The Development and Use of the Bonn Agreement Oil Appearance Code (BAOAC)

Alun Lewis, Oil Spill Consultant
121 Laleham Road
Staines, TW18 2EG, United Kingdom

1. INTRODUCTION

Visual observation of spilled oil on the sea surface continues to be the most important technique currently available for estimating the amount of spilled oil. Detecting, locating and measuring the area of spilled oil at sea can be achieved with a high degree of accuracy by the use of the appropriate remote sensing technique; satellite SAR (Synthetic Aperture Radar) or SLAR (Side-Looking Airborne Radar) in aircraft to detect and locate spilled oil, UV (Ultra-Violet) to accurately measure the area of spilled oil and thermal IR (Infra-Red) to estimate areas of relative oil thickness. However, these remote sensing techniques cannot answer the question “How much spilled oil is there on the sea?” Visual observation remains the primary method for estimating spilled oil layer thickness and, combined with a measurement of the different areas visible within an oil slick, the quantity of spilled oil.

2. FROM BA COLOUR CODE TO BA OIL APPEARANCE CODE

Over the years, several different organisations around the world have devised their own “colour codes” that relate colour to the thickness of spilled oil. In 1993, the Bonn Agreement (BA) was using the version of the BA Colour Code shown in Table 1.

BA Code	Approximate thickness (µm)	Approximate volume (m^3/km^2)	Appearance / Colour
1	0.02	0.02	Silvery
2	0.1	0.1	Grey
3	0.3	0.3	Rainbow
4	1.0	1	Blue
5	5.0	5	Blue/brown
6	15-25	15-25	Brown/black
7	>100	>100	Dark brown/black
	see note		Brown/orange mousse

Note: A brown/orange mousse shows the presence of water-in-oil emulsion. While the thickness is usually 1-4 mm, it may be even higher. The percentage of oil in the emulsion can only be assessed with samples. The presence of mousse, however, shows a very high quantity of oil which would, in the case of discharges dealt with in this Manual, correspond to an exceptionally large discharge.

Table 1. 1993 Bonn Agreement Colour Code

Observers in the surveillance aircraft found the the BA Colour Code difficult to use in several respects. Some of the Colour Codes were difficult to distinguish from each other ("Brown/black" and "Dark brown/black") and the "blue" colour was in two other categories ("Blue" and "Blue/brown"). Oils of different types that may be spilled at sea have many colours, from transparent through orange to brown and black, but are never blue and the use of this classification was difficult to justify. In 1997, the BA Working Group on Operational, Technical and Scientific Questions Concerning Counter Pollution Activities (OTSOPA) decided that the BA Colour Code needed to be revised and refined. SINTEF in Trondheim, Norway undertook the project.

2.1 Theory of oil film thickness and colour

The first stage was to review the literature and the theory of the effect of oil on a water surface on the appearance. The literature review revealed that most of the original work had been conducted in the USA (House of Representatives, 1930 and Hornstein 1972 and 1973), in Europe in the past (Wardley Smith, 1969) in more recent times (Rijkswaterstaat, 1992). Subsequent references referred to the earlier work and little original work has been conducted.

Very thin oil films

Below approximately 0.04 µm thickness oil films at sea are invisible, even in perfect viewing conditions. There is not enough oil present to affect the appearance of the sea surface. In less favourable viewing conditions, or in the presence of substantial waves, even thicker oil films cannot be reliably detected by the human eye. The very thin films of oil reflect the incoming white light slightly more effectively than the surrounding water (Figure 1) and will therefore be observed as a silvery or grey sheen.

Figure 1. Light reflection from very thin oil films

The rainbow region

Thicker oil films have the appearance of colours of the rainbow; yellow, pink, purple, green, blue, red, copper and orange; this is caused by constructive and destructive interference between different wavelengths (colours) that make up white light. When white light illuminates a thin film of oil, it is reflected from both the surfaces of the oil and of the water. Constructive interference occurs when the light that is reflected from the lower (oil / water) surface combines with the light that is reflected from the upper (oil / air) surface. If the light waves reinforce each other the colours will be present and brighter (Figure 2).

Figure 2. Constructive Interference

During destructive interference the light waves cancel each other out and the intensity of the apparent colour is reduced in the reflected light and appears darker (Figure 3).

Figure 3. Destructive Interference

Oil films with thicknesses near the wavelength of different coloured light (blue, 400nm or 0.4 µm, through to red, 700nm or 0.7µm) will exhibit the most distinct rainbow effect, but there can be harmonic effects that cause the effect to be observed, with reduced intensity, with oil layers that are thicker and thinner than this range. All oils in films of this thickness range will show a similar tendency to produce the 'rainbow' effect.

Thicker oil layers

With thicker oil layers, the reflection of light from the oil/water surface is reduced and the reflection of light from the oil/air interface begins to be the dominant effect. The true colour of the oil (black, brown or some other colour) will not necessarily be obvious because the oil may have insufficient optical density and be partially transparent at these thicknesses. The rainbow effect cause by interference is much reduced, but the appearance of the oil in this region cannot be described as a general colour. Some of the light will pass through the oil and be reflected off the water surface. The oil will therefore act as a filter to the light (Figure 4).

Figure 4. Reflection from oil/air interface with reduced contribution from oil/water interface

Thickest oil layers
For the thickest oil films the light is being reflected solely from the oil surface with no contribution from reflection from the sea surface (Figure 5). No information about the oil layer thickness will be available from visual observation and the colour will be the true colour of the oil.

Figure 5. Reflection solely from the oil/air interface

2.2 Laboratory investigation

The next stage of the investigation was to carry out a series of carefully controlled experiments in the laboratory to determine the actual oil layer thicknesses that caused the different effects described above. Ten oils (several crude oils, a condensate, MGO (Marine Gas Oil), two residual IFO (Intermediate Fuel Oil) grade fuel oils and simulated bilge and slop mixtures) were used. Quantities of these oils were placed on seawater contained in trays to produce oil films of seven average known oil thicknesses; 0.5, 1, 5, 10, 50, 100 and 200 µm. These oil layers were then photographed with a variety of background colours. Pad samples were taken to measure the precise thickness in different regions of the trays and these were related to the colour, or appearance, of the oil in the photograph. An example of the type of results obtained is shown in Figure 6.

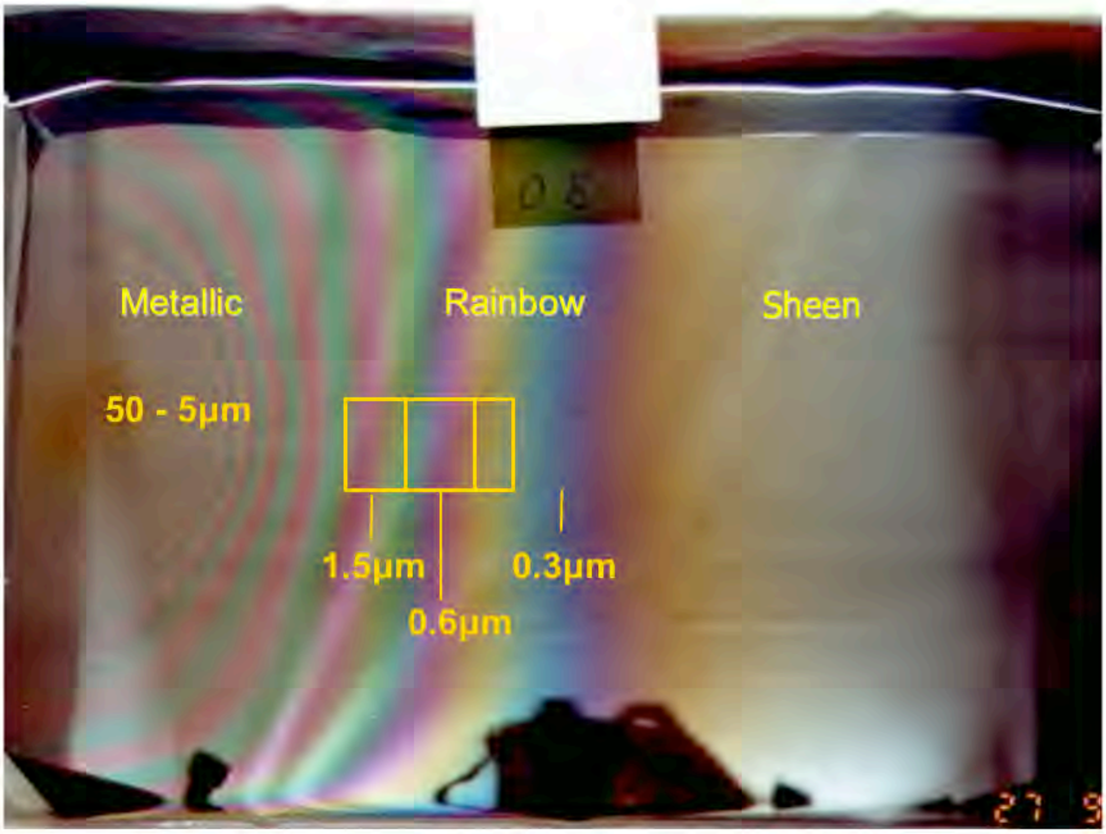

Figure 6. Oil appearance and oil layer thickness

The main findings from this study were that:

- The theoretical limit for visual observation of an oil film on water was confirmed; an oil layer 0.05 µm thick was the minimum thickness that could be observed in laboratory conditions. The BA colour Code 1 ("Silvery", 0.02 µm) was not supported.
- The effects observed for BA Colour Codes below Code 5 ("blue/brown", 5 µm) were found to be independent of oil type, but for Colour Code 5 and above the colour observed depended on the oil type.
- The rainbow effect occurred over a wider range of oil thickness than theory would suggest. All oil layers of 0.5 µm and 1 µm thickness caused this effect and it was evident at 5 µm, although less pronounced, compared to the 0.2 to 1.5 µm range suggested by theory.
- The apparent blue colours of BA Colour Codes 4 and 5 were found to be reflections of background colours. While the blue colour would be observed under conditions with a blue sky, the effect of a grey sky would cause a grey contribution. It was found that the actual colours photographed were those of the background as if reflected in a metallic mirror; brassy, coppery or golden hues were apparent, rather than a true colour. This effect, after discussion within the BA OTSOPA, was designated "Metallic".

2.3 Fjord studies

In order to validate the findings from the laboratory study, a series of experiments were undertaken in boomed areas on a fjord in Muruvik, Norway (Figure 7).

Figure 7. Oil layer thickness experiments in Muruvik, Norway

Pad samples were taken at various locations within the oil to establish the precise thickness and these were correlated with the appearance in photographs. These experiments confirmed the new oil appearance / oil layer thickness ranges in the evolving Bonn Agreement Oil Appearance Code (BAOAC). The appearance oil films thicker that 50 µm is complicated because the many oils do not spread as a layer of even thickness. Instead, the oil spreads as thicker individual patches within a layer of thinner oil. This effect can be seen in Figure 8. In area A in the photograph the majority of the area is covered with patches of thicker oil, while in area B only a minority of the area is covered with thicker patches.

The ability to distinguish the thicker patches of oil from the background layer of thinner oil is a function of their size, the colour contrast, the visual acuity of the observer and depends on the distance of the observer form the oil. A person with good vision ("20/20 vision" in the USA and "6/6 vision" in Europe) is just able to decipher a black letter on a white background (in standard eye test conditions) that subtends a visual angle of *5* minutes of arc at the eye (there are 60' of arc in 1 degree). The further away an observer is from an object, the bigger an object must be for it to be distinguished from the background. This effect is of obvious importance to the observation of spilled oil at sea, since visual observation from aircraft at altitudes of 1000' is routinely undertaken. Even observers with perfect eyesight would be incapable of discriminating patches of thicker oil that were less than 1 metre across from these altitudes.

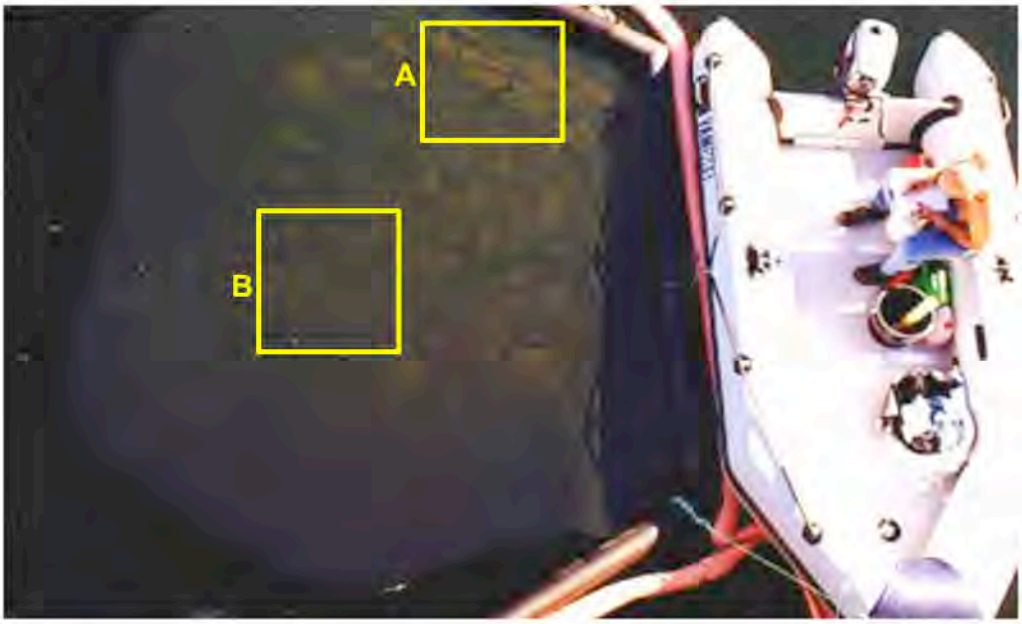

Figure 8. Patches of thicker oil ('true' oil colour) in a layer of thinner oil.

2.4 Assessing the BAOAC at experiments at sea

The opportunity was taken to use experiments being conducted at sea for other purposes to assess the applicability of the now-developing BAOAC (Table 2).

Code	Description Appearance	Layer Thickness Interval (μm)	Litres per km^2
1	Sheen (silvery/grey)	0.04 to 0.30	40 – 300
2	Rainbow	0.30 to 5.0	300 – 5000
3	Metallic	5.0 to 50	5000 – 50,000
4	Discontinuous True Oil Colour	50 to 200	50,000 – 200,000
5	Continuous True Oil Colour	200 to More than 200	200,000 – More than 200,000

Table 2. The Bonn Agreement Oil Appearance Code

DeepSpill Experiments, Norwegian Sea, June 2000
The objective of the work was to validate the BAOAC in comparison to the then existing Bonn Agreement Colour Code. However, this objective was only partially met because of the very poor observation conditions that prevailed. From the limited observations that were made, it was concluded that the BAOAC did provide a much more accurate estimate of total slick volume than the previous BA Colour Code, within the range for which the BAOAC has been calibrated i.e. slick thickness up to 200 microns thickness, but had limitations is assessing very thick oil layers.

BONNEX 2002
Three oil slicks, each of 3 m^3 and with two of IFO-30 fuel oil (one point release and one released as a strip across the wind) and one of MDO (Marine Diesel Oil) were used as targets for observation. The two oils and two different methods of oil release were used to provide oil slicks with a wide variety of oil layer thickness. The point release of 3m^3 of IFO-30 is shown in Figure 9.

Figure 9. Slick of 3m^3 of IFO-30 at BONNEX 2002

Sampling boats took samples and thickness measurements of the oil slick at various locations and these were correlated with the visual appearance as recorded in photographs. The analysis of the results indicated that using the BAOAC produced spilled volume estimates that were reasonably close to the actual spill volumes. Because of the oils used, the methods of oil release and the prevailing weather and sea conditions, the BAOAC Codes most often observed were Sheen, Rainbow and Metallic. There were some over- and under-estimates and these inaccuracies were principally due to inaccurate estimations of the total area of the slick and the areas of different appearance within the oil slicks.

NOFO 2006 Oil on Water Exercise
The object of participation in the NOFO 2006 Oil-on-Water Exercise was to validate or improve Codes 4 and 5 of BAOAC. However, the poor visibility and low cloud at the exercise allowed only a very limited set of observations. The limited amount of work that was conducted did not unambiguously validate the oil thickness intervals for Discontinuous True Colour (Code 4, 50 to 200 μm) and Continuous True Colour (Code 5, greater than 200 μm). In particular, the distinction between Codes 4 and 5 was not visible from the surveillance aircraft, but Code 4 – Discontinuous True Colour - was visible from the sampling boats as small patches of thicker oil only a few centimetres across (Figure 10).

The inability of the observers to distinguish these patches is not surprising for the reasons given above; any observer in an aircraft is simply too far away to see these small oil patches.

Figure 10. Discontinuous True Colour (Code 4, 50 to 200 μm) as observed from a sampling boat

3. THE USE OF THE BAOAC

The BAOAC is a tool to be used by trained observers in surveillance aircraft to estimate spilled oil volumes. Within the limitations imposed by the physical phenomena that cause oil layers of varying thickness to appear different and the capabilities of human vision, it is as accurate tool as it can be using visual observation to estimate the quantity of spilled oil on the sea surface. The BAOAC is superior to the previously used BA Colour Code and other colour codes because:

- It is in accordance with scientific literature and previously published scientific papers,
- The theoretical basis is supported by small-scale laboratory experiments,
- It is supported by mid-scale outdoor experiments,
- It is supported by the results obtained in large-scale experiments at sea trials.

The individual Codes can be, and have been, recognised as such by trained observers in aircraft (Figures 11 and 12). The differences between Sheen (Code 1), Rainbow (Code 2) and Metallic (Code 3) can be reliably discriminated. Continuous True Colour (Code 5) can be black, brown or other colours depending on the type of spilled oil and is obvious to observers, although Code 4, Discontinuous True Colour, can be difficult to recognise.

Figure 11 Aerial photograph of BAOAC Codes 1 to 3

Figure 12 Aerial photograph of BAOAC Code 5

Although the BAOAC has been developed solely on the basis of visual appearance, the BAOAC should not be used in isolation when other sensors are available.

The BA Aerial Surveillance Handbook stresses the need for post-flight analysis. As described in Part 3; Guidelines for Oil Pollution Detection, Investigation and Post Flight Analysis / Evaluation, of the Bonn Agreement Aerial Surveillance handbook (available on www.bonnagreement.org) the information collected from the use of the BAOAC should be integrated with information from SLAR that is used to detect oil on the sea surface and, if available, accurate area measurement taken from a UV image. Thermal IR images are useful in confirming whether thick oil layers are present in an oil slick. These can be used to confirm observations of Code 5 – Continuous True Colour – areas, since these areas will contain a very high proportion of the spilled oil volume.

Use of the BAOAC to estimate spilled oil volume on the sea surface involves:

1. Estimating the total area of oil on the sea surface (by visual estimates and photographs or more accurately by using measurements of a SLAR image for larger oil slicks, or of a UV camera image for smaller oil slicks). When determining the oiled area coverage it is essential to remember that the main body of an oil slick may have 'areas' of clear water, especially near the trailing edge of the slick.

2. The ‘oiled’ area should be sub-divided into areas that relate to a specific oil appearance according to the BAOAC. Great care should be taken in the allocation of coverage to appearance, particularly the appearances that relate to higher thicknesses.

3. The areas of the oil slick for each of the different BAOAC Codes are calculated and the estimated volumes, both minimum (using the lower thickness limit for each BAOAC Code) and maximum (using the upper thickness limit for each BAOAC Code) are calculated for each BAOAC Code. These are then totalised to produce two estimates of spilled oil volume:
    - A maximum volume.
    - A minimum volume.

These two estimates are an inevitable result of the fact that the different appearance of an oil layer does not occur at an individual discrete thickness, but the different appearances change from one to another as the thickness increases. The previously used BA Colour Code would have had the same feature, but it had been simplified by taking the average oil layer thickness to be representative of the BA Colour Code. Although the use of a minimum and maximum spilled volume estimate adds some complexity to the calculations it also adds certainty to the estimates produced. The minimum spilled oil volume estimate is the minimum volume of oil that could be present, while the maximum oil volume estimate is the maximum volume of oil that could be present. The ‘truth’, the actual volume of oil present, lies somewhere in between but cannot be more precisely determined.

As stated in the Bonn Agreement Aerial Surveillance Handbook Part 3, Oil Pollution Detection, Investigation and Analysis, Section 9: Oil Volume Estimate Usage:

- “It is suggested that in general terms the <u>maximum quantity</u> should be used together with other essential information such as location <u>to determine any required response action</u>.
- It is suggested that the <u>minimum volume</u> estimate should be used <u>for legal purposes</u>.

The logic for this is the need for a ‘burden of proof’ in legal cases. The minimum spilled oil volume used for legal purposes, such as in support of a prosecution for illegal discharge of oil at sea, is the minimum amount of oil that could possibly be present. In all probability, the oil volume would be substantially greater, but it is certain that at least the volume of oil reported would have been present. The requirement is not the same for oil spill response purposes. A ‘best estimate’ is required and this should err on the ‘worst case’ side of the argument. The maximum spilled oil volume therefore represents the maximum amount that could be present and that would possibly require active oil spill response measures.

3.1 The need for training in the use of the BAOAC

As with any tool, the operator (or observer) requires training and practice to use the BAOAC most effectively. The routine surveillance flights carried out by aircraft of the Bonn Agreement regularly detect illegal oil discharges. Some countries have recently introduced a ‘sliding-scale’ of fines based on discharged oil volume. BAOAC Codes 1 to 3, the most validated of the Codes with the least uncertainty, are the Codes most likely to be involved in the observation of illegally discharged oil. It is therefore important that the observers in the aircraft are adept in the use of the BAOAC to ensure a justified and successful prosecution using their evidence. The BA aircraft observers and crews have much less experience of larger oil spills where BAOAC Codes 4 and 5 would be used, for the very good reason that such incidents are rare and, according to the statistics, are becoming even less frequent. The opportunity to observe a larger oil spill by an individual crew or observer is therefore becoming less likely. It is therefore important that crews get the opportunity to practice the use of the BAOAC at exercises involving oil on the sea and that they receive regular training on the use of the BAOAC.

4. CONCLUSIONS

The work that has been conducted over the past 12 years shows that the BAOAC, as shown below, is a valid way of relating the appearance of the oil on the sea surface to the thickness of the oil layer and thus calculating the spilled oil volume.

Code	Description Appearance	Layer Thickness Interval (μm)	Litres per km^2
1	Sheen (silvery/grey)	0.04 to 0.30	40 – 300
2	Rainbow	0.30 to 5.0	300 – 5000
3	Metallic	5.0 to 50	5000 – 50,000
4	Discontinuous True Oil Colour	50 to 200	50,000 – 200,000
5	Continuous True Oil Colour	200 to More than 200	200,000 – More than 200,000

It has been found that the BAOAC is most accurate in providing volume estimates where only Codes 1, 2 and 3 are observed, and this is most often the case for suspected illegal discharges. The use of the minimum estimated spill volumes for such cases provides a source of scientifically, and practically, justified evidence.

The general validity of Codes 4 and 5 has been demonstrated at sea, although inclement weather at several exercises has frustrated attempts to provide full validation of Codes 4 and 5. Nevertheless, on the basis of all the experimentation conducted, the thickness minima and maxima for these Codes are valid, although the observation of Code 4 from aircraft is inevitably limited by the limitations of human eyesight.

The BAOAC has now been accepted for use by the Contracting Parties of the Bonn Agreement and by HELCOM (Helsinki Commission).

Acknowledgements

The Contracting Parties of the Bonn Agreement OTSOPA funded the work described in this paper as a series of several projects conducted over many years. The author would like to thank Mr Sjon Huisman of Rijkswaterstaat North Sea for his encouragement and commitment to this topic over this time. The author acknowledges the cooperation and contribution of Mr Per Daling and others at SINTEF and Mr David 'Perry' Mason on the technical and practical aspects of aerial surveillance. And a further thank you to all the crews (past and present) of the BA surveillance aircraft who took part in the exercises and sea-trials that were used to validate the BAOAC (when the weather permitted this to be done).

References

All of the documentation referred to in this paper regarding the development of the BAOAC can be found on the Bonn Agreement web-site at www.bonnagreement.org

Hornstein, B. 1972. The Appearance and Visibility of Thin Oil Films on Water, Environmental Protection Agency, Office of Research and Monitoring, Edison Water Quality Research Laboratory, Edison, New Jersey. Report No. EPA-R2-72-039, September 1972.

Hornstein, B. 1973. The Visibility of Oil-Water Discharges, Proceedings of Joint Conference on Prevention and Control of Oil Spills, American Petroleum Institute, Washington D.C. USA pp 91-99. 1973.

Rijkswaterstaat, 1992. VISIBILITY LIMITS OF OIL DISCHARGES - Investigation into the visibility limits of operational oil discharges from ships. Rijkswaterstaat, North Sea Direcorate, in co-operation with the Directorate-General of Shipping and maritime Affairs. The Netherlands, July 1992.

US House of Representatives, 1930. Report on Oil Pollution Experiments - Behaviour of Fuel Oil on the Surface of the Sea. Hearings before the Committee on Rivers and Harbors, House of Representatives, 71st Congress, 2nd Session, on H.R. 10625, Part 1., 41-49, May 2nd, 3rd and 26th 1930.

Wardley-Smith J. and F. Shuttleworth 1969. Tests taken to establish the Life of oil Slicks. Warren Spring Laboratory Report no. LR 104(E1). Ministry of Technology, London UK. 1969