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Tricolor Incident: oil pollution monitoring and modelling in support of Net Environmental Benefit Analysis (NEBA).

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Abstract. Three European institutes, MUMM, CEDRE and SINTEF, have developed a common approach for monitoring oil spilled at sea and dispersant effectiveness. The study was performed in the framework of project "NEBAJEX", which was co-funded by the European Commission. The aim of this project was to demonstrate how a Net Environmental Benefit Analysis process (NEBA; *i.e.* the evaluation of the overall environmental impact of an oil spill depending on different response options, leading to the selection of the most appropriate one) during a major oil pollution incident can benefit from real-time field monitoring. Several aspects were developed and tested during an exercise at sea: procedures for aerial monitoring of an oil spill, and a set of strategies and procedures for ground-truth monitoring and sampling of oil at the sea surface and in the water column. In September 2003, the NEBAJEX monitoring exercise was organized at the site of the 'Tricolor' shipwreck, a large car-carrier that had sunk in December 2002 in the middle of the Dover Strait. At the time of the exercise, a continuous leakage was observed from the wreck, but the estimated oil volumes were small. Aerial monitoring with a dedicated remote sensing aircraft showed that the oil slicks were linked to the Tricolor wreck, and were rapidly disappearing from the sea surface. The ground-truth monitoring results indicated that the oil, sampled at the surface shortly after release from the wreck, had a markedly higher viscosity than the reference heavy fuel oil (HFO), and a density close to that of seawater, making it plausible that the oil submerged. It was demonstrated that natural dispersion of the stable water-in-oil (w/o) emulsion was negligible and that the emulsion was not amenable to chemical dispersion. The results suggested that the HFO still remaining in the wreck in September 2003 had most probably already weathered before it escaped during the wreck removal operations. The observation of rapidly disappearing (submerging) oil slicks, supported with model simulations of drift and spreading (with SINTEF's OSCAR model and MUMM's oil behaviour model), indicated that the sensitive and nearby coastlines of the southern North Sea were not directly threatened.

Key words: oil pollution monitoring, NEBA, oil spill modelling, oil properties, aerial surveillance, heavy fuel oil, Tricolor incident.

1. Introduction

1.1. The NEBAJEX pilot project

Three European marine research institutes, MUMM, CEDRE and SINTEF, started in 2001 with a European pilot project called "Net Environmental Benefit Analysis Joint Exercise –

NEBAJEX". The main goal of this two-year pilot project was to organize an oil pollution exercise at sea in order to carry out an effective monitoring in real time, and to develop a common monitoring approach, in support of a Net Environmental Benefit Analysis (NEBA). NEBA is an evaluation and decision-making concept for response to major oil spills that is accepted by governmental (e.g. IMO, 1995; Bonn Agreement, 1998) and non-governmental organizations (e.g. IPIECA, 2000; ITOPF, 2002). Figure 1 schematically summarizes a NEBA evaluation and decision-making process.

NEBA can be defined as a means to determine the most appropriate response option(s) in order to minimize the overall environmental impact of an oil spill. It can also be described as a method of selecting the best oil spill response alternative through weighting of the advantages and disadvantages of the different response alternatives at sea and of their expected net benefit towards, or net reduction of the overall environmental impact (see 'loop 1' in Fig. 1). With regard to NEBA it is important to have good knowledge about the ecological sensitivity of marine and coastal areas, about the vulnerability of the human uses in that area, and of the environmental outcome of a proposed response (IPIECA, 2000). Much of this evaluation can be done at the contingency planning stage. Every oil spill situation is unique however, and NEBA evaluations need to be performed during an incident.

With regard to a NEBA evaluation and decision-making process during an incident, it is very important to have a good knowledge about the expected behaviour of the type of oil being spilt at sea. Different oil types have a large variation in physical and chemical properties and their behaviour when spilled at sea may vary a lot. The effectiveness of different response actions depends to a large extent on the weathering and physical properties of the specific oil type. The most important parameters are evaporation, pour point, flash point, viscosity of oil and w/o emulsion, density, water uptake, the chemical composition, and the time window for effective use of dispersants. Information on the chemical composition of the oil is also valuable for the purpose of NEBA, e.g. information on concentrations of toxic poly-aromatic hydrocarbons (PAHs) for environmental impact evaluations, or asphaltene content for a better evaluation of the emulsification processes. The chemical aspects however are not further discussed in this document.

Although NEBA is basically a qualitative evaluation by oil pollution experts and decision-makers, based on impact and response evaluations and forecasts, it should also be considered as a continuous process that is to be repeated during an incident in the light of new information concerning the behaviour of spilt oil, the overall environmental impact, and/or the effectiveness of the activated response technique (see two loops in Fig. 1). During an incident, such valuable extra information can be obtained (1) through an early characterisation and real-time monitoring of the spilt oil, and (2) via mathematical modelling of drift, spreading and behaviour of the oil spill, and of the effect of different response strategies, using obtained oil properties data, ocean current data and wind forecasts.

The NEBAJEX oil pollution exercise at sea was especially meant to demonstrate how useful information obtained in real time from the monitoring and modelling of oil pollution at sea can feed this continuous NEBA process during a major oil pollution incident. The primary objectives of the exercise were:

(1) to validate procedures for surface and subsurface oil pollution monitoring; both aerial and ground-truth monitoring procedures were to be tested in an exercise;

(2) if dispersants were to be used, to test procedures to evaluate the effectiveness of dispersants;
(3) to apply dedicated mathematical models for near-future simulations;
(4) to use these monitoring and modelling results as extra input in a NEBA evaluation process.
The exercise was originally planned in French Exclusive Economic Zone (EEZ) off Brittany with the French Navy as on scene commander, and was scheduled mid-September 2003.

1.2. The TRICOLOR incident

On 14 December 2002 the car carrier 'Tricolor' collided with the containership 'Kariba' in French EEZ off Dunkirk in the Dover Strait, near UK and Belgian waters. The oil pollution resulting from this initial collision was limited. The Kariba, which was only slightly damaged, sailed to the port of Antwerp (Belgium). The Tricolor however sank on the spot, in the middle of an important shipping lane, at location 51°22' N and 02°12' E. The ship sank at a depth of ca. 35 m, and the portside was visible at the sea surface at low tide. The wreck represented an imminent danger for further collisions, and for the marine environment. The Tricolor carried 1988 tons of at least four different heavy fuel oils (HFO), 167 tons of marine diesel oil (MDO), some 50 tons of lubricating oil, and several tons of gas oil and gasoline (automotive fuel of cargo). The French authorities ordered the oil to be pumped out and the wreck to be removed. The ship owner and company agreed. The removable oil volumes were pumped out by the end of February 2003. A salvage consortium *"Combinatie Berging Tricolor"* started with the difficult task of salvage of the more than 200 m long car carrier. Although several safety measures were taken, such as navigation warnings, placing of warning buoys and positioning guard vessels, other collisions and pollution incidents took place, apart from numerous near-collisions:

(1) On 16 December 2002, the small vessel 'Nicola' collided with the Tricolor wreck. The damage to the Tricolor and resulting pollution was minimal, because the Nicola was empty.
(2) The tanker 'Vicky', carrying 66.000 m³ of diesel, collided with the wreck on January 1, 2003. Again an amount of HFO escaped from the Tricolor, whereas the Vicky lost at least 200 m³ of oil (mainly intermediate fuel IFO-180, also diesel). Several hundreds of oiled seabirds stranded along the Belgian coast.
(3) On 22 January 2003, the hull of the wreck got damaged during salvage operations and resulted in a major oil spill incident at sea. At least 200 m³ of (mainly) HFO escaped from the cracked and partially collapsing hull. The oil spill had a huge impact on wildlife. Because of periods of strong onshore winds, more than 18.000 seabirds stranded along the North-French, Belgian and Southwest-Dutch coastline. Along the Belgian coast 9.177 birds of 32 different species were collected (Haelters *et al.*, 2003).

Although further collisions or incidents were avoided in 2003, the surrounding coastal states were fully aware of the fact that oil spillages could not be avoided during the salvage operations. The wreck was to be cut in nine pieces, and each hull section hoisted on a pontoon and transported to the port of Zeebrugge (Belgium). During these cutting and hoisting operations, it was expected that the oil remaining in the wreck could escape into the sea. The total oil remaining in the wreck was estimated at ca. 200 m³ HFO, up to 20 m³ MDO, up to 10 m³ of lubes, and a couple of tons of automotive fuel (*i.e.* estimates from salvage consortium). In the weekend of 6-7 September 2003 a significant amount of oil escaped from the wreck due to intense cutting operations, and drifted towards and within the Belgian EEZ. The oil spill was spotted by Dutch authorities, who sent a dedicated oil pollution combating vessel on site, which recovered ca. 50 m³ of w/o emulsion in two days. The ‘Union Beaver’, a mechanical recovery vessel from the salvage consortium that was on continuous standby at the Tricolor wreck, also started recovery operations. Early on Monday 8 September, the Belgian and Dutch remote sensing aircraft observed a major oil pollution spread out in the Belgian EEZ, with a length of 40 km and an estimated volume of more than 100 m³. Later that day, the British and French remote sensing aircraft also spotted the oil spill, reporting however a drastic decrease in estimated volumes and dimensions. The aerial observers also reported the presence of debris and macro-algae floating in the oil slick. The next morning, when the Belgian aircraft was surveying the Belgian EEZ, the ‘major’ oil spill observed the day before had entirely disappeared from the sea surface. No immediate explanation could be found for this strange oil behaviour.

Although the major oil pollutio n of September 2003 had partly been combated and had disappeared from the surface, significant oil releases could still be expected during planned cutting and hoisting operations in week 38 (15-19 September 2003). The NEBAJEX exercise, which was originally planned off the Brittany coast that week, got cancelled. After agreement with CEDRE, SINTEF and the European Commission, and with the kind permission of the French Maritime Prefect, MUMM decided to hold the NEBAJEX exe rcise at the Tricolor site. This ‘adapted’ NEBAJEX exercise aimed at monitoring and evaluating oil pollution that would accidentally escape from the wreck during week 38. It was considered beneficial that an intense monitoring campaign for the purpose of NEBA could be performed in the light of the real Tricolor incide nt, because the weathering properties of the oils from the Tricolor were hardly known before the exercise. The three scientific institutes also hoped that useful information would be obtained that could explain the unusual behaviour of the oil spill the week before. The NEBAJEX exercise started on Monday 15 September and the oil pollution monitoring activities lasted till Thursday 18 September. At Thursday noon, the weather conditions got worse and the working limits for the exercise were exceeded, and the exercise was stopped.

2. Monitoring procedures, instruments and mathematical models

2.1. Initial characterisation of the oil

The impact of a spill, and the way it is most effectively combated, can vary a lot, depending on the type of oil that is spilt. An initial characterization of the original oil, or of ‘fresh’ oil that is sampled at the sea surface shortly after spillage, offers important information for a NEBA evaluation of an oil pollution incident. In order to characterize the type of oil, various physical and weathering properties of the oil can usefully be analyzed in a chemical lab. The obtained data lead to a better evaluation of the expected oil behaviour, the weathering and fate of the oil, its impact and its combatability at sea. They can also serve as an input for mathematical modelling purposes. Via CEDRE, a reference oil sample of one of the HFOs from the Tricolor (sample from the fuel tanks taken in the beginning of the incident), could be obtained for use in the NEBAJEX project. Table 1 gives an overview of the different physical and weathering properties that were analyzed in the specialized chemical labs, mentioning the instrument and/or method used.

2.2. Aerial monitoring of an oil spill and guidance

It is common knowledge that aerial surveillance is crucial for a good and rapid evaluation of a major oil spill, for the purpose of NEBA, and for assisting response operations. In a relatively short period of time, an aircraft can fly over large sea areas. The magnitude and combatability of spotted oil slicks can be rapidly evaluated by trained aerial observers. Dedicated remote sensing aircraft can track oil slicks day and night. Aircraft also play a very important role of guidance of combating units at sea, either recovery vessels or dispersant spraying vessels and aircraft. The NEBAJEX exercise has confirmed that an aircraft can usefully guide monitoring units towards or within a slick.

The Belgian remote sensing aircraft participated in the NEBAJEX exercise at the Tricolor site. This aircraft has several sensors on board, such as Side Looking Airborne Radar or SLAR, an Infrared (IR) sensor and a Ultraviolet (UV) sensor. In major oil spills, thicker slick parts and especially w/o emulsions can easily be detected with the IR sensor because these thicker parts are heated up by the sun and have a higher temperature, whereas thin, sheen-like slick parts have a lower temperature. With an IR sensor in the 'white hot' mode, w/o emulsions become visible as white spots on the IR screen Other instruments on board of the aircraft are a camera, a video-camera, a GPS, marine VHF, and a portable computer. The aircraft had to combine several monitoring and guidance tasks:

(1) Observation and documentation of the oil surface slick: location and dimensions of oil spill, oil appearances, coverage and form of slick(s), location and description of thicker parts within the slick(s).
(2) Observation and documentation of subsurface oil plume (of dispersed oil): location, form, appearance and dimensions (only if dispersants were to be used).
(3) Where needed, guidance of small workboats performing bulk sampling within and/or UVF measurements under the oil slick(s), or in oil plume of chemically dispersed oil.
(4) Guidance of dispersant spraying and/or mechanical recovery units (if response option initiated).

The most important information on the oil spill that is to be collected by the aircraft is summarized in Table 2 The new Bonn Agreement Oil Appearance Code (Bonn Agreement, 2003), used for oil volume estimations, is shown in Table 3.

2.3. Ground-truth monitoring of an oil spill

Via ground-truth monitoring at sea of the oil spill, real-time qualitative and quantitative data can be obtained which describe the changes of the weathering properties of the oil and enables a better understanding of the fate of the oil spill. Ground-truth monitoring can also lead to a better evaluation of the effectiveness of certain response techniques.

For the NEBAJEX exercise, it was decided that oil spills originating from the Tricolor had to be scientifically monitored according to the developed strategies, procedures and methods of the NEBAJEX pilot project. The Belgian oceanographic vessel 'Belgica' (a Belgian Navy vessel managed by MUMM) took on the role of central monitoring platform. A monitoring team of 12 scientists from the three participating institutes embarked on board of the research vessel. The Belgica transported two rigid inflatable boats (RIB), which were used on site as small workboats for monitoring tasks within the oil slick(s). At the Tricolor site, the French On Scene Commander (OSC) was informed of the exercise, as well as the salvage coordinator. The Belgian Navy agreed to keep a vessel with dispersant spraying capacity on standby in the port of Zeebrugge. The Navy vessel could be called upon by the Belgica if needed for the purpose of the exercise (cf. second exercise objective, see above) and/or for pollution combating as such. The ground-truth monitoring of oil slicks encountered during the NEBAJEX exercise consisted of two parts: surface monitoring and subsurface monitoring.

2.3.1. Surface monitoring

The monitoring of the surface oil started with bulk sampling of oil and water-in-oil emulsion (w/o emulsion) by means of a net and separation funnel. Film thickness measurements of slick parts thicker than 3 mm could be performed in real time with a specially designed cylinder. One RIB was dedicated to this task. On board the Belgica, the bulk sample was sub-sampled, and important parameters were analyzed to define the weathering properties and evaluate the combat method. Table 4 gives an overview of the properties measured in the field, the methods/instruments used, and the time needed to get analysis results.

2.3.2. Monitoring of the subsurface oil

The monitoring of the naturally dispersed oil droplets and dissolved oil components in the water column was performed using different Ultra Violet Fluorescence (UVF) instruments. A second RIB was dedicated to this task. Two types of UVF fluorimeters were used:
(1) a Turner UVF fluorimeter: a continuous flow-through Turner model 10 AU 005, used by CEDRE and SINTEF.
(2) an Aquatracka-MiniBAT system: an Aquatracka UVF fluorimeter attached to a miniaturized towed undulating platform, called MiniBAT. This UVF system had recently been purchased by MUMM and was to be tested during the exercise.

For this NEBAJEX exercise, UVF tracking was done with aerial guidance. The subsurface oil monitoring strategy was therefore simplified whereby only one track would be made through an oil slick, following the long axis of the slick downwards, while zigzagging around the axis (the latter only for the larger slicks). In this way, any subsurface oil would be monitored in one single track from the beginning to the end of the slick.

2.4. Mathematical models

Oil spill models are very powerful tools that are commonly used during oil pollution incidents at sea. Most operational oil spill models are models that can simulate the trajectory of the spilt oil over a period of a couple of days. CEDRE calls upon Météo France for oil spill trajectory simulations with the Mothy model, while MUMM uses its Mu-Slick and Mu-Slicklets model to simulate the trajectories of the spill. With its OSCAR model, SINTEF can also simulate the surface oil trajectory. The SINTEF Oil Weathering Model (OWM) relates oil properties to a chosen set of conditions such as oil/emulsion thickness, sea state and sea temperature, and predicts the rate in change of properties of oils and their behaviour at the sea surface (Aamo *et al.*, 1993). The input data are based on laboratory weathering studies of the oils. The validity of the predictions has in recent years been documented by correlation studies on field data from experimental oil spills (Daling *et al.*, 1999). The OSCAR model has been developed to supply a tool for objective analysis of alternative spill response strategies. OSCAR provides, for alternative spill response strategies, a basis for comprehensive, quantitative environmental impact assessments in the marine environment. The 3D model can calculate and record the distribution of the contaminant in time on the sea surface, along shorelines, in the water column and in sediments. The model facilitates linkages to a variety of standard and customized databases and tools allowing users to create or import time series, current fields, and grids of arbitrary spatial resolution, and to map and graph model outputs. Oil and chemical databases supply physico-chemical and toxicological parameters required by the model. Also the response action and its effectiveness can be modelled, based on information supplied by the user or from databases, and taking account of mobilisation times. Algorithms used to simulate the various processes controlling physical fates of substances are described in Aamo *et al.* (1993) and Reed *et al.* (1995; 2004). It should be noted however that the OSCAR model is continuously further developed, and that some algorithms may have been updated since these papers were published.

3. Results

3.1. Results from the initial characterisation of the oil

Apart from minor quantities of MDO, lubes, gasoil and gasoline, the Tricolor originally carried almost 2000 m³ of HFO, of which an estimated volume of 200 m³ remained in the wreck after the pumping operations. This HFO is in fact a sum of at least four different HFO oils. CEDRE disposed of a reference sample of one of the HFO oils (directly taken from one of the fuel tanks in the beginning of the incident), with sufficient oil volume to perform an initial characterisation. The analysis results of the most important physical properties of this Tricolor reference HFO, and its dispersibility, are shown in table 5. CEDRE already measured the viscosity and density of the one reference HFO before the exercise. The analyses at SINTEF were only performed after the exercise, due to the last minute decision to hold the NEBAJEX exercise at the Tricolor site. The initial characterisation results indicate that both density and viscosity are high for the initial (reference) HFO. At SINTEF, the viscosity of the Tricolor oil was measured at a shear rate of $10s^{-1}$ from 0 to 50°C. The obtained viscosity curve indicated that the intermediate fuel oil (IFO) grade of the one reference Tricolor oil is between 500 and 540 cSt. The density approached 0,99 g/ml. This confirms that the one reference Tricolor fuel is an extra heavy fuel oil (HFO) (Lewis, 2002; Dicks *et al.*, 2002). The reference HFO contained no water and the pour point was below 0°C. The dispersibility of this 'fresh' Tricolor HFO was tested with an IFP test using the dispersant Corexit 9500. The measured efficiency with the IFP test was high (approximately 80%). This indicates that chemical dispersion could have been effective if applied on 'fresh' HFO oil immediately after release. The potential of certain dispersants (such as Corexit 9500) for effectively dispersing HFO oils has been shown in systematic dispersibility studies and field trials at SINTEF (Daling, 1998).

3.2. Results from aerial monitoring and guidance

The oil spills originating from the Tricolor wreck during the exercise were monitored by a remote sensing aircraft. The observations and evaluation of the aerial monitoring are listed in table 6. The aircraft and the central monitoring platform 'Belgica' arrived at the Tricolor site on

Monday 15 September at noon. At that moment, the salvors were just finishing the hoisting of two sections of the Tricolor wreck on a large pontoon. It was most probably as a result of these lifting operations and the calm weather that day, that a combatable oil spill was observed with compact, thicker oil patches drifting at the sea surface. At ca. 14 local time (LT), a polluted area of 9 km long and 500 m wide was observed and documented by the aircraft, with low oil coverage. A minor part of the oil slick consisted of discontinuous true oil colour and water-in-oil (w/o) emulsion (4% and 1% of total oil coverage respectively). The observers made a distinction between true oil colours and w/o emulsion, because the latter seemed thicker, had a brighter, granular-like appearance, and consisted of a distinct patch or trail, with a sharp border towards other appearances such as 'metallic'. The w/o emulsions were detected by IR in a very unusual way: except for some small white dots, the visually observed w/o emulsion patches were seen as black patches on a 'white hot' IR image, indicating that the emulsions were not hotter than the surrounding water surface (as w/o emulsions usually are), but colder (see Figure 2). The order of magnitude of the oil volume of that slick was estimated at 1 to 10 m³. The Union Beaver started with a mechanical recovery of the slick, on the basis of the information obtained from the aircraft. The aerial observers reported that the oil slick seemed to change and disappear rapidly: some thicker parts of the slick seemed to become covered by a small water layer, as if the oil was floating just under the surface. At 16:30 LT, the aircraft flew a second time over the Tricolor area, and the observers found a very different square-like oil slick of 3 km long and 3 km wide, with a lot more patches and trails of discontinuous true oil colour spread over the entire slick. The w/o emulsion was described in the same way as earlier that day, and was again not detected by IR as white patches, indicating that the w/o emulsion was not heated by sunlight. They observed more w/o emulsion (5 % of the total oil coverage) than a couple of hours earlier. The oil observation was reported to the Belgica, the RIBs and the Union Beaver. The latter started again with recovery operations, with extra guidance from the aircraft. From Tuesday 16 September till Thursday 18 September, no further significant oil pollution was observed. This was mainly due to the fact that, although important cutting operations were planned that could lead to new oil releases, the salvage consortium encountered several technical difficulties that week and continuously had to postpone the cutting operations. The oil pollutions observed by the aircraft during the rest of the week were therefore of a minor order of magnitude (below 1 m³). The slicks consisted mainly of sheen and metallic appearances, with some sporadic traces of true oil colour. These slicks were too small to be combated, but there were small areas with oil/emulsion patches to perform bulk sampling of the oil and to continue ground-truth monitoring operations. At the last day of the exercise, on Thursday 18 September, the minor oil slick that was observed from the air in the morning disappeared rapidly when weather conditions got worse, with wind speeds increasing from 3-4 Bft in the morning to 6 Bft at noon.

Good communications between aircraft and RIBs, and good aerial guidance of the ground-truth monitoring teams were shown to be key elements for effective ground-truth oil pollution monitoring at sea. Both RIBs had a portable marine VHF on board. The first surface bulk sampling RIB was regularly guided by the aircraft to find the patches of thicker oil films. The second RIB, that performed subsurface oil monitoring, was also guided by the aircraft. In the latter case, the aircraft gave information on the location and dimensions of the slicks, and gave directions to the RIB to orient or correct its tracking.

3.3. Results from ground-truth monitoring

3.3.1. Surface oil monitoring

During the NEBAJEX exercise the surface oil sampling teams collected 14 bulk samples in the area for further analysis on board of the Belgica (code: *D1-TRIEX-xx*). The oil in these bulk samples varied from very viscous w/o emulsions, to mouldable, semi-solid oil lumps. Four bulk samples were also taken from two different tanks of the mechanical recovery vessel 'Union Beaver' (code: *UB-triex-xx*): two bulk samples (UB-triex-1 and UB-triex-2) were taken from a tank containing Tricolor HFO that was pumped out of the Tricolor in the beginning of the Tricolor incident in the winter of 2003; two other bulk samples (UB-triex-3 and UB-triex-4) were taken from a tank where oil was collected that was recovered at sea over the whole incident period. On board of the Belgica, a team of scientists was ready to receive the bulk samples, and to start with the real-time analysis of density, viscosity, water content, emulsion properties and dispersibility testing.

The analysis results obtained in real time on board of the Belgica are summarized in Table 7. SINTEF further determined the viscosity and water content of surface oil bulk samples after the exercise, in a specialised lab. These results are also added in table 7. Just a few measurements of viscosity and density could be performed in real time on board the Belgica. The ***viscosity*** of the surface samples exceeded the limits of both the Haake Rhotovisco VT550 (bob and cup) and the combined Anton Paar density/viscosity meter. A few samples were measured at sea temperature and some samples were measured at higher temperature. The obtained data were however very valuable for a better understanding of the oil behaviour and thus of its probable fate and impact (see below). The few ***density*** measurements that could be performed with the Anton Paar density meter were done on an oil sub-sample after water content extraction from the original w/o emulsion sample. The density measured at 19°C of water-free surface oil from one sample (D1-triex-1) was 1.017 g/ml. Only with one sub-sample of oil taken from the Union Beaver, UB-triex-1, the density could also be measured starting from the original w/o emulsion, without water separation. Because of the problems encountered in the field, the viscosity and density of some of the samples were measured at the SINTEF laboratory after the exercise. The lab results show that viscosity of the surface samples ranged from 110.000-4.000.000 mPas at sea temperature (19°C). The viscosity of the samples taken on board of the Union Beaver, of oil pumped from the wreck in the winter of 2003 and of oil recovered from the sea surface during past salvage operations, had lower viscosity and density values due the lower degree of weathering. The ***water content*** of the samples was measured in the field by use of the emulsion breaker Alcopol O 60 %. The water content of the surface samples ranged from 30-50 vol.%. Also oil samples coming from the Union Beaver were measured in the field. The obtained results were 6 to 17 vol. %. The water content measured by Karl Fisher titration in the SINTEF lab after the exercise was in the order of 50 vol. % for surface oil samples, and 50 to 65 vol. % for oil samples from the Union Beaver. These differences between field and lab results show that breaking of emulsion by use of Alcopol O 60 % was not effective. In other words, the Alcopol O 60% method for water content analysis in the field can become unreliable for heavy bunker fuel spills and highly viscous, asphalthenic crude oils. The few ***emulsion stability*** and ***emulsion breaker effect*** tests illustrated that the surface w/o emulsions were very stable. The ***dispersibility*** tests showed that the w/o emulsions sampled at the sea surface were not chemically dispersible with Dasic NS, nor with Corexit 9500. Only the UB-triex-1 oil sample, coming from the Union Beaver, showed a slight or reduced dispersibility with Corexit 9500. Finally, interesting information was obtained from some visible and/or qualitative aspects of the sampled oil. Some oil samples contained a considerable amount of organic matter and fine mud particles; some others contained air-filled, berry-like vesicles of Japweed (*Sargassum muticum*; macroalgae). Some contained mud tubes of small, colonizing crustaceans of the genus *Jassa* (Isopoda), whereas others contained living crustaceans of the genus *Idotea* (Amphipoda) (pers.comm. F.Kerckhof, MUMM).

3.3.2. Subsurface oil monitoring

A second RIB dedicated to subsurface oil monitoring, was on turn equipped with two Turner UVF instruments or with the Aquatracka-MiniBAT UVF system. Several UVF tracks were performed under the oil slicks observed that week. With the Aquatracka-MiniBAT UVF system several test tracks were performed at 2-10 m depth. Minor fluorescence peaks were observed over a very short period on Monday 15 September, under the thickest parts of the major oil slick that afternoon, after guidance from the aircraft. After calibration of the instrument with Tricolor HFO, the concentration values deduced from these UVF peaks amounted to max. 78 ppb. These concentration figures however have a high degree of uncertainty, because (1) the instrument is still in a testing phase, (2) no validation samples were taken during this short period of peak measurements and (3) the calibration in lab was performed with dissolved oil only, whereas subsurface oil at sea consists not only of dissolved oil components but also of dispersed oil droplets. The fluorescence measured by the Turner UVF instruments at two different depths (at 1 and 5 meter) on the following days could not confirm the intial Aquatracka measurements. The Turner UVFs showed no significant variations from background levels, even below thicker, true oil colour parts of the slicks. The very low, hardly detectable concentrations of dispersed or dissolved oil in the water column were confirmed by GC-MS analysis of several water samples taken at sea to validate the UVF measurements. Natural dispersion of oil depends on factors as film thickness, viscosity of oil and w/o emulsions, interfacial tension and presence of breaking waves. Heavy fuel oils normally have a high viscosity and thicker layers of oil on the sea surface, resulting in a very low natural dispersion rate.

3.4. Oil spill model results

The oil spill trajectory simulations performed in real time during the exercise, and of which two examples are shown in Figure 3, all indicated that, taking into account the small volumes involved, the observed oil spills were never a direct threat for the more sensitive coastlines of the Dover Strait and the adjacent southern North Sea area. Due to the low wind speeds that week, the slicks remained in the vicinity of the Tricolor before submerging, hereby drifting in an ellipsoid movement, mainly under influence of the local tidal currents.

Normally the results from the real-time monitoring of the surface oil spill, together with data on other oil types earlier tested at the SINTEF laboratory are used to predict the weathering properties of the specific oil type with the OWM model from SINTEF. For the NEBAJEX exercise however the oil samples collected at the sea surface near the Tricolor were most probably a mixture of different types of HFO, with an unknown time and degree of weathering. The uncertainty of the predictions of weathering properties, on the basis of the analysis results from the complex oily mixture samples and initial characterization data of only one reference HFO, would be too high. As an example, the collected w/o emulsion samples have therefore been plotted against predictions of viscosity of the Prestige oil at 19°C (see Figure 4). The reference heavy fuel oil from the Tricolor has a lower initial viscosity than the Prestige oil, but measured viscosities on some of the most weathered samples are higher than the viscosities predicted for the Prestige oil after 20 days of weathering. This comparative simulation indicates that the oil sampled in the immediate vicinity of the Tricolor during the exercise was probably already weathered to a large extent before it escaped from the wreck.

4. Discussion and conclusions

4.1. Evaluation of monitoring procedures, instruments and models used

Aerial monitoring by trained observers on board a remote sensing aircraft remains essential to make a rapid evaluation of a large oil spill floating at the sea surface: information is rapidly obtained on the location and spreading of the spill, its forms, its thicker, combatable parts, presence of w/o emulsions, the spill dimensions, a first estimation of the oil volume, and the weather conditions. This information is vital for an impact and response evaluation, and is valuable as input for mathematical models. The information obtained by aerial monitoring however remains predominantly qualitative, and only limited information is obtained about the weathering degree, dispersibility and threat of the oil. Information from aerial monitoring should therefore ideally be combined with (semi-)quantitative information on the type of oil and its behaviour, obtained through different analyses performed in lab or in the field, and through mathematical modelling. It has also been demonstrated that good communications between aerial and ground-truth monitoring teams is crucial for a successful ground-truth monitoring.

An initial characterization of the original or freshly spilt oil in the beginning of an incident by a specialized laboratory leads to a better understanding of the oil type, the probable effectiveness of response techniques, and the probable impact of a spill. This is especially important in case the various properties of the spilt oil are unknown, which is the case for most refined petroleum products such as intermediate and heavy fuel oils. However, making an evaluation of the weathering, evolution and behaviour of the oil at sea for the purpose of NEBA remains relatively uncertain, even with the most powerful mathematical models. With a real-time, ground-truth monitoring of the spilt oil at the sea surface and in the water column, and where several important physical and weathering properties are analyzed in the field, valuable quantitative or semi-quantitative information can be collected on important weathering properties such as water content, emulsion properties, changes in viscosity and density, dispersion, and dispersibility of the oil. These data are directly useful for NEBA evaluation and decision-making. Of all the ground-truth monitoring methods and instruments used and tested, it was learned that highly viscous oils can pose serious problems to analytical instruments such as the Haake Rotovisco for viscosity measurements, the Anton Paar density meter, and the Alcopol O 60% for water content measurements. The Paar Physica Rheometer and Karl Fischer Titration proved to be more effective for viscosity and water content measurements of the highly viscous w/o emulsions.

For this exercise, the involved research institutes used their available analytical instruments and standardized methods. Further research could be invested in the development and validation of a field test kit for use in field monitoring operations during a major oil pollution incident. In the late 1970's, Fina developed a first Oil Spill Test Kit. This 'Fina' kit could measure 11 oil properties, but the measurements lacked accuracy because rough (non-standardized) empirical methods were used. In the 1990's, Environment Canada developed their own Portable Field Kit, using modern portable instruments and standardized methods for various properties measurements such as density, viscosity, water content and flash point (Lambert *et al.* 1991; Lambert *et al.* 1994). Further research could start by reconsidering and re-evaluating these kits in the light of the NEBAJEX exercise findings with very viscous HFO oils.

4.2. Evaluation of results

Analysis results show that the surface oil that was observed and sampled during the NEBAJEX exercise in the immediate vicinity from the Tricolor wreck was highly viscous, forming stable w/o emulsions, had a high water content, a density close to that of seawater and a very low natural dispersion rate. The drifting w/o emulsions were not detected as white but as black patches by the IR sensor on board of the remote sensing aircraft, indicating that the emulsions were not heated up, but were colder than the surface water. When comparing the viscosity of the Tricolor emulsions to the HFO from the Prestige, it was found that the Tricolor emulsions had a very high viscosity as if the oil had been drifting at sea for weeks, which was not the case. Moreover, the w/o emulsions sampled near the Tricolor had a high organic matter content and mud tubes of colonizing amphipods were observed at the surface of the stable, semi-solid w/o emulsions. Finally, the oil spill observed from the air had a higher estimated volume several hours after the end of hoisting operations of two major hull parts on the first day of the exercise, than immediately after the hoisting operations. These monitoring results suggest that the oil escaping from the wreck, which was in fact a complex mixture of several HFO oils, was most probably already weathered to a significant degree before it got released. This is not surprising, due to the fact that the wreck was severely damaged and part of it was directly affected by the waves, and the marine areas around the wreck are characterised by strong tidal currents (maxima in the order of 1 m/s) and a relatively high suspended particular matter load (average SPM of 10-20 mg/l in winter season (Van den Eynde *et al.*, 2004)) compared to deeper offshore areas. Stable, highly viscous and dense w/o emulsions were most probably already formed within the severely damaged and collapsing wreck. As a result of this, the total oil pollution volume that was remaining in the wreck in September was probably significantly higher than estimated by the salvage consortium, due to w/o emulsion forming inside the wreck. When the oil got released during salvage operations, it is supposed that it only slowly mounted towards the sea surface, while drifting away from the wreck by tidal currents. This result also explains why the Union Beaver, the recovery vessel that was on continuous standby in the immediate vicinity of the Tricolor, couldn't observe thicker patches and trails of oil originating from the wreck and only appearing several kilometers further in the direction of the current.

Because of the high density and weathering degree of the oil at the surface, and due to small wave actions and turbulence, it is plausible that the surface oil could submerge for some time. This could also explain the disappearing of an oil spill observed at the sea surface the week before the exercise, with an estimated volume of more than 100 m³. It remains difficult however to explain why the large oil spills observed that month changed and disappeared so drastically, or why the thicker oil patches did not resurface later. Scientists from the ground-truth monitoring teams described the thicker oil parts around the Tricolor as wax-like continuous patches with sharp edges, but with rather thin film thicknesses for w/o emulsions - although the patches also contained thicker emulsion parts and oil lumps. The lack of a better description of these complex oil patches hampers a better understanding of the behaviour of the sub-surface oil.

The ground-truth monitoring results obtained in real time showed that the w/o emulsions were no longer dispersible, and were so viscous that only recovery means that could deal with highly viscous emulsions would still be effective. Oil spill trajectory simulations indicated that the sensitive coastlines of the southern North Sea were under immediate threat by the observed oil slicks, due to the calm weather conditions. However, because the w/o emulsions were very stable and persistent, they could easily drift in the water column over a very long period before sinking or stranding ashore and polluting a coastline. Therefore, the monitoring team immediately informed the Union Beaver about the combatable oil patches and trails on Monday 15 September 2003 and requested to start recovery operations guided by the remote sensing aircraft, before the oil slick would become too fragmented or would disappear from the surface.

Scientific institutes such as CEDRE and SINTEF dispose of a large dataset of oil properties of various oil types. These oil properties datasets are very useful in support of NEBA in case of a major release of one of these oil types in the marine environment. The characteristics of crude oils are better documented than those of refined products such as intermediate and heavy fuel oils. The NEBAJEX exercise has shown that in case a coastal state has to respond to a marine pollution incident with a major release of an unknown oil types (such as HFO oils), valuable extra information can be obtained quite rapidly on the oil behaviour and combatability at sea, through a strategic monitoring and modelling effort. This has been demonstrated for the Tricolor incident for the period of September 2003, with spills consisting of highly viscous, complex mixtures of (mainly) HFO oils. Valuable information was not only obtained via aerial monitoring of oil spills, but also from different analyses of important oil properties obtained in real-time in the field or performed in a specialized lab, and from oil spill trajectory and oil weathering models. Several oil spill assessment steps were successfully tested in this project: the initial characterization of a reference oil sample in a specialized lab, the real-time monitoring at sea of the behaviour, weathering and fate of the spilt oil, and the dispersibility of the oil. The collected results were highly useful for a better understanding of the oil behaviour and for ongoing NEBA evaluations during the Tricolor incident.

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Tables and Figures

Table 1: overview of physical and weathering properties of oil measured in lab, the method or instrument used, and the institute performing the analysis for NEBAJEX.

Parameter	Instrument/method	Lab performing analysis
Viscosity	Haake Rotovisco VT550 Paar Physica Rheometer	CEDRE SINTEF
Density	Anton Paar density meter	SINTEF, CEDRE
Pour point	ASTM method D97-65	SINTEF
Water content	Karl Fischer Titration	SINTEF
Dispersibility	IFP Test	SINTEF

Table 2: overview of oil spill parameters that were obtained in real-time with the Belgian remote sensing aircraft during the NEBAJEX exercise.

Parameter	Instrument/method
Location	GPS
Dimensions of polluted area (length – width)	Visual evaluation, SLAR and UV sensor
Coverage percentage of oil in polluted area	Visual evaluation
Estimated oil volume (order of magnitude)	Bonn Agreement Oil Appearance Code (BAOAC)
Thicker parts of slick	Visual evaluation, IR sensor
Presence of w/o emulsions	Visual evaluation, IR sensor
Form (shape) of slick	Visual evaluation
Combatability	Visual evaluation, of thicker parts of slick + weather conditions, for recovery operations.
Weather conditions	Visual evaluation (Bft)

Table 3: Bonn Agreement Oil Appearance Code, as accepted in BONN Contracting Parties meeting of 2003 (Bonn Agreement, 2003).

Code	Description	Layer thickness interval (µm)	Volume per km² (in litres or m³)
1	Sheen (silvery-grey)	0.04 – 0.30	40-300 litres
2	Rainbow	0.30 – 5.0	0.3 - 5 m³
3	Metallic	5.0 – 50	5 - 50 m³
4	Discontinuous true oil colour	50 – 200	50 – 200 m³
5	Continuous true oil colour	200 – more than 200	200 m³ – more than 200 m³

Table 4: Overview of physical, weathering and response effectiveness properties of the oil or w/o emulsion measured in real-time at sea during the exercise, the method or instrument used and the analysis time.

Parameter	Instrument or method	Analysis time
Viscosity	Haake Rotovisco VT550	15 min.; *but during exercise much more time-consuming or almost impossible because the viscosity of the w/o emulsion was outside the measuring range of the instrument at real sea temperature.*
Density	Anton Paar SVM 3000 Stabinger viscosimeter	< 15 min.; *but during exercise more time-consuming or almost impossible. The density meter was not designed for such highly viscous emulsions.*
Water content	Alcopol O 60% + heating	2 hours
w/o emulsion stability	Measuring free water separated from emulsion after period of time	First results: 30' Final results: 24 h *A first indication on the stability can already be obtained in 2 min. via the emulsion breaker effectiveness test.**
Film thickness (>3mm) of oil or w/o emuls. slick	Oil film thickness cylinder SINTEF	Instantaneous reading (*was not used during exercise, due to minor volumes and strongly fragmented slicks*)
Chemical dispersibility	Small field test (Concawe, 1988)	5 min.
Effectiveness of emulsion breaker	Alcopol O 60%	First results: 2' * Final results: 24 h

Table 5: Results from characterisation of physical properties and dispersibility of reference oil in lab.

Physical properties	Value	Lab which performed analysis
Viscosity *(shear rate 10 s^{-1})*	23.000 mPas at 10°C 6.500 mPas at 20°C 11.000 mPas at 19°C[1]	CEDRE SINTEF
Density	0,985 g/ml at 10°C 0,984 g/ml at 20°C 0,989 g/ml at 15,5°C[2]	CEDRE SINTEF
Water content	0 %	SINTEF
Pour point	< 0°C	SINTEF
Dispersibility *(ratio 1:20, at 20°C, using Corexit 9500)*	80%, high	SINTEF

[1] Viscosity was measured by SINTEF after the exercise at 19°C, because this was the sea temperature at the time of the exercise.
[2] Density was measured at 15,5°C (ASTM standard).

Table 6: Aerial monitoring results obtained during NEBAJEX exercise.

Parameter	**1st observation 15 September 03**	**2nd observation 15 September 03**	**Observation 16 September 03**
Time (LT)	13:57	16:30	09:30
Location slick (Begin-End)	51°22.0'N 002°10.0'E till 51°18.2'N 002°07.4'E	51°18.5'N 002°09.5'E till 51°19.5'N 002°11.4' E	from Tricolor wreck till 51°26.2'N 002°03.7'E
Length	9 km	3 km	15 km
Width	0.5 km (20m at begin, 500m at end)	3 km	10 km
Coverage %	10 %	30%	Very low, widespread
Est. volume	< 10 m^3	Between 10 and 50 m^3	< 1 m^3
Thicker parts	true oil colour + w/o emulsion, at: - 51°19.0'N 002°08.0'E - 51°21.0'N 002°11.2'E - 51°20.6'N 002°10.8'E	More patches and trails of true oil colour + w/o emulsion	Trail of 3 km on 50m, with < 1% true oil colour, till 51°26.8'N 002°19.0'E (NE part of slick)
w/o emulsion	Detected in 1 % of slick	Detected in 5 % of slick	Not detected
Form of slick	Fragmented, but changing and disappearing rapidly	Square, with fragmented thicker patches	Small oil trails
Combatable	Yes	Yes	No
Weather cond.	1 Bft, N wind, sunny	2 Bft, NW wind, sunny	2 Bft, NW wind, sunny
Parameter	**1st Observation 17 September 03**	**2nd Observation 17 September 03**	**Observation 18 September 03**
Time, LT	09:55	16:10	09:57
Location slick	From Tricolor wreck till 51°23.5'N 002°13.0'E	Spreading from Tricolor wreck in east-west axis	From Tricolor wreck in NE direction
Length	(small trail)	2 km	3 km
Width	(-)	20 m	20 m
Coverage %	(-)	(-)	(-)
Est. volume	<<< 1 m^3	<<< 1 m^3	<<< 1 m^3
Thicker parts	No (mostly sheen, some metallic, sporadically true oil colour)	No (mostly sheen, some metallic)	No (mostly sheen, some metallic, few true oil colour patches close to wreck)
w/o emulsion	Not detected	Not detected	Not detected
Form of slick	Small trail	Small trail	Small trail
Combatable	No	No	No
Weather cond.	2 Bft, SW wind, sunny	2 Bft, W-SW wind, sunny	3 to 4 Bft, SW wind, low clouds

Table 7: Analysis results of several important oil properties, obtained in real-time in the field, or later in the SINTEF laboratory. In a.: density, viscosity and water content; in b. emulsion stability, emulsion breaking and dispersibility.

a.

Sample	Real-time analysis results obtained at sea				SINTEF lab results	
	Density[3] (g/ml)	Viscosity, Haake Rhotovisco VT550 (mPas [4], 10-s^{-1})	Temp (°C)	Water content Alcopol O 60% (vol.%)	Water content, Karl Ficher titration (vol. %)	Viscosity, Physica rheometer (mPas, 10s^{-1})
D1-triex-1	1.017	np	19	39	-	-
D1-triex-5	np	np	19	52	-	-
D1-triex-9	np	89.900	40	33	-	-
D1-triex-12	np	np		-	50	110.000
D1-triex-13	np	np	19	44	-	-
D1-triex-14	np	np	19	-	-	>1.000.000
D1-triex-15	np	np	19	-	-	4.000.000
D1-triex-16	np	np	19	31	-	-
D2-triex-FL	np	np	19	-	50	700.000
UB-triex-1	1.003	np	10	6	-	-
	(0.977)[5]	24.000	19			
UB-triex-2	np	np	19	-	50	27.200
UB-triex-3	1.011	44.500	19	17	-	-
UB-triex-4	np	np	19	-	65	49.400

b.

Sample	Real-time analysis results obtained at sea												
	Emulsion Stability (%)				Effect of emulsion breaker (%)			Dispersability test Dasic NS Field test			Dispersability test Corexit 9500 Field test		
	30'	1h	4h	24h	2'	1h	24h	good	red.	bad	good	red.	bad
D1-triex-9	0	0	6	19	0	0	24			XX			XX
D1-triex-13	26	32	35	47	0	12	35			XX			XX
D1-triex-16	0	0	12	19	0	0	26			XX			XX
UB-triex-1	0 after 24 h				0 after 24 h				X	X	X	X	

[3] 'np' = not possible for density measurements because oil was too viscous.
[4] 'np' = not possible for viscosity measurements because oil was too viscous.
[5] Density measured of w/o emulsion (without water extraction), after heating to 60°C.

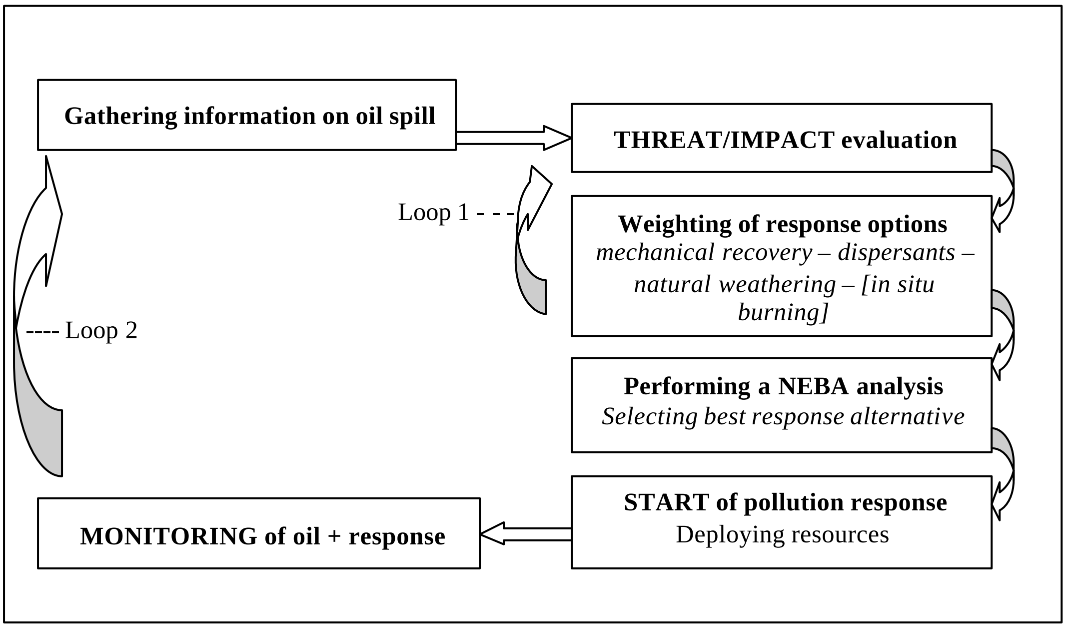
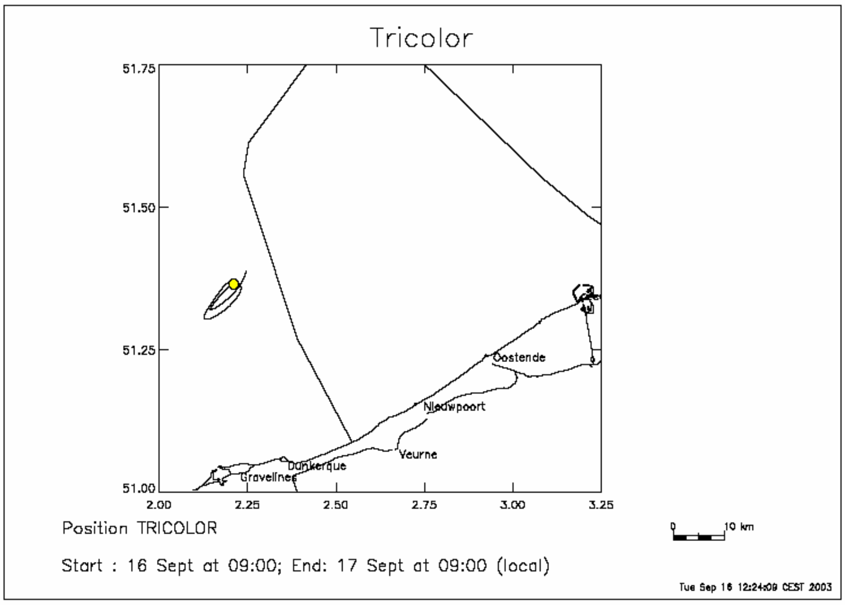
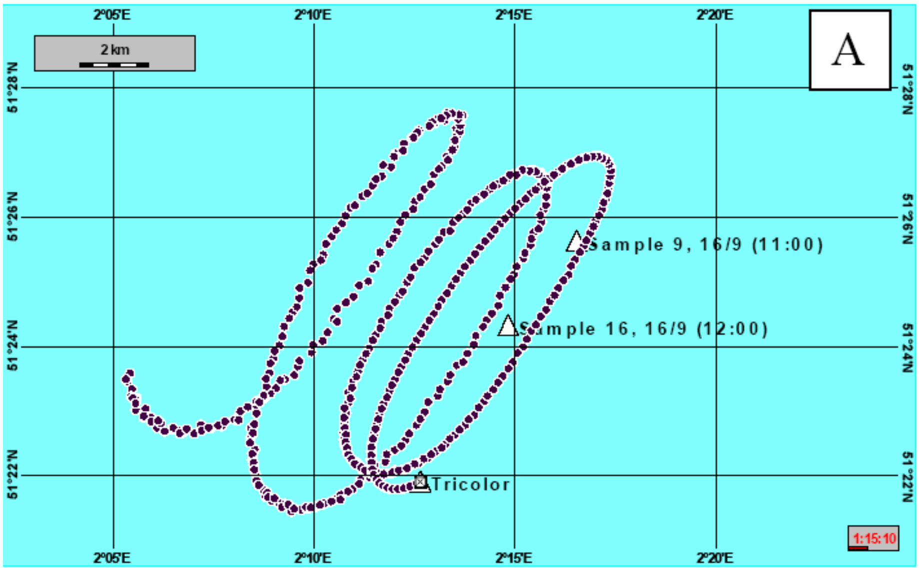


Figure 1: NEBA evaluation and decision-making scheme.

Figure 2: Infra Red (IR) sensor image of 'Tricolor' oil pollution observed on 15.09.03 (time in UTC), with w/o emulsions clearly visible as black patches, with the IR sensor in 'white hot' mode (photo MUMM).



a.



b.

Figure 3: Examples of oil spill trajectory simulations made in real time during NEBAJEX exercise: a. Mu-SLICK trajectory simulation (MUMM) on 15 Sept. 03; b. OSCAR trajectory simulation (SINTEF) on 16 Sept. 03 (Singsaas, 2004).

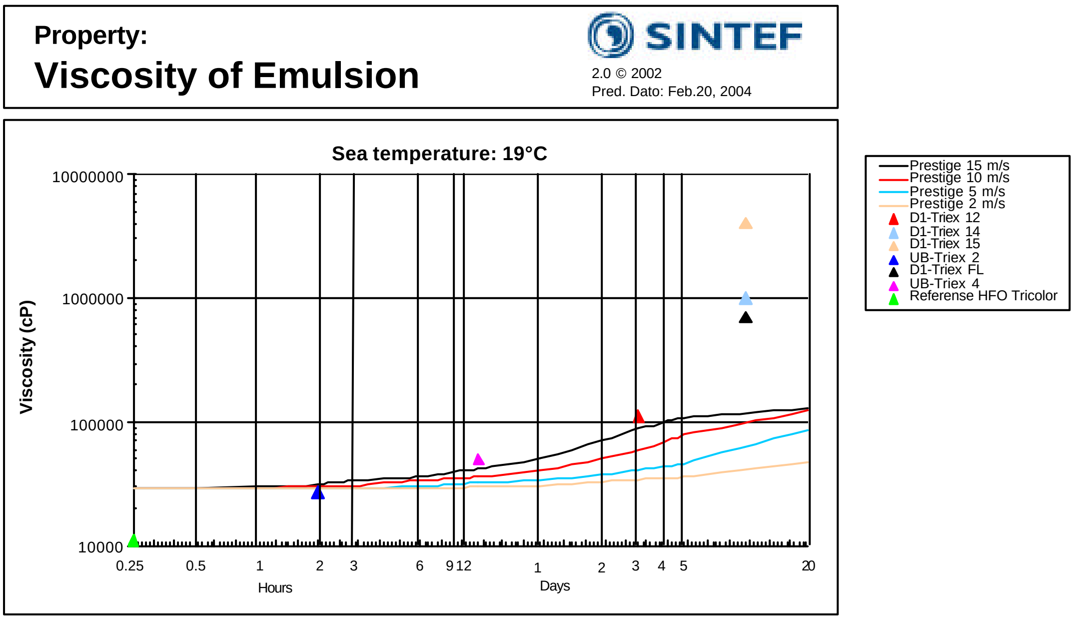


Figure 4: SINTEF OWM simulation of viscosity of w/o emulsion of Tricolor samples compared to Prestige oil at sea temperature of 19°C. (initial/terminal oil film thickness 20 mm/2mm; release rate: 1.33 MT/min).