OSPAR COMMISSION

Background Document concerning Techniques for the Management of Produced Water from Offshore Installations

Offshore Industry Series

2013

OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the “OSPAR Convention”) was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. The Contracting Parties are Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Convention OSPAR

La Convention pour la protection du milieu marin de l'Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d'Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998.
Les Parties contractantes sont l'Allemagne, la Belgique, le Danemark, l’Espagne, la Finlande, la France, l’Irlande, l’Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni de Grande Bretagne et d’Irlande du Nord, la Suède, la Suisse et l’Union européenne.

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Executive Summary

This background document is related to OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations and to OSPAR Recommendation 2012/5 for a risk-based approach to the Management of Produced Water Discharges from Offshore Installations. It contains brief descriptions of principles, basic elements and operational aspects of techniques which may be applied on offshore installations for the treatment of produced water.

An overview of various techniques for the removal of heavy metals, dissolved oil, dispersed oil and offshore chemicals from produced water is presented in Table 1. For a number of techniques that are currently available or emerging for the treatment of produced water from offshore oil and gas installations as part of a BAT/BEP solution, fact sheets are presented. A short description of principles, basic elements, operational aspects and other factors relating to each type of these systems is presented in the tables A – 1 to C – 14. An overview of the techniques for which fact sheets have been prepared is presented in Table 2. This table contains examples of techniques that are currently available or emerging for the treatment of produced water from offshore oil and gas installations as part of a BAT/BEP solution.

Although the physical and chemical principles of techniques described are generally applicable, the technical and economical features mentioned in the current version of this background document draw mainly on experience principally of operations in OSPAR Region II (Greater North Sea).The validity of the cost and technical data is therefore limited, and this should be taken into account when evaluating the applicability of techniques in other areas and in other circumstances.

It is the intention that this background document be revised to update the data as experiences with these techniques increase. Furthermore this background document is intended to be updated regularly in order to allow for the inclusion of descriptions of new techniques when these emerge.

Récapitulatif

Le présent document de fond concerne la Recommandation OSPAR 2001/1, sur la gestion de l'eau de production des installations offshore et la Recommandation OSPAR 2012/5 sur une approche basée sur le risque pour la gestion des rejets d'eau de production provenant des installations offshore. Il décrit brièvement les principes, les éléments de base et les aspects opérationnels des techniques susceptibles d'être appliquées à bord des installations offshore pour le traitement de l'eau de production.

Une vue d'ensemble des diverses techniques d'élimination des métaux lourds, des hydrocarbures dissous, des hydrocarbures dispersés et des produits chimiques d'offshore provenant de l'eau de production est présentée au tableau 1. Pour plusieurs des techniques disponibles ou émergentes pour le traitement de l'eau de production des installations pétrolières et gazières en offshore, à titre de partie intégrante des BAT/BEP, des fiches de caractéristiques sont présentées. Une brève description des principes, des éléments de base, des aspects opérationnels et d'autres facteurs concernant chacun des types de ces systèmes est donnée aux tableaux A – 1 à C – 14. Une synthèse des techniques au titre desquelles des fiches de caractéristiques ont été dressées est présentée au tableau 2. Ce tableau donne des exemples des techniques disponibles ou émergentes pour le traitement de l'eau de production des installations pétrolières et gazières en offshore, à titre de partie intégrante des BAT/BEP.

Bien que les principes physico-chimiques des techniques décrites soient généralement applicables, les caractéristiques techniques et économiques mentionnées dans la version actuelle du présent document de fond sont pour l'essentiel fondées sur l'expérience principalement acquise dans les opérations dans la région II d'OSPAR (mer du nord au sens large). De ce fait même, la validité des données de coût et des données techniques est limitée, ce point devant être pris en compte lorsque l'on juge de l'applicabilité des techniques dans d'autres régions et dans d'autres circonstances.

Il est prévu de revenir sur ce document de fond pour mettre à jour les données lorsque les expériences avec ces techniques auront été acquises. De plus, il est prévu d'actualiser régulièrement le présent document de fond afin d'y intégrer des descriptions des nouvelles techniques au fur et à mesure qu'elles apparaîtront.

1. Introduction

The planning and management of operations at offshore installations should be in accordance with the integrated approach. A “tailor-made” combination of BAT and BEP should be applied for produced water management on offshore oil and gas installations in order to prevent and minimise pollution by oil and other substances as much as reasonably achievable. Whereas BAT is mainly focusing at application of techniques, BEP focuses on environmental control measures and strategies (management options). Reference is made to the definition of BAT and BEP in Appendix 1 of the OSPAR Convention.

Produced water treatment techniques may either be based on the reduction of volume of produced water or on the reduction of the concentration of substances in produced water. Furthermore, techniques may be applicable for oil and/or gas installations. Some techniques are well established and may be considered as current BAT, or present techniques. Some systems cannot be regarded as BAT as such, but may form part of a BAT solution when applied in a series of treatment systems. Other systems should be considered as emerging techniques, which are candidates for inclusion in the list of techniques that may form part of BAT solutions for produced water in the future.

The definition of BAT, including a mechanism of how a set of processes, facilities and methods of operation should be evaluated with a view to determine whether these constitute the best available techniques in general or in individual cases, is described in Appendix 1 of the OSPAR Convention.

An overview of various techniques which may be applied for the treatment of (produced) water is presented in Table 1. Not all these techniques are currently suitable for the treatment of produced water on offshore installations, for various reasons. For a number of techniques that are currently available or emerging for the treatment of produced water from offshore oil and gas installations as part of a BAT/BEP solution, fact sheets are presented in the tables A – 1 to C - 14. An overview of the techniques for which fact sheets have been prepared is presented in Table 2. This table contains examples of techniques that are currently available or emerging for the treatment of produced water from offshore oil and gas installations as part of a BAT/BEP solution.

The cost and technical data in tables A – 1 to C – 14 of this background document draw mainly on experience principally of operations in OSPAR Region II (Greater North Sea). Estimates of performance and cost (see Annex 1) are based on model scenarios that reflect operations in this basin and are unlikely to be applicable rigorously in other areas. It is the intention that the tables in this background document be revised to include data on the applicability of techniques as experiences in the application of these techniques developed. Furthermore new tables on techniques mentioned in table 1, and not mentioned in tables A – 1 to C – 14 will be added in this background document in future updates of this document. The process of continuous updating will also allow for inclusion of (new) techniques when these emerge.

In view of the fact that the characteristics of produced water can be different from one installation to another and can vary widely both in the short and the long term at a single installation, the applicability of each type of system, or combination of systems, on a platform can only be evaluated on a case-by-case basis. Factors influencing the applicability of a system include, amongst other factors:

- the amount of produced water, which may increase in the course of the lifetime of an installation;
- the characteristics of the produced water flow;
- available deck space; and
- the need for and extent of retrofitting.

Moreover, techniques have intrinsic limitations and limitations relating to specific circumstances in which an offshore installation operates. The techniques in the tables are available techniques. A combination of techniques, selected on the basis of specific conditions and other factors, could form a “best available solution for the treatment of produced water” on an offshore installation or “best available package”.

Irrespective of which method is considered and evaluated, it should be realised that the success of any method is dependent, amongst others, on the local environment in which it will be operated. The local reservoir conditions as well as the local operational conditions may strongly influence the effectiveness and operability of the method in question e.g. it cannot be concluded that a method, which has been operated successfully at one installation, may achieve the same results at another location.

Motion of floating installations may render gravity-separation devices less efficient under extreme conditions.

Physical/chemical aspects have not been taken into account: oil-water emulsions may break down more or less easily, depending on the composition of the oil and water. Again, this underlines the importance of case-by-case evaluations and the selection of treatment techniques for specific platforms should take this feature into account.

It is noted that the rows in the tables concerning the indication of costs of each technique contain estimates for the treatment of the indicated flows of produced water under certain circumstances only. Furthermore, it should be noted that the indicated (relative) costs stem from calculations based on pre-defined model situations. The definition of the model situations is applicable to a limited amount of offshore operations, it should be taken into account that these figures could vary from region to region or even from country to country. An evaluation of costs of application of a certain (series of) treatment technique(s) on a specific offshore installation, should be made on a case-by-case basis.

Cross-media effects and other impacts should also be considered when evaluating a system. Issues that may be covered by a cross-media effect evaluation include, but are not limited to, energy consumption, use of chemicals, waste production, fate and/or effect of substances in the effluent discharged that are not separated but may affect the treatment method and health and safety aspects.

For the assessment of the fate and / or effect of all substances present in the effluent discharged a risk based approach has been developed by the OSPAR Commission. In the OSPAR Recommendation 2012/5 for a risk-based approach to the Management of Produced Water Discharges from Offshore Installations, this approach is described. Based on techniques described in this document a choice can be made for the best risk reduction measures in order to manage those risks.

Table 1 List of potential measures for the removal of heavy metals, dissolved oil, dispersed oil and offshore chemicals from produced water

A. Preventive techniques • Down-hole oil-water separation (DHWS) • Down-hole gas-water separation (DHWS) • Mechanical water shut-off • Chemical water shut-off **B. Process integrated techniques** • Methanol recovery unit • Glycol regeneration (incl. Drizo) • Overhead vapour combustion (OVC) • Macro Porous Polymer Extraction (MPPE) (partial flow) • High pressure condensate-water separation • Steam stripping (glycol regeneration water) • Insulation of pipelines • Stainless steel lines and casks • Alternative methods of gas drying (IFPEXOL etc.) • Labyrinth type choke valve • Glycol overheads backflow to separator • Degassers **C. End of pipe techniques** **Conventional techniques** • Gas flotation (DGF/IGF) • Flotation cells • CPU compact flotation unit • Plate separator (CPI/PPI) • Hydrocyclone • Axiflow cyclones • Skimmer tank • Centrifuge • Disk stacked centrifuges • Produced water re-injection (PWRI) • Filter coalescer, incl. - sand filters - filters filled with oleophilic resins - etc. • Screen coalescers • Pall coalescers • In-line coalescing technology (incl. Mare's Tail and PECT-F) • Performance enhancing coalescer fiber • FU filter unit • Integral plate packs in three phase separators **Biological techniques** • Aerobic • Bioreactor (anaerobic) • Membrane bioreactor (MBR) • Enzyme reactor • Compost filter (glycol overhead) • Bacterial treatment	**Membrane techniques** • Micro-filtration • Ultra-filtration • Nano-filtration • Membrane separator • Reversed osmosis • Pertraction • Emulsion pertraction • Electro-dialyse • Membrane assisted affinity sorption (MAAS) **Absorption / adsorption techniques** • Absorption filter • Granular active carbon • Powder carbon • Ion exchange • Centrifugal absorption techniques • Zeolites • MPPE (end flow) • MPPS • Reusable oil adsorbent (RPA) **Stripping techniques** • Steam stripping (end flow) • Air stripping • Gas stripping **Evaporation** • Evaporation system • Freezing concentration **Oxidation techniques** • O_3 • H_2O_2 • Oxidation / neutralisation / de-watering (OND) • Vertech • $KMnO_4$ • Natural air • Electron beam • Plasma • Sonolysis • Photo catalytic oxidation • Low temperature hydro-thermal gasification (LTHG)

Table 1 Cont.

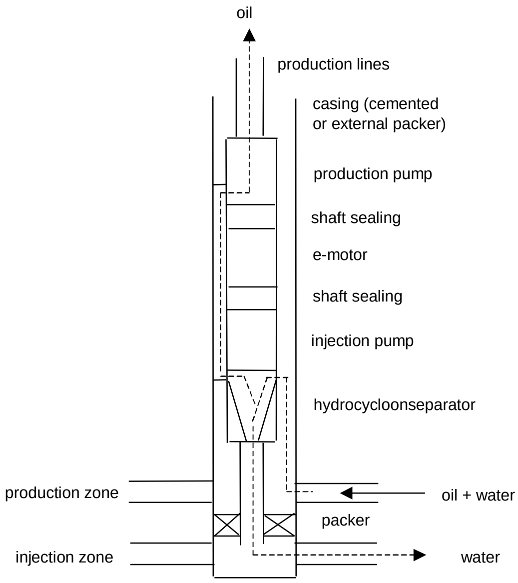
Other techniques	**Combination of techniques**
• Multimedia filtration/coalescers • Coagulation/flocculation • Electro-coagulation • Electrolytic treatment • Chalk precipitation • Sulphide precipitation • Grain reactor • High gradient magnetic separation • Pack of balls in PPI • Monitoring en control • Good operating practices • Optimal application of CHARM • Processes based on gas drying by adsorption • Glycol cleaning • Electrolysis	• Flocculation & hydrocyclone • Cyclone & electro-coalescer • Glycol regeneration and steam stripping

Table 2 Examples of techniques that are currently available or emerging for the treatment of produced water from offshore oil and gas installations as part of a BAT/BEP solution

			Gas production *		Oil production *	
	Table	*Page*	*Present*	*Emerging*	*Present*	*Emerging*
Preventive						
Downhole water separation - oil	Table A - 1	13			X	
Downhole water separation - gas	Table A - 2	15		X		
Mechanical water shut off	Table A - 3	17	X		X	
Chemical water shut off	Table A - 4	19	X		X	
Stainless steel tubing, flow lines, pipelines	Table A - 5	21	X		X	
Insulation of pipelines	Table A - 6	23	X			
Coalescing pump - separator	Table A - 7	25				X
Process integrated, including split stream treatment						
Overhead Vapour Combustion (OVC)	Table B - 1	28	X			
Fluid from condensor to production separator	Table B - 2	30	X			
Alternative methods of gas drying	Table B - 3	32	X			
MPPE (split stream)	Table B - 4	34	X			
Steam stripping, split stream	Table B - 5	36	X			
HP water condensate separator	Table B - 6	38	X			
Methanol recovery unit	Table B - 7	40	X			
Labyrinth type choke valve	Table B - 8	42		X		
End of pipe						
Skimmer tank	Table C - 1	46	X		X	
Produced water re-injection (PWRI)	Table C - 2	48	X		X	
DGF/IGF	Table C - 3	50	X		X	
PPI / CPI (gravitation separation)	Table C - 4	52	X		X	
Hydrocyclones	Table C - 5	54	X		X	
MPPE (end stream)	Table C - 6	56	X			X
Centrifuge	Table C - 7	61	X			
Steam stripping, end stream	Table C - 8	63	X			
Adsorption filter	Table C - 9	65	X			
Membrane filtration	Table C - 10	67		X		X
V-Tex	Table C - 11	69		X	X	
Filter coalescer	Table C - 12	71		X		X
CTour	Table C - 13	73		X		
Cyclotech	Table C - 14	76	X		X	
Compact flotation	Table C - 15	80			X	
Condensate induced extraction	Table C - 16	85	X		X	
Tail shaped pre-coalescer	Table C - 17	88	X		X	
Advanced oxidation process	Table C - 18	91		X		X
Screen (cartridge type) coalescing technique	Table C - 19	94			X	
TwinZapp	Table C - 20	96				X
Fibra Cartridge	Table C – 21	99		X		X
Pertraction	Table C - 22	102		X		
Ion exchange	Table C - 23	104				
Oxidation - Vertech	Table C - 24	106				
Oxidation – Hydrogen peroxide	Table C - 25	108				
Oxidation - Ozone	Table C - 26	109		X		
Oxidation – electron beam	Table C - 27	111				
Oxidation - sonolysis	Table C - 28	113				
Oxidation – KMnO4	Table C - 29	115				
Oxidation – Photocatalytic oxidation	Table C – 30	116				
Oxidation - Plasma	Table C - 31	118				

PPI / CPI = Parallel Plate Interceptor / Corrugated Plate Interceptor (gravitation separation)
DGF / IGF = Dissolved Gas Flotation / Induced Gas Flotation
HP = High Pressure
MPPE = Macro Porous Polymer Extraction

* Although a distinction is made in this table between oil and gas producing installations, the limits of applicability of specific techniques may not be as rigid. These limits are, amongst other factors, dependent on the composition of the oil / condensate / gas and water produced.

<table>
<tr><th colspan="7">Table A - 1: Table down hole oil-water separation (DHS) - oil</th></tr>
<tr><td>Principle</td><td colspan="6">DHS for oil is a technique in which the production of an oil-water mix at the bottom of a production well is separated by a hydrocyclone. Separated water is injected into a suitable underground zone and the remaining oil-water mix is pumped to the surface. In this way, the amount of produced water can be reduced by more than 50%. This will result in a higher oil production, a relatively low water production and the use of less chemicals. The discharge and treatment of produced water is considerably reduced or the water injection installation could be considerably decreased.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Pump(s), hydrocyclone(s), e-motor, seals, instrumentation and changes in the well (deepening of well and /or additional perforations and packers)</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
■ Cadmium
■ Zinc
■ Lead
■ Mercury
■ Nickel</td><td rowspan="2">R [%]
50
50
50
50
50</td><td rowspan="2">Production chemicals
□ Methanol
□ Glycols
■ Corrosion inhibitors
■ Anti-scale solutions
■ Demulsifiers</td><td rowspan="2">R [%]

50
50
35</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]
50
50
50
50</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
50</td></tr>
<tr><td colspan="6">Remarks:
The 50% reduction is based on a 50% effectiveness of the hydrocyclone in the well. Less offshore chemicals need to be added, although the use of demulsifiers is usually not proportionately smaller.</td></tr>
<tr><td>Technical details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. water treatment installation
Mass of equipment for injection vs. water treatment installation</td><td colspan="2">Oil
175 m^3/h
less
smaller</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">The availability of a suitable water injection zone, which allows for fracturing, as well as an appropriate well configuration is a prerequisite for the application of this technique. Produced solid materials are separated largely into the water phase and may plug the injection zone. DHS is only suitable for oil > 20 °API and a water cut >50%. The composition of the injection water must be compatible with the injection zone. Production and injection zones must be sufficiently isolated. The diameter of the casings must be large enough to allow for a DHS system. DHS is seldom suitable in horizontal wells.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">Results presented are variable: only 60% of the test installations produce more oil than previous installations, and one third of the failures was the result of plugging of the injection zone. Some installations have been operational for more than 2 years, while others failed within a few days. The life span of a DHS installation is estimated to be half that of a standard pump installation.</td></tr>
</table>

Indication of costs	

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	n.a.	n.a.	n.a.	n.a.
gas platform, large	n.a.	n.a.	n.a.	n.a.
oil platform	2 450 000	1 290 000	959 400	523 000

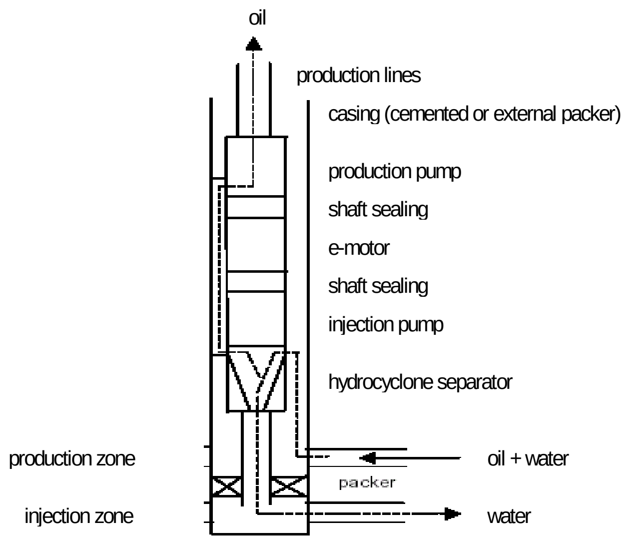
Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil					1 460	796
dispersed oil	n.a.	n.a.	n.a.	n.a.	88	48
zinc equivalents					41 261	22 494

Remarks:

Costs were presented for one DHS installation of 50 m^3/h. In order to reduce a nominal water production of 150 m^3/h by 50%, a minimum of 3 DHS installations would be required. Depreciation in the OPEX for an existing offshore installation is based on deepening an existing well and installing a liner ad. € 2 MM. Costs for a workover of a DHS installation were estimated at € 550 000. Cuts on costs for reduced energy consumption on an existing offshore installation were not taken into account, neither was additional production of wells that are not producing on maximum capacity. For new offshore installations, large savings may be possible regarding the water treatment system.

Cross media effects	**Air**	Decreased energy use leads to decreased air emissions, especially when diesel fuel is used.
	Energy	Decreased energy use for water transport pumps. Possible increased or decreased energy use for the pumps in the well, depending on the required injection pressure.
	Added chemicals	Possibly scale inhibitor or acid to stimulate the injection zone.
	Waste	The decreased water through flow should result in a decrease in sludge in the water treatment installation. The sludge is often slightly radioactive (NORM).
Other impacts	**Safety**	Slight increase in view of increased number of workovers.
	Maintenance	Maintenance of the water treatment installation for existing installations will definitely decrease. Replacement of the DHS installation on average every 1,5 years.

Practical experience	**General**	**Offshore**
	The results to date are very variable. The technique is considered very promising but is still in the development stage.	DHWS is mostly used onshore, in situations where the water treatment capacity is limited.
Conclusion	☐ BAT	■ Emerging Candidate for BAT, very promising technique
Literature source	[1]	

<table>
<tr><th colspan="7">Table A - 2: Down hole oil-water separation (DHS) - gas</th></tr>
<tr><td>Principle</td><td colspan="6"></td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Pump(s), hydrocyclone(s), e-motor with variable number of revolutions, seals, instrumentation and changes in the well (deepening of well and /or additional perforations and packers)</td></tr>
<tr><td rowspan="4">Suitable for the removal of:

R = removal efficiency</td><td>Heavy metals</td><td>R [%]</td><td>Production chemicals</td><td>R [%]</td><td>Oil</td><td>R [%]</td></tr>
<tr><td rowspan="2">■ Cadmium
■ Zinc
■ Lead
■ Mercury
■ Nickel</td><td rowspan="2">50-100
50-100
50-100
50-100
50-100</td><td rowspan="2">■ Methanol
■ Glycols
■ Corrosion inhibitors
■ Anti-scale solutions
■ Demulsifiers</td><td rowspan="2"><75%
<75%
100
50-100
15-35</td><td>■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>50-100
50-100
50-100
50-100</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
50-100</td></tr>
<tr><td colspan="6">Remarks:
The 50-100% removal efficiency is applicable to the amount of formation water, which is 25-50% of the total water production. E.g.: if 50% of the formation water production (1,4 m^3/h) stems from one well, DHWS will reduce the total water production from this well by 75% x 50% x 1,4 m^3 = 0,53 m^3/h. Reduction of chemicals is less than proportionate. Lower salt concentrations lead to more oil/water emulsions, in some cases leading to increased use of demulsifiers and higher dispersed/dissolved oil concentrations. Lower salt concentrations will lead to increased use of methanol/glycol (hydrate inhibitors). A large part of the condensation water will be produced (depending on the well pressure).</td></tr>
<tr><td>Technical details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. water treatment installation
Mass of equipment for injection vs. water treatment installation</td><td>Gas 1
1 m^3/h
n.a.
n.a.</td><td>Gas 2
6 m^3/h
less
lower</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">DHS is only suitable for gas wells with little condensate production. Presence of a suitable layer for water (and condensate) injection and for fracturing and suitable (existing) well configurations is required. Composition of injection water must be compatible with the injection zone (swelling of clay etc.). Production and injection zones must be adequately isolated. Depressurising the well in order to pull the injection pump may cause damage to the production zone.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">From the few references it is evident that results vary. Problems may be expected when produced water contains sand or clay particles, which could plug the injection zone.</td></tr>
</table>

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	n.a.	n.a.	n.a.	n.a.
gas platform, large	2 550 000	1 390 000	890 600	444 200
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	n.c.	n.c.	1 320	659	n.a.	n.a.
dispersed oil			4 842	2 415		
zinc equivalents			64 438	32 635		

Remarks:
Costs have been included for a DHS installation of 0,7 m^3/h, although an installation for 2 m^3/h would cost little extra. In order to achieve a 75% reduction of formation water, each well would have to be fitted with a DHS installation. Depreciation in the OPEX for an existing offshore installation is based on deepening an existing well and installing a liner ad. € 2 MM. Costs for a workover of a DHWS installation were estimated at € 4 000 000. The reduction of condensate production was not taken into account.

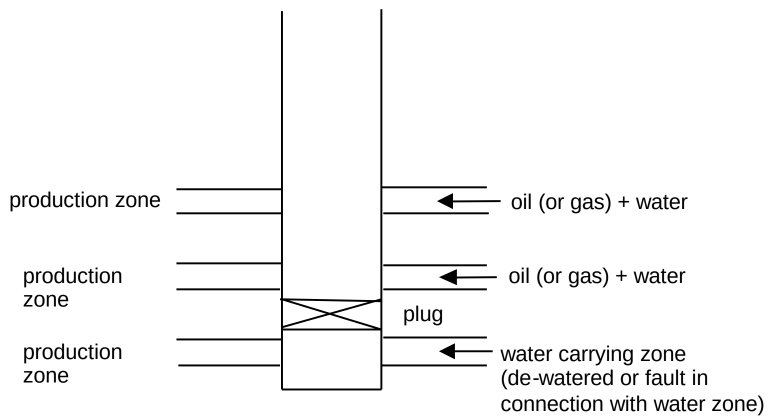
Cross media effects	**Air**	Higher energy consumption will increase air emissions, especially when using diesel fuel.
	Energy	Energy consumption for the pumps in the well depends on the required injection pressure and the amount of water.
	Added chemicals	Possibly scale inhibitor or acid to stimulate the injection zone.
	Waste	The decreased water through flow should result in a decrease in sludge in the water treatment installation. The sludge is often slightly radioactive (NORM).
Other impacts	**Safety**	Slight increase in view of increased number of workovers.
	Maintenance	Maintenance of the water treatment installation for existing installations will definitely decrease. Replacement of the DHS installation every 2 years.

Practical experience	**General**	**Offshore**
	There are few references. The technique is in the phase of development.	It is expected that this technique will be tested onshore first. Currently, pumping of water to the surface is preferred.
Conclusion	☐ BAT	■ Emerging Candidate for BAT
Literature source	[1]	

Table A - 3: Mechanical water shut-off

Principle	When water breakthrough occurs in oil or gas production, production zones with high water cuts can be sealed by installing mechanical barriers. This may, dependent on well configuration, be achieved by mechanical or inflatable plugs, cementing, placement of a patch (expansion pipe) or pack-off, possibly in combination with chemical treatment (see table on Chemical water shut off). If total sealing of the water production is not desired, a regulating mechanism or restriction plate may be placed in the well.

Process diagram



Basic elements	Mechanical plugs, cement, pack-off etc. Preferably, the process of completion of a well takes into account the possibility of sealing of zones which may produce large amounts of water, e.g. by cementing casings.

Suitable for the removal of:

R = removal efficiency

Heavy metals	R [%]	Production chemicals	R [%]	Oil	R [%]
■ Cadmium	50-75	■ Methanol	<55	■ **Dissolved oil**	50-75
■ Zinc	50-75	■ Glycols	<55	■ BTEX	50-75
■ Lead	50-75	■ Corrosion inhibitors	50-75	■ Benzene	50-75
■ Mercury	50-75	■ Anti-scale solutions	50-75	■ PAHs	50-75
■ Nickel	50-75	■ Demulsifiers	15-35	**Dispersed oil**	**R [%]**
				■ Oil	50-75

Remarks:
The effectiveness of a sealing is dependent on successfully installing the plug and the way the well was completed, e.g. the sealing around the casing or liner. Reduction of chemicals is less than proportionate. Lower salt concentrations lead to more oil/water emulsions, in some cases leading to increased use of demulsifiers and higher dispersed/dissolved oil concentrations. Lower salt concentrations will lead to increased use of methanol/glycol (hydrate inhibitors). Formation water will inevitably be produced in view of natural water saturation (conate water).

Technical details				
	Type of installation	Gas 1	Gas 2	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
	Area required for water treatment	less	less	less
	Mass of equipment for water treatment installation	lower	lower	lower

Critical operational parameters	Study is required to identify the source of water production and reduce the risk of plugging the production. Mechanical water shut off is mainly applicable for multi-layer reservoirs. In horizontal wells, this technique is often more difficult and more expensive. Possible leakage of existing sealings around casing (cement or packer) may reduce the effect of the sealing. Production lines must be pulled out unless inflatable plugs can be placed via these lines. Inflatable plugs and some patches are resistant to limited pressures. Sometimes water sealing leads to production loss.
Operational reliability	The reliability of mechanical and cement plugs is modest, absolute certainty about closing in water is rare. Dependent on the well configuration, the rate of success is 40-70% (closer to 40% for gas installations). Inflatable plugs and pack-offs are less reliable (failure by high pressure or damage). When a patch doesn't seal well, e.g. because of salt deposition in tubings, erosion and corrosion may occur.

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	200 000-800 000	n.a.	50 800-209 200	n.a.
gas platform, large	200 000-800 000	n.a.	48 800-207 200	n.a.
oil platform	170 000-300 000	n.a.	20 900-45 200	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	1 374-5 660	n.a.	116-491	n.a.	106-229	n.a.
dispersed oil	2 062-8 490		424-1 802		6,4-13,8	
zinc equivalents	39 564-162 928		5 642-23 954		2 986-6 457	

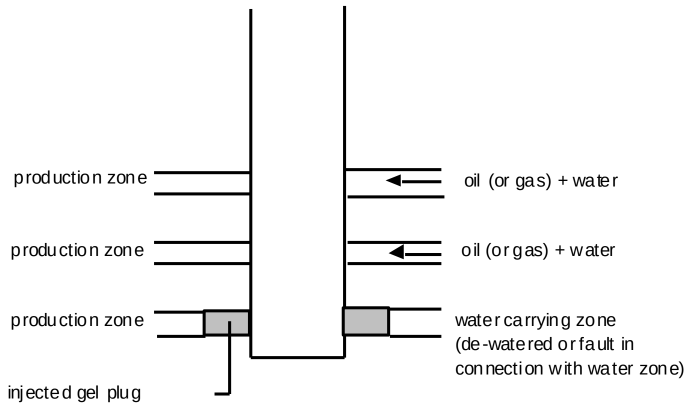
Remarks:

- The technique is only applied on existing offshore installations, although provisions can be made on new installations.
- Including costs of removal and replacement of production lines with drilling rig (gas). On oil installations, the installation is combined with the replacement of pumps (ESP), therefore only additional costs should be calculated. Lower costs are for use of a platform rig. Possible costs for loggings should be calculated.
- The KEw is difficult to assess, since the costs vary and production may reduce. KEw may be calculated but should be raised with risk.
- The costs model situation is presented for one well and a reduction of 62,5% of formation water. In case that the amount of formation is 75% or 50% of the total water production, the reductions are 62,5% x 75% x 0,2 m^3/h and 62,5% x 50% x 1,4 m^3/h respectively. Oil platforms also require extra costs for reducing 1/5 of the water production by 50% (for one well 50% of 30 m^3/h). A total of 5 wells is required for similar reservoir and production.
- Costs for horizontal wells are usually higher.
- Possible slight savings in energy costs were not calculated, neither was possible additional oil or gas production.

Cross media effects	**Air**	Less energy consumption will reduce air emissions, especially when diesel fuel is used.
	Energy	Reduced energy consumption for water pumps etc.
	Added chemicals	Reduced use of chemicals for water treatment e.g. scale inhibitors, corrosion inhibitors, demulsifier.
	Waste	Less (often slight radioactive, NORM) sludge deposition in view of reduced water production.
Other impacts	**Safety**	None.
	Maintenance	Maintenance of water treatment facilities will definitely reduce. In principle no maintenance on mechanical seal needed.

	General	**Offshore**
Practical experience	Mechanical water shut off is applied frequently.	These techniques can be applied offshore.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

Table A - 4: Chemical water shut off

Principle	When water breakthrough occurs with oil or gas production, production zones with high water cuts can be sealed by the placement of special polymers. By adding cross-linkers, gel is formed which blocks water. Chemical sealing is often applied in higher production zones. The advantage in comparison with mechanical shut off is that the full diameter of the well remains available for any well repairs and the chance for flow behind the tubing is less, since the gel perforates the formation deeply. The disadvantage is that the gel normally cannot be removed anymore when production proves less. Sometimes polymers are injected to reduce the relative permeability for water, whereas the permeability for gas remains the same.
Process diagram	
Basic elements	Polymer, cross-linker, catalyst, filler. There are many types of anorganic and bio-polymers. In gas wells, the gel is often placed by a coiled tubing. In oil wells, a workover, or production lines may be appropriate. Preferably, the process of completion of a well takes into account the possibility of sealing zones which may produce large amounts of water, e.g. by cementing tubings.

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
■ Cadmium	50-75	■ Methanol	<55	■ **Dissolved oil**	50
■ Zinc	50-75	■ Glycols	<55	■ BTEX	50
■ Lead	50-75	■ Corrosion inhibitors	50-75	■ Benzene	50
■ Mercury	50-75	■ Anti-scale solutions	50-75	■ PAHs	50
■ Nickel	50-75	■ Demulsifiers	50-75	**Dispersed oil**	**R [%]**
				■ Oil	50

Remarks:

The effectiveness of sealing is dependent on successful placement of the gel and of the physical interaction between oil or gas and water. Reduction of chemicals is less than proportionate. Lower salt concentrations lead to more oil/water emulsions, in some cases leading to increased use of demulsifiers and higher dispersed/dissolved oil concentrations. Lower salt concentrations will lead to increased use of methanol/glycol (hydrate inhibitors). Formation water will inevitably be produced in view of natural water saturation (conate water).

Technical details				
	Type of installation	Gas 1	Gas 2	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
	Area required for water treatment installation	less	less	less
	Mass of equipment for water treatment installation	lower	lower	lower

Critical operational parameters	Study is required to identify the source of water production and reduce the risk of plugging the production. The maximum allowable temperature is 150 °C (dependent on type of gel). Chemical water shut off is mainly applicable for multi-layer reservoirs (water should not be able to flow around the blockade) but it can also be applied in horizontal wells. For the sealing of fractures, large amounts of activated gel are needed, followed by gel and filler.
Operational reliability	The reliability of chemical plugging is modest, absolute certainty about closing-in water is rare. Dependent on the communication between zones, the rate of success is 30-70%. Advantage of polymers that reduce relative permeability is that they need not to be injected in a specific zone, which increases the reliability of sealing.
Indication of costs	

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	170 000-480 000	n.a.	42 900-124 700	n.a.
gas platform, large	170 000-480 000	n.a.	40 900-122 700	n.a.
oil platform	150 000-520 000	n.a.	15 600-113 300	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	1 161-3 374	n.a.	97-291	n.a.	79-575	n.a.
dispersed oil	1 741-5 061		356-1 067		4,7-34	
zinc equivalents	33 411-97 118		4 728-14 185		2 229-16 186	

Remarks:

- The technique is only applied on existing offshore installations, although provisions can be made on new installations, that may later on reduce CAPEX (costs for these provisions should not be added when calculating KEw, costs are based on 1 000-1 500 €/m^3 gel).
- CAPEX includes coiled tubing (gas). On oil installations, polymer injection is combined with the replacement of pumps (ESP); therefore only additional costs should be calculated. A platform rig requires lower costs than a jack-up rig and sealing of fractures (high volume needed). Possible costs for loggings should be calculated.
- The KEw is difficult to assess, since the costs vary and production may reduce. KEw may be calculated but should be raised with risk.
- Costs for model situation platforms are for 1 well, needed to reduce 62,5% formation water. If formation water forms 75% or 50%, the reduction is 62,5% x 75% x 0,2 m^3/h and 62,5% x 50% x 1,4 m^3/h respectively, for an oil installation also costs for 1 well to reduce 1/5 of the water production with 50% (50% of 30 m^3/h) (a total of 5 wells needed if reservoir and production are similar).
- Costs for sealing of fractures are usually high in view of large quantity of gel needed.
- Possible slight savings in energy costs were not calculated, neither was possible additional oil or gas production.

Cross media effects	**Air**	Less energy consumption will reduce air emissions, especially when diesel fuel is used.
	Energy	Reduced energy consumption for water pumps etc.
	Added chemicals	Reduced use of chemicals for water treatment e.g. scale inhibitors, corrosion inhibitors, demulsifier.
	Waste	Less (often slight radioactive, NORM) sludge deposition in view of reduced water production.
Other impacts	**Safety**	None.
	Maintenance	Maintenance of water treatment facilities will definitely reduce. In principle no maintenance on chemical seal needed.

Practical experience	**General**	**Offshore**
	Chemical water shut off is applied frequently.	These techniques can be applied offshore.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

<table>
<tr><th colspan="7">Table A - 5: Stainless steel tubing, flow lines, pipelines</th></tr>
<tr><td>Principle</td><td colspan="6">In the presence of free water during the transport of oil and gas where H_2S and/of CO_2 are present, corrosion could occur where carbon steel is used. Depending on the degree of corrosion (depending on the temperature, the CO_2 level, the pressure of the medium and the planned life span) a combination can be used of control measures such as the development of corrosion margins, the use of corrosion inhibitors or the use of corrosion resistant material.
The use of corrosion inhibitors in combination with a high pressure step can lead to formation of stable oil-water emulsions with a small particle size that are difficult to separate. The use of corrosion resistant material, possibly in combination with high pressure separation, requires little or no use of corrosion inhibitors, which leads to a decrease of aromatic hydrocarbons in overboard water.
For low pressure lines, synthetic materials (GRE/GRP) may be used, but for high pressure lines and pipelines duplex steel (>18% Cr / 5% Ni) or (Inconel) coating is used. Stainless steel vessels may be used or vessels may be coated with a protective coating.</td></tr>
<tr><td>Process diagram</td><td colspan="6">Not applicable</td></tr>
<tr><td>Basic elements</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Suitable for the removal of:

R = removal efficiency</td><td>Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td>R [%]</td><td>Production chemicals
☐ Methanol
☐ Glycols
■ Corrosion inhibitors
☐ Anti-scale solutions
■ Demulsifiers</td><td>R [%]

100

50-100</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs
Dispersed oil
■ Oil</td><td>R [%]
*
*
*
*
R [%]
*</td></tr>
<tr><td colspan="6">Remarks:
*: The removal efficiency for dissolved and dispersed oil depends, amongst others, on produced water treatment systems installed and whether high pressure oil water separation is applied. If demulsifier is in injected, the specific removal efficiency may reduce considerably.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Required area (LxWxH)
Mass (filled)</td><td>Gas 1
1 m³/h
n.a.
n.a.</td><td>Gas 2
6 m³/h
n.a.
n.a.</td><td>Oil 1
175 m³/h
n.a.
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Operations and control of the oil content in produced water are enhanced when less corrosion inhibitors are injected. Corrosion increases exponentially with raising temperature. The need for use of corrosion inhibitors may be reduced considerably when the water treatment facilities are operated in a way so as to prevent oxygen entering (possibly separated systems).</td></tr>
<tr><td>Operational reliability</td><td colspan="6">The resistance of stainless steel against corrosion and erosion is better and therefore the life span is longer.</td></tr>
</table>

<table>
<tr><td>Indication of costs</td><td colspan="3">The use of materials that are resistant against corrosion leads to savings in the use of corrosion inhibitors and maintenance. For a gas pipeline with a capacity of 1,5 MM Nm^3/d, these savings total € 34 000 per year. With a life span of 15 years, this totals € 510 000. If no corrosion inhibitor injection system is needed, a further saving of investments of € 40 000 is achieved. Additional investments for stainless steel in comparison with carbon steel pipelines amounts approximately to € 375 per meter (for 10” and 12” € 500/m and € 750 respectively). The break even point for such a pipeline would be 1,5 km. Since this is much shorter than most pipelines, this investment would not be justifiable. When production is higher and when other business economic factors are taken into account, or when the gas is very corrosive, the use of stainless steel may be preferred.
Since duplex steel is more resistant against erosion, smaller diameters can often be applied, thus reducing costs. In some cases the use of smaller diameter pipelines renders cementing pipelines unnecessary.</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="2">None.</td></tr>
<tr><td>Energy</td><td colspan="2">None.</td></tr>
<tr><td>Added chemicals</td><td colspan="2">Reduction of corrosion inhibitors, for gas 10 l/MM Nm^3 and water approximately 100 mg/l.</td></tr>
<tr><td>Waste</td><td colspan="2">None.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="2">Safer, since less drums with corrosion inhibitors need to be handled (satellite platforms) and because of reduced leakage and corrosion problems.</td></tr>
<tr><td>Maintenance</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="2">General</td><td>Offshore</td></tr>
<tr><td colspan="2"></td><td>Corrosion resistant materials are frequently applied for (pipe)lines and vessels.</td></tr>
<tr><td>Conclusion</td><td colspan="2">■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="3">[1]</td></tr>
</table>

<table>
<tr><th colspan="7">Table A - 6: Insulation of pipe lines</th></tr>
<tr><td>Principle</td><td colspan="6">When gas is transported under high pressure from a satellite to a treatment facility on a central installation, there is a danger of hydrate formation as the mixture of gas and water cools down. This may lead to blockages in the pipeline. There are three different methods available to prevent this problem:
1. Injection of methanol or glycol (MEG/TEG), or other chemicals that may, or may not be retrieved and regenerated on the central platform;
2. Maintaining the temperature as much as possible by burying and possibly adding insulation to the pipeline;
3. Lowering the pipeline pressure, in order to allow for operation outside the hydrate-regime. This may be possible when sufficient compression facilities are installed on the central platform, but usually this is not desired since this reduces the pipeline capacity considerably and energy is wasted.
The only alternative for continuous injection of chemicals is therefore insulation of the pipeline. This is only effective when production is continuous and a minimum production is maintained. During start up and when producing below the required minimum, methanol will need to be injected in order to prevent the formation of hydrates.</td></tr>
<tr><td>Process diagram</td><td colspan="6">Not applicable</td></tr>
<tr><td>Basic elements</td><td colspan="6">Insulated and/or buried pipelines.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
■ Methanol
■ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]
>90
100</td><td>Oil
☐ Dissolved oil
☐ BTEX
☐ Benzene
☐ PAHs</td><td>R [%]
*
*
*
*</td></tr>
<tr><td>Dispersed oil
☐ Oil</td><td>R [%]</td></tr>
<tr><td colspan="6">Remarks:
For start up operations and production below the required minimum, injection of small amounts of methanol is required. This will be discharged with produced water.

*: When glycol is used, the insulation renders re-feeding of water with a high content of aromatic hydrocarbons from the condensor of the regenerator unnecessary.</td></tr>
<tr><td>Technical details</td><td colspan="2">Platform
Produced water volume (design)
Pipeline length
Pipeline diameter</td><td>Gas 1
1 m^3/h
3-10 km
8”-10”</td><td colspan="2">Gas 2
6 m^3/h
3-15 km
14”- 16”</td><td>Oil
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">The formation of hydrates may occur at a pressure/temperature relation of approximately 25 bar/4 °C or 100 bar/20 °C. Salt in produced water will reduce the formation of hydrates. A minimum production needs to be maintained in order to keep the pipeline at a certain temperature. With the ageing of the field and reduced reservoir pressure, methanol injection will be reduced.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">The use of methanol will still be needed during start up operations. Insulation is less effective when the throughput is low.</td></tr>
</table>

<table>
<tr><td>Indication of costs</td><td colspan="2">The costs of insulation are dependent on the required level of insulation. The use of advanced systems (e.g. pipe-in-pipe) may double the costs for a pipeline. For gas-condensate lines, additional costs are approximately € 230 000/km.

A considerable saving is achieved by the elimination of a methanol recovery unit or glycol regenerator. Savings due to reduced methanol use may vary from 5% to 30% of the amount of produced water. With decreasing pressure, this percentage is lower until no injection is needed at a pipeline pressure of 25 bar.</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td>No emissions due to regeneration of methanol or glycol.</td></tr>
<tr><td>Energy</td><td>No energy consumption for regeneration of methanol or glycol.</td></tr>
<tr><td>Added chemicals</td><td>Insulation prevents the continuous injection and regeneration of methanol/glycol. No regeneration loss from methanol/glycol, no loss of methanol to gas and condensate phase or use of other chemicals.</td></tr>
<tr><td>Waste</td><td>None.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td>No risks due to transfer of large amounts of methanol.</td></tr>
<tr><td>Maintenance</td><td>No maintenance on methanol or glycol regeneration systems.</td></tr>
<tr><td rowspan="2">Practical experience</td><td>General</td><td>Offshore</td></tr>
<tr><td>Insulation and burying the pipeline is used frequently in the oil and gas industry.</td><td>Insulation is also applied offshore.</td></tr>
<tr><td>Conclusion</td><td>■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="2">[1]</td></tr>
</table>

Table A - 7 : Coalescing Pump (Coalescer / Separator)

Principle

The Dynamic Centrifugal Coalescer (DCC) uses the principles of centrifugation to enhance the separation of micron-sized phases from a carrier liquid. In particular, the DCC is used to increase the droplet size of oil in produced water. The difference in density between the fluids is the driving force in this process.

The core component of the DCC is a rotating element, as seen in figure 1. The element consists of many thousands of small channels, rotating at high velocity. In these channels, high G-forces drive micron-sized oil droplets to the channel wall, where they coalesce and form an oil film. This film builds up and, at the end of the channel, breaks up into large droplets. These large droplets, together with the rest of the fluids, are now available for separation downstream of the DCC. A novelty of the DCC is that the element is integrated in a multistage centrifugal pump housing, therefore combining fully proven pump technology with state of the art coalescing techniques.

A rotating bundle of mm-sized tubes (see below fig 1) inside the centrifugal pump housing enlarges tdroplets of between 2-20 micron to a size sufficiently large to be separated out with conventional techniques such as IGF, DAF, and Hydro Cyclones. See below for a typical droplet size distribution before and after the coalescer.

fig 1: bundle of teflon tubes (core)

The coalescing element is build inside the housing of a normal centrifugal pump, making the unit extremely easy to service also in remote locations with scarce technical expertise.

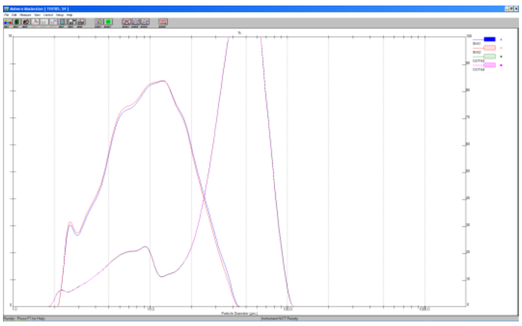


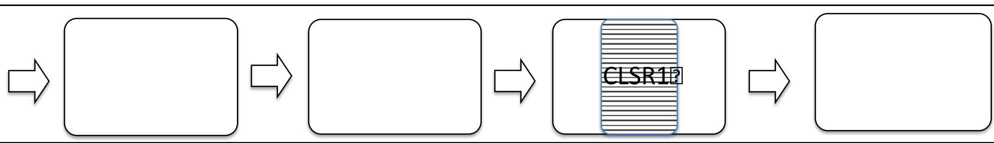
fig2: droplet size distribution at in and outlet of the coalescing pump

The rotating element, the heart of the DCC, consists of an array of axially oriented small tubes, potted in epoxy resin (see also figure 1). The element has a length and outer diameter of respectively 170 mm and 150 mm for the DCC-15, and 700 mm and 300 mm for the DCC- 30.

The tubes of the element are standard 1,4 mm in diameter and are made from stainless steel AISI 316. Optional, tubes are made from a special PTFE (Teflon). This proved to be extremely non-stick and is therefore an ideal option when the risk of plugging is present (high solids content).

In case of a chemically stabilized emulsion, an add-on is supplied to destabilize the emulsion prior to entering the coalescer (see the process diagram below)

Process diagram



Basic elements

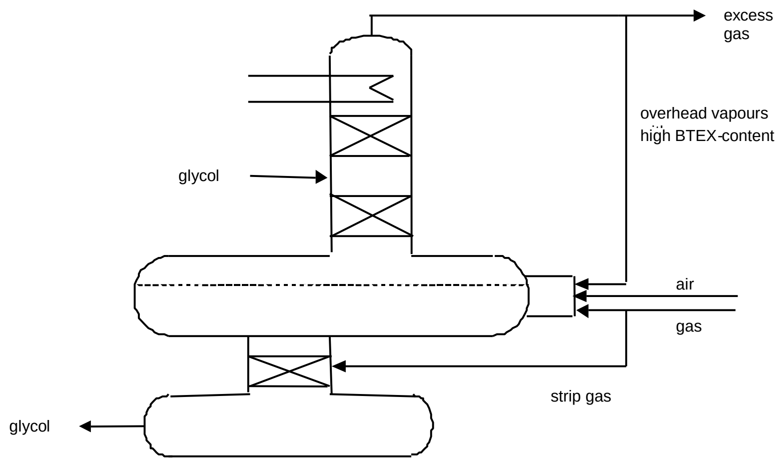
ELOX (IF REQUIRED) AND COALESCING PUMP

Suitable for the removal of:	✓ **Dispersed oil**		
	Remarks:		
Technical details	Per Unit Treatment capacity (m3 produced water per hour) Gross Package volume (LxWxH) Operating weight CAPEX (€) OPEX (€/year) Cost per m3 produced water(€/m3)	Minimum $2M^3$/hour 1,5 x 0,4 x 0,4 m 150 Kg 30.000 4.000 0,5	Maximum 150 M3/HOUR 2 ,5 x 0,8 x 0,8 m 1200 Kg 250.000 25.000 0,05
Critical operational parameters	electrical power		
Operational reliability, incl. information on downtime	There should be little or no downtime. Only to service the pump (seals and bearing) .If the system fails, water will still flow through it. Plugging is difficult since the unit uses Teflon internals		
	Remarks:		
Cross media effects	**Air**	None	
	Energy	Requires 0,05 kW/m3	
	Added chemicals	None	
	Waste	None	

Other impacts	**Health and safety**	None	
	Maintenance interval & availability (% per year)	95%+	
Practical experience	**General**		**Onshore / Offshore**
State of development	☐ Implemented offshore ☐ Used onshore ✓ Offshore field trials ✓ Testing		Practical applicability: PRODUCED WATER, POLYMER FLOODING, ASP
			Driving force for implementation : effluent quality of separation train reduces at increasing water cut
			Example plants:
Literature source	[1] J.J.H. BROUWERS. Phase separation in centrifugal fields with emphasis on the rotational particle separator. Experimental Thermal and Fluids Science 26 (2002) 325-334. [2] G.P. WILLEMS, M. GOLOMBOK et al. Condensed rotational separation of CO2 from natural gas. AIChE Journal (2010): Chemical Engineering Research and Development, 56(1), 150-159. [3] http://www.otcnet.org/2011/pages/general/awards.php		

	Suitable for		Removal Efficiency (Typical %)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	

Hydrocarbons - Dispersed oil - Dissolved oil **Specific oil components:** - BTEX - NPD - PAH’s 16 EPA - Others (indicate)	✓		50-90%		Removal efficiency of last separator increased with 50-90%
Heavy metals	☐	☐	☐	☐	
Offshore chemicals - methanol - glycol - corrosion inhibitors - biocides - scale inhibitors - surfactants - others (indicate)					

<table>
<tr><th colspan="7">Table B - 1: Overhead vapour combustion (OVC)</th></tr>
<tr><td>Principle</td><td colspan="6">Application of OVC eliminates the most important source of BTEX in produced water, i.e. condensate from the glycol regeneration unit. OVC does not condense the vapours from regeneration but these vapours are incinerated under controlled conditions in the burner of the glycol regenerator.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Special burner (suitable for wet gas) with ‘fire way’ and higher stack.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
■ Methanol
☐ Glycols
■ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]
> 99% *

**</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]
>99
>99
>99
>99</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
>99**</td></tr>
<tr><td colspan="6">Remarks:
Almost all hydrocarbons, including strip gas, are burned.
*: When used.
**: The hydrophobic part is removed.</td></tr>
<tr><td>Technical details</td><td colspan="2">Platform
Produced water volume (design)
Partial flow (design)
Required area (extra) (LxWxH)
Mass (extra)</td><td>Gas 1 (small)
1 m^3/h
0,05 m^3/h
negligible
negligible</td><td colspan="2">Gas 2 (large)
6 m^3/h
0,1 m^3/h
negligible
negligible</td><td>Oil 1
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">The design should take due account of possible methanol injection. Installation of a new ‘fire way’ / burner, a higher stack and temperature regulation with air are the most important features when OVC is installed on an existing platform. A shut down period of 1-2 weeks is required. This renders high costs unless the installation is shut down for other reasons as well.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">As reliable as regular regeneration systems. The functioning of OVC is not affected very much by gas quality fluctuations, but may be affected if gas contains glycol due to malfunctioning of regeneration.</td></tr>
</table>

Indication of costs

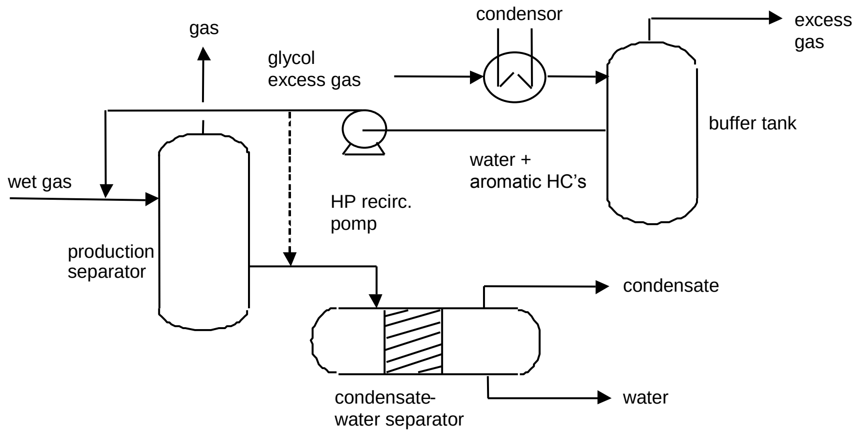
Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	308 000	20 000	87 300	3 300
gas platform, large	381 000	0	108 600	0
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
benzene	532	20	94	0	n.a.	n.a.
aliphatic hydrocarbons						
zinc equivalents						

Remarks:
For smaller new installations (< 3 MM m^3/day) the CAPEX is approximately equal. For larger installations, the costs are lower since less equipment is needed (no condensor, gas scrubber, pump, instrumentation). Retrofitting on an existing installation amounts approximately to € 200 000 (materials).

Cross media effects	**Air**	Substantive reduction of air emissions. Other gases may also be used when OVC is installed (flash gas etc.) instead of them being vented. When a relative large amount of strip gas is needed, use of other gases is limited. NO_x emissions are less than 150 mg/m^3.
	Energy	Lower energy consumption in view of use of other gases.
	Added chemicals	None.
	Waste	None.
Other impacts	**Safety**	None.
	Health	No air emission of hydrocarbons.

Practical experience	**General**	**Offshore**
	More than 15 years of experience with OVC onshore industrial wastewater treatment.	OVC is applied offshore in new installations since 2000.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

Table B - 2: Fluid from condensor to production separator	
Principle	Condensation of overhead vapours from the glycol regenerator produces a watery stream with a high concentration of dissolved oil. This relatively small stream is brought into contact, under high pressure, with a large amount of production water, gas and condensate in the production separator. The condensate and gas will extract a large part of aromatic hydrocarbons (dissolved oil), thus reducing discharge of aromatic hydrocarbons (dissolved oil). The glycol regeneration water is most effectively injected before the slug catcher or gas cooler, but may also be pumped to the water-condensate separator.
Process diagram	
Basic elements	Line elements, buffer tank, recycle pump

Suitable for the removal of: R = removal efficiency	Heavy metals	R [%]	Production chemicals	R [%]	Oil	R [%]
	☐ Cadmium		■ Methanol	*	■ **Dissolved oil**	>50
	☐ Zinc		☐ Glycols		■ BTEX	>50
	☐ Lead		☐ Corrosion inhibitors		■ Benzene	>50
	☐ Mercury		☐ Anti-scale solutions		■ PAHs	>50
	☐ Nickel		☐ Demulsifiers		**Dispersed oil**	**R [%]**
					■ Oil	*

Remarks:
The removal efficiency is related to the partial flow and dependent on the composition of gas and condensate and the quality of treatment systems.

*: Partially removed if present.

Technical details	Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	n.a.
	Partial flow (design)	0,05 m^3/h	0,1 m^3/h	
	Required area (LxWxH)	0,8 x 0,5 x 1 m	1 x 0,6 x 1,5 m	
	Mass (filled)	0,3 tonnes	0,5 tonnes	

Critical operational parameters	The advantages of this technique depend on the composition of gas and condensate, the separator pressure and temperature and may best be evaluated by using a process simulation.
Operational reliability	High.

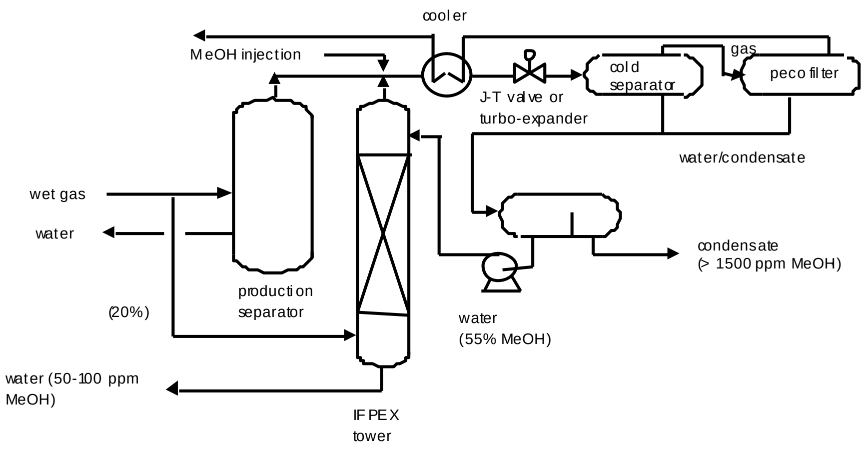
Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	138 423	102 433	42 773	22 840
gas platform, large	159 187	117 660	49 694	26 854
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	520	278	86	47	n.a.	n.a.
dispersed oil	-	-	-	-		
zinc equivalents	-	-	-	-		

Cross media effects	**Air**	Little influence.
	Energy	For HP re-circulation
	Added chemicals	None.
	Waste	None.
Other impacts	**Safety**	None.
	Maintenance	Only pump maintenance.

	General	**Offshore**
Practical experience		Is already applied offshore
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

<table>
<tr><td colspan="7">Table B - 3: Alternative methods of gas drying</td></tr>
<tr><td>Principle</td><td colspan="6">Usually, gas washers are used for gas drying. The gas is washed in counter-flow with glycol (TEG or DEG). The solubility of aromatic hydrocarbons in glycol is high, causing high concentrations of aromatic hydrocarbons in water in the process regeneration of glycol. Alternative ‘washing fluids’ which render aromatic hydrocarbons less soluble, reduce the amount of aromatic hydrocarbons being removed. Alternative ‘washing fluids’ are MEG or methanol via the IFPEX process. These alternative ‘washing fluids’ will also remove less water, rendering this technique suitable especially in the case of the less stringent requirements with regard to dew point.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">IFPEX towers (strip towers), J-T valve (or turbo expander), cold separator, filter, water-condensate separator, pump</td></tr>
<tr><td rowspan="2">Suitable for the removal of:

R = removal efficiency</td><td>Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td>R [%]</td><td>Production chemicals
☐ Methanol
■ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td>R [%]

100</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs
Dispersed oil
☐ Oil</td><td>R [%]
35-85
35-85
35-85
?
R [%]</td></tr>
<tr><td colspan="6">Remarks:
Removal efficiencies of the IFPEX process, using methanol as ‘washing fluid’.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Partial flow (design)
Required area (LxWxH)
Mass (filled)</td><td>Gas 1 (small)
1 m^3/h
0,05 m^3/h</td><td>Gas 2 (large)
6 m^3/h
0,1 m^3/h</td><td>Oil 1
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Only applicable when gas drying is not very critical. Relatively high use of methanol in view of absorption in gas and condensate, part of the methanol is lost in the water phase. Sufficient gas pressure is required in order to allow cooling with J-T valve (or more cooling capacity is needed). The cooling process preferably takes place below – 20 °C, in order to limit methanol losses. Energy may be needed for recompression.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">Relatively easy operation. The IFPEX tower may also be installed on satellite platforms. No heat needed for regeneration. No foam forming or breaking up due to (over-) heating.</td></tr>
</table>

<table>
<tr><td>Indication of costs</td><td colspan="3">In view of the fact that replacement of existing systems is concerned, no detailed cost analysis was performed. Rather a comparison of investment and operational costs with existing systems took place.</td></tr>
<tr><td></td><td colspan="3">Table 1: Comparison of investments common systems vs. IFPEX
Saving investments IFPEX compared to common systems

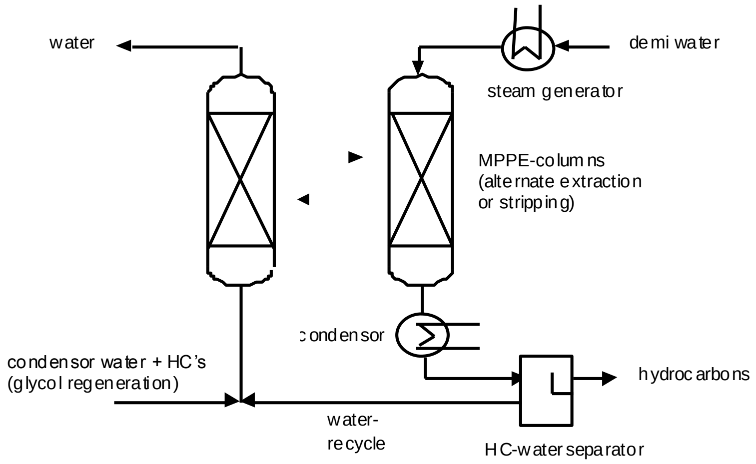
TEG-system 25-30%
MEG-system 10%

Table 2: Comparison of operational costs common systems vs. IFPEX
Saving investments IFPEX compared to common systems

TEG-system 25-30%
Glycol injection system 20%</td></tr>
<tr><td></td><td colspan="3">Remarks:
The major advantage of an IFPEX-1 system over more commonly applied systems is that no glycol regenerator is needed. Thus CAPEX and energy consumption are much lower. Moreover, process control is better. An IFPEX-system uses more methanol compared with traditional TEG gas drying systems. There are almost no air emissions. An IFPEX unit, however, does use large amounts of methanol.

The IFPEX-1 system can easily be combined with the IFPEX-2 process for the removal of acidic gases (CO_2 and H_2S).

Other alternative gas drying systems are:
- Twister supersonic separator (see table C-13); and
- DRIZO process; regeneration of DEG at lower temperature (160 °C) using solvent.</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="2">No emissions of BTEX and VOS (incl. strip gas)</td></tr>
<tr><td>Energy</td><td colspan="2">IFPEX requires 80-90% less energy than a glycol system, provided that pressure is sufficient to allow cooling.</td></tr>
<tr><td>Added chemicals</td><td colspan="2">Methanol consumption approximately 275 l/day (small gas platform) and 1 900 l/day (large gas platform).</td></tr>
<tr><td>Waste</td><td colspan="2">Methanol (50-100 mg/l) in (small amount of) water from the IFPEX tower. No glycol consumption.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="2">No glycol chain in area with potential danger of explosion.</td></tr>
<tr><td>Maintenance</td><td colspan="2">Far less maintenance.</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="2">General</td><td>Offshore</td></tr>
<tr><td colspan="2">Limited experience with alternative gas drying systems. Worldwide approximately 10 systems.</td><td>No difference with onshore application, except that J-T valve or expander is not economically feasible, since gas needs high pressure for transportation in the pipeline.</td></tr>
<tr><td>Conclusion</td><td colspan="2">■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="3">[1]</td></tr>
</table>

<table>
<tr><th colspan="9">Table B - 4: Macro porous polymer extraction (MPPE) (partial flow)</th></tr>
<tr><td>Principle</td><td colspan="8">On gas platforms, hydrocarbons can be removed from condensed water from the glycol regeneration process using Macro Porous Polymer Extraction (MPPE). Water from the glycol regeneration is directed through a column packed with a bed of MPPE material. An extraction fluid, immobilized in the MPP matrix, extracts hydrocarbons from the water phase. Treated water can be discharged immediately. Prior to reaching the (maximum) required effluent concentration, the feeds are lead through a second column; the first column is regenerated with low-pressure steam. Once the second column is saturated, the feeds are switched back to the first column. After a second cycle, the feeds are redirected to the first column again. A characteristic cycle lasts 1 to 2 hours. Steam and hydrocarbon vapours are condensed, and may easily be separated because of the high concentration of hydrocarbons. Hydrocarbons are lead to the condensate treatment system, the small amount of water is redirected into the installation and treated.</td></tr>
<tr><td>Process diagram</td><td colspan="8">
</td></tr>
<tr><td>Basic elements</td><td colspan="8">2 columns filled with MPPE material, condenser, settling tank, steam generator (electric).</td></tr>
<tr><td rowspan="2">Suitable for the removal of:

R = removal efficiency</td><td colspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
■ Mercury
☐ Nickel</td><td>R [%]

?</td><td colspan="2">Production chemicals
■ Methanol
☐ Glycols
■ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td>R [%]
>99 *

**</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs
Dispersed oil
■ Oil</td><td>R [%]
>99
>99
>99
>99
R [%]
>99 **</td></tr>
<tr><td colspan="8">Remarks:
The removal efficiency of benzene and other dissolved hydrocarbons, including TEX, is very high: reductions of 2 000-3 000 mg/l to < 1 mg/l are possible. The occurrence of the removal of mercury during a test operation could not sufficiently be established.
*: if present
**: the hydrophobic part is removed.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Partial flow (design)
Required area (LxWxH), including steam generator
Mass (filled)</td><td colspan="2">Gas 1 (small)
1 m^3/h
0,05 m^3/h
1 x 1,5 x 1,7 m

1,5 tonnes</td><td colspan="2">Gas 2 (large)
6 m^3/h
0,1 m^3/h
1 x 1,7 x 2 m

2 tonnes</td><td>Oil 1
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="8">The MPPE material should be replaced in order to avoid loss of effectiveness. The feed water for the steam generator should be demineralised.</td></tr>
<tr><td>Operational reliability</td><td colspan="8">The process is not affected very much by fluctuations in flow or BTEX-concentrations and can be fully automated (remote control).</td></tr>
</table>

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	324 000	276 000	99 800	59 200
gas platform, large	368 000	313 000	117 300	71 200
oil platform	n.a.	n.a.	n.a.	n.a.

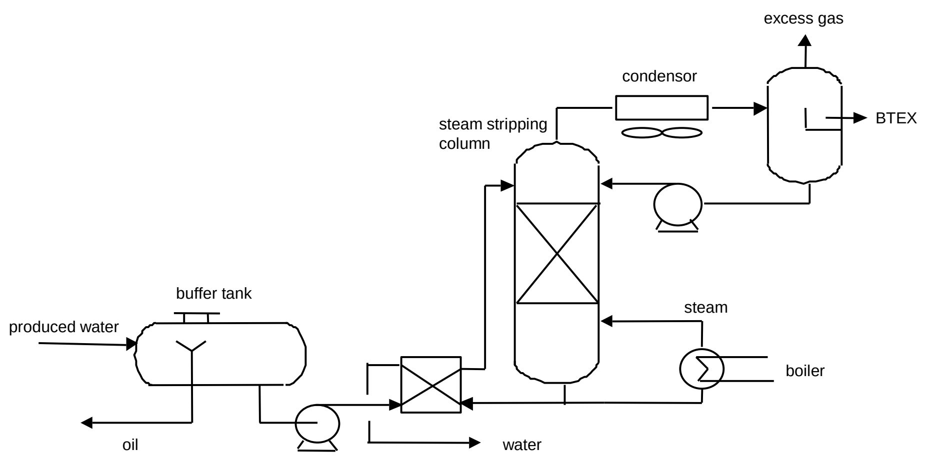
Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
Benzene	608	361	102	62	n.a.	n.a.
BTEX	486	289	82	50		

Remarks:
Including costs for replacement of MPPE extraction fluid.

Cross media effects	**Air**	Required energy will lead to increased air emissions.
	Energy	Electricity for steam generation (6-2,5 kg LP steam per m^3 water) and for pumps (total for 0,008 / 0,005 m^3/h resp. 4,4 / 13,2 MWh/year).
	Added chemicals	Extraction fluid is consumed very slowly, and is transported with the BTEX via the separator. Possibly chemicals for demineralisation of feed water for LP steam production.
	Waste	The MPPE bed should be replaced approximately every 2 years.
Other impacts	**Safety**	None.
	Maintenance	Relatively little.

	General	**Offshore**
Practical experience	Operational experience with MPPE-process in industrial waste water treatment. Successful treatment (partial flow and end flow) of produced water at TFE in Harlingen, the Netherlands.	Successful tests on partial flows.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1] [6]	

Table B - 5: Steam stripping (partial flow)

Principle	Hydrocarbons can be removed from condensed water from glycol regeneration on gas platforms by means of steam stripping. The water is fed into a packed column and brought into intense contact with steam (known as stripping). This technique is suitable for the removal of dissolved oil (BTEX), but will also remove aliphatic hydrocarbons. Steam and hydrocarbon vapours are condensed and separated easily because of the high hydrocarbon content. Hydrocarbons that have been separated by steam can be directed to the condensate treatment system; water can be discharged.
Process diagram	
Basic elements	Buffer tank, feeding pump, heat exchanger, stripping column, condensor, BTEX-accumulator, re-circulation pump, condensate pump, (electric) re-boiler.

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
□ Cadmium		■ Methanol	10-90*	■ **Dissolved oil**	>99
□ Zinc		□ Glycols		■ BTEX	>99
□ Lead		■ Corrosion inhibitors	**	■ Benzene	>99
□ Mercury		□ Anti-scale solutions		■ PAHs	>99
□ Nickel		□ Demulsifiers		**Dispersed oil**	**R [%]**
				■ Oil	>97*

Remarks:

The removal efficiency for BTEX is very high: reductions from 500-4 000 mg/l to < 1 mg/l, aliphatic hydrocarbons from 40 mg/l to < 1,5 mg/l.

*: When present.

**: The hydrophobic part is partly removed.

Technical details

Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
Produced water volume (design)	1 m^3/h	6 m^3/h	n.a.
Partial flow (design)	0,05 m^3/h	0,1 m^3/h	
Required area (LxWxH) (incl. steam generator)	3 x 2 x 3 m	4 x 3 x 4 m	
Mass (filled)	8 tonnes	15 tonnes	

Critical operational parameters	In order to guarantee a constant flow, a buffer tank needs to be installed. This buffer tank also allows for skimming oil, avoiding disturbance of the process in the column. When the flow is very low, it may be necessary to add water in order to maintain the temperature at the top of the column. The steam line must be large enough in order to allow for equal levels in boiler and column (and above the bundle of the boiler).
Operational reliability	The technique is reliable and is considered a proven technique for the treatment of glycol regeneration water.

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	170 000	135 000	57 900	35 100
gas platform, large	265 000	210 000	90 700	55 000
oil platform	n.a.	n.a.	n.a.	n.a.

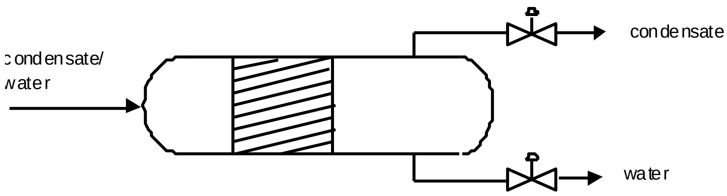
Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
benzene	354	214	79	48	n.a.	n.a.
BTEX	283	171	63	38		

Remarks:
Energy consumption is relatively high, despite the fact that part of the heat is recovered. Energy consumption can be reduced considerably when heat of the exhaust gases from turbines is used.

Cross media effects	**Air**	Required energy will increase air emissions. After the condensor little gases remain.
	Energy	Approximately 40 kWh/m^3 regeneration water (mainly for boiler).
	Added chemicals	None.
	Waste	None.
Other impacts	**Safety**	No significant influence.
	Maintenance	Relatively little.

Practical experience	**General**	**Offshore**
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

Table B - 6: High pressure water condensate separator

Principle	On gas platforms the dispersed and dissolved oil content in produced water can be reduced by a high pressure (HP) water condensate separator, which operates at approximately the same pressure as the primary production separator. With this, exposure of the water-condensate mixture to a high pressure drop, resulting in the formation of emulsions, is prevented. The formation of small condensate droplets in water (emulsion) in the level regulating valve is prevented by separating the mixture and by releasing pressure in separate valves. With this, acceptable oil concentrations are achievable using relatively simple add-on treatment equipment. The technique may also be used for condensate-water mixtures from the gas filter / separator and high pressure scrubbers.
Process diagram	
Basic elements	High pressure water-condensate separator

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
☐ Cadmium		☐ Methanol		■ **Dissolved oil**	>30
☐ Zinc		☐ Glycols		■ BTEX	>30
☐ Lead		☐ Corrosion inhibitors		■ Benzene	>30
☐ Mercury		☐ Anti-scale solutions		■ PAHs	>30
☐ Nickel		■ Demulsifiers	50-100	**Dispersed oil**	**R [%]**
				■ Oil	>20

Remarks:

Technical details	Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	n.a.
	Required area (extra) (LxWxH)	negligible	negligible	
	Mass (extra) (filled)	1,5 tonnes	4 tonnes	

Critical operational parameters	The technique is process integrated and should be evaluated during the development phase and is therefore mainly applicable on new offshore installations. The use of corrosion inhibitors should be minimised, since these cause emulsion formation. When using piston compressors, the lubricant-condensate mixture, which is recovered in scrubbers, may also form stable emulsions. The use of HP separation of these flows may be very effective.
Operational reliability	High

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	n.a.	36 000	n.a.	2 800
gas platform, large	n.a.	86 000	n.a.	3 400
oil platform	n.a.	n.a.	n.a.	n.a.

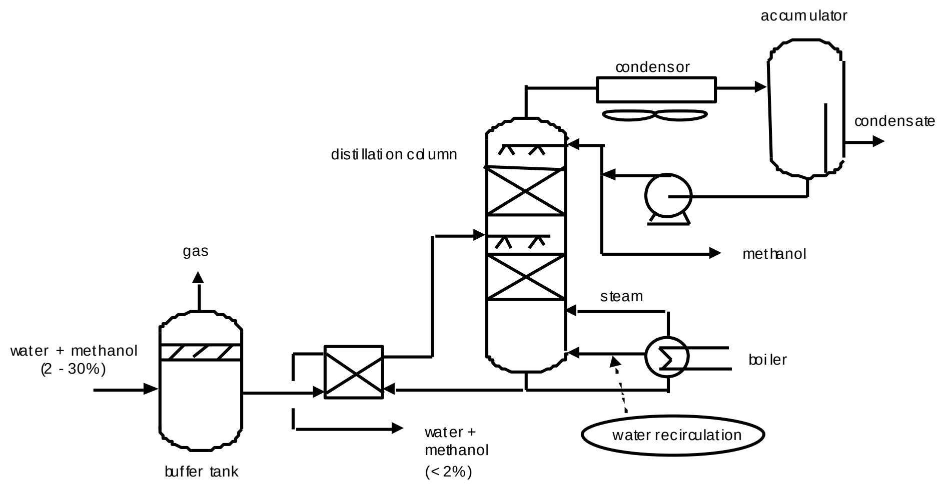
Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	n.a.	93	n.a.	5	n.a.	n.a.
dispersed oil		76		4		
zinc equivalents		226		39		

Remarks:

In the above costs, only elevated costs in comparison with an LP installation was calculated. In view of the fact that condensate pumps are not necessary in the first phase of production (when condensate production is highest), smaller pumps can usually be installed, resulting in lower investments. Costs for existing offshore installations are not relevant, since the installation would have to be shut down too long in order to allow for replacement of the water-condensate separator, and since costs for investments are relatively high.

Cross media effects	**Air**	Fewer emissions because of lower energy consumption.
	Energy	Saves energy in condensate injection pumps as long as pressure in the production separator is higher than in the pipeline.
	Added chemicals	Less demulsifier.
	Waste	None.
Other impacts	**Safety**	None.
	Maintenance	None.

	General	**Offshore**
Practical experience		Is applied frequently offshore.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

<table>
<tr><th colspan="2">Table B - 7: Methanol recovery unit</th></tr>
<tr><td>Principle</td><td>Methanol is injected on gas platforms in order to prevent hydrates. It may be recovered from produced water by means of a methanol recovery unit. The methanol-water mixture is heated up to 99 °C, then the methanol is vaporised in a distillation column. The temperature in the top of the column is maintained at approximately 75 °C by the methanol reflux. This is to prevent too much evaporation of water. After condensation, the methanol is fed back to the methanol storage tank. The methanol content of produced water, which usually does not exceed 30%, is reduced to less than 2%.</td></tr>
<tr><td>Process diagram</td><td>
</td></tr>
<tr><td>Basic elements</td><td>Buffer cask, heat exchanger, methanol boiler, distillation column, condensor, accumulator, transport pumps, scale inhibitor injection.</td></tr>
<tr><td>Suitable for the removal of:

R = removal efficiency</td><td><table>
<tr><td>Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td>R [%]</td><td>Production chemicals
■ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td>R [%]
20-90*</td><td>Oil
☐ Dissolved oil
☐ BTEX
☐ Benzene
☐ PAHs

Dispersed oil
☐ Oil</td><td>R [%]

R [%]</td></tr>
<tr><td colspan="6">Remarks:
Removal efficiency dependent on (fluctuations in) water throughput and methanol content.</td></tr>
</table></td></tr>
<tr><td>Technical details</td><td><table>
<tr><td>Platform</td><td>Gas 1 (small)</td><td>Gas 2 (large)</td><td>Oil 1</td></tr>
<tr><td>Produced water volume (design)</td><td>1 m^3/h</td><td>6 m^3/h</td><td>n.a.</td></tr>
<tr><td>Required area (LxWxH)</td><td>5 x 4 x 3 m</td><td>6 x 5 x 4 m</td><td rowspan="2">(MeOH injection is rarely applied in oil production.)</td></tr>
<tr><td>Mass (filled)</td><td>8 tonnes</td><td>17 tonnes</td></tr>
</table></td></tr>
<tr><td>Critical operational parameters</td><td>The distillation process is very much affected by to fluctuations in throughput, which affects the quality of methanol reduction. If produced water contains salts, these may be deposited in the heat exchanger and especially in the methanol boiler. In order to prevent concentration of salts in the boiler, it is recommended to establish a small throughput from the boiler to the column by means of a re-circulation line. Relatively high energy consumption unless combined with heat recovery.</td></tr>
<tr><td>Operational reliability</td><td>Since methanol is often injected on satellite platforms, the water production is usually irregular, which results in lower removal efficiency and low methanol quality. Salt in produced water leads to deposits in the methanol boiler, which leads to frequent shut downs for maintenance.</td></tr>
</table>

Indication of costs

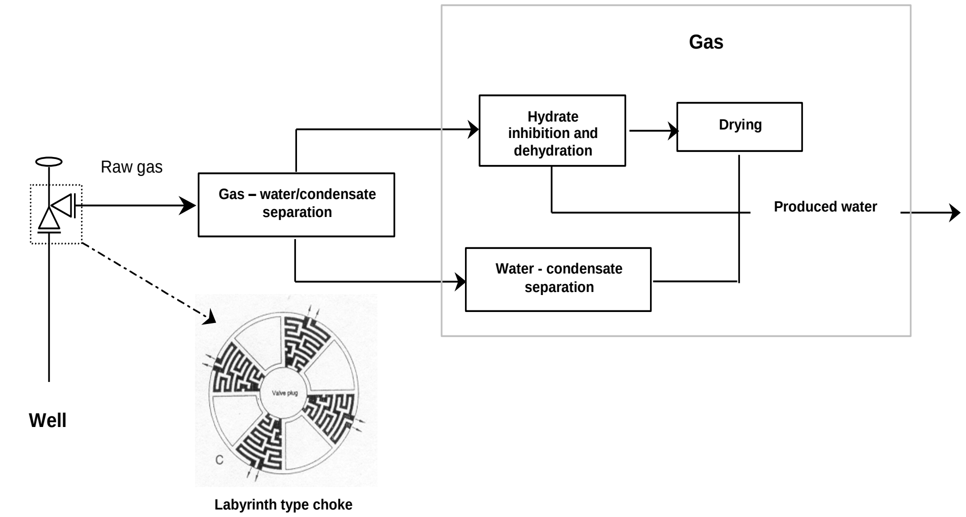
Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	New
gas platform, small	905 000	752 000	291 500	171 600
gas platform, large	1 755 000	1 546 000	602 000	365 900
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
methanol	22	4,3	6,5	1,2	n.a.	n.a.

Remarks:
Methanol savings are dependent on methanol content in water and are based on a maximum content of 10-30%, average 4-10% over 1 year or average 6% over 10 years.

Cross media effects	**Air**	Energy, required for heating of produced water, for pumps and cooling, will increase air emissions, especially when diesel fuel is used.
	Energy	Energy for heating, pumps and cooling.
	Added chemicals	Scale inhibitors (to prevent salt deposition) and corrosion inhibitor (dependent on corrosivity of water and materials used).
	Waste	In the buffer cask sludge will deposit. In the heat exchanger scale will probably deposit, which will need to be removed using acids.
Other impacts	**Safety**	No significant influence.
	Maintenance	Maintenance on boiler and heat exchangers may be considerable, in the case of formation of NORM complicated procedures and higher costs arise.

	General	**Offshore**
Practical experience	Recovery of methanol is applied in a number of onshore and offshore gas production operations. Many problems in the operation of systems were encountered.	Offshore, the situation is not much different from onshore operation, except that the fluctuations in the water throughput are usually less. When needed, it is easier to install larger buffer casks.
Conclusion	☐ BAT	■ Emerging Candidate for BAT
Literature source	[1]	

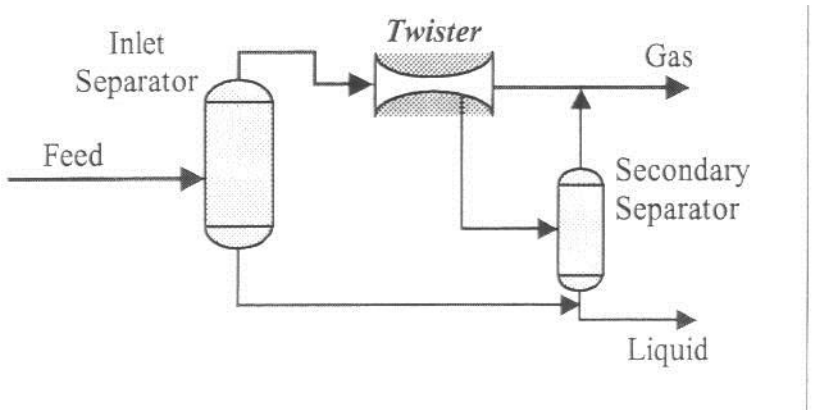
<table>
<tr><th colspan="7">Table B - 8: Labyrinth type choke valve</th></tr>
<tr><td>Principle</td><td colspan="6">With labyrinth type choke valves, gas is depressurised through friction instead of smothering as in conventional chokes. The gas speed in the choke is lower (subsonic instead of sonic). It is expected that hydrocarbon particles would then be less likely to be broken up. This advances the previous oil-water separation. This type of valve was originally developed to restrict the sound produced by chokes.
On oil producing installations, labyrinth type choke valves may be used as means to minimising shear and maximising oil droplet size, rendering subsequent separation steps more efficient.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Choke valve of the labyrinth</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]</td></tr>
<tr><td colspan="6">Remarks:
This technique added to the oil-water separation process leads to improved separation. Depending on the subsequent technique, there may be a yield improvement. There is no influence on the removal of dissolved components. There is no information available regarding an improvement in yield.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Required area (LxWxH)
Mass (extra)</td><td>Gas 1 (small)
1 m^3/h
negligible
negligible</td><td>Gas 2 (large)
6 m^3/h
negligible
negligible</td><td>Oil 1
175 m^3/h
negligible
negligible</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Control of the gas speed through the valve.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">Uncomplicated to apply. No working parts. Choke is a standard part of platform installation.</td></tr>
</table>

<table>
<tr><td rowspan="12">Indication of costs</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Costs</td><td colspan="2">Investment costs (CAPEX)
[€]</td><td colspan="3">Exploitation costs (OPEX)
[€ / year]</td></tr>
<tr><td>present</td><td>new</td><td>present</td><td colspan="2">new</td></tr>
<tr><td>gas platform, small
gas platform, large
oil platform</td><td colspan="5">No sufficient data available for an economic analysis</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas platform, small</td><td colspan="2">Gas platform, large</td><td>Oil platform</td></tr>
<tr><td></td><td>Existing [€/kg]</td><td>New [€/kg]</td><td>Existing [€/kg]</td><td>New [€/kg]</td><td>Existing [€/kg] / New [€/kg]</td></tr>
<tr><td>dissolved oil
dispersed oil
zinc equivalents</td><td colspan="5">No data available on model situation</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
</table>

<table>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td>None.</td></tr>
<tr><td>Energy</td><td>None.</td></tr>
<tr><td>Added chemicals</td><td>None.</td></tr>
<tr><td>Waste</td><td>None.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td>None.</td></tr>
<tr><td>Maintenance</td><td></td></tr>
<tr><td rowspan="2">Practical experience</td><td>General</td><td>Offshore</td></tr>
<tr><td></td><td>Field tests in 1997.</td></tr>
<tr><td>Conclusion</td><td>☐ BAT</td><td>■ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="2"></td></tr>
</table>

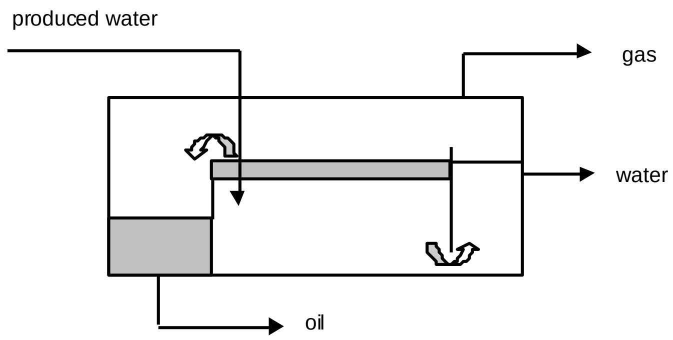
Table B - 9: Twister supersonic separator

Principle	Twister technology is a static piece of equipment with characteristics similar to those of a Turbo-Expansion /Compression system. Gas is expanded adiabatically in a Laval nozzle, creating supersonic velocities and low temperatures (for example a temperature at inlet of 20 °C drops mid-Twister to –50 °C). The low temperature creates a fog-like condensation, which is typically a mixture of water and heavier hydrocarbons. Chemical hydrate suppression is not required due to the very short residence time as well as the supersonic velocities within the tube. Still at supersonic velocities, the mixture of gas and liquid droplets enters the win section, generating a high velocity swirl. The resulting swirl forces the condensation outward to form a liquid film on the inner wall of the tube. The liquid film is then removed using either a co-axial tube or slits in the wall of the separation tube. The dry gas core remains as the primary stream. After inducing a weak shock wave, 70-80% of the initial gas pressure is recovered using a diffuser. Current natural gas applications are dehydration and hydrocarbon dew pointing, with bulk H2S and CO2 removal under investigation. The technology is currently suitable for offshore and onshore applications with sub-sea under investigation.
Process diagram	
Basic elements	Inlet separator, Twister tube, secondary separator, heat integration of applicable

Suitable for the removal of: R = removal efficiency	**Heavy metals**	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
	☐ Cadmium ☐ Zinc ☐ Lead ☐ Mercury ☐ Nickel		■ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers		■ **Dissolved oil** ■ BTEX ■ Benzene ■ PAHs	
					Dispersed oil	**R [%]**
					■ Oil	
	Remarks: Twister currently (mid 2000) achieves a zero degree dew point, with lower dew points expected as the technology develops further. Dew points of – 18 degrees are expected by mid 2003. The quoted dew points depend on the specific process conditions and may differ per application.					

Technical details	Capacity: LxBxH (m) Typical skid: Weight (tons) Typical skid: Saves space.	1 to 5 mln m3/day, 100 bar per tube, Multi tube arrangements are possible. 10x3x3 40 tons
Critical operational parameters	Vapour composition under mid-Twister conditions must be well within product stream specifications.	
Operational reliability		

<table>
<tr><td rowspan="9">Indication of costs</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Costs</td><td colspan="3">Investment costs (CAPEX)
[€]</td><td colspan="3">Exploitation costs (OPEX)
[€ / year]</td></tr>
<tr><td>present</td><td colspan="2">new</td><td>present</td><td colspan="2">new</td></tr>
<tr><td>gas platform, small
gas platform, large
oil platform</td><td colspan="6">No data on model situation available</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas platform, small</td><td colspan="2">Gas platform, large</td><td colspan="2">Oil platform</td></tr>
<tr><td></td><td>Existing
[€/kg]</td><td>New
[€/kg]</td><td>Existing
[€/kg]</td><td>New
[€/kg]</td><td>Existing
[€/kg]</td><td>New
[€/kg]</td></tr>
<tr><td>dissolved oil
dispersed oil
zinc equivalents</td><td colspan="6">No data on model situation available</td></tr>
<tr><td colspan="7">Remarks:</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="6">No emissions to atmosphere.</td></tr>
<tr><td>Energy</td><td colspan="6">Fixed pressure ratio device, increasing need for wellhead compression.</td></tr>
<tr><td>Added chemicals</td><td colspan="6">No additional chemicals are needed.</td></tr>
<tr><td>Waste</td><td colspan="6">None.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="6">None.</td></tr>
<tr><td>Maintenance</td><td colspan="6">None.</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="3">General</td><td colspan="4">Offshore</td></tr>
<tr><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Conclusion</td><td colspan="3">☐ BAT</td><td colspan="4">■ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="7">[4]</td></tr>
</table>

Table C - 1: Skimmer tank	
Principle	In order to reduce the content of dispersed oil in produced water, a skimmer tank can be used. Separation is based on the difference between the specific gravity of oil and water and the coalescence of oil droplets. When the retention time is sufficient, oil floats to the surface and can be separated by an overflow. This technique is suitable only for non-dissolved components such as dispersed oil with a sufficiently large particle size. Dissolved materials such as benzene and heavy metals cannot be separated using this technique. The skimmer tank or its modified version, parallel plate interceptor (PPI) or corrugated plate interceptor (CPI), is mostly used as part of a set of a number of techniques for the removal of dispersed oil.
Process diagram	
Basic elements	LP-tank with internal plates for oil-water separation and possibly a pump

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
☐ Cadmium ☐ Zinc ☐ Lead ☐ Mercury ☐ Nickel		☐ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers		☐ **Dissolved oil** ☐ BTEX ☐ Benzene ☐ PAHs	
				Dispersed oil	**R [%]**
				■ Oil	20-90

Remarks:

Removal efficiency for oil is 100% for droplets > 150 µm, dependent on specific gravity and temperature. In practice in the offshore industry, removal seems possible up to oil contents of 200 mg/l. Additional techniques are required to achieve the performance standard for dispersed oil.

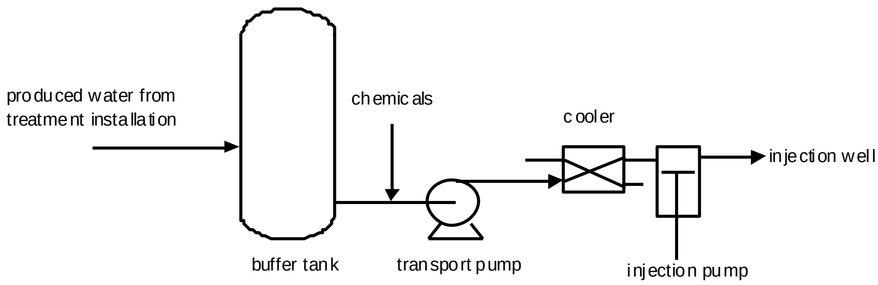
Technical details

Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
Required area (LxWxH)	1,2 x 2,5 x 2 m	2,4 x 2,5 x 2 m	n.a.
Mass (filled)	2 tonnes	6 tonnes	

Critical operational parameters	The orientation of the oil-water interface (level control in the tank) is determined by the difference in specific gravity. When an intermediate layer is formed, because of emulsion formation or e.g. ferrous oxides, this interface is not easy to control. The relationship between settling time and acceptable dimensions of equipment offshore limits the separation efficiency to 200 mg/l. A skimmer tank is hardly feasible for oil producing platforms, since a skimmer tank is too large in comparison with a PPI.
Operational reliability	High, requires regular cleaning. Capable of handling relatively large oil content fluctuations of the influent, with limited effect on the effluent oil content.

<table>
<tr><td>Indication of costs</td><td colspan="3">Remarks:
Costs should be evaluated in comparison with the much more efficient PPI or CPI. For an installation with comparable dimensions, the costs of a skimmer tank would approximately be half.</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="2">None.</td></tr>
<tr><td>Energy</td><td colspan="2">None.</td></tr>
<tr><td>Added chemicals</td><td colspan="2">None.</td></tr>
<tr><td>Waste</td><td colspan="2">Because of a low flow velocity, relatively large amounts of sludge may deposit, mainly sand and clay, which may be slightly radioactive (NORM).</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="2">Risk of exposure to benzene on gas producing installations during cleaning operations.</td></tr>
<tr><td>Maintenance</td><td colspan="2">Tank requires regular cleaning.</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="2">General</td><td>Offshore</td></tr>
<tr><td colspan="2">Well known and accepted principle for separation. Much operational experience in the process industry.</td><td>Technique is mainly applied on gas producing installations.</td></tr>
<tr><td>Conclusion</td><td colspan="2">■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="3">[1]</td></tr>
</table>

Table C - 2: Produced water re-injection (PWRI)

Principle	Produced water may be re-injected in the underground through a well. The water is usually filtered, and chemicals are added in order to prevent the formation of bacteria and corrosion. Preferably, the water treatment system will be oxygen-free. When cold fracturing is applied using cooled water, the capacity of the injection pumps will be considerably less. Sometimes, produced water can be injected directly into a producing reservoir, in order to maintain pressure or in order to achieve water flooding.
Process diagram	
Basic elements	Water treatment (oxygen-free), transport and/or injection pumps. Possibly: buffer tank, injection of chemicals and coolers.

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
■ Cadmium	100	■ Methanol	100	■ **Dissolved oil**	100
■ Zinc	100	■ Glycols	100	■ BTEX	100
■ Lead	100	■ Corrosion inhibitors	100	■ Benzene	100
■ Mercury	100	■ Anti-scale solutions	100	■ PAHs	100
■ Nickel	100	■ Demulsifiers	100	**Dispersed oil**	**R [%]**
				■ Oil	100

Remarks:
A 100% removal efficiency, although a small part of components will remain in filters and coolers.

Technical details

Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
Required area (extra) (LxWxH)	4 x 4 x 2 m	6 x 4 x 3 m	8 x 6 x 3 m
Mass (extra)	5 – 10 tonnes	15 – 25 tonnes	30-80 tonnes

Critical operational parameters	Presence of a suitable layer for produced water re-injection and possibly suitability for cold fracturing. The quality of output of (existing) water treatment systems, e.g. content of oxygen and particles. Possibly deposition of scales and paraffins in filters and coolers. Availability of an existing well, suitable for modification for injection (leads to considerable cost reduction).
Operational reliability	PWRI is reasonably reliable, although production and injection quantities cannot be estimated with a very high degree of certainty. The result of cold fracturing is even harder to predict. Filters require regular cleaning, the efficiency is hard to predict as is the oxygen content. Corrosion of tubing or production lines in wells is often problematic, as is deposition of salts and paraffins in tubing and lines.

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	11 530 000	11 380 000	3 079 000	1 888 500
gas platform, large	12 975 000	12 620 000	3 497 100	2 128 100
oil platform	6 715 000	6 100 000	2 258 600	1 478 000

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	39 054	23 954	2 592	1 578	1 146	751
dispersed oil	58 582	35 930	9 505	5 784	69	45
zinc equivalents	1 121 750	688 015	128 469	78 180	32 378	21 216

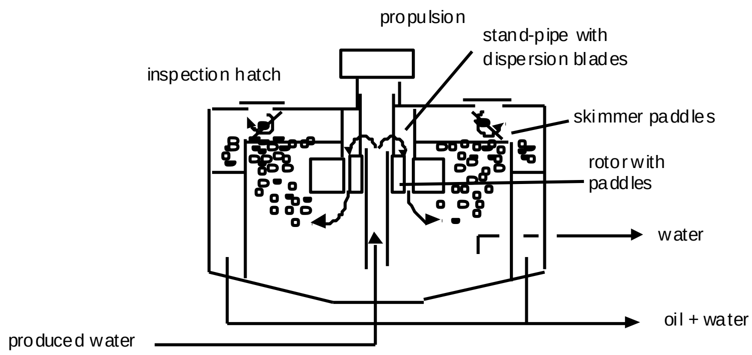
Remarks:

Depreciation in the OPEX is based on the assumption that a new well needs to be drilled, in an oil field from € 4,5 MM, in a gas field from € 11,8 MM. When an existing well is available for modification for PWRI, these costs may be reduced to € 0,9 MM – 1,8 MM and in the case of dual completion to € 1,4 MM – 2,3 MM. Costs for reservation of space and weight were not included. Costs for energy consumption for oil producing installations may be reduced considerably when cold fracturing is applied.

Cross media effects	**Air**	Energy for injection pumps etc. will increase air emissions, especially when diesel fuel is used.
	Energy	Energy for transport and injection pumps and possibly cooling pumps.
	Added chemicals	Dependent on the installation: scale inhibitor, corrosion inhibitor, oxygen scavenger, biocides, acids, etc.
	Waste	Sludge, which may be slightly radioactive (NORM), will deposit in the buffer tank.
Other impacts	**Safety**	PWRI influences safety very little, since the injection water hardly contains any gases.
	Maintenance	Maintenance of filters and coolers is fairly intensive, requires complicated procedures and high costs in case of NORM deposition. Possible salt deposition in tubing requires regular treatment with acids.

	General	**Offshore**
Practical experience	PWRI is applied onshore and offshore for a number of years in oil fields. Water production in gas fields is often too small to allow cold fracturing.	Injection in gas fields is technically feasible, but is applied rarely. Costs for investments and maintenance offshore are higher than onshore.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1] [2]	

Table C - 3: Dissolved gas/induced gas flotation (DGF/IGF)

Principle	In the process of gas flotation, a gas is finely distributed in the produced water. Raising gas strips oil droplets from produced water. Gas bubbles and oil form a foam on the water, which is skimmed, often by means of a paddle wheel. The foam and part of the water is skimmed into an overflow. Gas may be injected under pressure (Dissolved Gas Flotation, DGF) or by means of an impeller or pump (Induced Gas Floatation, IGF). Dissolved particles such as benzene and heavy metals are not removed, although gas injection may “strip” some volatile components. Sometimes, air is used instead of gas, in which case a major part of BTEX is also removed from the produced water. DGF/IGF usually is the “polishing” step in a multiple-step procedure to remove dispersed oil from produced water.
Process diagram	
Basic elements	Low pressure tank with impellers or pumps for gas injection

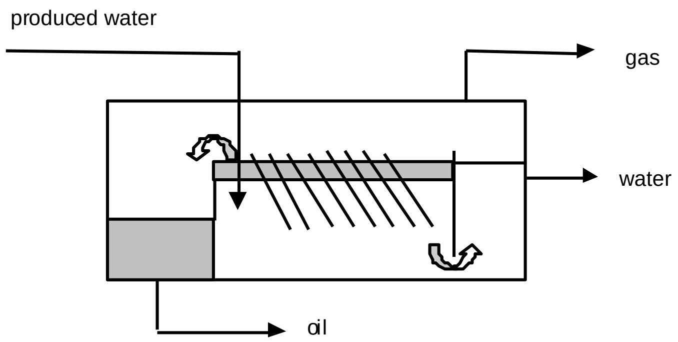
Suitable for the removal of: R = removal efficiency	**Heavy metals**	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
	☐ Cadmium ☐ Zinc ☐ Lead ■ Mercury** ☐ Nickel		☐ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers		■ **Dissolved oil** ■ BTEX ■ Benzene ■ PAHs	 0-20
					Dispersed oil	**R [%]**
					■ Oil	60-90*

Remarks:
*: Dependent on, amongst others, specific gravity of the oil (and water) and the temperature, oil contents are reduced from 100-300 mg/l to 20-40 mg/l. Higher removal efficiencies may be achieved when retention time is longer.
**: Mercury is not removed actively, but free mercury may separate because of low flow velocity.

Technical details	Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
	Required area (LxWxH)	1,8 x 1 x 2 m	2 x 1,5 x 2 m	10 x 2,5 x 3 m
	Mass (filled)	1,4 tonnes	3 tonnes	45 tonnes

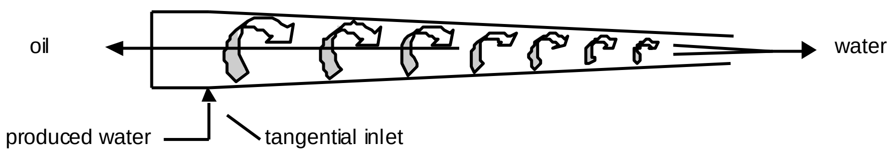
Critical operational parameters	Level control and the amount of water which is transported via the overflow, determine to a great extent the efficiency and the oil content of the effluent. Demulsifiers which are applied in the oil-water separator may have negative effects on the DGF/IGF. For this reason, some foaming agents may need to be applied. When air is used, problems may occur as a result of deposition of salts and ferrous oxides, formation of bacteria and corrosion, and is therefore rarely applied.
Operational reliability	The installation requires regular cleaning in order to remove deposited salts (scale) and other deposits (sludge).

<table>
<tr><td>Indication of costs</td><td colspan="2">Remarks:
In view of the dimensions of the equipment, space may need to be created by modification of existing steel constructions. This may involve considerable costs. An IGF installation with a capacity of 175 m³/h costs approximately € 250 000 (complete installation € 435 000, possibly modification of steel constructions).</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td>Low pressure gas which is resolved. In order to limit air emissions (also in view of health reasons) it is recommended to install portholes in covers for visual inspection of the foam layer.</td></tr>
<tr><td>Energy</td><td>Energy consumption approximately 5 / 15 / 50 kWh for capacity of 1 / 6 / 175 m³/h.</td></tr>
<tr><td>Added chemicals</td><td>Foaming agent may need to be applied.</td></tr>
<tr><td>Waste</td><td>Because of a low flow velocity, relatively large amounts of sludge may deposit, mainly sand and clay, which may be slightly radioactive (NORM).</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td>None.</td></tr>
<tr><td>Maintenance</td><td>Protective clothing necessary during cleaning operations: on gas producing installations in view of benzene and possibly mercury, on oil producing installations because of NORM and sometimes mercury.</td></tr>
<tr><td rowspan="2">Practical experience</td><td>General</td><td>Offshore</td></tr>
<tr><td>Technique is frequently applied for water treatment. Much operational experience in process industry.</td><td>Frequently applied offshore for removal of dispersed oil.</td></tr>
<tr><td>Conclusion</td><td>■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="2">[1]</td></tr>
</table>

<table>
<tr><th colspan="7">Table C - 4: Plate interceptors (PPI/CPI)</th></tr>
<tr><td>Principle</td><td colspan="6">In order to reduce the dispersed oil content in produced water, a parallel plate interceptor (PPI) or corrugated plate interceptor (CPI) may be applied. Separation is based on the difference between the specific gravity of oil and water and the coalescence of oil droplets on the plates. Since the distance between the plates is small, small oil droplets need to rise over a short distance, allowing for separation after a relatively short retention time. On the plates small oil droplets coalescence to larger droplets and therefore rise easier to the water surface. In CPIs, the undulating plates are almost horizontal. Larger oil droplets float to plates above through holes in the lower plates. When the oil layer becomes thicker, oil flows over and is redirected into the process.
This technique is applicable only for non-dissolved components such as dispersed oil with sufficient particle size. On oil producing installations, this technique may form part of a series of techniques for the removal of dispersed oil. On gas platforms, this technique sometimes suffices to achieve the performance standard.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">LP-tank with internal pack of plates and pump</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
☐ Dissolved oil
☐ BTEX
☐ Benzene
☐ PAHs</td><td>R [%]</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
80-95</td></tr>
<tr><td colspan="6">Remarks:
Removal efficiency for oil is 100% for oil droplets > 35 µm, dependent on specific gravity and temperature. In the offshore industry removal efficiencies up to 95% are achieved (from 1 000-4 000 mg/l to 100-300 mg/l). A pack of balls in the inlet compartment may raise removal efficiency considerably.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Required area (LxWxH)
Mass (filled)</td><td>Gas 1 (small)
1 m^3/h
2,5 x 0,6 x 1,8 m
2,5 tonnes</td><td>Gas 2 (large)
6 m^3/h
2,5 x 1,2 x 2,1 m
5,5 tonnes</td><td>Oil 1
175 m^3/h
2,3 x 5 x 3,5 m
38 tonnes</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Level of oil-water interface in the PPI is critical for adequate operation. Separation efficiency is dependent on retention time, stability of the emulsion and temperature.
Additional techniques are required in order to achieve the performance standard.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">High but requires regular cleaning.
Capable of handling relatively large oil content fluctuations of the influent, with limited effect on the effluent oil content.</td></tr>
</table>

Indication of costs	*Remarks:* Dimensions and weight for a PPI for 175 m^3/h are presented for 1 installation. In practice, a second PPI may need to be installed as standby equipment. For this reason, on oil producing installations it is recommended to divide the required capacity over a number of PPIs in order to allow for cleaning. The PPI described costs approximately € 400 000 (fully installed).		
Cross media effects	**Air**	Energy for oil pump will increase air emissions.	
	Energy	Energy consumption for oil pumps.	
	Added chemicals	None.	
	Waste	Because of a low flow velocity, relatively large amounts of sludge may deposit, mainly sand and clay, which may be slightly radioactive (NORM).	
Other impacts	**Safety**	Risk of exposure to benzene on gas producing installations during cleaning operations.	
	Maintenance	Pack of plates requires regular cleaning.	
Practical experience	**General**	**Offshore**	
	Well known and accepted principle for separation. Much operational experience in the process industry.	Technique is frequently applied on oil producing installations, but also on gas platforms.	
Conclusion	■ BAT	☐ Emerging Candidate for BAT	
Literature source	[1]		

<table>
<tr><th colspan="2">Table C - 5: Hydrocyclones</th></tr>
<tr><td>Principle</td><td>Oil-water separation in hydrocyclones is based on centrifugal forces and the difference between specific gravity of oil and water. Produced water is injected under pressure tangentially. The shape of the cyclone causes an increase of speed, resulting in large centrifugal forces and separation of oil and water. The heavier water will move in a vortex towards the exit of the cyclone, whereas the lighter oil will move in a secondary vortex in the centre of the cyclone towards the inlet. Dissolved components, such as benzene and heavy metals will not be removed.
Recently, rotating cyclones were developed, which are a ‘compromise’ between a hydrocyclone and a centrifuge. Rotating cyclones have higher removal efficiencies than a static hydrocyclone.
See also Table C - 7 on centrifuges.</td></tr>
<tr><td>Process diagram</td><td>
</td></tr>
<tr><td>Basic elements</td><td>Hydrocyclone and the required intake and outlet pipes. For high capacity applications, a number of cyclones are placed in parallel and integrated into one set of equipment.</td></tr>
<tr><td>Suitable for the removal of:

R = removal efficiency</td><td>
<table>
<tr><th>Heavy metals</th><th>R [%]</th><th>Production chemicals</th><th>R [%]</th><th>Oil</th><th>R [%]</th></tr>
<tr><td>☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td></td><td>☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td></td><td>☐ Dissolved oil
☐ BTEX
☐ Benzene
☐ PAHs

Dispersed oil
■ Oil</td><td>

R [%]
Up to 98</td></tr>
</table>
Remarks:
Removal efficiency for oil is up to 98% for droplets > 15 - 30 μm, resulting in effluent dispersed oil contents of 60 mg/l (static cyclone) and 40 mg/l (rotating cyclone). When the oil content in the inlet is more than 1.000 mg/l, effluent oil contents may be considerably higher.</td></tr>
<tr><td>Technical details</td><td>
<table>
<tr><td>Platform</td><td>Gas 1 (small)</td><td>Gas 2 (large)</td><td>Oil 1</td></tr>
<tr><td>Produced water volume (design)</td><td>1 m^3/h</td><td>6 m^3/h/</td><td>175 m^3/h</td></tr>
<tr><td>Required area (LxWxH)</td><td>0,8 x 2,5 x 1 m</td><td>1 x 3 x 1,2 m</td><td>3 x 4 x 1,7 m</td></tr>
<tr><td>Mass (filled)</td><td>0,7 tonnes</td><td>1,7 tonnes</td><td>9 tonnes</td></tr>
</table></td></tr>
<tr><td>Critical operational parameters</td><td>Disadvantage is that only large particles (>15 μm) can be removed, depending on the specific gravity of the oil. Oil-water emulsions can hardly be treated, neither can particles which are covered by an oil layer and which are neutrally buoyant. Rotating cyclones can remove particles up to 5 μm.
In order to allow for adequate operation of hydrocyclones, a constant inlet pressure and constant flow is required. The process could therefore be affected by the presence of gas.</td></tr>
<tr><td>Operational reliability</td><td>The system is robust and compact. Usually, subsequent treatment techniques are installed in order to comply with the performance standard for dispersed oil. Since the oil content is highly dependent on the throughput, the system is less reliable when fluctuations in the process occur. It is recommended to divide the required capacity over multiple cyclones.
A rotating cyclone is vulnerable and may require frequent maintenance because of rotating parts.</td></tr>
</table>

Indication of costs

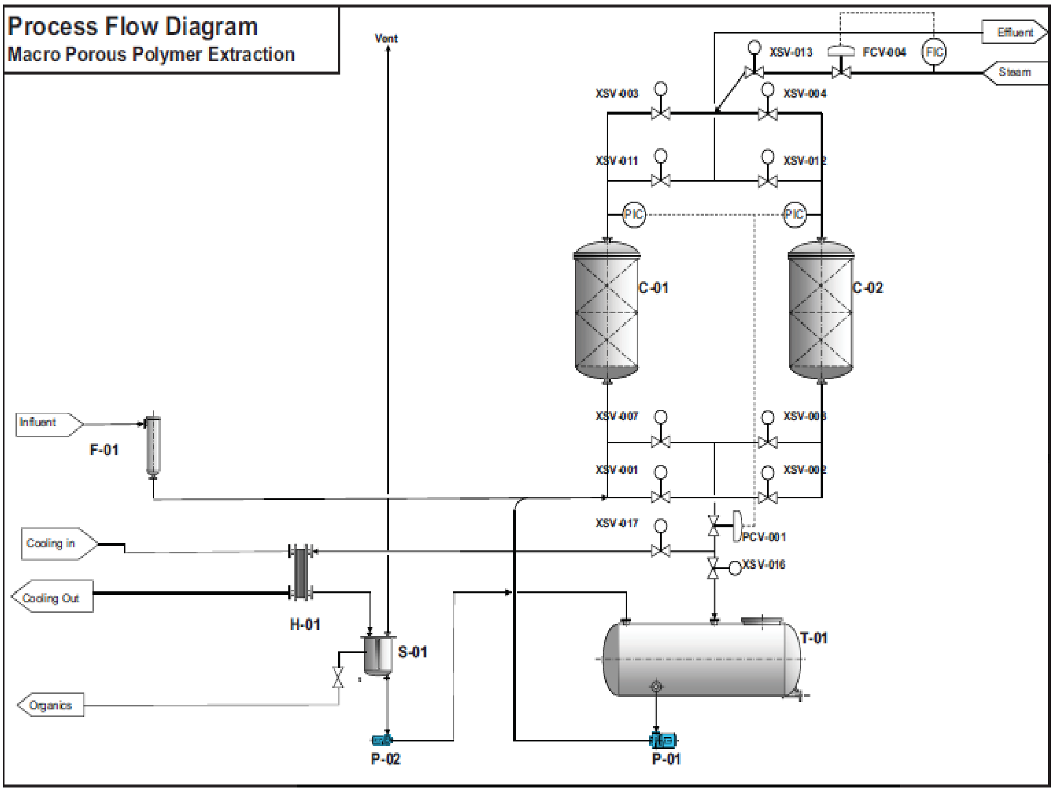
Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	Present	new	present	new
gas platform, small	n.c.	n.c.	n.c.	n.c.
gas platform, large	n.c.	n.c.	n.c.	n.c.
oil platform	790 000	650 000	248 700	147 100

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dispersed oil	n.c.	n.c.	n.c.	n.c.	38	22

Remarks:

Cross media effects	**Air**	Comparable to other techniques, in view of energy consumption.
	Energy	Energy for pumps to pressurise influent, 24-30 kW (0,2 kWh/m^3).
	Added chemicals	None.
	Waste	The ‘heavy phase’ (sand etc.) and depositions in equipment (scaling), possibly slightly radioactive (NORM).
Other impacts	**Safety**	None.
	Maintenance	Relatively little, although scale may deposit on hydrocyclones.

	General	**Offshore**
Practical experience	Well known and much used principle for separation. Much operational experience in the process industry.	Much experience in offshore oil-water separation. Has a long history of development.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

<table>
<tr><th colspan="2">Table C - 6: Macro porous polymer extraction (MPPE) (end stream)</th></tr>
<tr><td>Principle</td><td>A Macro Porous Polymer Extraction (MPPE) unit consists of two columns, containing a packed bed of MPPE material. The MPPE material contains an extraction liquid that enables the extraction of hydrocarbons from the water flow.
In general the inlet water, after passing a cartridge filter, is fed bottom up into a column C-01 and extraction process takes place immediately. This flow continues until a pre-calculated time has passed and then the inlet is switched to the second column (C-02).
After this switch, the regeneration step of column (C-01) starts, by injecting low-pressure steam top down. The low-pressure steam is being led through the column and enables evaporation of the hydrocarbons from the MPPE material. The steam transports the hydrocarbons out of the column, through a condenser, towards a separator tank.
In this tank the condensed phase separates, based on different densities of the organic phase and the water phase. The organic phase is practically 100% pure organics and can be re-used or disposed, in accordance with national and/or local regulations. The water phase from the separator is recycled into the columns of the MPPE system.
Parallel to the feeding of the first column, the second column (C-02) is being regenerated. This ongoing process of feeding, switching and regenerating is checked and controlled by the PLC and enables a conversion from a typical batch-driven-operation into a fully-automated-continuous-operation.</td></tr>
<tr><td>Process diagram</td><td>

The MPPE unit can be configured to be completely self-supporting and can even be equipped with its own power generator, steam generator, cooling system and dry air supply on board. The process has only one flow in (hydrocarbons containing water) and two flows out (pure hydrocarbons and treated water).</td></tr>
<tr><td>Basic elements</td><td>SKID MOUNTED
-2 MPPE COLUMNS
-AN INTERNAL BUFFERTANK
-AN HEAT EXCHANGER
-A SEPARATOR</td></tr>
</table>

Suitable for the removal of: R = removal efficiency	**Heavy metals** ☐ Cadmium ☐ Zinc ☐ Lead ☐ Mercury ☐ Nickel	**R [%]** ? 	**Production chemicals** ☐ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers	**R [%]** >99 * ** 	**Oil** ■ **Dissolved oil** ☐ BTEX ☐ Benzene ☐ PAHs **Dispersed oil** ■ Oil	**R [%]** **R [%]**
	Remarks: *Proven operational record since 1994 on Offshore Gas, Condensate and LNG Produced Water (> 50 years of accumulated experience).*					

Technical details	**Per Unit**	**Minimum**	**Maximum**
	Treatment capacity (m3 produced water per hour)	0,3-15	150
	Gross Package volume (LxWxH)	6,2 x 4 x 3 m	10 x 6 x 12
	Operating weight	10 ton	250 ton
	CAPEX (€)	1 000 000	10 000 000
	OPEX (€/year)	50 000	250 000
	Cost per m3 produced water(€/m3)	0,60	0,24

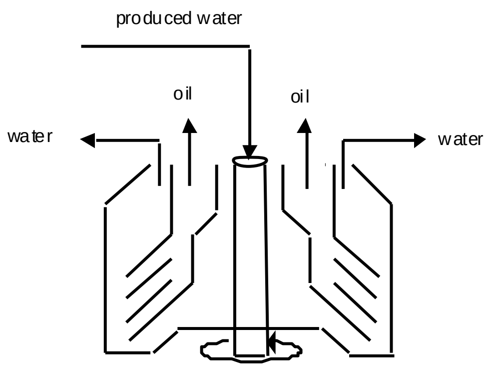
Critical operational parameters	The main critical parameter is the measured outlet concentration vs. discharge limit. If this comes close to the discharge limit the MPPE material needs to be replaced. This is a very slow process (Years) and can be done say on a weekly basis. The reduction performance is very stable and does not change overnight.
Operational reliability incl. information on downtime	-The MPPE unit is fully automatic and remote controlled and has been in operation on an unmanned platform since 2002 -Every 2 to 4 years the MPPE material have to be replaced by exchanging the columns with MPPE material (several hours for exchange). A set of spare columns with fresh MPPE material is always available onshore at clients premises. *Remarks:* -The unit has a turn down/up ratio from >100% design flow to 0%. -The reduction performance is independent of the inlet concentration. So also during upsets leading to 5-10 x higher inlet concentrations than design the reduction factor remains 99%. - At lower flows than design the reduction factor improves (10% lower flow than design allows a 50% higher inlet level while still meeting the demanded discharge level). -MPPE unit is immediate at separation performance after start up. -MPPE unit can operate batchwise

Cross media effects	**Air**	No air emission
	Energy	Steam 3-5 kg per m3
	Added chemicals	No
	Waste	No
Other impacts	**Health and Safety**	
	Maintenance interval and availability (% per year)	
Practical experience	**General**	**Offshore**
State of development	X Implemented offshore X Used onshore Vermilion (Total) (Harlingen) , Netherlands (3) Shell/Exxon (NAM B.V.), k15A, Offshore Netherlands Shell/Exxon (NAM B.V.), k15B, Offshore Netherlands Total F15A E&P , Offshore Netherlands Statoil/Shell, OrmenLange, Norway Onshore Statoil Kollsnes, Norway Onshore (4) Statoil Kollsnes, Norway Onshore (5) Statoil Hydro Åsgard Å, Offshore Norway (2) Offshore South China Sea, Offshore Malaysia (2) Woodside Pluto, LNG Terminal, Australia Shell Floating LNG Prelude Offshore Australia Inpex Ichthys FPSO Offshore Australia BP West Nile, Onshore Egypt (1) $1m^3/h$ = 4,4 gpm (2) Long duration test (3) Combined groundwater and process water (4) Mobile unit 2005 – 2011 (5) Permanent unit replaced mobile unit in 2011	Practical applicability: -Offshore Gas, Condensate, LNG produced water (since 1994 > 50 years accumulated experience). -Onshore Shale gas produced water (proven Field tested) -Onshore Shale oil produced water (proven bench scale tested) Driving force for implementation (e.g. legislation, increased yield, improvement product quality): -legislation -discharge water quality:; 95 to 99% Environmental Impact Factor Reduction (published data Norwegian Industry) -removal of toxic content for Zero Harmful Discharge -Removal of toxic content to protect bio treatment from toxicification /collapse if produced water is treated onshore (Ormen Lange; Kollsnes:Pluto). -full recovery of hydrocarbons -no waste stream; 100% water and separated oil/hydrocarbon recovery Example plants *MPPE Gas / Condensate/LNG Produced Water :* *Accumulated proven industrial performance > 50 years* *Constituents Inlet ppm Removal* *Dispersed oil (C6 – C24) 100 – 1300 > 99%* *Aromatics (BTEX) 300 – 3000 > 99%* *PAHs 2 – 80 > 99%* *NPDs 2 – 80 > 99%* *Field chemicals 20-50%* *Environmental Impact Factor reduction 95-99%*

Literature source	BERGERSEN, L. AND JACOBSSON, J. 2006—New Offshore Tie-ins and impact on Onshore Facilities, Field Case Kollsnes. *Tekna Produced Water Management Conference*, Stavanger, Norway. BERGERSEN, L., JACOBSSON, J. AND MEIJER D.TH. 2006—Solving the Impact of High Toxic Loads in the Produced Water at the Kollsnes Gas Terminal by Applying the MPPE technology. *NEL Produced Water—Best Management Practices*, Kuala Lumpur, Malaysia, 29–30 November. BULLER, A. T., JOHNSEN, S. AND FROST, K. 2003—Offshore produced water management—knowledge, tools and procedures for assessing environmental risk and selecting remedial measures. Memoir 3. Stavanger, Norway: *Statoil Research and Technology Offshore*. CHEN, G.Z. AND EBENEZER T.I. 2012—Produced water treatment technologies. *Faculty of Engineering, Department of Chemical and Environmental Engineering, and Energy and Sustainability Research Division, University of Nottingham*, Nottingham NG7 2RD, United Kingdom. 4 July. DALEN, A.V. 2004—Produced Water Regulations in the Netherlands. *NEL Oil-in-Water Monitoring Workshop*, Aberdeen, United Kingdom, 22–23 September. *ERT/ORKNEY WATER TECHNOLOGY CENTER*, 1997— The removal of dissolved and dispersed organic components from produced water. ERT F92/178, requested by Exxon Mobil, Total, Amarada Hess. GRINI, P.G., HJELSVOLD, M. AND JOHNSEN, S. 2002— Choosing produced water treatment technologies based on environmental impact reduction. *HSE Conference, Kuala Lumpur*, Malaysia, 20–22 March, SPE paper 74002. ITHNIN, I.B. AND CHRISTOPHER, G. 2006—The discharge of produced water from oil and gas production: Legislation requirement in Malaysia. *NEL Produced Water—Best Management Practices*, Kuala Lumpur, Malaysia, 29–30 November. KAA, C.C.R. VAN DER AND PETRUSEVKI, B. 1988— Inventarisation of removal techniques to reduce the benzene heavy metal emissions from offshore platforms. (In Dutch). *NOGEPA (Netherlands Oil and Gas Exploration and Production Association) and Dutch Government*, Report 61944-00-32-301-2. KLOPPENBURG, M.F.C. AND VENEMA, W. 1997—De-oiling condensed glycol regenerator overhead vapours by steam stripping. 1997 *SPE/UKOOA European Environmental Conference*, Aberdeen, United Kingdom, 15–16 April, SPE paper no. 37846. LOWE, I. 2006—Shaping a sustainable future—challenges for Australia's oil and gas industry. *APPEA Environment Conference, Coolum*, Australia, 19–21 November.

	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					
- Dispersed oil	☐	X	☐	99%	
- Dissolved oil	☐	X	☐	99%	
Specific oil components:					
- BTEX	☐	x	☐	99%	
- NPD	☐	x	☐	99%	
- PAH's 16 EPA	☐	x	☐	99%	
- Others (indicate)	☐	x	☐	99%	
- Alkyl Phenols					
Heavy metals	☐	X	☐	X	Measured on 4 different Offshore produced water streams
- **MERCURY**		X		81-99%	
Offshore chemicals					
- methanol	☐	☐	☐	☐	
- glycol	☐	☐	☐	☐	
- corrosion inhibitors	☐	x	☐	20-50%	
- biocides					
- scale inhibitors	☐	☐	☐	☐	
- surfactants	☐	x	☐	20-50%	
- Others (indicate)	☐	☐	☐	☐	
- H2S scavengers	☐	x	☐	x	
- Emulsion breaker		X		20-50%	
- Anti foam		X		20-50%	
		X		20-50%	

Table C - 7: Centrifuge	
Principle	A centrifuge may be used in order to reduce the dispersed oil content in produced water. Oil-water separation in a centrifuge is based on centrifugal forces and the difference in specific gravity of oil and water. Degassed produced water is injected into the centrifuge where it is brought in rotation. Water will collect at the outside of the centrifuge, oil will collect in an inner layer. Oil and water are removed separately, under controlled conditions. An oil-water interface needs to be maintained. Oil is pumped back into the process, water is discharged. A centrifuge allows for separation of smaller oil droplets than a hydrocyclone. The energy consumption is higher. Centrifuges are usually applied as a polishing step when the performance standard cannot be achieved. On oil producing installations the use of centrifuges may be useful to clean skimmings from degassers and induced gas flotation units, thereby avoiding build-up of sludges.
Process diagram	



Basic elements						
Suitable for the removal of: R = removal efficiency	**Heavy metals**	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
	☐ Cadmium		☐ Methanol		■ **Dissolved oil**	*
	☐ Zinc		☐ Glycols		■ BTEX	*
	☐ Lead		☐ Corrosion inhibitors		■ Benzene	*
	☐ Mercury		☐ Anti-scale solutions		■ PAHs	*
	☐ Nickel		☐ Demulsifiers		**Dispersed oil**	**R [%]**
					■ Oil	95

Remarks:

Removal efficiency for oil is 100% for droplets > 3 µm, depending on specific gravity and temperature. Removal of dispersed oil from 400 mg/l to 40-10 mg/l.

Dissolved components (heavy metals, benzene) will not be removed.

*: In the case of high aromatic hydrocarbon content, e.g. in case of process malfunction, part of the aromatic hydrocarbons will be removed via the condensate.

Technical details	Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	175 m^3/h
	Required area (LxWxH)	2 x 1,2 x 2 m	2,3 x 1,5 x 2,8 m	n.a.
	Mass (filled)	2,1 tonnes	3,1 tonnes	

Critical operational parameters	Especially suitable for small water streams. Relatively high energy consumption. Requires water degassing prior to feed. Use of corrosion resistant materials is recommended, especially in cases of high temperature or water which contains oxygen.
Operational reliability	Centrifuges require frequent cleaning (contamination) and maintenance. A second centrifuge is often installed as standby equipment.

Indication of costs

Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	235 000	175 000	83 000	49 500
gas platform, large	395 000	310 000	162 400	108 600
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dispersed oil	1 663	991	465	311	n.a.	n.a.

Remarks:

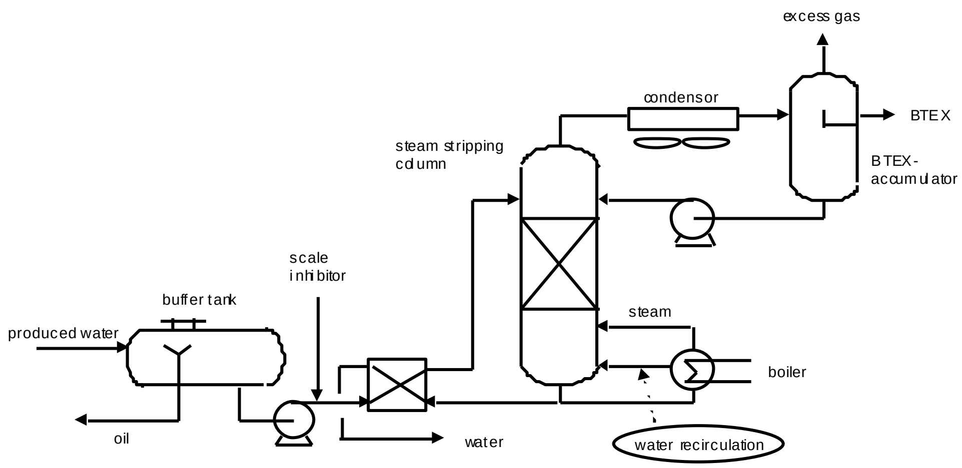
Cross media effects	**Air**	Energy for centrifuge and pump will increase air emissions.
	Energy	Energy for centrifuge and pump: 1,5 kW (small gas installation), 10 kW (large gas installation).
	Added chemicals	None.
	Waste	Deposited material in equipment (sand, clay, scale etc.) which may be slightly radioactive (NORM).
Other impacts	**Safety**	Risk of exposure to benzene during cleaning operations.
	Maintenance	Centrifuges require cleaning every few days, self-cleaning mechanisms in centrifuges are often insufficient to remove sludge.

Practical experience	**General**	**Offshore**
	Much operational experience in the processing industry.	Centrifuges are applied offshore for produced water treatment, mainly on gas producing installations.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

Table C - 8: Steam stripping (end flow)

Principle	Hydrocarbons can be removed from produced water by means of steam stripping. The water is fed into a packed column and brought into extreme contact with steam (known as stripping). This technique is suitable for the removal of dissolved oil (BTEX), but will also remove aliphatic hydrocarbons. Steam and hydrocarbon vapours are condensed and separated easily because of the high hydrocarbon content. Hydrocarbons that have been separated by steam can be directed to the condensate treatment system; water can be discharged.

Process diagram



Basic elements	Buffer tank, feeding pump, heat exchanger, stripping column, condensor, BTEX-accumulator, re-circulation pump, condensate pump, (electric) re-boiler

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
☐ Cadmium		■ Methanol	10-80	■ **Dissolved oil**	>90
☐ Zinc		☐ Glycols		■ BTEX	>90
☐ Lead		■ Corrosion inhibitors	*	■ Benzene	>90
☐ Mercury		■ Anti-scale solutions	*	■ PAHs	>90
☐ Nickel		■ Demulsifiers	*	**Dispersed oil**	**R [%]**
				■ Oil	>85

Remarks:

The expected removal efficiency for BTEX is high: reduction from 50 mg/l to < 6 mg/l, aliphatic hydrocarbons from 30 mg/l to < 3 mg/l

*: The hydrophobic part is partly removed.

Technical details

Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
Produced water volume (design)	1 m^3/h	6 m^3/h	n.a.
Required area (LxWxH)	3 x 2 x 5 m	6 x 3 x 5 m	
Mass (filled)	12 tonnes	20 tonnes	

Critical operational parameters	Since produced water usually contains salts and solid particles, problems with depositions (scale) may occur in the boiler and the heat exchanger. In order to prevent concentration of salts in the boiler, it is recommended to create a slight throughput by means of a re-circulation line from the boiler to the column. The steam line must be large enough in order to allow for equal levels in boiler and column (and above the bundle of the boiler). In order to guarantee a constant throughput, a buffer tank is required. This also provides the possibility to skim off oil, avoiding disruption of the process in the column.
Operational reliability	When the produced water contains large amounts of salts, the installation will need to be shut down regularly to enable removal of salt depositions.

Indication of costs

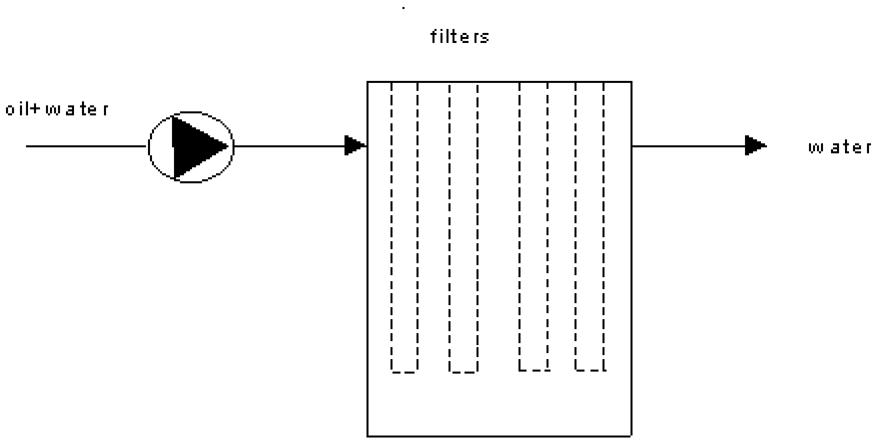
Costs	Investment costs (CAPEX) [€]		Exploitation costs (OPEX) [€ / year]	
	present	new	present	new
gas platform, small	670 000	560 000	238 000	169 200
gas platform, large	990 000	840 000	401 400	276 900
oil platform	n.a.	n.a.	n.a.	n.a.

Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil	3 404	2 412	327	226	n.a.	n.a.
dispersed oil	3 064	2 171	277	191		
zinc equivalents	5 050	3 578	1.212	836		

Remarks:
Energy consumption is relatively high, despite the fact that part of the heat is recovered. Consumption can be reduced considerably when heat from the process or from the exhaust gases from turbines is used.

Cross media effects	**Air**	Required energy will increase air emissions. After the condensor very few gases remain.
	Energy	Approximately 40 kWh/m^3 produced water (mainly for boiler).
	Added chemicals	Scale inhibitor is needed in order to prevent deposition of salts in the heat exchanger and boiler as much as possible. Corrosion inhibitors in view of high temperatures (dependent on materials applied).
	Waste	Sludge will deposit in the buffer tank. Salt depositions need to be removed from the boiler regularly (mechanically or using acids).
Other impacts	**Safety**	No significant influence.
	Maintenance	Maintenance on boiler and heat exchanger may be considerable when the salt content in produced water is high. Complicated procedures and high costs in case of NORM deposition.

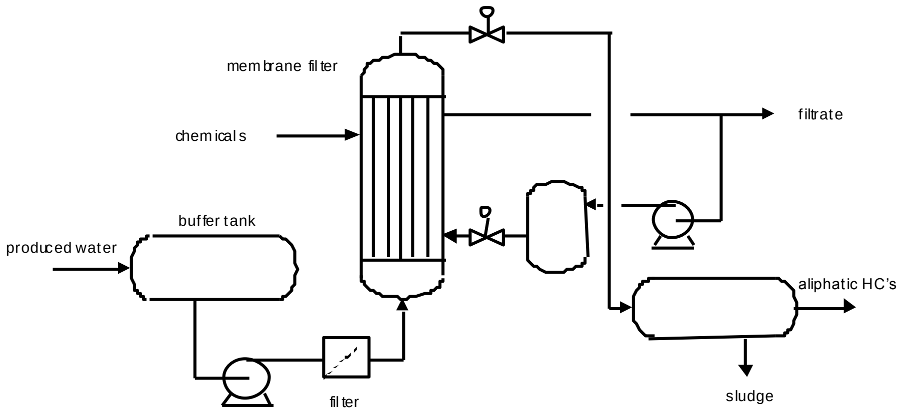
	General	**Offshore**
Practical experience	Practical experience was gained in onshore gas production operations and on partial streams offshore.	Practical experience was gained offshore on partial streams. Currently there are no offshore applications of end stream treatment operations.
Conclusion	■ BAT	☐ Emerging Candidate for BAT
Literature source	[1]	

<table>
<tr><th colspan="7">Table C - 9: Adsorption filters</th></tr>
<tr><td>Principle</td><td colspan="6">Adsorption filters may be applied for the removal of aliphatic hydrocarbons. Water is pumped through a process tank with filters. These filters contain chemically treated cellulose fibres which adsorb aliphatic hydrocarbons and, to a lesser extent, aromatic hydrocarbons. Regeneration of the filters is not possible since contaminants are adsorbed mainly chemically.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Process tank with filters and pump.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
■ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]

>50</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]
<10*
<10*
<10*
<10*</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
95</td></tr>
<tr><td colspan="6">Remarks:
Dissolved components, excluding aromatic hydrocarbons, will not be removed. Heavy metals are only removed as solid particles > 20 µm, sometimes in the form of scale.
*: When the filter is new, this removal efficiency may be considerably higher, but when the aromatic hydrocarbons content is high, the filter will soon be saturated.</td></tr>
<tr><td>Technical details</td><td colspan="3">Platform
Produced water volume (design)
Required area (extra) (LxWxH)
Mass (extra)</td><td>Gas 1 (small)
1 m³/h
1,6 x 0,8 x 2 m
1,3 tonnes</td><td>Gas 2 (large)
6 m³/h
2,1 x 1 x 2 m
1,9 tonnes</td><td>Oil 1
n.a.</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Filters require frequent replacement. Particles > 20 µm will be removed but may also lead to clogging. Removal efficiency dependent on composition of produced water, and should be determined by means of field tests, i.e. on existing offshore installations.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">High, although frequent replacement is required. Mainly applicable in situations in cases of problems in the regular process, in order to be able to achieve the performance standard for dispersed oil.</td></tr>
</table>

Indication of costs	*Remarks:* An adsorption filter with a capacity of 15 m^3/h costs approximately € 45 000, excluding pump, equipment and installation costs. OPEX are estimated to be € 0,4 /m^3.		
Cross media effects	**Air**	Energy for feed pump will increase air emissions.	
	Energy	Energy for feed pump.	
	Added chemicals	None.	
	Waste	Saturated filters (aliphatic hydrocarbons, clay, sand, scale which is often slightly radioactive – NORM).	
Other impacts	**Safety**	Risk of exposure to benzene when filters are replaced.	
	Maintenance	Filters need frequent replacement.	
Practical experience	**General**		**Offshore**
			Applied offshore on some installations.
Conclusion	■ BAT		☐ Emerging Candidate for BAT
Literature source	[1]		

Table C - 10: Membrane filtration	
Principle	Aliphatic hydrocarbons may be removed by means of membrane filtration. Water (low pressure, approximately 3,5 bar) is guided along a number of ceramic or synthetic filter elements which contain pores of 0,1 – 0,2 µm. Build-up of filter cake is avoided by a cross flow and a turbulent flow along the membrane surface. Part of the permeate is directed to the pressure-pulse system for cleaning of the membranes, the remaining part is discharged. The components that remain in the membrane after the pressure pulses need to be removed with chemicals periodically. The main part of aliphatic hydrocarbons and solids remain in the concentrate, which is directed to a settling tank, where the oil can be separated easily in view of the high concentrations.
Process diagram	
Basic elements	Buffer tank, pre-filter, membrane filtration unit, pressure-pulse system, settling tank.

Suitable for the removal of:

R = removal efficiency

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
☐ Cadmium		☐ Methanol		■ **Dissolved oil**	*
☐ Zinc		☐ Glycols		■ BTEX	*
☐ Lead		☐ Corrosion inhibitors		■ Benzene	*
☐ Mercury		☐ Anti-scale solutions		■ PAHs	*
☐ Nickel		☐ Demulsifiers		**Dispersed oil**	**R [%]**
				■ Oil	70-90

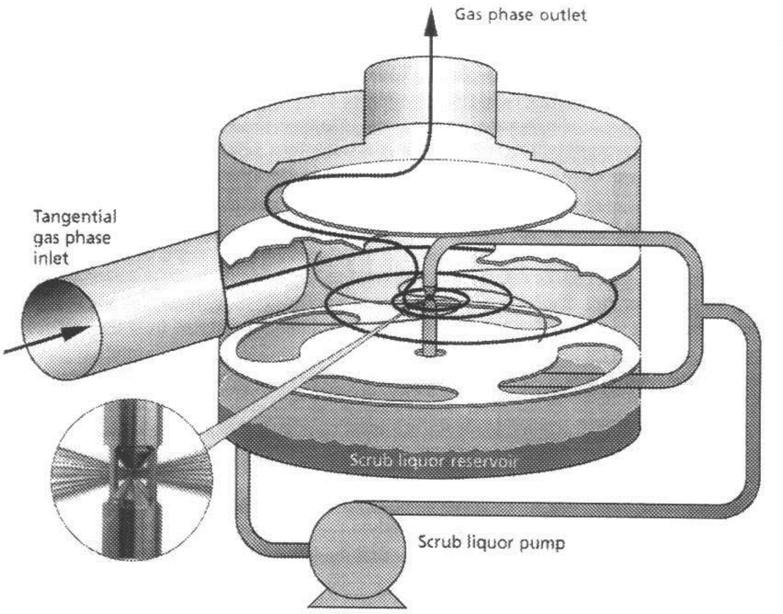
Remarks:
Measurements during tests revealed removal of 150 mg/l to 15 mg/l, from 110 mg/l to 30 mg/l and from 70 mg/l to 10 mg/l.

Technical details	Platform	Gas 1 (small)	Gas 2 (large)	Oil 1
	Produced water volume (design)	1 m^3/h	6 m^3/h	n.a.
	Required area (LxWxH)	2 x 2 x 2 m	2 x 4 x 2,5 m	
	Mass (filled)	4 tonnes	10 tonnes	

Critical operational parameters	When produced water contains large amounts of salts, membranes will clog easier. Especially barium sulphate and strontium sulphate are difficult to remove chemically. Chemicals for regeneration of membranes need to be suitable for the removal of these sulphates and clay particles. Ceramic membranes are more robust and more resistant to chemicals than polymer membranes. Pre-filtration is required in order to avoid erosion of the membranes. A relatively constant flow speed (buffer tank) is needed for optimal filtration. No oxygen should be able to enter the equipment in order to avoid formation of ferrous oxides. When the permeate for the back pulse is not free of oxygen, filtration of ferrous oxides is required. Duration and frequency of pressure pulses are critical and need to be established empirically.
Operational reliability	During offshore testing, membrane elements were not fully regenerated, rendering this technique insufficiently reliable. It is expected that this equipment would require frequent shut down for maintenance. Furthermore, relatively intense supervision is required. Experience onshore confirms problematic removal of aliphatic hydrocarbons from salty water.

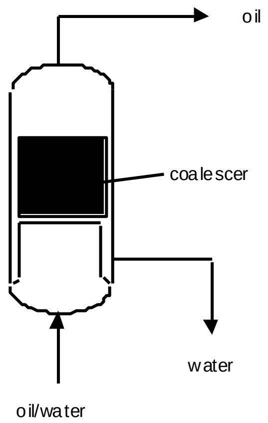
<table>
<tr><td rowspan="9">Indication of costs</td><td colspan="6"></td></tr>
<tr><td>Costs</td><td colspan="2">Investment costs (CAPEX)
[€]</td><td colspan="3">Exploitation costs (OPEX)
[€ / year]</td></tr>
<tr><td></td><td>present</td><td>new</td><td>present</td><td colspan="2">new</td></tr>
<tr><td>gas platform, small
gas platform, large
oil platform</td><td>555 000
915 000
n.a.</td><td>455 000
745 000
n.a.</td><td>216 000
448 200
n.a.</td><td colspan="2">143 900
328 000
n.a.</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas platform, small</td><td colspan="2">Gas platform, large</td><td colspan="2">Oil platform</td></tr>
<tr><td></td><td>Existing
[€/kg]</td><td>New
[€/kg]</td><td>Existing
[€/kg]</td><td>New
[€/kg]</td><td>Existing
[€/kg]</td><td>New
[€/kg]</td></tr>
<tr><td>aliphatic hydrocarbons
BTEX</td><td>5 140
-</td><td>3 419
-</td><td>1 523
-</td><td>1 115
-</td><td>n.a.</td><td>n.a.</td></tr>
<tr><td colspan="7">Remarks:</td></tr>
</table>

<table>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td>Little effect on air emissions in view of low energy consumption.</td></tr>
<tr><td>Energy</td><td>Estimated energy consumption: 1,2 kWh/m^3 produced water.</td></tr>
<tr><td>Added chemicals</td><td>Chemicals for periodical cleaning and conditioning of membranes.</td></tr>
<tr><td>Waste</td><td>Relatively large amounts of sludge in settling tank. Membranes are clogged relatively fast with sulphates which are hard to remove and may contain NORM. This would cause complex cleaning procedures or removal. Pre-filters to be regarded as waste after use.</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td>Working with various chemicals, which may cause injury (burns). Risk of exposure to benzene when filters and membranes are replaced.</td></tr>
<tr><td>Maintenance</td><td>Relatively high maintenance: replacement of filters and membranes, removal of sludge from settling tank.</td></tr>
<tr><td rowspan="2">Practical experience</td><td>General</td><td>Offshore</td></tr>
<tr><td>Well-known and applied principle for water treatment in onshore process industry.</td><td>At least three offshore gas / gas-condensate producing installations offshore the Netherlands are equipped with cross flow membrane units.</td></tr>
<tr><td>Conclusion</td><td>■ BAT</td><td>☐ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="2">[1]</td></tr>
</table>

<table>
<tr><th colspan="7">Table C - 11: V-Tex</th></tr>
<tr><td>Principle</td><td colspan="6">Gas enters the circular flat vortex chamber of a gas liquid contactor tangentially, through a series of vanes, evenly located around the chamber rim. The gas follows the circular contour of the chamber and moves inwards towards an outlet port, mounted on the central axis of the chamber. This relatively slow radial movement increases the tangential velocity, which can increase to as much as 15 m/s. At the same time, the liquid phase of the scrubbing liquor is sprayed into the centre of the chamber forming droplets, which fly out towards the chamber periphery, making contact with the rotating gas. Closing contact speeds can be high, allowing intense mass and heat transfer. As they continue to pass through the spinning gas, the droplets develop a tangential velocity component and this generates a centrifugal acceleration which disentrains the drops by spinning them towards the chamber wall.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Stripper with integral sump mounted on a Carbon Steel skid, electrical pre-heater, centrifugal pumps</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
■ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td rowspan="4">Technical details</td><td colspan="2">Throughput (m^3/day)</td><td colspan="2">Weight (dry / wet, Te)</td><td colspan="2">Overall size l x h x w (m)</td></tr>
<tr><td colspan="2">10</td><td colspan="2">1,0 / 1,5</td><td colspan="2">2,0 x 1,15 x 2,0</td></tr>
<tr><td colspan="2">100</td><td colspan="2">2,25 / 3,0</td><td colspan="2">2,75 x 1,55 x 2,78</td></tr>
<tr><td colspan="2">500</td><td colspan="2">4,0 / 5,5</td><td colspan="2">3,75 x 2,5 x 3,75</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">The column has a design temperature range of –10 °C to 50°C, a design pressure of 3 bar. The material of construction will be carbon steel.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">The result of several trails showed that this technology was highly effective in removing a wide range of hydrocarbons (both aromatics and aliphatic hydrocarbons) from such mixtures.</td></tr>
</table>

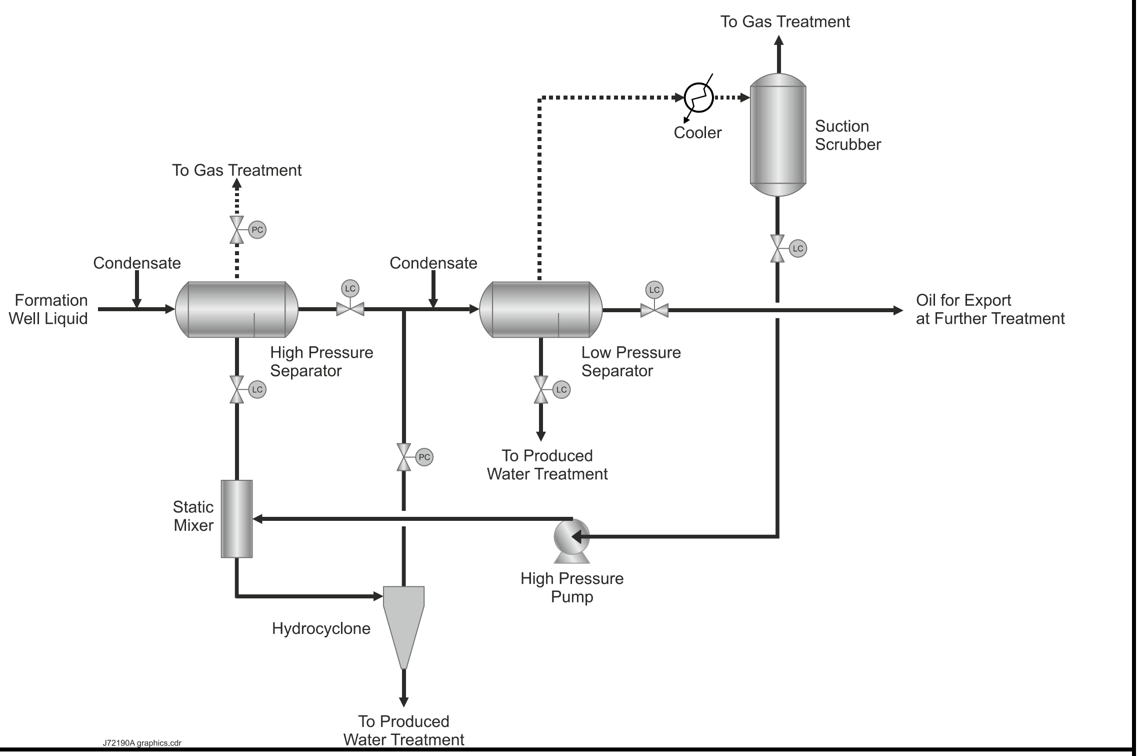
<table>
<tr><td rowspan="8">Indication of costs</td><td colspan="13"></td></tr>
<tr><td rowspan="2">Costs</td><td colspan="6">Investment costs (CAPEX)
[€]</td><td colspan="6">Exploitation costs (OPEX)
[€ / year]</td></tr>
<tr><td colspan="3">present</td><td colspan="3">new</td><td colspan="3">present</td><td colspan="3">new</td></tr>
<tr><td>gas platform, small
gas platform, large
oil platform</td><td colspan="12">No data on model situation available</td></tr>
<tr><td colspan="13"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="4">Gas platform, small</td><td colspan="4">Gas platform, large</td><td colspan="4">Oil platform</td></tr>
<tr><td></td><td colspan="2">Existing
[€/kg]</td><td colspan="2">New
[€/kg]</td><td colspan="2">Existing
[€/kg]</td><td colspan="2">New
[€/kg]</td><td colspan="2">Existing
[€/kg]</td><td colspan="2">New
[€/kg]</td></tr>
<tr><td>dissolved oil
dispersed oil
zinc equivalents</td><td colspan="12">No data on model situation available</td></tr>
<tr><td></td><td colspan="13">Remarks:</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="12"></td></tr>
<tr><td>Energy</td><td colspan="12"></td></tr>
<tr><td>Added chemicals</td><td colspan="12"></td></tr>
<tr><td>Waste</td><td colspan="12"></td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="12"></td></tr>
<tr><td>Maintenance</td><td colspan="12"></td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="7">General</td><td colspan="6">Offshore</td></tr>
<tr><td colspan="7"></td><td colspan="6"></td></tr>
<tr><td>Conclusion</td><td colspan="7">☐ BAT</td><td colspan="6">■ Emerging Candidate for BAT</td></tr>
<tr><td>Literature source</td><td colspan="13">[3]</td></tr>
</table>

<table>
<tr><th colspan="7">Table C - 12: Filter coalescer</th></tr>
<tr><td>Principle</td><td colspan="6">Dispersed oil may be removed from produced water by means of a filter coalescer. The coalescer consists of a vessel containing packed media of corrugated sheets, mesh, co-knit or irregular wool format. The produced water flows through the media where the small oil droplets (< 10 µm) conglomerate and form larger droplets. These larger droplets rise to the surface quicker than smaller ones and can then be removed from the top of the vessel. The technique may be used only as a coalescer to enlarge oil droplets, which can then be separated in a secondary treatment unit.
This technique is not suitable for removal of dissolved components as benzene and heavy metals.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">Pump, vessel, filter, media</td></tr>
<tr><td rowspan="3">Suitable for the removal of:

R = removal efficiency</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
☐ Dissolved oil
☐ BTEX
☐ Benzene
☐ PAHs</td><td>R [%]</td></tr>
<tr><td>Dispersed oil
■ Oil</td><td>R [%]
30</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td>Technical details</td><td colspan="3">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 1 (small)
1 m³/h
1 x 1 x 2 m</td><td>Gas 2 (large)
6 m³/h
1,5 x 1,5 x 2,5 m</td><td>Oil 1
175 m³/h</td></tr>
<tr><td>Critical operational parameters</td><td colspan="6">Proper operation depends on droplet size of the input. Not suitable for emulsions. Pressure in coalescer preferably equal to the pressure in the next treatment step, since large differences in pressure pumps and valves may undo the results achieved in the coalescer. Applicability is often established empirically.

Fine media which may be required to give coalescing of smaller oil particles are particularly subject to fouling. Pre-treatment may be necessary to remove solids from the produced water before entering the filter coalescer.</td></tr>
<tr><td>Operational reliability</td><td colspan="6">Operation of the filter will depend on the type of media used and the amount of solids in the produced water.</td></tr>
</table>

<table>
<tr><td rowspan="7">Indication of costs</td><td>Costs</td><td colspan="2">Investment Costs (CAPEX)
[€]</td><td colspan="2">Exploitation Costs (OPEX)
[€ / year]</td><td colspan="2"></td></tr>
<tr><td>Gas Platform, small
Gas Platform, large
Oil Platform</td><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas Platform, small</td><td colspan="2">Gas Platform, large</td><td colspan="2">Oil Platform</td></tr>
<tr><td></td><td>Existing</td><td>New</td><td>Existing</td><td>New</td><td>Existing</td><td>New</td></tr>
<tr><td>Dissolved oil
Dispersed oil
Zinc equivalents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="6">None.</td></tr>
<tr><td>Energy</td><td colspan="6">None.</td></tr>
<tr><td>Added chemicals</td><td colspan="6">None.</td></tr>
<tr><td>Waste</td><td colspan="6">Little</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="6">None.</td></tr>
<tr><td>Maintenance</td><td colspan="6">Sand, clay and scale are hard to remove, rendering frequent cleaning or replacement of the filter material necessary. Removed material may be slightly radioactive (NORM).</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="3">General</td><td colspan="4">Offshore</td></tr>
<tr><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Conclusions</td><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Literature source</td><td colspan="7">Produced Water Management Technology Descriptions, Fact Sheet – Coalescence
Liquid-Liquid Coalescer design manual. ACS Industries. LP</td></tr>
</table>

<table>
<tr><td colspan="7">Table C - 13: Ctour process system</td></tr>
<tr><td>Principle</td><td colspan="6">The CTour Process System is based on the extraction of hydrocarbons from water using gas condensate, normally extracted from a gas train scrubber. The gas condensate acts as extraction-solvent; the oil will have a high affinity towards the condensate. The condensate and the oil form large, low-density droplets that are easily removed by the downstream hydrocyclone. The principle of the extraction process is to add an immiscible solvent in a solution that will absorb the solute (in this case dissolved oil, BTEX etc.) because of the higher affinity towards the extraction solvent. The extraction process is based on thermo dynamical equilibrium between two liquid phases and is thus dependent on the actual composition of the extraction-solvent (and of the solution). In the Ctour process the extraction solvent is the gas condensate, often taken from the gas compression train scrubber. The actual efficiency of the extraction process will therefore depend on composition of the condensate, which in turn is dependent on the operating pressure and temperature of the scrubber.</td></tr>
<tr><td>Process diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic elements</td><td colspan="6">HP and LP Separators, Booster Pump, Injection Mixer, ReMixer, Hydrocyclone, Flash Tank and Condensate</td></tr>
<tr><td rowspan="2">Suitable for the removal of:

R = removal efficiency</td><td>Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td>R [%]</td><td>Production chemicals
☐ Methanol
☐ Glycols
■ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers
■Others (indicate)</td><td>R [%]

40**

80***</td><td>Oil
■ Dissolved oil
■ BTEX
■ Benzene
■ PAHs
Dispersed oil
■ Oil</td><td>R [%]
*
*
*
*
R [%]
*</td></tr>
<tr><td colspan="6">Remarks:
(*) Removal efficiencies were reported following scale up of the process to 150,000BWD in the Norwegian North Sea (Voldum, et al, 2007). The CTour processes studied confirmed removal guarantees in the range of 80-85% (PAH, Napthalenes) and 30-35 %(Phenols & BTEX). NB: Heavy Phenol removal efficiency was reported at >80%. The e process promises a >80% reduction of PW Environmental Impact Factor (EIF). Where gas condensate contains objectionable components (BTEX, Napthalenes) gas conditioning may be required.

(**) Specific class of corrosion inhibitors. (OSPAR, 2006)

(***) Log (octanol/water partition) greater than 2.0. (OSPAR, 2006)</td></tr>
</table>

Technical details	Type of Installation	Min.	Max.	
	Produced water volume (M3/Hr)	10	500	
	Gross package volume (LxWxH, m)	3x1,5x2	10x2x3	
	Operating weight (tonnes)	3	13	
Critical operational parameters	Typically, the design condensate volume is set as 2% of the produced water production rate. Produced water from the HP and LP system is boosted up to a pressure in excess of 40 bar (exceeding the bubble point of the NGL by 10 bar) to enable the NGL to be in a liquid state at the hydrocyclone reject pressure.			
Operational reliability	Heavily dependent on condensate composition. In the liquid state the condensate must remain in the reject line upstream of the hydrocyclone reject control valve. In the gaseous state the condensate should have the same atmospheric pressure and temperature as the produced water.			

Indication of costs

Costs	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€/Year]	
	Present	New	Present	New
Min.	-	1,4 Million	Low	Low
Max.	-	4,4 Million	Low	Low

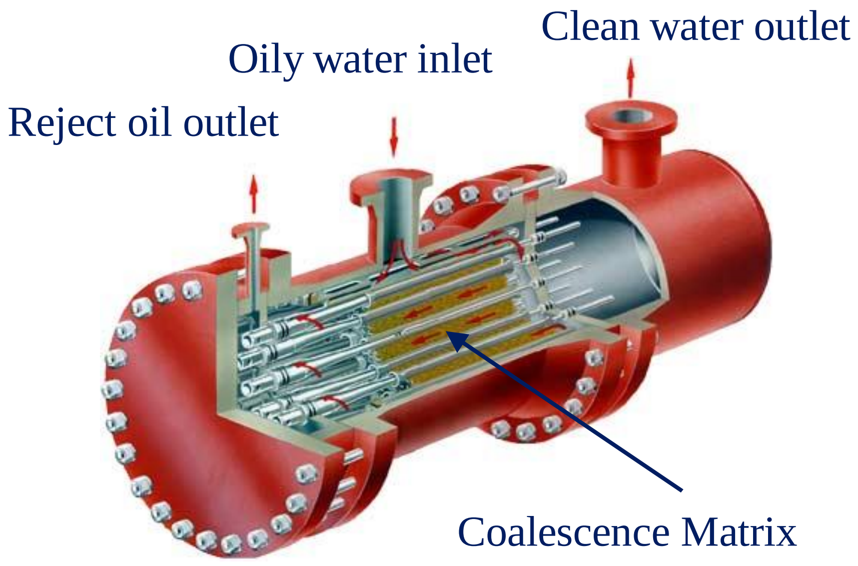
Cost/kg removed	Gas platform, small		Gas platform, large		Oil platform	
	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
dissolved oil dispersed oil zinc equivalents	No data on model situation available					

Remarks:
Installation costs are understood to be considerable. CTour has been widely applied in the Norwegian North Sea where the governments Zero Discharge policy has driven the feasibility of this polishing process. Costs for retrofit implementation of the condensate induced extraction process are case specific, depending on field specific conditions and the target removal efficiency.

Cross media effects	**Air**	Energy to raise produced water pressure will increase air emissions.
	Energy	Energy to generate high pressure by condensate booster pump.
	Added chemicals	
	Waste	
Other impacts	**Safety**	Reclassification of the produced water system to a hydrocarbon containing system.
	Maintenance	The functional unit of the process is not mechanical. The maintenance demands are therefore limited to the booster pump and separator tanks.

Practical experience	**General**	**Offshore**
		There are 24 units installed in the Norwegian North Sea for the extraction of dissolved oil.

<table>
<tr><td rowspan="3">State of Development</td><td rowspan="3">☒ Implemented Offshore
☒ Used Offshore
☒ Offshore Field Trials
☒ Testing</td><td>Practical applicability:</td></tr>
<tr><td>Driving force for implementation (e.g. legislation, increased yield, improvement product quality):
Legislation and economic drivers caused by increased water cut</td></tr>
<tr><td>Example plants:
Successful testing at:
Statfjord B and C
Ekofisk 2/4J
Snorre A
Aasgard A
Troll C
Full-scale implementation at:
Statfjord A, 2000 m3/h
Statfjord B, 3000 m3/h
Statfjord C, 4300 m3/h
Snorre A, 1000 m3/h
Ekofisk 2/4J&M, 2000 m3/h</td></tr>
<tr><td>Literature source</td><td colspan="2">(Voldum, et al, 2007) The CTour Process, an option to comply with "zero harmful discharge legislation" in Norwegian waters. Experience of CTour installation on Ekofisk after start up 4'th quarter 2007. Kåre Voldum and Eimund Garpestad ConocoPhillips Norway; Nils Olav Anderssen and Inge Brun Henriksen ScD ProPure, Norway, SPE-118012-PP, Abu Dhabi International Petroleum Exhibition and Conference held in Abu Dhabi, UAE, 3–6 November 2008.
(OSPAR, 2006) Addendum to the OSPAR Background Document Concerning Techniques for the Management of Produced Water from Offshore Installations (Publication number 162/2002)</td></tr>
</table>

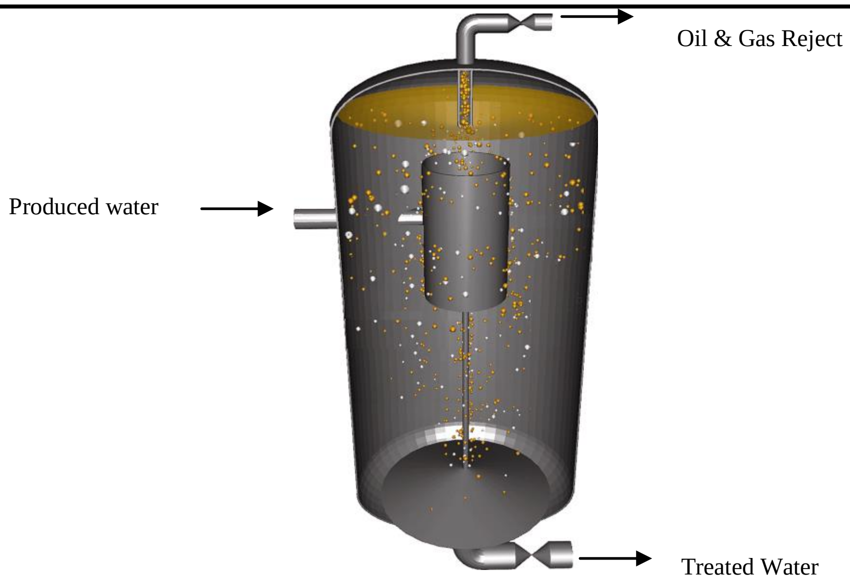
Table C - 14: In Vessel Coalescence Technology for Improved Performance of Deoiling Hydrocyclones		
Principle	Cartridge assembly containing specialised coalescence media installed into either the inlet chamber of the Deoiling Hydrocyclone vessel or into a vessel located upstream of the PWT system. The inlet chamber of a conventional Deoiling Hydrocyclone can have a residence time of up to 20 seconds. This residence time is used constructively to achieve partial droplet coalescence while maintaining a high insensitivity to solids blocking. This is achieved by optimising a number of the technology design parameters including media material selection, media density, media surface treatment, flow regime and mechanical orientation. The resulting enhanced coalescence activity can boost the performance of the downstream deoiling hydrocyclones and reduce the oil in water concentration in the discharge stream by up to 80%. Installing this technology in the inlet chamber of a deoiling hydrocyclone vessel has many benefits: • it allows flow velocities to be low (crucial for good coalescence) • technology can be retrofitted without the requirement of any modification to plant or hot work • Low risk and very cost effective to install (installation possible within one shift)	
Process diagram		
Basic elements	Cartridge housing typically constructed from 316L or Duplex Stainless Steel, containing support plates fitted with the optimised media material which is surface treated to optimise performance for specific applications.	
Suitable for the removal of:	Hydrocarbons ■ **Dispersed oil** ■ **Dissolved oil (partially)**	☐ Other contaminants **(specify)** **See table at the bottom of the next page**
	Remarks:	

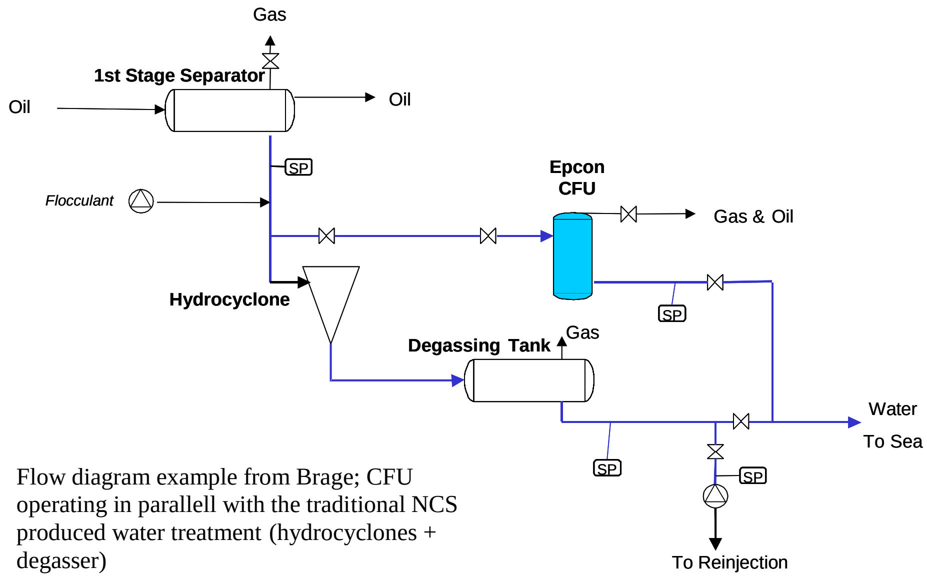
Technical details	**Per Unit**	Minimum Maximum
	Treatment capacity (m3 produced water per hour)	Units can be designed for any capacity. Typical capacities are to 5 000 m3/h
	Gross Package volume (LxWxH)	As the unit normally fits inside an existing vessel, there is no additional space required.
	Operating weight	Weight typically ranges from 10 to 300 kg, depending on the size of unit
	CAPEX (€)	CAPEX typically ranges from € 5 000 to €100 000 depending on the capacity
	OPEX (€/year)	OPEX is normally nil
	Cost per m^3 produced water(€/m^3)	Based on 4 years continuous operation, < € 0,01/m^3
Critical operational parameters	Temperature, droplet size, water density, viscosity, wax content, solids content and type.	
Operational reliability, incl. information on downtime	On the basis that the unit is operated and maintained fully in accordance with the O & M Manual, then operational reliability has been found to be very high. Only minimal downtime is required to remove the cartridge from the Hydrocyclone vessel for cleaning, unless media is to be replaced.	
	Remarks:	
Cross media effects	**Air**	Not applicable
	Energy	No energy input required
	Added chemicals	The technology is structurally insensitive to typical oilfield chemicals e.g. corrosion inhibitor, scale inhibitor, demulsifier although its performance improvement potential can be influenced by excessive addition of some corrosion and scale inhibitors since these chemicals can have a dramatic impact on the water chemistry (particularly interfacial tension).
	Waste	The technology does not generate any specific waste
Other impacts	**Health and safety**	None – Passive, no moving parts
	Maintenance interval & availability (% per year)	It is recommended that the internals are inspected on an annual basis. Availability > 99.8%

Practical experience	**General**	**Onshore / Offshore**
State of development	■ Implemented offshore, commercial technology ☐ Used onshore ☐ Offshore field trials ☐ Testing	Practical applicability: The technology is a highly practical technology, suitable both for new facilities and for retrofits
		Driving force for implementation (e.g. legislation, increased yield, improvement product quality): OSPAR Legislation Improved Hydrocyclone Performance Operator stretch targets
		Example plants: Britannia, Bruce, Nelson, Draugen, Heidrun, Balmoral
Literature source	"Choosing Produced Water Treatment Technologies Based on Environmental Impact Reduction", SPE Paper 74002. "Performance Enhanced Hydrocyclone Systems: Development & Field Experience", 7th IBC Production Separation Systems, Oslo, 23rd – 25th May 2000. "A Novel Pre-Coalescence Technology to Improve Deoiling Hydrocyclone Efficiency" 3rd IBC Water Management Offshore, Stavanger, 20thMay 1999.	

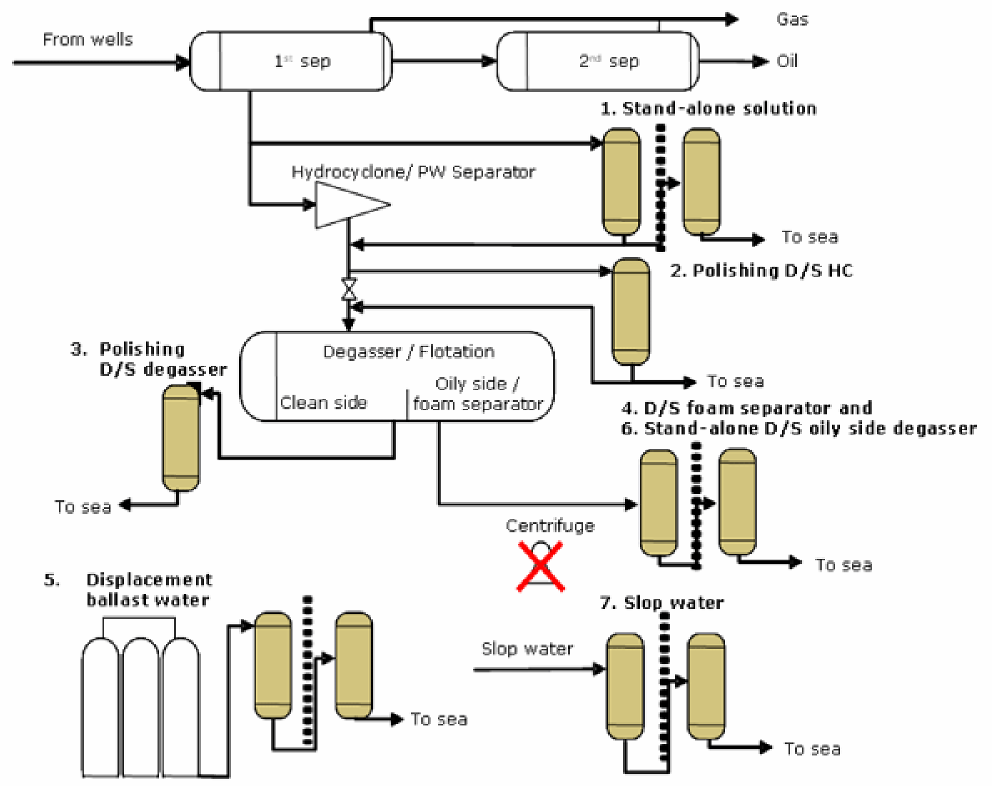
	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					Field test reports.
- Dispersed oil	√	√	Up to 99%	Up to 99%	Commissioning reports.
- Dissolved oil	√	√	> 50%	> 50%	"Choosing Produced Water Treatment Technologies Based on Environmental Impact Reduction", SPE Paper 74002. "Performance Enhanced Hydrocyclone Systems: Development & Field Experience", 7th IBC Production Separation Systems, Oslo, 23rd – 25th May 2000. " A Novel Pre-Coalescence Technology to Improve Deoiling Hydrocyclone Efficiency", 3rd IBC Water Management Offshore, Stavanger, 20thMay 1999.
Specific oil components:					Whilst the technology is primarily designed to remove free oil droplets, reports (eg SPE paper 74002) show that BTEX's and PAH's often partition to a significant proportion into free oil droplets. Therefore, the technology can reduce the total discharges of BTEX's and PAH's. The actual efficiency will depend on the chemistry of the application, which will vary widely from platform to platform. No work has been done on the effectiveness of the technology on NPD's.
- BTEX	√	√	> 50%	> 50%	
- NPD	Unknown	Unknown	Unknown	Unknown	
- PAH's 16 EPA	√	√	> 50%	> 50%	
- Others (indicate)					
Heavy metals	*	*	*	*	* Heavy metals will only be removed if they partition into the free oil phase.
Offshore chemicals					* The technology is not affected by these oilfield chemicals. The extent of removal of these chemicals depends on the extent to which they partition into the oil phase.
- methanol	*	*	*	*	
- glycol	*	*	*	*	
- corrosion inhibitors	*	*	*	*	
- biocides	*	*	*	*	
- scale inhibitors	*	*	*	*	
- surfactants	*	*	*	*	
- others (indicate)	*	*	*	*	

<table>
<tr><th colspan="2">Table C - 15: Compact Flotation Unit (CFU) Separation process</th></tr>
<tr><td>Principle</td><td>The CFU is a vertical pressure vessel separating oil and gas from produced water. The CFU is a compact unit with detention time down to 0.5 minute. Centrifugal forces (G-forces up to 10-20) and gas-flotation enhance the separation process. The produced water inlet is tangential on the CFU vessel. Oil droplets are coalesced into larger agglomerates during the transport through the vessel. The CFU has a compact design making it especially suitable for offshore installations where space is a limiting factor. The technology is flexible, and once optimised for site specific conditions, simple in operation. Several stages can easily be added in series or in parallel to improve treated quality, to account for changes in upstream facilities or to increase capacity according to the flexibility needed on site. Smaller units can be used to treat problematic fluids separately from the bulk fluid.

The oil and gas together with a small amount of water is skimmed from the surface by a suspended pipe. The oil content in the reject varies from 10 to 50 %. Typically, the reject is approximately 1 % of the total flow. Treated water exits the vessels at the bottom outlet for discharge to sea, produced water re-injection or to further water treatment downstream. The reject is routed to the closed drain or to a separate treatment stage depending on local requirements. The effectiveness of flotation depends on the amount of residual gas present in the produced water. When limited or no gas is available in the system, the effectiveness of the flotation process is maintained by injecting additional gas (nitrogen or fuel gas) upstream of each CFU vessels. The amount of gas injected is ≤ 0.1 Sm^3/m^3 produced water per vessel. Normal operation pressure will be from 0.5 barg and upwards. Flocculants will occasionally aid the effectiveness of the separation process.</td></tr>
<tr><td>Process diagram</td><td>



Flow diagram example from Brage; CFU operating in parallell with the traditional NCS produced water treatment (hydrocyclones + degasser)</td></tr>
</table>



Comparisons of the CFU vs. traditional produced water trains.

Comparable information	Relative comparison of the CFU applied offshore		
	Hydrocyclones and degasser	1 stage CFU	2 stages CFU
Capacity basis Bpd m^3/h	 81,000 540	 81,000 540	 81,000 540
Wet weight (metric tons)	45	8	16
Footprint (m^2)	30	6	12
Performance OiW (mg/l)	<40	<30	<10
Sensitivity to upstream - oil slugging - flow variation - solids - gas - movement (FPSO)	 High High High Sensitive (<5%) Low	 Less sensitive Low Low Not sensitive Low	 Low Low Low Not sensitive Low
Minimum inlet pressure required (barg)	5	0.7	1.5
Performance on high pressure	Good	No negative effect, but only tested to 30 bars	
CAPEX	High	Low	Medium
OPEX	High	Low	Low

Source: Vik and Engebretsen, 2005

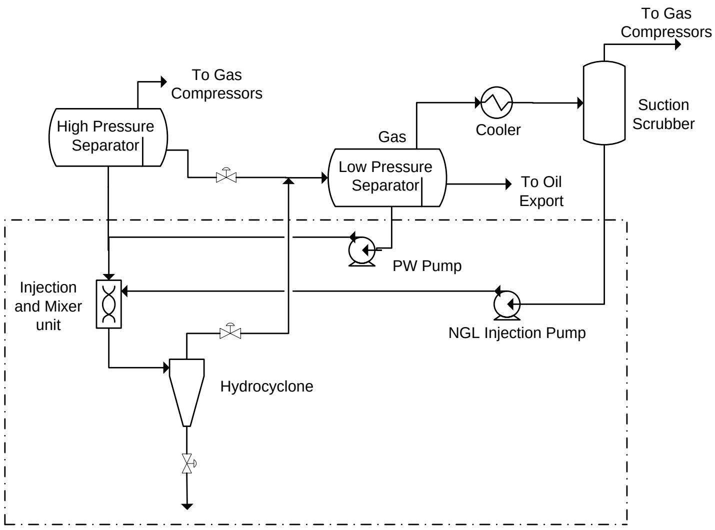
Basic elements	Gas flotation combined with centrifugal forces (Soft cyclone) and coalescing effect.	
Suitable for the removal of:	**Hydrocarbons** Dispersed oil droplets down to 3 µm droplet size	✓ **Other contaminants** (specify) PAH, BTEX, phenols (C5+), Oil soluble chemicals

Technical details	Treatment capacity (m^3/h) 1)	Minimum 3 m^3/h	Maximum 2200 m^3/h
	Gross Package volume (LxWxH) Operating weight CAPEX (€) OPEX (€/year)	3.5 x 2.5 x 3.5 m 2) Dry weight 6.5/11 tons 2) NOK 7 million (€ 900.000) (Duplex steel)3) Minimal: no maintenance, no energy required	
	Remarks: 1. Capacity mentioned is related to projects installed or under installation. 2. Figures on weight and footprint is based on CFU standard equipment 2xCFU220 (540 m^3/h). 3. CAPEX & OPEX is related to same standard equipment		
Critical operational parameters	Oil droplet size, surfactants stabilising small oil droplets, gas in water, some well and operational chemicals backflowed to the produced water system, oil coated solids		
Operational reliability, incl. information on downtime	100% reliable, no downtime, no maintenance on the technology equipment, no operators, no rotating parts or small bore openings. Large operational window (down to 20% of design flow). Not vulnerable for solids or scaling.		
	Remarks: Regarded as proven technology by Norsk Hydro, Statoil, ConocoPhillips, Shell, ChevronTexaco and others.		
Cross media effects	**Air**	No impact on air. Gas is returned to the oil system.	
	Energy	Low or no additional energy needed. The pressure drop is down to 0.5 bar	
	Added chemicals	If needed in general process (flocculant)	
	Waste	No waste generation. Oil and gas are normally returned to oil system	
Other impacts	**Health and safety**	No negative effects. If high benzene concentrations in produced water, special precautions needed during water sampling	
	Maintenance interval & availability (% per year)	Limited maintenance required for the CFU since solids are not accumulated in the system. Maintenance during normal shutdown periods.	
Practical experience	**General**	**Onshore / Offshore**	
State of development	✓ Implemented offshore (15) ✓ Offshore field trials (37)	Practical applicability: Offshore / Onshore The Compact Flotation Unit (CFU) was first installed offshore on the Norwegian Continental Shelf (NCS) in 2001, and has since then been further developed, tested and installed on several installations.	
	Driving force for implementation (e.g. legislation, increased capacity, improved water quality): Legislation and economic drivers caused by increased water cut		

Literature source	*Descousse, A., Mönig, K. and Voldum, K. (2004): Comparison of new and traditional produced water treatment technologies for their potential to remove dissolved aromatic components, 2nd Produced Water Workshop 21-22 April 2004, NEL East Kilbride, Glasgow* *Dolonen, O.S. (2004): Operational experiences at Snorre/Vigdis. Produced Water – Zero Discharge. Myth or Reality? Tekna 15-16 January 2004, Stavanger, Norway* *Hammerstad, T. and Rinde, S. (2004): New purification technology lowers discharges on Troll. Hydro, 5.07.2004. Presentation on OTC, Houston. Http://www.hydro.com/cgi-bin/* *Jahnsen, L. (2004): Epcon CFUs- a produced water treatment technology improving environment and efficiency of oil production, International Seminar on Oilfield Water Management, Rio, Brasil August 16th – 18th4* *Jahnsen, L. (2005): Epcon CFU Technology: The alternative to traditional produced water treatment systems. Russian Arctic Offshore and CIS Continental Shelf, September 13-15, 2005, St.Petersburg, Russia* *Jahnsen, L. (2005): Epcon CFU Technology – A produced water treatment technology improving the environment and the efficiency of oil production, Iran Oil & Gas Show, April 14th 2005* *Jahnsen, L. and Vik, E.A. (2003): Field Trials with Epcon Technology for Produced Water Treatment, Produced Water Workshop 26th-27th March 2003, NEL East Kilbride Glasgow* *Pollestad, A. (2005): The Troll Oil Case – Practical Approach Towards Zero Discharge. Tekna Produced Water Conference 18-19 January 2005, Tekna* *Vik, E. A. (2005): Environmental Risk Based Wastewater Treatment in the E&P Industry. Editorial Input to Business Briefing: Exploration & Production: The Oil & Gas Review* *Vik, E.A. and Bruås, L. (2005): Results of the Epcon CFU Zero Discharge Tests. Case studies 2001-2005. Aquateam Report no. 04-025. Version 2.* *Vik, E.A. and Engebretsen, S. (2005a): Documentation of Performance of the Epcon CFU Process. Case Studies Year 2001-2005. Aquateam Report No. 05-039* *Vik,E.A. and Dinning, A.J. (2005): Upscaling the Epcon CFU Technology. Comparison of test and full scale performance data from 2000-2005. Aquateam Report No. 05-057.* *Vik, E.A. and Engebretsen, S. (2005): Technology Assessment of Epcon CFU. Aquateam Report No.05-052.* *Vik, E.A., Folkvang, J., Jahnsen, L. and Oseroed, S.E. (2002): Improved Offshore Produced Water Treatment and Increased Technical Flexibility using the Epcon Compact Flotation Unit. Discussion of Case Studies from Norsk Hydro Brage and Troll C Platforms, 13th International Oil Field Chemistry Symposium, Norwegian Society of Chartered Engineers.*

	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					Applications have so far focussed on oil installations
- Dispersed oil	✓	☐	80-95	☐	Removal efficiency depends on starting point (Vik and Engebretsen, 2005 a)
- Dissolved oil	☐	☐	Low	☐	
Specific oil components:					Vik and Bruås (2005).
- BTEX	✓	☐	40-80	☐	BTEX removal is dependent on the gas rate used (stripping effect) and the cleanliness of the gas with respect to BTEX. Removal efficiency of other compounds are depending on starting level in the water
- NPD	✓	☐	45-60	☐	
- PAH's 16 EPA	✓	☐	60-85	☐	
- Naphthalenes	✓	☐	40-60	☐	
- C6-C9 phenols	✓	☐	40-60	☐	
Heavy metals	☐	☐	☐	☐	Not measured
Offshore chemicals					Not measured, but expected to have same removal efficiency for removing oil soluble chemicals as for removing dispersed oil, but reduced efficiency for removing water soluble chemicals. Efficiency is related to degree of water solubility.
- methanol	☐	☐	☐	☐	
- glycol	☐	☐	☐	☐	
- corrosion inhibitors	☐	☐	☐	☐	
- biocides	☐	☐	☐	☐	
- scale inhibitors	☐	☐	☐	☐	
- surfactants	☐	☐	☐	☐	
- others (indicate)	☐	☐	☐	☐	

<table>
<tr><th colspan="4">Table C - 16: Condensate induced extraction</th></tr>
<tr><td>Principle</td><td colspan="3">Condensate induced extraction is based on extraction of hydrocarbons from produced water, using condensate (NGL) from a suction scrubber in the production stream. Condensate (NGL) is injected and mixed with the produced water stream, by means of a special designed injection & mixing system.
The condensate acts as a solvent, i.e. extracts the water soluble aromatic components from the water into the condensate phase. The condensate and the oil particles coalesces into larger, low-density droplets that are efficiently separated from the produced water by the downstream separation unit (i.e. hydrocyclone, compact flotation unit or similar).

The condensate requirement for a given removal efficiency is proportional to feed Oil-in-Water concentration into the condensate induced extraction process.</td></tr>
<tr><td>Process diagram</td><td colspan="3">
</td></tr>
<tr><td>Basic elements</td><td colspan="3">Condensate, injection & mixing system</td></tr>
<tr><td rowspan="2">Suitable for the removal of:</td><td colspan="2">Hydrocarbons
√ Dispersed oil
√ Dissolved oil</td><td>☐ Other contaminants (specify)
Production chemicals with
Log (octanol/water partition) greater than 2.0.
See table at the bottom of the next page</td></tr>
<tr><td colspan="3">Remarks:
For dissolved oil: the technique is suitable for the removal of dissolved aromatic hydrocarbons.</td></tr>
<tr><td>Technical details</td><td>Per Unit (typical)*

Treatment capacity (m3 produced water per hour)
Gross Package volume, LxWxH, m
Operating weight, tons
CAPEX (€)
OPEX (€/year)
Cost per m3 produced water(€/m3)</td><td>Minimum

10

3 x 1.5 x 2
3
0,5 million</td><td>Maximum

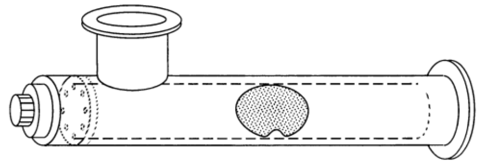
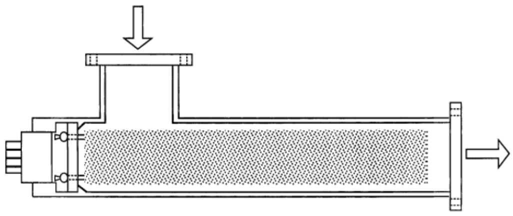
500

10 x 2 x 3
13
1,5 million</td></tr>
<tr><td>Critical operational parameters</td><td colspan="3">Produced water pressure must be sufficiently high to keep the condensate in the liquid phase during the separation process. If the operating pressure does not match the phase properties of the condensate, boosting of the produced water or condensate processing might be required. This can be done without compromising the extraction process efficiency.</td></tr>
</table>

Operational reliability, incl. information on downtime	The condensate induced extraction process is highly reliable, presumed operating within the design specifications and with a reasonable sparing philosophy.	
	Remarks: Costs for retrofit implementation of the condensate induced extraction process are case specific, depending on field specific conditions and the target removal efficiency.	
Cross media effects	**Air**	
	Energy	Energy for pumping (and potentially condensate processing)
	Added chemicals	none
	Waste	none
Other impacts	**Health and safety**	Reclassification of the produced water system to a hydrocarbon containing system.
	Maintenance interval & availability (% per year)	
Practical experience	**General**	**Onshore / Offshore**
		On and Offshore
State of development	✓ Implemented offshore ✓ Used onshore ✓ Offshore field trials ✓ Testing	Practical applicability: This can be done without compromising the extraction process efficiency. Driving force for implementation (e.g. legislation, increased yield, improvement product quality): Legislation and economic drivers caused by increased water cut Example plants: Successful testing at: Statfjord B and C Ekofisk 2/4J Snorre A Aasgard A Troll C Full-scale implementation at: Statfjord A, 2000 m3/h Statfjord B, 3000 m3/h Statfjord C, 4300 m3/h Snorre A, 1000 m3/h Ekofisk 2/4J&M, 2000 m3/h
Literature source		

	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					
- Dispersed oil	√	√	95	95	
- Dissolved oil	√	√	95	95	.
Specific oil components:					
- BTEX	☐	☐	90 (*)	80 (*)	
- NPD	☐	☐	90	90	
- PAH's 16 EPA	☐	☐	95	95	
- Others (indicate)	☐	☐	☐	☐	
Heavy metals	☐	☐	☐	☐	
Offshore chemicals					
- methanol	☐	☐	☐	☐	
- glycol	☐	☐	☐	☐	
- corrosion inhibitors	√	√	40 (**)	40 (**)	
- biocides	☐	☐	☐	☐	
- scale inhibitors	☐	☐	☐	☐	
- surfactants	☐	☐	☐	☐	
- others (indicate)	☐	☐	80 (***)	80 (***)	

Removal efficiency is referenced to a standard hydrocyclone discharge of 20 ppm. (*) Removal efficiency depending on BTEX content of condensate. (**) Specific class of corrosion inhibitors. (***) Log (octanol/water partition) greater than 2.0.

Table C - 17: Tail shaped pre-coalescer			
Principle	In a tail shaped pre-coalescer, fluid enters the coalescer housing via an axial inlet nozzle, and then is forced to flow along the housing in the same longitudinal direction as the fibrous coalescer bundle. As fluid travels along the oleophilic fibres, small oil droplets are retained on the surface of the fibres. The droplets coalesce with other droplets on the fibre surface, and therefore grow as they migrate along bundle towards the outlet. Fluid drag increases as the droplet diameter grows, and eventually larger droplets are released at the end of the bundle. It is important to note that there is no phase separation in the coalescer. All the inlet fluid leaves through a common outlet, but the outlet mean droplet size is considerably enhanced, leading to easy gravity separation downstream. The coalescing action occurs within two seconds in the bundle, making a very compact device. The combination of flow along the fibres, rather than across as conventional coalescers, and relatively high fluid velocities, mean that solids are generally passed straight through the coalescer, and the product is therefore much less sensitive to fouling than conventional coalescing media.		
Process diagram	 FIGURE 1  FIGURE 2		
Basic elements			
Suitable for the removal of:	**Hydrocarbons** ✓ **Dispersed oil** ✓ **Dissolved oil**	☐ **Other contaminants** (specify) **See table at the bottom of the next page**	
	Remarks: The technology itself, does not actually remove oil but improves the performance of downstream equipment (such as hydrocyclones) by coalescing the oil droplets and making them easier to separate. Hence the name pre-coalescer. Use of the technology upstream of hydrocyclones has been shown in practice that both dispersed and dissolved (naphthalenes, 2-4 ring PAH and C6-C9 phenols) oil removal can be enhanced.		
Technical details	Per Unit	Minimum	Maximum
	Treatment capacity (m3 produced water per hour)	Lower limit is typically 5 m3/hr for a 2” diameter unit	Largest units built to date have capacity of 260 m3/hr (per single unit)
	Gross Package volume (LxWxH)	Approx 2.2 x 0.07 x 0.2 m	Approx 3.5 x 0.5 x 1.0 m
	Operating weight	Approx 30 kg	Approx 1500 kg
	CAPEX (€)	Approx €15,000 (duplex)	Approx €90,000 (duplex)
	OPEX (€/year)	Unknown – insufficient operating data	Unknown – insufficient operating data
	Cost per m3 produced water(€/m3)		
Critical operational parameters	Must be at least 0.5 bar head available at inlet to pre-coalescer to drive liquid through unit. Pressure drop across unit during normal operation requires monitoring. Media is typically changed out when the pressure drop reaches 3 bar.		

<table>
<tr><td>Operational reliability, incl. information on downtime</td><td colspan="2">Yet to be fully established as number of full scale units in service is limited. Field tests have shown that pilot scale units can operate reliably for 3 months or more before the media requires changing. Media changeout takes only a short time, after which the unit can be brought back in service.

The technology is not recommended in applications where wax dropout occurs or where naphthanates are present in the produced water.</td></tr>
<tr><td></td><td colspan="2">Remarks:</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td></td></tr>
<tr><td>Energy</td><td></td></tr>
<tr><td>Added chemicals</td><td>Certain oilfield chemicals should not injected upstream of the technology. In particular, deoilers injected upstream will have a detrimental effect on the coalescing performance, as the media strands can stick together as a result of chemical action.</td></tr>
<tr><td>Waste</td><td></td></tr>
</table>

<table>
<tr><td rowspan="2">Other impacts</td><td>Health and safety</td><td>Disposal of oil wetted media needs to be considered. This can be packed into specially designed shipment containers for return to shore.</td></tr>
<tr><td>Maintenance interval & availability (% per year)</td><td>Pressure drop should be checked daily. Operational availability should be > 95%.</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="2" align="center">General</td><td align="center">Onshore / Offshore</td></tr>
<tr><td colspan="2"></td><td></td></tr>
<tr><td rowspan="3">State of development</td><td colspan="2" rowspan="3">✓ Implemented offshore
☐ Used onshore
✓ Offshore field trials
✓ Testing</td><td>Practical applicability: Applicable for both offshore and onshore applications. Easy to install.</td></tr>
<tr><td>Driving force for implementation (e.g. legislation, increased yield, improvement product quality):

Legislation, improvement in discharges to sea (reduction in oil discharged)</td></tr>
<tr><td>Example plants: Shell Pierce field (recently installed), offshore Brazil</td></tr>
<tr><td>Literature source</td><td colspan="3"></td></tr>
</table>

	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					
- Dispersed oil	✓	✓	n.i.	n.i.	
- Dissolved oil	✓	✓	n.i.	n.i.	
Remark: The tail shaped pre-coalescer technology only promotes oil droplet growth and does not remove the oil in itself. Offshore trials have demonstrated that the use of the technology upstream can lead to significantly enhanced dispersed oil and dissolved oil removal. Oil droplet growth can be typically 400% growth in the median oil droplet size.					
Specific oil components:					
- BTEX	n.i.	n.i.	n.i.	n.i.	
- NPD	n.i.	n.i.	n.i.	n.i.	
- PAH’s 16 EPA	n.i.	n.i.	n.i.	n.i.	
- Others (indicate)	n.i.	n.i.	n.i.	n.i.	
Remark: Offshore analysis has shown that the use of the technology upstream of hydrocyclones has resulted in an improvement in the removal of both dispersed and dissolved (naphthalenes, 2-4 ring PAH and C6-C9 phenols) oil removal.					
Heavy metals	☐	☐	☐	☐	
Offshore chemicals					
- methanol	☐	☐	☐	☐	
- glycol	☐	☐	☐	☐	
- corrosion inhibitors	☐	☐	☐	☐	
- biocides	☐	☐	☐	☐	
- scale inhibitors	☐	☐	☐	☐	
- surfactants	☐	☐	☐	☐	
- others (indicate)	☐	☐	☐	☐	

<table>
<tr><th colspan="3">Table C - 18: Advanced Oxidation Process</th></tr>
<tr><td>Principle</td><td colspan="2">All AOP systems degrade organic species by utilising the powerful hydroxyl radical ($OH^{\cdot}$). This results in degradation of the organics to carbon dioxide, water and inorganic salts. The UV/O_3 process is the best developed AOP method currently available to industry. The generation of the hydroxyl radicals is thought to happen by one of the following processes:

$O_3 \xrightarrow{h\upsilon} O_2 + O^{\cdot}$ (1)

$O^{\cdot} + H_2O \longrightarrow 2OH^{\cdot}$ (2)

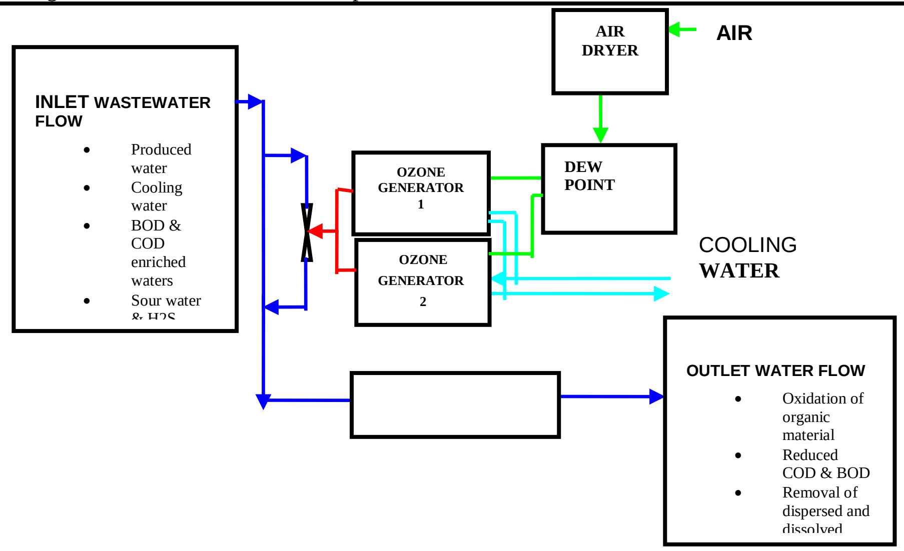
$O_3 + H_2O \xrightarrow{h\upsilon} H_2O_2 + O_2$ (3)

$H_2O_2 \xrightarrow{h\upsilon} 2OH^{\cdot}$ (4)

With the production of the Hydroxyl radicals, interaction with an organic substrate can occur by a number of reaction mechanisms of which the most likely to occur is the Hydrogen abstraction process:

$OH^{\cdot} + RH \qquad R^{\cdot} + H_2O$ (5)

On completion of this reaction an organic radical is produced ($R^{\cdot}$) which will start a series of chain reactions that will eventually lead to the complete mineralisation of the organic molecule.

Ozone may be injected into the waste-water stream as part of an airstream. The ozone starts to react with the water to form hydroxyl radicals but this process is enhanced in the presence of Ultraviolet light. Following injection of ozone, the water is passed through a vessel containing Ultraviolet lamps, encased in quartz glass. This is the essence of the process.</td></tr>
<tr><td>Process diagram</td><td colspan="2">
</td></tr>
<tr><td>Basic elements</td><td colspan="2">Ozone injection and UV vessel</td></tr>
<tr><td rowspan="2">Suitable for the removal of:</td><td>Hydrocarbons

✓ Dispersed oil

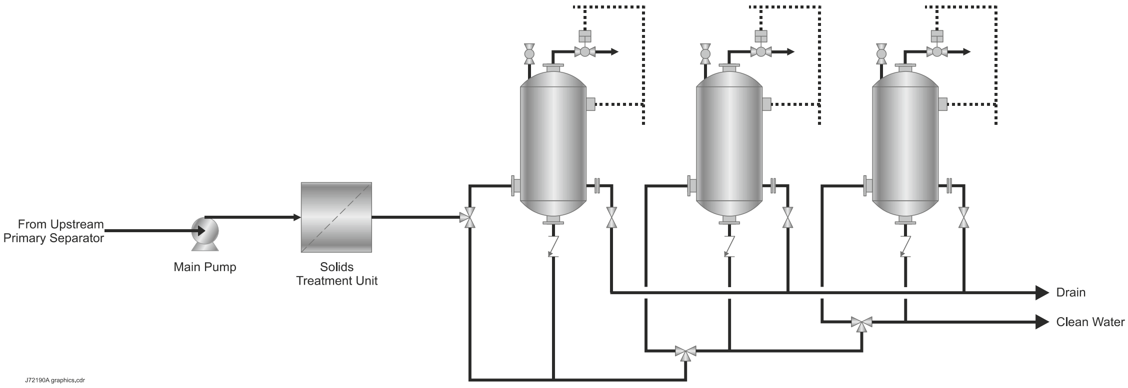
✓ Dissolved oil</td><td>✓ Other contaminants (specify)

See table at the bottom of the next page</td></tr>
<tr><td colspan="2">Remarks:</td></tr>
</table>

Technical details	Per Unit Treatment capacity (m3 produced water per hour) Gross Package volume (LxWxH) Operating weight CAPEX (€) OPEX (€/year) Cost per m3 produced water(€/m3)	Minimum No minimum, nominally $2M^3$/hour 2 x 1.5 x 2 3000 Kg 400,000 40,000 25 (in first year – 2.28 thereafter)	Maximum No Maximum – Built up in units of 70 – $350M^3$/hour 3.5 x 1.5 x 2 5000 Kg 750,000 75,000 0.27 (in first year – 0.024/year thereafter))
Critical operational parameters	Requires dry air, cooling water that is chloride free, and electrical power		
Operational reliability, incl. information on downtime	There should be little or no downtime as there is little in the way of moving parts in the kit. If the system fails, water will still flow through it.		
	Remarks:		
Cross media effects	**Air**	None	
	Energy	Requires 23 kW for 66 m^3/h unit	
	Added chemicals	None	
	Waste	None	

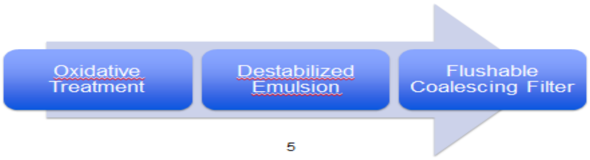
Other impacts	**Health and safety**	Ozone is toxic and operators must not be exposed to this gas
	Maintenance interval & availability (% per year)	Maintenance interval: Estimated at between 1- 6 months Availability: 95%+
Practical experience	**General**	**Onshore / Offshore**
State of development	☐ Implemented offshore ☐ Used onshore ✓ Offshore field trials ☐ Testing	Practical applicability:
		Driving force for implementation (e.g. legislation, increased yield, improvement product quality):
		Example plants:
Literature source	"A Practical Method for the Reduction of Hydrocarbon Concentration in Produced Water using an Advanced Oxidation Process", Sneddon et al, GPA, Bergen, 13th May 2002.	

	Suitable for		Removal Efficiency (Typical %)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					
- Dispersed oil	✓	✓	50	75	
- Dissolved oil	✓	✓	50	75	
Specific oil components:					
- BTEX	✓	✓	50	75	
- NPD	✓	✓	50	75	
- PAH's 16 EPA	✓	✓	50	75	
- Others (indicate)	✓	✓	[☐]	[75]	
Heavy metals	☐	☐	☐	☐	
Offshore chemicals					
- methanol	✓	✓	50	75	
- glycol	✓	✓	50	75	
- corrosion inhibitors	✓	✓	50	75	
- biocides	✓	✓	50	75	
- scale inhibitors	✓	✓	50	75	
- surfactants	✓	✓	50	75	
- others (indicate)	✓	✓	50	75	

<table>
<tr><th colspan="7">Table C - 19 : Screen (Cartridge Type) Coalescing Technique</th></tr>
<tr><td>Principle</td><td colspan="6">Screen (Cartridge Type) coalescing units facilitate separation of water and dispersed oil by a combination of adsorption, viscosity difference and gravity separation. Water & dispersed oil is passed through a cartridge of media under pressure differential. The media properties will temporarily adsorb oil to its surface and the viscosity difference between water and oil as they flow through the medias pores will encourage oil droplets to grow before being released to float to the surface of the unit. Media which becomes inactive or fouled can either be replaces or regenerated. One model of the process uses a back flow arrangement which utilises the oil to remove fouling from the media.</td></tr>
<tr><td>Process Diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic Elements</td><td colspan="6">The basic elements consist of an untreated water feed pump, two housing vessels (usually in series) containing one or more media cartridges. Associated oil recovery equipment may required; oil separator/water</td></tr>
<tr><td rowspan="2">Suitable for the removal of:</td><td>Heavy Metals
☐ Cadmium
☐ zinc equivalents
☐ Lead
☐ Mercury
☐ Nickel</td><td>R[%]</td><td>Production Chemicals
☐ Methanol
☐ Glycols
☐ Corrosion Inhibitors
☐ Anti-scale Solutions
☐ Demulsifiers</td><td>R[%]</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHs
Dispersed Oil
☒ Oil</td><td>R[%]

R[%]
*</td></tr>
<tr><td colspan="6">Remarks: There are examples of this technology that can accept and coalesce dispersed oil droplets as small as 0,5-2µm and can therefore separate some emulsified hydrocarbons. These systems will not remove dissolved oils. The systems are less effective at separating tight oil emulsions caused by the addition of certain detergents and process chemicals.</td></tr>
<tr><td rowspan="4">Technical Details</td><td colspan="4">Type of Installation</td><td>Gas 1</td><td>Gas 2   Oil 1</td></tr>
<tr><td colspan="4">Produced Water Volume (design)</td><td></td><td></td></tr>
<tr><td colspan="4">Area required for water treatment Installation</td><td></td><td></td></tr>
<tr><td colspan="4">Mass of equipment for water treatment installation</td><td></td><td></td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6">The oil being treated must be immiscible in water. A pre-filter must be used to prevent media fouling and performance deterioration. The feed pump used should be of a type to avoid emulsifying the solution, e.g. progressive cavity pump.</td></tr>
<tr><td>Operational Reliability</td><td colspan="6">The majority of these units will need a pre-filtration stage and the presence of solids in the produced water could require these to be changed out frequently.</td></tr>
</table>

Indication of Costs							
	Costs	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€/Year]			
		Present	New	Present	New		
	Gas Platform, small Gas Platform, large Oil Platform						
	Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
		Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
	Dissolved oil Dispersed oil Zinc equivalents						
	Remarks:						
Cross Media Effects	Air						
	Energy	Energy to run the feed pump					
	Added Chemicals	-					
	Waste	Spent media cartridges					
Other Impacts	Safety						
	Maintenance	Replacement of spent media cartridges and inspection of cartridges.					
Practical Experience	General			Offshore			
State of Development	☐ Implemented Offshore ☒ Used Offshore ☒ Offshore Field Trials ☒ Testing			Practical applicability: There are examples of this technology used offshore for well test and polishing produced water applications Driving force for implementation (e.g. legislation, increased yield, improvement product quality): Example plants: Accurate (June 2009): Various, Brazil, West Africa, Middle East.			
Literature Source	(TORR, A) TORR De-oiling technology overview document, www.prosep.com (TORR, 2009) TORR Produced Water Treatment Experience List, June 2009, www.prosep.com (SEPRATECH, 2007) Separatech COP FAQ Document, www.sepratech.com/copsystem, 2007						

Table C - 20 : TwinZapp	
Principle	**Oxidation / Filtration** The presence of corrosion inhibitors and foam lift can cause very stable emulsions. The solution is a combination of technologies - electrical oxidation (Elox) - separation / filtration (Fibra) Electrical oxidation cells consist of multiple pairs of metal electrodes separated by a few millimeters and arranged so that the water to be treated flows through the plates at a moderate rate, a direct current voltage is applied across the plates. Release of reactive oxygen, hydroxyl and other radicals destabilize the present surface-active components. The bulk of the solids as well as free oil created in the Elox is separated with a standard separator. The usually abundant neutrally buoyant particles (as a percentage of TSS) requires the use of the Fibra filter to finally reduce TSS along with associated oil ppm in the polishing step of the process. (pls refer to BAT on Fibra Cartridge Filter). Along with the free oil, the process addresses the presence of BTEX as well. Test results on produced water from the last skimmer of a Southern North Sea platform reduced free oil from ca. 500 to 3 ppm and BTEX from 50 to 6 ppm. Similar field tests verified reductions of this order of magnitude on produced water as well as slop water.
Process diagram	TwinZapp technology is a two-step approach to removal of dispersed as well as dissolved oil in produced water. Emulsions are destabilised using an electro-oxidation process. The contaminants are then removed using a coalescing filter.  Neither step makes use of consumables; the patented coalescer is fully re-generable, making this technique useful for unmanned installations. The required energy input is low at around 0.5 kW / m3. The simplest setup employs both steps in a serial setup operating on the last atmospheric skimmer tank. More detailed information is available on www.brilliantwater.org
Basic elements	Electro-oxidation followed by coalescing / filtration
Suitable for the removal of:	Hydrocarbons √ **Dispersed oil** √ **Dissolved oil** √ Other contaminants **(specify)** **BTEX, PAH's, surfactants, corrosion inhibitors**
	Remarks:

<table>
<tr><td rowspan="7">Technical details</td><td>Per Unit</td><td>Minimum</td><td colspan="2">Maximum</td></tr>
<tr><td>Treatment capacity (m3 produced water per hour)</td><td>1-5</td><td colspan="2">NA</td></tr>
<tr><td>Gross Package volume (LxWxH)</td><td>1.5 x 4.0 x 1.5 (estimated)</td><td colspan="2"></td></tr>
<tr><td>Operating weight</td><td>2.5 tonnes (estimated)</td><td colspan="2"></td></tr>
<tr><td>CAPEX (€)</td><td>None (rental)</td><td colspan="2"></td></tr>
<tr><td>OPEX (€/year)</td><td>300k EU / yr</td><td colspan="2"></td></tr>
<tr><td>Cost per m3 produced water(€/m3)</td><td>0.1 Eu / m3</td><td colspan="2"></td></tr>
<tr><td>Critical operational parameters</td><td colspan="4">Atmospheric conditions are required for a standard design unit.</td></tr>
<tr><td>Operational reliability, incl. information on downtime</td><td colspan="4">First unit will be in service as of April 2012. The longest field trial of 30 days has not indicated a requirement for service shorter than an estimated 3-6 month interval.</td></tr>
<tr><td></td><td colspan="4">Remarks:</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="3">50Nm3/hr</td></tr>
<tr><td>Energy</td><td colspan="3">0.5 kW / m3 electrical energy</td></tr>
<tr><td>Added chemicals</td><td colspan="3">None</td></tr>
<tr><td>Waste</td><td colspan="3">< 1% effluent to be disposed</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Health and safety</td><td colspan="3">None, ATEX certified</td></tr>
<tr><td>Maintenance interval & availability (% per year)</td><td colspan="3">(see earlier) > 3 months estimated interval, 12 hours downtime per interval.</td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="2">General</td><td colspan="2">Onshore / Offshore</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td rowspan="3">State of development</td><td colspan="2" rowspan="3">☐ Implemented offshore
☐ Used onshore
√ Offshore field trials
☐ Testing</td><td colspan="2">Practical applicability: lack of consumables make this suitable for all manned / unmanned installations without additional POB. Including slop water treatment systems.</td></tr>
<tr><td colspan="2">Driving force for implementation (e.g. legislation, increased yield, improvement product quality):
Improved water quality to far below 30 ppm free oil OSPAR discharge limits
No chemicals required.</td></tr>
<tr><td colspan="2">Example plants:</td></tr>
<tr><td>Literature source</td><td colspan="4"></td></tr>
<tr><td></td><td>Suitable for</td><td>Removal Efficiency
(%)</td><td colspan="2">Reference to source documentation</td></tr>
</table>

	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons					
- Dispersed oil	√	√	95	95	
- Dissolved oil	√	√	60	60	
Specific oil components:					
- BTEX	☐	☐	☐	☐	
- NPD	☐	☐	☐	☐	
- PAH's 16 EPA	☐	☐	☐	☐	
- Others (indicate)	☐	☐	☐	☐	
Heavy metals	☐	☐	☐	☐	
Offshore chemicals					
- methanol	☐	☐	☐	☐	
- glycol	☐	☐	☐	☐	
- corrosion inhibitors	☐	☐	☐	☐	
- biocides	☐	☐	☐	☐	
- scale inhibitors	☐	☐	☐	☐	
- surfactants	☐	☐	☐	☐	
- others (indicate)	☐	☐	☐	☐	

Table C - 21 : Fibra Cartridge	
Principle	Filtration/ Coalescing A filtration/coalescing technology based on the use of a bundle of fibre filaments placed in a cartridge (2 inch pipe). A special design of the element allows backwashing of the element. • Developed in a JV between Shell, Brilliant Water Investments and Twin Filter. • Patented technology. • No use of consumables, the patented Fibra Cartridge is fully re-generable, making this technique useful for unmanned installations. • The filter bed is formed from a bundle of fine fibres, potted at one end. • The bundle is mounted vertically in a vessel, and compressed quite close to the free end to form a fine filtration bed. • **<u>Compression is achieved by the flow of the liquid to be filtered.</u>** • Feed enters the filter vessel and flows through the bed to provide a clarified filtrate downstream of the compression point. The high physical removal means that where chemicals were traditionally used they may be unnecessary or greatly reduced, providing a lower cost, environmentally more acceptable filtration solution.
Process	• Based on depth filtration and effective for high dirt loads • An automatic flush technique allows the fibers to be cleaned simply in a matter of seconds using the filter liquid itself, without interruption of the process • Additional vibration shocks further clean the fibres • Minimal flush-loss • Can be combined with existing compressed air • External back flush pump not necessary • Removal of > 90% of particles above 3 µm • Open system, can be combined with UV for disinfection • No need for consumables (Low OPEX) • Compact: Single vessel of ø 600 mm allows up to 5-7 m3/hour • Low maintenance • Modular set-up • Fully automatic with PLC controller **Filtration / Coalescing** • Feed enters the filter vessel and permeates the bundle, flowing through the bed to provide clarified filtrate downstream of the compression point. • The fibre density at the entry is relatively low, becoming progressively tighter towards the compression point, thus providing an effective gradation of pore size. This ensures that reasonably high solids loadings can be dealt with. **Flushing** • When the cartridge element is getting plugged, which is detected through the pressure difference over the cartridges, an air purge forces a strong and very short (1-2 seconds) back flushing, providing recoveries of at least 95%. • Efficiency of the fibrous bed is high providing typical removals > 90% for particles above 3 µm. This means that the particulate removal capability is an order of magnitude finer than a granular media filter, and positions the technology between conventional filtration and membrane filtration. More detailed information is available on www.twinfibra.com

Basic elements	Normal Filter laid out for use with normal filter cartridges.		
Suitable for the removal of:	Hydrocarbons √ **Dispersed oil** Solids √ **(oil contaminated) Solids**		
	Remarks:		
Technical details	**Per Unit**	Minimum	Maximum
	Treatment capacity (m3 produced water per hour)	0,1	20
	Gross Package volume (LxWxH)	0,2 x 0,2 x 0,6	0,8 x 0,8 x 1,0
	Operating weight	20 kg	150 kg
	CAPEX (€)		
	OPEX (€/year)		
	Cost per m3 produced water(€/m3)		
Critical operational parameters	Atmospheric conditions are required for a standard design unit.		
Operational reliability, incl. information on downtime	First unit will be in service as of April 2012. The longest field trial of 30 days has not indicated a requirement for service shorter than an estimated 3 month interval.		
	Remarks:		
Cross media effects	**Air**	<1 Nm3/hr	
	Energy	<0,05 kW/m3, required to push liquid through filter	
	Added chemicals	None	
	Waste	< 1% effluent to be disposed	
Other impacts	**Health and safety**	None	
	Maintenance interval & availability (% per year)	6-12 months estimated interval, 1-2 hours downtime per interval. Reduced attention required. Filter cartridge changes greatly reduced. Causing less waste!	
Practical experience	**General**	**Onshore / Offshore**	
State of development	√ Implemented offshore √ Offshore field trials √ Onshore trials	**Practical applicability**: • Sea water re-injection (Oil&Gas) • Completion Fluid Filtration (Oil&Gas) • Reversed Osmosis pre-filtration • Replacement of Nominal filter cartridges: down to 1 micron , especially on unmanned platforms and remote locations, Sand Filters, Multi media filters and DE filters with and without body feed.	

		Driving force for implementation (e.g. legislation, increased yield, improvement product quality): • Reduced waste caused by used filter elements • Potential to use as a coalescing element on solids and oil contaminated waters • Solutions for improving produced water treatment system for polymer flooding (coalescing element!) •
		Example plants:
Literature source		

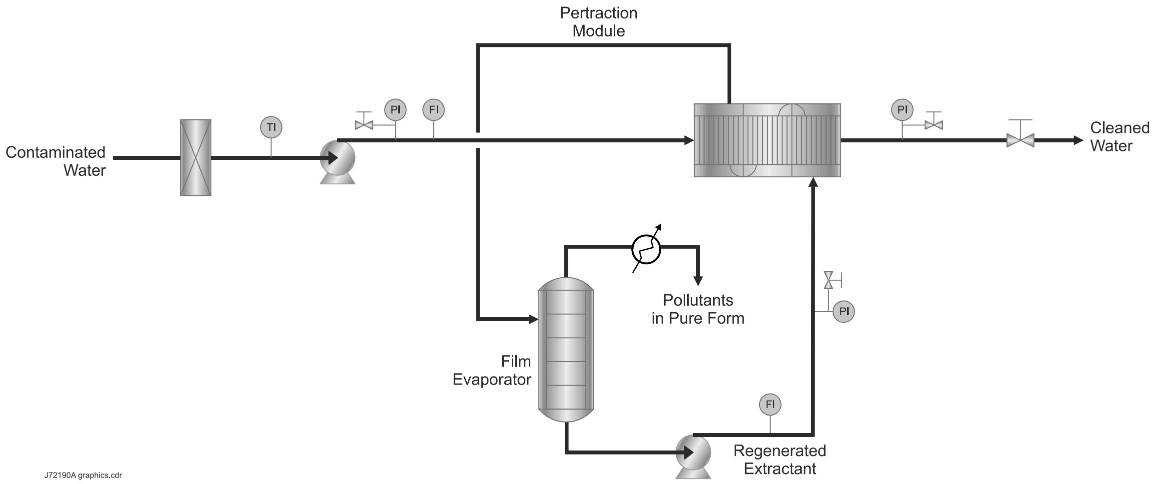
	Suitable for		Removal Efficiency (%)		Reference to source documentation
	Oil installations	Gas installations	Oil installations	Gas installations	
Hydrocarbons - Dispersed oil - Dissolved oil Specific oil components: - BTEX - NPD - PAH's 16 EPA - Others (indicate)	√	√	>95	>95	Depending on droplet size distribution.
Heavy metals	☐	☐	☐	☐	
Offshore chemicals - methanol - glycol - corrosion inhibitors - biocides - scale inhibitors - surfactants - others (indicate)	☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐	

Table C - 22 : Pertraction

Principle

Pertraction involves extracting organic substances such as aromatics or chlorinated hydrocarbons from process water through a membrane; pollutants from process water dissolve into an organic extractant through the membrane. The membrane prevents mixing of the two phases; therefore, no separation of water and extractant is necessary. The membrane allows for independent control of both phase flows for relatively easy process optimisation. Pertraction installations can be considered a flexible and compact alternative to conventional techniques like air stripping or activated carbon filtration.

Process Diagram



Basic Elements

Contaminated Water Pump, Pertraction Module, Vacuum film Evaporator, Extractant booster pump

Suitable for the removal of:

Heavy Metals	R[%]	Production Chemicals	R[%]	Oil	R[%]
☐ Cadmium		☒ Methanol	*	☒ Dissolved Oil	*
☐ zinc equivalents		☒ Glycols	*	☐ BTEX	
☐ Lead		☐ Corrosion Inhibitors		☐ Benzene	
☐ Mercury		☐ Anti-scale Solutions		☒ PAHs	*
☐ Nickel		☐ Demulsifiers		Dispersed Oil	R[%]
				☐ Oil	

Remarks: Pertraction has been shown to be economically attractive for chlorinated solvents, PCB's, di- and tri-chlorobenzene, pesticides and higher polycyclic hydrocarbons. A full scale installation, with a capacity of 15 m3/hr has been operated successfully in an industrial plant. In particular for low pollutant concentrations, this process is very efficient. Removal of dissolved components from waste water produced by the oil & gas industry is proven in the laboratories.

Technical Details

Type of Installation	Gas 1	Gas 2	Oil 1
Produced Water Volume (design)			
Area required for water treatment Installation			
Mass of equipment for eater treatment installation			

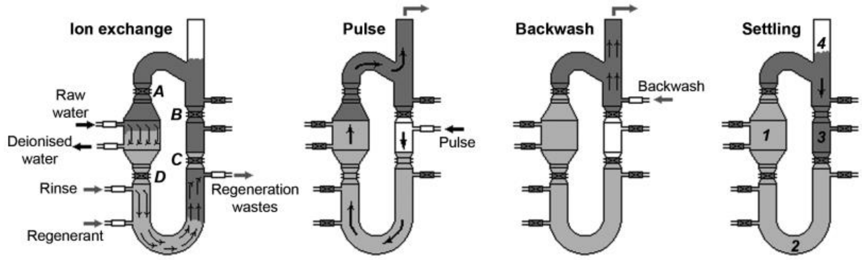
Critical Operational Parameters

The pollutants being removed must have a strong affinity to the extract ant used. There is potential for this process to utilise recovered process fluids as extract ant. The independent nature of the fluid flows suggests that the risk of cross contamination from objectionable components is low.

Operational Reliability

The efficiency of the process will be affected by the reliability of the evaporator unit which will remove pollutants from the extract solvent. Membrane regeneration requirements are unknown for Oil & Gas applications.

Indication of Costs							
	Costs	Investment Costs (CAPEX) [€]			Exploitation Costs (OPEX) [€/Year]		
		Present		New	Present		New
	Gas Platform, small Gas Platform, large Oil Platform						
	Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
		Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]	Existing [€/kg]	New [€/kg]
	Dissolved oil Dispersed oil Zinc equivalents						
	Remarks:						
Cross Media Effects	Air	-					
	Energy	Booster pumps and vacuum pumps will place an energy demand on the system, details of which will depend on scale up requirements as the technique is developed.					
	Added Chemicals	-					
	Waste	Depending on their nature and concentration, pollutants may either be recycled or collected for disposal.					
Other Impacts	Safety						
	Maintenance	Cleaning or replacement of the membrane; maintenance demands associated with vacuum equipment.					
Practical Experience	General			Offshore			
	Small scale plant.			No offshore application.			
Conclusion	☐ Implemented Offshore ☐ Used Offshore ☐ Offshore Field Trials ☒ Testing			Practical applicability: Driving force for implementation (e.g. legislation, increased yield, improvement product quality): Example plants: There is a pilot industrial plant (15m3/Hr) which has been used as a test facility.			
Literature Source	(TNO, 2005) Separation Technology, Pertraction for Water Treatment, IT-A 015e/18-02-2005, www.TNO.nl						

Table C - 23: ION EXCHANGE	
Principle	Ion exchange is the removal of specific ions or compounds through the exchange of pre-saturated ions with target ions. It is most commonly used in produced water for the removal of salt and other inorganic chemicals such as calcium, magnesium, barium, strontium and radium if using cation exchange resins or fluoride, nitrates, fulvates, humates, arsenate, selenate and chromate if using anion exchange resins . The produced water is passed through columns containing charged resin which attracts the ions and bind with the chemicals. The resins can be designed to selectively remove a specific chemical and mixed beds may be designed to remove cations and anions. The resins require period backwashing (often with an acid) and recharging, and the ions that have been removed then require disposal in the backwash water. Offshore, this would normally require transport back to shore or reinjection. It is unlikely to be suitable for removal of dispersed or dissolved oils but may remove polar organic substances and may remove specific metals, although most existing plants target Group I and II metals. Removal of heavy metals typically requires a chelating resin that forms a stable compound with the heavy metal. Backwash of chelating resins similarly requires a disposal route, and chelating resins are several times more expensive than simple ion exchange resins.
Process Diagram	 The Higgins contactor consists of four sections separated by valves (A-D) - a deionisation section, regeneration section, propulsion section and expansion section. The concentration of ions is reflected in the dark background. Through flow must stop while the pulse, backwash and settling stages take place.
Basic Elements	Piping, valves, inlet pumps, backwash pumps, resin filled column.
Suitable for the removal of:	**Heavy metals** ■ Cadmium ■ Zinc ■ Lead ■ Mercury ■ Nickel **R [%]**: Insufficient data **Production chemicals** ☐ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers **R [%]** **Oil** ☐ Dissolved Oil ☐ BTEX ☐ Benzene ☐ PAHs **R [%]** **Dispersed Oil** ☐ Oil **R [%]** *Remarks:* Ion exchange can be targeted at specific heavy metals using chelating resins in commercially available systems with high efficiencies reported. There is, however, insufficient data on the application to produced water to draw reliable conclusions. The ionic removal is aimed at a specific ionic balance, and its efficiency may be sensitive to variations in produced water composition due to changes in wells being produced or new fields.
Technical Details	Type of installation: Gas 1 / Gas 2 Produced water volume (design): $1 m^3/h$ / $6 m^3/h$ Required area for injection vs. Water treatment installation: Less / Less Mass of equipment for injection vs. Water treatment installation: Lower / Lower
Critical Operational Parameters	Ion exchange is only suitable for low water flows and removal of specific cations or anions, and it is frequently used to remove Group II metals rather than heavy metals. It requires a disposal route for concentrated backwash fluids. It could be applicable as a polishing technique if there is a specific ionic contaminant to remove. Resins may foul if used as a pre-treatment method. Multiple columns would normally be required to allow continuous operation while backwashing.
Operational Reliability	Influent must be low in suspended solids, scale forming materials and oxidised metals to prevent fouling and the treatment units are likely to require occasional disinfection.

Indication of Costs	**Costs**	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€ / year]		
	Gas Platform, small Gas Platform, large Oil Platform	na	na	Na	na	

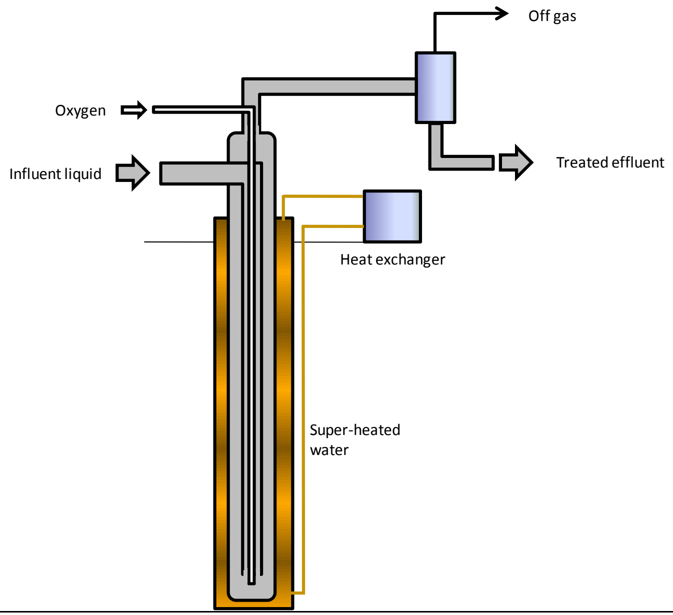
Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
	Existing	New	Existing	New	Existing	New
Dissolved oil Dispersed oil Zinc equivalents	na	na	na	na	na	na

Remarks: Operational costs will vary considerably depending the quality and quantity of the feed water, and the system requires minimal energy requirements.

There is insufficient applicable information to estimate costs for offshore produced water treatment. However one study estimated that after a conventional pretreatment (e.g., coagulation, flocculation, and sedimentation), ion exchange treatment costs for surface water vary between €0.2 and €0.6 per cubic metre at flow rates of 60 – 240 m^3/hour. Operating costs were in the region of 70-80% of the total cost with regenerants, raw water, labour and maintenance making the most significant contributions. Chelating resins for removing heavy metals are several times more expensive.

Cross media effects	**Air**	Emissions from power generation for pumping.
	Energy	Power generation to run circulation and backwashing pumps.
	Added chemicals	Chemicals embedded in resin, require periodic recharging. Occasional disinfection required.
	Waste	Backwash water will require reinjection or disposal to shore. Spent resin solution requires disposal and neutralisation.
Other impacts	**Safety**	Chemicals (including acids) required on site for regenerating resins, neutralising spent solution and for disinfection.
	Maintenance	Occasional disinfection required. Careful monitoring of influent to check for fouling and scale forming materials. IX is sensitive to free chlorine oxidation.

Practical experience	**General**	**Offshore**
	Ion exchange is a commonly used technology and has a long history of use in water treatment and wastewater treatment. It is particularly commonly used as water softening and in the removal of heavy metals from drinking water. It has some use in the treatment of produced water from coalbed methane to soften the water and reduce scaling.	No applications found
Conclusions	Ion exchange is an effective polishing technique for removing dissolved salts in onshore applications.	There is no information on the application to produced water or the offshore environment, therefore technique not currently available,
Literature source	Ion Exchange Materials - Properties and Applications. Author(s): Andrei A. Zagorodni ISBN: 978-0-08-044552-6 An Integrated Framework for Treatment and Management of Produced Water, Technical Assessment of Produced Water Treatment Technologies, 1st Edition, 2009, Colorado School of Mines. Produced Water Management Technology Descriptions, Factsheet – Ion Exchange. NETL Technical Assessment of Produced Water Treatment Technologies. 1st Edition. RPSEA Project 07122-12. Colorado School of Mines. REMCO Engineering Ion Exchange Systems process description, from website reviewed October 2011.	

Table C - 24: OXIDATION, VERTECH	
Principle	Vertech aqueous phase oxidation system is a form of non-catalytic Wet Air Oxidation. It is consists of two concentric tubes and a heat exchange system and operates via a high-pressure oxidation reaction below ground taking advantage of hydrostatic pressure at a depth of 1200-1500m, producing dissolved and suspended oxidation products. In the only operating example in the Netherlands, residual solids are landfilled after dewatering, while residual dissolved contaminants are treated biologically. Off-gases are treated by thermal incineration with a catalytic reactor as backup.
Process Diagram	
Basic Elements	A recirculating well approximately 1200m deep and 1m in diameter, 250 Celsius water supply, oxygen supply, heat exchanger and piping installed in wellbore.

Suitable for the removal of:

Heavy metals	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
☐ Cadmium		☐ Methanol		☐ Dissolved Oil	
☐ Zinc		☐ Glycols		☐ BTEX	
☐ Lead		☐ Corrosion inhibitors		☐ Benzene	
☐ Mercury		☐ Anti-scale solutions		☐ PAHs	
☐ Nickel		☐ Demulsifiers		**Dispersed Oil**	**R [%]**
				☐ Oil	

Remarks: In an onshore pilot plant it is reported to be efficient at converting high organic load sludges into water, CO_2 and ash. There is no data on its effectiveness at removing organic pollutants in produced water or similar 'weak' effluents. It would not be effective at removing metals, but it may oxidise and/or break down complex chemicals.

Technical Details

Type of installation	Gas 1	Gas 2
Produced water volume (design)	1 m^3/h	6 m^3/h
Required area for injection vs. Water treatment installation	Much smaller	Much smaller
Mass of equipment for injection vs. Water treatment installation	Much smaller	Much smaller

Critical Operational Parameters	Requires weekly stop for descaling of tubes with nitric acid. Further treatment of the effluent is required to remove residual reaction products (including ash). High temperature must be maintained, which for produced water would require energy input in the absence of a high organic load as fuel.
Operational Reliability	No data. Scaling is clearly a potential issue, but the onshore pilot plant has operated for many years. Continuous operation would require multiple units.

Indication of Costs

Costs	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€ / year]	
Gas Platform, small Gas Platform, large Oil Platform	No data	No data	No data	No data

Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
	Existing	New	Existing	New	Existing	New
Dissolved oil Dispersed oil Zinc equivalents	No data	No data	No data	No data	No data	No data

Remarks: Existing wells would not be suitable for the process as currently described, requiring a 1m diameter well of 1.2km depth. To create a well of such dimensions offshore would be €10s of millions and a technical first. Superheated water and an oxygen supply would also be expensive to install and operate offshore.

Cross media effects	**Air**	Air emissions from power generation, small amounts of CO_2 from process	
	Energy	Energy required for continuous superheated water supply and pumping. Once operating continuously, energy requirements are offset by oxidation reaction energy, but this would be limited for an effluent with low organic load such as produced water.	
	Added chemicals	None	
	Waste	Ash suspended in effluent	
Other impacts	**Safety**	Superheated water generator and supply	
	Maintenance	Downhole problems could require major intervention	
Practical experience	**General**		**Offshore**
	A prototype reactor based on the Prenso wet oxidation technology has been run in Apeldoorn, the Netherlands. The reactor has been operational from 1992 to 2004, and has treated between 20,000 and 28,000 dry tonnes of sludge annually.		None
Conclusions	Tested on an industrial scale but not tested on produced water and not widely available.		Would require significant investment to develop laboratory scale tests, with intrinsic difficulties for offshore operation. Technique not currently available.
Literature source	Wet air oxidation: past, present and future. F Luck , Anjou Recherche, Vivendi Water Research Center, 78603 Maisons Laffitte, France Providentia Environmental Solutions B.V. (2010) Prenso Wet Oxidation Technology Information Memorandum Genesyst UK website reviewed October 2011, History and development of superheated water conversion of biomass.		

<table>
<tr><th colspan="8">Table C - 25: Oxidation, Hydrogen Peroxide</th></tr>
<tr><td>Principle</td><td colspan="7">Hydrogen peroxide treatment is a type of chemical oxidation. The hydrogen peroxide is dosed into the influent stream, the conditions of the dosing and mixing such as the pH, reaction time, concentration and temperature are controlled to target the pollutants that require removal.

Hydrogen peroxide can be used in conjunction with other types of oxidation processes to provide an advanced oxidation process through the formation of hydroxyl radicals. When mixed with ferrous iron as a catalyst, it is known as Fenton’s reagent.</td></tr>
<tr><td>Process Diagram</td><td colspan="7"></td></tr>
<tr><td>Basic Elements</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Suitable for the removal of:</td><td>Heavy metals
Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td>R [%]</td><td>Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td>R [%]</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHSs
Dispersed Oil
☐ Oil</td><td colspan="2">R [%]

R [%]</td></tr>
<tr><td colspan="7">Remarks:</td></tr>
<tr><td>Technical Details</td><td colspan="5">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 1
1m3/h</td><td>Gas 2
6 m3/h</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="7">High chemical usage.</td></tr>
<tr><td>Operational Reliability</td><td colspan="7"></td></tr>
</table>

<table>
<tr><td rowspan="6">Indication of Costs</td><td>Costs</td><td colspan="2">Investment Costs (CAPEX)
[€]</td><td colspan="2">Exploitation Costs (OPEX)
[€ / year]</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Gas Platform, small
Gas Platform, large
Oil Platform</td><td></td><td></td><td></td><td></td></tr>
</table>

Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
	Existing	New	Existing	New	Existing	New
Dissolved oil Dispersed oil Zinc equivalents						

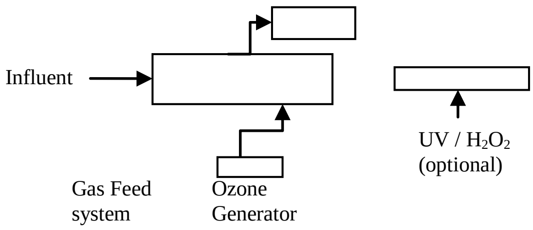
Remarks:

Cross media effects	**Air**	
	Energy	
	Added chemicals	
	Waste	
Other impacts	**Safety**	Strong oxidising agent used
	Maintenance	

	General	Offshore
Practical experience		
Conclusions		
Literature source		

<table>
<tr><th colspan="7">Table C - 26: Oxidation, Ozone Treatment</th></tr>
<tr><td>Principle</td><td colspan="6">Ozone is a gas consisting of 3 oxygen atoms, which easily degrade and break down to form oxygen molecules leaving one free oxygen atom. Ozone can react through direct oxidation or, through advanced oxidation, by the production of hydroxyl free radicals. Advanced Oxidation is the most efficient use of ozone and requires the addition of UV or H_2O_2 to produce hydroxyl free radicals and improve the rate of treatment. UV is most commonly used but H_2O_2 is used where oxidisation of the substance is particularly difficult, a combination of UV and H_2O_2 is also available.

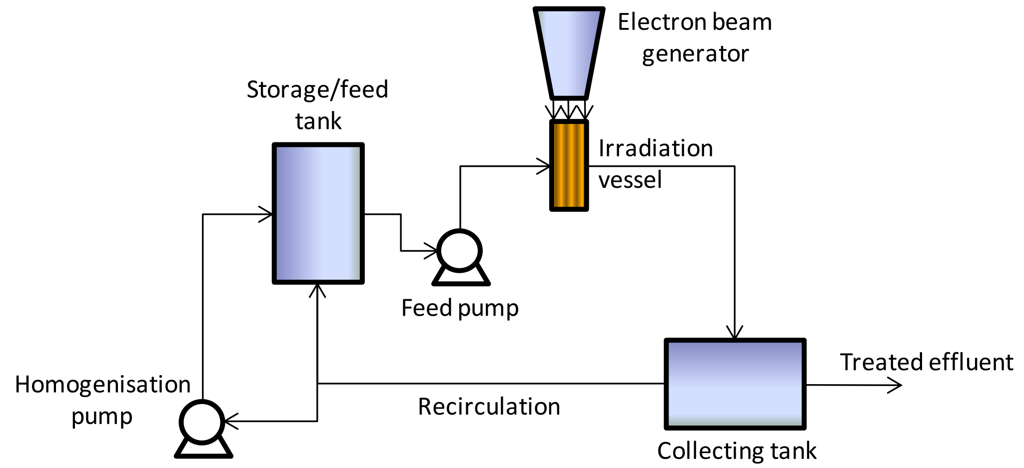
Ozone removes a wide variety of contaminants, has a short reaction time and does not require the addition of chemicals to the water. Ozone oxidises various metals to form metal oxides that can be removed with filtration or chemical oxidation. Ozone is generated at the point of application from electricity and either dried air or from oxygen delivered to site in liquid form.

The reaction produces by-products, some of which may be harmless e.g. CO_2, but there is little documentation on this aspect.</td></tr>
<tr><td>Process Diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic Elements</td><td colspan="6">Ozone generator and diffusers, ozone contactor, ozone off-gas decomposer, oxygen or air feed system, supply and discharge pumps, monitoring and control systems. When used in conjunction with UV -UV lamps, lamp sleeves, lamp cleaning system. Monitoring and control system.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:</td><td rowspan="2">Heavy metals
□ Cadmium
□ Zinc
□ Lead
□ Mercury
□ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
□ Methanol
□ Glycols
□ Corrosion inhibitors
□ Anti-scale solutions
□ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
■ Dissolved Oil
■ BTEX
■ Benzene
■ PAHs</td><td>R [%]
50-65%</td></tr>
<tr><td>Dispersed Oil
■ Oil</td><td>R [%]
50-65%</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td>Technical Details</td><td colspan="3">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. water treatment installation</td><td>Gas 1
1 m³/h
Similar
Lower</td><td>Gas 2
6 m³/h
Similar
Lower</td><td>Oil
175 m³/h
No data</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6">The feed water may affect the treatment process, organic matter, pH, metal ions and carbonate ions will all affect the availability of hydroxyl radicals required in the treatment process. The effluent from ozone plants may need settlement prior to discharge. Electrical power is required.</td></tr>
<tr><td>Operational Reliability</td><td colspan="6">Ozone systems have improved reliability over the past few years. The working parts are often external to the flow line and can be easily replaced without interruption of flow line.</td></tr>
</table>

Indication of Costs							
	Costs	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€ / year]			
		Existing	New	Existing	New		
	Gas Platform, small Gas Platform, large Oil Platform	€400,000 €750,000 No data	No data	€40,000 €75,000 No data	No data		
	Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
		Existing	New	Existing	New	Existing	New
	Dissolved oil Dispersed oil Zinc equivalents	€1666 - €152 €714 - €66 n/a0		€18 - €1.6 €7.8 - €0.6 n/a		No data	
	Remarks: Based on 2002 prices. Price range is between the first year and subsequent years. Excludes installation cost, incidental costs of making offshore platform modifications, maintenance and downtime.						
Cross media effects	**Air**	Ozone destruction required prior to venting.					
	Energy	Requires 23 kW for 66 m^3/h unit					
	Added chemicals	None					
	Waste	None					
Other impacts	**Safety**	Ozone is a toxic gas and is a potential fire hazard.					
	Maintenance						
Practical experience	**General**			**Offshore**			
	Ozone is a common type of treatment that has been used for many years is the treatment of clean water and for polishing in wastewater treatment. An onshore unit has been trialled at the Flotta Terminal.			Some offshore units have been trialled, and a commercial unit is planned on the ConocoPhillips Judy platform.			
Conclusions	Process can be used to reduce dispersed and dissolved oil compounds. Presence of ozone is a safety issue.			Process can be used offshore to reduce dispersed and dissolved oil compounds. Awaiting first commercial scale installation offshore. Technique on the verge of being available.			
Literature source	Environmental Improvements in Produced Water and Wastewater Treatment Technology, Argo Environmental Engineering Limited. Addendum to the OSPAR Background Document Concerning Techniques for the Management of Produced Water from Offshore Installations (Publication number 162/2002) ConocoPhillips press release via website, reviewed October 2011						

<table>
<tr><th colspan="7">Table C - 27: Oxidation, Electron Beam</th></tr>
<tr><td>Principle</td><td colspan="6">Advanced oxidation is a chemical process that produces hydroxyl radicals that can destroy a wide range of organic and inorganic compounds in water. Advanced oxidation systems can remove many pollutants from the water that are not removed by other treatment methods.

Electron Beam treatment is a form of advanced oxidation that uses electron beam ionization to induce the radiolysis of water molecules to produce radicals. It can treat a wide range of flows but may be most economically viable for larger flows. The process claims to be less affected by characteristics of the influent including colour and turbidity than other methods.

The first full scale treatment plant using this technology has been operational since 2006 and there have been numerous trials worldwide but there is no specific experience of using this technology on produced water or offshore. The technique appears, however, to be relatively energy efficient and with a small footprint.</td></tr>
<tr><td>Process Diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic Elements</td><td colspan="6">Storage tank, Feed tank, feed pump, Electron beam accelerator, beam scanner, irradiation chamber, pipework, valves, control system.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]
No data</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]
No data</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHs</td><td>R [%]
No data</td></tr>
<tr><td>Dispersed Oil
☐ Oil</td><td>R [%]
No data</td></tr>
<tr><td colspan="6">Remarks:
Existing operations have reduced by two orders of magnitude concentrations of halogenated methane and ethylene, sulphonic acids and alkylphenol ethoxylates and eliminated oestrogenic activity, and EC50 concentrations for Daphnia were raised to a point of not being measurable at high doses. It is likely that the technique can destroy petrogenic compounds in produced water, but there is no specific data. It would not remove metals.</td></tr>
<tr><td>Technical Details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 2
6m³/h
Smaller
Smaller</td><td>Oil
175m³/h
Smaller
Smaller</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6">The technology is said to be most economically effective at high flows (>5,000m3/d) but plants are available from 100 to 150,000m3/d. Existing plant uses shielded concrete room in which irradiation takes place.</td></tr>
<tr><td>Operational Reliability</td><td colspan="6"></td></tr>
</table>

Indication of Costs

Costs	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€ / year]	
	Existing	New	Existing	New
Gas Platform, small Gas Platform, large Oil Platform	No data	No data	No data	No data

Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
	Existing	New	Existing	New	Existing	New
Dissolved oil Dispersed oil Zinc equivalents	No data	No data	No data	No data	No data	No data

Remarks:
There is insufficient data for reliable costs for offshore produced water treatment. Costs for an onshore plant treating 13,800 m^3/d were $4million with operating costs of $460,000 per annum (2006 prices).

Cross media effects	**Air**	Emissions from fuel use for power.
	Energy	400kW for a 13,800 m^3/d plant
	Added chemicals	None
	Waste	None
Other impacts	**Safety**	Radiation risks requiring shielding
	Maintenance	

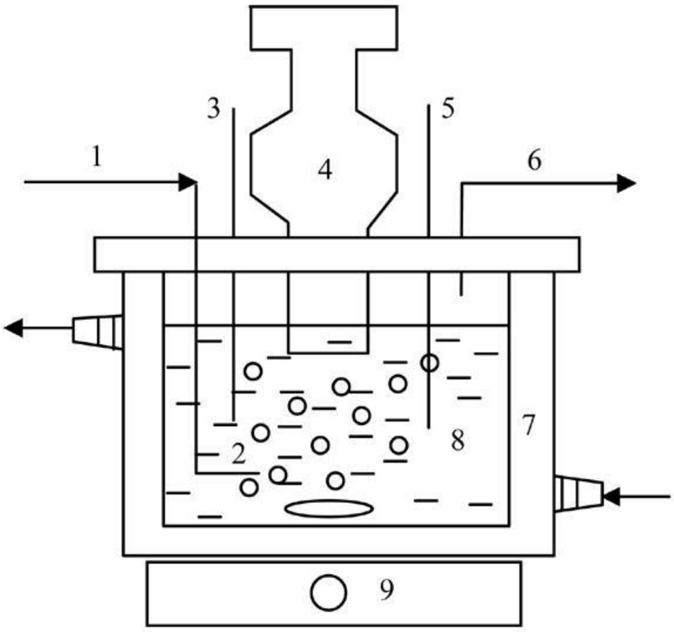
	General	**Offshore**
Practical experience	This is a fairly new use of irradiation technology. Trials have been carried out in the treatment of wastewater and there is at least one full scale plant treating industrial waste.	No information found.
Conclusions	This treatment shows some possibilities for future treatment options but it is still a relatively unknown option and not enough information was found to make a judgement on its applicability to produced water.	Technique not currently available.

Literature source	Radiation treatment of polluted water and wastewater, International Atomic Energy Agency, September 2008 – a synthesis of many research papers. Advanced oxidation process by electron-beam-irradiation-induced decomposition of pollutants in industrial effluents. C.L Duarte, M.H.O Sampa, P.R Rela, H Oikawa, C.G Silveira, A.L Azevedo. Institute for Energetic and Nuclear Research-IPEN-CNEN/SP, Radiation Technology Center-TE, P.O. Box 11049-CEP 05499-970. Available online 7 November 2001.

<table>
<tr><th colspan="7">Table C - 28: Oxidation, Sonolysis</th></tr>
<tr><td>Principle</td><td colspan="6">Advanced oxidation is a chemical process that produces hydroxyl radicals that can destroy a wide range of organic and inorganic compounds in water. Advanced oxidation systems can remove many pollutants from the water that are not removed by other treatment methods.

Sonolysis is an advanced oxidation system that uses ultrasound waves produced at low frequency and high energy. The ultrasound produces bubbles within the water (acoustic cavitations), the collapse of the bubble causes localised supercritical conditions which in turn produce the hydrogen radicals. As in other forms of advanced oxidation the hydrogen radicals break down the pollutants.

Sonolysis may be used in combination with other types of oxidation processes to improve treatment and removed pollutants that it is unable to remove alone.

INSUFFICIENT DATA TO FORM ANALYSIS</td></tr>
<tr><td>Process Diagram</td><td colspan="6">
</td></tr>
<tr><td>Basic Elements</td><td colspan="6">1: O_3/O_2 inlet; 2: Coarse fritted-glass diffuser; 3: Thermometer; 4: Transducer; 5: Sample out; 6: Vent gas; 7: Cooling water jacket; 8: Reactor; 9: Magnetic agitator</td></tr>
<tr><td rowspan="3">Suitable for the removal of:</td><td rowspan="2">Heavy metals
Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHSs</td><td>R [%]</td></tr>
<tr><td>Dispersed Oil
☐ Oil</td><td>R [%]</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td>Technical Details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 1
1m3/h</td><td>Gas 2
6 m3/h</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6"></td></tr>
<tr><td>Operational Reliability</td><td colspan="6"></td></tr>
</table>

<table>
<tr><td rowspan="10">Indication of Costs</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Costs</td><td colspan="3">Investment Costs (CAPEX)
[€]</td><td colspan="3">Exploitation Costs (OPEX)
[€ / year]</td></tr>
<tr><td colspan="2"></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Gas Platform, small
Gas Platform, large
Oil Platform</td><td colspan="2"></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas Platform, small</td><td colspan="2">Gas Platform, large</td><td colspan="2">Oil Platform</td></tr>
<tr><td></td><td>Existing</td><td>New</td><td>Existing</td><td>New</td><td>Existing</td><td>New</td></tr>
<tr><td>Dissolved oil
Dispersed oil
Zinc equivalents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Remarks:</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="6"></td></tr>
<tr><td>Energy</td><td colspan="6"></td></tr>
<tr><td>Added chemicals</td><td colspan="6"></td></tr>
<tr><td>Waste</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="6"></td></tr>
<tr><td>Maintenance</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="3">General</td><td colspan="4">Offshore</td></tr>
<tr><td colspan="3">Ultrasound waves have had some use in wastewater sewage systems but as probes are getting more powerful it is hoped that the technology will have a wider range of uses.</td><td colspan="4"></td></tr>
<tr><td>Conclusions</td><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Literature source</td><td colspan="7">Chemical Oxidation Applications for Industrial Wastewaters By Olcay Tunay, Isik Kabdasli, Idil Arslan-alaton, Tugba Olmez-hanci

Journal of Zhejiang University Science. Ozonation with ultrasonic enhancement of p-nitrophenol wastewater. Xian-wen Xu,† Hui-xiang Shi, and Da-hui Wang. Department of Environmental Science and Engineering, Zhejiang University. Received October 15, 2004; Accepted January 27, 2005</td></tr>
</table>

Table C - 29: Oxidation, KMnO4	
Principle	Potassium permanganate is a strong oxidant that does not generate toxic by-products. It will oxidise a wide range of organic and inorganic substances. It is supplied in dry format and mixed into a solution on-site. Potassium permanganate is regulary used in the water treatment industry to removed iron and hydrogen sulphide.
Process Diagram	
Basic Elements	Storage tanks, mixing tanks, controls, metering pumps,

Suitable for the removal of:	**Heavy metals**	**R [%]**	**Production chemicals**	**R [%]**	**Oil**	**R [%]**
	Cadmium ☐ Zinc ☐ Lead ☐ Mercury ☐ Nickel		☐ Methanol ☐ Glycols ☐ Corrosion inhibitors ☐ Anti-scale solutions ☐ Demulsifiers		☐ Dissolved Oil ☐ BTEX ☐ Benzene ☐ PAHSs	
					Dispersed Oil ☐ Oil	**R [%]**
	Remarks:					

Technical Details	Type of installation Produced water volume (design) Required area for injection vs. Water treatment installation Mass of equipment for injection vs. Water treatment installation	Gas 1 1m3/h	Gas 2 6 m3/h
Critical Operational Parameters			
Operational Reliability			

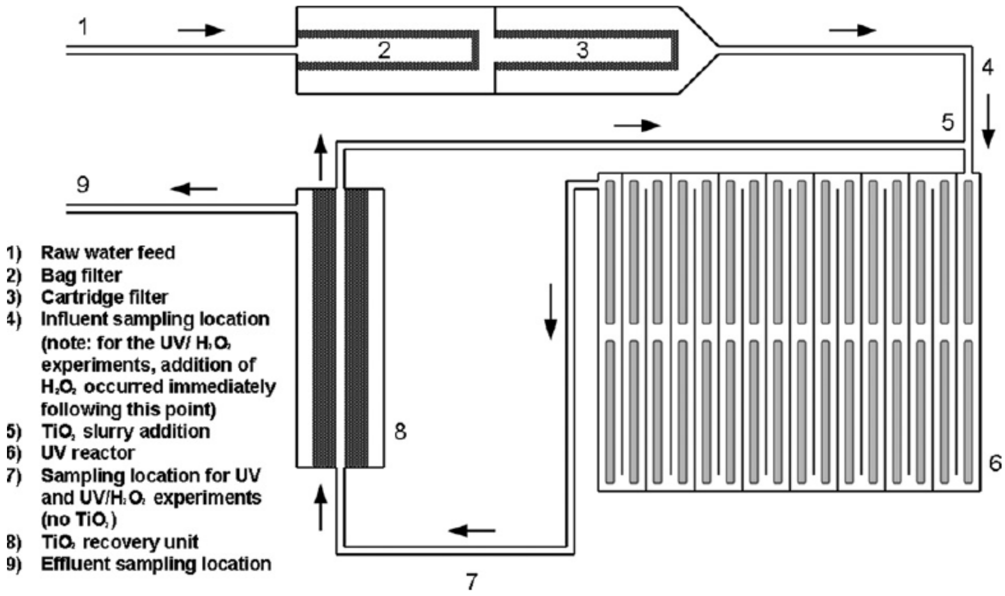
Indication of Costs	**Costs**	Investment Costs (CAPEX) [€]		Exploitation Costs (OPEX) [€ / year]	
	Gas Platform, small Gas Platform, large Oil Platform				

	Cost/kg removed	Gas Platform, small		Gas Platform, large		Oil Platform	
		Existing	New	Existing	New	Existing	New
	Dissolved oil Dispersed oil Zinc equivalents						
	Remarks:						

Cross media effects	**Air**	
	Energy	
	Added chemicals	
	Waste	
Other impacts	**Safety**	Potassium permanganate should be handled with care, it is a skin and inhalation irritant, can cause serious eye injuries and may cause death if swallowed. Full PPE must be used when handling. Risk of violent reaction with some chemicals.
	Maintenance	

Practical experience	**General**	**Offshore**
Conclusions		
Literature source	EPA guidance manual, alternative disinfectants and oxidants. April 1999.	

<table>
<tr><th colspan="7">Table C - 30: Oxidation, Photocatalytic Oxidation</th></tr>
<tr><td>Principle</td><td colspan="6">Advanced oxidation is a chemical process that produces hydroxyl radicals that can destroy a wide range of organic and inorganic compounds in water. Advanced oxidation systems can remove many pollutants from the water that are not removed by other treatment methods.

Photocatalytic oxidation is a form of advanced oxidation that produces hydroxyl radicals through the use of a catalyst such as titanium oxide (the most commonly used), nickel oxide, copper oxide, manganese dioxide, or chromium oxide which absorbs the pollutants and then breaks them down under UV light. The catalyst is not used up during the process and so there is no requirement for additional chemicals. The process is also reported to have low maintenance and low energy requirements. The technique has been trialled as a polishing process and has seen recent development into membrane systems. It may be suitable for produced water treatment although there is limited data, relating to photoelectrocatalysis.</td></tr>
<tr><td>Process Diagram</td><td colspan="6">


- General schematic of photocatalytic reactor membrane pilot system (Benotti et al., 2009).</td></tr>
<tr><td>Basic Elements</td><td colspan="6">UV lamps, catalyst media, contacting chamber for catalyst and UV exposure.</td></tr>
<tr><td rowspan="3">Suitable for the removal of:</td><td rowspan="2">Heavy metals
☐ Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]
No data</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHs</td><td>R [%]
No data</td></tr>
<tr><td>Dispersed Oil
☐ Oil</td><td>R [%]
No data</td></tr>
<tr><td colspan="6">Remarks:
Not enough data relevant to produced water to draw conclusions. Trials have shown 50-80% reduction in COD and 70% reduction in endocrine disruptors in industrial wastewaters. Trials of photoelectrocatalysis on produced water showed 85% COD removal for low COD loads with greater efficiencies when combined with hydrogen peroxide oxidation..</td></tr>
<tr><td>Technical Details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 1
1m3/h
Smaller
Smaller</td><td>Gas 2
6 m3/h
Smaller
Smaller</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6">The process operates at ambient conditions. No sludge disposal. The catalysis is not used up so no chemicals are used. Titanium oxide is cheap and widely available. Contact time of several hours may be required.</td></tr>
<tr><td>Operational Reliability</td><td colspan="6"></td></tr>
</table>

<table>
<tr><td rowspan="9">Indication of Costs</td><td colspan="7"></td></tr>
<tr><td>Costs</td><td colspan="3">Investment Costs (CAPEX)
[€]</td><td colspan="3">Exploitation Costs (OPEX)
[€ / year]</td></tr>
<tr><td></td><td colspan="2"></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>Gas Platform, small
Gas Platform, large
Oil Platform</td><td colspan="2"></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas Platform, small</td><td colspan="2">Gas Platform, large</td><td colspan="2">Oil Platform</td></tr>
<tr><td></td><td>Existing</td><td>New</td><td>Existing</td><td>New</td><td>Existing</td><td>New</td></tr>
<tr><td>Dissolved oil
Dispersed oil
Zinc equivalents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Remarks:
Insufficient data to estimate costs for produced water.</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="6">Emissions from fuel use for power</td></tr>
<tr><td>Energy</td><td colspan="6">16 kW per m^3/day in existing trials</td></tr>
<tr><td>Added chemicals</td><td colspan="6">Catalyst (recovered and reused)</td></tr>
<tr><td>Waste</td><td colspan="6">Spent catalyst</td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="6">UV generation within closed vessel</td></tr>
<tr><td>Maintenance</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="3">General</td><td colspan="4">Offshore</td></tr>
<tr><td colspan="3">Existing plants have small footprint and zero waste.</td><td colspan="4">Photoelectrocatalysis has been trialled on produced water. No evidence of testing in offshore environment.</td></tr>
<tr><td>Conclusions</td><td colspan="3">Photocatalytic oxidation has most use in wastewater treatment plants (rather than produced water). It is still in its early stages of development but small scale units are in operation and the system is currently commercially available for a variety of wastewater types. There have been a number of studies looking at optimising the process and it may become a good, low cost, zero waste technology.</td><td colspan="4">Not currently available</td></tr>
<tr><td>Literature source</td><td colspan="7">MUTAGENICITY ASSESSMENT OF PRODUCED WATER DURING PHOTOELECTROCATALYTIC DEGRADATION. GUIYING LI, TAICHENG AN, XIANGPING NIE,GUOYING SHENG, XIANGYING ZENG,JIAMO FU,ZHENG LIN, and EDDY Y. ZENG State Key Laboratory of Organic Geochemistry, Guangdong Key Laboratory of Environmental Protection and Resources Utilization,
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China , Institute of Hydrobiology, Ji'nan University, Guangzhou 510632, China. School of Environmental and Chemical Engineering, Shanghai University, Shanghai 200072, China (Received 29 May 2006; Accepted 26 September 2006)

Global NEST Journal, Vol 10, No 3, pp 376-385, 2008. USE OF SELECTED ADVANCED OXIDATION PROCESSES (AOPs) FOR WASTEWATER TREATMENT – A MINI REVIEW. A.S. STASINAKIS* Water and Air Quality Laboratory, Department of Environment. University of the Aegean, University Hill, Mytilene 81100, Greece

Catalysystems website, reviewed October 2011.

Recent developments in photocatalytic water treatment technology: A review (2010) Meng Nan Chong, Bo Jina, Christopher W.K., Chow, Chris Saint.

Photoelectrocatalytic decontamination of oilfield produced wastewater containing refractory organic pollutants in the presence of high concentration of chloride ions (2006) Guiying Li, Taicheng An, Jiaxin Chen, Guoying Sheng, Jiamo Fu, Fanzhong Chen, Shanqing Zhang, Huijun Zhao

Benotti, M.J., Stanford, B.D., Wert, E.C., Snyder, S.A., 2009. Evaluation of a photocatalytic reactor membrane pilot system of pharmaceuticals and endocrine disrupting compounds from water. Water Res. 43, 1513e1522.</td></tr>
</table>

<table>
<tr><th colspan="7">Table C - 31: Oxidation, Plasma</th></tr>
<tr><td>Principle</td><td colspan="6">Advanced oxidation is a chemical process that produces hydroxyl radicals that can destroy a wide range of organic and inorganic compounds in water. Advanced oxidation systems can remove many pollutants from the water that are not removed by other treatment methods.

Plasma oxidation is related to a number of the oxidation techniques described separately in this report. Ozone, UV and electron beam can all be regarded of plasma treatment with ozone being remote and UV and electron beam being an indirect method of Plasma treatment.

Plasma treatment may also be direct through an electrical discharge to water and plasma injection - a discharge above the water. Direct plasma treatment could form the basis of a treatment technology separate to ozone, UV and electron beam, but there is insufficient data to complete an analysis at this time.</td></tr>
<tr><td>Process Diagram</td><td colspan="6"></td></tr>
<tr><td>Basic Elements</td><td colspan="6"></td></tr>
<tr><td rowspan="3">Suitable for the removal of:</td><td rowspan="2">Heavy metals
Cadmium
☐ Zinc
☐ Lead
☐ Mercury
☐ Nickel</td><td rowspan="2">R [%]</td><td rowspan="2">Production chemicals
☐ Methanol
☐ Glycols
☐ Corrosion inhibitors
☐ Anti-scale solutions
☐ Demulsifiers</td><td rowspan="2">R [%]</td><td>Oil
☐ Dissolved Oil
☐ BTEX
☐ Benzene
☐ PAHSs</td><td>R [%]</td></tr>
<tr><td>Dispersed Oil
☐ Oil</td><td>R [%]</td></tr>
<tr><td colspan="6">Remarks:</td></tr>
<tr><td>Technical Details</td><td colspan="4">Type of installation
Produced water volume (design)
Required area for injection vs. Water treatment installation
Mass of equipment for injection vs. Water treatment installation</td><td>Gas 1
1m3/h</td><td>Gas 2
6 m3/h</td></tr>
<tr><td>Critical Operational Parameters</td><td colspan="6"></td></tr>
<tr><td>Operational Reliability</td><td colspan="6"></td></tr>
</table>

<table>
<tr><td rowspan="9">Indication of Costs</td><td colspan="7"></td></tr>
<tr><td>Costs</td><td colspan="3">Investment Costs (CAPEX)
[€]</td><td colspan="3">Exploitation Costs (OPEX)
[€ / year]</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td>Gas Platform, small
Gas Platform, large
Oil Platform</td><td></td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>Cost/kg removed</td><td colspan="2">Gas Platform, small</td><td colspan="2">Gas Platform, large</td><td colspan="2">Oil Platform</td></tr>
<tr><td></td><td>Existing</td><td>New</td><td>Existing</td><td>New</td><td>Existing</td><td>New</td></tr>
<tr><td>Dissolved oil
Dispersed oil
Zinc equivalents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Remarks:</td></tr>
<tr><td rowspan="4">Cross media effects</td><td>Air</td><td colspan="6"></td></tr>
<tr><td>Energy</td><td colspan="6"></td></tr>
<tr><td>Added chemicals</td><td colspan="6"></td></tr>
<tr><td>Waste</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Other impacts</td><td>Safety</td><td colspan="6"></td></tr>
<tr><td>Maintenance</td><td colspan="6"></td></tr>
<tr><td rowspan="2">Practical experience</td><td colspan="3">General</td><td colspan="4">Offshore</td></tr>
<tr><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Conclusions</td><td colspan="3"></td><td colspan="4"></td></tr>
<tr><td>Literature source</td><td colspan="7"></td></tr>
</table>

2. References

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2 Environmental aspects of on and off-site injection of drill cuttings and produced water, OSPAR 2001, ISBN 0 946956 69 3
3 Removal of hydrocarbons from produced water, OIC 01/8/Info.3, Oslo, 13-16 February 2001
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Annex 1: Basis for figures in fact sheets

1. Model situations

Three model situations were established, i.e.:

1. small gas installation (based on 26 gas installations with small produced water discharges);
2. large gas installations (based on 27 gas installations with larger produced water discharges);
3. oil installations (based on 7 oil installations).

For each model situation, representative produced water quality and quantity figures were established. For water quality figures, the mediane and the 90 percentile values were established for each component, whereas the average design flow was used as point of departure for quantity values. For establishment of cost figures, new and existing offshore installations were distinguished.

The following points of departure were established on the basis of a considerable amount of data. It is noted that these data may not be representative for the all produced water discharges from all types of installations in the OSPAR area; the model situations were established on the basis of a limited amount of installations in a limited area. Other model situations may need to be defined when modifications of this background document are considered.

Model situation	**Average volume m^3/h**	**Design volume m^3/h**
Gas platform, small	0,2	1
Gas platform, large	1,4	6
Oil platform	150	175

Concentrations and loads for gas platform, small

		concentrations			**load per year**	
		median	90-percentile		median	90-percentile
Volume*	m^3/u	0,2	n.a.			
Benzene	mg/l	45	250	kg/year	79	438
BTEX	mg/l	50	300	kg/year	88	526
Cadmium	mg/l	0,0025	0,250	kg/year	0,004	0,44
Mercury	mg/l	0,0011	0,004	kg/year	0,002	0,007
Lead	mg/l	0,025	2,2	kg/year	0,04	4
Nickel	mg/l	0,040	0,080	kg/year	0,07	0,14
Zinc	mg/l	1,3	90	kg/year	2	158
Aliphatic HC’s	mg/l	30	40	kg/year	53	70

* average volume in 1998

Concentrations and loads for gas platform, large

		concentrations			**load per year**	
		median	90-percentile		median	90-percentile
Volume*	$m^3/$	1,4	n.a.			
Benzene	mg/l	110	520	kg/year	1 350	6 375
BTEX	mg/l	130	550	kg/year	1 600	6 745
Cadmium	mg/l	0,0025	200	kg/year	0,030	2,45
Mercury	mg/l	0,0011	6	kg/year	0,013	0,074
Lead	mg/l	0,03	9	kg/year	0,4	110
Nickel	mg/l	0,030	60	kg/year	0,37	0,74
Zinc	mg/l	2	60	kg/year	25	735
Aliphatic HC’s	mg/l	30	40	kg/year	370	490

* average volume in 1998

Concentrations and loads for oil platforms

		concentrations			load per year	
		median	90-percentile		median	90-percentile
Volume	m^3/	150	n.a.			
Benzene	mg/l	1,5	1,9	kg/year	1 970	2 500
BTEX	mg/l	2,5	3	kg/year	3 285	3 940
Cadmium	mg/l	0,0004	0,0006	kg/year	0,53	0,72
Mercury	mg/l	0,00003*	-	kg/year	0,039	-
Lead	mg/l	0,01*	0,025	kg/year	13,1	33
Nickel	mg/l	0,005*	-	kg/year	6,6	-
Zinc	mg/l	0,02*	0,1	kg/year	26,3	131
Aliphatic HC’s	mg/l	25	40	kg/year	32 850	52 560

* = value established by judgement, below detection limit

The concentrations referred to in the column ‘median’ have been used for the model situations.

2. Cost figures

For each possible measure, model situations were established (where possible / relevant), including cost figures. Capital expenses (CAPEX) and operational expenses (OPEX) were estimated on the basis of market conformity (price level 2000). Estimates were based on price indications from suppliers, designers and fitters. Furthermore, use was made of data from information and experiences in the industry and other parties involved in offshore oil and gas activities.

CAPEX

Investment estimates for each technique is based on the following costs:

- design and project management;
- equipment;
- transport;
- fitting; and
- unforeseen.

Design and project management costs are dependent on the complexity of the installations, but were estimated to be 10% of the total investments.

For each technique, the treatment system will be formed of specific equipment and other equipment, necessary for proper functioning of the apparatus. These may be buffer tanks and pumps. Prices were based on information from more than one supplier where possible.

Transport costs are important when the technique is installed on existing offshore installations. For new installations, transport costs were assumed 0.

Fitting activities are dependent on the complexity of the installation, and will differ per technique and per situation (existing or new platform, etc.).

Use of space on offshore installations involves costs. For two exemplary situations, investment for use of space on a new platform was calculated.

Part of the investment costs cannot be estimated. Therefore, unforeseen costs have been incorporated in the calculations. On existing offshore installations, more unforeseen circumstances may be expected, therefore these costs may be higher than on new installations. For existing offshore installations unforeseen costs were estimated to be 15% of the total costs, for new installations these are estimated to be 10%.

Capital expenses of investments were calculated on the basis of the annuity method, taking account of the following situations:

		New platform	Existing platform
Depreciation period	[years]	10	5
Interest rate	[%]	10	10
Annuity	[% of total investment]	16,3	26,4

Total investment costs are the sum of design and project management costs, equipment, transport, fitting and unforeseen costs. The calculations above are based on the assumption that no rest value will remain. Re-use of parts is limited, rest value will usually be the scrap value and is assumed zero.

OPEX

All costs were based on the price level of the reference year 2000 (the Netherlands). For future estimates, price escalations of approximately 3% per year should be taken into account. Points of departure for calculation of yearly operational costs are presented in the table below. For each technique and model situation, yearly operational expenses were calculated (where possible).

	New offshore installation	Existing offshore installation
depreciation	0,163 x I	0,264 x I
maintenance	€/m^3 (i.s./e.f.) x Q	€/m^3 (i.s./e.f.) x Q
spare parts	€/m^3 (i.s./e.f.) x Q	€/m^3 (i.s./e.f.) x Q
use of chemicals	€/kg x kg/m^3 (i.s.) x Q	€/kg x kg/m^3 (i.s.) x Q
use of potable water	€ 3,40 /m^3 x amount m^3/year (i.s.)	€ 3,40/m^3 x amount m^3/year (i.s.)
other regular uses	i.s.	i.s.
operation (crew)	€ 32,--/uur x amount hours/year (e.f.)	€ 32,--/hour x amount hours/year (e.f.)
energy	€ 0,14/kWh x kWh/year (i.s.)	€ 0,14/kWh x kWh/year (i.s.)
Removal of sludge • regular quantity	€ 365,--/ton x 1 000 kg/ton x amount kg sludge/m^3 (e.f.) x Q;	€ 365,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q;
• small quantity (< 3 500 kg/year)	€ 680,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q;	€ 680,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q;
Mercury containing sludge	€ 1 140,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q	€ 1 140,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q
Radioactive waste	€ 15 000,--/ton x 1 000 kg/ton x amount kg m^3 (e.f.) x Q	€ 15 000,--/ton x 1 000 kg/ton x amount kg/m^3 (e.f.) x Q

I : total investment costs in Euro (CAPEX);

Q : yearly treatment flow in m^3/year;

i.s. : information supplier;

e.f. : best estimate by authors fact sheet.

Usually, yearly OPEX will amount approximately 35 – 45% of the CAPEX (I).

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