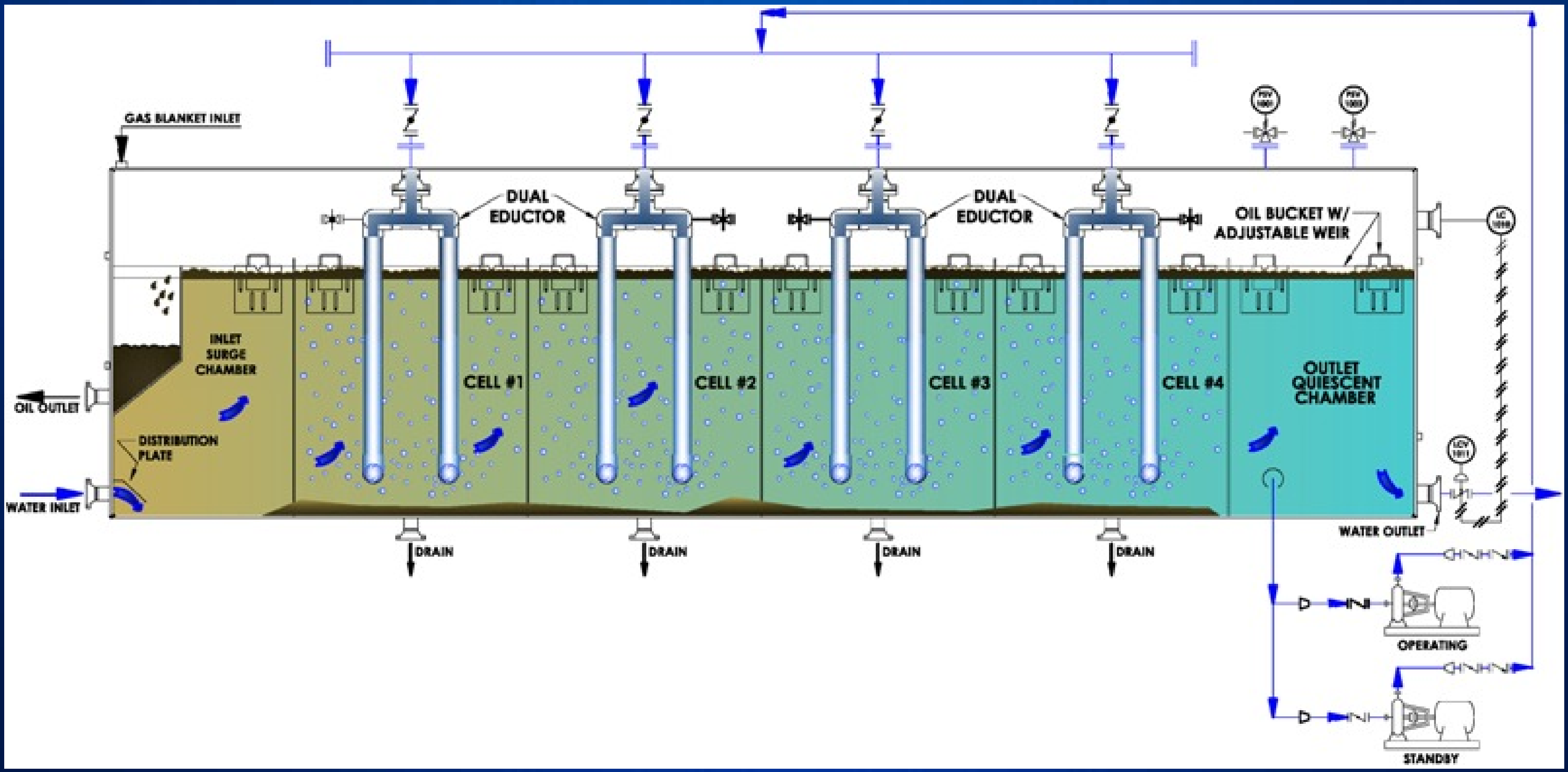
ENVIRO-TECH SYSTEMS

Enviro-Sep™



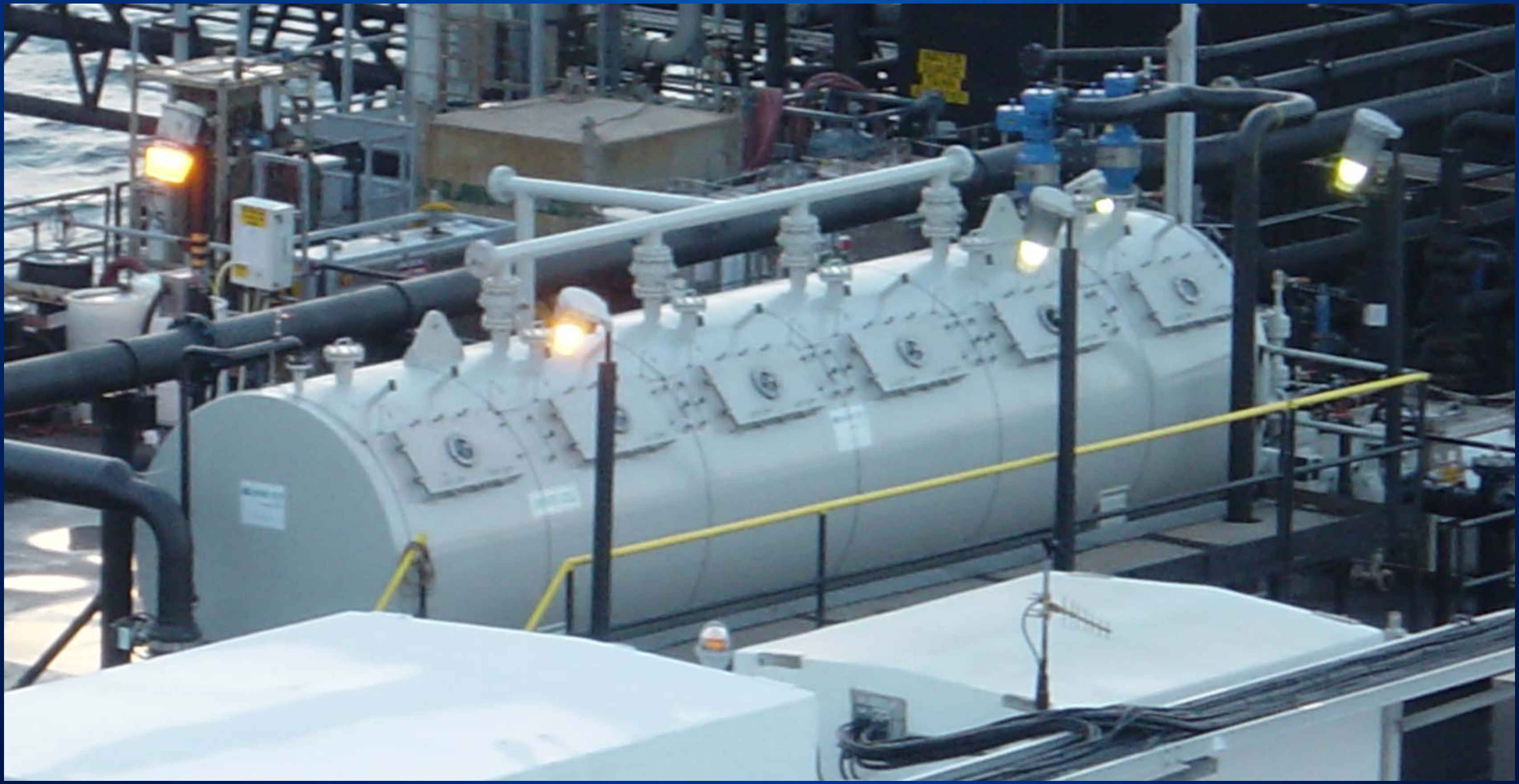
ENVIRO-TECH SYSTEMS

Enviro-Cell™



ENVIRO-TECH SYSTEMS

Enviro-Cell™

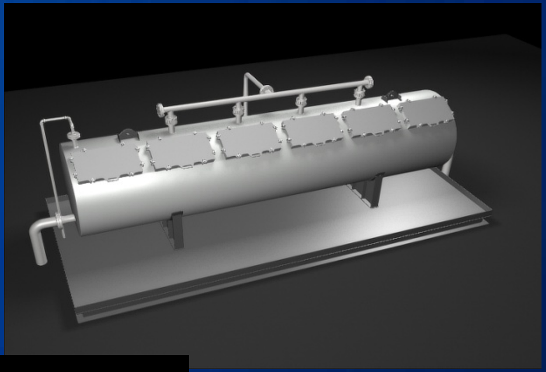


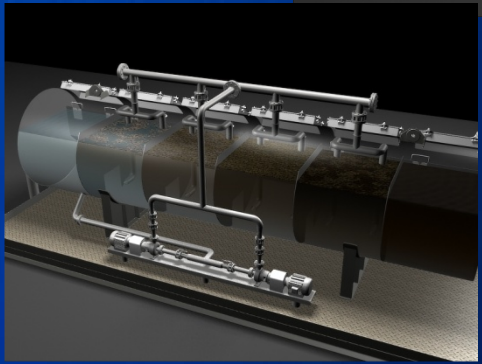
ENVIRO-TECH SYSTEMS

Enviro-Cell™

IGF Features and Benefits

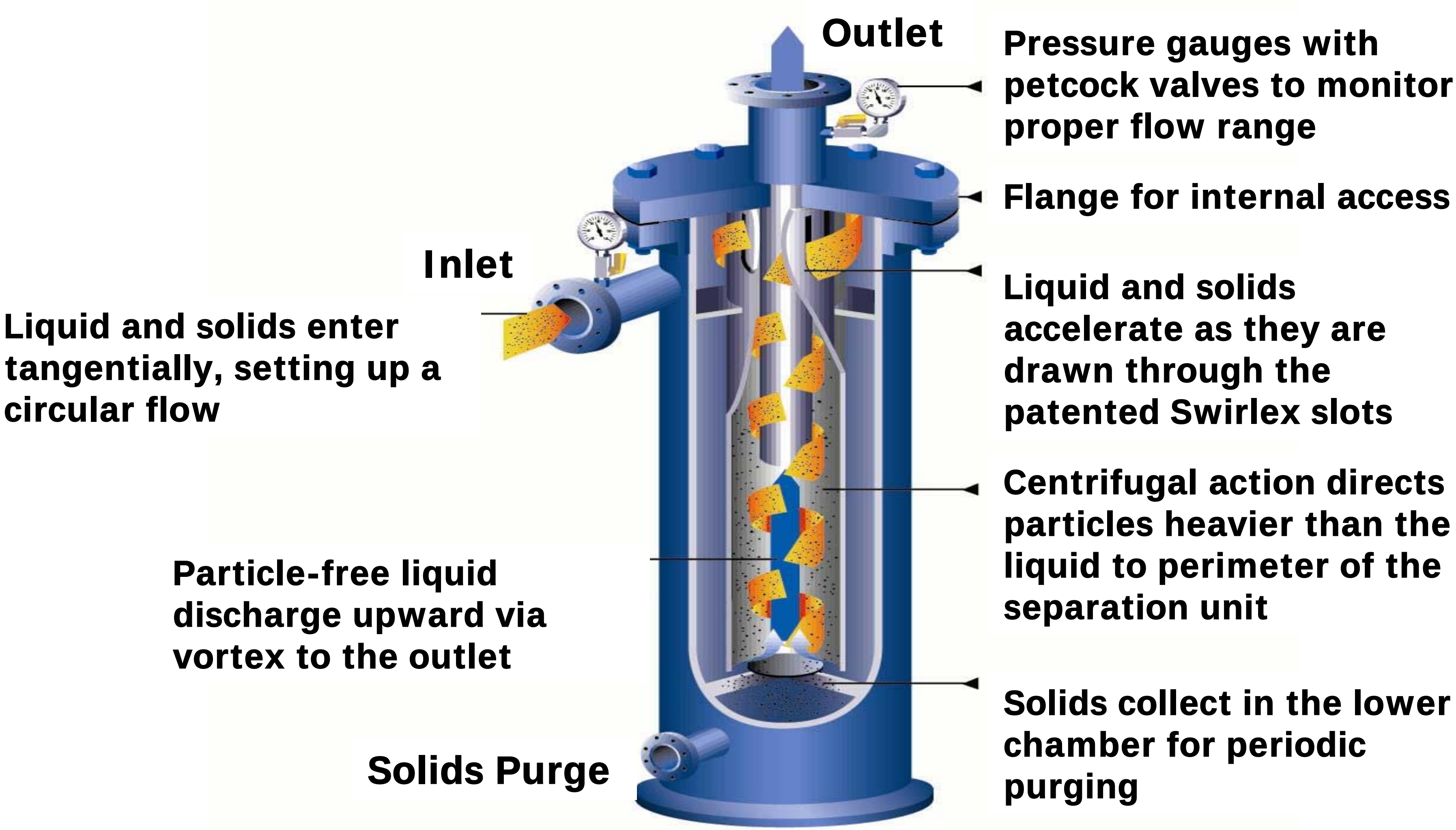
- Full 5 minute retention time including recycle
- Inlet Surge Cell with skimming
- Clearwell (Quiescent Cell)
- Four (4) active Cells
- No moving parts inside vessel
- Adjustable Oil Weir Assembly in each cell
- Cylindrical design for structural integrity and minimum corrosion
- Multiple Eductors for maximum separation
- Low Maintenance





ENVIRO-TECH SYSTEMS

Enerscope

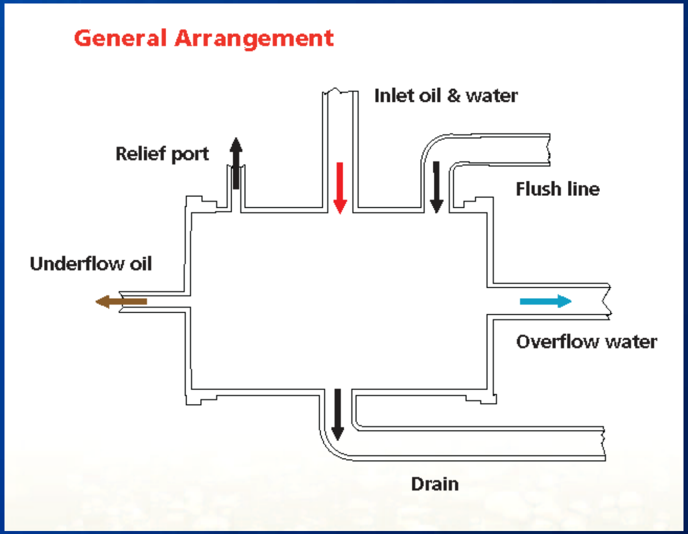


ENVIRO-TECH SYSTEMS

Enerscope Hydrocyclone

Key Features

- Stable oil core provides higher separation performance
- No Moving Parts – saves maintenance time and cost
- Low and steady pressure loss saves energy and provides predictable flow rates and operating system
- Designed to handle slugging, upset situation and high solids loading provides predictable operating system
- Enhanced inlet ports for optimum oil recovery
- Choice of profiles to accommodate space and piping limitation making for an easy layout and installation



ENVIRO-TECH SYSTEMS

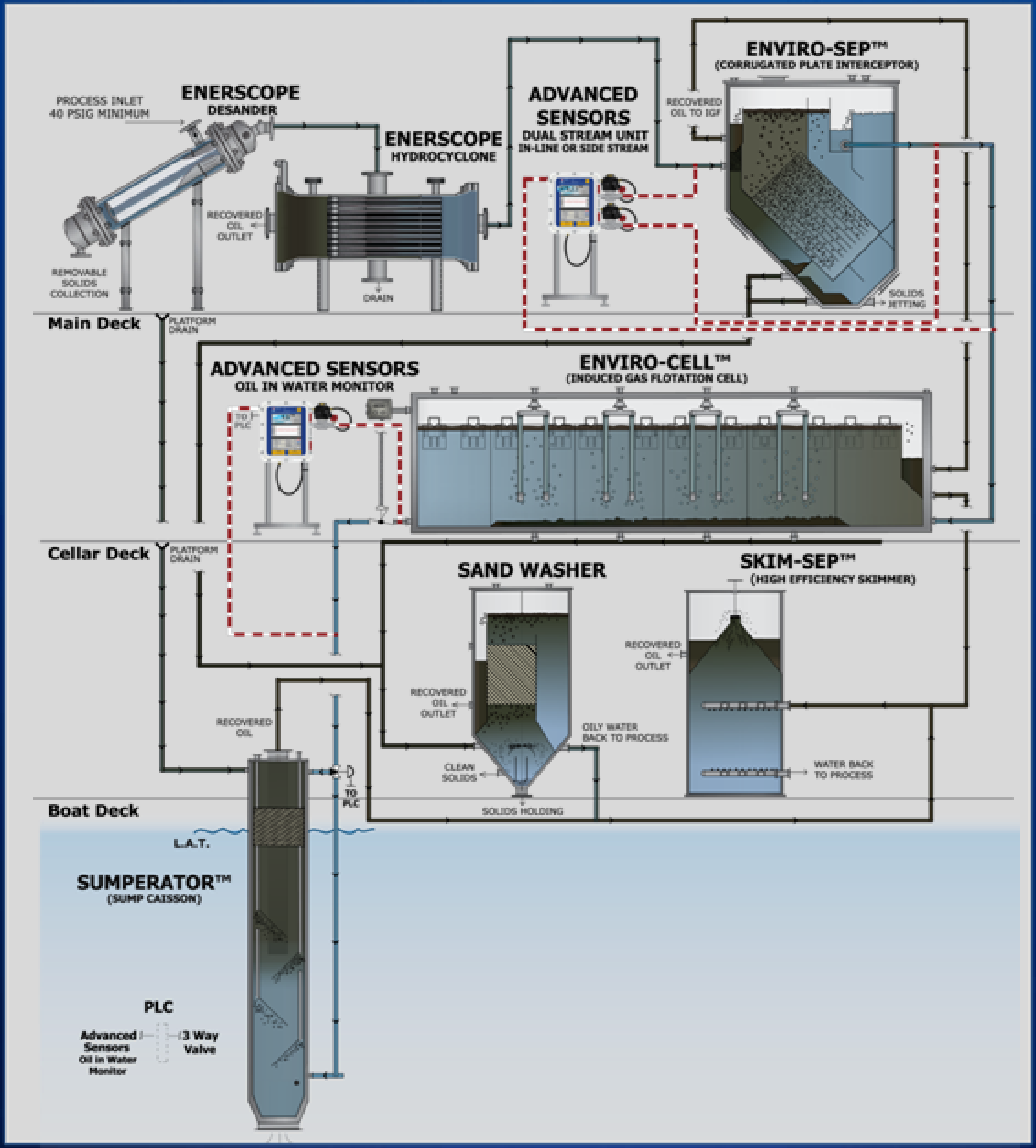
Advanced Sensor PPM Monitor

Key Features

- **Patented Ultrasonic Industry technology:**
  - **Maintenance Free Self Cleaning – 100% successful!**
  - **Sample homogenization so measurement is oil droplet size tolerant**
  - **Continuous Flow and Accurate Measurement**
  - **Enhanced Measurement Range**
  - **0 to 3,000 ppm Standard**
  - **0 to 20,000 ppm Optional**
  - **± 1 % Accuracy of scale**
  - **Easy Installation, Commissioning, Use, and Maintenance**
  - **EXD Housing: purged air, 3 phase power, cooling water Not required**

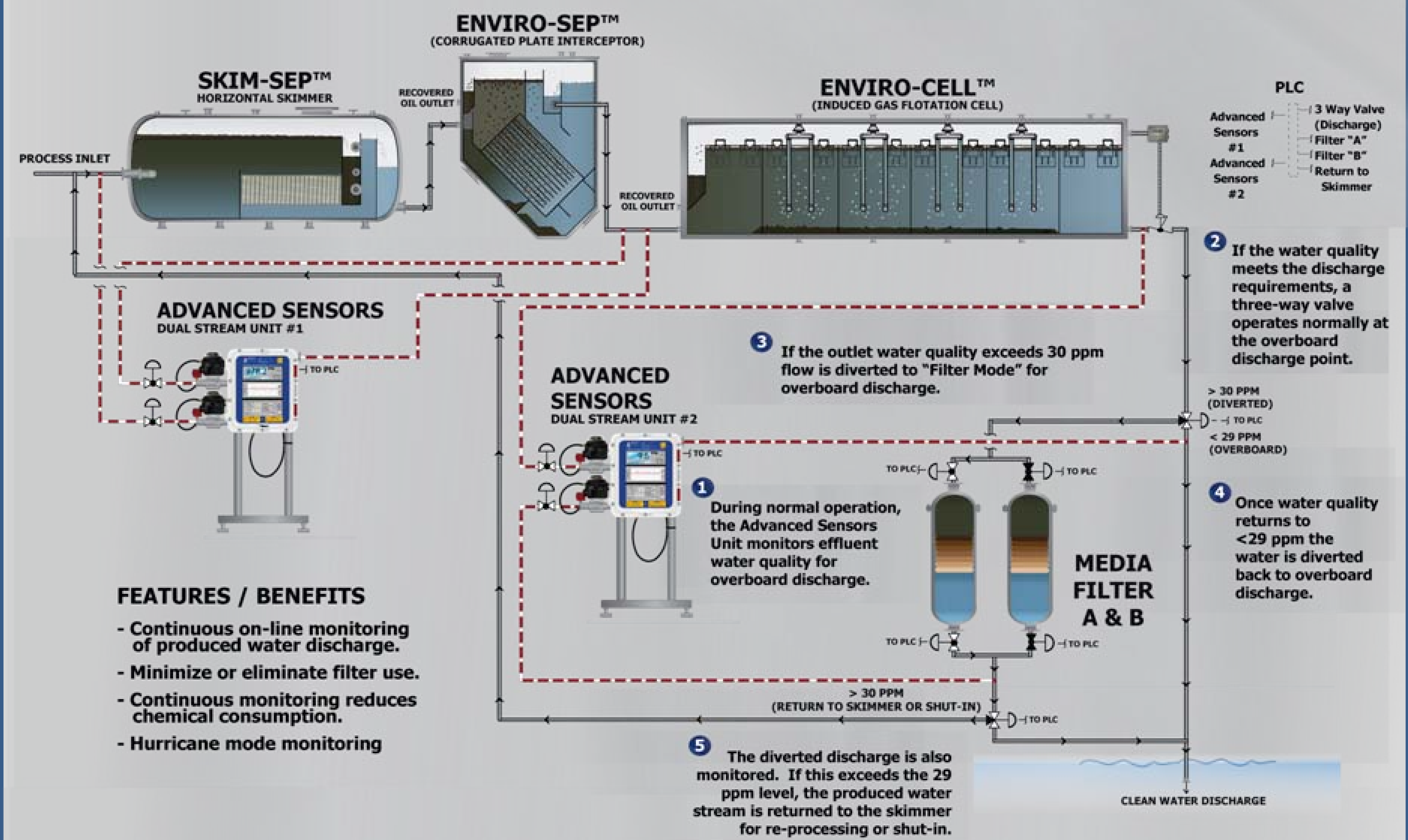
ENVIRO-TECH SYSTEMS

Smart Water Technology



ENVIRO-TECH SYSTEMS

Smart Water Discharge



FEATURES / BENEFITS

- Continuous on-line monitoring of produced water discharge.
- Minimize or eliminate filter use.
- Continuous monitoring reduces chemical consumption.
- Hurricane mode monitoring

ENVIRO-TECH SYSTEMS

Full Service Solution Provider

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- Refurbishment
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- Onsite Pilot Testing
- Flo-Clean™ Filtration System

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APPENDIX XII

Ceramic Membrane Technology

Ceramic Ultra- and Nanofiltration Membranes for Oilfield Produced Water Treatment: A Mini Review

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[2]*Department of Chemical Engineering, Kansas State University, Manhattan, Kansas, USA*

Abstract: Produced water is any fossil water that is brought to the surface along with crude oil or natural gas. By far, produced water is the largest by-product or waste stream by volume associated with oil and gas production. The volume of produced water is dependent upon the state of maturation of the field. There is a need for new technologies for produced water treatment due to increased focus on water conservation and environmental regulation. Each time regulatory agencies initiate more stringent environmental control treatment technologies are refined to meet the updated standards. The European standard for effluent from onshore petroleum activities requires less than 5 mg/l total hydrocarbons (HC) and less than 10 mg/l suspended solids; such low concentrations are unattainable when classical separation processes are used. To overcome the challenges posed by more stringent regulations, operators have turned to membrane filtration schemes which have the potential to minimize additional costs and disposal issues. Ceramic ultra- and nanofiltration membranes represent a relatively new class of materials available for the treatment of produced water. They can be manufactured from a variety of starting materials and can be processed in different ways to yield products with broad ranges of physical-chemical advantages and applications. While these membranes are effective in the separation of oils, emulsions and silts, they are prone to fouling by waxes and asphaltenes. The issues needing to be addressed are the prevention of membrane fouling during operation and the provision of an expedient, cost-effective and non-hazardous means of cleaning fouled membranes. Currently, there are not enough existing studies related to the treatment of oilfield produced water using ceramic membranes.

Keywords: Oilfield produced water, ceramic membrane, water treatment, waste stream, membrane fouling, pressure-driven membrane processes, membrane cleaning.

INTRODUCTION

Oilfield wastewater known as *produced water* is generated in large quantities in onshore and offshore oil exploitation. On average, U.S. oil wells produce more than 7 billion barrels (bbl) of water for each barrel of oil. Moreover, water can comprise as much as 98% of the material brought to the surface from crude oil wells nearing the end of their productive lives [1]. According to the American Petroleum Institute (API), about 18 bbl of produced water were generated by U.S. onshore operations in 1995 [2]. In the United Kingdom sector of the North Sea, the volume of produced water has exceeded crude oil volume since 1988 [3]. In 1996, 206 million tons of produced water was associated with a total crude oil production of 115.9 million tons [3]. In 1999, an average of 210 million bbl of water was produced elsewhere in the world each day [4].

Wastewaters from oilfields produced during many stages of crude oil production, recovery and transportation represent a major environmental and processing problem for the petroleum industry [5]. In addition, oil drilling operations can produce large quantities of contaminated water. These volumes represent huge amounts of contaminated water that require economical, environmentally friendly methods of treatment [6]. Furthermore, the water coming from the primary separation process (separation of wastewater from the oil) requires further treatment. Conventional treatment systems rely on: separation by gravity (skimmers and corrugated plate interceptors, or "CPI"), gas flotation, filtration and separation by centrifugal force (hydrocyclones) [7]. Generally, the produced wastewater should be reused for enhancing oil recovery or discharged into the environment after treatment. However, the characteristics of oily wastewater make it difficult to treat using commercial methods. Crude oil floating in the water can easily be removed by filtration or an alternate commercial system. Oil in water emulsions can be disposed of by chemical and physical treatments such as flotation column and centrifugation or by biological methods. Other components dissolved in the wastewater such as organic and inorganic substances, radionucleotides as specified below, and tiny oil drops are harmful to the environment and difficult to treat. Some components, including dissolved hydrocarbons, are highly toxic and difficult to break down in the environment.

If the wastewater is to be released as surface water, it must be treated to remove not only floating oil and suspended solids (SS) but virtually all of the dissolved components that contribute to the high chemical oxygen demand (COD) of the water as well [5]. There are several options for handling produced water including disposal, reinjection and treatment. The most popular option for handling produced water is to re-inject it back into the formation. Produced Water Re-Injection (PWRI) requires skillful planning to avoid formation damage yet it requires minimal or modified treat-

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1874-2335/07

ment before injection to meet the needed quality of reinjection water. Jun Wan *et al*. showed that treatment of produced water before re-injection gives better performance [8].

CHARACTERISTICS OF OILFIELD PRODUCED WATER

Produced water always contains a complex mixture of organic and inorganic materials similar to those found in crude oil and natural gas, whose compositions vary with the location and over the lifetime of a producing field [9]. Average levels of some critical organic and inorganic pollutants found in oilfield waters are shown in Table **1** [10-13]. The basic components can be grouped into the following categories:

- *Organic substances* including benzene, napthalene, toluene, phenantrene, bromodichlormethane, pentachlorphenol and free oil.
- *Inorganic substances* such as Pb, As, Ba, Sb, SO_4, Zn, total dissolved solids (TDS) up to 250000 ppm.
- *Radionucleotides* including U and Radium, respectively [14].

Generally, most of the produced wastewater is reused and reinjected into the underground for enhancing oil recovery after a certain treatment yet large amounts of produced wastewater are discharged directly into the environment. In recent years, the ecological problems connected with crude oil pollution have become apparent through the observed presence of oil derivatives in the environment as a result of the complex composition of produced water [9].

AVAILABLE TECHNOLOGIES FOR PRODUCED WATER TREATMENT

There are a number of methods used for produced water treatment, each having its respective advantages and disadvantages. No single technique currently used is suitable for all needs. In 1995 the American Petroleum Institute (API) made its recommendation for the best available technology for produced water management on offshore gas and oil installations as follows [6]:

Carbon Adsorption (Modular Granular Activated Carbon Systems)

Advantages: Removes hydrocarbons and acid, base and neutral compounds; low energy requirements; higher throughput than other treatments (except biological); treats a broad range of contaminants; very efficient at removing high molecular weight organics.

Disadvantages: Fouling of carbon granules is problematic; produces waste stream of carbon and backwash; requires some pre-treatment of produced water stream.

Air Stripping (Packed Tower with Air Bubbling Through the Produced Water Stream)

Advantages: Removes 95% of volatile organic compounds (VOCs) as well as benzene, toluene, naphthalene, and phenols; H_2S and ammonia can be stripped with pH adjusting; higher temperature improves removal of semi-volatiles; small size; low weight and low energy requirements.

Disadvantages: Can be fouled by oil; risk of iron and calcium scale formation; generates an off-gas waste stream that may require treatment; requires some pre-treatment of produced water stream.

Ultra-Violet Light (Irradiation by UV Lamps)

Advantages: Destroys dissolved organics and both volatile and non-volatile organic compounds, including organic biocides; does not generate additional waste stream; handles upset or high loading conditions.

Disadvantages: Will not treat ammonia, dispersed oil, heavy metals, or salinity; relatively high energy requirements; UV lamps may become fouled; residues may be toxic if peroxide is used; requires some pre-treatment of produced water stream.

Chemical Oxidation (Ozone and/or Hydrogen Peroxide Oxidation)

Advantages: Removes hydrogen sulfide (H_2S) and particulates; treats hydrocarbons, acid, base and neutral organics, volatiles and non-volatiles; low energy requirements if peroxide system used; operation is straightforward.

Disadvantages: High energy inputs for ozone system; oil may foul catalyst; may produce sludge and toxic residues; requires some pre-treatment of produced water stream.

Biological Treatment (Aerobic System with Fixed Film Biotower or Suspended Growth)

Advantages: Treats biodegradable hydrocarbons and organic compounds, H_2S, some metals and, in some conditions, ammonia; "fairly low" energy requirements; handles variable loadings, if acclimated.

Table 1. Characteristics of Oilfield Wastewaters: Organic Contents, Adapted from [15]

Components	Concentration (mg/L)		
	Norway [11]	Gulf of Mexico [12]	Campos Basin [15]
Benzene, Toluene, Xelyole (BTX)	8	B:1,318	T:0,990
		T:1,065	o-X:0,135
Naphthalenes	1,5	0,132	0,106
Phenols	5	1,049	4,3
Total organic carbons (TOC)		70-650	386

Disadvantages: Large, heavy plant required for long residence times; build-up of oil and iron hinders biological activity; aeration causes calcium scale formation; produces gas and sludge requiring treatment; requires some pre-treatment of feed.

Membrane Filtration (Nanofiltration and Reverse Osmosis Polymeric Membranes)

Advantages: Effective removal of particles, dispersed and emulsified oil; small footprint size; low weight and low energy requirements; high throughput rates.

Disadvantages: Doesn't remove volatiles or low molecular weight compounds; oil, sulfides or bacteria may foul membrane, which requires daily cleaning; effluent by-product may contain radioactive material; requires some pre-treatment of feed stream.

This recommendation, makes clear that required pre-treatment of produced water stream (feed) is a major disadvantage of all treatment technologies. However, the combining of different technologies affords the possibility to reduce the pollutants in produced water to almost undetectable levels.

MEMBRANE TECHNOLOGY FOR PRODUCED WATER TREATMENT

Membrane filtration is a technology that has been successfully practiced for many decades and demonstrates obvious technical and economical feasibilities [16].

Overall, the membrane field has advanced immensely. Membranes are economical, environmentally friendly, versatile and easy to use, making them a leading choice for water purification applications which should continue to be the case for many years to come [17]. Membrane technology is widely accepted as a means of producing various qualities of water from surface water, well water, brackish water and seawater. Membranes are also used in industrial processes and wastewater treatment. Recently, membrane technology has been applied in the areas of secondary and tertiary municipal wastewater treatment and oil field produced water treatment [18]. Distinct advantages of membrane technology for treatment of produced water include reduced sludge, high quality of permease, and the possibility of total recycle water systems. These advantages coupled with the small space requirement, moderate capital costs and ease of operation associated with membrane technology make it a very competitive alternative to conventional technologies [19]. Pressure-driven membrane processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). MF and UF often serve to remove large organic molecules, large colloidal particles and microorganisms. MF performs as a porous barrier to reduce turbidity and some types of colloidal suspensions. UF offers higher removals than MF, but operates at higher pressure. UF can reject bacteria, macromolecules such as proteins and large particles and microorganisms. RO membranes exclude particles and even many low molar mass species, such as salt ions and organics.

Membranes are typically made from polymeric materials, ceramic (inorganic) though metal oxide membranes are also available and are traditionally used for ultrafiltration processes.

CERAMIC MEMBRANES

Porous ceramic membranes are an important membrane category that is of particular interest in applications requiring high chemical or thermal stability [20]. Tubular ceramic membranes are formed by a porous support (generally α-alumina), one or more layers of decreasing pore diameter and an active or separating layer (α-alumina, zirconia, etc.) covering the internal surface of the tube (Fig. **1**). Depending on the requirements of each particular application, a wide range of ceramic membrane designs (Fig. **2**) and stainless steel membrane housing (Fig. **3**) are commercially available. The use of ceramic membranes for microfiltration and ultrafiltration solutions is of great interest due to the potential to remediate fouling problems associated with those processes and solutions (adsorption or deposition of macromolecules on the membrane pores/surface) that strongly reduce volume flow and make the use of hard chemical and high temperatures in cleaning procedures necessary, which in turn causes damage to polymeric membranes [21].

THE ADVANTAGES OF CERAMIC MEMBRANES

- Narrow and well-defined pore size distribution, in comparison with their polymeric counterparts allows membranes to achieve a high degree of particulate removal at high flux as demanded by such diverse applications as the removal of emulsified oils from wastewaters.
- Material stability in harsh environments can provide cost-efficient high temperature deashing of spent lubricants and the removal of submicron suspended/dissolved solids from industrial solvents.
- Membrane cleaning with harsh chemicals (if necessary) does not reduce membrane performance stability, which is critical in dealing with waste streams that constantly vary or display a high propensity for membrane fouling [22].

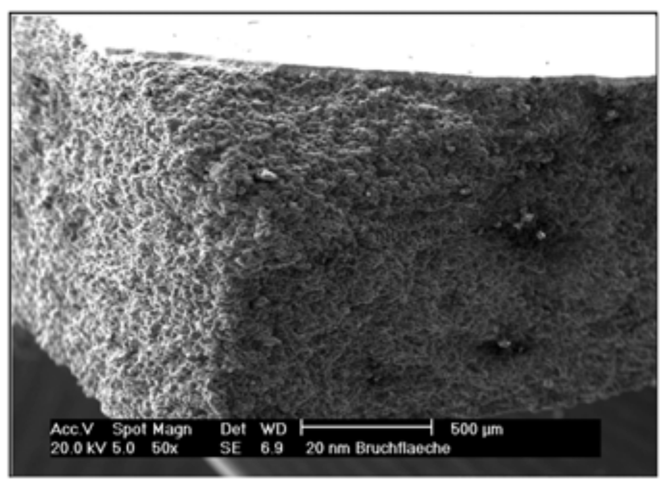

Fig. (1). Scanning electron microscopy picture of a ceramic membrane.

PRODUCED WATER TREATMENT USING CERAMIC MEMBRANES

In recent years, ceramic membranes have become popular due to their superior mechanical, thermal and chemical

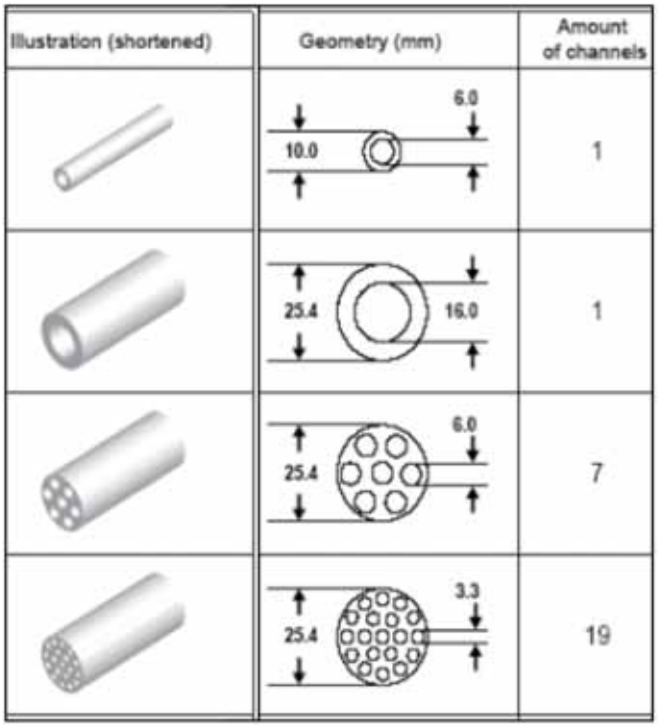

Fig. (2). Four different ceramic membrane designs, adapted from atech innovations GmbH, Gladbeck, Germany.

Fig. (3). Ceramic membranes and steel housings.

stability though their chemical selectivity and the available pore size range is limited. The use of ceramic UF membranes has not only grown in water treatment but also in the treatment of oil and detergent containing aqueous waste streams that are produced by various industrial operations (e.g. metal finishing, petroleum refining, bilge water treatment, railroad machining operations) [23]. In particular, ceramic UF membranes have been shown to be very effective in treating waste oil, grease and detergent-containing effluents with the purpose of removing oil contaminants while recycling the detergents. Ceramic membranes, particularly zirconia membranes, show better separation performance such as higher flux, less fouling and higher oil rejection than polymer membranes [23, 24]. Aside from all these depicted benefits, one problem of water treatment using ceramic membranes lies in the reduced efficiency of ceramic UF membranes due to fouling by oily constituents and their resulting diminished lifetime [25].

FLUX LOSS DUE TO MEMBRANE FOULING

With the proven success of membranes in the water treatment arena, membrane technology continues to advance. Major problems still needing attention are membrane fouling and suitable cleaning strategies.

Reduced fouling would make membranes even more cost-effective by extending their operational lifetime and lowering their energy requirements. The permeate flux of a model solution (produced water from waste oil, C_{oil} in feed: 5%) as a function of time in the case of ultrafiltration experiments using two different ceramic membranes under continuous operation is shown in Fig. (**4**) [26].

During the membrane filtration process, permeate flux may decrease significantly and rapidly until a final steady state is attained at which the flux no longer decreases. The decline in flux is commonly connected to two phenomena: concentration polarization and fouling [27]. There are four major types of fouling:

Biofouling results from microbial contamination of feed water, producing a biofilm on the surface of the membrane which increases the resistance to water permeation through the membrane.

Scaling arises from the precipitation and deposition of salts on the membrane surface.

Organic fouling occurs when substances such as hydrocarbons coat the surface and/or plug pores in the porous support layer.

Colloidal fouling mainly results from particles such as clay or silica accumulating on the surface of the membrane.

Fouling can be controlled to some extent by adding disinfectants, anti-scaling agents, and other pre-treatment steps [28]. The level of membrane fouling depends on feed suspension properties (particle size, particle concentration, pH, ionic strength), membrane properties (hydrophobicity, charge, pore size) and hydrodynamics (cross-flow velocity, transmembrane pressure) [29]. Also, the flux through UF membranes may be reduced due to concentration polarization, a problem more common to the use of UF than to other membrane processes due to the nature of the solutions being treated, i.e. organic components occurring in wastewater [30].

The feed flow velocity is a crucial parameter in controlling the flux. The choice of cross-flow velocity is usually a compromise between membrane performance (flux) and energy consumption. Flux increases linearly with pressure. A cross-flow velocity of 3 m/s is normal; higher velocities further minimize the rate of fouling of the membrane surface, thereby maintaining a higher average flux. However, the use of overly high pressures may result in severe fouling and perhaps also membrane compaction. Therefore, there is an acceptable pressure range which should be adhered to for different membrane applications.

CERAMIC MEMBRANE CLEANING METHODS

Fouling is frequently cited as the most important factor limiting the utilization of membranes in produced water

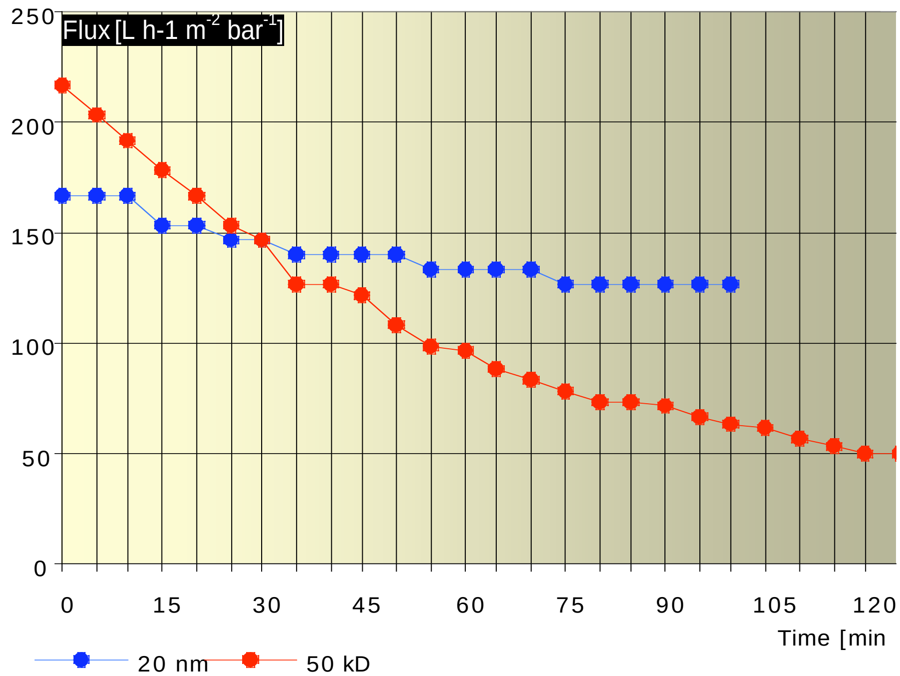

Fig. (4). Comparison filtrate flux of the 20 nm and 50 kDa ceramic membranes. Model solution (produced water from waste oil) was used in a membrane-assisted continuous reactor at 30°C, TMP = 1 bar.

treatment. Currently, the most commonly used methods to clean ceramic membranes and reduce membrane fouling include:

Cross-flushing in which the effect of a forward flush may be improved by the addition of air bubbles (AirFlush®) [31].

Back flushing reverses the flow and permeate is flushed through the membrane pores. If components are strongly adsorbed onto the membrane, back flushing is usually not very effective.

Chemicals might be used to displace, to dissolve, or to chemically modify the foulants. The chemicals used for cleaning can be classified as follows [32]:

- *Acids* are used to dissolve calcium salts and metal oxides
- *Alkalis* are used to remove silica, inorganic colloids and many biological/organic foulants
- *Surfactants* are used to displace foulants, to emulsify oils and to dissolve hydrophobic foulants
- *Oxidants* are used for oxidation of organic material and bacteria (disinfection)
- *Sequestrates* (chelating agents) are used for removal of metal cations from a solution
- *Enzymes* are used to degrade foulants.

Ultrasound associated cleaning is performed at 45 kHz or vibration at 50-1000 Hz of the module [33, 34]. The use of ultrasound in conventional membrane filtration has recently come under investigation. Ultrasound increases the flux primarily by breaking the cake layer and by decreasing the solute concentration at the membrane surface.

Many studies of current membrane cleaning technologies include hydraulic, chemical, mechanical, and ultrasound associated methods have been reported [33-37]. Backwashing, a common hydraulic cleaning technique, is not ideal because it not only experiences degradation of flux between backwashes but requires a break in operation to be performed as well [38]. Problems with other cleaning techniques include chemical costs, waste disposal, and significant capital investments for equipment [39].

PERFORMANCE STUDIES BY APPLICATION OF CERAMIC MEMBRANES FOR PRODUCED WATER TREATMENT

Hua *et al*. studied the cross-flow microfiltration (MF) processes with oily wastewater using a ceramic (α -Al_2O_3) membrane with 50 nm pore size [40]. The influence of parameters such as trans-membrane pressure (TMP), cross-flow velocity (CFV), oil concentration in feed on the separation behaviours were investigated by the measurements of permeate flux and total organic carbon (TOC) removal efficiency. In this study, the microfiltration process was successfully applied for the produced water treatment.

Table 2a. Effects of TMP on Permeate Flux

TMP (MPa)	0.05	0.1	0.15	0.2
Flux ($Lm^{-2}h^{-1}$)	30	70	110	170
TOC removal efficiency (%)	97.3	97	95.2	93

Experiment conditions were CFV: 1.68ms^{-1}, oil conc.: 500 mg L^{-1} (n = 14), adapted from Hua *et al*. [40].

The high permeate flux was achieved under high TMP, high CFV and low oil concentration. The results also indicated that the permeate flux decreased either under high salt concentration or under low pH value in the feed solution.

The TOC removal efficiencies were higher than 92.4% for all experimental conditions. The variations of permeate flux at TMP from 0.05 to 0.3 MPa are shown in Table **2a**. The steady permeate flux was highly dependent on TMP. It was also found that the increase of permeate flux under lower TMP was greater than that under higher TMP. When the TMP was greater than 0.2 MPa, the rate of increase of permeate flux was reduced. The effect of CFV on the permeation flux with the CFV ranged from 0.21 to 1.68 ms^{-1} is shown in Table **2b**. The results indicated that the higher CFV led to a higher steady permeate flux. This could be explained by the change of Reynolds number.

Table 2b. Effects of CFV on Permeate Flux

Cross flow velocity (m s^{-1})	0.17	0.42	0.8	1.7
Flux (L $m^{-2} h^{-1}$)	122	135	140	165
TOC removal efficiency (%)	97.5	97.4	97.5	97.4

Experiment conditions were TMP: 0.2 MPa, oil conc.: 500 mg L^{-1} (n = 14), adapted from Hua *et al*. [40].

Tompkins et al. report that the U.S. Navy has successfully developed a system capable of meeting oily wastewater discharge regulations [41]. This system uses dense-pack ceramic ultrafiltration membranes (full scale module with 11.2 m^2 surface area) and produces approximately 374 liters of clean effluent acceptable for overboard discharge for every 379 liters of OWS (Oil/Water Separators) effluent processed. Permeate quality averaging less than 5 ppm and below 15 ppm has been achieved aboard ship 95% of the time.

A series of tests was performed to determine the relationship between the permeate flux rate and the associated fouling rate. The tests were conducted in a similar manner to that described above except that valves were used to throttle the permeate flow rate to constant values.

Table 3. Effect of Permeate Flux Rate On Membrane Fouling, Adapted from Tompkins *et al.* [41]

Flux [L $m^{-2} h^{-1}$]	Resistance Allowed [bar $L^{-1} m^{-2} h^{-1}$]	Estimated Lifetime [h]
51	0.08	3.55
76	0.05	>>2.5
102	0.04	3.8
127	0.03	1.35
153	0.02	200

Results given in Table **3** indicate that maximum membrane life is achieved at permeate flow rates below 102 L $m^{-2} h^{-1}$ (lmh).

J. Zhong *et al*. studied the performance of MF using ceramic membranes combined with traditional chemical method-flocculation as pretreatment [42]. After flocculation, the effluents were treated with micro-filtration using zirconia membranes. The average membrane layer of the asymmetric microporous ZrO_2 membranes was about 30 µm thick and the nominal pore size was 0.2 µm. The membrane elements were placed in 20 cm long stainless steel housing.

Table 4. MF Results With and Without Flocculation Pre-treatment with Ceramic Membrane, Adapted from Zhong *et al*. [42]

	MF	Flocculation+MF
Flux (L $m^{-2} h^{-1}$)	120	173.5
COD (mg L^{-1})	154	108
Oil content (mg L^{-1})	34.68	8.762

Permeate after MF 30 min used for COD and oil-content analysis trans-membrane pressure: 0.110 MPa, cross-flow velocity: 2.56 m/s, operation temperature: 25°C.

The results of filtration tests show that the membrane fouling decreased and the permeate flux and permeate quality increased with flocculation as pre-treatment (Table **4**). The permeate obtained from flocculation and micro-filtration using 0.2 µm ZrO_2 membrane is second only to that obtained after MF alone and meets the Chinese National Discharge Standard. The effects of process parameters including flocculation conditions, filtration conditions, etc. on the quality of effluent are also investigated.

Mueller *et al.* studied two α-alumina ceramic membranes (0.2 and 0.8 µm pore sizes) for the treatment of oily water containing various concentrations (250-1000 ppm) of heavy crude oil from Hueneme field in California [19]. This crude oil was added to various concentrations of top water. Each ceramic membrane has 35% porosity and an asymmetric surface layer of 4-5 µm thickness. They have a tubular geometry, with an i.d. of 0,7 cm, a useful length of 20.6 cm and a surface area of 45.3 cm². The membranes carried a negative charge of pH levels typical of produced water (6,6-7,8). Table **5** shows the results derived from the two α-alumina ceramic membranes. Increased oil concentrations in the feed decreased the final flux whereas the cross-flow rate, the trans-membrane pressure, and the temperature appeared to have relatively little effect on the final flux. Total resistance versus time curves from the flux decline data were used to identify the fouling mechanisms. The 0.2 and 0.8 µm ceramic membranes appeared to exhibit internal fouling followed by external fouling.

SUMMARY

Every oilfield is characterized by a concomitant presence of fossil water and gas that come to the surface during oil extraction. The separated water, called *"produced water"* in the scientific literature, accounts for the majority of the waste derived from the production of crude oil.

Produced-water is always cleaned to some extent and the level of cleaning is dependent upon the intended use and/or current discharge regulations. Current technologies used consist of clarifiers, dissolved air flotation, hydrocyclones, and disposable filters/absorbers. After a primary process of separation from the oil, these technologies leave the water containing drops of oil in emulsion in concentrations as high as 2000 mg/l, requiring the produced water to be further treated before it can be discharged.

Existing technologies are not typically capable of reaching the new levels of cleanliness demanded by regulations without using additional expensive chemicals for coagulation, settling and the like, which increases operating expenses and produces greater volumes of hazardous wastes. The international standards demand more efficient separation systems than those now in common use.

Table 5. Summary of the Results Derived from the Two Microfiltration Ceramic Membranes

Initial Flux	Final Flux	Flux Change	C_{oil}, Feed	Oil Removal
0.8 µm Ceramic				
[kg m^{-2} h^{-1}]	[kg m^{-2} h^{-1}]	[%]	[ppm]	[%]
678±51	33±6	-95.-1	250	99.9
998±500	40±22 (o)	-95.6	250	99.7
800±128	46±6 (+)	-94.2	250	99.3
471±15	26±11 (o)	-94.5	1000	99.4
0.2 µm Ceramic				
211±19	32±13 (o)	-84.8	250	98.2
301±52	25±6 (o)	-91.7	1000	99.4
305	312	+ 1.6	250	98
281	577	+ 105.4	250	98.5

In all cases, the permeate was of very high quality, containing < 6 ppm total hydrocarbons.
The results are shown as an average of three repetitions, plus and minus one standard deviation, with +, - and o representing positive, negative, and insignificant differences, respectively, from baseline results at the 90% confidence level, adapted from Mueller *et al*. [19].

Ceramic membrane systems under nano- and ultrafiltration conditions have proven to be economically attractive for the treatment of produced waters with elevated concentrations of oil and low-to-middle diameters of the particles. The issues needing to be addressed are the prevention of membrane fouling by waxes and asphaltenes during operation and to provide an expedient, cost-effective, and non-hazardous means of cleaning the membranes when they become fouled.

There are several desirable characteristics attributable to the use of ceramic membranes for the treatment of oilfield produced water that need to be developed, including modification of the cake layer properties to provide a constant filtration resistance, rapid cleaning of hydrocarbon fouling of the ceramic membrane surface, and ideally, better handling of higher concentrations of hydrocarbons in the feed by the filtration membranes without fouling.

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APPENDIX XIII

Mycelx Technology

PRODUCED WATER REPORT
FOR ENGINEERS AND INDUSTRY PROFESSIONALS
by Produced Water Society +1 (281) 480-3087 www.producedwatersociety.com

Deoiling for discharge-quality water

An innovative chemical-affinity filtration process helped Anadarko to discharge water with a stringent 10-ppm oil content standard.

Parthasarathy Harikrishnan, MyCelx; **Ron Schlicher** and **Jack Yu,** MWH Global

Produced water from Anadarko's gas drilling and production operation in Vernal, Utah, contains light fuel condensate, as well as dissolved salts and suspended solids. While most of the condensate is recovered at wellsites by allowing produced water to settle in large gun-barrel tanks, a considerable fraction of the oil is still finely dispersed, or emulsified, in the produced water. The light fuel condensates are made up of diesel- and gasoline-range organics. Once they become mixed with produced water during drilling, they cannot be completely removed or separated easily using gun-barrel tanks alone. These hydrocarbons in the water are also not necessarily environmentally benign.

Reinjecting this organic-laden produced water for refracturing is generally not preferred because the organics can plug underground reservoirs. Reinjection into disposal wells was also not preferred because of this reason, and because of the high cost of transporting the water to a suitable injection site. Thus, Anadarko considered options to treat the produced water for discharge.

The company planned to use evaporation ponds at the end of its water treatment train. Regulations governing discharge to the ponds require a "no visible oil sheen" standard, to protect wildlife from being affected by oil or hydrocarbon vapor emissions from the ponds. However, Anadarko set its discharge criterion to more stringent standard of 10 ppm.

Consistently meeting the 10-ppm discharge standard and maintaining an economically viable operation posed a substantial technological and engineering challenge. In early 2007, Anadarko contracted MWH Global to design and implement a failsafe produced water treatment process that met these criteria. The resultant facilities, built and in use by late 2007, include an innovative filtration system that uses chemical affinity to polish the produced water to an exceptionally high quality. The facilities have a combined maximum processing capacity of about 45,000 bbl of water per day, and are designed to effectively handle variable water volumes in keeping with the site's gas production rate demands.

TREATMENT SELECTION

Various oil removal and water treatment technologies were considered. Results from a water sample analysis showed that the produced water from the gas wells had the following contamination characteristics:

- Oil and grease (O&G): 10–400 ppm
- Total suspended solids: 20–50 ppm
- Total dissolved solids (salt): 25,000–35,000 ppm

Evaporation ponds were chosen as the last stage of the treatment process. The produced water held there could be used later for reinjection. Further desalination of the water to remove dissolved solids and produce freshwater was not economically viable. In the short term, however, holding the produced water in lined ponds would only be possible if the treated water had no visible oil sheen on its surface, a regulatory standard that would be easily accomplished if the treatment process could meet Anadarko's 10-ppm oil content standard.

The free and soluble oils found in the produced water from the gas wells posed a challenge to this goal. The contamination included light fuel condensate, which consists of diesel-range organics, some gasoline-range organics, paraffin waxes and oil-coated solids. In order to produce a final treated water quality of 10-ppm oil in water, soluble oils needed to be removed in addition to free oil and waxes.

Traditional technologies that have been deployed and evaluated in other treatment schemes include: settling tanks, oil-water separators and coalescers, float cells (e.g., induced gas flotation, dissolved air flotation), and nutshell and multimedia filters. These technologies were incorporated into Anadarko's produced water treatment train, Fig. 1.

Settling tanks, which were selected as the first stage of the treatment train, work using gravity and time. Produced water sits for anywhere between an hour and a full day to separate the contaminants from the water. The free product (in this case, light fuel condensate) is recoverable from the tanks for sale.

Oil-water separators enhance this gravity separation using plates and weirs, while coalescers cause small free oil particles to join together into bigger ones that separate out of the water more easily. These technologies were placed in the treatment train to remove and recover any free oil remaining in the water after the settling tanks.

Float cells were also deployed to remove free and finely dispersed oils in the water. Finely dispersed air or gas introduced into the float cells enable the small oil droplets to rise to the surface, where they are separated and recovered. Sometimes chemicals are added in this process to flocculate the solids and to treat oily water emulsions.

Walnut-shell filters, also known as backwashable granular media filters, are used to remove trace amounts of finely dispersed oils and solids in produced water. The media bed is backwashed intermittently to regenerate the media's effectiveness.

Though the above-mentioned devices are useful in recovering some relatively free products in produced water, they have

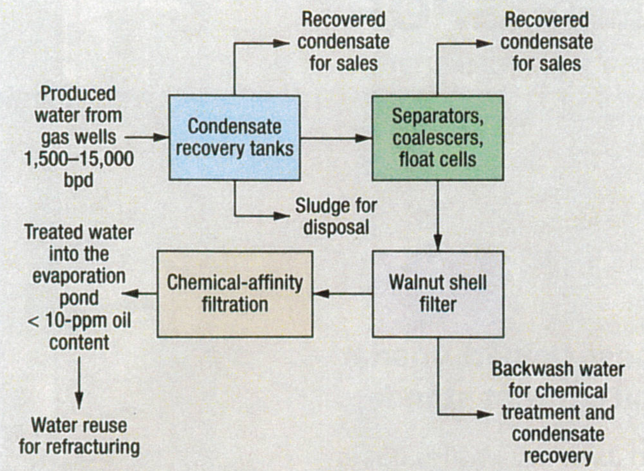

Fig. 1. Produced water treated scheme.

performance limitations that make them incapable of producing water with oil content of 10 ppm or less. The cost of implementing them on the scale necessary to meet this standard at the Anadarko operation would be economically prohibitive. Other key operating limitations include the inability to remove emulsified or soluble oils in water, or to handle process upset, high loading conditions, high fouling tendencies leading to high maintenance, or high waste generation volumes.

An additional treatment stage was needed to remove emulsified oils even under such difficult process conditions. Traditional technologies like organoclay and activated carbon were considered, but, for this project, their limitations outweighed any benefit. These limitations included susceptibility to fouling by upset oil loading conditions; inability to handle both waxes and emulsified oils efficiently; high maintenance requirement; and high operational cost.

CHEMICAL AFFINITY FILTRATION

To remove dissolved oils and polish water to less than 10 ppm O&G for discharge to evaporation ponds, a patented chemical affinity-based filtration system was selected.

The water polisher, provided by MyCelx, employs a patented molecule integrated into the filter media that exhibits high chemical affinity to hydrocarbon molecules. This affinity binds together and coagulates oils and semi-volatile organics into a water-repellant mass, enabling efficient capture of oil. Because chemical affinity is the separation mechanism instead of gravity or mechanical means, separation is accomplished without developing differential pressure across the filter.

There is no desorption or leaching, as the process permanently captures and immobilizes oil onto filters. In operational terms, the contact time for oil removal is less than 1 s and the process entails less than 1 psi operational pressure drop. The filtration system does not foul even under upset loading conditions. Fixed oil removal capacity per filter cartridge is 5–8 lb of oil, and is not affected by influent oil loading.

Another advantage is low waste generation relative to high oil removal capacity, since the filters do not hold water. Used media can be incinerated or otherwise disposed.

At the Vernan, Utah, operation, the polisher system is used to remove trace oils that remain in the water after it has passed through the settling tanks, oil-water separators, hydrocyclones, float cells and walnut shell filters.

TABLE 1. Performance data of the produced water treatment system

Outlet of condensate recovery tanks	Outlet of API separator/ coalescer	Outlet of walnut shell filter	Outlet of polisher system
O&G, ppm	O&G, ppm	O&G, ppm	O&G, ppm
48	21	18	< 2
149	145	121	< 5
14	13	8	< 5

IMPLEMENTATION AND RESULTS

A pilot system with a flow capacity of 10,000 bpd was installed in 2007. After undergoing 6–7 months of intensive field observation and study, the produced water treatment scheme was optimized and finalized for its full-scale implementation. The treatment facilities were enclosed in a structure built by MWH to allow continuous operation even during the harsh Utah winter.

As of October 2009, the process has effectively treated and discharged over 5 million bbl of water with an average treated water quality of less than 5 ppm oil in water, Table 1. The facilities have consistently treated and discharged water at variable influent oil loadings and process upset conditions. Maintenance and operating costs have been well below estimated costs.

"With the process that Anadarko Petroleum Company implemented for handling produced water, we were able to eliminate the conventional ground pits used by other operators for oil-water separation," said William Perry, Anadarko's facilities manager for the operation. "The installation of the MyCelx filtration gives Anadarko an assurance that no oil will be discharged to our open evaporation pits. This guarantee eliminated the need for netting and other intrusive precautions regarding wildlife."

Operating costs for the water treatment train are less than $1 per barrel, with the water polisher comprising less than 15% of overall costs.

Anadarko has also received positive feedback on the operation of the disposal ponds from the Utah Department of Oil Gas and Mining, which nominated the company for an environmental excellence award in 2008, which Anadarko went on to win. **WO**

THE AUTHORS

Parthasarathy Harikrishnan is the Manager of Applications and Technical Services for MyCelx. With a master's degree in chemical engineering from the University of North Carolina, Hari is an expert in oily water separation processes. He is a professional member of the North American Membrane Society, the American Filtration and Separation Society and the Society of Naval Architects and Marine Engineers (SNAME).

Ron Schlicher is a Vice President and Principal Engineer in MWH's Salt Lake City office, with 25 years' experience performing and managing industrial wastewater/waste management and treatment projects. Mr. Schlicher manages MWH's Produced Water Management and Treatment Services Group, as well as industrial wastewater and waste treatment services for clients throughout the US. He has a master's degree in environmental engineering and a bachelor's degree in civil engineering.

Jack Yu is a Senior Environmental Engineer for MWH with 22 years of consulting and manufacturing experience in industrial and municipal water/wastewater treatment. He has planned, designed and constructed physical, chemical and biological treatment processes for a variety of industries. Mr. Yu has a master's degree in environmental engineering and a bachelor's degree in chemical engineering. He is a registered chemical and civil engineer in the United States and Canada.

Offshore

Close

MyCelx clean water technology system recognized

MyCelx has won an OTC Spotlight Award for its clean water technology system, an advanced oil/water separation application designed to remove low-level hydrocarbons and WSOs from produced water. Units range in size from 1,000 bpd to 250,000 bpd and can be either stand-alone or retrofitted into any treatment train to ensure oil in water discharge between 0 and 10ppm.

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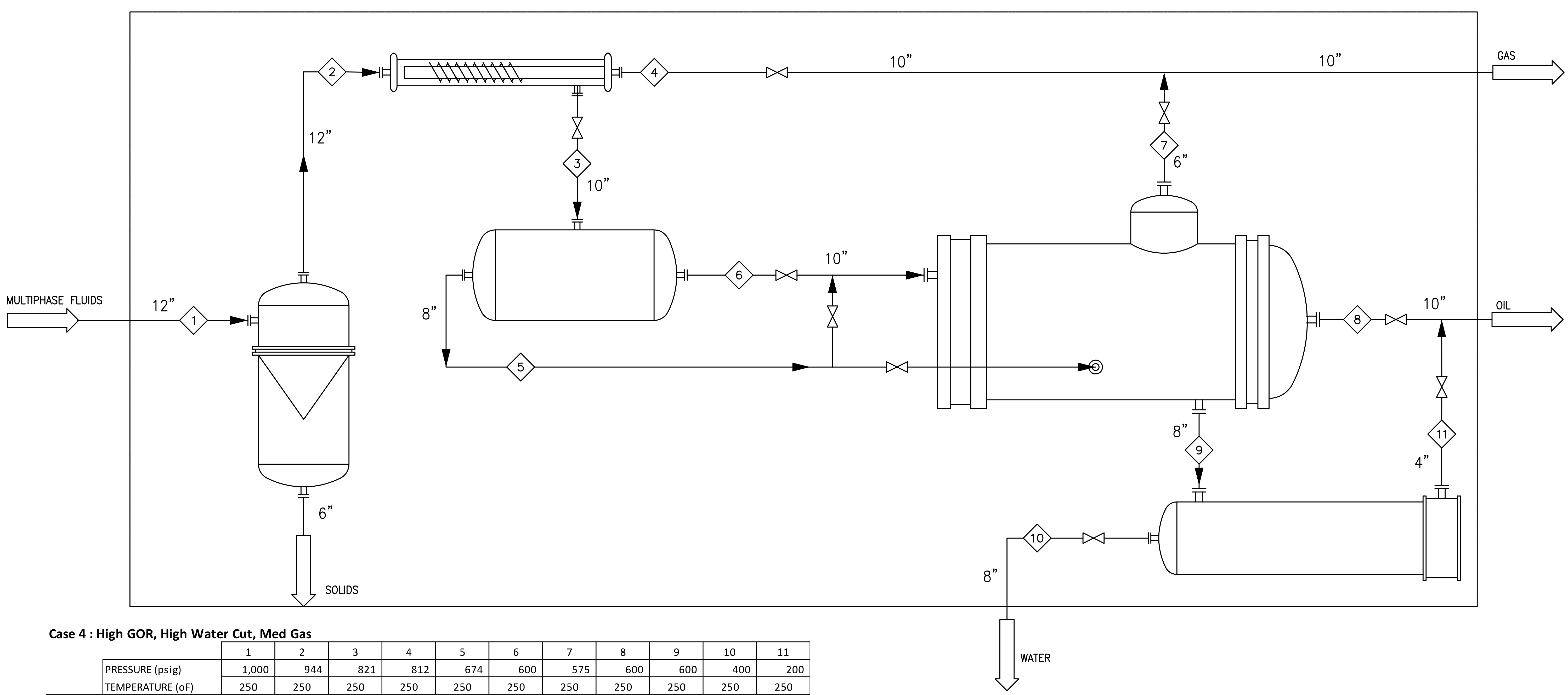
http://www.offshore-mag.com/offshore/en-us/index/article-tools-template.articles.offshore.company-news.us-gulf-of-mexico-2.2011.April.mycelx-clean_water.html

Appendix XIV

eProcess Proposal and Diagrams

WELLHEAD DESANDER	AXIAL FLOW CYCLONE	DEWATERER CYCLONE	SMART SEPARATOR	DEOILER CYCLONE
Solids Fluids Separator	Gas Liquid Separator	Coalecser / Dehydrator	Polishing Separator	Oil Water Separator
SIZE: 750x1500mm	SIZE: 200–300x3000mm	SIZE: 750x2000mm	SIZE: 1400x3800mm	SIZE: 750x1500mm
DESIGN: 10K API 6A	DESIGN: 10K API 6A	DESIGN: 1500# ASME	DESIGN: 900# ASME	DESIGN: 600# ASME
OPERATING: 1,000 PSIG	OPERATING: 880 – 950 PSIG	OPERATING: 800 – 850 PSIG	OPERATING: 600 – 850 PSIG	OPERATING: 600 PSIG
CAPACITY: 80,000 BFPD / 4 – 160 MMSCFD	CAPACITY: 80,000 BFPD / 4 – 160 MMSCFD	CAPACITY: 0 – 80,000 BFPD	CAPACITY: 80,000 BFPD / 1 – 32 MMSCFD	CAPACITY: 0 – 64,000 BWPD



Case 4 : High GOR, High Water Cut, Med Gas

		1	2	3	4	5	6	7	8	9	10	11
	PRESSURE (psig)	1,000	944	821	812	674	600	575	600	600	400	200
	TEMPERATURE (oF)	250	250	250	250	250	250	250	250	250	250	250
OIL	Flowrate (bpd)	16,000	16,000	15,680	320	333	15,347	-	15,347	333	0.94	332
	S.G.	0.887	0.887	0.887	0.887	0.887	0.887		0.887	0.887	0.887	0.887
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
WATER	Flowrate (bpd)	64,000	64,000	62,720	1,280	62,387	333	-	333	62,387	61,139	1,248
	S.G.	1.00	1.00	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
GAS	Flowrate (mmscfd)	32	32	6.4	25.6	-	6.4	6.4	-	-	-	-
	S.G.	0.75	0.75	0.75	0.75	0.75	0.75	0.75				
	D50 (microns)	100	100	100	100	100	100	100				
SOLIDS	Flowrate ppm (vol/vol)	100	0.7	0.7	0.7	0.49	0.21	-	0.21	0.49	0.49	-
	S.G.	2.65	2.65	2.65	2.65	2.65	2.65		2.65	2.65	2.65	
	D50 (microns)	100	20.7	20.7	20.7	20.7	20.7		20.7	20.7	20.7	

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DRG. NO. | REFERENCE DRAWINGS

DATE | No. | REVISION RECORD | DRN | CHK | APP

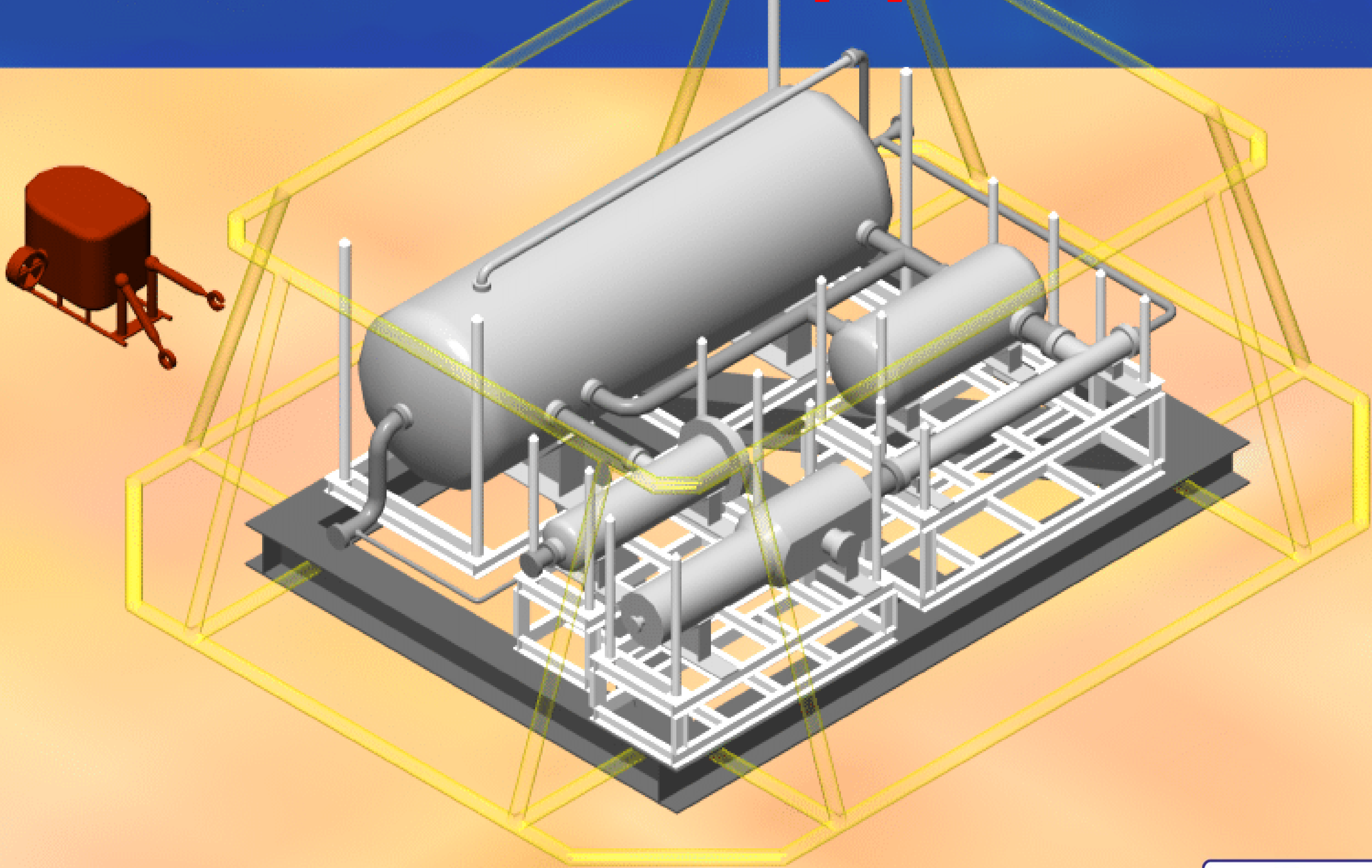
FOR INFORMATION

DRAWING TITLE:
PROCESS FLOW DIAGRAM
ePROCESS SUBSEA SEPARATION
FLUOR OFFSHORE SOLUTIONS
BASIS OF DESIGN FOR RPSEA STUDY

CLIENT PROJECT No.
CLIENT JOB No.
CLIENT P.O. No.
DESIGNED
CAD FILE No.
DRAWN ADR
SCALE:
DATE: OCT 11
CHECKED JCD
DRAWING NUMBER: E1135-DP-001
REV A
PROJECT MAN. APPROVAL
LOCATION APPROVAL

Subsea Separation

Illustrative View - Main Equipment Items



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Conceptual Design Proposal

Subsea Separation

Prepared For

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eProcess Technologies
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on

October 28th, 2011

eProcess technologies

1. Introduction

Fluor Offshore Solutions have requested that eProcess Technologies provide a proposal for a Subsea Separation system utilising their technology, based on a ‘Basis of Design’ (BOD) document.

eProcess Technologies are Compact Separation Specialists with a range of equipment based on their cyclonic technologies & products. eProcess equipment is utilised comprehensively in Topsides applications, either upstream (API) or downstream (ASME) of the choke.

eProcess has also supplied equipment for Downhole applications, and Subsea separation is an area of ongoing conceptual design by the company over many years. eProcess has been involved in numerous studies and designs for various companies.

eProcess believes separating one or all of the (potentially) co-produced products including Oil, Water, Solids, and Gas on the sea floor, represents one of the major technological challenges to unlocking the huge hydrocarbon resources in deep water.

Initially water separation attracted highest priority, due to largest benefits to be gained in the short term. Solids separation have become increasingly important especially in locations where its production probability is high, and finally gas separation allows for a totally integrated separation system; bringing topsides to the sea floor.

eProcess understands that Subsea Separation is only one part of a multi-component system that makes up Subsea Production. It is one of the last items attracting activity due to past technical difficulties and available technologies. eProcess believes that today the technology is available, and in use topsides, with significant track records. No new equipment is required. However packaging designs will significantly differ from topsides designs when exploiting resources in very deep water.

eProcess’s Subsea Separation proposal is summarized in the attached Process Flow Diagram (PFD). The various equipment sizes and performances were evaluated with eProcess in-house programs and include:

2. Main Equipment Items

Wellhead Desander

The Wellhead Desander (WHD) is a robust, simple and effective solids removal separator. eProcess Wellhead Desanders are pressure drop dependant, where multiphase fluids are directed into the cyclone causing the fluids to spin under a centrifugal force. These strong forces cause the solids and fluids to separate.

Gas in particular, disengages and separates quickly. The heavier solids are forced outward toward the cyclone wall, and the lighter fluids and gas phases migrate in the opposite direction toward a centre core.

Solids spiral down the cyclone to the underflow outlet, while the remaining fluids are forced in the opposite direction to the overflow. The process is a simple and effective separator, with a 2-3 second retention time, and no moving parts.

The WHD in all BOD cases is based on our single 20inch insert. This is a particularly large sized cyclone for a typical oil & gas application, but given the high inlet flowrate requirements, this size is required. An alternative would be the provision of a number of smaller sized units housing smaller inserts. For example 2 off 16inch size insert units, or 3-4 10inch size insert units. The smaller units would separate smaller sized solids and therefore would be more efficient. They would also allow for a level of operating redundancy. On the downside however, smaller multiple units would add size and weight to the process package.

For the range of BOD process conditions, the WHD provided a recovery of between 11 to 35 microns sized solids in the outlet stream corresponding to 99.9 to 95.9% separation efficiency, at an operating pressure drop between 44 – 113 psig.

Axial Flow Cyclone

Axial Flow Cyclones (AFC) provide cost effective and efficient compact gas liquid separation. Multiphase fluids enter the base of an eProcess AFC and rotate from the action of centrifugal forces. Stationary helical vanes force the heavier liquids to the wall of the cyclone, and the lighter gas phase migrates to the centre. Dry gas is separated and directed to the outlet stream, and the remaining partially degassed multiphase stream continues axially through the separator.

Due to the nature of the separation process, individually sized AFC's are required for such a large variable gas flowrate. AFC sizes of 8, 10, and 12 inch are required to cover the operating range. These AFC's would be bundled together and synchronised to operate over the required range of inlet gas conditions.

For the range of BOD process conditions, the AFC provided a gas separation efficiency of approximately 80% actual gas volume, with less than 2.5% entrained liquids. The units had an operating pressure drop of between 80 – 155 psig.

Dewaterer Cyclone

The Dewaterer Cyclone is still a new technology although the few installations which exist are over 20 years old. An eProcess Dewaterer can provide efficient and cost-effective solutions for the bulk oil water coalescing and separation, for crude dehydration applications. Typically Dehydration applications can decrease BS&W from 40% to export spec., and Preseparation can debottleneck high water cut production facilities from 80 – 90% water cut down to below 10%

Dewaterer cyclones are pressure drop dependant, where fluids are directed into the Dewaterer inlet causing the fluids to spin under a centrifugal force. These strong forces cause the two immiscible liquids (oil and water) to separate. The heavier water phase is forced outward toward the cyclone wall, and the lighter oil phase migrates toward the centre core.

In the cases where water is present and needs to be processed, the Dewaterer can reduce the water in the oil phase significantly so that it can be separated and sent directly to the low residence time water section of the Smart Separator for treatment by the Deoiler Cyclone.

For the range of BOD process conditions, the Dewaterer operated at an oil separation pressure of 500 psig, which although arbitrary, is required to be defined so that the number of Dewaterer liners can be calculated. In the BOD cases this equated to approximately 34 large sized Dewaterer liners which would be housed in a nominal 30inch vessel.

Smart Separator

We have assumed that there is always a need for a gravity based, residence time separator as part of any Subsea Separation System. The basis of design for such separators are built around field proven correlation's based on Stokes Law, and published mechanistic principles to generate inlet momentum versus shear relationships (gas and liquid shear), gas carry under, liquid carryover, liquid-liquid separation, and equipment sizing.

Various models can be segmented into seven main areas, made up of one inlet or staging zone, which reflects the impact of baffle plates or other (cyclone) inlet devices, and six separation zones which individually or collectively determine the criteria for the sizing of the separator. These include the bulk gas, gas-liquid separation (demister), bulk crude, oil/gas emulsion, bulk water, oil/water emulsion zones.

As a result options for internals, such as baffles, inlet devices (cyclones, momentum plate, cascades, etc.), coalescence plates, vane packs, mist pads, weirs, and buckets can all be individually addressed based on specific fluid conditions.

We have design our separator here based on a very short residence time as it is assumed little to no separation of any of the phases is required. We also assume that the flow conditions are steady state in nature, and that no upset flow conditions exist or need to be addressed.

Deoiler Cyclone

Hydrocyclone based systems, are one of the most cost-effective solutions for tough produced water treatment clean up. Located directly downstream on the water outlet of the production separator, and upstream of the water level control valve, these systems operate in a proportional "pressure ratio" control manner.

eProcess Deoiler hydrocyclones are pressure drop dependant, where fluids are directed into the deoiler tube causing the fluids to spin under a centrifugal force. These strong forces cause the two immiscible liquids (oil and water) to separate. The heavier water phase is forced outward toward the cyclone wall, and the lighter oil phase migrates toward the centre core.

By accurately controlling the pressures across the hydrocyclone, the water phase is sent in one direction to the underflow, and the oil phase is sent in the opposite direction to the overflow. The process is a simple and effective separator, with a 2-3 second retention time, and no moving parts.

In the cases where water is present and needs to be processed, the Deoiler can clean the resultant produced water to less than 15ppm. This is due to the very high temperature of the water at 250oF, a level not seen in typical topsides applications. Of course due to the nature of the Deoiler technology, the higher the water temperature the more efficient the separation.

For the range of BOD process conditions, the Deoiler operated at an oil separation pressure of 200 psig, which although arbitrary, is required to be defined so that the number of Deoiler liners can be calculated. In the BOD cases this equated to approximately 90 small sized Deoiler liners which would be housed in a nominal 30inch vessel.

3. Process Package

Resultant Proposed Package

The resultant Process Packed is shown in our attached PFD. The PFD and resultant information provides approximate equipment sizes based on the range of process conditions provided in the BOD document. We have made an estimate of the reduction in the vessel design ratings of the downstream items, and of course these can change to match actual requirements.

As an example of the type of equipment performance expected, we have also provided a simple material balance (on the PFD) of the main (oil, water, gas, solids) component items for one (Case 4) of the BOD cases. This case includes the need for water treatment, and as such provides a good representative example of a typical system setup.

Process Package Optimization

The individual components provided here are shown in their mechanical manifestations as typical topside process equipment packages. We have attached illustrative view of this setup. For the subsea environment we expect a significant modification of this equipment, specifically from a mechanical design point of view, to provide a better ‘fit for purpose’ outcome.

There are numerous optimization options available for this system. The first and most dramatic is the potential consolidation of the Dewaterer, Separator, and Deoiler vessels into a single integrated unit. This would have significant savings in size and weight of the resultant package.

There is a lot of follow up work that can be done from this stage onward. eProcess for its part is happy to be involved in any significant, and properly resourced common industry project, which can take this concept to the next level.

4. Future Work

eProcess Technologies has a wealth of experience in compact separation technologies. Key personnel available for future resourced subsea separation design studies include:

R&D Investigators
One of eProcess's principal investigators is Dr. C. Hank Rawlins. Dr. Rawlins is the Director and Principal Engineer of eProcess Technologies U.S. and Montana Process Research. He has degrees in Metallurgical Engineering with emphasis in mineral processing, and is a registered Professional Engineer. He works in association with Montana Tech University in several capacities. Dr. Rawlins industrial experience includes 22 years in mineral, petroleum, and metals processing. He has broad depth in material analysis and characterization as applied to particulate and solid-state processing, process engineering especially pertaining to fluid mechanics, applied research, and field work in the offshore oil & gas industries. He has managed 13 joint industry projects for the oil & gas industry.

Dr. Rawlins expertise is in the area of research, development, and implementation of cyclonic technology for phase separations and he is a world leader in separation and handling of solids in oil & gas production. In these areas he has led the industry through several initiatives including the following;

- Field engineer for the world's first wellhead desander test at BP Wytch Farm in 1994.
- Conducted laboratory testing and designed first process model for multiphase desander which is a hybrid of pneumatic cyclone and hydraulic hydrocyclone models (Rawlins Ref. 8). This model is still in use today and forms the basis for most of the multiphase desanders deployed in the oil & gas industry.
- Lead process engineer for the first fifteen commercial wellhead desander installation in the world.
- Design, process, and field test engineer for the first auger separator field trial and commercial installations.
- Design and process engineer for the first full solids handling system on a fixed platform including separation, cleaning, dewatering, and transport bin.
- Organizer and chair of the world's first Facilities Sand Management conference (SPE Houston 2002)
- Process engineer and field test engineer for the first In-line Rotary Separator (IRIS™) for compact gas-liquid separation.
- Process engineer and field test engineer for the first offshore biphase turbine for gas-liquid separation combined with power generation.

Another principal investigator is John Ditria. John is Director of eProcess Technologies Pty. Ltd. He has a degree in Chemical Engineering and an MBA. John has been involved in the oil and gas industry for over 30 years and has over 20 years' experience with all aspects of the process technologies business from concept engineering, product development, field testing and commissioning, project management and supply of integrated process packages, to marketing and sales.

John's expertise has revolved around a number of significant "firsts" with cyclonic technology, specifically:

- Commissioning the first multi-barrel water treatment hydrocyclone vessel arrangement in the Middle East in the late 1980's, which allowed for a significant decrease in the size and weight, and a significant increase in the systems flexibility.
- Initiated laboratory and field testing with the first high efficiency small hydrocyclone including evaluations in natural pressure drive systems offshore, and onshore pumped applications, in the late 1980's.
- Involved in the product development and first use of hydrocyclone technology in dehydrating applications including the first field trials in Australia and in the USA at Grand Isle in the late 1980's.
- He is the inventor of PACS (Packaged Active Cyclone Systems) which allows infinite on-line turndown of hydrocyclone systems, in the early 1990's.
- Oversaw the development and commercialization of solid liquid cyclones specifically for the oil & gas industry. This included conventional solids removal from water streams, to the R&D work undertaken on the removal of solids from multiphase fluid streams with the wellhead desander technology in the mid 1990's.

John's recent work has focused on the design integration of cyclonic and conventional gravity based separation equipment to provide a total systems separation solution which is flexible, compact, and highly effective, at a lower capital and operating cost.

Finally a key investigator is Ky Doucet. Ky Doucet is Director of eProcess Technologies Sdn Bhd. He has a Bachelor of Science, Civil and Environmental Engineering, 1996 from Louisiana State University, Baton Rouge, Louisiana USA.

Ky has been involved in the Oil and Gas industry for over 12 years focusing mainly on oil and gas production systems. He started his career with a specialized water treatment company, Engineering Specialties Inc. (ESI), which supplied leading edge water treating technology to oil and gas companies globally. He subsequently became the international business development manager for ESI and focused on developing and identifying markets in Asia and the Middle East. Through an acquisition of ESI by NATCO in 2002, Ky was relocated to Singapore to grow and develop NATCO's process equipment business in SE Asia. Since 2002, Ky has been involved in all aspects of oil, gas and water process systems for upstream and downstream Oil and Gas applications. His most recent experience is more focused on CO_2 Membrane technology for removing bulk CO_2 from natural gas production. Ky has been involved in the technical development and of business development of the largest offshore CO_2 Membrane systems operating today in SE Asia.

Relevant Publications from the Project Researchers.

Dr. Hank Rawlins:

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1. “Produced Water Treatment Using Underwater Oil/Water Separation” 1998, Produced Water Management Technical Forum & Exhibition, American Petroleum Institute Teche Chapter, Lafayette, Louisiana, Ky A. Doucet and Uncas B. Favret - Engineering Specialties, Inc.
2. “Maximum Space, Weight & Cost Savings on Produced Water Treatment Systems Using New Combined Process Technology” 1999 Latest Advances In Offshore Processing Aberdeen, Scotland, Ky A. Doucet and Uncas B. Favret - Engineering Specialties, Inc.
3. “Total Systems Approach to Wastewater Processing” 1999, United Engineering Foundation Conference, Environmental Technology for Oil Pollution, Jurata, Poland, Ky A. Doucet and Uncas B. Favret – Engineering Specialties, Inc.
4. “Total Systems Approach To Produced/Oily Water Treatment” 2000, CGPA Calgary, Alberta Canada, Ky A. Doucet and Uncas B. Favret - NATCO Group Inc.
5. “Sand Control and Management” 2004, IQPC Sand Control Conference, Kuala Lumpur, Malaysia, Paul Salter and Ky A. Doucet - NATCO Group Inc.
6. “Applying Membranes on Large Offshore CO_2 Removal Applications” 2004, SPE ATW Workshop Hanoi, Vietnam, Ky A. Doucet - NATCO Group Inc.

Together Hank, John, and Ky bring an unparalleled wealth of knowledge and experience to any research and development task.

5. <u>Attachment</u>

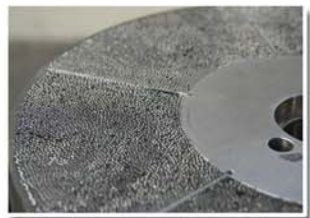
5.1 Subsea Separation Process Flow Diagram.

5.2 Illustrative View of Main Equipment Items.

APPENDIX XV

Coalesense Technology

CoalesSense
a new dimension to separation



CLSR Coalescing Pump

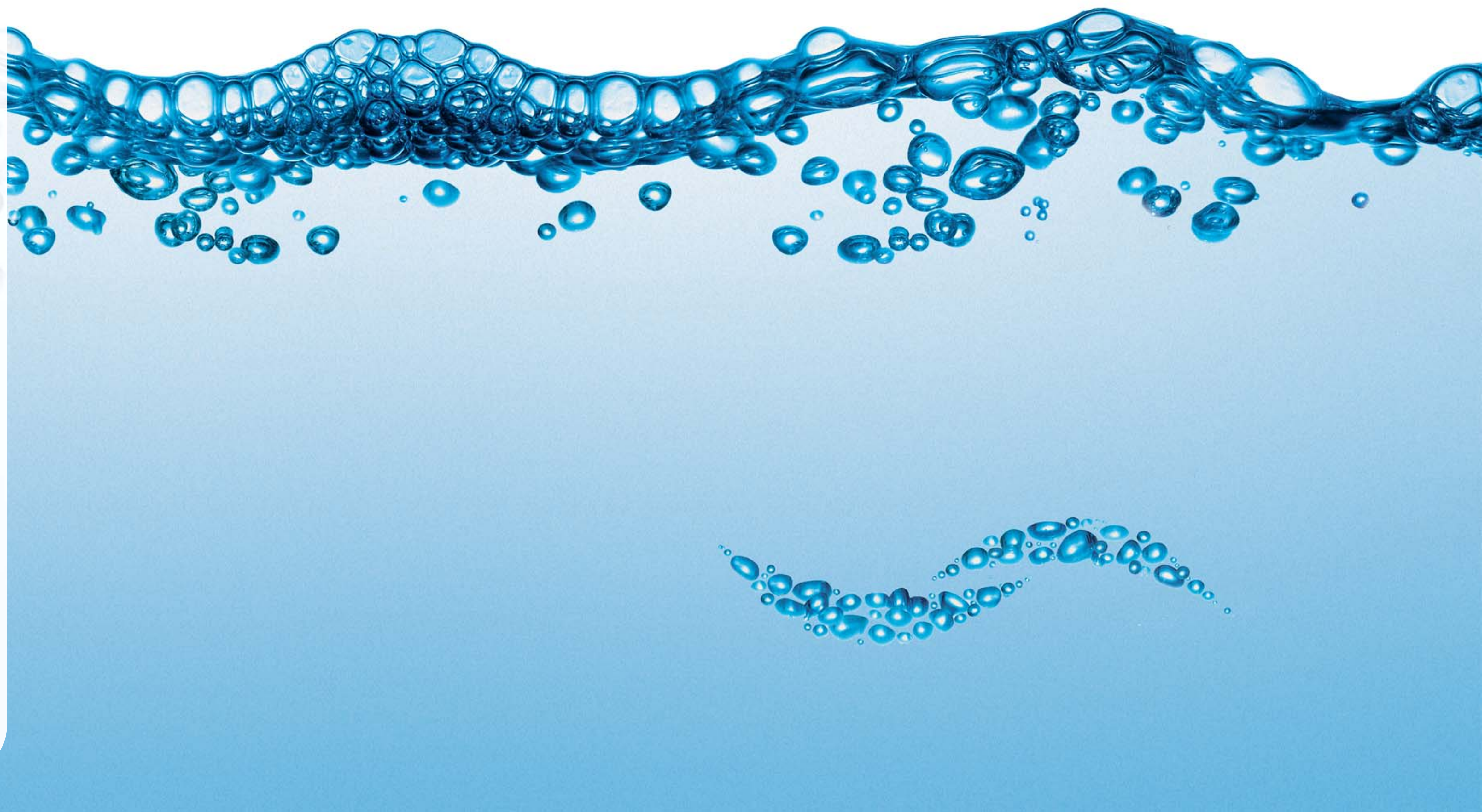
Performance improvement of Separators

Innovative Technology
Our patented device has been developed in The Netherlands for a range of multi phase liquid separation applications. CoalesSense provides solutions to specific problems encountered in a number of industries.

Optimum Solution
The operations are managed from our headquarters in The Hague, The Netherlands. Our Research and Development facilities are located in Eindhoven, The Netherlands. Attention to continuous process development enables us to progressively expand the range of applications. Our engineers visit sites to evaluate specific problems, produce feasibility studies and organise pilot trials to provide the optimum solution in terms of capital cost and operating efficiency.

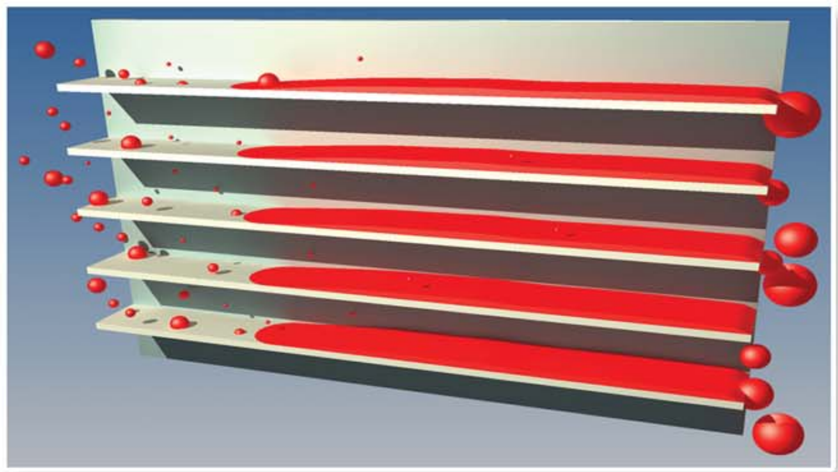
Expanding Network
We seek to create a network of global distributors that can bring the benefits of CoalesSense Technology to solve a variety of multi-phase separation challenges. CoalesSense actively works to extend this network and expand our reach by developing partnerships in new countries and markets.

Contact Us
CoalesSense BV
van Lennepweg 4
2597LJ The Hague
The Netherlands
info@coalessense.com
+31 64 609 0544



CLSR-series Coalescing Pump

The treatment of produced water is getting ever more challenging in oil & gas production. The water cut is increasing while discharge water quality regulations are getting stricter. The CLSR Coalescing Pump is designed to support and improve the performance of produced water treatment systems.



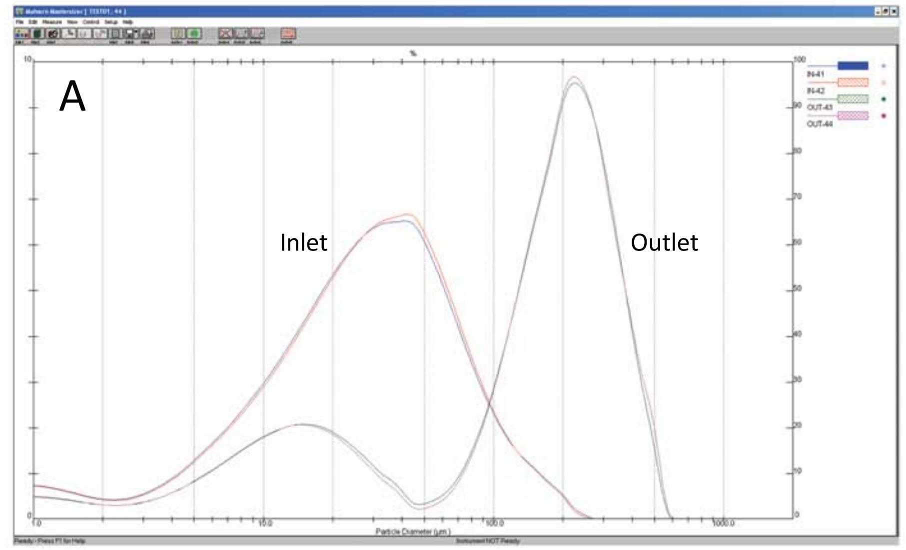
How it works

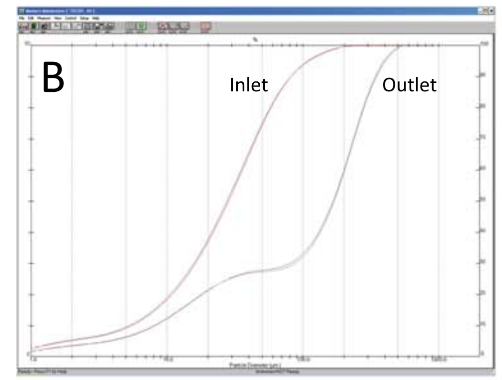
A rotating bundle of mm-sized tubes inside a centrifugal pump collects small oil droplets and produces large droplets. With no plugging, no pressure drop and no consumables, the CLSR Coalescing Pump optimizes the separation process.

Trial results with CLSR

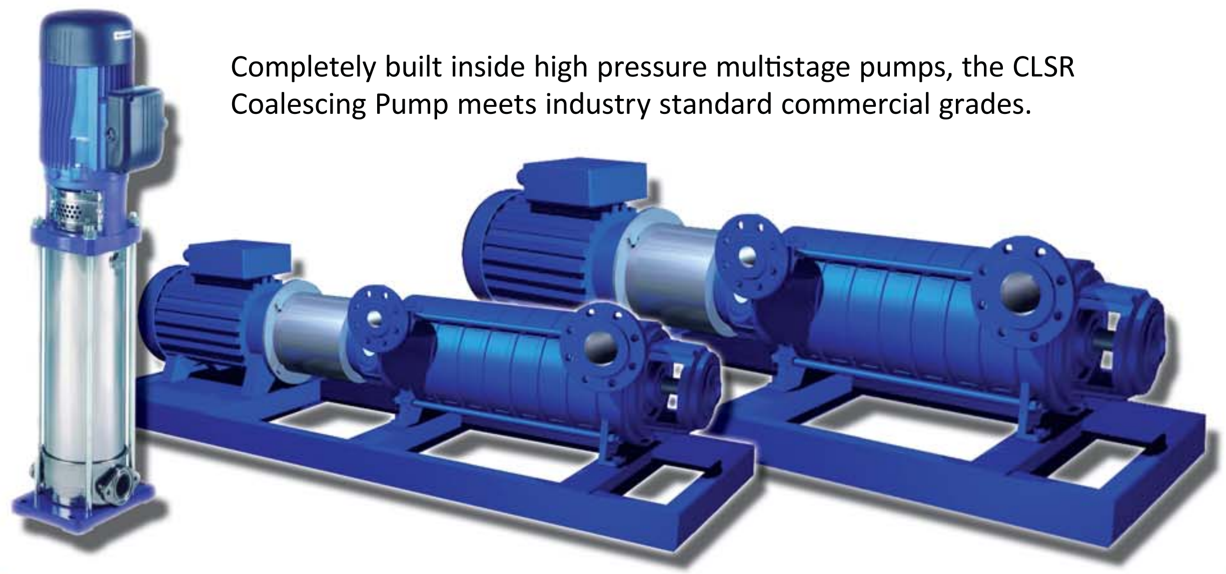
Key target of the CLSR-series Coalescing Pump is to collect the smallest oil droplets present in the water and create large droplets which are easy to separate downstream. Droplets down to 1 micron are collected and coalesced to larger droplets.

Trials with an installed CLSR-15 show that in a single-pass setup, the average droplet diameter is enlarged from 27 micron to 170 micron. Over 90% reduction of droplets smaller than 10 micron can be achieved.





Droplet size graphs before and after CLSR-15. Probability (A) and cumulative (B) distribution.



Completely built inside high pressure multistage pumps, the CLSR Coalescing Pump meets industry standard commercial grades.

CLSR Features & Benefits

Simple to operate	• Straightforward centrifugal pump technology
	• No absorbers, chemicals or consumables needed
Efficient	• Collects droplets down to 1 micron
Wide operational window	• Performs under varying conditions, with respect to volume flow, pressure, temperature, specific gravitiy and oil concentration
	• Applicable for all separators (hydrocyclones, IGF, DAF, CPI, etc.)
Small footprint & weight	• Compact pump design
	• Allows for steep increase of hydraulic capacity of separators
Scalabilty	• 3 models cover capacity range up to 100 m3/hr
	• Ability to perform low cost, non-disruptive testing
Low cost	• Limited capex and opex requirements
Robustness	• Tolerant to high motion operation (FPSOs)
Rugged construction	• Long operating life
	• Minimal maintenance requirement

Specifications CLSR Coalescing Pump

	CLSR-15	*CLSR-30*	*CLSR-45*
• Capacities ranging from 1 to 100 m3/hr	1 - 5 m3/hr	15 - 40 m3/hr	50 - 100 m3/hr
• Footprint	< 1 m2	< 2 m3	< 3 m3
• Wet weight	< 100 kg	< 500 kg	< 1000 kg
• Energy requirement per m3	< 0,3 kW	< 0,1 kW	< 0,1 kW
• Horizontal with outer bearings on both sides		x	x
• Vertical with outer bearings on both sides	x		
• ATEX electric motor	x	x	x
• Maximum operating temperature	90 °C	90 °C	90 °C
• Maximum operating pressure	15 barg	30 barg	30 barg

APPENDIX XVI

Enerscope Desanders

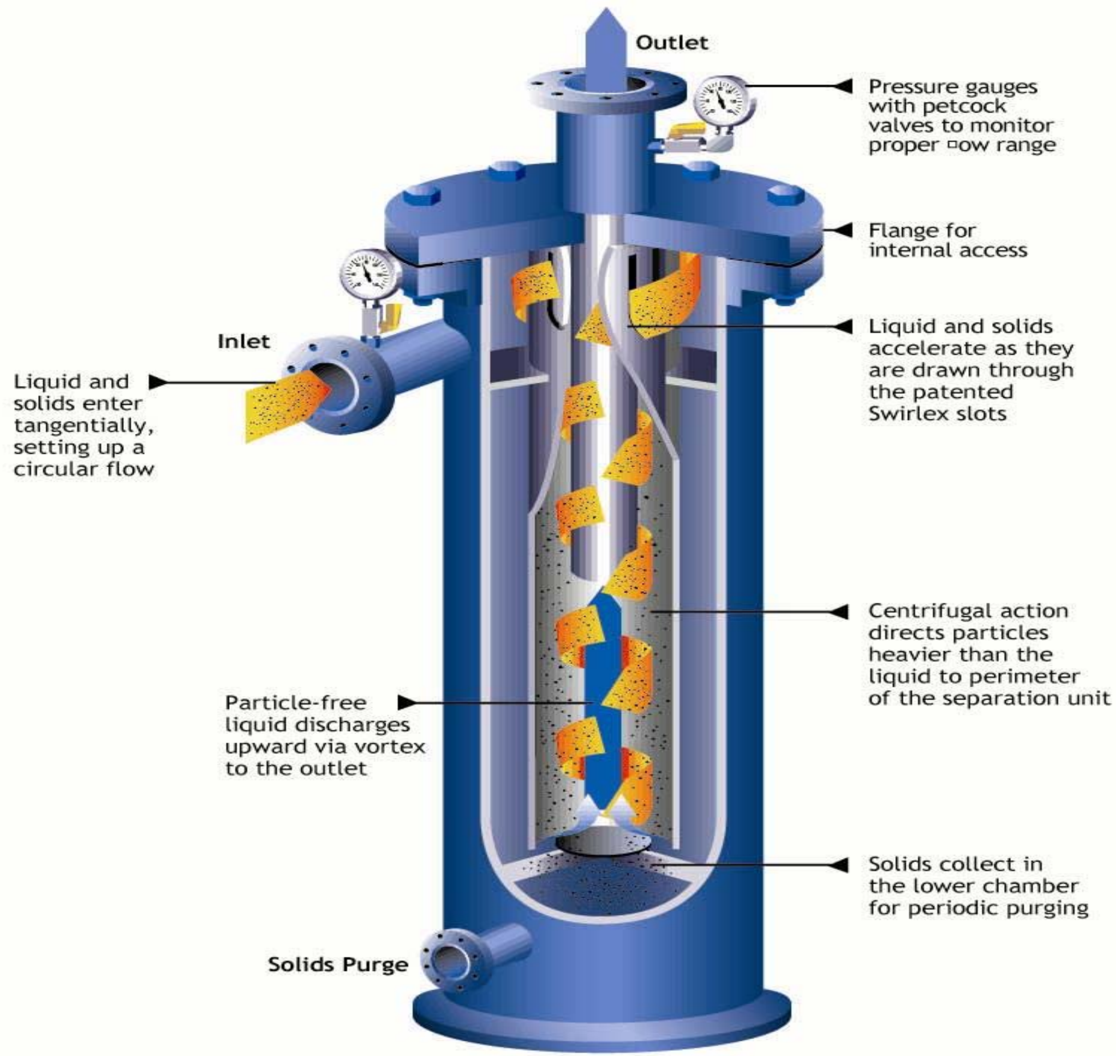
Presented by:
Steve Coffee, Enerscope Systems Inc.

ENERSCOPE SYSTEMS INC.

Overview

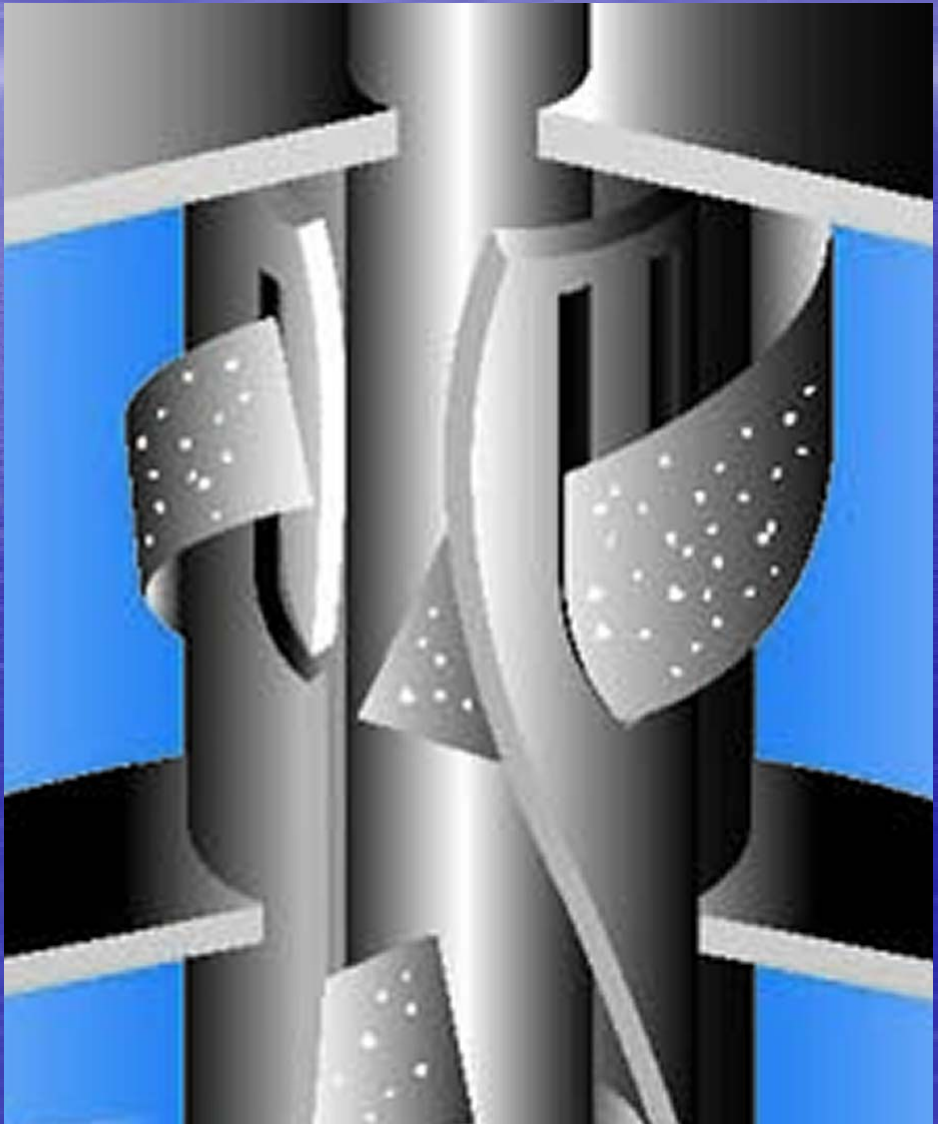
- How It Works
- Performance
- Applications
- Installations
- Benefits of Enerscope Desanders

How It Works



Outlet
Pressure gauges with petcock valves to monitor proper flow range
Flange for internal access
Inlet
Liquid and solids enter tangentially, setting up a circular flow
Liquid and solids accelerate as they are drawn through the patented Swirlex slots
Centrifugal action directs particles heavier than the liquid to perimeter of the separation unit
Particle-free liquid discharges upward via vortex to the outlet
Solids collect in the lower chamber for periodic purging
Solids Purge

How It Works



Enerscope Desander Performance

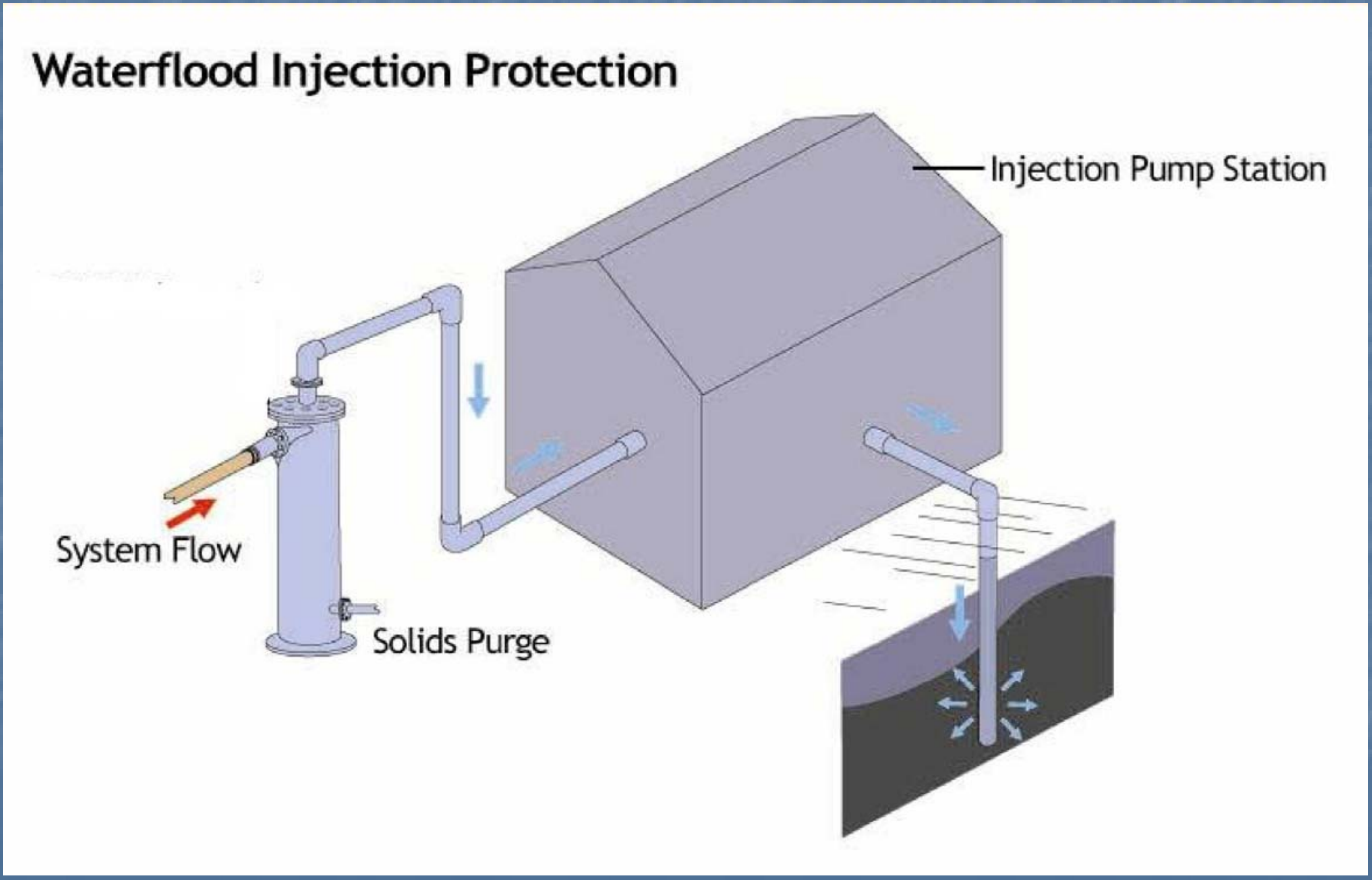
Particle Sizes in the System	Solids Distribution in the System	Enerscope Capability	Expected Enerscope Performance
> 74 Microns	15%	98%	14.7%
74 – 40 Microns	30%	95%	28.5%
40 – 20 Microns	35%	84%	29.4%
< 20 Microns	20%	50%	10.0%
	Aggregate Solids Removal Capability:		**82.6 %**

ENERSCOPE SYSTEMS INC.

Enerscope Desander Performance

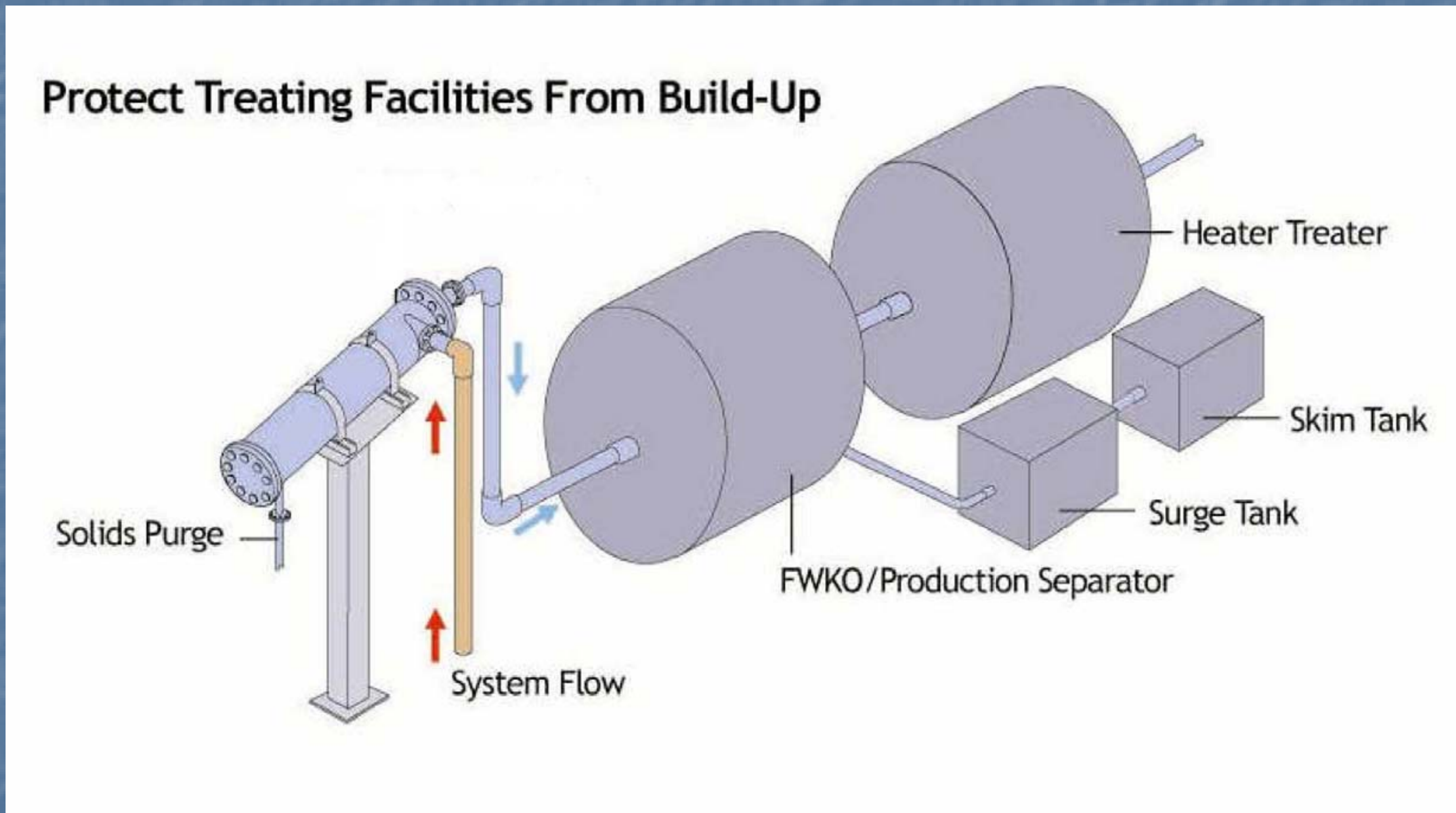
ENERSCOPE SYSTEMS INC.

Enerscope Applications

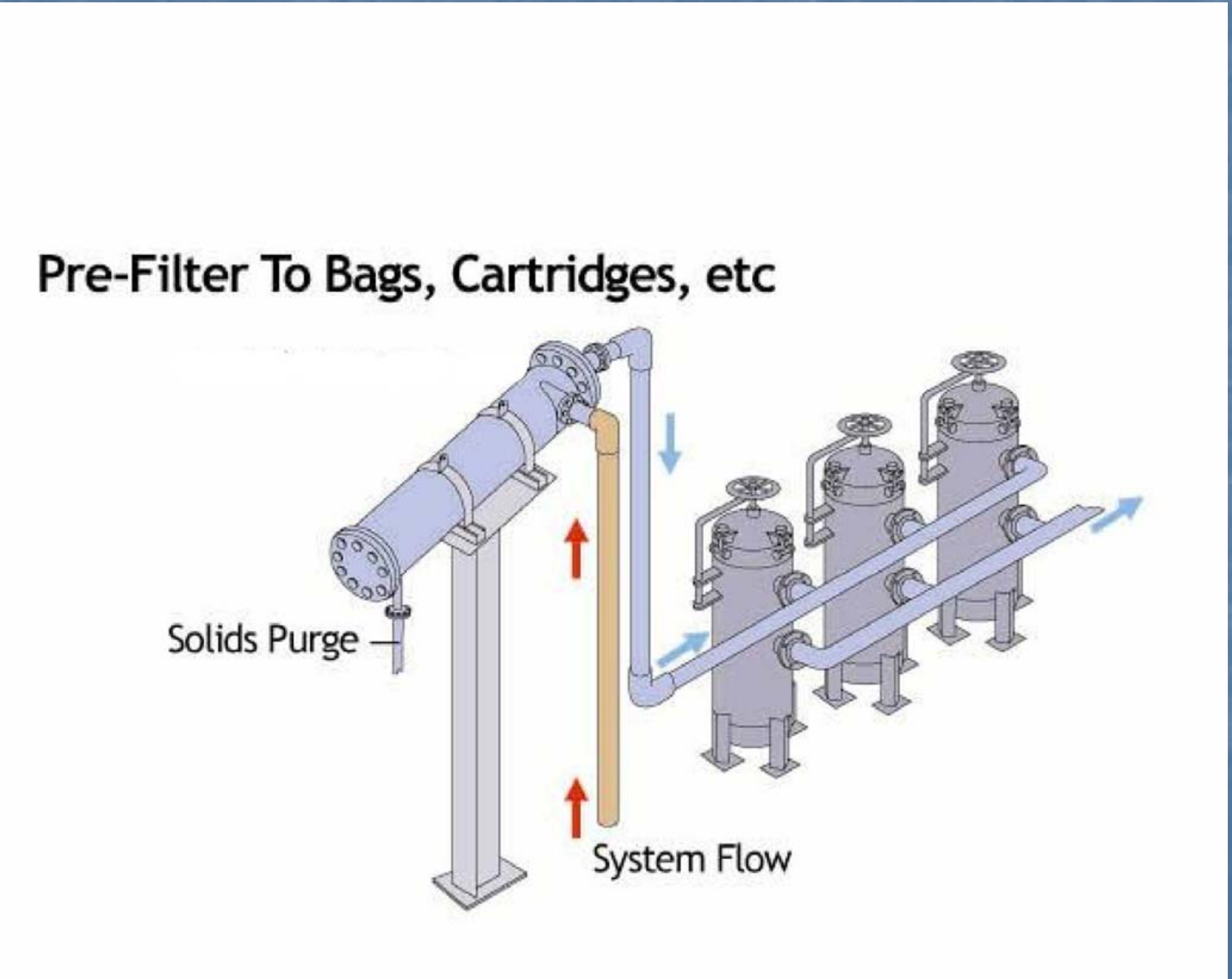


ENERSCOPE SYSTEMS INC.

Enerscope Applications



Enerscope Applications



Other Common Applications

- **Drilling Mud**
- **API Tank Filtration**
- **IGF Systems Prefiltration**
- **Oil Recovery Systems**
- **Centrifuge Protection**
- **Source Water Filtration**
- **Vessel Desanding**
- **Hydrocyclone Protection**

ENERSCOPE SYSTEMS INC.

Other Common Applications

- Completion Wells
- Frac Systems
- Injection Pump Protection
- Heat Exchanger Protection
- Catalyst Separation/Removal
- Spray Nozzle Protection
- Media Filter Protection
- Instrumentation/Sensor Protection

Some of our customers...

Anadarko	Norse Hydro
Apache	Occidental
BP	Pemex
CNRL	PetroChina
ConocoPhillips	Petrobras
Crestar	PetroCanada
Devon Energy	Petronas
EnCana	Royal Dutch Shell
Exxon Mobil	Sinopec
Gazprom	Statoil
Lukoil	Total
Marathon	Yukos

Recent Installations

- Cetco
- CNRL Horizon (7 Systems)
- ConocoPhillips
- Bruderheim– Process Cooling Water Filtration
- DOW Hydrocarbons (3 Systems)
- ExxonMobil– Prefiltration to Cartridge Housings
- EnCANA (4 Systems)
- Enterprise Products- Brine Filtration (6 Systems)
- Eveready- Global Dewatering (2 Systems)
- Husky Energy- (36 Systems)
- Luseland– Prefiltration of Trucked Disposal Water (3 systems)
- Shell
- Suncor Energy (5 Systems)
- Syncrude Oil Sands (3 Systems)
- Total Petrochemicals
- Total Separation Solutions
- Verlo Battery- Heater Treater Protection
- Weatherford (4 Systems)

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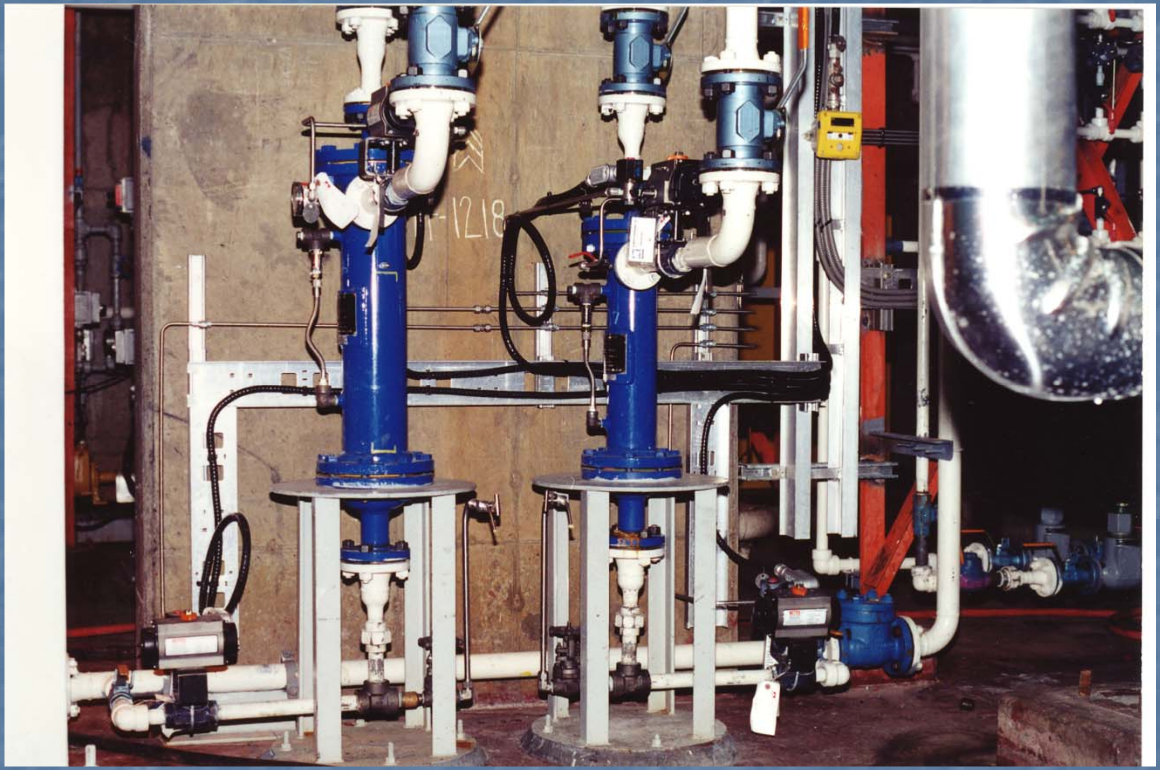
Recent Installations

- Aera Energy
- Cantaur East Battery- FWKO
- CanOxy Tawilla I, II, III, IV and Qataban Trains- Hydrocyclone Protection
- Crestar Energy
- Crimson Energy
- Ferus Gas (6 Systems)
- Gulf Canada
- Nations Energy
- Nexen Energy (4 Systems)
- North Smiley– FWKO
- Petro-Canada (3 Systems)
- Petrovera (2 Systems)
- PXP
- Ross Lake– FWKO
- Swift Current Battery- FWKO & Injection Pump Protection
- Talisman Energy (2 Systems)
- Wapiti Energy

Nexen Energy

PetroCanada – Robb Gas Plant



DOW Hydrocarbons

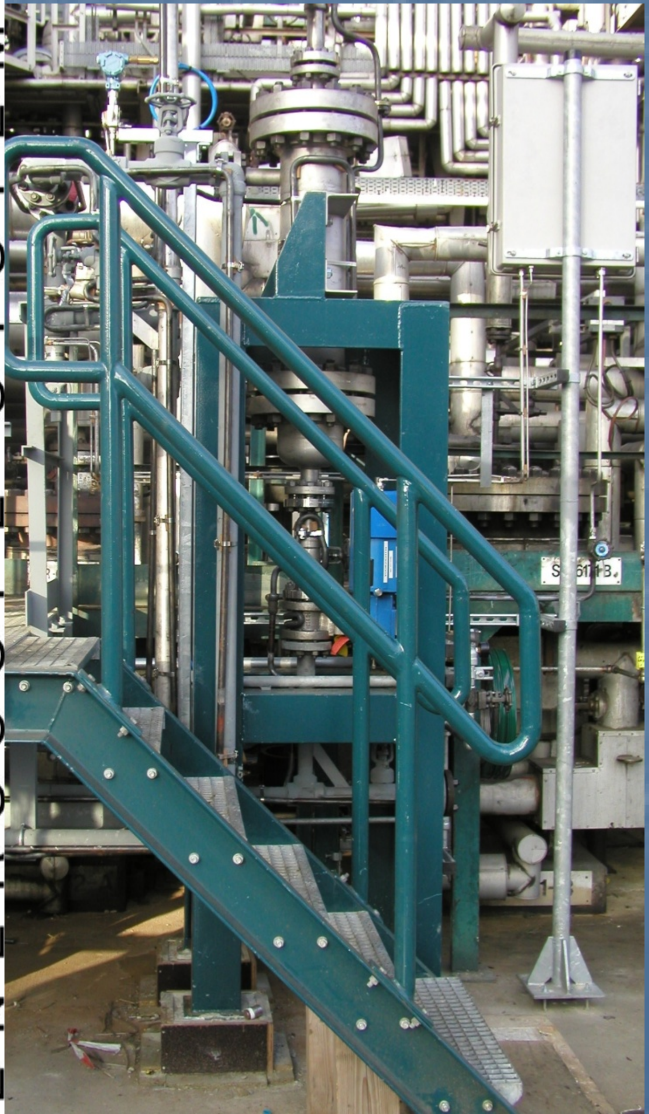
Weatherford Industries

Anderson Exploration

Nexen Energy- Yemen

ENERSCOPE SYSTEMS INC.

Exxon Refinery-Rotterdam



Flow Range:	14-23 m3/hr
Inlet/Outlet:	2-inch, Flanged
Purge:	2-inch, Flanged
Configuration:	Vertical
Material of Construction:	316L Stainless Steel
Codes:	ASME, PED
ANSI Design:	600# RF Weld-neck Flanges
Design Pressure:	33 Bar
Design Temperature:	376 C
Maximum Pressure Loss:	1 Bar
Minimum Pressure Loss:	0.3 Bar
Maximum Particles Size:	9.5 mm
Flow:	19 m3/hr
System Liquids:	Crude
System Solids:	Coke
System Temperature:	376 C
Solids Concentration:	1-20000 ppm
Specific Gravity of Solids:	1.7+
Minimum Particle Size:	1 micron
Maximum Particle Size:	9.5 mm
System Pressure:	15 Bar
Minimum Inlet Pressure:	4 Bar
Max. Pressure Differential:	1 bar
Minimum Back Pressure:	0.5 Bar
Design Pressure:	33 Bar
Design Temperature:	0 – 376 C

Why Install Enerscope?

Advantages

- **Minimal changes to existing processing facility**
- **Very low , steady pressure drop**
- **Continuous solids separation with no impact on production capacity**
- **Efficient and environmentally friendly removal and disposal of collected solids**
- **Higher processing equipment operating efficiency**
- **Reduced wear of pipes, valves, pumps, and vessels**
- **Reduced operating cost**
- **Small footprint, low installation cost, easy retrofit**

Questions

Thank you!

enerscopesystems.com

ENERSCOPE SYSTEMS INC.

APPENDIX XVII

Colorodo School of Mines RPSEA Study

An Integrated Framework for Treatment and Management of Produced Water

Technical Assessment of Produced Water Technologies

RPSEA Project 07122-12

An Integrated Framework for Treatment and Management of Produced Water

TECHNICAL ASSESSMENT OF PRODUCED WATER TREATMENT TECHNOLOGIES

1st EDITION

RPSEA Project 07122-12

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

November 2009

TECHNICAL ASSESSMENT OF PRODUCED WATER TREATMENT TECHNOLOGIES

This report presents a comprehensive literature review and technical assessment to evaluate existing and emerging technologies that have been used for treatment of produced water or novel technologies that could be tested and considered in the future. This technical assessment includes stand-alone water treatment processes, hybrid configurations, and commercial packages developed for treatment of oil and gas produced water and zero liquid discharge (ZLD). This assessment considers pretreatment, desalination, post-treatment, and concentrated waste disposal to meet the required water quality standards for beneficial use scenarios. It should be noted that many commercially available products for produced water treatment are usually unique combinations of unit processes. This document focuses on primary unit processes, and attempts to include the major commercial packages/processes for produced water treatment. This document can be used to evaluate various treatment processes in a generic fashion even if their vendors are not listed in the report.

The report was developed as part of a collaborative research project (#07122-12) led by the Colorado School of Mines (CSM) and funded by the Research Partnership to Secure Energy for America (RPSEA).

TECHNOLOGIES ASSESSED

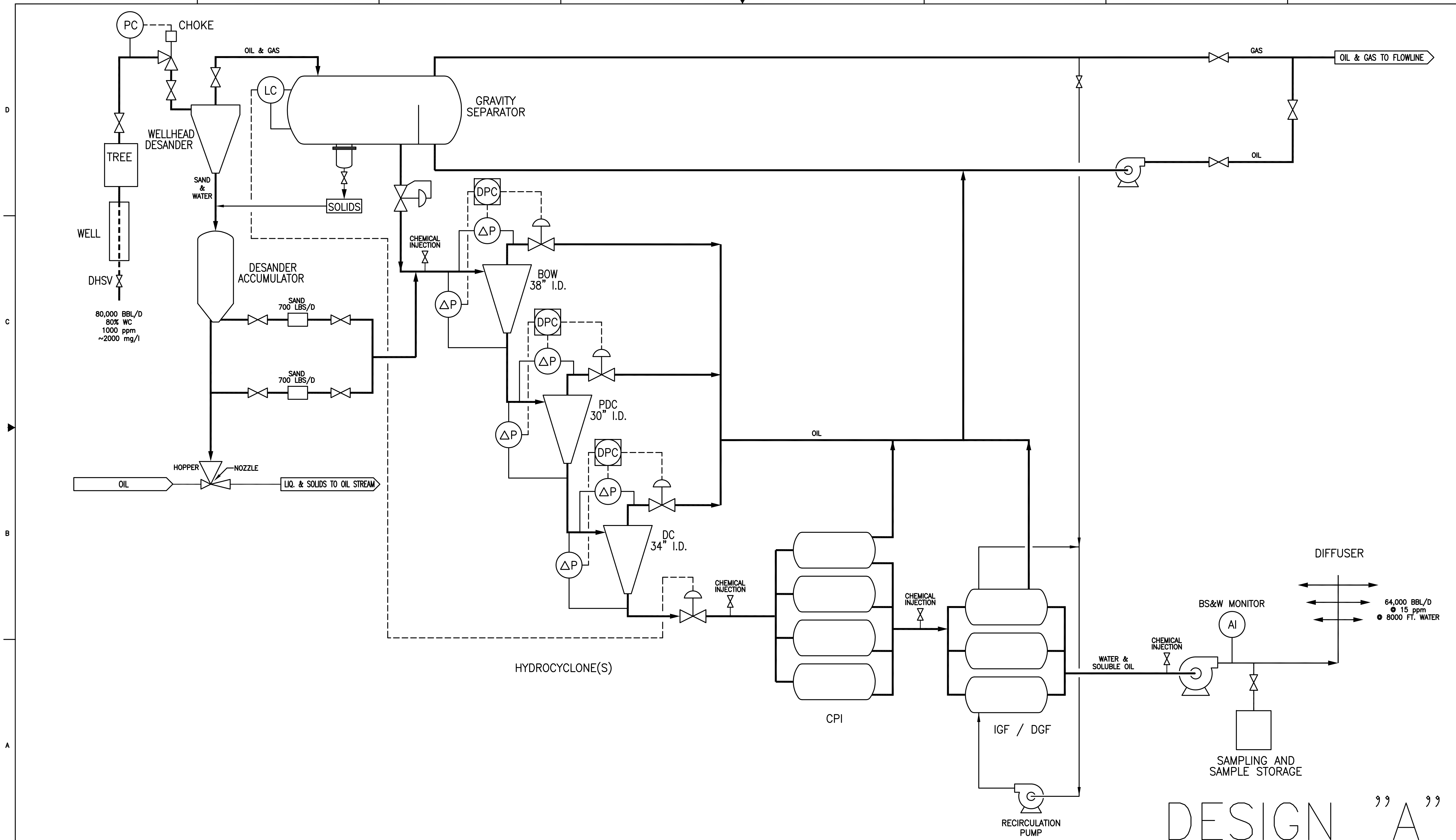
A total of 54 technologies were reviewed and assessed in the study. The technologies are classified into stand-alone technologies and combined treatment processes.

Stand-alone/primary	Multi-technology processes
Basic Separation o Biological aerated filters o Hydroclone o Flotation o Settling o Media filtration **Membrane Separation** o High pressure membranes ▪ Seawater RO ▪ Brackish water RO ▪ Nanofiltration (NF) ▪ VSEP o Electrochemical charge driven membranes ▪ Electrodialysis (ED), ED reversal (EDR) ▪ Electrodionization (EDI) o Microfiltration/ultrafiltration ▪ Ceramic ▪ Polymeric o Thermally driven membrane ▪ Membrane distillation (MD) o Osmotically driven membrane ▪ Forward osmosis (FO)	**Enhanced distillation/evaporation** o GE: MVC o Aquatech: MVC o Aqua-Pure: MVR o 212 Resources: MVR o Intevras: EVRAS evaporation units o AGV Technologies: Wiped Film Rotating Disk o Total Separation Solutions: SPR – Pyros **Enhanced recovery pressure driven** o Dual RO w/ chemical precipitation o Dual RO w/HEROTM: High Eff. RO o Dual RO w/ SPARRO o Dual pass NF o FO/RO Hybrid System **Commercial treatment RO-based processes** o CDM o Veolia: OPUS™ o Eco-Sphere: Ozonix™ o GeoPure Water Technologies

Remaining pages of RPSEA Project 07122-12 report are not included in this Appendix

Appendix 18

Conceptual Designs for Study



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RPSEA

TYPICAL
PRODUCED WATER TREATMENT
UDW SEABED DISCHARGE PROJECT

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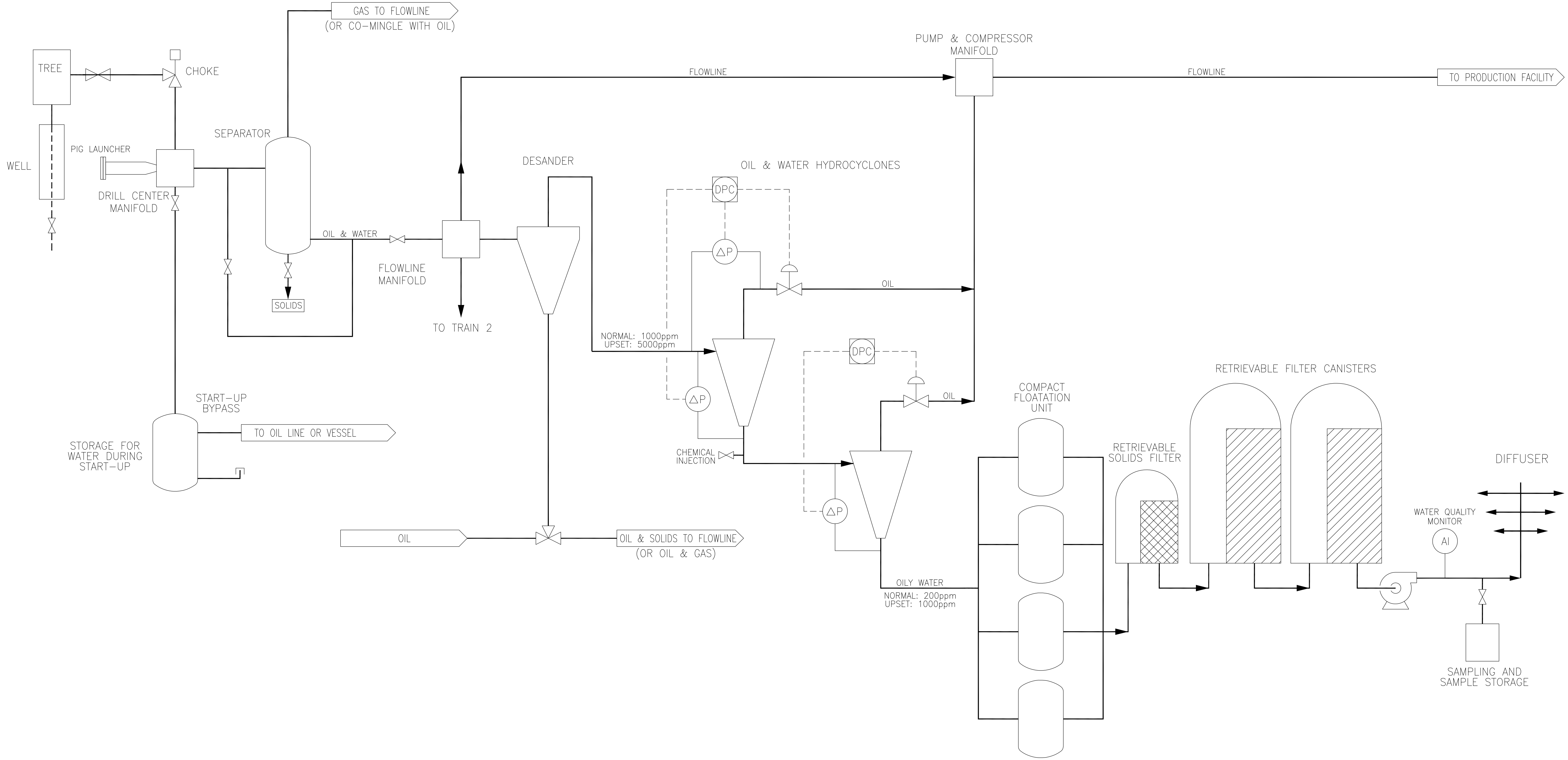

NOTES

1. DISSOLVED VOLATILES?

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UDW SEABED DISCHARGE PROJECT

SCALE NONE

DRAWING NUMBER PFD-RPSEA-7

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SAP NWA

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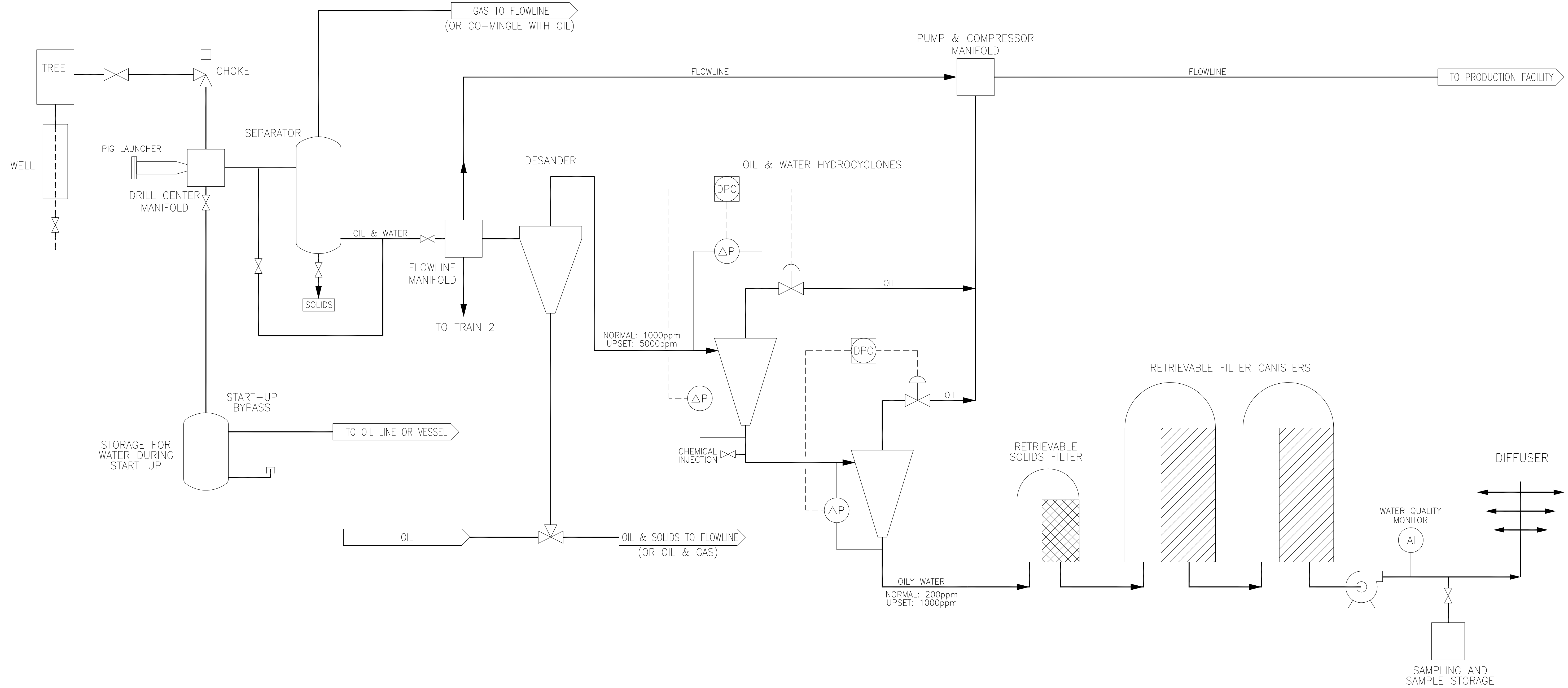

NOTES

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UDW SEABED DISCHARGE PROJECT

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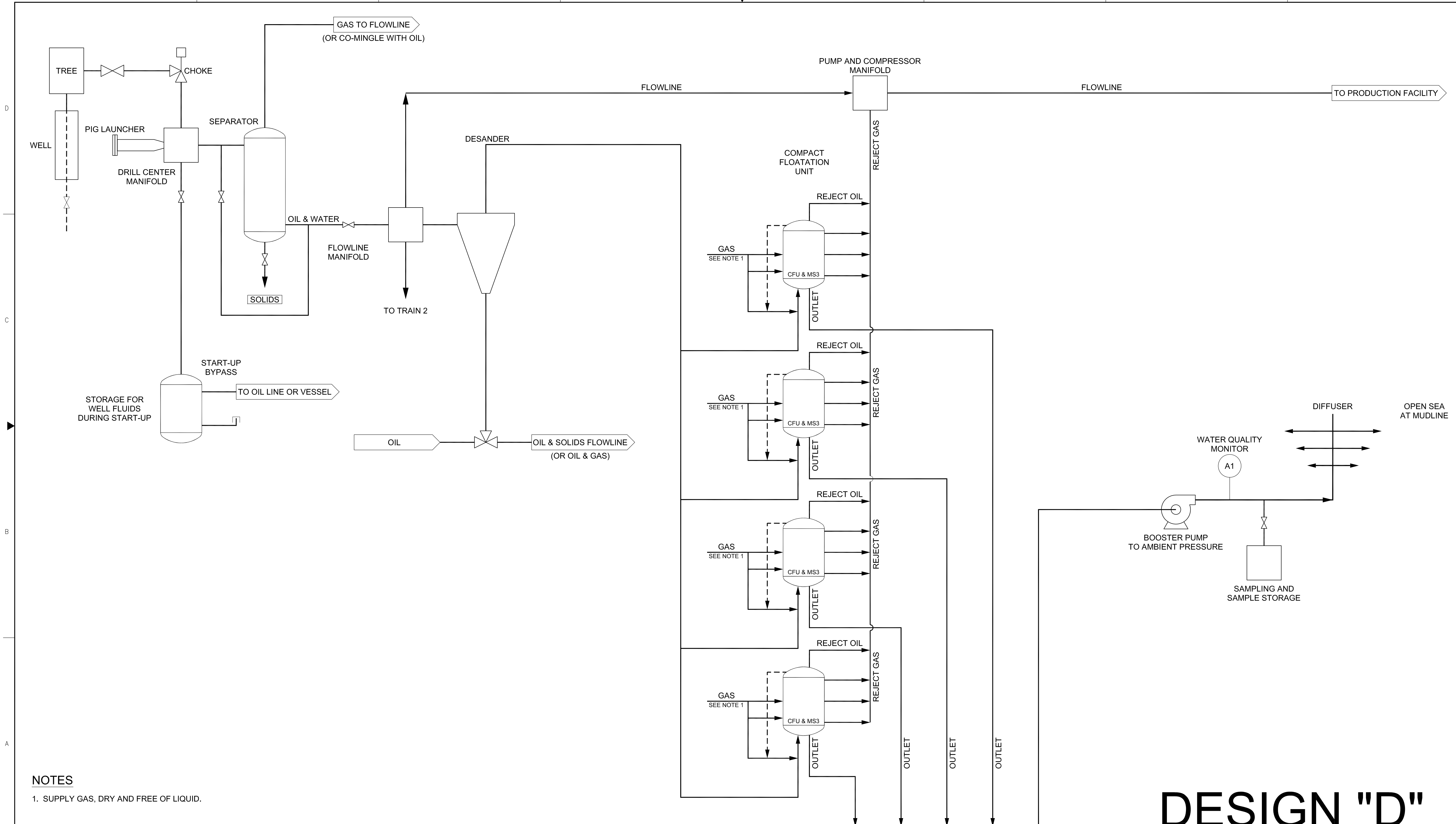

NOTES

1. SUPPLY GAS, DRY AND FREE OF LIQUID.

DESIGN "D"

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RPSEA

TYPICAL
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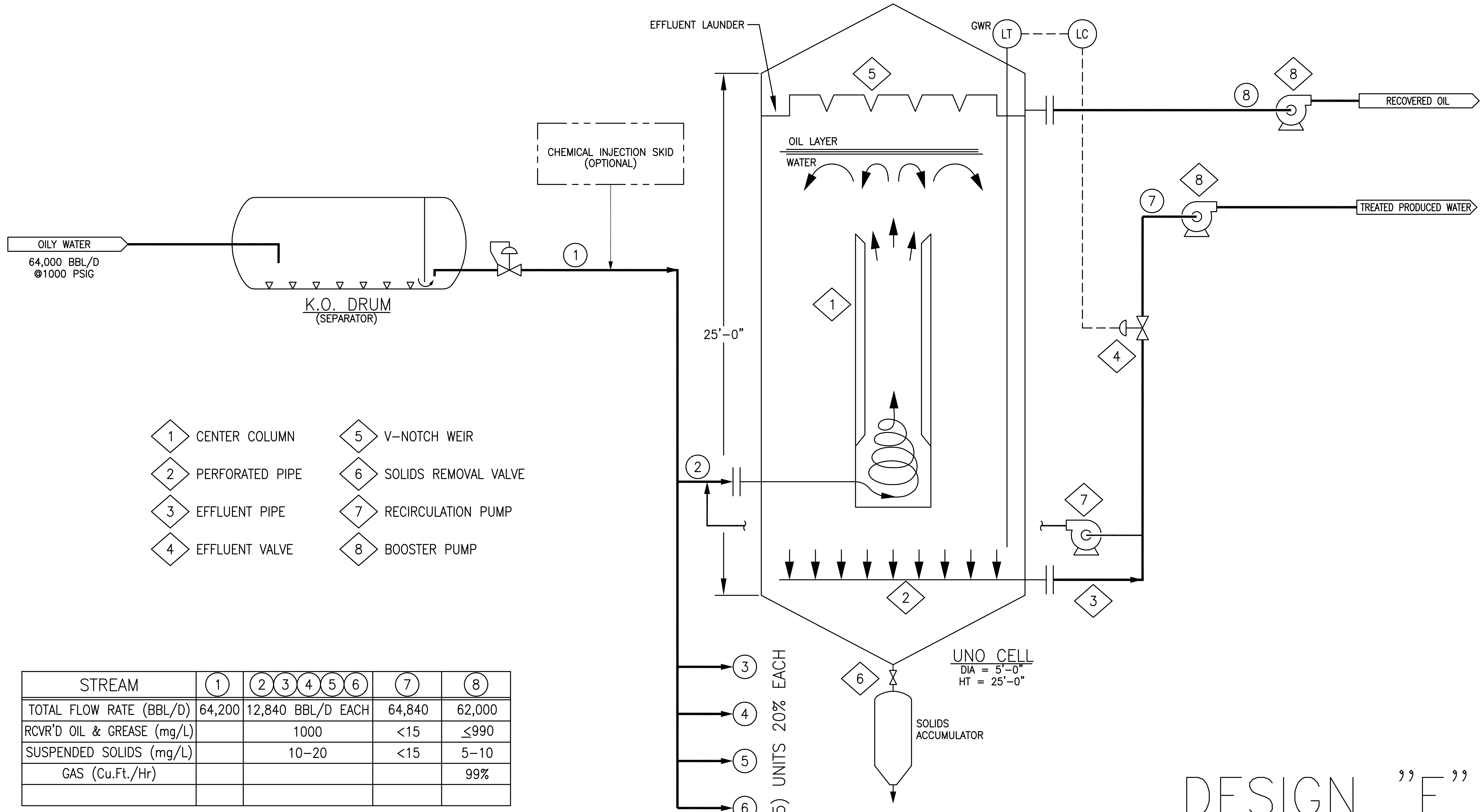

STREAM	1	2 3 4 5 6	7	8
TOTAL FLOW RATE (BBL/D)	64,200	12,840 BBL/D EACH	64,840	62,000
RCVR'D OIL & GREASE (mg/L)		1000	<15	≤990
SUSPENDED SOLIDS (mg/L)		10–20	<15	5–10
GAS (Cu.Ft./Hr)				99%

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A	8/5/11	PRELIMINARY REVIEW	DWH	TD	

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RPSEA

ADVANCED PRODUCED WATER TREATMENT
UDW SEABED DISCHARGE PROJECT

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WELLHEAD DESANDER
Solids Fluids Separator

SIZE: 750x1500mm
DESIGN: 10K API 6A
OPERATING: 1,000 PSIG
CAPACITY: 80,000 BFPD / 4 – 160 MMSCFD

AXIAL FLOW CYCLONE
Gas Liquid Separator

SIZE: 200–300x3000mm
DESIGN: 10K API 6A
OPERATING: 880 – 950 PSIG
CAPACITY: 80,000 BFPD / 4 – 160 MMSCFD

DEWATERER CYCLONE
Coalecser / Dehydrator

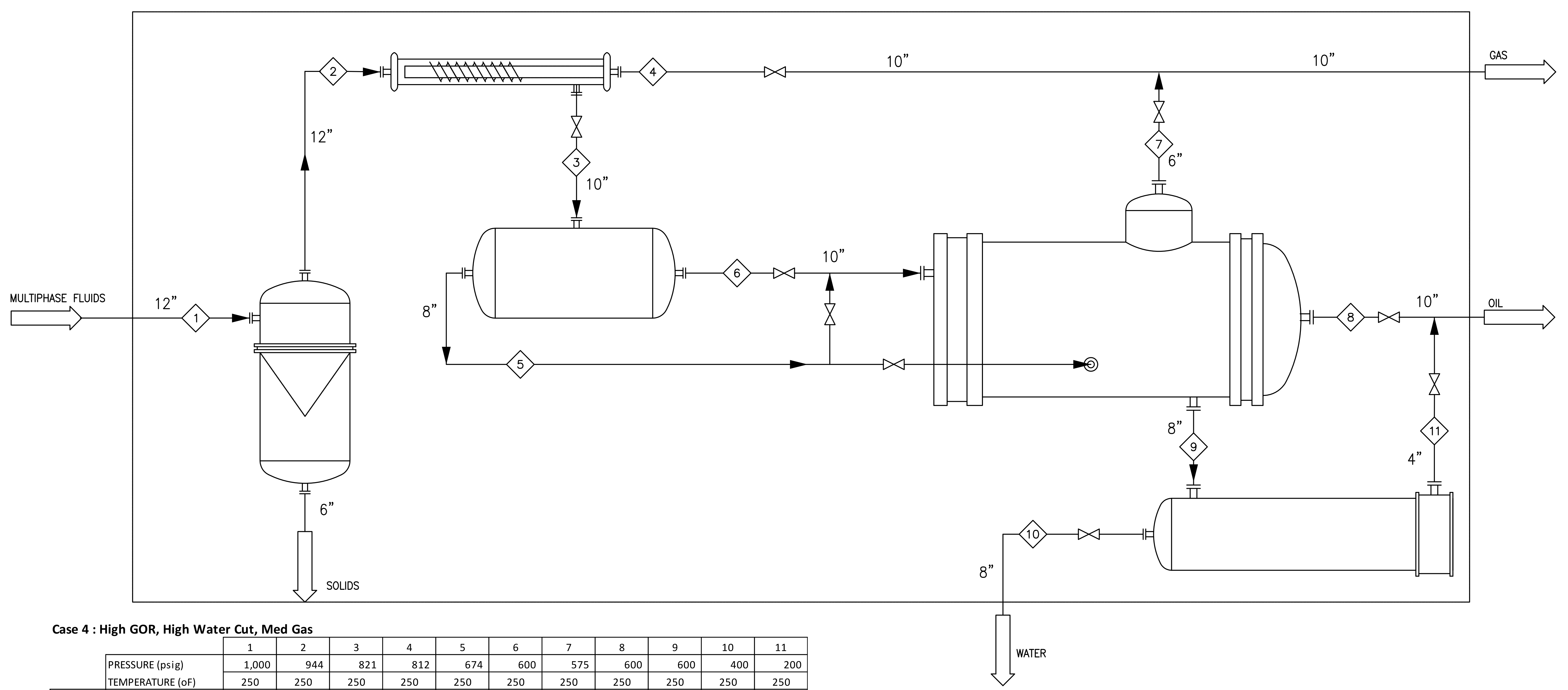
SIZE: 750x2000mm
DESIGN: 1500# ASME
OPERATING: 800 – 850 PSIG
CAPACITY: 0 – 80,000 BFPD

SMART SEPARATOR
Polishing Separator

SIZE: 1400x3800mm
DESIGN: 900# ASME
OPERATING: 600 – 850 PSIG
CAPACITY: 80,000 BFPD / 1 – 32 MMSCFD

DEOILER CYCLONE
Oil Water Separator

SIZE: 750x1500mm
DESIGN: 600# ASME
OPERATING: 600 PSIG
CAPACITY: 0 – 64,000 BWPD



Case 4 : High GOR, High Water Cut, Med Gas

		1	2	3	4	5	6	7	8	9	10	11
	PRESSURE (psig)	1,000	944	821	812	674	600	575	600	600	400	200
	TEMPERATURE (oF)	250	250	250	250	250	250	250	250	250	250	250
OIL	Flowrate (bpd)	16,000	16,000	15,680	320	333	15,347	-	15,347	333	0.94	332
	S.G.	0.887	0.887	0.887	0.887	0.887	0.887		0.887	0.887	0.887	0.887
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
WATER	Flowrate (bpd)	64,000	64,000	62,720	1,280	62,387	333	-	333	62,387	61,139	1,248
	S.G.	1.00	1.00	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
	D50 (microns)	100	100	100	100	100	100		100	100	100	100
GAS	Flowrate (mmscfd)	32	32	6.4	25.6	-	6.4	6.4	-	-	-	-
	S.G.	0.75	0.75	0.75	0.75	0.75	0.75	0.75				
	D50 (microns)	100	100	100	100	100	100	100				
SOLIDS	Flowrate ppm (vol/vol)	100	0.7	0.7	0.7	0.49	0.21	-	0.21	0.49	0.49	-
	S.G.	2.65	2.65	2.65	2.65	2.65	2.65		2.65	2.65	2.65	
	D50 (microns)	100	20.7	20.7	20.7	20.7	20.7		20.7	20.7	20.7	

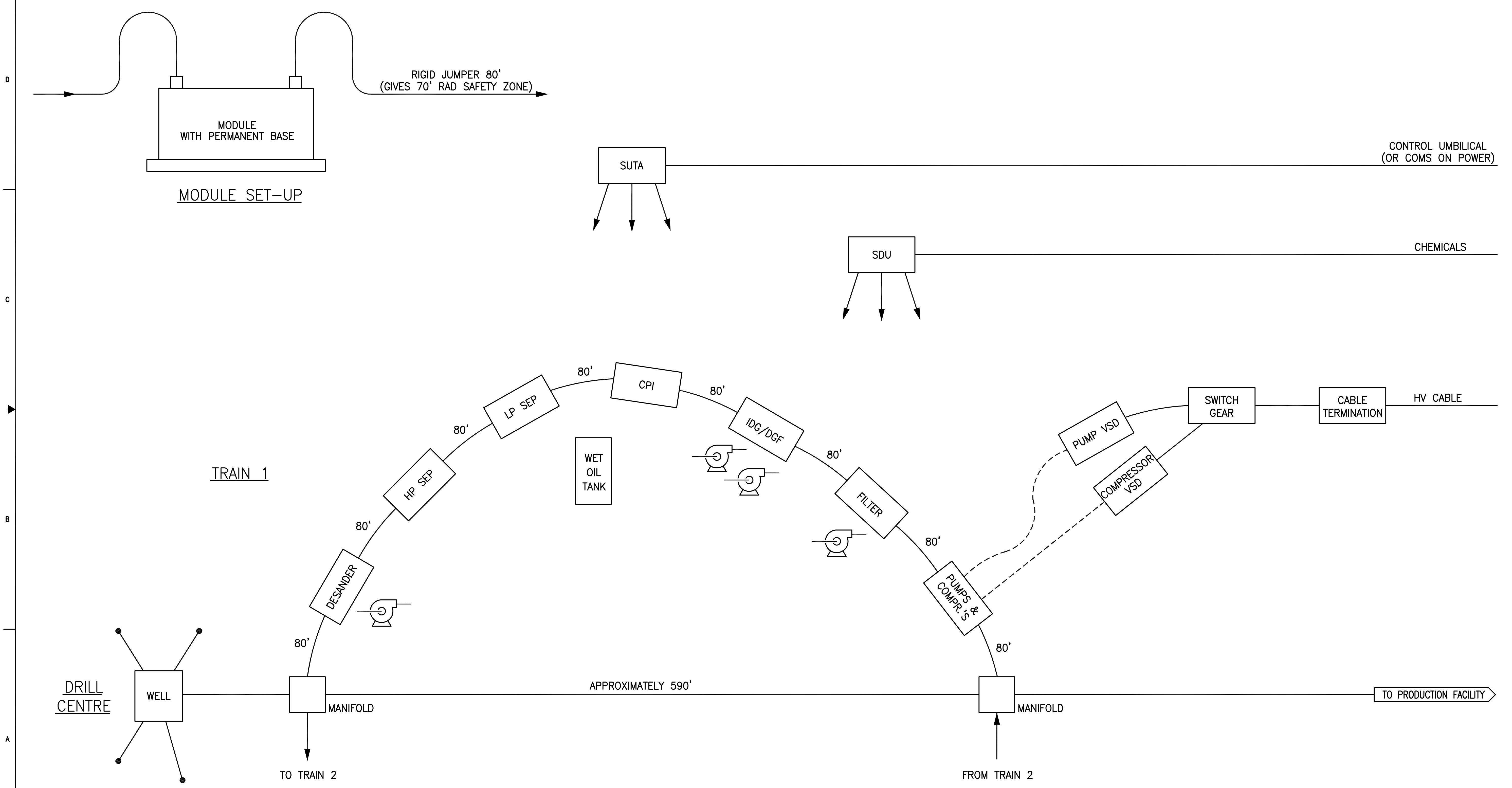
ePROCESS TECHNOLOGIES

DRG. NO.	REFERENCE DRAWINGS			
DATE	No.	REVISION RECORD	DRN	CHK	APP

FOR INFORMATION

DRAWING TITLE: PROCESS FLOW DIAGRAM ePROCESS SUBSEA SEPARATION FLUOR OFFSHORE SOLUTIONS BASIS OF DESIGN FOR RPSEA STUDY

CLIENT PROJECT No.
CLIENT JOB No.
CLIENT P.O. No.
DESIGNED
CAD FILE No.
DRAWN ADR
SCALE: DATE: OCT 11
CHECKED JCD
PROJECT MAN. APPROVAL
DRAWING NUMBER: E1135-DP-001
REV A
LOCATION APPROVAL



REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REFERENCE DWG NUMBER	REFERENCE DRAWINGS
A	8/26/11	PRELIMINARY REVIEW	BSH	DH									

F-D.DWG 01APR01

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DESIGNED BY
B. HALFIN

CHECKED BY
T. DAIGLE

SUPERVISOR	APP DATE
LEAD ENGR/SPEC.	APP DATE
FLUOR	APP DATE
CLIENT	APP DATE

RPSEA

TYPICAL
SCHEMATIC FIELD LAYOUT
UDW SEABED DISCHARGE PROJECT

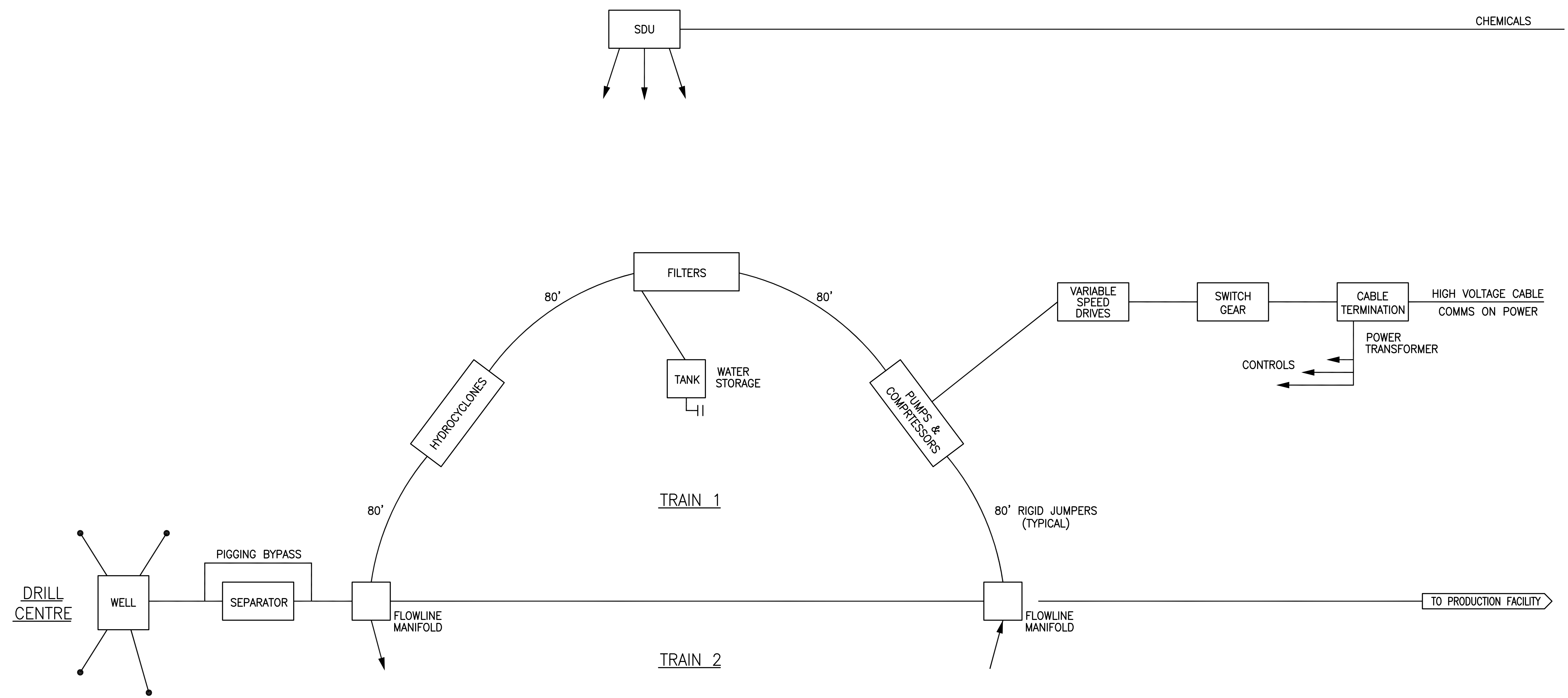
SCALE	DRAWING NUMBER	REV
NONE	SK-SEABED-1	A

SAP NWA

DIST CODE

XREF ATTACHED – YES ☐ NO ☐ MANUAL CHANGES MADE – YES ☐ NO ☐ DWG FILE UPDATED – YES ☐ NO ☐ MODEL UPDATED – YES ☐ NO ☐

CAD FILE NAME SK-SEABED-1.DWG



REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REFERENCE DWG NUMBER	REFERENCE DRAWINGS
A	8/26/11	PRELIMINARY REVIEW	BSH	DH									

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TYPICAL
SCHEMATIC FIELD LAYOUT
UDW SEABED DISCHARGE PROJECT

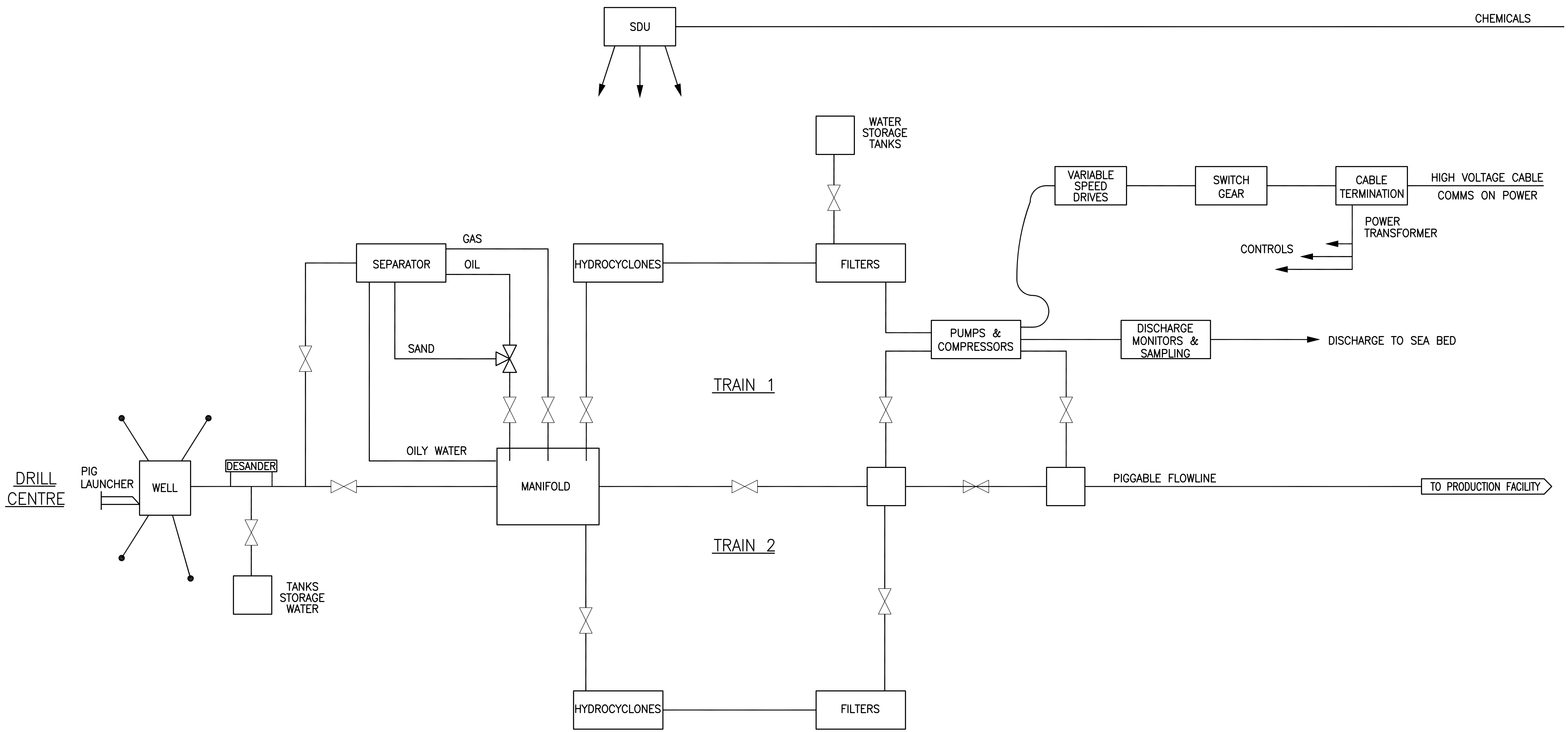
SCALE: NONE
DRAWING NUMBER: SK-SEABED-2
REV: A
CAD FILE NAME: SK-SEABED-2.DWG

SAP NWA
DIST CODE

PLOT DATE: \foldername\drawingname.dwg date time username

XREF ATTACHED - YES ☐ NO ☐ MANUAL CHANGES MADE - YES ☐ NO ☐ DWG FILE UPDATED - YES ☐ NO ☐ MODEL UPDATED - YES ☐ NO ☐

F-D.DWG 01APR01



REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REV	DATE	REVISION DESCRIPTION	BY	CHK	APPV	REFERENCE DWG NUMBER	REFERENCE DRAWINGS
A	8/27/11	PRELIMINARY REVIEW	BSH	DH									

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TYPICAL
SCHEMATIC FIELD LAYOUT
UDW SEABED DISCHARGE PROJECT

SCALE NONE | DRAWING NUMBER SK–SEABED–3 | REV B

SAP NWA | DIST CODE

XREF ATTACHED – YES ☐ NO ☐ MANUAL CHANGES MADE – YES ☐ NO ☐ DWG FILE UPDATED – YES ☐ NO ☐ MODEL UPDATED – YES ☐ NO ☐

CAD FILE NAME SK–SEABED–3.DWG

PLOT DATE: \foldername\drawingname.dwg date time username

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