2017:00007 A- Unrestricted

Report

SubSea Dispersant Injection (SSDI) – a "state of the art" and the need for further documentations

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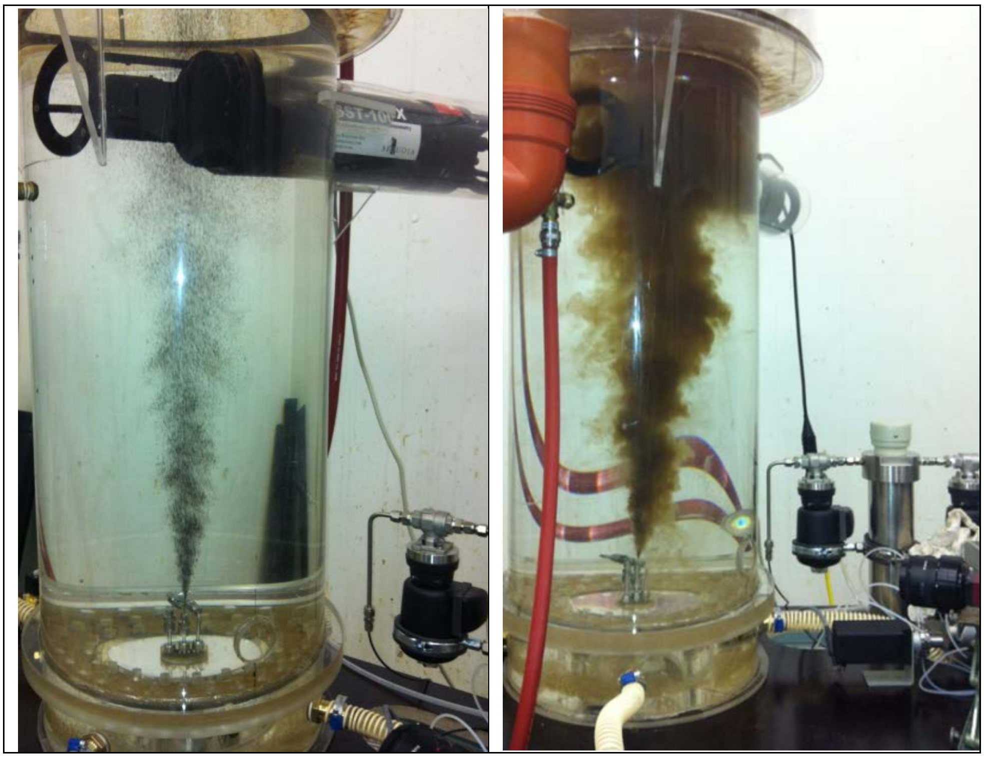

Dispersant Injection Effectiveness Test (DIET) using the SINTEF MiniTower

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2017-06-20

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KEYWORDS:

Report

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VERSION 2.0	**DATE** 2017-06-20

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CLIENT(S) Norwegian Oil and Gas Association	**CLIENT'S REF.** Egil Dragsund
PROJECT NO. 102009669	**NUMBER OF PAGES/APPENDICES:** 18 + 6 Appendices

ABSTRACT

The aim of this pre-project has been to give a "State-of the art" and describe the R&D challenges and documentation needed in order to perform robust NEBA (Net Environmental Benefit Analysis) where SubSea Dispersant Injection (SSDI) is included as an acceptable countermeasure option. In spill scenarios where such NEBA assessments show that SSDI is an appropriate response option, this should be included in the operator's emergency response plans for the specific location on the Norwegian Continental Shelf (NCS). SSDI is a response technology that has a potential to be used in connection to subsea releases (blow-outs) from both "shallow" depth (< 400-500 m) as well as deeper releases (>500m). SSDI is considered as a "stand alone" countermeasure technique.

The project has been a co-operation between SINTEF and Institute of Marine Research (IMR), and is a result of several scientific meetings with NOROG and individual oil companies. A focus has been on identifying documentation, relevant requirements and regulatory procedures (guidelines) needed as a basis for the national Authorities to consider SSDI as an operative oil spill response option according to present regulations for dispersant use in Norway. The identified gaps are taken into account the present findings from ongoing SSDI-related R&D projects (e.g. projects funded by the Research Council in Norway, API and IPIECA).

This pre-project is recommending a R&D program / JIP over the coming 3 years (2016-2018) divided into 6 research areas (work packages) described in this report.

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REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
2017:00007 A	978-82-14-06227-4-	Unrestricted	Unrestricted

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KEYWORDS:
Keywords

Report

SubSea Dispersant Injection (SSDI) – a "state of the art" and the need for further documentations

VERSION	**DATE**
1.0	2016-01-08

AUTHOR(S)
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REPORT NO.	**ISBN**	**CLASSIFICATION**	**CLASSIFICATION THIS PAGE**
SINTEF F27437	-	Restricted	Restricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1.0	2016-01-08	Final Version
2.0	2017-06-20	Classification changed from Restricted to Unrestricted on SINTEF report F27437 in agreement with Egil Dragsund, Norwegian Oil and Gas Association.

Table of contents

1 Purpose with this pre-project - abstract

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The project has been a co-operation between SINTEF and Institute of Marine Research (IMR), and is a result of several scientific meetings with NOROG and individual oil companies. In this process, a focus has been on identifying additional documentation, relevant requirements and regulatory procedures (guidelines) needed as a basis for the national Authorities to consider SSDI as an operative oil spill response option according to present regulations for dispersant use in Norway. The identified gaps are taken into account the present findings from ongoing SSDI-related R&D projects (e.g. projects funded by the Research Council in Norway, API and IPIECA).

This pre-project is recommending a R&D program / JIP over the coming 3 years (2016-2018) dividing into 6 research areas (work packages) described in Appendices in this report.

2 Background

2.1 SubSea Dispersant Injection – previous R&D and experiences in the Macondo-/ DWH-incident

As a part of the research program “Dispersion of Oil on Sea” (DOOS), already in the 1980’s SINTEF evaluated the possibility of injecting oil spill dispersants into a blowing well (Audunson et al. 1987). This study was mainly concerned with the potential for down-hole injection of dispersants by methods commonly applied for injection of drilling and production chemicals into the well. It was concluded that dedicated dispersant injection systems could be installed with existing technology in completed wells, but that pre-installation of such systems was more difficult in the drilling phase.

In a follow-up project funded by Chevron called “Assessment of methods for dispensing dispersants into subsea blowouts” (Johansen and Carlsen, 2002), the potential for subsea application of dispersants were studied theoretically for both down-hole injection and injection of dispersants into the exiting oil flow. It was concluded that down-hole injection could be effective with very low dispersant-to-oil ratios (DOR), while injection into the exiting oil flow might be inefficient even with high DOR due to rapid dilution of the dispersant into the water phase entrained into the plume of oil. However, it was pointed out that deep water blowouts might imply a potential for SSDI as the dilution rate could be reduced due to strong gas compression.

During the Macondo (also called the MC-252 DeepWater Horizon, DWH) incident in the Gulf of Mexico (GoM) in 2010, subsurface dispersant injection was for the first time used extensively in a real case. About 3000m^3 was injected totally, typically at a rate of 30 – 40 L per minute. In the first period of the release, the dispersant was injected down-hole into the damaged riser (see figure 1a). After cutting the riser, the dispersant was injected into the oil-gas plume using different injection systems (see figure 1 b-d). Figure 2 shows the visual effect of SSDI on the sea surface, leading to far less oil entering the near-zone surface area around the source, and also a significant reduced exposure of volatile components (VOCs) to the response personnel involved with ongoing containment operations at the source (e.g. the LMRP -Lower Marine Riser Package).

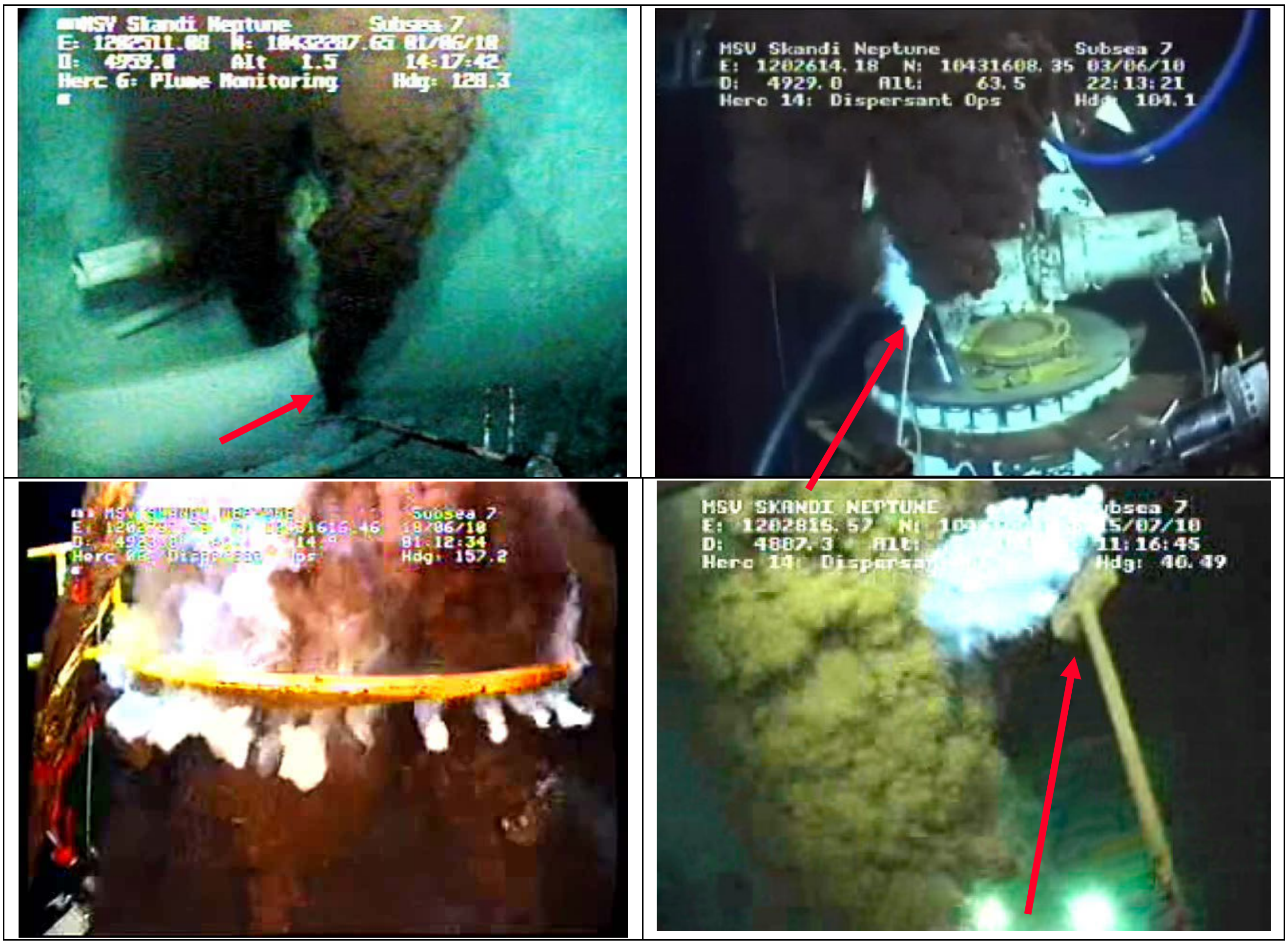

Figure 1. Examples of different SSDI techniques used during the Macondo incident in GoM, 2010

Figure 2. Examples of visual effect of SSDI on the sea surface. Left: May 9th Prior SSDI, Right: During SSDI

The Joint Industry Oil Spill Preparedness & Response Task Force[1] wrote in their report on the findings from the Macondo (DWH) incident:

> *Based on extensive research and applications to oil spills over the past 40 years, chemical dispersants are considered by industry experts and environmental stewards to be an acceptable, and often preferred, means of minimizing the environmental impact of oil spills. Although they are one of several tools available to combat oil spills, dispersants are a necessary component of an effective response to large volume offshore spills.*
>
> *The DWH incident response was no exception: application of dispersants (both surface and subsea) played a key role in the effectiveness of the response. However, better communication is needed to promote understanding of the benefits and limitations of the technology. Additionally, more work is needed to refine the technology to improve dispersant effectiveness and more fully evaluate the potential for environmental harm; to improve the regulatory approval processes for dispersant types and use during a response; and to study potential long-term impacts of dispersants and of dispersed oil on the GOM environment.*

The main research efforts the last years regarding SSDI effectiveness has been coordinated by the American Petroleum Institute (API). They initiated an Oil Spill Prevention Response Joint Industry Task Force (JITF) in 2012 (www.oilspillprevention.org). The International Association of Oil and Gas Producers (IOGP) and the global oil and gas industry association for environmental and social issues (IPIECA) formed in 2011 a Joint Industry Project (JIP), governed by the fourteen funding companies. This JIP, covering a wide area of oil spill response methods had also a work package focusing on SSDI - JIP 2 (SSDI/Efficacy). More details are found at their website: http://oilspillresponseproject.org/.

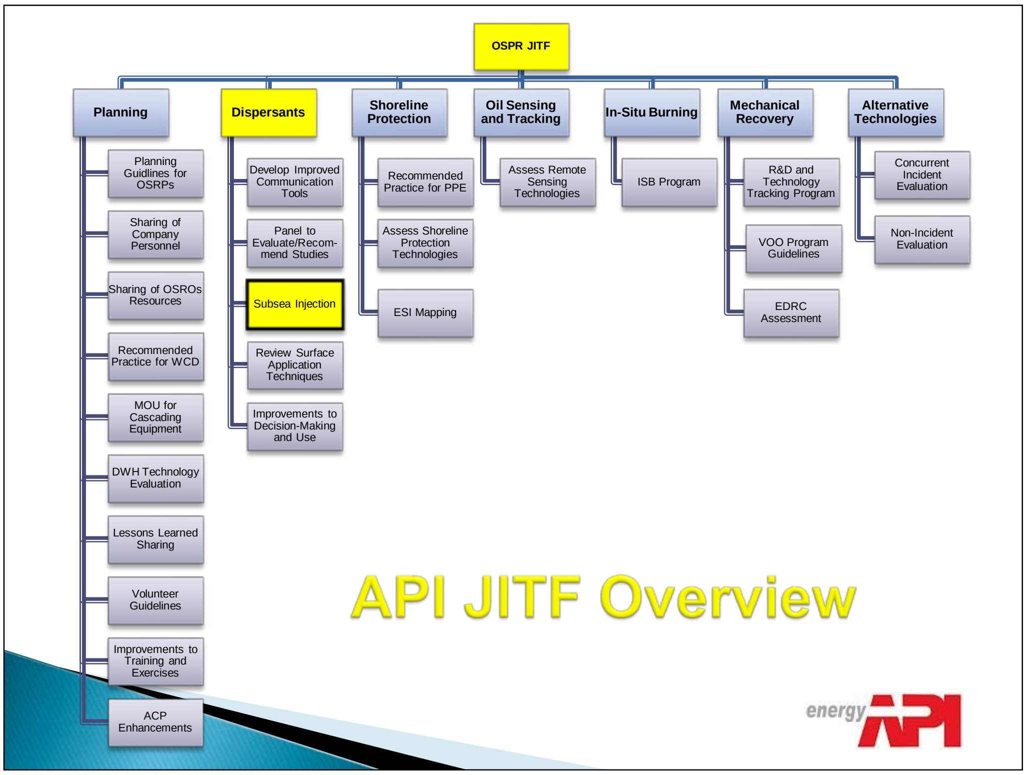

Figure.3: Overview of the Tasks within the API OSPR JITF, where the study of SSDI effectiveness often is referred to as D3 since it is the third activity within the Dispersant task (yellow boxes).

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[1] Recommendations of the Joint Industry Oil Spill Preparedness & Response Task Force, Draft Report September 3, 2010

2.2 Present regulations for use of dispersants in Norway

In Norway, all enterprises in charge of oil handling operations (e.g. oil terminals, refineries, offshore oil fields) are obliged to submit emergency response plans where they have to evaluate which response options lead to the overall least environmental impact. If such scenario-based response analysis shows that dispersants may be an appropriate countermeasure in relevant oil spill scenarios, the use of dispersants must be documented as a combat strategy in their oil spill contingency plans. Use of quantitative 3-D spreading and exposure models are today important tools in connection with the science-based NEBA assessments of relevant oil spill scenario that are carried out by expertise personnel with environmental and oil spill response competence.

The Norwegian Environment Agency (NEA) is the regulator for the pollution preparedness requirements and considers the enterprises' emergency response analyses and can make specific requirements to include the use of dispersants in the contingency plans and also makes specific requirements on the capacity of the dispersant application system. The present regulations for dispersants usage were adopted in 2002 (Chapter 19 in the Pollution regulations: *"Composition and use of dispersants and shoreline–cleaning agents to combat oil pollution"*, *(https://lovdata.no/dokument/SF/forskrift/2004-06-01- 931/KAPITTEL_7#KAPITTEL_7*). Some minor revision of the regulations entered into force in 2009. This was linked to the inclusion of shoreline cleaning agents into the same regulations, and that the Norwegian Coastal Administration (NCA) became the supervising authority when an incident occurs.

In the regulations, there are dispersant testing protocols both for acute toxicity and effectiveness. There is no official approval list of the dispersants, however, the requirements of the regulation must be fulfilled and documented in all contingency plans involving use of dispersants. The toxicity test method determines the acute toxicity of the dispersant alone, by testing it on a planktonic algae (Skeletonema costatum test, ISO/DIS 10253). This is one of the standardized internationally accepted ecotoxicity tests used by the "OSPAR" Convention.

Enterprises that produce or process oil, have to prove the effectiveness of the dispersants on their own oils, using the so-called IFP (Institut Français du Pétrole) dilution test, which is the same "low energy" test as used in France. There is no specific effectiveness threshold for approval, as different oils are used. The aim of the screening is to select effective dispersants and to optimize the dosage ratios required for the specific oil. The enterprises also have to test the dispersibility at varying weathering degrees for the relevant oil in order to estimate the "time window" for effective use of dispersants under various turbulence conditions. For this, the IFP test is used in combination with the MNS (Mackay, Nadeau and Steelman) test, representing two turbulence conditions. It has to be emphasized that these test methods are designed for mimicking and testing effectiveness of dispersant application on oil weathered on the sea surface.

NEA and NCA have issued documents / guidelines that clarify the assessments needed to be documented in emergency response analyses and in the oil spill contingency plans before dispersants can be used. Two documents, a "Control form" and a "Decision matrix", have been compiled. The needed assessment before use includes information on e.g.: weathering properties, the chemical and natural dispersibility of the relevant oil, vulnerable natural resources/sensitive areas, salinity of the water, depth and distance to shore, possible stranding of oil, wind conditions, strategy for spraying of dispersants, operations in darkness, spraying capacity, monitoring for assessing efficacy and criteria for terminating the dispersant treatment operation. In this connection, a methodology for conducting emergency response analysis of relevant discharge scenarios including use of dispersants has been developed (Sørheim et. al, 2010). The methodology forms a basis for preparing generic response plans most suited to an individual oil spill situation. Enterprises that have such documentation and evaluation in their contingency plans, can in a spill situation submit the "Control form" and a dispersant operation can be initiated immediately if this is in accordance to the scenario described in the contingency plan. If such documentation is not included in the contingency plans, a specific application for using dispersants is needed, which will be a much more time-demanding process for getting an approval for use of dispersants in case of a spill situation.

The present regulations for use of dispersants in Norway are based on the scientific research, technology development, and operative experience gained through the series of field-experiments including testing of surface application of dispersants over the last 25-30 years. In addition the experiences from real incidents have shown that use of dispersants can be an appropriate and effective response strategy either as an alternative or a supplement to mechanical recovery in many spill situations.

However, the present regulations do not attend to relevant test criteria and documentation needed to perform robust and science-based NEBA assessment including SSDI as a response option in connection to underwater blowout situations.

3 Summary of the research Area for documentation needs in connection to SSDI

In this pre-project, six research areas (work-packages, WPs) are described in Appendixes A1 – A6 with respect to present status / ongoing R&D, knowledge gaps and further documentation needed. Below is a short summary of each of these WPs.

3.1 WP1 Effectiveness of SSDI under "relevant Norwegian conditions"

SSDI implies injecting dispersants directly into the subsea oil release and the dispersant is mixed with warm and fresh oil under highly turbulent conditions. The dispersants can either be injected into the oil line just before release or in the turbulent jet-zone immediately after the release point. The time available for the surfactants to lower the interfacial tension and influence droplet formation is very limited after the oil is released, in real cases, only the first seconds above the release.

During the last 3 years, SINTEF has performed extensive laboratory work in our Tower Basin focusing on subsea releases of oil and gas. These projects have focused on basic droplet formation as a function of oil properties and release conditions and the effectiveness of dispersant injection. This has primarily been financed by the international oil industry, mainly BP, API (incl. Statoil) and IPIECA-OGP. These studies have focused on the ability of the dispersants to reduce droplet size distribution under a variety of environmental conditions, and have clearly shown the potential of SSDI.

The results from the SINTEF Tower Basin have led to development of algorithms for initial droplet formation (modified Weber algorithm, (Johansen et al., 2013). This algorithm is now implemented in most models used to describe the fate of subsea releases, including SINTEF OSCAR model. In the coming months, new results will be available from the API project (phase III, IV, V and VI, see figure A.1.1 from Statoil) regarding SSDI effectiveness (for example mixed releases of oil & gas, deep water releases including "live oil" and the effect of secondary droplet break-up mechanisms).

However, there will be a need for additional work on these topics also after the API project is closed (2015/2016). Particularly, it will be important to ensure that the results and conclusions are also relevant for Norwegian scenarios. This will likely include validation studies using the SINTEF Tower Basin (Brandvik et al. 2013) and the Mini Tower (described below) on oil types, dispersants and test conditions relevant for "Norwegian release situations".

The SINTEF Mini Tower (also called Dispersant Injection Effectiveness Test – DIET) is a "bench-scale apparatus that has been developed at SINTEF during the past two years. Preliminary protocol documentation has been developed for IPIECA-OGP OSR-JIP (Brandvik et al. 2014). The DIET apparatus has been customized for performing "rapid" effectiveness screening experiments of SDDI. The capability of this new bench-scale method allows performing several tests per day by varying parameters like: Dispersant products, oil types, turbulence levels, injection techniques and dispersant dosages. This new bench-scale test protocol is documented by comparing results with large-scale testing in the SINTEF Tower basin. With some limited refinement and documentation, the DIET test could be adopted to the present regulations as a new protocol for SSDI effectiveness testing.

Based on the available information we suggest the following activities for further SSDI research related to WP1 Effectiveness:

- Developing new guidelines for testing and approval of dispersant for SSDI
- Using a test version of OSCAR to better understand and describe SSDI
- Documenting the influence of oil temperature for SSDI effectiveness
- Develop and test a prototype unit for subsea dispersant injection
- Exploring the potential of supplemental subsea mechanical dispersion (SSMD)

Further details are given in Appendix A1.

3.2 WP2 Combining model tools - spreading and resource models for use in response analysis and NEBA assessment

The oil spill and fate model OSCAR has been successfully coupled in offline mode to biophysical models for early life stages (ELS) of fish for various surface oil spill scenarios (Vikebø et al. 2014). Adding dispersants in OSCAR to combat oil enables comparison of individual exposure to dissolved toxic components in oil with the outcome if dispersants are not used (Vikebø et al. 2015). A mid-term goal should be to further refine model tools used today (e.g. Sørheim et al., 2010) to also include SSDI as a response option in connection to response analysis of spill scenarios as a basis for NEBA assessment. Up until now, only dissolved oil has been investigated in this context, not the oil droplets. The existing coupling of models may be extended to address both surface and subsea oil spills including effects of oil droplets with and without the use of dispersants.

It will be important to combine 3D-spreading models with dynamic models of relevant marine biological resources in the water column. For the Lofoten area these have traditionally been fish ELS, seabirds, corals/sponges, and zooplankton. If considering new areas, e.g. close to the ice in the Barents Sea, it will be important to consider which species are particularly vulnerable to oil and represent key species for the local ecosystem functioning.

Furthermore, using dispersants to combat surface or subsurface oil spills clearly shows that more oil is distributed in the water column and this could have significant impact on exposure rates of marine organisms also at a distance from the sea surface including benthic communities. Hence, besides quantifying exposure rates on specific species and stages one should also consider adverse effects on a combination of key species. For the Lofoten area, these should include the species listed above, though in particular it is necessary to address several fish species, e.g. Northeast Arctic (NEA) cod and haddock, and Norwegian Spring Spawning (NSS) herring, because of their different ELS features (sticky NEA haddock eggs, pelagic vs seabed NEA cod and NSS herring eggs). It is expected that the load on seabirds in general becomes less if using dispersants (though this might not be correct for diving seabirds), while the opposite might occur for benthic species (Valentin et al. 2014). It is difficult to speculate on the combined effect of dissolved oil and droplets with and without the use of dispersants on ELS fish if also including indirect effects on their key prey item *Calanus finmarchicus*. This has to be considered in a model framework based on laboratory studies providing effects of oil exposure on single species at various exposure rates and durations enabling parameterizations. Such a model system will make it possible to test hypotheses and identify gaps and needs for further documentations of e.g. acute and chronic toxic exposure levels. A more long-term R&D goal will therefore be to continuously fill in with new R&D requirements and results from robust and relevant experimental studies as we move along and are able to get new projects prioritized and funded (see part 3.4).

Further description of WP2 and prioritised research activities are given in Appendix A2.

3.3 WP3 Biodegradation and long-term fate of dispersed oil from underwater releases

Biodegradation plays an important role in underwater blowouts. The reason for using SSDI is to generate small-droplet oil dispersions. If SSDI reduces droplet size in the underwater plume, this will result in increased interfacial area between the oil and the water, and oil compounds will therefore become more bioavailable for degradation in the water column. In recent studies with surface spills we have shown that use of dispersants will generate median droplet sizes of 10-30 µm which behave as neutrally buoyant particles in the seawater, while larger oil droplets may end up on the surface where they may start forming a very slowly degradable emulsion on the surface (Brakstad et al., 2014).

SINTEF has performed several biodegradation studies of dispersed oil droplets relevant for underwater releases. Presently, SINTEF is running a project for the Research Council of Norway (RCN) and is also involved in a project for the Gulf of Mexico Research Initiative (GoMRI). The aims of these projects are to study how dispersant strategies may affect the biodegradation of oils under different conditions (oil types, temperatures, droplet size distribution) and the impacts of gas compounds (methane, ethane, propane) in "live oils" on oil degradation. Knowledge gaps that will not be covered through these project are: A) effects of pressure on biodegradation, B) biodegradation of oil on the seabed as the result of possible sedimentation of aggregates ("flocs") from degraded dispersed oil and microorganisms / bacteria in connection to such aggregate formation and possible sedimentation on the seabed, and C) biodegradation in subsea areas of the world where low oxygen concentrations may reduce oil biodegradation under low oxygen concentrations (not relevant for NCS with mainly well oxygenated water masses). There will be a need for combining biodegradation and effect studies on relevant sea bed organisms (including fungi and corals, see part 3.4.). An on-going API-report ("State of the Science and GAP analysis") on biodegradation regarding SSDI will be available during 3Q 2015, and should be taken into account in the pre-project. Further description of WP3 is given in Appendix A3.

Based on the available research information we suggest the following biodegradation priority areas for SSDI research related to the NCS (see Table A.3.3):

- Oil-microbe flocculation and long-term fate as the result of SSDI
- Correlation between oil biodegradation and acute toxicity
- Oil droplet size distribution by SSDI and biodegradation rates

3.4 WP4 Potential toxic effects and effect thresholds related to SSDI under "relevant Norwegian conditions".

The conditions created during a subsea oil spill where oil and gas is dispersed directly into the sea at high pressure, deviate from the conditions of a surface dispersion in several aspects. For instance most of the volatile oil fraction is expected to be retained in the water column. In addition small gas bubbles as well as small oil droplets may be entrained and partly dissolved into the water column.

IMR and SINTEF have during recent years developed unique methodology for testing and studying the effects of dissolved and dispersed oil with and without the use of oil spill dispersants (Nordtug et al. 2011). Both institutions have been involved in several effect studies to provide parameterized data on oil toxicity that is aimed at providing input to environmental modelling (see attached list of references). In parallel, model simulations have been performed to evaluate the impact of using chemical dispersion on the overlap between fish larvae and oil in time and space (Vikebø et al., 2013 and 2015). Both the toxicity studies and the model simulations have been designed to simulate surface oil spills, assuming that oil has been weathered by evaporation and dissolution with very low fractions of volatile components and no gas components present.

Chemical dispersants make oil break up into smaller droplets, which remain in the water column and increase dilution and biodegradation of oil components. The dispersants themselves display lower acute toxicity than oil (Hansen et al., 2014), and thus are expected to have a limited contribution to the toxicity of oil dispersion (Olsvik et al., 2012). They do, however, increase oil concentrations and bioavailability in the water column (Adams et al. 2014) and potentially enhance benthic transport and sedimentation of oil (White et al., 2014).

So far, no exposure studies have been performed with oil and gas dispersed directly into the water column that has direct relevance to subsea oil releases with oil containing all volatile components (BTEX compounds; benzene, toluene, ethylbenzene and xylenes) and gas entrained under pressure. Thus, there is a lack of information on effect thresholds related to these conditions for relevant species in the water column (e.g. Northeast Arctic cod and haddock, Norwegian Spring Spawning herring, zooplankton (e.g. *Calanus*)). Early life stages (embryos and larvae) are assumed to be particularly sensitive and may be affected by feeding on zooplankton enriched with oil due to filtration of oil droplets (Nepstad et al., 2015, Nordtug et al., 2015).

New studies have shown that adhesion may represent an additional route of exposure of haddock embryos to oil components (Sørhus et al., 2015). Differences in surface tension of oil droplets dispersed mechanically (e.g. by wave action) and chemically (by dispersants) may affect their capacity to adhere to surfaces, and there is a need to study if chemically dispersed oil has similar direct toxicity as mechanically dispersed oil droplets.

IMR has mapped occurrence of corals along the Norwegian continental shelf in the MAREANO project (www.mareano.no). Community structure and ecological function of deep-water sponge grounds in the Norwegian continental shelf has been documented by Kutti et al. (2013 and 2014). However, the sensitivities of benthic species like corals and sponges to mixtures of volatile oil components and gas are not well documented.

To fill in knowledge gaps, the following activities are recommended:

- Experiments that can give more data on body burden and threshold levels for volatile compounds and PAHs components on selected organisms, as input to risk assessments and decision making.
- Experimental research to describe the fate and effects of gases at high pressures with or without dispersants.
- Studies aimed at describing the potential for oil droplets to adhere to biological membranes focussing on changes in adhesion potential as a function of weathering degree of oil and different biological membranes (e.g. eggs, larvae, copepods etc).
- How may increased levels of oil droplets due to chemical dispersion affect exposure to fish eggs. Such effects without use of dispersants have been reported from haddock (Sørhus et al., 2015). It may well be an increased effect of use of dispersants that should be tested for selected species. Short term exposure studies on Atlantic haddock, Atlantic cod and Atlantic herring embryo. Contributions of oil droplets to embryo toxicity may be an important parameter that should be included in risk assessments.
- Determine if high levels of BTEX from non-weathered oil increase the toxicity during chemical dispersion compared with data with weathered oils. These studies should focus on early life stages of Atlantic herring since its benthic egg make it vulnerable for subsea oil spill.
- Studies on effects of crude oil with and without chemical dispersants on benthic organisms like corals (*Lophelia sp.)* and sponges (*Geodia baretti*).
- Exposure studies on whether *Calanus finmarchicus* is more affected by dispersed “fresh oil” compared with earlier studies on weathered oils. *Calanus* are key species in Norwegian Seas. Due to its high ability to accumulate lipophilic compounds it may transfer oil compounds to predators like fish larvae.

Further description of WP4 is given in Appendix A4.

3.5 WP5 Validation by controlled field experiments

A final step in the R&D JIP would be to validate the scientific findings through controlled field experiments including SSDI. In the same way as the international reputed "Deep-spill" experiment in 2000, this will have a great scientific value both for validating experimental studies performed under controlled laboratory and basin experiments (both effectiveness and biological effects) and in testing the robustness of numerical models developed during the R&D program. Additionally, a full-scale experiment will be of high value for documenting SSDI as an operational countermeasure technique and in testing different monitoring systems under realistic field conditions.

Based on the previous experiences field trials with sub-sea releases (Brandvik et al. 1996, Rye et al., 1997, Johansen et al. 2003), we recommend designing the coming field experiments as similar as possible to the series of subsea releases in shallow water in 1996 and in deep water in 2000. The main difference would be to include the testing of SSDI as an additional varying parameter. This will be the most cost–effective way to cover the knowledge gaps and verifying the effect of SSDI in these field experiments. Such an approach will imply the following series of field trials:

- June 2017: Field experiments with sub-sea oil /gas releases and SSDI in shallow water (106 m depth at the Frigg field in the North Sea)
- June 2018: Field experiments with sub-sea oil /gas releases and SSDI in deep water (850 m depth at the Helland Hansen in the Norwegian Sea)
- Using the similar oil types and release rates as in the 1996 / 2000 experiments

Further description of WP5 is given in Appendix A5.

3.6 WP6 Monitoring – sensor instrumentation

At the SSDI workshop in May 28 2015, it was decided to have monitoring / sensor instrumentation as a separate WP. One important presumption for getting a release permit from the Authorities for a field trial is to have a good documentation for monitoring. Secondarily to this, an in-situ monitoring effort to quantify the effectiveness of SSDI processes associated with potential longer-term effects of an accidental release (i.e. ecological impacts) will provide a unique data-set for advancing scientific understanding of these processes at more realistic scales.

Together, SINTEF and IMR have extensive experience and capability for monitoring of both the details of SSDI effectiveness and the larger ecological impacts of a subsea release. This monitoring effort will consist of multiple components, including: the necessary background met-ocean information (water column density structure, wind & wave conditions); background measurements associated with biological activity (e.g. fish eggs and plankton abundancies); macro-scale plume characteristics (e.g. plume shape, geometry and plume movement); aerial imagery of the surface processes above the release; detailed in-plume measurements of the released oil and gas droplets.

In a field experiment that would be appropriate for evaluating SSDI, IMR will contribute with research vessels and monitoring instrumentation, such as high resolution fluorescence meters for measuring PAH-concentrations on component level. Recent generation of acoustic sensors are also used to study dynamic vertical distribution of fish eggs, that otherwise can easily be mistaken for oil droplets. After the Deepwater Horizon incident, there has been a significant progress in the development of in situ fluorescence sensors (e.g. Conmy et al., 2014) using AUVs and gliders platforms, the deployment of which should be considered in an offshore field trial. Other macro-scale measurements of the subsurface plume can be obtained by use of methods developed and employed during recent large-scale gas releases, as part of the SURE JIP (SINTEF project). For detailed measurements of subsurface plume geometry and cap rise velocities, the CodaOctopus EchoScope is mounted on an ROV, and together with the data treatment methods developed at SINTEF, can be used to reconstruct the plume migration through the water column in three dimensions. This can provide valuable information for model calibration / validation of parameters relating to entrainment and gas dissolution, for example. The Maritime Robotics OceanEye has also proved a useful tool for characterising the surfacing plume in such operations, and has been used to provide time-series of the plume boiling zone diameter from offshore gas releases. It remains, however, important that further updates to, and calibration of, the imaging platform on this airborne system are considered as a pre-requisite to future scientific measurements of offshore releases, in order to make sure that the OceanEye is properly equipped for scientific purposes in addition to the uncalibrated visual pictures and poor temporal-resolution of the camera gimbal, provided by the present system.

In addition to macro-scale plume measurements, it is of critical importance to obtain information on the oil droplet size distribution and gas bubble size distribution within the plume. These measurements provide the most valuable information relating to the effectiveness of SSDI. Over the last two years, SINTEF has developed a suite of novel in-situ particle imaging systems that overcome many of the challenges associated with in-plume measurements such as high concentrations, large multi-mm droplets, and mixed oil and gas. These systems make use of a silhouette-based approach for imaging particles suspended in seawater, and are capable of distinguishing between oil droplet, gas bubble and other particulates in suspension (e.g. marine snow and planktonic organisms). The use of the SINTEF Silhouette Camera systems will be necessary for quantification of the effectiveness of any dispersant injection, and also for measurements of undispersed droplet sizes. The ability to segregate the size distributions of multiple particle types (e.g. oil droplets, gas bubbles and other), is also of critical importance in evaluating the influence of the gas-oil ratio on subsurface dispersant injection. The removal (or additional analysis) of other types of particle present is also necessary in order to avoid over-counting of oil droplets or gas bubbles, and quantification of plankton abundancies may also be valuable from an ecological impact perspective (which can be fed into the filter-feeding mode within OSCAR). The Silhouette Cameras are fully submersible, but currently require a tether to the surface for power and data recording. The integration of the Silhouette Camera system with ROVs will be an important pre-requisite to any offshore field trial, and should form part of the preparations for such an experiment.

In summary, the following activities are suggested in order to obtain the accurate measurements needed for quantification of SSDI effectiveness:

- Integration of the SINTEF Silhouette Camera with ROV so that SSDI effectiveness can be quantified using in-plume droplet and bubble size distribution measurements.
- Laboratory testing of acoustics for oil and gas.
- Combined technology for dynamic, in-situ calibration of large-volume acoustic measurements.

Further description of WP6 is given in Appendix A6.

4 Suggested timeline for the SSDI R&D JIP

Based on the description of the prioritised research areas within the six work-packages (WPs) that are summarised in chapter 2 and described in Appendixes A1 – A6, a very tentative overall timeline is suggested in the figure 4 below.

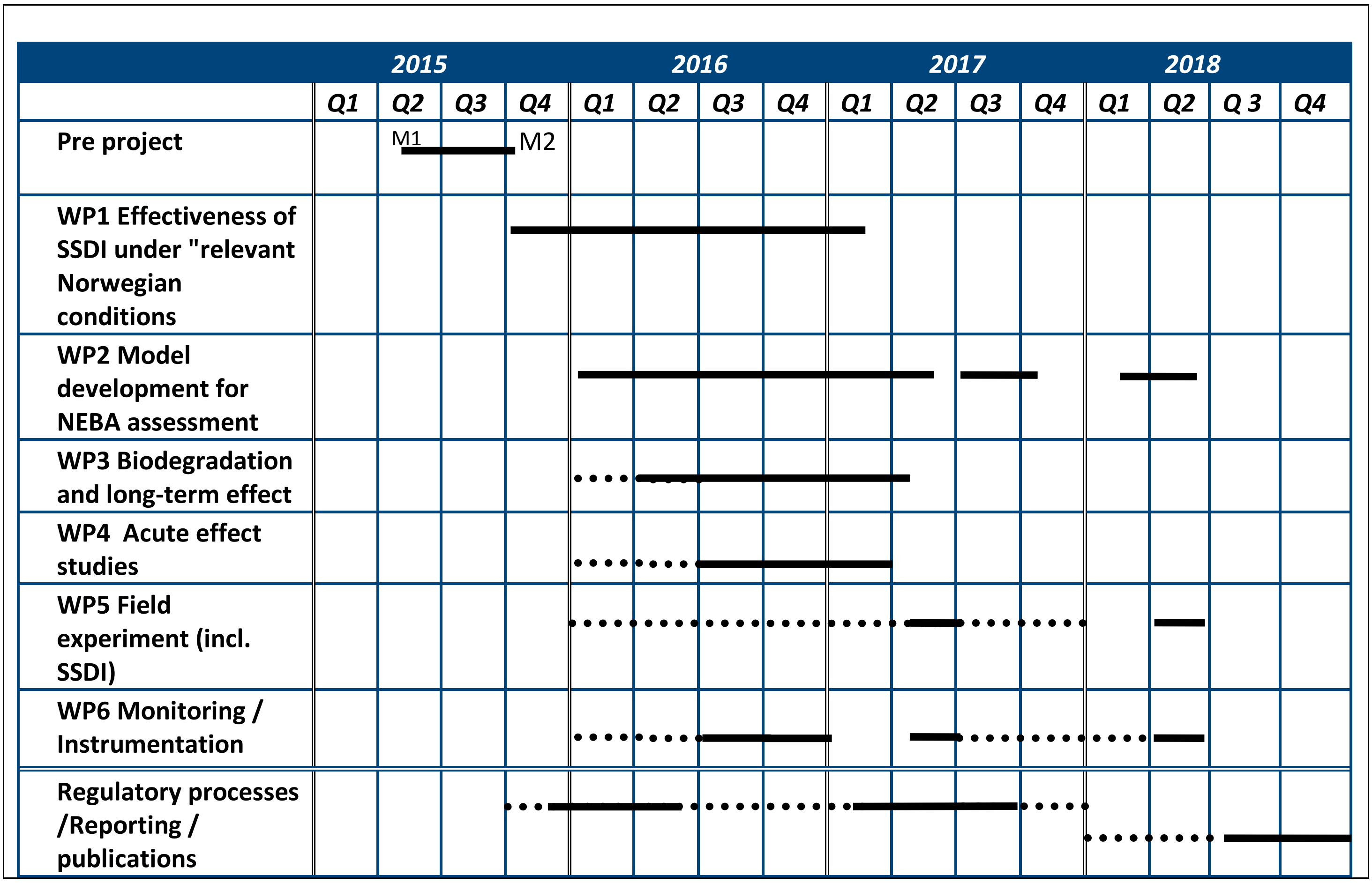

Figure.4: Tentative overall timelines for the SSDI research areas

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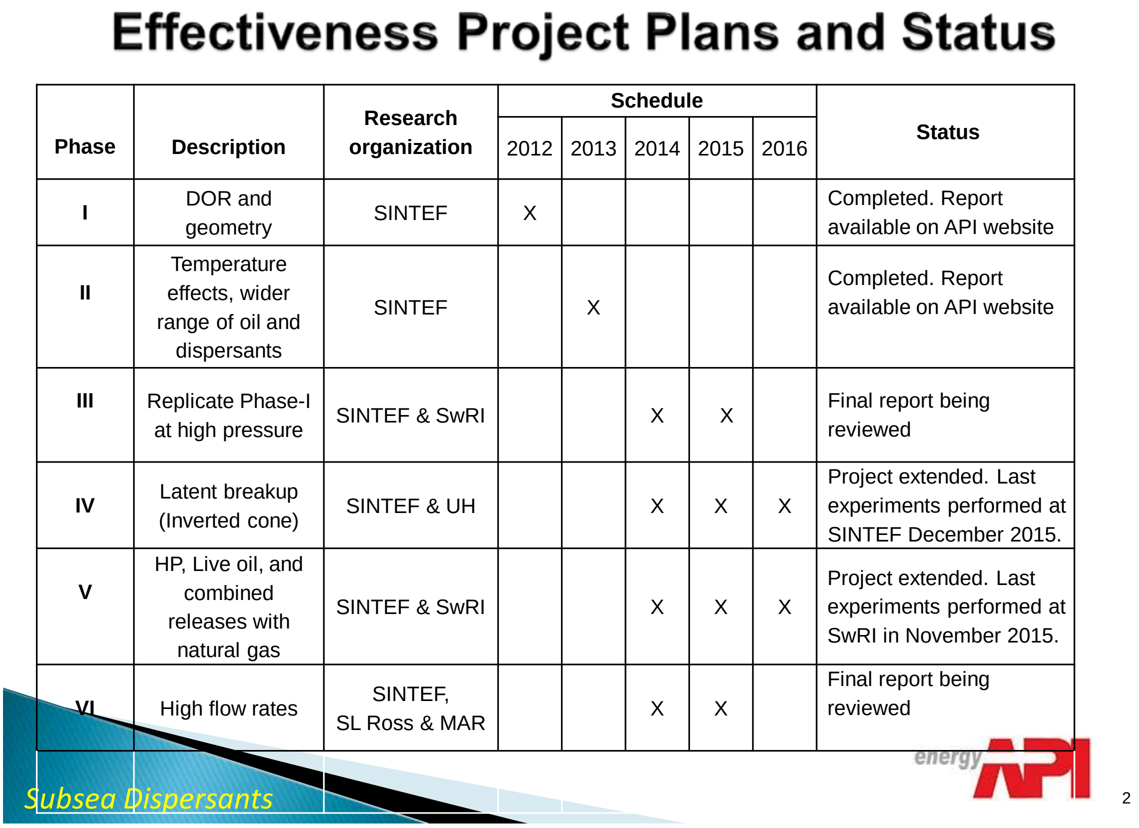
A Appendixes: WP descriptions

A.1 WP1 Effectiveness of SSDI under "relevant Norwegian conditions"

These sections describe the main previous R&D efforts, status and activities needed to implement SSDI into Norwegian contingency plans as a response method.

A.1.1 Recent and ongoing research efforts

The main research efforts the last years regarding SSDI effectiveness have been coordinated by the American Petroleum Institute (API). They initiated an Oil Spill Prevention Response Joint Industry Task Force (JITF) in 2012 (www.oilspillprevention.org). The International Association of Oil and Gas Producers (IOGP) and The global oil and gas industry association for environmental and social issues (IPIECA) formed in 2011a Joint Industry Project (JIP), governed by the fourteen funding companies. This JIP, covering a wide area of oil spill response methods had also a work package focusing on SSDI - JIP 2 (SSDI/Efficacy). More details are found at their website: http://oilspillresponseproject.org/.



Effectiveness Project Plans and Status

Phase	Description	Research organization	Schedule					Status
			2012	2013	2014	2015	2016	
I	DOR and geometry	SINTEF	X					Completed. Report available on API website
II	Temperature effects, wider range of oil and dispersants	SINTEF		X				Completed. Report available on API website
III	Replicate Phase-I at high pressure	SINTEF & SwRI			X	X		Final report being reviewed
IV	Latent breakup (Inverted cone)	SINTEF & UH			X	X	X	Project extended. Last experiments performed at SINTEF December 2015.
V	HP, Live oil, and combined releases with natural gas	SINTEF & SwRI			X	X	X	Project extended. Last experiments performed at SwRI in November 2015.
VI	High flow rates	SINTEF, SL Ross & MAR			X	X		Final report being reviewed

Figure A.1.1: Overview and status of the projects within API OSPR JITS - D3.

In summary (3.1) it is stated that some more work is needed as follow-up (NCS conditions) after “Figure A.1.1 work” is completed. These gaps are for example developing national guidelines for Norwegian conditions, implementing findings into models describing subsea releases (OSCAR), further explore the effect of oil temperature on SSDI effectiveness and developing further dispersant injection techniques studied during the API D3 JITS.

A.1.2 New guidelines for testing and approval of dispersant for SSDI

In most SSDI scenarios the dispersant will be injected directly into fresh warm oil under highly turbulent conditions and often in presence of gas. This is a situation which is very different from surface application of dispersants (weathered oil, low turbulence and challenging application). Current regulations regarding testing and approval are made to document the effectiveness of dispersant for surface application. A study performed by SINTEF for IPIECA/OGP concludes that other tests should be used to document effectiveness of dispersants for SSDI and a new bench-scale test method was suggested (Brandvik et al., 2014). This new bench-scale method, SINTEF Dispersant Injection Effectiveness Test (DIET), is suggested as a possible new standard test for SSDI effectiveness, see Figure A.1.2 below. The test offer efficient and low-cost testing of different dosages and dispersant products on a specific oil type. This is done with injection methods and turbulence regimes wich are operational representative for a subsea release of oil and gas.

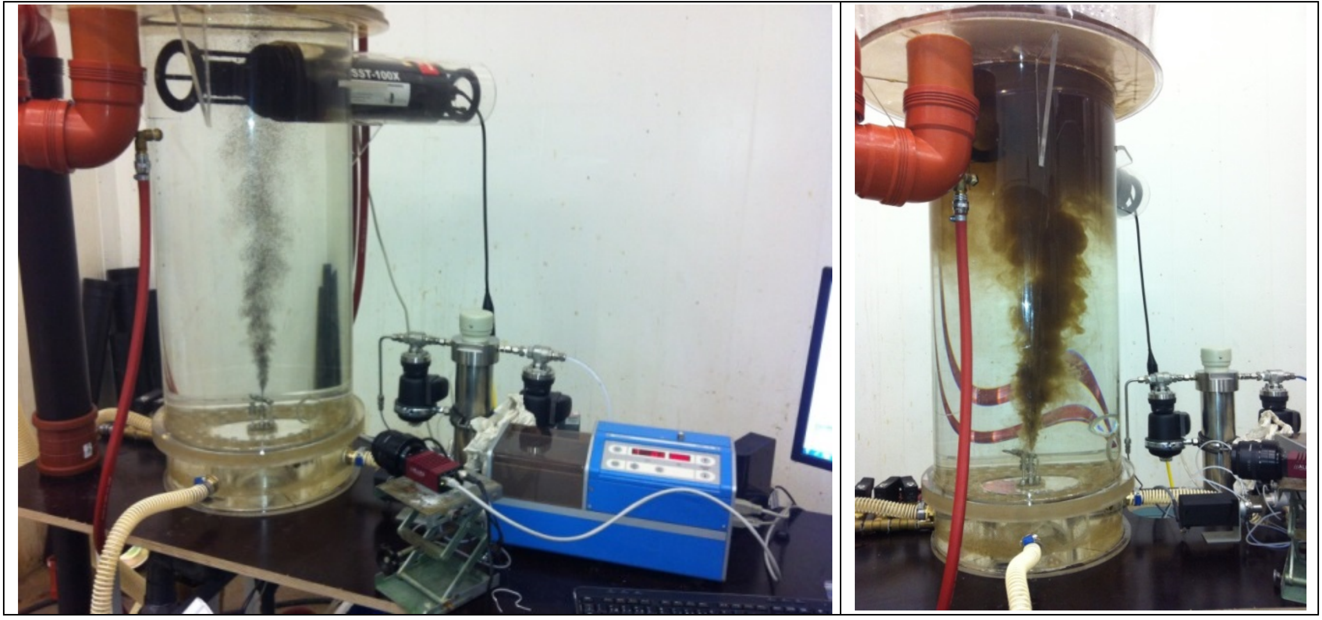


Figure A.1.2: Continuous rising plume of untreated Oseberg blend (A) and oil treated with Corexit 9500 DOR 1:100 (B). Dispersant injection syringe pump (blue box) is shown (A).

Figure A.1.3 below shows the relative effectiveness (ranking) of five dispersants for surface application in the right part of the figure (existing test protocol with the IFP test). The left part of the figure shows the ranking of the SSDI effectiveness according the recommended test procedure from the IPIECA/OGP report. The ranking of the products shows significant differences, which is expected since the requirements for the dispersants are very different in these two cases. A surface dispersant has to handle weathered emulsions, which means that it must be able to penetrate into viscous emulsions, break them and disperse the water free oil. In case of SSDI the dispersant doesn't have to break any emulsions, but it has to react very fast, the droplets are formed in the highly turbulent jet, only milliseconds after injection (lab scale).

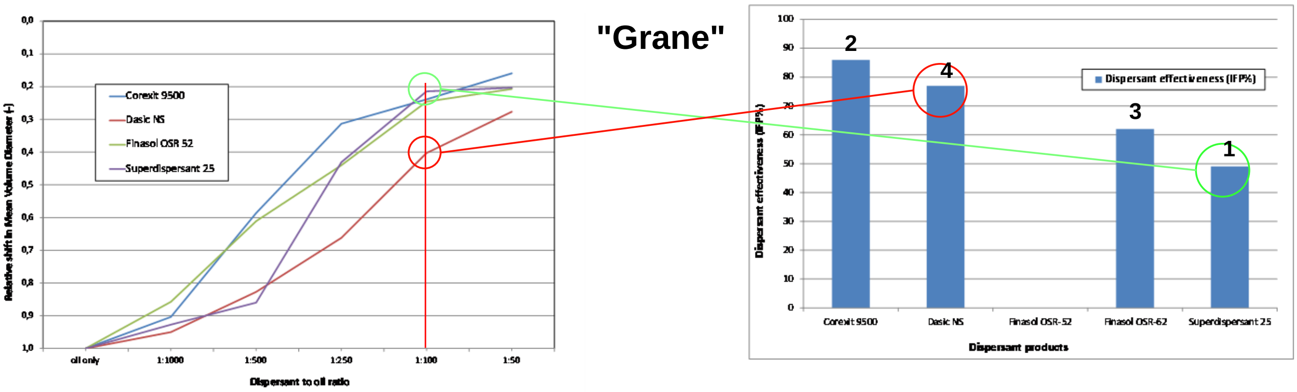


Figure A.1.3: Comparison of relative SSDI effectiveness (left) and relative surface application effectiveness (right) for an asphaltenic crude. Number indicate ranking for SSDI effectiveness.

We propose the following activities to produce this supporting material to establish SSDI as an operational option in Norway;

1. Prepare a prototype for a standardised lab test for SSDI effectiveness testing based on the recommendations in the IPIECA/IGP report (Brandvik et al., 2014a), the SINTEF Mini Tower.
2. Document the prototype (SINTEF Mini Tower) with testing two new oil types where we already have performed dispersant testing/screening for surface dispersant application (five dispersants with five different dosages from 4% to 0.01%).
3. Finalize and submit a scientific paper to Marine Pollution Bulletin (Elsevier) describing the test system and explaining why it is needed.
4. Possible outreach activities towards Miljødirektoratet (Norwegian Environmental Agency). Assisting NOROG in presenting the new approach for the authorities and assisting in working out supporting material for new guidelines to be implemented into the present regulations for use of dispersants in Norway.
5. Develop and test a prototype device for subsea injection of dispersant. The prototype is based on the small-scale testing of multiple injection techniques in the SINTEF Tower Basin as a part of the API D3 JITS.
6. We suggest to explore the potential of a novel and supplemental method to SSDI, called Subsea Mechanical Dispersion (SSMD). This method is based on using mechanical forces to reduce the droplet size after intial droplets formation.

A.1.3 Using a test version of OSCAR to better understand and describe SSDI

SINTEF released a new version of OSCAR with an improved algorithm for initial oil droplet formation (modified Weber scaling) in 2013. This new algorithm was based on experiments from the SINTEF Tower Basin performed in a BP funded project 2011-12 (Johansen et al., 2013). The main advantage with this new algorithm is that it also includes contributions from;

a. oil properties e.g. viscosity
b. turbulence created by the buoyancy flux and
c. the gas void fraction

However, when using the new version of OSCAR on various subsea scenarios we have experienced that modified Weber number also introduced additional challenges, especially when SSDI is included. The equation has oil viscosity in the numerator and the interfacial tension (IFT) in the dominator (Johansen et al., 2013), this means that at low IFT values (use of dispersant), oil viscosity will be very influential on the predicted droplet sizes. The consequence of this is that both how oil viscosity is measured (shear rate & temperature), the rheology of the oil itself and the oil release temperature used for droplet formation, strongly influence the predicted droplet sizes when using SSDI.

These three factors (viscosity measurements, oil rheology and release temperature) had only minor influence on predicted droplet sizes in earlier versions of OSCAR. We have to admit that neither SINTEF nor the consultancy companies, using OSCAR in projects for the oil industry, have paid sufficient attention to this new and increased significance of oil viscosity data when running the newly released version of OSCAR. The present oil database in OSCAR contains viscosity data that are dedicated for characterizing the viscosity of the oil on the sea surface (with respect to temperatures and shear rates). By using these oil viscosities directly from the oil database for subsea releases simulations, especially with SSDI, one could significantly overestimate droplet sizes in some scenarios.

A high viscosity for an asphaltenic crude measured at low shear rate and 13°C is highly relevant for oil behaviour in a low turbulent surface oil slick. However, viscosities for many oil types may be very shear thinning at such low temperatures. By measuring at a higher shear rate (e.g. 1000 s^{-1}) and at more relevant temperatures (e.g. 60 °C), viscosity can be reduced with a factor of several hundred. This will strongly influence the predicted droplet sizes. As an example, a viscosity of 250 mPas for an asphaltenic oil (13°C &

low shear rate) gives a d_{50} of approx. 1200 µm, compared to using a viscosity of 5 mPas (60 °C & high shear rate) would give a d_{50} of approx. 200 µm (with SSDI, 1% C9500, IFT: 0.2 mN/m). The last viscosity measurement would probably be more representative for the viscosity in a subsea blowout (warm oil and high shear rates >10 000 for the released oil).

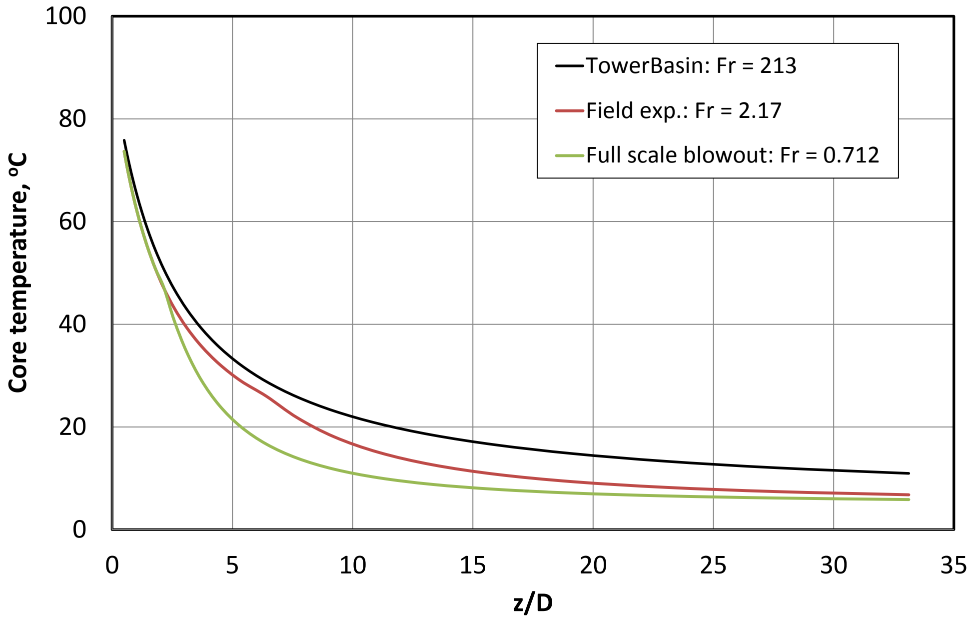


Figure A.1.4: Preliminary estimates of oil temperature (core of oil jet) during cooling from the surrounding water versus distance from the nozzle (nozzle diameters). The preliminary predictions are for three different cases (SINTEF Tower basin, DeepSpill and full scale similar to DWH in 2010). The oil temperature at release is assumed to be 90°C and the water temperature 5°C.

Droplet formation occurs very close to the nozzle where the turbulence is highest (dissipation energy is drastically reduced with distance from the nozzle). The figure above indicates that the initial temperature is reduced to a third within a distance of 5D where most of the droplet formation is expected to take place.

This proposed project contains activities to study the different factors influencing oil viscosity and the prediction of initial droplet size, especially during SSDI. Statoil has expressed interest in the experiments on droplet-size dependent biodegradation that have been undertaken in the PETROMAKS biodegradation project. Therefore, a task has been added for analysing the sensitivity of experimental data, proposing a model based on the data, and demonstrating a proof of principle test of the model in OSCAR. The following activities are suggested:

1. Select ten oil types where most of them have a challenging rheology (high wax/asphaltene content). Produce viscosity data as a function of shear rate and temperature (three shear rates: 10, 100 and 1000 s^{-1} at 5 – 70 °C).
2. Establish a model for the viscosity as a function of temperature. Several functions are reported in the literature as an alternative to the one selected for OSCAR
3. Viscosity change versus temperature and reduction in temperature during initial droplet formation (from warm initial oil (e.g. 120 °C) to cold surrounding bottom water (e.g. 4 °C) and use the laboratory data for calibration.
4. Implement this in an internal test version of OSCAR (improved criteria for oil temp/viscosity during droplet formation).

5. Implement a preliminary model for biodegradation which takes droplet size into account. This will make use of experimental results recently obtained from the ongoing PETROMAKS biodegradation project. The model will be implemented in OSCAR for the purpose of a proof of principle demonstration.
6. Run example scenarios and write a brief report.

The activities above and the example scenarios will produce new insight into the sensitivities of predicted droplet sizes on oil viscosity. It will also give us important information on how to characterize oil rheology more relevant for subsea releases and use of SSDI.

A preliminary algorithm for biodegradation taking droplet sizes into account will also visualize increased biodegradation as a function of increased area (smaller droplets) and increased time suspended in water (smaller droplets). This will offer a better representation of the environmental effect of SSDI, since the present version of OSCAR uses the same biodegradation rate regardless of droplet sizes.

A.1.4 Documenting the influence of oil temperature for SSDI effectiveness

SINTEF has performed extensive studies of various aspects of SSDI for API through their D3 Effectiveness of subsea dispersant injection JITS. Phase-II of this JITS included studies of SDDI as a function of oil temperature (13-90 °C). This study strongly indicates a reduced effectiveness (larger droplets) at increased temperatures. One hypothesis to explain this could be that today's dispersants are optimized to work at Arctic to tropic conditions (0-50 °C) and that possible changes in surfactant structures above this temperature alter the surfactant packing efficiency at the oil-water interphase (Brandvik et al., 2014). This temperature effect could be compensated by increasing the dispersant dosage, but this approach introduces logistical challenges during high flow rate releases like the DWH blow-out in GOM in 2010.

However, more recent and detailed investigations as a part of a MSc project at SINTEF (Dunnebier, 2015), indicated that this temperature effect is dependant of oil properties. The reduction in SSDI effectiveness observed in the API study, was reproduced for paraffinic oils, but not observed for Napthenic oils as illustrated in Figure A.1.5 with Kobbe and Troll B. Both untreated oils show a reduction in droplets sizes with increased temperature (due to reduced viscosity & IFT) while the treated oils show very different behaviour. The paraffinic Kobbe shows a significant increase in droplet size and the effect of dispersant injection at 80-90 °C is marginal. The trend for the treated oil is very different for the napthenic Troll B, with an initial increase in effectiveness (smaller droplets) which levels out above 50 °C.

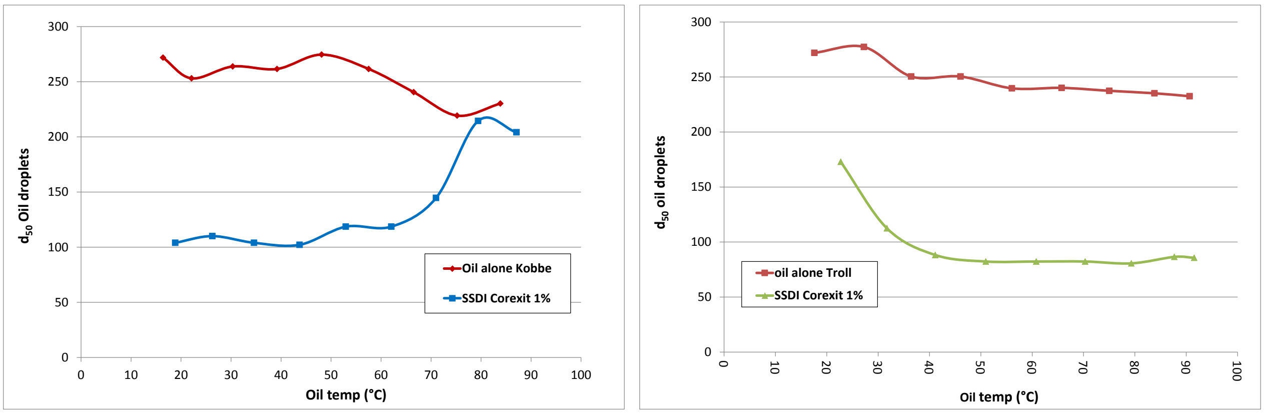


Figure A.1.5: Relative SSDI effectiveness (d_{50}) as a function of temperature for the paraffinic Kobbe (left) and the Napthenic Troll B (right) from Dunnebier, 2015.

This proposed project contains activities to study the effect of the temperature of the released oil on SSDI effectiveness:

1. Testing of SSDI effectiveness as a function of temperature with the new proposed bench-scale test with one dispersant on four new oil types spanning out oil properties (i.e. wax/asphaltene content, viscosity, density, pour point…). The bench-top test system will be modified with a heat exchange system for continuous heating of the oil (Dunnebier, 2015). The main objective with this activity is to generate data to study the influence of oil properties on the temperature effect.
2. Test four-five different commercially available dispersants (e.g. C9500, OSR-52, Dasic NS, Super dispersant or Radiagreen) on two oil types with different behaviour e.g. Kobbe and Troll B as shown in Figure A.1.6. Two of the dispersants-oil combinations have already been tested in the activity described above. The main objective with this activity is to generate data to study any possible differences in temperature effect between the commercial available dispersants.

The tests described above have similarities with the work performed as a part of the API D3 Phase-I study performed by SINTEF (Brandvik et al., 2014b). The main difference is the resolution. In the API work we did tests in the Tower basin with oil heated in specialised 7 L tanks, performing experiments at high (70 °C) and low temperature (15 °C). With the system developed during Dunnebier's MSc project, we are capable of doing continuous measurements (untreated/treated) using the MiniTower while we are heating the oil (15 - 90°C). The main advantage with this system is the high resolution in temperature, comparable treated/untreated measurements and the reduced time & cost. These results are regarded as more informative and reliable than the API D3 results, since we are comparing trends in a continuous data set (see Figure A.1.5) rather than single point measurements.

A.1.5 Developing a prototype unit for subsea dispersant injection

Injecting dispersants into a subsea release of oil and gas can be performed with multiple techniques. SINTEF has studied several alternative injection techniques as a part of a larger study for API (Brandvik et al., 2014b). This were down-scaled studied performed in SINTEF Tower Basin, see Figure A.1.6. below.

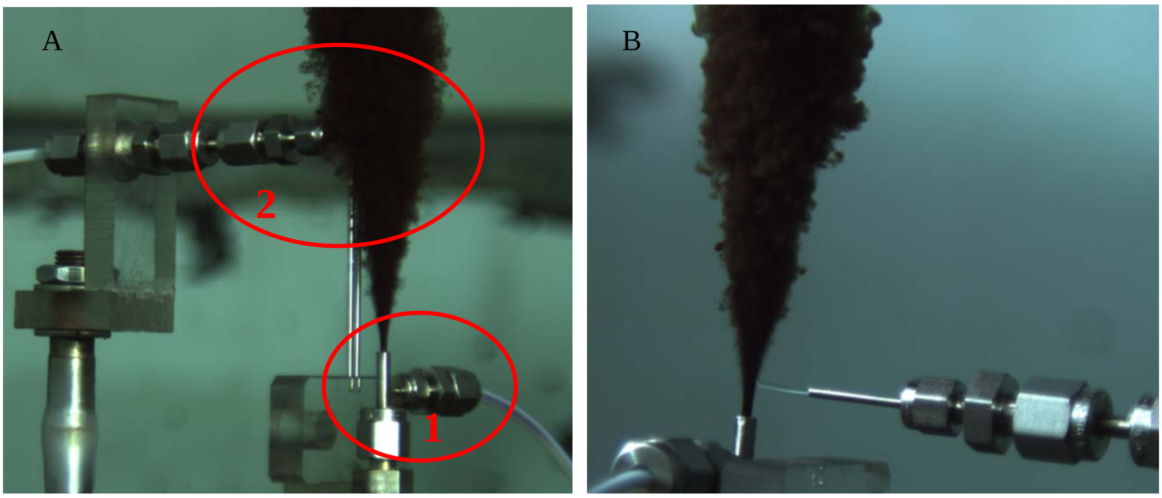


Figure A.1.6: Release arrangement (1.5 mm nozzle) with A: Options for injection of dispersant by the "Simulated insertion tool" (1) and "injection in the oil above the nozzle" (2), B: Options for injection dispersant horizontally into the oil..

The main conclusion from this down-scaled laboratory study was that the dispersant has to be injected into the oil & gas either just before the outlet ot just after. Reductions in initial droplet size were fairly insensitive to the dispersant injection method as long as the dispersant was injected close to the release point (with less than six release diameters). Most of the laboratory testing has for this reason, been performed with the so-called Simulated Insertion Tool (SIT), basically simulating a wand-like tool inserted into the release opening (6 release diameters). See Figure A.1.6 and Brandvik et al., 2014 for further details.

The concept of "Simulated insertion tool" is well tested as a down-scaled prototype in the SINTEF Tower Basin. However, to implement this technique operational it should be tested as an upscaled version in the lab and implemented as a tool operated by a suitable ROV.

We suggest a technology development & verification project together with one of the engineering companies offering offshore ROV services. This should include upscaled basin testing, design production and full-scale testing mounted on a ROV with the needed equipment to inject dispersants. No oil is needed to test this injection system in full size. This can be performed with partial funding from the DEMO2000 program.

This system will be a stand-alone system for SSDI which offer a quicker and low-cost alternative to mobilizing larger systems for "Cap & Containment", which usually has a module for SSDI included.

A.1.6 Exploring the potential of supplemental subsea mechanical dispersion (SSMD)

SINTEF has performed a proof of concept study to test the use of mechanically induced shear to induce dispersion of subsea oil releases. The results indicate that droplet sizes from a subsea release can be reduced more efficiently by mechanical induced shear than chemical dispersant injection (Brandvik et al., 2015). This report assesses the feasibility of two different mechanical dispersion devices to reduce oil droplet sizes from a subsea release. They represent two contrasting operating principles – one by mechanically-induced shear, and the other by ultrasonic cavitation. Down-scaled prototypes of these two new approaches were compared to the use of chemical dispersants.

Both devices were found to be effective at reducing oil droplet sizes. The ultrasonic device created a broad distribution of oil droplet sizes, spanning 10-100 µm in diameter. The mechanical shearing technique dispersed oil droplets into a narrower size distribution, centred on 16 µm (see Figure A.1.7). An additional benefit of this device was the strong physical dispersion of the oil droplets radially from the device. This separation will reduce coalescence immediately after the initial droplet formation. Absolute droplet sizes should be interpreted with care since they are a function of the laboratory conditions.

Parallel to the proof of principle study at SINTEF, BP performed a CFD study of a third concept for mechanical subsea dispersion, water jetting. The impact from a high pressure water jet is used to mechanical reduce the droplet size of the released oil (see Figure A.1.8). Several options for this approach were tested during this modelling study. Several types of commercial available high capacity pumps e.g. for well stimulation, should be suitable for this concept.

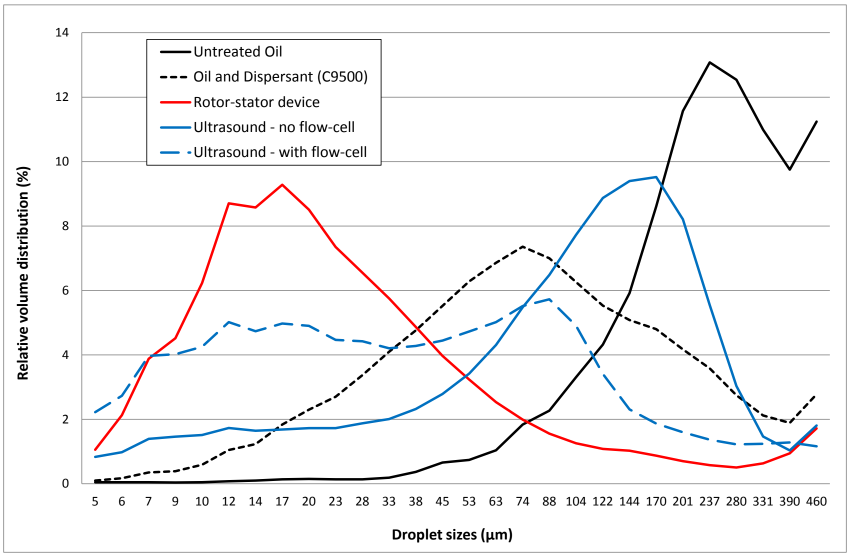


Figure A.1.7: *Droplet size distributions from untreated oil with the two mechanical treatment devices (Rotor-stator & Ultrasound) and chemical dispersion in the SINTEF TowerBasin. For ultrasound the medium-size flow-cell (dashed lines) and no flow-cell (solid lines). The untreated oil (black line) was Oseberg blend, released from a 1.5mm nozzle at a rate of 1.2 L/min. The dispersant was Corexit C9500 at a dosage of 1%.*

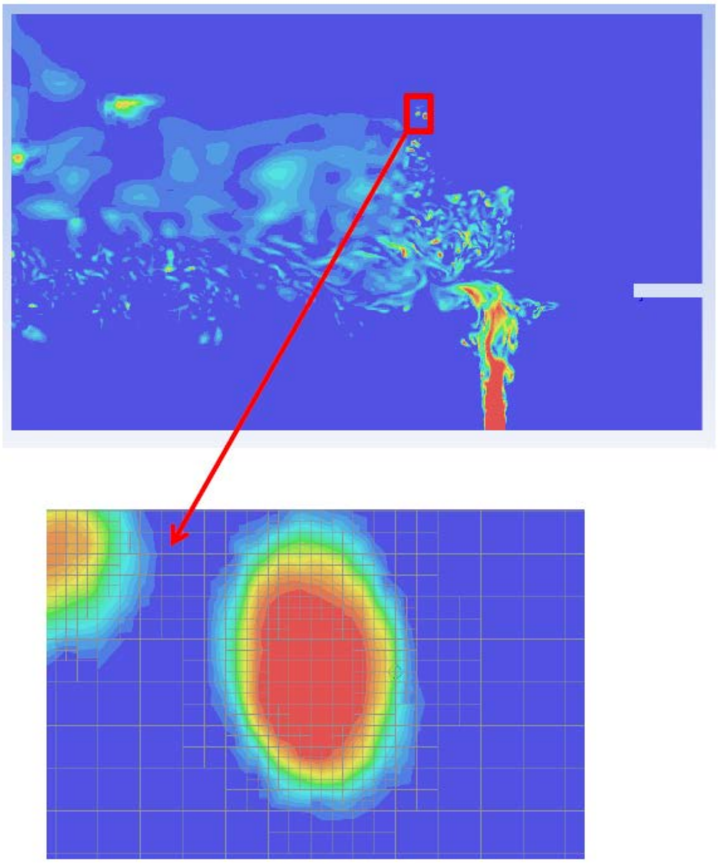


Figure A.1.8: *Example of results from the CFD modelling showing reduction in oil droplet size resulting of horizontally high capacity water jetting (from BP study: Water jetting)***.**

BP has invited the other major oil companies to form a JIP to investigate this promising option and it is our recommendation that this initiative should be an integrated part of this NOROG initiative. There are also several activities e.g. prototype testing which can be performed in SINTEFs Tower Basin.

A.1.7 References

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A.2 WP2 Combining model tools - spreading and resource models for use in response analysis and NEBA assessment

This section describes the status, knowledge gaps and recommendations on models used to evaluate the effectiveness and ecosystem impacts of dispersants applied to combat subsurface oil spills relevant to NEBA assessment.

Two topics are suggested in the following as the primary goals to improve risk assessments as compared to how they are carried out today. First, models used for risk assessment must be able to address subsurface oil spills and the effect of response options such as dispersants for both dissolved oil and oil droplets. In this way one can compare the different response options of combatting subsurface oil spills at depth or when surfacing. Secondly, the models must be further developed so that they can provide an integrated assessment across key species experiencing adverse effects as a result of combatting oil spills with e.g. dispersants. Clearly, the use of dispersants will change the vertical distribution of oil and therefore change the toll on species occupying different parts of the water column.

A.2.1 Required models for NEBA assessments of using dispersants to combat surface and subsurface oil spills

When combatting oil with dispersants, this human intervention may change the dispersal and fate of the oil and subsequently the ecosystem impacts. It is necessary to document that such interventions do not amplify the impact on the environment and its inhabitants. To do this we need models where we can test hypotheses such as:

- The use of dispersants under a given set of environmental conditions reduces the overall load on the ecosystem following an oil spill
- The use of dispersants reduces the impact of an oil spill on seabirds and ELS of fish, but significantly increases the load on the benthic community
- The use of dispersants increases the number of oil droplets and therefore the contact rate with vulnerable species and stages of marine organisms, and, hence, increases the ecosystem effects of the oil spill

Models include:

- state-of-the-art regional ocean model representing physical processes at relevant temporal and spatial scales
- oil spill and fate models including modules for applying dispersants
- generic individual-based biophysical models representing spatiotemporal distribution of vulnerable marine species, stages and trophic interactions
- body burden models for quantifying effects on species of exposure to toxins
- single- or multi-species population models that relate effects on individuals to population recruitment and time to restitution

We see the need for development of kinematic body burden models for uptake and depuration of oil pollution, population models to quantify change in recruitment due to addition mortality at ELS of fish, and comparison with ecosystem models such as Atlantis that may quantify trophic cascading, but here we recommend a focus on the following topics due to limitation in available funds.

A.2.2 Subsurface vs surface oil spill scenarios, and toxicity of oil droplets vs dissolved oil

Vulnerable marine biota, often represented by fish ELS or seabirds, may be harmed by accidental subsurface oil spills. Typically, fish ELS are represented by a particle-tracking model with build-in modules for individual physiological and behavioural responses in eggs and larvae to ambient forcing. Particles, representing either eggs or larvae, move according to the modelled circulation features. Each particle keeps track of biotic and abiotic spatiotemporal varying forcing, e.g. temperature and concentrations of oil components, allowing quantification of growth, distribution and mortality. Seabird interactions with the environment or biota are typically addressed by considering overlapping areas based on estimates of seabird feeding migration distances around the colony, and seasonal migration. Exposure estimates are done by considering the sea surface concentrations of oil. Less attention has been put at considering trophic interactions e.g. loss of prey due to toxins, bio magnification, change of behaviour, or sublethal effects of toxins.

OSCAR has previously been successfully coupled (offline) to biophysical models for early life stages (ELS) of Northeast Arctic (NEA) cod (Vikebø et al. 2014). Adding dispersants in OSCAR has enabled comparison of individual exposure to dissolved toxic components in oil if using dispersants to combat oil (Vikebø et al. 2015). However, currently this has only been investigated in the case of surface releases of oil. Also, only the effects of dissolved oil have been investigated. The same coupling of models may also be used to address subsea/seabed oil spills and the additional effects of oil droplets. Quantification of contact rates between fish larvae and their prey is already available in the model framework and it should therefore only require a moderate effort to enable quantifications of contact rates between oil droplets and planktonic organisms. With the recent findings of stickiness in NEA haddock eggs (Sørhus et al. 2015) causing oil droplets to attach to the egg surface considerations of oil droplets in addition to dissolved oil ought to be prioritized. Furthermore, the model development should be generic and made available for implementation in NEBA assessment.

We propose the following activities to quantify the effects on fish ELS of subsurface vs surface oil spills, toxicity of droplets vs dissolved oil, and species-specific sensitivity to oil:

1. Rerun the oil spill scenarios in Vikebø et al. (2014, 2015) but as subsurface oil spills.
2. Enable quantification of contact rates between planktonic stages of fish and oil droplets in a coupled oil spill/fates and biophysical ELS fish models to consider the additional toxicity of oil droplets to the dissolved oil.
3. Repeat the simulations above for situations with and without dispersants.
4. Summarize the main findings and submit a manuscript to a high-ranking peer-review journal.

A.2.3 Adverse effects of using dispersants across key ecosystem species

Using dispersants clearly show that more oil is maintained in the water column and this is expected to have major impact on exposure rates of feeding sea birds and benthic communities. Hence, besides quantifying exposure rates on specific species and stages one should also consider adverse effects on a combination of key species. We suggest these should include sponges/corals, the zooplankton Calanus Finmarchicus, ELS of Northeast Arctic cod and haddock, Norwegian Spring Spawning herring, and relevant seabird species. It is expected that the load on seabirds in general becomes less if using dispersants, while the opposite might occur for benthic species. But it is difficult to speculate on the combined effect of dissolved oil and droplets with and without the use of dispersants on ELS fish if also including indirect effects on their key prey item C. Finmarchicus. This has to be considered in a model framework based on laboratory studies providing effects of oil exposure on single species at various exposure rates and durations enabling parameterizations.

We propose the following activities to quantify adverse effects of subsurface vs surface oil spills, toxicity of droplets vs dissolved oil, and species-specific sensitivity to oil;

1. Develop biophysical models of sponges and corals to enable quantification of effects of exposure to oil in the water column. Use Mareano cruise data that have mapped their spatial locations, and the results of several recent NFR-funded projects that have mapped their functioning and response to various cues and thereby data that may be used for parameterization of the models.
2. Utilize the various oil spill scenarios listed above together with a biophysical model of ELS of relevant fish species, a biophysical model of spatiotemporal concentrations of *Calanus Finmarchicus*, and the SEAPOP database for presence of feeding seabirds, to enable an integrated assessment of the effects of using dispersants to combat subsurface oil spills.
3. Quantify indirect effects on larval fish of either i) less prey due to additional mortality in Calanus Finmarchicus because of exposure to lethal concentrations of oil or ii) contaminant food.
4. Summarize the main findings and submit two manuscripts to a high-ranking peer-review journal, one on adverse effects and one on indirect effects through reduced or contaminant food.

A.2.4 Oil spill and fate models

Numerous models exist for the prediction of transport and fate of oil spills in the marine environment. The level of sophistication and general applicability varies greatly; for the purpose of describing spreading of oil in the water column from sub-sea blow-outs, fully three-dimensional models are required. These can typically predict time-dependent concentrations of one or more oil component groups in the water column (3D + time). Examples of such models include MIKE3 by DHI, SIMAP by RPS and OSCAR by SINTEF (Reed et al. 2000).

In particular, such models must calculate the size distribution of droplets formed in the highly turbulent region where the oil and gas mix enters the water column. If dispersants are injected at this point, a change in the size distribution occurs due to the change in interfacial tension between oil and water. This can alter the fate of the oil, as well as the overall biological impact, both through changes in the amount and concentration of dissolved oil, as well as the direct biological impact of more numerous smaller droplets. By exporting the size-resolved droplet concentrations from OSCAR to the biophysical model, its impact contribution can be explicity calculated.

Recently, the possibility of running the full OSCAR model in ensemble simulation mode was demonstrated, where a large number of parallel simulations are run based on automatic sampling of various input data, with an aggregation step at the end (Nordam *et al.* 2015). Such capabilities can be useful in the present context by enabling calculation of probabilities for impact, and thereby risk quantification.

We propose the following activity to quantify the effects of droplets with and without the use of dispersants:

1. Calculate gridded oil droplet size distributions over time in the water column for use as input to the biophysical model.
2. Make the gridded oil droplet size distribution available to the biophysical model through an offline coupling scheme, extending the existing capability.
3. Adapt OSCAR, including modification from task 1, to enable ensemble simulation based on the 10 year current dataset from task A.1.5.1, for probability and risk calculations.

A.2.5 Establish and evaluate a decadal-long high-resolution ocean model archive along the Norwegian Coast and develop the possibility of seemless dispersal across various ocean model grids

The research front of regional ocean model is today concerned with data-assimilation, multiple realisations for statistical analysis, high-resolution atmospheric forcing or fully coupled ocean-atmosphere circulation models, two-way nested grids enabling high-resolution fjord and near-coast dynamics to propagate into coarser grids, atmosphere-ocean boundary-layer processes e.g. waves that modify upper ocean turbulence and stratification. Many of these scientific challenges are dealt with in ongoing studies, e.g. the NFR-project RETROSPECT (partners: MET, IMR, NERSC) during 2015-2017 addressing upper ocean dynamics of importance to planktonic free drift and benefits of applying data-assimilation.

The quality of the ocean model applications used as forcing for both oil drift and fate and biophysical dispersal models of relevant marine species is paramount to the results. Typically, high-resolution near-coast model applications cover small domains and are run for short durations, while coarser-scale resolved model applications cover larger domains and much longer periods. When following an oil spill scenarios over time both the toxins and vulnerable planktonic species may disperse out of the high-resolution model domain. Hence, if not already available, biophysical and oil spill/fate models, typically lagrangian (particle-based), should be further developed so that they may be able to handle multiple gridded input and thereby always choosing the highest resolved ocean model forcing available. Furthermore, every ocean model application used as forcing when assessing ecosystem effects of oil spills need to be thoroughly evaluated against available in situ observations to ensure that they resolve key features of the ocean climate. Finally, it is necessary to repeat the oil spill scenarios not only for various spatial locations but also for various times within and between years.

We propose the following activities to i) ensure a consistent high-resolution ocean model archive evaluated against field observations and to ii) enable particle-tracking across multiple ocean model grids so that one may always use the best available ocean model application dependent on the individual oil or planktonic drift trajectory;

1. Run the Norkyst800 (800m resolution) for the entire Norwegian Continental shelf for a decade with a 2-hourly model output and carefully evaluate against field observations.
2. Further develop the biophysical ELS fish model so that it may handle multiple data archives with gridded climate information.
3. Further develop the oil spill and fate model so that it may handle multiple data archives with gridded climate information.
4. Repeat the experiments described in all paragraphs above for several years to quantify sensitivity to temporal changes in ocean circulation.
5. Summarize the main findings and submit a manuscript to a high-ranking peer-review journal.

A.2.6 References

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A.3 WP3 Biodegradation and long-term effects

A.3.1 Background

The objective of SSDI is primarily to reduce the amount of oil reaching the sea surface and eventually polluting coastal beaches. The dispersants, consisting of mixtures of surfactants and solvents, will change the characteristics of the oil, creating a more hydrophilic oil surface, and this will result in the generation of small droplets with lower rising velocity, according to Stokes Law.

One of the main implications of oil dispersant treatment is that the natural biodegradation of the oil in the marine water column is improved, and in that respect dispersant treatment may be considered to be a bioremediation (biostimulation) tool. Oil droplet reductions will result in larger surface-to-volume ratios, and the attachment sites for oil-degrading microbes will increase. The topics described here are not specific for the Norwegian continental shelf, since the research gaps related to SSDI and oil biodegradation is of a general character. Some of the research gaps discussed here are relevant for surface and subsurface conditions.

A.3.2 The underwater environment

The typical bathypelagic environment (1000-4000 m depth, "midnight" zone) is characterized by constant low temperatures, constant darkness and increasing pressure. *Temperature* is an important factor for oil biodegradation, darkness is probably not important, while *pressure* may be of importance. *Dissolved oxygen* and inorganic nutrients like *nitrate*, *phosphate*, iron and micronutrients are important for optimal biodegradation, and typically the deeper parts of the Norwegian shelf is well oxygenated (ref. comment in 3.3), while nitrate (15 µmol/L or less at 1000m depth) and phosphate (appr. 1 µmol/L at 1000 m depth) are fairly low (http://www.nodc.noaa.gov/OC5/ WOA09F/).

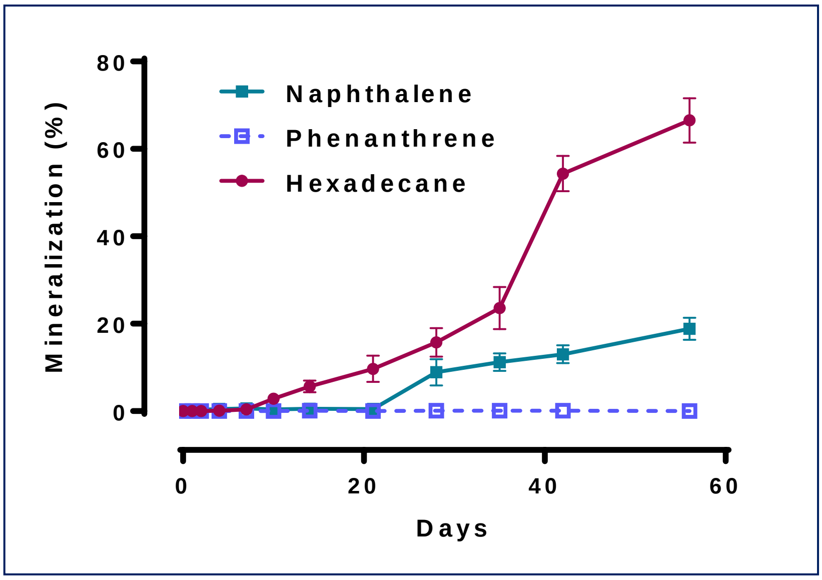
A.3.2.1 Seawater temperature

At low temperatures, oil viscosities increase. Especially for wax-rich oils with high pour points evaporation, dilution and dispersion are reduced, since precipitated wax may build a matrix which limits the internal mixing of the oil and acts as a diffusion barrier between the oil and the water. Several studies have been performed to compare biodegradation at different temperatures, and hydrocarbon biodegradation at temperatures above the freezing point of seawater (approximately -1.8°*C*) is well documented. This is exemplified in Figure A.3.1, showing the mineralization curves of ^{14}C-labelled naphthalene, phenanthrene and hexadecane in seawater at 0°*C* when the compounds were spiked into crude paraffinic oil.

A Q_{10} approach is often used to compensate for temperature changes in seawater, based on the Arrhenius curve (Arrhenius 1896).

$$\mathbf{Q10 = k1_{t+10} / k1_t}$$

A Q_{10} of 2.0 describes a doubling of the rate coefficient (k1) for every 10°C. Comparison of data from marine oil biodegradation experiments performed at different temperatures indicated that this value is a fairly good approximation in a temperature range of 5–27 °*C* Bagi et al. (2013). However, at lower temperatures the Q10 may increase significantly due to physical-chemical changes of the oil, making it less bioavailable for the bacteria Brakstad and Bonaunet (2006); (Bagi *et al.* 2013). However, this may vary from oil to oil, and the properties of individual oils are very important in this respect. Biodegradation studies have also revealed that some essential microbes in Arctic and deepwater environments are related (e.g. Brakstad et al., 2008; Hazen et al., 2010).



Studies of temperature-related biodegradation of physically or dispersed oils have been the subject of many studies, and is an important topic in an ongoing Petromaks project, sponsored by the Research Council of Norway (RCN) and several oil companies: "*Oil Spill Dispersant Strategies and Biodegradation Efficiency*". No specific research need on this topic is therefore required outside the ongoing projects.

Figure A.3.1. Mineralization in seawater at 0°C of ^{14}*C-labelled hydrocarbons spiked in crude oil (from Brakstad and Bonaunet, 2006).*

A.3.2.2 Pressure

Increasing pressure with depth may be an important factor for deepwater spills. The studies of the oil-degrading microbial communities during the DWH spill indicated that the most important degraders were not affected by pressure, since several of these were cultured at atmospheric pressure in the laboratory (Hazen et al., 2010; Bælum et al., 2012; Mason et al., 2014). However, while oil compound solubility is not significantly affected by pressure, gas compounds become more soluble by pressure and reduced temperature (Johansen, 2003). This increased gas solubility may be important also for oil compound biodegradation, since it was suggested during the DWH spill that gas compounds like propane and ethane were involved in the propagation of oil-degrading bacteria (Valentine et al., 2010; Redmond and Valentine, 2011).

Oil degrading microbes have been detected in several deepwater environments, including the Pacific, Atlantic, and Mediterranean oceans (Shao et al., 2010; Cui et al., 2008; Wang et al., 2008; Grossi et al., 2010; Tapilatu et al., 2010). Of specific interest were the communities associated with deepwater oil biodegradation during the DWH spill (e.g. Hazen et al., 2010; Valentine et al., 2010; Redmond and Valentine, 2012; Dubinsky et al., 2013). However, studies of pressure-related biodegradation are extremely challenging. IRIS and SINTEF performed a biodegradation study of volatile organic compounds (VOC) from oil with seawater sampled from 1000 and 2000 m in the Atlantic, financed by the Norwegian Deepwater Program. Results from experiments performed at the same pressures and temperatures as the original seawater sources indicated reduced biodegradation rates with increased pressure (Kjeilen-Eilertsen, 2007), but it is this author's opinion that the results were influenced by the experimental methods (de- and re-compression of seawater). In a recent study with oil-degrading strains it was suggested that high pressure had a strong influence on oil compound biodegradation (Schedler et al., 2014), but the strains used were not collected from any deepwater origin. For metabolic studies of deepwater organisms it has been suggested that studies should be performed without changes in pressure and temperature (Deming, 1997).

Research gaps related to pressure include establishing and performing reliable oil biodegradation experiments under high pressure. This is a challenging issue, especially with respect to laboratory experiments. Sampling water with de-compression, transport onshore and injecting oil for degradation experiments is one option. A second option would be to use oil- or hydrocarbon-baited Biotraps which are placed at relevant depths (e.g. with an ROV and positioning equipment. These Biotraps, which are commercially available, may be used both for determining oil biodegradation and oil-degrading microbial communities, to determine if oil degrading deepwater degradation and communities differ from those in more shallow water.

A.3.2.3 Nutrients

The concentrations of nutrients for biodegradation is related to the carbon content of the oil, and this has been utilized during fertilizer preparations for bioremediation actions, where typical ratios between carbon, nitrogen and phosphorous of 100/10/1 have often been used (e.g. (Bouchez et al. 1995); (Obbard et al. 2004). The concept of the "Redfield ratio" closely links elemental ratios in the ocean's biogeochemical cycles. This ratio of 106C:16N:1P describes, on average, production or respiration of organic matter in the sea (Redfield, 1934). As mentioned, continental shelf seawater contain a few µM available nitrogen, and less than 1µM phosphate, but this is enough to provide the appropriate concentrations of nutrients for the growth of organisms biodegrading a few ppm hydrocarbon (Johnson 2010), and a deepwater plume is rapidly reduced in concentration below these concentrations.

We do not consider the impact of nutrient content on oil biodegradation to be an important research gap for SSDI.

A.3.3 Subsea oil and gas releases

A.3.3.1 Gas compounds

As mentioned, while oil compound dissolution is only affected moderately of negligible by high pressure and low water temperature, both these conditions increase gas compound solubility. Studies from the DWH spill indicated that dissolved gas compounds like propane and ethane were rapidly metabolized in the deepwater plume, and the microbes involved in this metabolism increased in numbers, and became subsequently involved in oil compound biodegradation (Valentine et al., 2010; Redmond and Valentine, 2012). Methane was metabolized at a slower rate than propane and ethane, but it was also suggested to be completely oxidized (Kessler et al., 2011).

Oxidation rates for the gas compounds methane, ethane and propane are scarce, and controlled experimental evidence for gas compound degradation rates and contribution to oil compound biodegradation in live oil is a research gap. We plan to cover this topic at SINTEF, as part of the DROPPS II project in collaboration with University of Texas at Austin (UTA) in a project financed by the Gulf of Mexico Research Initiative (GoMRI). No further actions are therefore recommended until the data from the DROPPS II project are available.

A.3.3.2 Oil compounds

Oils contains thousands of compounds, and biodegradation of these will differ enormously in the marine environment – from rapid degradation within hours, to no depletion even after years. Typically, hydrocarbon degradation in seawater has been reported to follow the order n-alkanes >branched alkanes > low molecular weight aromatics > cyclic alkanes (Perry,1984), but the picture is more complex, since the physical-chemical properties of the oil is also detrimental for the degradation, especially at low water temperatures.

Water-soluble compounds

Components dissolved from the oil phase are available for biodegrading microbes in the water column. In cold seawater the dissolution of oil compounds is decreased compared to temperate water (Faksness 2008). The typical oil compounds in a water-soluble fraction (WSF) from fresh oils include phenols, naphthalenes and 2-3 ring PAHs. In addition, the WSF contains considerable amounts of highly polar compounds with nitrogen, sulphur, and oxygen atoms in their structures (so-called NSO compounds), often present as a chromatographic "hump", termed the "unresolved complex mixture" (UCM). In a study of WSF from an in-reservoir biodegraded oil (Troll) approximately 70 % of the WSF was separated by preparative high-pressure liquid chromatography, into a polar fraction (Melbye et al. 2009). The non-polar compounds of the WSF are often considered to be rapidly biodegraded in the marine environment (Brakstad and Faksness 2000), and biodegradation of these compounds may result in a significant increase in the UCM concentration relative to other crude oil components (e.g. Meredith et al., 2000), highlighting their persistence (Han et al. 2008).

While volatile organic compounds (VOC) with low boing points (e.g. saturates up to nC_{11}, mono- and some diaromatic hydrocarbons) are rapidly evaporated after surface spills, these are dissolved in the seawater column after subsurface releases, and may therefore become subject to biodegradation. At high concentrations these compounds may prolong microbial lag-phases and delay the onset of biodegradation (Atlas and Bartha, 1972; Hokstad et al., 1999), although it is not known if this will have an impact on biodegradation under field conditions.

Hydrocarbons with low water-solubility and oil droplet size

Hydrocarbons with slow or negligible water-solubility will mainly rely on the bioavailability for their biodegradation potential. Typically, C_7/C_8 n-alkanes and 4-5 ring PAHs show low dissolution from a thin oil film compared to naphthalenes and 3-ring PAH, as shown in Figure 2.

The importance of the droplet size is exemplified in a biodegradation study of dispersed Macondo 252 (MC252) oil with different oil droplet size distribution (Figure 3), demonstrating that most of the oil compound groups defining 70-80% of the oil was biodegraded faster in 10 µm than in 30 µm dispersions (Brakstad et al., 2015a).

It has recently been claimed from experimental studies (financed through the GoMRI project) that deepwater dispersant treatment did not reduce oil droplet sizes significantly (Aman et al., 2015), and it has even been suggested that the dispersant treatment inhibited oil biodegradation (Kleindienst et al., 2015a; Kleindienst et al., 2015b). As described above, investigations of oil droplet size reduction caused by SSDI is of crucial importance in relation to enhanced oil biodegradation and should be addressed.

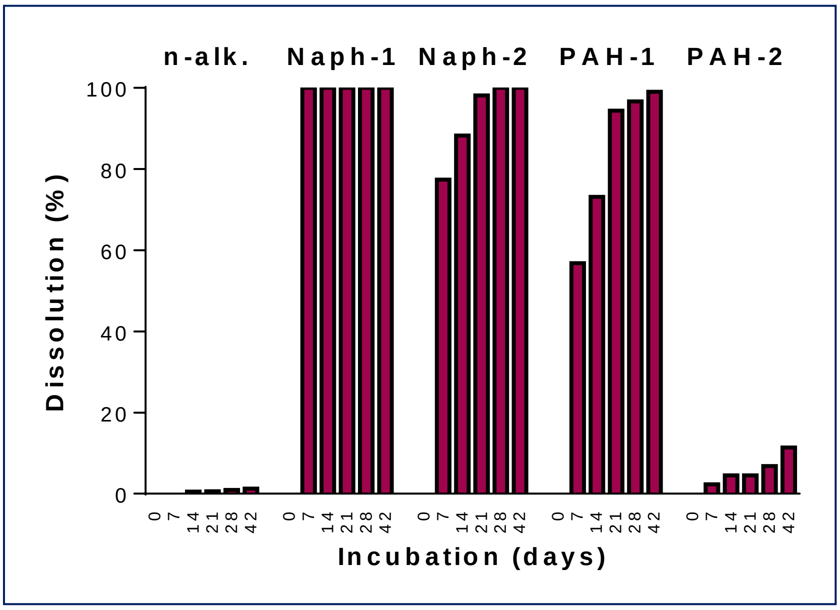


Figure A.3.2. Calculated dissolution from a thin oil film (10-20 µm thick) of n-alkanes (C_{12}-C_{36}), C_0-C1 naphthalenes (Naph-1), C_2-C_3-naphthalenes (Naph-2), C4-naphthalenes and C0-C1 three-ring aromatics (PAH-1), and C2-C4 three-ring aromatics and four- to five-ring aromatics (PAH-2) during a period of 0-42 days in a seawater-based flow-through system (ref. Brakstad et al., 2004)

Oil compounds with few biodegradation data available

Most oil compound biodegradation data are available for a limited number of compounds, including alkanes (linear and cyclic), monoaromatic hydrocarbons (BTEX), naphthalenes and 3-5 ring PAHs. Other compound groups, like naphthenes (saturates cycloalkanes paraffinic side chains), which may constitute more than 50 % of the oil, have also been subject to biodegradation studies (Perry, 1984; Lai et al., 1996; Prince and Suflita, 2007; Prince et. al., 2008). And larger cycloalkanes as Hopanes are used as biomarkers during biodegradation of oil compounds, i.e. a demonstration of the non-biodegradable characteristics of these compounds (Prince et al., 1994).

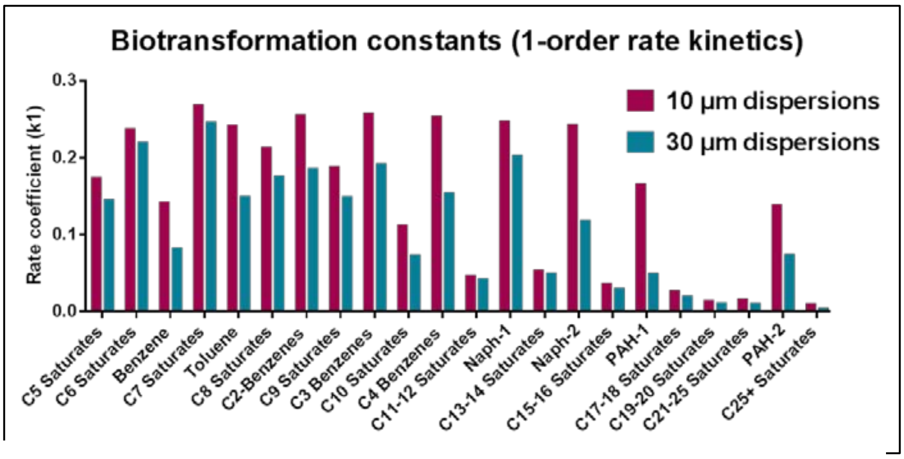


Figure A.3.3 Biotransformation rates (k1) for 22 oil component groups (normalized against Hopane), with a boiling point range of approximately 25-500°C.

There are still a vast number of oil compounds that we do not know the long-term fate of, and this is therefore a significant gap in our knowledge of the long-term effects of oil, especially related to subsea dispersions that never reach the sea surfaces and the final fate and destinations of these dispersions. The multitude and complexity of all these compounds make it a challenge to organize them in a sensible way for degradation studies. Novel high-resolution analytical instrumentation like the Fourier transform ion cyclotron resonance mass spectrometer (FT-ICR MS) enable the detection and potential identification of hundreds to thousands of oil compounds, but the data treatment and organization remain a challenge. During the Petromaks project "Oil Spill Dispersant Strategies and biodegradation Efficiency" we will look deeper into this topic.

Metabolites

Oil biodegradation results in temporary generation of metabolites before complete mineralization to inorganic carbon (CO_2). Often, when biodegradation is determined in complex mixtures like crude oil, degradation is determined from chemical analyses, i.e. as biotransformation. The period between compound depletion and full mineralization is therefore not accounted for. The difference between biotransformation and mineralization is exemplified with hexadecane (*n*C16) in Fig. A.3.4A. Metabolization will result in the generation of oxidized compounds with increased polarity and thus becoming more soluble than most hydrocarbons. In cold waters (e.g. deepwater) the time window between biotransformation and mineralization may be longer than in surface waters with higher temperatures, due to slower processes at low temperature. We have previously measured temporary increases in some substances like phenols during biodegradation of oil (Figure A.3.4B), mainly associated with biotransformation of BTEX (Brakstad et al., 1999). The metabolite generation may also have implications for the toxicity of the oil compounds. The effect concentrations, described as the LC_{50}, for individual oil components, are often determined using regressions between octanol-water (LogKow) and $LogLC_{50}$ (e.g. French-McCay, 2002). The biodegradation process should result in increased polarity of HCs during biodegradation, which eventually should result in decreased toxicity, but has not been proven experimentally, to our knowledge. This relation between the fate and the toxicity for the oil is therefore a knowledge gap. SINTEF has submitted a proposal to NRC (Marinforsk) to address this topic.

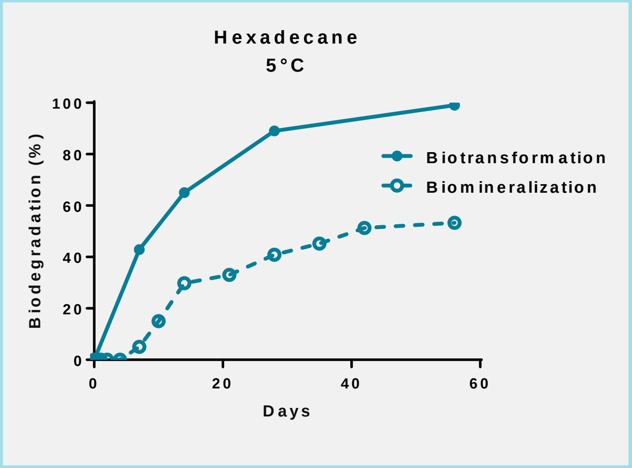


Fig. A.3.4A: Biotransformation (GC-MS analyses) and mineralization ($^{14}CO_2$-evolution) of hexadecane during biodegradation with marine enrichment cultures at 5°C (Brakstad and Bonaunet, 2006)

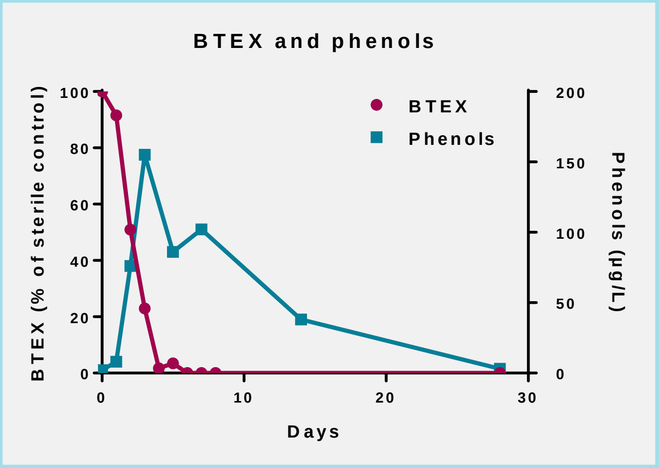


Fig. A.3.4B: Biotransformation of monoaromatic HCs (BTEX) in seawater related to temporary increases in phenol concentrations measured by GC-MS analyses (Brakstad et al., 1999).

A.3.3.3 Subsurface use of dispersants

Our biodegradation studies with chemically dispersed oil have shown that the use of dispersants like Corexit 9500 and Dasic NS promote biodegradation, and that the increased biodegradation is related to reduced droplet size. These studies have been conducted under conditions relevant for both surface and subsurface conditions (Brakstad et al., 2014; Brakstad et al., 2015a). Several other studies under different conditions have also shown the same results (e.g. Siron et al. 1995; Venosa and Holder, 2007; Prince et al., 2013, McFarlin et al., 2014). However, some studies have not shown any positive effects on oil biodegradation by dispersant treatment (e.g. Lindstrom and Braddock, 2002; Davies et al., 2001), and even inhibitory impacts of dispersant components on oil biodegradation rates have been suggested (Kleindienst et al., 2015a; Kleindienst et al., 2015b). However, several of these studies showing no or negative effects of dispersants on oil biodegradation were conducted with very high and unrealistic concentrations of dispersed oil or dispersant, which may limit biodegradation due to nutrient depletion (Lee et al., 2013). It is therefore paramount to perform biodegradation studies under conditions of surplus oxygen and nutrients.

Also the use of dispersants have provided significant controversies, especially after the DWH spill, where appr. 2.9 million L of dispersant was applied at the wellhead (Kujawinski et al., 2011). Laboratory studies showed that the glycols and dioctylsulfosuccinate (DOSS) in the dispersant Corexit 9500 used in the DWH spill were degraded at different rates with hydrocarbon-degrading bacterial communities from uncontaminated Gulf of Mexico deepsea waters (Bælum et al., 2012). Furthermore, bacterial oil-degrading isolates from the DWH deepwater plume were able to degrade various Corexit components, including DOSS and dipropylene glycol n-butyl ether (Chakraborti et al., 2012). Thus, there were no indications of dispersant toxicity or inhibitory effects on the tested oil-degrading bacteria, and this is in agreement with our results which only show stimulatory effects of the dispersants on oil biodegradation low oil concentrations and realistic dispersant dosages (DOR = 1:100).

There are still some knowledge gaps concerning the use of chemical dispersants for improved oil biodegradation including biodegradation temperature, oil types, oil weathering conditions and dispersant component degradation rates. These gaps are currently being investigated in the Petromaks project "Oil Spill Dispersant Strategies and biodegradation Efficiency".

A.3.4 Marine snow and oil sedimentation

During a subsurface oil spill it has been suggested that some of the oil may end up on the seabed as part of oil-biomass flocs (Valentine et al., 2014). One sedimentation process may be the result of oil droplet attachment to particles with higher density than water. A topic that has gained a focus lately is the generation of flocs in the oil plume and around surface, spills, so-called marine snow.

A.3.4.1 Marine snow – floc generation

These flocs have been shown to contain mixtures of oil and biomass (Hazen et. al., 2010; Bælum et al., 2012). These are phenomena that are easily reproduced in laboratory experiments, and therefore can be examined under controlled conditions. When we (SINTEF) perform biodegradation experiments with dispersed oil, we always visually observe floc generation within 1-2 weeks after start of experiments, and the flocs increase in size to several centimeters during the experiments (Brakstad et al., 2015a). These flocs are a variant of marine snow that is commonly observed around surface oil spills. For surface spills the marine snow may be generated by 1) physical coagulation of phytoplankton, detritus and oil-mineral aggregates, or 2) by biological snow production, involving organisms feeding on the oil, bacterial mucus and, zooplankton feces (Størdal et al., 2015). After sedimentation and microbial modifications/degradation the snow may be deposited on the seabed (MOSSFA, 2013). Marine snow has also been suggested to be responsible for considerable fallout of oil from the deepwater plume (Valentine et al., 2014). While surface-generated marine snow may contain material with higher density than water (e.g. silica-rich alga, protozoal feces, inorganic particles), these components are less abundant in deepwater, where the snow primarily will consist of oil and bacterial mucus. One may therefore speculate if surface-generated marine snow will sink faster than deepwater-generated snow.

The issue of marine snow has resulted in controversies around the fate of the oil after the DWH spill. If a significant amount of the oil ended up in these flocculates, being denser than seawater, this would imply significant impacts on the long-term fate and effects of the heavily weathered oil, with some of the discharged oil sedimented and partly degraded on the seabed in the Gulf of Mexico. Burial of the oil in the sediments could then stop further biodegradation due to oxygen and nutrient depletion in the sediments. However, processes related to marine snow and seabed sedimentaton of oil are not yet verifiied. , and the lack of clarity around these processes should open for extensive research to obtain better understanding of the floc generation and the impacts for the long-term fate and effects of the oil. The implications of SSDI for these processes will therefore be of importance.

The issue of marine snow is being investigated during several projects financed by GoMRI, e.g. C-IMAGE, DEEP-C, ECOGIG- and DROPPS-projects. A specific workshop was arranged on the marine snow aspect in 2013, and a report was prepared from this workshop (MOSSFA, 2013). The Petromaks project "*Oil Spill Dispersant Strategies and Biodegradation Efficiency*" will have a limited focus on this issue, but only on characterization of fully formed flocs of bacteria and oil. Additional attention on this topic is therefore important in relation to SSDI. API has recently launched for project proposals for critical reviews of the research performed on marine snow after the DWH spill.

A.3.4.2 Oil degradation on the seabed

The fate of the oil ending up on the seabed will depend on the access to oxygen/nutrients supplied by fresh seawater. Normally the oxic/anoxic transient zone is 3-7 cm down in the sediment, depending on the sediment quality. In oxygenated sediments microbial benthic communities responded rapidly to sedimented oil, indicating fast onset of biodegradation (Main et al., 2015). However, high input of organic material (like oil) may raise anoxic zone towards the seabed surface, as shown around piles of drill cuttings, as observed from mesocosm studies (e.g. Schaanning et al. 2008). The same effects have also been measured with sedimented oil (e.g. Brakstad et al., 2000). Biodegradation of oil in the anoxic sediment layers will be significantly reduced, or even be absent. This was demonstrated during a project sponsored by the UKOOA

R&D Initiative (Kjeilen et al., 2001). Although hydrocarbons may be degraded also under anoxic conditions, the lack of seawater replenishment will be the main obstacle against further degradation, since consumed nutrients will not be replaced. However, macrobenthic processes in the sediment (bioturbation) may result in some seawater exchanges, although also bioturbation may be reduced by high oil input. Oils sedimented in shallow water (e.g. < 70 m depth) may be spread by resuspension/erosion caused by wave actions, as shown with experiments with drill cuttings (e.g. Vefsnmo and Lothe, 2001). They showed that erosion may be an important factor for oil resuspension and oxygen exposure. Although some studies have been performed (e.g. the UKOOA R&D Initiative), the long term fate effects of sedimented oil is still not well explored.

A.3.5 Microbiology

The microbiology related to SSDI described here is related to the part of the oil remaining as an underwater plume below the thermocline, at constant low water temperature. The indigenous microbes are therefore constantly facing low temperature and increasingly higher pressure by depth. We know a lot about the adaption to low temperature, but much less about the impacts of high pressure. Most of the knowledge related to deep-sea microbiology was summarized at a workshop arranged by API in October 2012 (NewFields, 2012).

A.3.5.1 Oil-degrading bacteria

The typical oil-degrading bacteria, often called hydrocarbonoclastic bacteria, are able to biotransform hydrocarbons. In general, different bacterial groups transform alkanes and aromatic hydrocarbons. While biodegradation of aromatic hydrocarbons in marine environments have been associated with genera like *Cycloclasticus*, *Pseudoalteromonas* and *Colwellia*, typical alkane-degrading bacteria include members of the genera *Alcanivorax*, *Oleiphilus*, *Oleispira* and *Thalassolituus*. In addition, some bacteria are able to degrade a variety of aliphatic and aromatic oil compounds, like *Colwellia* and *Pseudomonas* (Yakimov et al., 2007).

The capabilities of deepwater bacterial communities to biodegrade oil are currently under investigations for a number of deepwater basins worldwide, with different temperatures and salinities. The plans are to complete surveys of eight deepwater basins, including physical oceanography, microbial communities in the water column and the seabed sediments, and perform oil biodegradation studies with water from the basins. This is a collaboration between UTK, MIT and BP. So far, the study from the Caspian Sea (100-600 m depth) has been published (Mahmoudi et al., 2015). SINTEF will probably be involved in data evaluation of these studies.

A.3.5.2 Low temperature – psychrophilic bacteria

Constantly cold environments favour so-called psychrophilic ("cold-loving") or phychrotolerant ("cold-tolerant") microbes, which have specific structural and metabolic features to grow at temperatures well below freezing point, for instance in the brine channels of marine ice (Junge et al., 2004), and several of these are able to grow on oil, even in the ice structures (Brakstad et al, 2008).

During the DWH spill extensive work was performed to identify the different microbes involved in the degradation of different oil compounds in the deepwater plume. Microbial respiration and increased biomass was measured in the plume, compared to the non-affected deepwater (Hazen et al., 2010), as well as increased abundances of oil-degrading bacteria associated with gas or oil compound degradation (Table 1). These outcome of these investigations opens up for the possible use of microbial community analyses (metagenome sequencing) as part of future oil spill monitoring to determine the spill status and environmental restitution, since microbial analyses are extremely sensitive to the state of pollution.

Table A.3.1. Bacterial groups detected in the DWH deepwater plume (900-1300 m) associated with biodegradation of different oil compound groups (references: Redmond and Valentine, 2012; Hazen et al., 2010; Valentine et al., 2010).

Class/group	Order/family/genus	Degradation Function
Alphaproteobacteria	*Rhodobacterales*	Oil
Betaproteobacteria	*Methylococcaceae*	Methane oxidation
Betaproteobacteria	*Methylophilaceae*	C1-assimilation
Gammaproteobacteria	*Oceanospirillales*	Alkane and metabolites
Gammaproteobacteria	*Cycloclasticus*	Aromatic hydrocarbons, ethane, propane
Gammaproteobacteria	*Colwellia*	Ethane, propane, metabolites
Gammaproteobacteria	*Methylophaga*	C1-assimilation
Flavobacteria	*Polaribacter*	Metabolites
Flavobacteria	*Owenweeksia*	Metabolites

A.3.5.3 High pressure – piezophilic bacteria

Bacteria are generally resistant to pressure, living in equilibrium with the pressure conditions outside the cells. However, as pressure conditions increases typical piezophilic ("pressure-loving") or piezotolerant ("pressure-tolerant") bacteria become abundant. Piezophilic microbes require high pressure (> 1 bar) for optimal metabolic activities, and these bacteria are mainly associated with the abyssopelagic zones of the oceans (deeper than 4000 m), which is below what is currently relevant for oil production. Little is known about the potential for oil biodegradation by piezophilic microbes, since no oil-degrading piezophilic microbe has yet been identified.

A.3.6 Biodegradation used in a spill modelling - OSCAR

Biodegradation as an important fate process is included in the OSCAR model. Biodegradation rates of 25 oil compound groups (Table A.3.2), representing 70-80 % of typical crude oil, according to the true boiling point curve (Pasquini and Bueno, 2007). Biodegradation is represented by biotransformation data, and knowledge of the biodegradation products before complete mineralization is not available. This time window between transformation and mineralization becomes increasingly important in environments with low temperature (and high pressure??) as described above. We have addressed this topic in a proposal for 2016 to RCN (Marinforsk), as described above.

In Figure. A.3.5 the OSCAR model is used for simulation of a deepwater oil spill of DWH size from 1100 m depth outside the Norwegian coast, demonstrating that biodegradation became an important fate process, using the current data biodegradation from the OSCAR model. The biodegradation data for the OSCAR model are currently being validated for chemically dispersed oil

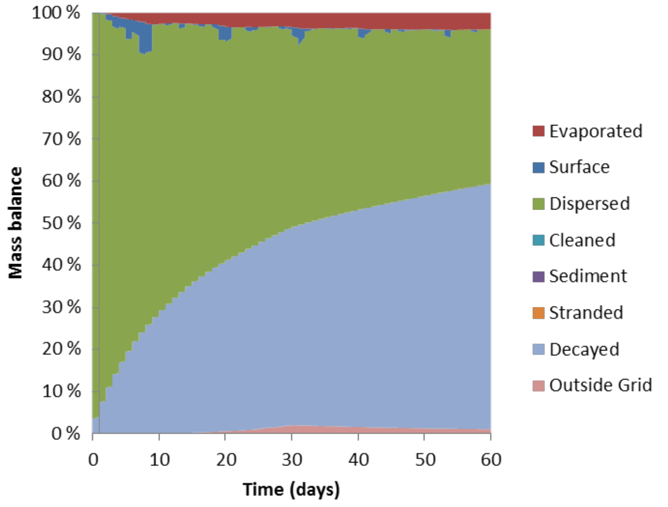


Figure A.3.5: Mass balance of a simulated (OSCAR) 60-days underwater blowout at 1100 m depth outside the Norwegian coast. Biodegradation accounts for 60% of the depletion from the water column in the simulation (Brakstad et al., 2011).

in the Petromaks project "*Oil Spill Dispersant Strategies and Biodegradation Efficiency*" at temperatures relevant for underwater discharges, but pressure is not a topic in the project.

A.3.6.1 OSCAR group data

The OSCAR model includes both gas (C_1-C_4) and oil compound groups. While degradation data for oil compounds are available in the OSCAR model, gas data are only used as default values. Since studies of the DWH spill indicated that gas compounds were of importance for oil degradation (Valentine et al., 2010; Redmond and Valentine, 2012; Kessler et al., 2011) SINTEF will generate gas data for the OSCAR model by participation in the DROPPSII project, in collaboration with UTA, financed by the GoMRI program.

Also the dispersant itself should be considered to be included as a compound group in the OSCAR model. This will be partly addressed in the Petromaks project "*Oil Spill Dispersant Strategies and Biodegradation Efficiency*".

The aspect of marine snow is not currently included in the OSCAR model.

Table A.3.2. OSCAR grouping. The grouping is based on boiling point differences. The model also includes possibilities for including one or several metabolite groups (Reed et al., 2000).

Group no.	Group name	Compounds	Group no.	Group name	Compounds
1	C1-C4 Sat	C_1-C_4 gases	14	Phenols	C0- to C4-
2	C5-Saturates	n-/iso-/cyclo-	15	Naph-1	C0- to C1-
3	C6-Saturates	n-/iso-/cyclo-	16	C13-/C14-Saturat	n-/iso-/cyclo-
4	Benzene		17	UCM	
5	C7-Saturates	n-/iso-/cyclo-	18	Naph-2	C2- to C3-
6	C1-Benzene	Toluene	19	C15-/C16-Saturat	n-/iso-/cyclo-
7	C8-Saturates	n-/iso-/cyclo-	20	PAH-1	2- to 3-ring
8	C2-Benzenes	Ethyl-/xylenes	21	C17-/C18-Saturat	n-/iso-/cyclo-
9	C9-Saturates	n-/iso-/cyclo-	22	C19-/C20-Saturat	n-/iso-/cyclo-
10	C3-Benzenes		23	C21-/C25-Saturat	n-/iso-/cyclo-
11	C10-Saturates	n-/iso-/cyclo- (decalines)	24	PAH-2	4- to 6-ring
12	C4-/C5-Benzenes		25	C25+ -Sat (C26-C40)	n-/iso-/cyclo-
13	C11-/C12-Saturates	n-/iso-/cyclo-			

A.3.6.2 The unresolved saturate groups

As mentioned, the OSCAR groups represent 70-80 % of typical crude oils. Some heavy oil compounds that are not able to analyze by gas chromatography are not included in the model, and these are mainly considered to be poorly degradable (e.g. resin and asphaltene compounds). Also the OSCAR groups include a large amount of "unknown" compounds, often termed as the "hump" or the unresolved complex mixture (UCM). The UCM is comprised of thousands of environmentally persistent compounds (Gough and Rowland, 1990; Killops and Al-Jaboori, 1990). In the OSCAR model these are "hidden" in the saturate groups together with the n-alkanes. While the n-alkanes are rapidly biodegraded most of the UCM is considered slowly degradable, although we (SINTEF) have observed that degradation decreases with increasing boiling point (not yet published).

UCM has been addressed by several projects and is currently being investigated in the RESOLVE project for produced water as collaboration between NIVA, SINTEF, Biotrix, University of Plymouth and Batelle, with the objective of improved fractionation and characterization of these compounds. The outcome of the

RESOLVE project may be of importance for future degradation studies of UCM as well as consideration of their grouping in the OSCAR model.

A.3.6.3 Biotransformation and mineralization

As mentioned, the biodegradation data used in the OSCAR model are transformation data. However, the metabolites may also be included in the model, as previously described (Reed et al., 2000). This is addressed in a recently applied proposal the RCN (Marinforsk).

A.3.7 Relevant biodegradation studies and research proposals

Some of the most relevant studies known to us and their study objectives and outcomes are described below.

- BP biodegradation study with Norwegian seawater

  This study was performed by SINTEF with the Macondo oil and Norwegian seawater. The project was financed by BP Exploration & Production Inc., and the BP Gulf Coast Restoration Organization (GCRO). The project was a collaboration between SINTEF and Battelle Memorial Institute.

  An oil dispersion and carousel system was developed and used for generation and maintenance of small oil droplet dispersions under temperature conditions similar to the deepwater plume during the DWH spill. Biodegradation rates for the OSCAR model were generated (Brakstad et al., 2015a), and microbial community analyses showed similarities to GoM field data (Brakstad et al., 2015b).
- BP biodegradation study with GoM water

  This study was performed by Florida International University (FIU, Miami, Florida) with the Macondo oil and with water collected from the GoM (1000 m depth). The project was financed by BP Exploration & Production Inc., and the BP Gulf Coast Restoration Organization (GCRO). The project was a collaboration between FIU and Battelle Memorial Institute, and with SINTEF as consultant.

  The oil dispersion and carousel system developed by SINTEF was and used for generation and maintenance of small oil droplet dispersions in deepwater collected from the GoM. Experiments were performed under temperature conditions similar to the deepwater plume during the DWH spill. Biodegradation of oil compounds and microbial communities were determined (Wang et al., 2014).
- BP Deepwater basin study

  This study was performed by University of Tennessee, Knoxville (UTK) in collaboration with Massachusetts Institute of Technology (MIT). The project is financed by BP (UK). The objective has been to investigate the physical oceanography and microbiology of several deepwater basins, and performing immediate oil biodegradation studies (on deck). The deepwater basins include the Eastern and Central Mediterranean, North Sea, Caspian Sea, Trinidad, Angola, Great Australian Bight and Brazil. So far, draft reports from the Caspian Sea and the Great Australian Bight have been submitted. Respirometric analyses have been performed, and further studies are underway. SINTEF has been asked to be involved in data evaluations and investigating the potential use of the data in the OSCAR model.
- BP Oil biodegradation and potential oxygen demand

  Several ocean areas have low levels of dissolved oxygen (DO), and objective of this project was to investigate if low DO could reduce oil biodegradation. The study was performed by SINTEF for BP. Based on the NOAA World Ocean Atlas 2009 some ocean areas with low DO were selected. Oxygen consumption required for oil biodegradation was calculated based on current data in the OSCAR model, and with an estimated conversion factor for transferring biotransformation data to mineralization data. The estimated oil biodegradation oxygen consumption data may then be used to simulate oxygen depletion by the OSCAR model for selected ocean areas.
- Gulf of Mexico Research Initiatitive (GoMRI)

Several projects financed by GoMRI include oil or dispersant biodegradation studies in the water column or seabed or beach sediments, some of them described above (C-IMAGE, DEEP-C, ECOGIG- and DROPPS). SINTEF is involved in the DROPPSII project where the main objective relevant to biodegradation will be to determine the rates of gas compounds in "live" oil, and the implications for oil compound biodegradation rates. The rates will be used in the OSCAR model.

- Petromaks project - Oil Spill Dispersant Strategies and Biodegradation Efficiency

  This project (2013-2017) is run by SINTEF in collaboration with NTNU and UTK and is financed by the Research Council of Norway (RCN) and five oil companies. The objective of the project will be to provide reliable biodegradation data for the OSCAR model and improve our knowledge concerning oil dispersant strategies and biodegradation. The project has relevance both for surface and subsurface dispersant strategies. Several oils, weathering conditions and dispersants are included for investigations.
- API RFT for Improving how biodegradation Processes Are Modeled In Oil Spill Fate Simulations

  API is currently working with a Request For Tender (RFT) with the objective to investigate how different degradation processes (bio- and photodegradation) work across different oil fate models and to facilitate greater consistency in quantifying these processes among the models. This work is intended to be finished by the summer of 2016.
- Petromaks project proposal - Oil compound biodegradation and the implication for acute ecotoxicity

  The background for this project is current shortcomings in oil biodegradation data and the links between degradation processes and changes in oil toxicity. The proposal addresses both biotransformation and mineralization processes, the appearances of metabolites during the degradation, and the implications these processes will have for the acute toxicity to marine copepods. The studies are suggested to be conducted with selected single oil compounds, with emphasis on mono- and polyaromatic hydrocarbons, which are considered to contribute significantly to the acute toxicity of the oil.

A.3.8 Biodegradation - major research gaps related to SSDI

A number of research gaps have been identified above. These are summarized in Table A.3.3. Several of these are addressed in ongoing projects or in submitted applications. We have therefore ranked the topics of importance for SSDI not addressed elsewhere with the highest importance.

It is important to emphasize that the knowledge gaps related to SSDI and oil/dispersant biodegradation is not specific for the Norwegian CS, and all topics described in Table A.3.3 are of general character.

Table A.3.3. Suggested research needs related to SSDI and subsea biodegradation. The research needs are ranked by 1-3 for importance .

TOPIC$^{1)}$	**Specification**	**Comments**
Marine snow or floc generation and seabed fallout (1)	Determine if these processes are part of a long-term fate of oil in underwater plumes in relation to SSDI	This is partly addressed in a Petromaks project, but should be properly addressed in separate projects. This process may be included in the OSCAR model
Biodegradation and acute toxicity (1)	Determination of toxicity during biodegradation processes	This represents a knowledge gap which is not addressed in any of our on-going projects.
Oil droplet size (1-2)	Determine biodegradation rates relative to most probable droplet size generated by SSDI	This will be partly addressed in the current Petromaks project
Gas compounds (2)	Determine degradation rates of gas compounds and the influence on oil compound biodegradation	Is addressed in the DROPPSII project
OSCAR validation - deepwater (1-2)	Very important, but will be an outcome of studies described above	
Microbial metabolism (3)	Characterization of biodegradation metabolites and metabolization period at deepwater conditions	Addressed in pending application to the RCN for surface conditions, further actions should wait
Mineralization (3)	Closely connected to the topic above	
Unknown groups (UCM)(3)	Characterization of UCM and persistence of these	Addressed in the RESOLVE project. Further studies should wait for results from this study
Dispersant degradation (3)	Introduction of degradation rates in OSCAR	Will be addressed in current Petromaks project
Pressure (3)	Determine the effect of pressure on degradation rates of oil and gas	This is not likely to be an important factor for biodegradation of oil on the NCS, however it may be of importance at greater depths (e.g. >2000 m)

1) *Ranking: (1) – high importance for SSDI-related oil biodegradation and should be addressed for the Norwegian CS; (2) – high importance for SSDI-related oil biodegradation, but is addressed in other studies/projects; (3)-Medium importance for SSDI-related oil biodegradation, and is addressed in current projects or in submitted project applications.*

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A.4 WP4 Potential toxic effects and effect thresholds related to SSDI under relevant Norwegian conditions

A.4.1 Introduction

The decision for using or not using chemical dispersants to combat an acute oil spill will be based on an assessment of which biological resources inhabiting the area and their vulnerability. In cases where the oil spill has a large risk to damage birds and shore line, use of dispersants has been considered a useful mitigation option, while in areas with large occurrences of fish egg and larvae, there has been scepticism toward such use, due to uncertainties of which consequences a large increase of oil droplets and dissolved PAH may have on vulnerable life stages.

Egg- and larvae stages of fish have been focused on for several reasons. Pelagic fish eggs are concentrated mainly between 0 and 50 m, decreasing from the surface and downwards and may only be affected by oil and dispersants that reach the surface layers. Some species like herring spawn on bottom substrate and may be affected by a subsea blow out or sedimentation of oil or oil/dispersion solutions. Fish larvae have highest occurrence between 5 and 40 m depth with diurnal migration. The ratio of surface to volume is large and can give a relative higher uptake compared to a later in development and growth. Important organs are developed during egg and larvae stages. In this phase are the organisms extra vulnerable to pollutants.

The objectives of this work package are to review literature data of toxicity studies with crude oil and chemical dispersants on relevant organisms susceptible to a subsea blow out in Norwegian Seas in order to identify knowledge gaps on such information on relevant species, and to suggest experiments that could fill in some of the addressed gaps in knowledge.

The main objective is to be better prepared for decisions related to when chemical dispersion may be used in actions to mitigate subsea accidental oil spills. The decision to use or not use chemical dispersants to mitigate a subsea released oil spill is based on knowledge and experiences on which actions are considered most effective to reduce damage to the environment, or net environmental benefit analysis (NEBA).

To be able to perform risk assessments for such decision making we need knowledge on how pelagic and benthic organisms responds to dissolved crude oil and chemical dispersed crude oil in non-weathered conditions. A relevant selection of species of interest for Norwegian Seas for this study encompass:
Zooplankton e.g. *Calanus*
Fish, included early life stages of
    Norwegian Spring Spawning herring
    North East Arctic cod
    North East Arctic haddock
Common sponge, *Geodia baretti*
Corals (*Lophelia Sp.*)

IMR have updated spatial and temporary distribution of early phase stages for some fish species (North East Arctic cod, Norwegian spring spawning herring, and haddock), and made available maps of vulnerable and valuable areas for pelagic and benthic resources. This will be useful tools for identifying areas and seasons when resources are considered most vulnerable for oil exposure (ref. WP2 and Grøsvik et al., 2014).

A.4.2 Experiences with use of chemical dispersants from DWH

The research on environmental effects after use of chemical dispersants has been intensified after the incident at Deepwater Horizon (DWH) in the Gulf of Mexico in 2010. This incident led to discharge of 780 000 m^3 crude oil at approx 1500 m depth. During the mitigation action, large amount of chemical dispersants were used, mainly Corexit 9500 and Corexit 9527. Totally, 7000 tons dispersants were used. Of these, 2920 tons were injected into the discharge point at 1500 m depth. This is the first time where dispersants have been used at such depth. Little knowledge was established in advance on how dispersed oil behaves in subsea water.

Connected to the DWH incident, more sensitive analysing methods have been developed to analyse low levels of dioctyl sodium sulfosuccinate (DOSS) (a detergent constituting 10-30 % in Corexit 9527 and Corexit 9500) in sea water, and field observation connected to the aftermath of DWH have been performed (Gray et al. 2014; Kujawinski et al. 2011; Ramirez et al. 2013). Kujawinski et al. (2011) reported that the dispersants injected at the well at 1500 m depth follow the oil/gas plume and only to a small extent rose to the surface. DOSS is slowly degraded at this depth and low, but detectable levels of DOSS was found up to 300 km from the Macondo well 64 days after use of dispersants started (Gray et al., 2014). Measurements in surface water above the Macondo well showed levels of DOSS from <0.25 µg/l–225 µg/l (*Ibid.*). In spite of high levels close to the discharge point, the concentration levels decreased rapidly due to degradation and dilution to below levels of detection of 40 µg/l, given by US Environmental Protection Agency (USEPA). Area of oil on surface after the DWW incident was estimated to 17725 km^2 in May 2010 (Labson et al., 2010).

Some recent reports by Incardona et al. (2013 and 2014) discuss possibilities for damage to early developmental stages of fish spawning in the period after the DWH incident, like bluefin tuna. Conclusions on long term consequences as the DWH incident often takes many years to conclude, as for the Exxon Valdez incident (Incardona et al., 2015).

A.4.3 Toxicity of mechanical vs. chemical dispersed crude oil on different organisms and trophic levels

We have performed a literature review of studies on short term toxicity of dispersants and chemical dispersed oil on selected organisms that can have relevance for conditions in Norwegian Seas. Several of the studies have been selected to cover different trophic levels from zooplankton to sea birds and sea mammals, but the main focus have been on effects on early life stages (ELS) in fish, as ELS represent a particular vulnerable and important resource along the Norwegian coast. However, it is important to bear in mind that fish is also dependant of other species and a well functioning ecosystem and damage to other organisms can have consequences for fish even if it was not affected directly.

Zooplankton

I Norwegian Seas, *Calanus finmarchicus* is considered a key species in the ecosystem. Short time toxicity studies (48 or 96 hours) for *C. finmarchicus* exposed to mechanically (breaking wave water accumulated fraction, BWWAF) and chemically dispersed oil (CEWAF) demonstrated that CEWAF was more toxic than BWWAF at low oil concentrations. LC_{50} was reported to 0.49 mg/l total amount oil hydrocarbons, TPH (or 10.4 µg/l total PAH) for chemical dispersed oil and 0.8 mg/l TPH (16.1 µg/l total PAH) for mechanical dispersed oil (Hansen et al. 2012). Total PAH is calculated as sum of 2 to 5 rings PAH included alkylated homologues.

Studies of reproduction parameters (egg production, hatching success and reproductively active females) in the period after oil exposure only gave a limited contribution to reduced reproduction output, compared with effects on mortality after short time exposures (Olsen et al. 2013). This was confirmed by Hansen et al. (2015) who also found a concentration dependent delay in reproduction in females exposed to similar dispersions of chemically and mechanically dispersed oil. There were no differences in delay between the two oil treatments. However, at 5 mg oil/l the egg production as well as the nauplii production was lower in females exposed to chemically dispersed oil. PAH body residues did not differ between the two oil exposures types and no mechanistic explanation was given for the observed differences.

For Arctic zooplankton, *Calanus glacialis*, chemically dispersed oil (LC_{50}; 22-62 mg/l THC) was found to be less toxic than mechanically dispersed oil (LC_{50} of 4 mg/l THC) (Gardiner et al. 2013). Lower acute toxicity of dispersed oil to *Calanus glacialis* compared with *Calanus finmarchicus* is also confirmed by Hansen et al. (2013). Nørregaard et al., (2015) also found low toxicity of PAHs (phenanthrene, pyrene and benzo[a]pyrene) were in *Calanus hyperboreus*. The *Calanus hyperboreus* in this study were collected in November at high depth (>250 m) and represent *Calanus* that are in it resting stages for overwintering and preparing for egg production in early spring. These animals are extremely lipid rich (77 % lipid), accumulate high levels of PAHs, but have a very slow metabolism and excretion of PAH. After 77 days in clean water, the PAHs were still detectable in *Calanus hyperboreus*. The low toxicity and high bioaccumulation of PAHs, suggest that *Calanus* may transfer PAH to higher trophic levels, like fish larvae. More data are needed in order to include such effects in risk assessments.

Benthic organisms

Use of dispersants on shallow water will lead to increased sedimentation of oil (Page et al. 2000; Reed et al. 2004), and can lead to increased uptake of oil, e.g. in filtering species like bivalves (Michel et al. 1997). We lack knowledge on effects of oil and chemical dispersed oil on benthic organisms. Goodbody-Gringley et al. (2013) found that both dispersed oil and high doses of the dispersant (Corexit 9500) itself (50–100 mg/l) could be toxic to larvae stages from two different warm water corals from the Gulf of Mexico. Similar findings have also been reported from corals from the Red Sea. Epstein et al. (2000) warn against using chemical dispersant in areas with coral reefs.

We are lacking information on sensitivity of oil and chemical dispersed oil to coldwater corals and sponges. Species of relevance for the Norwegian Seas could be the cold water coral *Lophelia sp.* and the sponge *Geodia Baretti*. Such information could be coupled to maps of distribution of corals and sponges from the MAREANO project (ref WP2).

Fish

Early life stages of fish are considered to be highly sensitive to oil pollution, especially towards PAH components (Carls et al. 1999; Incardona et al. 2013). Doses as low as 0.5–20 µg total PAH/l have been shown to lead to several developmental malformations that will often lead to mortalities. Several studies show that the toxicity to oil after chemical dispersion may be increased up to 100 times, but this is caused by increased levels of dissolved oil components as a consequence of the increased amount of oil in the water column. When the effects are normalised to total oil components in the water, the chemical dispersed oil appears as less toxic than mechanically dispersed oil (Ramachandran et al. 2004; McIntosh et al. 2010; Olsvik et al. 2012; Wu et al. 2012; Adams et al. 2014).

Even if dispersants are toxic to fish/embryo/larvae, effective dose to e.g. Corexit 9500 is between 25 and 750 mg/l (”Committee on understanding oil spill dispersants”, 2005), doses that are significantly higher than what is realistic water concentrations used in mitigation actions after oil spills. The increased toxicity to early life stages of fish when using dispersants is primarily explained by an increase in dissolution rate of dissoluble components caused by higher oil concentrations and smaller droplets (Olsvik et al. 2012; Adams et al. 2014; Vikebø et al., 2015).

A.4.4 The effect of volatile components and gases at high pressure

For subsea oil releases with oil containing all volatile components (BTEX compounds) and gas entrained under pressure, there is a lack of information on toxicities and effect thresholds related to these conditions for relevant species in the water column (See species mentioned above). Such components may contribute most to the toxicity close to the discharge point.

A.4.5 Recommendations:

Table A.4.1. Suggested research needs related to SSDI and toxicity. The research needs are ranked by 1-3 for importance.

TOPIC$^{1)}$	**Specification**	**Comments**
Corals and sponges (1)	Determine sensitivities for exposure to crude oil with or without chemical dispersants for important benthic organisms like corals (*Lophelia sp*) and sponges (e.g. *Geodia baretti*).	Clear knowledge gap, there do not exist data after oil exposure to these cold and deep water species.
Early life stages of fish (1)	Determine if chemical dispersants affect the adhesion of oil droplets to fish eggs. Short term exposure studies on Atlantic haddock, Atlantic cod and Atlantic herring embryo.	How oil droplets contribute to embryo toxicity may be an important parameter that should be included in the risk assessments.
Egg, larvae, copepods (1)	Describe the potential for oil droplets to adhere to biological membranes focussing on changes in adhesion potential as a function of weathering degree of oil and different biological membranes (e.g. eggs, larvae copepods etc).	Important input to modelling effects of dispersants.
Early life stages of fish (2)	Determine if high levels of BTEX from non-weathered oil increase the toxicity during chemical dispersion compared with the data from laboratory studies with weathered oils. These studies should be focus on the embryo stages of Atlantic herring since its benthic egg make it vulnerable for subsea oil spill.	We lack information of non-weathered oil. Toxicity studies on ELS of fish have to consider the delayed mortality that are normally first seen during the first feeding period. These studies should prolong until 10-20 days after hatching.
Calanus (2)	Are *Calanus finmarchicus* more affected by dispersed "fresh oil" compared with earlier studies on weathered oils?	*Calanus* are a key species in Norwegian Seas. Because of its high ability to accumulate lipophilic compounds it may be important for transferring oil compounds to predators like fish larvae.

A.4.6 References

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A.5 WP5 Field Trials

A.5.1 Introduction / Justification:

A final step in a R&D program (JIP) dealing with SSDI would be to validate the scientific findings through controlled field experiments. In the same way as the international reputed "Deep-spill" experiment in 2000 (Johansen et al. 2003), this will have a great scientific value both for validating the studies performed under specific laboratory and basin conditions (both on effectiveness, fate and biological effect) and in testing the robustness of numerical model tools developed during the R&D program. Additionally, such a full-scale experiment will be of high value for validating the functionality and operative feasibility of relevant monitoring systems for documenting SSDI as an operative countermeasure technique under realistic field conditions. This is also in accordance to regulations in Norway saying that oil spill countermeasures and strategies included in an operators emergency plans are to be tested and validated through realistic conditions in regards of functionality and operative qualities (Facilities regulations/"Innretningsforskriften" §42).

From planning to accomplishment of a large –scale field trials is time consuming process. It is therefore important to start a dialog with the pollution authorities as early as possible in order to communicate the justifications for such full-scale releases, scope of work and the objective with the field trials. Location for the field trial and criteria for oil release, such as weather conditions, wild life, and oil spill contingency system will also be among the important topics to discuss with the authorities prior to applying for the permit to oil release. It is the Norwegian Environment Agency that approves the discharge permits on the Norwegian Continental Shelf.

In Norway, the progress within oil spill related R&D has traditionally been taken place through a combination of laboratory testing, basin studies, and field trials. We strongly recommend having such a scientific approach also in this SSDI- R&D program. Experimental under-water releases under controlled conditions including SSDI will therefore be a natural final step, and will play an important role for a scientific-based validation of the findings and in documenting the functionality of SSDI as an operative and reliable response countermeasure option in connection to acute subsea releases.

A.5.2 Status – Previous field experiments with subsea releases of oil

Since 1978, approximately 40 experimental oil spills have been performed under controlled conditions both shallow, deep and ice covered offshore waters in Norway (see figure A-5-1, Faksness et al, 2015) Three of these series of field trials, have include underwater releases, but not SSDI.

<u>Releases from shallow water:</u> Field experiments in the North Sea in 1995 and 1996:

Due to the increasing use of subsea installations and transport of oil and gas in pipelines, the focus on subsea releases increased in the early 1990s. The initial work was focused on releases from pipelines or releases from oil wells at shallow depth (< 200m). Releases from such depths were regarded as buoyant plumes in stagnant water, where the buoyancy was mainly related to the amount of gas released from the seabed. An initial field experiment in 1995 (at 106 m depth at the Frigg Field in the North Sea), 2 x 25 tons of stabilized crude oil (no gas) simulating a release from an oil pipeline. Relative large oil droplets (2 - 5 millimeter range) were generated at the source site, leading to a rapid rising to the sea surface (within 10 – 15 min, Rye et al, 1996) and an initial thick, concentrated oil slick - comparable to a surface batch release (Strøm-Kristiansen et. al.1995)

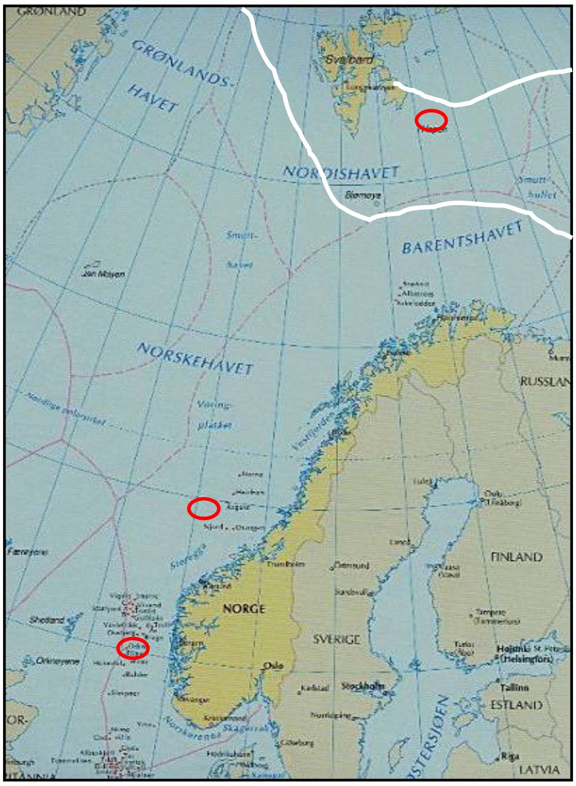


Figure A-5-1. Main test-sites for experimental oil releases both in shallow, deep and ice-covered water in Norway

In 1996 this was taken further (at the same area and depth) to include a combined oil & gas release where 43 tons of Troll crude with realistic gas-to-oil ratios (GOR) and release velocities of $1m^3$/min (Rye et al., 1996 and 1997). Five different release conditions were studied, one with oil & gas (GOR=67) and four with water and air (Gas-water ratio from 67 to 7). Monitoring of the spreading and dimensions of the rising plume (sonar) and the resulting thin surface oil slick (see figure 2) were comprehensive documented by oil sampling, thickness measurements and aerial surveillance (Strøm-Kristiansen et al., 1997). The obtained data was used to further develop and verify the early version of the SINTEF DeepBlow model (Rye, 1994).

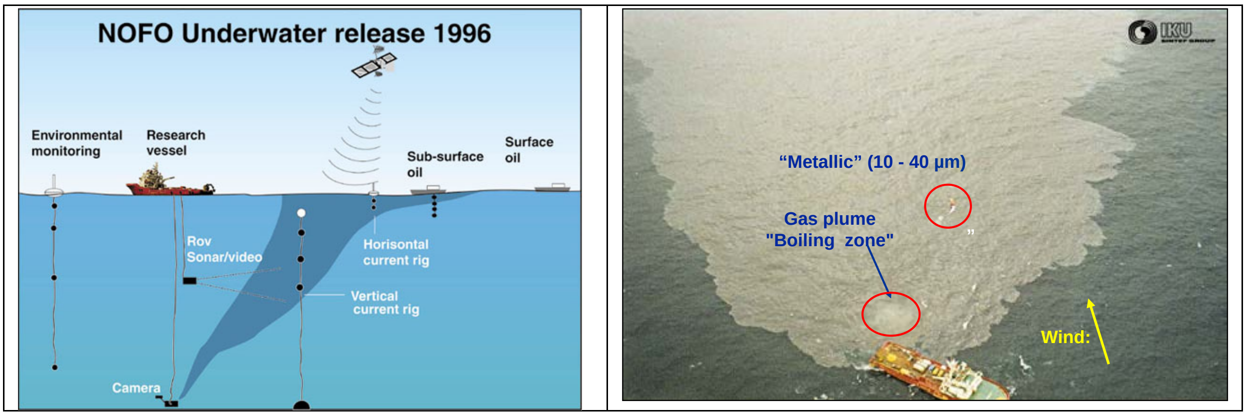


Figure A-5-2. Left: Schematics of the experimental oil-gas releases at the Frigg field in 1996. Right: gas penetrating the sea surface resulting in a thin initial oil film thickness

Releases from deep water: Field experiment in the Norwegian Sea (DeepSpill 2000)

As subsea exploration went into deeper waters, it became a need for the models to include non-ideal gas behavior, loss of buoyancy due to gas compression, increased gas solubility and formation of gas hydrates. These are all processes that could reduce buoyancy to such a degree that the plume does not surface, but gets trapped. Dissolution of gas from rising bubbles into ambient water may be negligible for shallow blowouts, since the residence time of the gas bubbles is generally short. For blowouts from deep waters, when gas bubble rise, time will be significant longer, and gas solubility is increased due to larger ambient pressure, a significant reduction in plume buoyancy may be expected. Formation of gas hydrates due to low temperatures and high ambient pressure will additionally contribute to reduction of plume buoyancy. Together, the above factors will cause a significant reduction in plume buoyancy. As a consequence, the plume will become more sensitive to cross currents and the presence of density stratification. To facilitate these modifications, the Eulerian concept of the original SINTEF Blow model was substituted by a Lagrangian concept for the new DeepBlow model (Johansen, 2000). Yapa and Zheng and (1998) extended the Lagrangian plume concept of Lee and Cheung (1990) to multiphase plumes to represent subsea releases of oil and gas. SINTEF DeepBlow model is described in detail by Johansen (1998) and the DeepSpill experiment in 2000 was used to verify this new model (Johansen, 2003). The DeepSpill experiment was performed at 840 meters depth at the Helland Hansen field outside mid-Norway and consisted of four different releases (N_2/seawater, LNG/seawater LNG/diesel and LNG/crude, see figure A-5-3). As expected the gas/water/oil plume lost its buoyancy after rising for 150-200 meters due to gas compression and dissolution (Johansen et al. 2003).

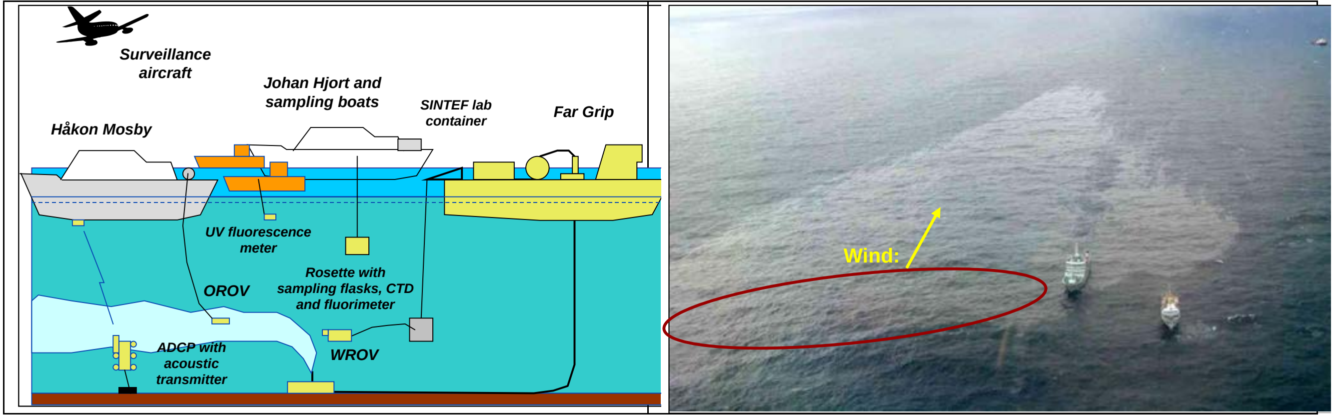


Figure A-5-3. Left: Schematics of the experimental oil-gas releases from 840 m depth at the Helland Hansen in 2000. Right: Gas did not penetrating the sea surface resulting in an initial thick oil film (> 200µm -see red circle) that emulsified after weathering on the sea surface.

2010-Deepwater Horizon incident – a "Spill of opportunity"?

The 3.5 months of continuous release (April 20th. July 16th, 2010) during the Macondo incident in the Gulf of Mexico, could have been a gigantic "Spill of opportunity" for documenting the near-zone droplet formation at 1500 m depth of both natural and chemically enhanced dispersed oil droplets and the further spreading through the water. However, in opposite to the extensive sampling and monitoring that took place in the more remote area from the source site and in coastal area, the more detailed documentation around the near-zone during the release period was very limited. The accessibility to the release site was very restricted due to the ongoing containment operations at the source (e.g. the LMRP -Lower Marine Riser Package). Furthermore, at that time, it was a lack of available relevant and reliable deep-water sensor systems (e.g for documenting *in-situ* oil droplet size distributions, monitoring the effective dosage of dispersant to the oil, "tipstreaming" through the water column etc.).

In the aftermath of the Macondo incident, there have been extensive efforts in developing sensors and sensor platforms for monitoring deepspill releases and for documenting SSDI (see WP 6). Field trials under controlled conditions would therefore be of high value for validating the functionality and operative feasibility of relevant monitoring systems used for documenting SSDI as an operative countermeasure technique under realistic field conditions.

A.5.3 Design of future field experiments with sub-sea oil releases and SSDI

Based on the previous experiences to carry out field trials with sub-sea releases, and to utilize the documentation obtained from these experiments as much as possible, we recommend to design coming field experiments as similar as possible to the series of releases at shallow water in 1996 and the deep water in 2000. The main difference would be to include the testing of SSDI as an additional varying parameter. This will be the most safety and cost–effective way to cover the knowledge gaps.

Such an approach will imply the following:

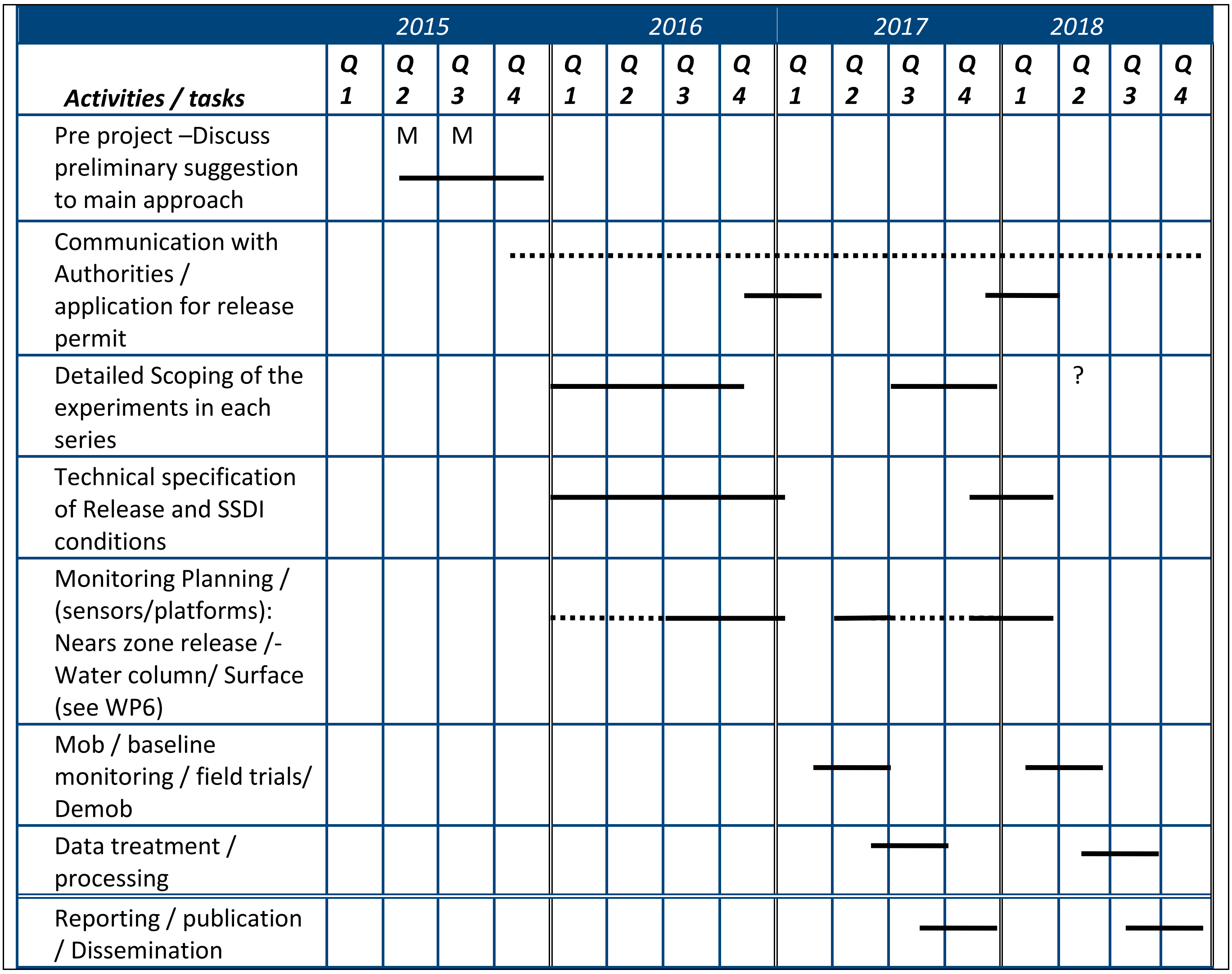
- Two series for field trials:
  - June 2017: Field experiments with sub-sea oil /gas releases and SSDI in shallow water (106 m depth at the Frigg field in the North Sea)
  - June 2018: Field experiments with sub-sea oil /gas releases and SSDI in deep water (850 m depth at the Helland Hansen in the Norwegian Sea)
- Using the similar oil types and release rates as in the 1996 / 2000 experiments (e.g 1m^3 crude oil / min over a total of 1-2 h of oil releases in each series).

The overall objectives for such series of controlled field experiments, are to:

- Strength the scientific value of this SSDI R&D program, both by validating studies performed under the specific laboratory and meso-scale basin studies within the other work-packages (both within effectiveness and biological effects), and particularly for documenting larger scale mechanisms / processes that are not possible to document otherwise in the laboratory (including extensive monitoring both close to the release source, through the water column, and fate and spreading of the oil entering the sea surface etc..).
- Validating the functionality and feasibility of relevant monitoring systems for documenting the SSDI methodology as an operative countermeasure under realistic field conditions
- Validate through ground-truth data the robustness of numerical model tools developed during the R&D program
- Fulfil regulative requirements in Norway saying that oil spill countermeasure and strategies included in an operators emergency plans have to be tested and validated through realistic conditions in regard of functionality and operative qualities.

The main planning activities for performing these two series of field trials within this suggested timeframe is illustrated in the tentative timeline below. At this stage we don't go into further detailed scoping and description of sub-activities within each activity (task).

A.5.4 Tentative timeline for main activities for planning and performing two series of experimental field trials:



	2015				*2016*				*2017*				*2018*			
Activities / tasks	***Q 1***	***Q 2***	***Q 3***	***Q 4***	***Q 1***	***Q 2***	***Q 3***	***Q 4***	***Q 1***	***Q 2***	***Q 3***	***Q 4***	***Q 1***	***Q 2***	***Q 3***	***Q 4***
Pre project –Discuss preliminary suggestion to main approach		M —	M —	—												
Communication with Authorities / application for release permit				···	···	···	···	··· —	··· —	···	···	··· —	··· —	···	···	···
Detailed Scoping of the experiments in each series					—	—	—				—	—		?		
Technical specification of Release and SSDI conditions					—	—	—	—				—	—			
Monitoring Planning / (sensors/platforms): Nears zone release /- Water column/ Surface (see WP6)					···	···	—	—		—	···	··· —	—			
Mob / baseline monitoring / field trials/ Demob									—	—			—	—		
Data treatment / processing										—	—			—	—	
Reporting / publication / Dissemination											—	—			—	—

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A.6 WP6 Monitoring – Sensor instrumentation

At the SSDI workshop in May 28 2015, it was decided to have monitoring / sensor instrumentation as a separate WP. One important presumption for getting a release permit from the Authorities for a field trial is to have good documentation for monitoring. This section outlines the suggested requirements for monitoring surrounding a large-scale field trial for SSDI, existing relevant capabilities, and suggestions for proprietary work and developments ahead of such as monitoring campaign.

The state-of-the-art in monitoring related to SSDI has been advanced recently during the API-funded program on SSDI (section 2.1 and A.1.1), in addition to advances in wider-scale ecologically-related acoustic measurements at IMR. The primary 'gaps' or pre-requisites for offshore monitoring related to SSDI are therefore driven by the need to operationalise and 'up-scale' the existing state-of-the-art so that it can be taken from the laboratory-scale experiments to a full offshore setting. In addition to providing key scientific information about SSDI, these advancements to the monitoring capabilities enables the technology to be tested and made 'ready' for use in a real spill scenario.

A.6.1 Requirements

During a large offshore experimental release used for evaluating SSDI, the requirements for monitoring a plume of released pollutant, and the effectiveness of dispersant injection, must cover a wide range of spatial scales. This spans from detailed in-plume measurements of individual particles, to larger-scale monitoring of the physical properties of the water column and plume migration. Here, we group the requirements based on the spatial situation in which each type of measurement should be made.

In-plume

In-plume monitoring of the particle size distributions of multiple particle types forms the most critical component of assessing the effectiveness of dispersant injection. This is because SSDI effectiveness can only be quantified accurately by measuring changes in the oil droplet size distribution for varying dispersant injection methods (or release rates), and comparing these measurements to the undispersed (no dispersant treatment) equivalent. It is therefore necessary for measurements of the oil droplet size distribution within the plume to be unaffected by other material suspended in the water.

Measurements must be made within relatively high concentrations of mixed oil and gas, together with other material suspended in the water column. This means that the size distribution of the oil droplets must be measured independently from other material within the water. In-plume particle measurements must also be capable of handling the range of droplet sizes expected during the releases. These droplets will be of the order of multiple millimeters in diameter for undispersed oil (no dispersant injection), and a number of hundred microns for chemically dispersed oil.

Information on gas bubble size distribution will also provide valuable data. The monitoring of in-plume size distributions should therefore be capable of discriminating between oil droplets, gas bubbles and other material.

Surfaced material

Monitoring of the extent of released material at the ocean surface is important for understanding both how the plume can be influenced by cross-currents, and also how dispersant injection influences oil slick thicknesses and spreading. Closure between the volume of oil released and the volumes measured / estimated at the surface and remaining within the water column is important, both for experimental error assessments and for verification of potential environmental impacts of the releases. This closure should be achievable within an appropriately monitored offshore experiment.

The surface extent of released oil should be monitored, and slick thickness area should be measured using the standard monitoring procedures adopted by NOFO and SINTEF. The surfacing diameter of the plume (if the plume is still intact at the surface) should be measured continuously during the release.

Plume geometry
Meso-scale monitoring of the plume geometry and movement provides valuable information on how cross-currents influence plume migration, in addition to variation in entrainment rates that result from SSDI. Tracking of the subsurface plume extent can provide important information on plume dynamics that can be used for model validation. Therefore plume geometry and tilt in response to cross-currents should be monitored. This includes the plume angle, centerline position, and surface diameter.

Large-scale oceanographic context
Standard background oceanographic measurements of the water column should be made, including CTD profiles and current measurements. Current measurements of the entire water column should be performed at a nearby location, continuously during the release in order for cross-current effects to be accounted for.

Wide, spatial scale monitoring of the ecological situation surrounding the site may also be valuable from an impact and toxicology perspective. This includes fish (and eggs), plankton, and the other suspended material (e.g. marine snow).

A.6.2 Existing capabilities

A.6.2.1 In-plume

For evaluation of SSDI effectiveness it is of critical importance to obtain information on the oil droplet size distribution and gas bubble size distribution within the plume. SINTEF has, over the last two years, developed a suite of novel *in-situ* particle imaging systems that overcome many of the challenges associated with in-plume measurements such as high concentrations, mixed particle types (oil, gas and other material), and large particle sizes. There is no single commercially-available instrument currently capable of tackling these challenges, which led to the motivation for the development of these bespoke particle imaging systems at SINTEF. These particle imaging systems make use of a silhouette-based approach for imaging particles suspended in seawater, and are capable of distinguishing between oil droplets, gas bubbles and other particulates in suspension (e.g. marine snow and planktonic organisms). The use of the SINTEF Silhouette Camera systems will be necessary for quantification of the effectiveness of dispersant injection, and also for measurements of undispersed droplet sizes (Figure A.6.1). The ability to segregate the size distributions of multiple particle types (e.g. oil droplets, gas bubbles and other material), is also of critical importance in evaluating the influence of the gas-oil ratio on subsurface dispersant injection (Figure **Error! Reference source not found.**A.6.2). The removal (or additional analysis) of other types of particle present is necessary in order to avoid over-counting of oil droplets or gas bubbles.

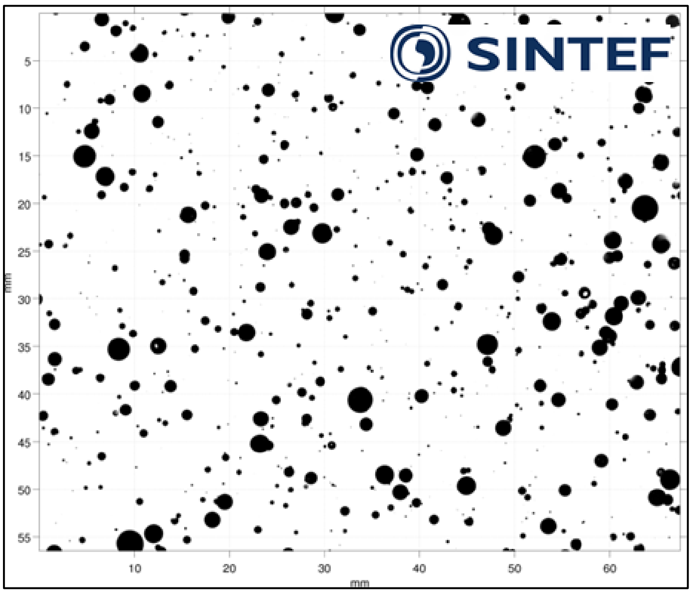

Figure A.6.1 : Images of large (multi-mm scale) oil droplets measured during up-scaled API experiments at OHMSETT, 2015. These images are used to quantify the size distribution of oil (and/or gas) covering size ranges from 30-10000 microns.

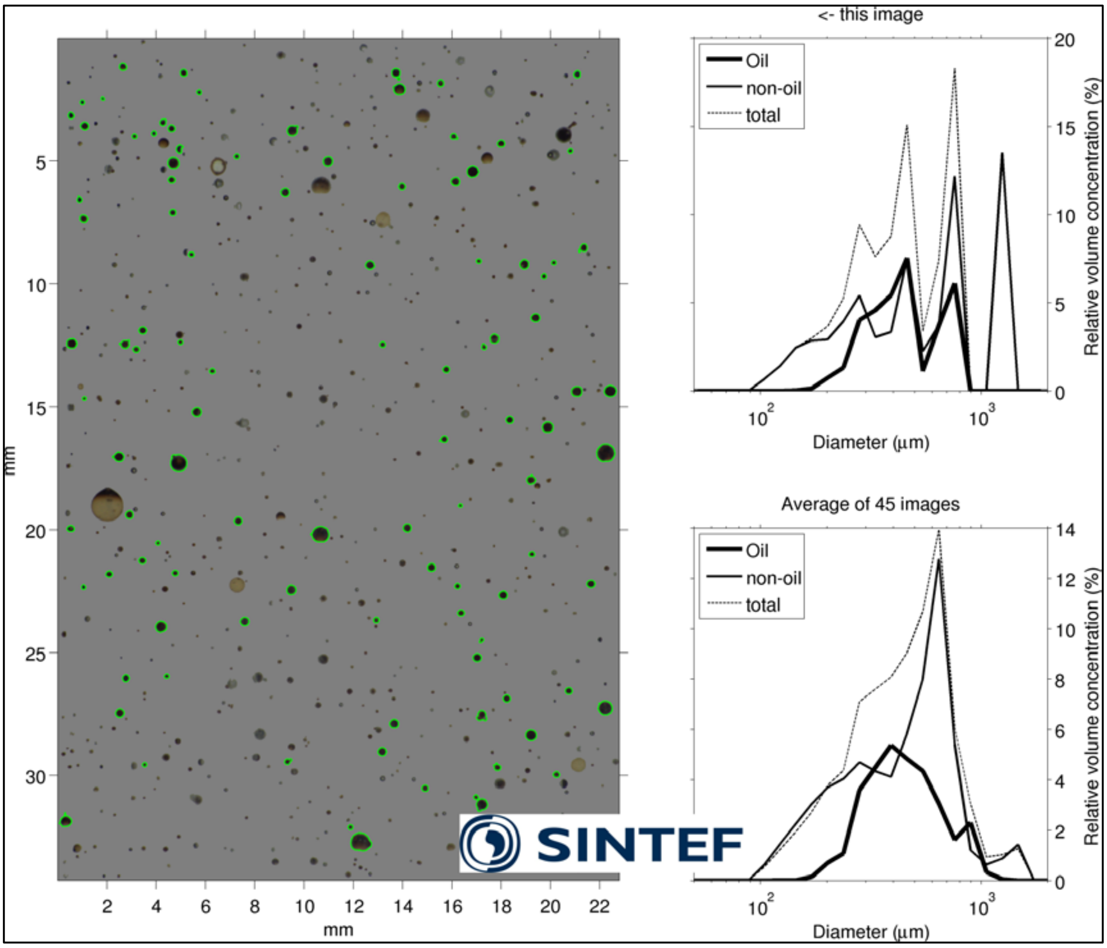

Figure A.6.2 : The SINTEF Silhouette Camera is also being used to separate oil droplets and gas bubbles in experiments involving mixed releases of oil and gas, together with dispersant injection.

A.6.2.2 Surface

OceanEye

The Maritime Robotics OceanEye has been used to good effect in monitoring surface slick using relatively stationary aerial imagery, and also more recently in quantifying the characteristics of the surfacing gas plumes during large-scale releases (as part of the SURE JIP project on subsurface gas releases at SINTEF). Data from the OceanEye (both visible and infrared imagery) can be re-projected into real-world co-ordinates and image analysis of the processes occurring at the surface can enable comparison with the subsurface measurements obtained with the EchoScope (discussed later together with Figure A.6.4). This includes time-series of both the boiling zone diameter for gas reaching the surface, and areas of any oil slicks before and after recovery.

Surface oil characteristics

The concentrations of oil close to the sea surface can be estimated using UV (ultraviolet) fluorescence. Figure A.6.3 shows how a UVF can be deployed onto a towed platform for relatively rapid mapping of large spatial areas, where changes in UV fluorescence can provide information on the extent of oil present just below the sea surface.

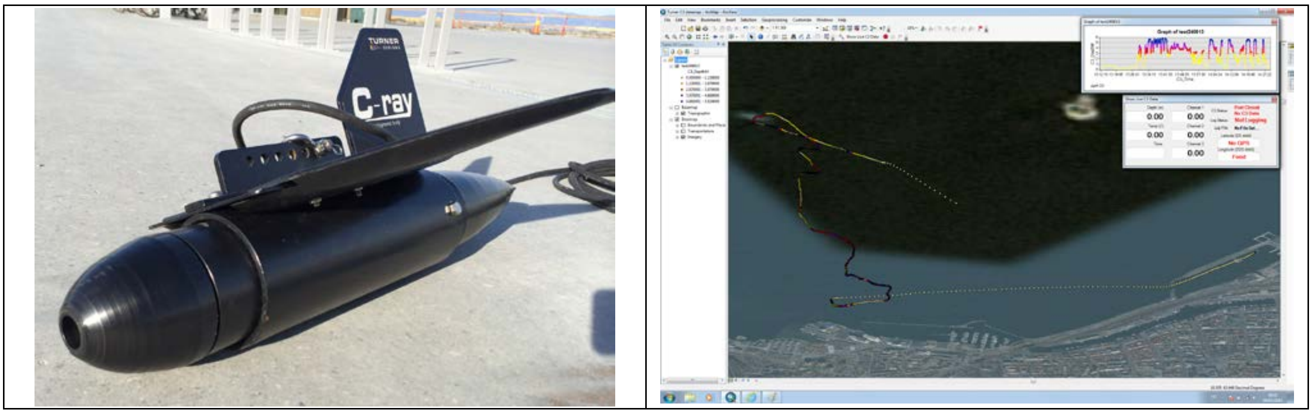

Figure A.6.3: Left: Turner UVF mounted on a C-ray towfish, which has been modified to improve tow performance. Right: An example screenshot of a live map view of measured fluorescence.

Unfortunately, the use of UV fluorescence provides information only on relative changes in oil concentration without measurement of droplet size. Droplet sizes could therefore be monitored, together with the UVF, using laser diffraction (in the form of the LISST-100), which can estimate the concentration of suspended particles within 32 logarithmically-spaced size classes over the range of 2.5-500 microns.

Measurements close to the sea surface can become limited in situations where breaking waves cause bubbles to become highly concentrated just below the sea surface. This poses challenges for both the UVF and LISST-100 measurements. The SINTEF Silhouette Camera system, however, is capable of differentiating between oil droplets, gas bubbles, and other suspended material. One of these imaging systems could therefore be used to measure the size and concentration of oil droplets close to the sea surface, and enable quantitative assessments of the errors associated with the more standard UVF measurements when exposed to wave-induce bubbles.

Water samples should be taken of the surfacing oil for later chemical laboratory analysis of the oil, and standard slick thickness estimates should also be made.

A.6.2.3 Meso-scale plume

EchoScope

SINTEF has, as part of the SURE project JIP, established methods for detailed monitoring of large-scale plumes from subsea releases (Figure A.6.4). To obtain measurements of the macro-scale dynamics (plume geometry, initial rise velocity, and plume tilt (in cross- currents), we have utilised the CodaOctopus EchoScope, together with a series of image processing-based data treatment techniques developed at SINTEF. This can provide three-dimensional data on subsurface plume geometry and motion (e.g. cap rise velocity). For the largest releases monitored during the SURE project the EchoScope was integrated with an ROV, which would flew vertically from the depth of the release, keeping the initial plume cap in view. Here, the EchoScope was configured to record features within a range of 20-80m from the instrument at the start of a release, and was capable of reconstructing the plume image over several hundred metres of rising through the water column (at a rate of ~12 Hz). Based either on the relative location of the rising plume to this piloted ROV, the range would be adjusted as needed.

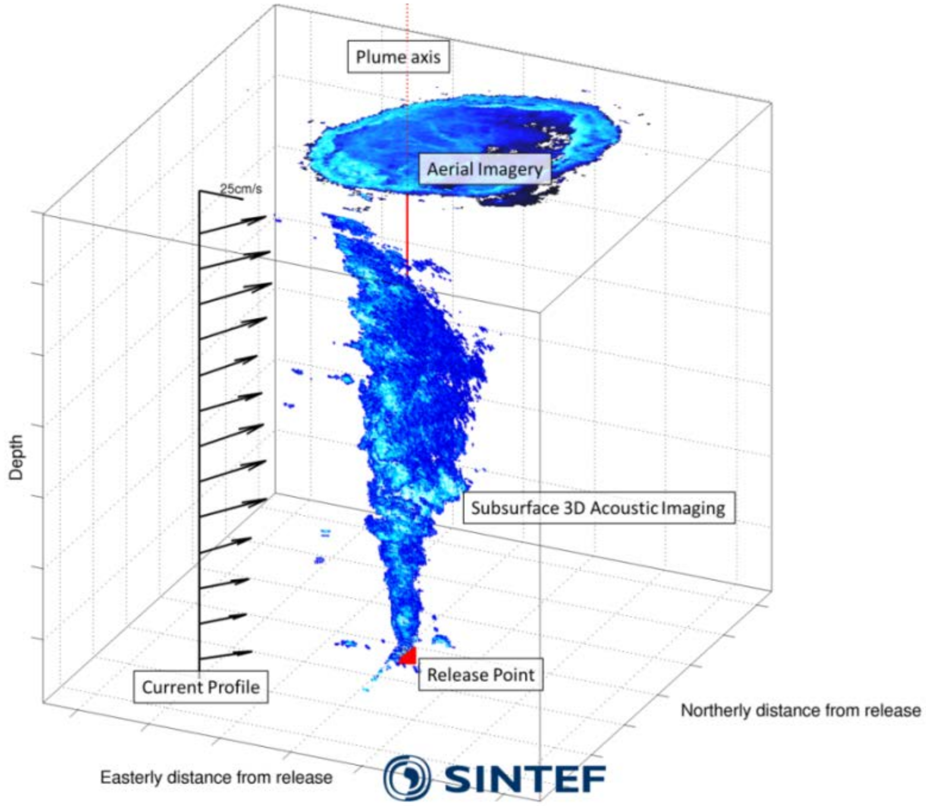

Figure A.6.4: Example macro-scale plume measurements made during a large-scale offshore release of gas during the SURE project. Data presented are of ocean currents (vector arrows), plume geometry (obtained with the ROV-mounted EchoScope), and surfacing plume (obtained with the OceanEye).

The measurement of plume geometry and initial rise velocity (Figure A.6.5), together with the ability to accurately quantify plume axis tilt in cross-flow and potential plume trapping, are all invaluable in validating our understanding of the behaviour of plumes created both with and without subsurface dispersant injection. This is because the modification to the droplet sizes instigated by the injection of dispersants greatly affects the macro-scale plume dynamics. For example, entrainment plays a greater role in holding the plume together when droplet sizes are smaller, and these dispersed plumes are subjected to greater influence from current shear layers and density interfaces. Measurements of subsurface plume cap rise velocity are also extremely valuable for model validation, beyond the initial droplet size (modified-Weber) model, as parameters associated with entrainment and gas dissolution (for example) can be validated and calibrated.

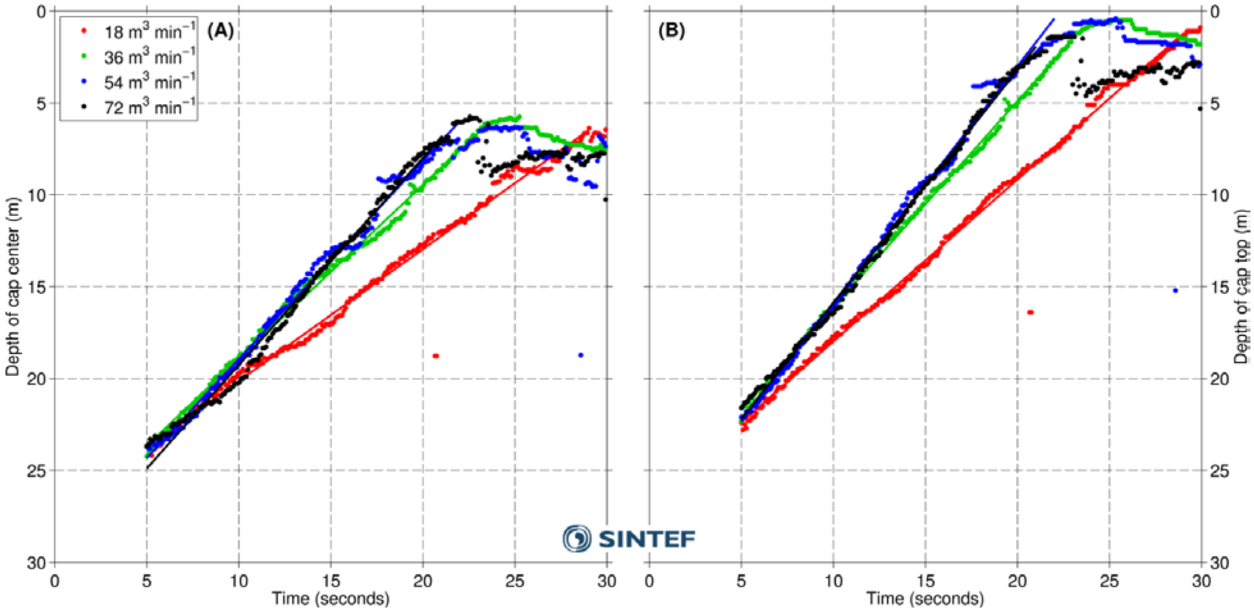

Figure A.6.5: An example time-series of subsurface plume cap depth, which can be obtained from tracking with plume tracked using image analysis of the ROV-mounted EchoScope data.

Ship-mounted Echosounders

Active acoustic leak detection of oil and gas has been targeted recently by the petroleum industry related projects funded through JIP (https://www.dnvgl.com/oilgas/joint-industry-projects/ongoing-jips/offshore-leak-detection-jip.html) and through the Norwegian Research Council (Contract 206972 Active Acoustic leak detection of oil and gas from subsea installation). These demonstrate the feasibility of using active acoustics to detect and quantify leaks down to droplet level under reasonably good conditions as expected during an experimental spill. Similarly, through an industry funded project IMR has shown in laboratory and is underway to confirm with field sampling, that active acoustics at high frequencies (<=200 kHz) may detect eggs and larvae of cod (Statoil Contract 4503205361 Field validation of fish egg and larvae sensor). Thus, active acoustics can be used to observe leaks at ranges of 500-800m using frequencies >=70 kHz while leaks and associated affected marine life can be observed with higher frequencies (<=200 kHz). An example of acoustic imaging of gas leakages that could be achieved in this manner is shown in (Figure A.6.6)

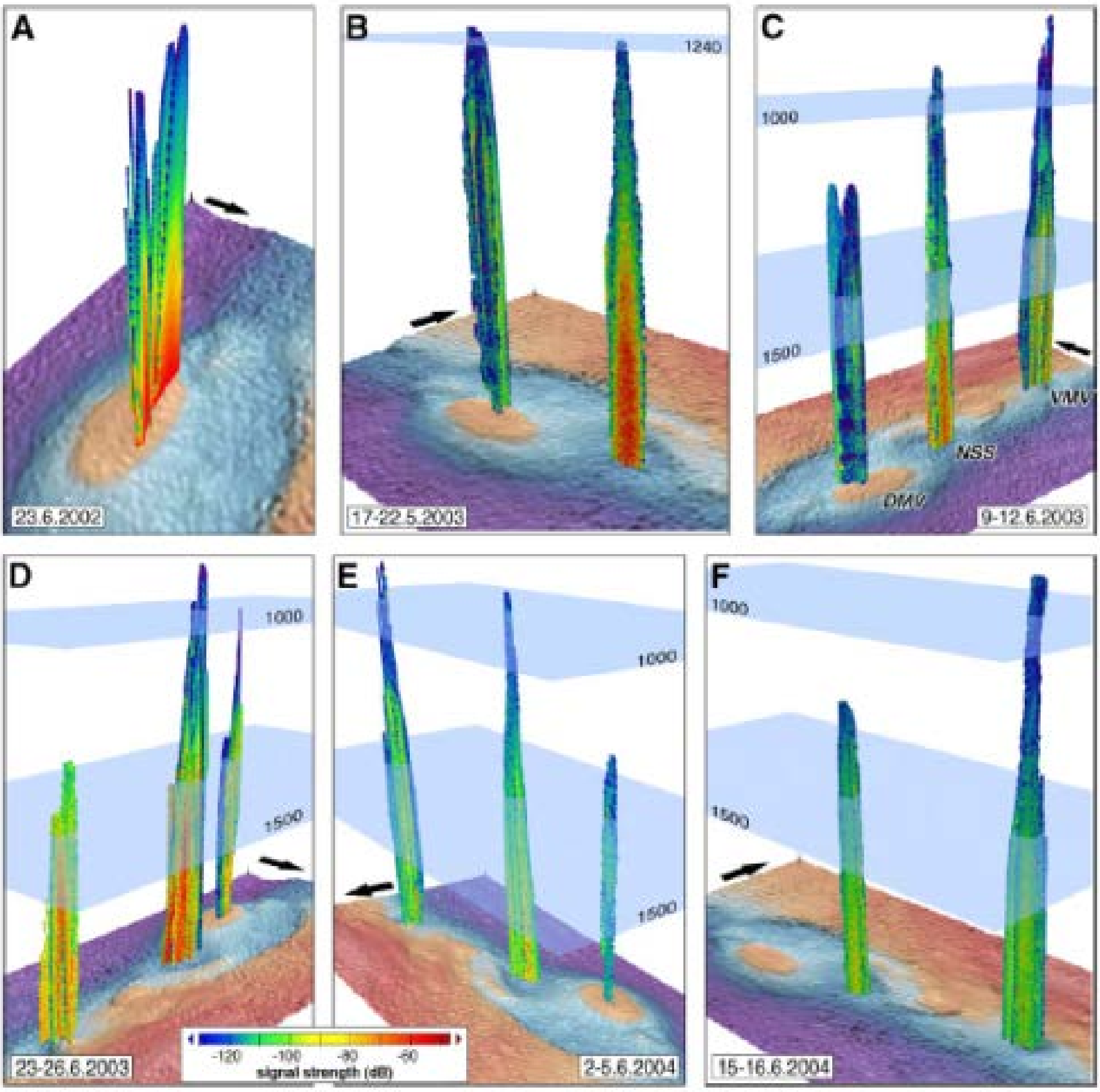

Figure A.6.6: An example of the 3D images that are possible from ship-mounted echosounders (from Greinert et al., 2006).

In a leak experiment two potential setups could be useful:

1. A sensitive broadband echosounder (30-100 kHz dependent on the range requirement) is mounted in buoy at the top of an anchored rig close to the release location, The echosounder is located close to the surface and equipped with a steerable transducer that can monitor a hemisphere covering the oil spill. Such system has been demonstrated to enable monitoring to at least 700m range.
2. Use of a high frequency broadband echosounder (150-500 kHz) mounted on an AUV together with an optical sampling device (like UVP or VPR). Based on the results from the above mentioned Statoil funded project, this system could continuously cover the plume and simultaneously monitor marine life including copepods, fish eggs and larvae.

A combination of the two methods, together with the deployment of the EchoScope on an ROV, would give the most optimal coverage in space and time, combining continuous and efficient mapping of the plume and simultaneous monitoring potential impact on sensitive marine life.

A.6.2.4 Large-scale oceanographic context

Ocean currents can be monitored continuously from a ship-mounted acoustic Doppler-based instrument, such as a 75 kHz ADCP or Nortek Continental. If water depths at the chosen site exceed the range of these low-frequency instruments, it may be necessary to also deploy an upward-looking bed-mounted long-range instrument in addition. The deployment of a bed-mounted current profiler would also enable longer-term, continuous monitoring of the ocean currents at the field site throughout the duration of the exercise.

The physical structure of the water column (salinity, temperature and density) is important to quantify so that the migration of the plume through any stratified layers of the water column can be understood. These measurements can be made using standard CTD profiles, and should be repeated at a sufficient temporal resolution to capture any tidal variability that may be present. It is also possible that the released plume can cause a breakdown of stratified layers, which should be measured by performing CTD profiles at the release site immediately before and after the releases.

Quantification of plankton abundancies and marine snow may also be valuable from an ecological impact perspective (Figure A.6.7). SINTEF has developed a filter-feeding model within OSCAR, which can be used for estimating uptake of oil by Calanus, which has been shown to play a significant role in the long-term fate of spilled oil. This model, however, requires knowledge of local Calanus abundances, which can be quantified automatically with the Silhouette Camera system, and estimate over large-scale using acoustic techniques.

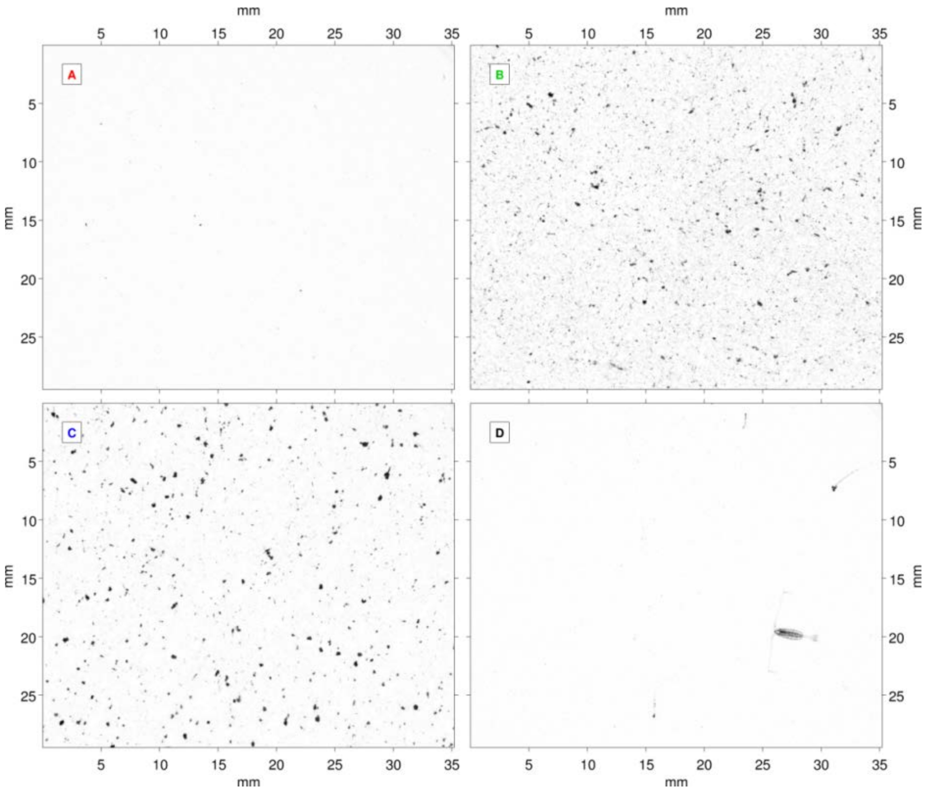

Figure A.6.7: 'Other' suspended particulate material can be quantified (or removed from in-plume measurements) using SINTEF's Silhouette Camera. In-situ measurements of Calanus abundances can also be fed directly into OSCAR for estimating of oil uptake by filter-feeders.

A.6.3 Suggested proprietary work

Integration of the SINTEF Silhouette Camera with ROV

As the only method for accurate quantification of in-plume oil and gas droplet sizes, it is of critical importance that the Silhouette Camera is capable of being deployed from an ROV. This requires little modification to the instrument. However, some hardware changes are necessary to ensure reliable integration with standard ROVs. We therefore suggest an activity to implement these modifications, and perform some field testing of the system integrated with an ROV ahead of an SSDI field trail. The result of such an activity will provide, for the first time, a method for real-time response monitoring for informing subsea dispersant injection. This will:

- provide instant guidance on required dispersant dosage for achieving targeted droplet sizes
- provide instant knowledge of dispersant effectiveness and whether dosage is correct (too much/too little)
- requires development of SilCam for integration on ROVs for measurement of in-plume droplet PSD and concentration
- estimates of oil-gas ratio within the plume
- information from this can be fed directly into models e.g. OSCAR through assimilation with the modified-Weber calculations (i.e. The SilCam will measure the key controlling parameters for model setup).

Appropriate developments in monitoring of this kind could then become integrated into SSDI monitoring procedures and support recommendations for improvements to protocols such as SMART and NEBA.

Laboratory testing of acoustics for oil and gas

The addition of dispersant alters the physical characteristics of the oil. How this affects the acoustic detectability is unknown and is an area for further study. We suggest some laboratory activities (together with SINTEF and IMR) to enhance our understanding of the acoustic responses to the expected changes in the characteristics of plumes with and without SSDI. This can be performed both numerically (using theoretical models for acoustic backscattering), and experimentally in the SINTEF Tower Basin. In such an experimental study, the standard optically-based monitoring instrumentation (LISST-100 and Silhouette Camera) will be used for ground-truthing and calibration of the acoustic response for untreated and treated releases covering a range of realistic droplets sizes.

Combining technology for dynamic, in-situ calibration

The combination of optics, imaging and acoustics can provide a very powerful tool for monitoring a large range of scales, from individual particles of a few microns in diameter, to hundreds of meters of large-scale particle concentrations. Many optical and acoustic techniques rely on either calibration to known material types and sizes, or a theoretical model for use in inverted the measured signal into a particle concentration or size. The deployment of *in-situ* imaging alongside these techniques enables the opportunity for the detailed particle information, obtained from such imaging systems, to be used for *in-situ* calibration of the other techniques.

We suggest a joint activity between with SINTEF and IMR to evaluate the potential of the combination of optics, imaging and acoustics for *in-situ* calibrations that are dynamic and respond to the changes present in a real-world and variable ocean system. This activity would consist of some laboratory work, where all three techniques are deployed together, so that their responses to varying types, sizes and concentrations of particles can be assessed. Following this, a short field deployment prior to an offshore SSDI field trail could be beneficial in testing the developed calibration methods within a realistic setting.

Table A.6.1: Suggested research needs related to monitoring of an large-scale SSDI experiment. The research needs are ranked by 1-3 for importance.

TOPIC[1)]	**Specification**	**Comments**
Oil droplet and gas bubble size distribution measurements (1)	Determine the size distribution of oil droplets and gas bubbles from in-plume monitoring using the SINTEF Silhouette Camera	Already tested and validated in small-scale experiments during API projects. An operationalization task is needed to deploy the system in an offshore scenario onboard an ROV. This task could also be valuable in providing a system that could also be used in a real spill response operation.
Laboratory testing of acoustics for oil and gas (2)	Progress acoustical measurements of oil and gas such that the point-measurements from the LISST-100 or SINTEF Silhouette Camera can be extended to the large special scales that can be captured by acoustics.	Standard optically-based monitoring instrumentation (LISST-100 and SINTEF Silhouette Camera) will be used for ground-truthing and calibration of the acoustic response for untreated and treated releases covering a range of realistic droplets sizes. This can be done experimentally, using the SINTEF Tower Basin.
Combining technology for dynamic, in-situ calibration (2)	Develop an effective multi-sensor system that can perform a real-time, in-situ calibration of the large-scale acoustic measurements by using detailed particle size, concentration and types measured using point measurements from optics and imaging (LISST-100 and SINTEF Silhouette Camera)	This activity would consist of some laboratory work, where all three techniques are deployed together, so that their responses to varying types, sizes and concentrations of particles can be assessed. Following this, a short field deployment prior to an offshore SSDI field trail could be beneficial in testing the developed calibration methods within a realistic setting.

Ranking: (1) – high importance for SSDI-related monitoring and should be addressed for the Norwegian CS; (2) – high importance for SSDI-related monitoring, but could be addressed in other studies/projects; (3)- Medium importance for SSDI-related monitoring, and is addressed in current projects or in submitted project applications.

A.6.4 References

Greinert, J., Artemov, Y., Egorov, V., De Batist, M., and McGinnis, D. 2006. 1300-m-high rising bubbles from mud volcanoes at 2080 m in the Black Sea: Hydroacoustic characteristics and temporal variability. Earth and Planetary Science Letters, 244: 1-15.

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