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DETERMINATION OF
THE LIMITING OIL VISCOSITY
FOR
CHEMICAL DISPERSION AT SEA

(MCA Project MSA 10/9/180)

**Final report for the DEFRA, ITOPF, MCA and OSRL
by
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EXECUTIVE SUMMARY

The ability to disperse spilled oils at sea depends on several factors, including oil properties, prevailing sea-state and the treatment rate of oil spill dispersant applied to the oil.

Oil spill dispersants function by allowing a high proportion of the spilled oil volume to be converted by cresting wave action into very small oil droplets that are permanently dispersed. Oil spill dispersants do this because the surfactants that they contain are capable of causing a very large decrease in the oil / water interfacial tension (IFT). IFT (or surface free energy) is caused by the dissimilarity between the polar nature of the molecules of water and the non-polar nature of the hydrocarbon molecules of oil.

There is a marked effect of oil viscosity. In the case of low viscosity oils, it is the IFT that provides the main barrier to dispersion and the application of dispersants can overcome this barrier. The dispersant-enhanced dispersion then proceeds much more rapidly, and to a greater extent, than natural dispersion. In the case of higher viscosity oils, such as HFOs (Heavy Fuel Oils) and highly weathered crude oils, the high viscosity exhibited by the oil, or the emulsified oil, is the major barrier than must be overcome by the dispersant, if the oil is to be dispersed. The high viscosity of a fuel oil or an emulsified crude oil can prevent dispersion in two ways:

(i)   The high viscosity of the oil may prevent the dispersant from penetrating into the oil before it is washed off and away into the sea by wave action. Dispersants are only effective if the surfactants that they contain can contact the oil / water interface from within the oil.

(ii)   The oil may exhibit a high enough viscosity, or is accompanied by an elastic component, that makes the oil capable of physically resisting the disruptive shearing forces caused by a breaking or cresting wave. Instead of forming oil droplets, the spilled oil layer is temporarily distorted and deformed, but subsequently retains its coherent form. This is, to some extent, sea-state dependent; rougher seas with more frequent and more intense breaking waves are more capable of creating oil droplets than calmer seas.

These two effects are often congruent and it has not been possible to say which is more dominant. The practical effect is to create a limiting oil viscosity for effective dispersion. This is of operational significance to oil spill responders since it imposes a limitation of the use of dispersants as an effective oil spill response method.

Attempts to correlate results with laboratory testing of oil spill dispersants with performance at sea have been difficult because of the inherent limitations of laboratory test methods; none of then can ever be said to be an accurate simulation of the mixing conditions at sea. In addition, the wave conditions at sea vary over an enormous range from flat calm to severe storms and, although a particular lab test method might simulate some aspect of some sea condition, it has not proved possible to correlate any lab test to any particular sea-state.

The work described in this report was a 'return to the basics' of using dispersants; an attempt to use a matrix of oil viscosity, dispersant brand, dispersant treatment rate and

prevailing sea conditions to provide information on the limiting oil viscosity of dispersion by using a very simple method of visual observation to determine whether dispersion was or was not occurring.

The main findings – under the conditions of testing which were a sea temperature of 15ºC, producing oil viscosities of 2,000 cP (IFO-180 grade fuel oil) and 7,000 cP (IFO-380 grade fuel oil) and waves associated with wind speeds of between 7 and 14 knots – were that:

- The IFO-180 fuel oil appeared to be totally and rapidly dispersed by Corexit 9500 used at a nominal DOR of 1:25 at 12 knots wind speed. Superdispersant 25 and Agma Superconcentrate DR 379 appeared to be somewhat less effective, but still caused moderate dispersion when use at a nominal DOR of 1:25. At lower wind speeds of 7 to 8 knots, Corexit 9500 at a nominal DOR of 1:25 was seen to be less effective, but still appeared to cause moderately rapid dispersion of IFO-180.

- The IFO-380 fuel oil did not appear to be rapidly and totally dispersed by any of the three dispersants when used at any of the treatments rates, ranging from nominal DORs of 1:25 to 1:100 at wind speeds of 7 to 9 knots. At wind speeds of 13 - 14 knots, the performance of both Superdispersant 25 and Corexit 9500 at a DOR of 1:25 improved to produce moderately rapid dispersion of IFO-380. The performance of Agma Superconcentrate DR 379 was less than that of the other two dispersants, but was not tested at the highest wind speeds.

Other findings are contained within the main report.

Comparison of the results from the sea-trials with results obtained using the WSL test method (the efficacy test used for the approval of dispersants in the UK) showed that a high level of visible dispersion was only achieved at sea by those combinations of test oil, dispersant brand and dispersant treatment rate that produced over 80% WSL results and that moderate visible performance was achieved by combinations that produced over 60% WSL results. These WSL result 'thresholds' are applicable to wind speeds of between 7 and 14 knots.

The report concludes that some oil spill dispersants will be an effective response to oils with viscosity of 2,000 cP, but will not be effective on oils with a viscosity of 7,000 cP or more, in waves associated with wind speeds of 7 to 14 knots. The precise limiting viscosity between 2,000 and 7,000 cP is not known. The limiting viscosity will increase with wind speed; it is possible that oil with a viscosity of 7,000 cP will disperse at 20 or more knots wind speed. However, it was not possible to test this at sea.

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1. REASONS FOR THE WORK

Many studies of oil spill dispersant effectiveness have been conducted around the world using a variety of laboratory test methods in recent years. The results from these laboratory tests indicate that the viscosity of spilled oil, together with several other factors, influence the effectiveness of oil spill dispersants. Higher viscosity oils are generally more difficult to disperse than lower viscosity oils.

The relationship between dispersant effectiveness and oil viscosity is not linear. There appears to be a narrow range of viscosity value which, when exceeded, prevents dispersants from being effective. However, this limiting oil viscosity varies with different test methods. While, it is reasonable to suppose that different laboratory test methods represent, to some degree, different sea states, this cannot be proven since no laboratory test method is an accurate simulation of the complex mixing processes that occur at sea. Several correlations between laboratory test results and dispersant performance at sea have been suggested, but none have been universally accepted.

The results from laboratory test methods give good <u>relative</u> results; the effect of different dispersant treatment rates and differences between the effectiveness achieved on various oils by different brands of oil spill dispersants appear to be significant. However, the results from laboratory test methods cannot be translated in an <u>absolute</u> way to likely performance of dispersants on spilled oil at sea. This is a major disadvantage when using the available information to plan for the operational use of oil spill dispersants.

2. DISPERSION OF SPILLED OIL AT SEA

The overall effect of successful dispersant use is to cause much more rapid dispersion of the entire slick of spilled oil than would be the case without dispersant addition. The dispersant-treated oil slick will therefore be dispersed much more quickly than an untreated oil slick. In the right circumstances, provided that the overall consequences are favourable, the use of dispersants can be a very useful oil spill response technique.

2.1 THE DISPERSION PROCESS

Dispersion of oil involves several sub-processes:

(i) The conversion of some, or all, of the volume of oil in a slick into oil droplets with a wide range of sizes by breaking or cresting wave action.

(ii) The distribution of these droplets, according to their size (buoyancy), into:

- Large oil droplets that resurface almost immediately to reform the oil slick.
- Small oil droplets that are only temporarily dispersed and which will resurface slowly to either reform the original oil slick or form sheen.
- Very small oil droplets that will be permanently dispersed.

The buoyancy of all sizes of oil droplets causes the oil droplets to float, but the mixing action of the sea, which is not constant and is sea-state dependent, can prevent the smallest oil droplets with low rising velocities from reaching the sea surface.

(iii) Horizontal and vertical dispersion of the smallest oil droplets in the water column in the ambient mixing zone beneath any wave action. This leads to rapid dilution of the dispersed oil concentration in the water column.

2.1.1 Initial phase of dispersion – creation of oil droplets

The initial phase of any dispersion (natural dispersion - without the addition of dispersants, or enhanced dispersion caused by the addition of dispersants) is the conversion of some of the volume of the slick of spilled oil into oil droplets of various sizes.

Dispersion does not proceed at an equal rate throughout the area of an oil slick. The initial phase of dispersion proceeds most rapidly in small localised areas of the slick that are exposed to breaking, or cresting, waves. The cresting waves will break up the oil slick in a localised area, disrupting the oil layer into 'streamers' or 'strands' of oil of a wide range of sizes. This produces areas of 'oil-free', or clean, water surface and the water tumbles through the oil slick for a short period of time over a limited distance as the cresting wave passes through the oil.

Some types of high-viscosity spilled oils, such as Heavy Fuel Oils (HFOs) are only broken into relatively large 'streamers' that possess enough cohesiveness to contract into large oil globules as the cresting wave passes through. These may be temporarily submerged to a shallow depth during the passage of the cresting wave, but most of the

oil will be in the form of globules that possess enough buoyancy to rapidly resurface, spread out and reform the oil slick.

Significant dispersion will not occur if the spilled oil possesses flow properties that can resist the shearing forces of the breaking or cresting waves so that small oil droplets are not formed. The intensity of the shearing forces will be related to the intensity of the turbulence in individual breaking or cresting waves and to the frequency with which these waves occur.

2.1.2 Dispersion or resurfacing of oil droplets

If the initial stage of dispersion does proceed and oil droplets of various sizes are formed, their subsequent fate is strongly influences by their size. The buoyancy, or rising velocity, of an oil droplet depends on its size (diameter) and the oil density in accordance with Stokes' Law:

$$\Delta h/t = \frac{D^2(\rho_w - \rho_o)g}{18\eta_w}$$

where;

Δh	=	settling path height for particle diameter D (cm)
t	=	settling time (sec)
ρ_w	=	aqueous phase density (gm/cm^3)
ρ_o	=	oil phase density (gm/cm^3)
η_w	=	aqueous phase viscosity (poise) 1 cP = 0.01 poise
g	=	acceleration of gravity = 981 cm/sec^2

All oil droplets will possess positive buoyancy, but the smaller oil droplets will be less buoyant and have much lower rising velocities than larger droplets. The rising velocity of an oil droplet needs to overcome any downward motion in the water column if the droplet is to rise to the sea surface. There is obviously no overall downward motion of water in the sea; the water in a wave moves up and down, but there is no net movement of water upward or downward and there is no horizontal movement of water. However, there are localised events that impart a temporary downward motion in the water.

Oil droplets of all the various sizes that are created by the action of the cresting wave will be propelled a short distance into the water column by the intense mixing action of the cresting wave. This initial downward movement of water ceases after the cresting wave moves through the localised area. The oil droplets will then begin to float back to the sea surface. The largest oil droplets will rapidly resurface and reform the oil slick.

The up and down motion of water of non-breaking waves creates circular movements that diminish with depth. This creates a well-mixed zone beneath the waves. The upward and downward motion of water in a wave balances out over time, but in the shorter term there is significant water movement that can overcome the low rising velocities of small oil droplets and carry them from near the surface into this well-mixed zone of water. Some oil droplets will possess sufficiently high rising velocities to eventually float free of the well- mixed zone and resurface under the original slick or elsewhere to form sheen on the sea surface.

A very small proportion of the oil volume may be converted by the cresting wave action into very small oil droplets that will be initially submerged by the cresting wave action, but that possess insufficient buoyancy to float free of the mixing zone that exists below any wave action. Very small oil droplets with very low rising velocities will be repeatedly re-submerged as wave action continues and these will be small enough to be retained permanently in suspension (i.e. are permanently dispersed) by the low level of ambient turbulence present beneath non-breaking waves

The precise size (diameter) of the oil droplets that can be considered to be permanently dispersed will depend on their rising velocity (and therefore density) and the combination of breaking, cresting and non-breaking waves that contribute to vertical water movement. This can best be summarised as the prevailing sea-state.

Measurements of dispersed oil droplet size distributions (naturally dispersed and enhanced dispersion caused by the uses of dispersants) at sea in moderate sea states have shown that the volume median diameter (VMD) is around 50 to 100 microns. These values were established for a relatively narrow range of oils and sea states.

Oil droplet rise velocity
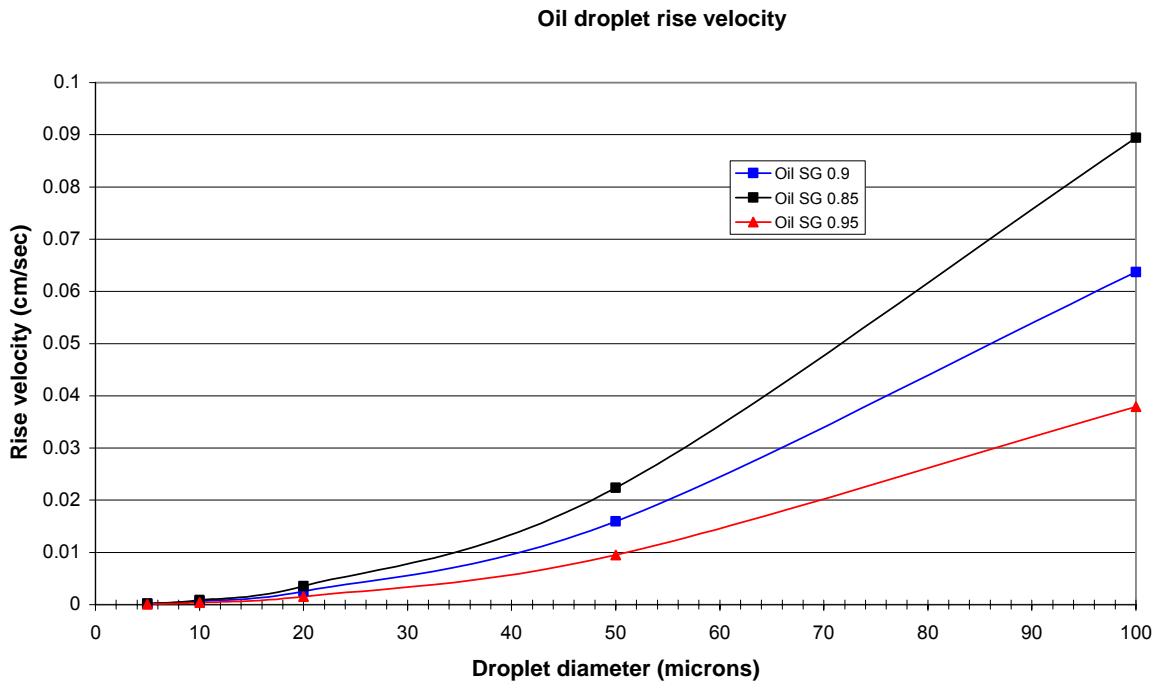
Figure 1.   Oil droplet rise velocities as function of size and density

Calculation of the Stokes' Law rise velocities (Figure 1) indicates that the rise velocity of the average oil droplet needs to be less than approximately 0.05 cm/sec for the oil droplet to be permanently dispersed in moderate sea conditions. This equates to an oil droplet diameter of 70 microns for an oil of density of 0.85, but diameters of 85 microns or 120 microns for oils with densities of 0.90 and 0.95 respectively.

Rougher sea-states will be more capable of creating smaller oil droplets of higher viscosity oils and of keeping larger oil droplets of less dense oils permanently dispersed than calmer sea states.

2.1.3 Subsequent dilution of oil droplets

An essential part of the dispersion process at sea is the subsequent vertical and horizontal dispersion of the oil droplets.

This is essential to reduce the dispersed oil concentration down to low levels that cause little, if any, effects on marine organisms. Dilution of the dispersed oil droplets also permits rapid biodegradation.

Significant coalescence of dispersed oil droplets will not occur at low dispersed oil concentrations because the individual oil droplets are far from each other Figure 2.

Mean distance between dispersed oil droplets
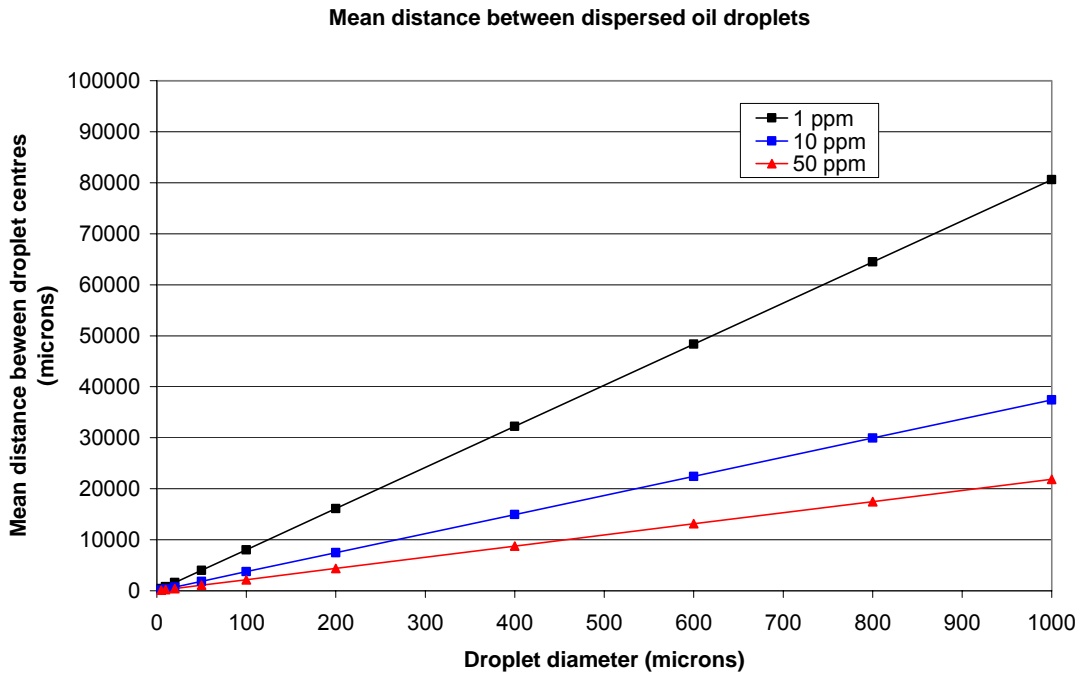
Figure 2.   Distances between dispersed oil droplets

2.2   THE EFFECT OF OIL SPILL DISPERSANTS

The oil properties resisting the initial stage of dispersion (the creation of oil droplets) are the viscosity (or more correctly the rheological properties) of the spilled oil and the interfacial tension (IFT) between the oil and seawater.

2.2.1   Effect of dispersant on spilled oil flow properties

Viscosity is the resistance to flow exhibited by a fluid. Higher viscosity oils such as HFOs exhibit a greater resistance to flow than lower viscosity oils such as freshly spilled crude oils. Many high viscosity oils exhibit non-Newtonian flow behaviour; the apparent viscosity varies with applied shear rate. Some high viscosity oils also have an elastic component to their flow behaviour; they can partially recover their original form if exposed to brief periods of distortion. A high viscosity oil can therefore be deformed by a breaking or cresting wave, but recovers to reform a large oil globule without the creation of small oil droplets.

Oil spill dispersants are blends of surfactants in solvents. Dispersants will readily mix into low viscosity oils. This will not produce a great change in the viscosity of a low viscosity oil, since the viscosity of the oil and the dispersant are similar.

Dispersants are of relatively low viscosity, compared to HFOs. The addition of the recommended treatment rates of modern oil spill dispersants, typically 2% to 4% by volume or DORs (Dispersant to Oil Ratios) of 1:50 or 1:25, would produce a marked reduction in the viscosity of an HFO, provided that the dispersant were well mixed into the oil. However, the likelihood of the relatively low viscosity dispersant being thoroughly mixed into very high viscosity oils, such as an HFO at sea temperature, after it has been sprayed onto the oil surface is not high. Although the mix of glycol and hydrocarbon solvents in some dispersants will help the dispersant to soak into the oil, there is still the possibility that the dispersant will be washed off of the spilled oil before it has thoroughly mixed into the oil. The dispersant would then have no, or very little, effect on the viscosity of the HFO.

2.2.3   Effect of dispersant on the oil / water IFT

The active ingredients in oil spill dispersants are surfactants. The function of the surfactants is to cause a very large reduction in the IFT between the spilled oil and seawater. A drastic reduction in the oil / water IFT will permit the shearing action of breaking or cresting waves to create many more oil droplets with a much smaller size distribution. A much greater proportion of the oil volume will be converted into very small oil droplets that will be permanently dispersed.

The addition of dispersant provides only the <u>potential</u> for rapid oil dispersion; the addition of energy from a cresting wave is needed for rapid dispersion to actually occur.

The surfactants in dispersants must reach the oil / water interface before they cause a very significant reduction in oil /water IFT. If the dispersant is washed off of the oil before the surfactants have soaked in, then there will be little effect from dispersant spraying of the oil.

2.3   MEASURING DISPERSANT EFFECTIVENESS IN THE LABORATORY

The effectiveness, or efficacy, of oil spill dispersants is often determined by laboratory test methods. These tests may be conducted for regulatory purposes to ensure that a dispersant meets a minimum level of efficacy with a specified test oil, or as part of a study of other parameters, such as oil 'weathering', temperature or salinity.

All laboratory test methods involve adding dispersant at the required treatment rate to a test oil placed on seawater and then subjecting the mixture to some form of agitation or mixing. The proportion of the test oil that was dispersed, <u>under the conditions of the test method</u>, is then determined by a variety of methods and this has become known as a measure of the effectiveness of the dispersant.

2.3.1   The WSL test method used in the UK

In the UK, all dispersants have to achieve a 'pass mark' of 60% efficacy in the WSL (Warren Spring Laboratory) rotating flask method before they can be approved by DEFRA.

The WSL rotating flask method uses MFO (Medium Fuel Oil) with a viscosity of 2000 cP at the test temperature of 10ºC. The test method involves adding 0.2 ml dispersant to 5 ml oil on 250 ml of seawater in a flask that is allowed to stand for one minute and is then rotated end-over-end at 30 rpm for 2 minutes. The flask and contents are allowed to stand for 1 minute and then 50 mls of the water containing some of the dispersed oil is run out. The oil is extracted with solvent, dried and then the amount of oil is measured using a colourimeter, by comparison with standard solutions.

The efficacy, or effectiveness, result is expressed as a percentage; 100% indicates total dispersion and 0% indicates no dispersion. A result of 100% indicates that the 50 ml of water run off would have contained 1 ml of oil in dispersion. This would mean that all of the oil had been converted into very small droplets so that none would have floated free of the sampling zone during the one-minute standing period. A result of 0% means that no oil was found in the sample of water and that no significant dispersion had occurred in the test. An intermediate result between 0 and 100% indicates that, although all of the oil may have been dispersed into the water during the mixing process, some of the oil would only have been converted to larger oil droplets with sufficient buoyancy to float clear of the sampling zone before the 50 ml water sample was run off.

The 60% 'pass mark', or any other value obtained in the WSL (Warren Spring Laboratory) test method, is a relative value used to compare the performance of dispersants. It does not indicate that only 60% of MFO at 10ºC treated with dispersant will disperse at sea.

The significance of the result obtained in the WSL test (or other laboratory test methods) has been the subject of much discussion and some speculation. It has been suggested that a result of 15% in the WSL method is an indicator that dispersion will proceed at sea at a reasonable rate. However, the evidence for this is not conclusive.

2.3.2 What is being simulated in the WSL test method ?

The WSL test method has some elements that are a broad simulation of the dispersion process at sea, but other elements that have been incorporated to reduce the variability in results that are produced. The basic elements are:

(i)   The dispersant is added to the oil and is allowed to soak into the oil during the one minute initial static period. This may represent a period of time before breaking or cresting wave action impinges on oil at sea. At sea, there is no standard period of time before the dispersant-treated oil is broken up and over-washed by a cresting wave. The practical reason in the WSL method is that as the flask rotates in an end-over-end fashion, there must be a discrete time before the flask is stoppered and the rotation can begin.

(ii)   The end-over-end rotation at 30 rpm for 2 minutes in the WSL flask creates a very rapid series of 60 miniature 'plunging breaker' wave actions as the air and water are displaced as the flask rotates. The 5 ml of test oil becomes thoroughly mixed into the 250 ml of synthetic seawater during this process. This is a relatively high-energy process.

(iii)   After 2 minutes of end-over-end rotation the motion of the flask is stopped, but the momentum of the water continues to cause circulation of the dispersed oil droplets for some time after the rotation has stopped. The one-minute period of standing at the end of the test method is intended to allow the largest oil droplets to float free of the sampling zone. These are thought to be representative of those that would be retained in dispersion at sea in a moderate sea-state.

Size of oil droplets sampled in the WSL test method

Only the oil droplets that are retained within the bottom 50 ml of the 255 ml of oil and water mixture in the flask are sampled, the largest oil droplets are allowed to float out of the sampling zone during the 1 minute standing period.

Taking the specified geometry of the WSL flask into account,, an oil droplet at the very bottom of the flask will have to float 8.74 cm in 1 minute (0.146 cm/sec) to escape the sampling zone. This will be the largest oil droplet that can be 'captured' – all oil droplets of the same size, or larger, will have floated clear during the one minute because they are higher up in the water column. The diameter of this oil droplet is designated $d_{0\%VOL}$ in the following treatment.

An oil droplet that is at a position in the flask where it will be present in the 25 ml of mixture sampled (i.e. the middle of the sampled volume) will only have to float 1.84 cm in one minute (0.0307 cm/sec) to escape being 'captured'. This is the largest droplet that will be captured in the 25th ml sampled (50% of the total sampled volume of 50 ml) and is designated to have a $d_{50\%VOL}$ diameter. Similarly, $d_{25\%VOL}$ and $d_{75\%VOL}$ are designated as the diameters of oil droplets that will be in positions in the flask equivalent to the first 25% (12.5 ml) and 75% (37.5 ml) of the oil/water mixture volume sampled. They have to travel 3.24 cm and 0.89 cm, equivalent to 0.054 and 0.015 cm/sec, respectively as described in Table 1.

	Distance needed in 1 minute to escape sampling (cm)	Rise velocity (cm/sec)
$D_{0\%VOL}$	8.74	0.1457
$d_{25\%VOL}$	3.24	0.0540
$d_{50\%VOL}$	1.84	0.0307
$d_{75\%VOL}$	0.89	0.0148

Table 1.   Rise velocities for oil droplets captured in the WSL test method

The size of the oil droplets of oils of widely differing density (IFO-380 fuel oil and Statfjord crude oil) sampled in the WSL method, calculated according to Stoke's Law, are contained in Table 2.

	Rise velocity (cm/sec)	Test IFO-380	Statfjord crude oil
Density at 15ºC gm/ml		0.983	0.834
$d_{0\%VOL}$ μm diameter	0.1457	265	124
$d_{25\%VOL}$ μm diameter	0.0540	161	75
$d_{50\%VOL}$ μm diameter	0.0307	121	57
$d_{75\%VOL}$ μm diameter	0.0148	84	39

Table 2.   Sizes of oil droplets sampled in the WSL test method

These droplets sizes are broadly in agreement with those measured for dispersed oil at sea.

Dispersed oil concentrations in the WSL test method

The dispersed oil concentration of 5 mls of oil in 250 ml of seawater for 100% dispersion, equivalent to 2% volume or 20,000 ppm, is far in excess of any dispersed oil concentration that has ever been measured at sea. The very high dispersed oil concentrations in the WSL method will cause far more droplet-droplet interaction leading to droplet coalescence than occurs at sea.

2.4   MEASURING THE EFFECTIVENESS OF OIL SPILL DISPERSANTS AT SEA

The successful use of a dispersant will cause the spilled oil to be rapidly transferred from the surface of the sea into the water column as very small oil droplets.

This will not happen evenly across the oil slick area; dispersion will be most rapid in the localised areas where the dispersant-treated oil is exposed to breaking, or cresting, wave action. This action will create individual plumes of dispersed oil underneath the oil slicks. These individual plumes will be diluted and dispersed into the water column, both vertically and horizontally. The plumes will gradually lose their individual identity as the localised increase in dispersed oil concentration reduces to a generally elevated background level. This process will continue until most of the dispersant-treated oil has been dispersed and little remains on the surface. Conversely, an unsuccessful, or partially successful, application of dispersant will result in none of, or only a proportion of, the surface oil being transferred into the water column and it will remain on the surface of the sea. There are therefore two, apparently obvious, ways of determining the effectiveness of dispersant treatment on test oil slicks at sea:

(i)   Measure the total amount of oil that remains on the sea surface, and how this changes (reduces) with time.

(ii)   Measure the amount of oil dispersed into the water column, and how this changes (increases) with time.

Unfortunately, it is impossible to conduct these quantifications with currently available techniques, and attempting to do so will unduly influence the dispersion process.

2.4.1   Measuring the amount of oil remaining on the sea surface

There is no method, by visual observation or using remote-sensing methods, that can accurately quantify the amount of oil on the sea by determining the oil layer thickness and hence the oil volume in a measured oil slick area.

Spilled oil spreads out to form a slick of varying thickness, from very thin sheen that is less than one micron thick, up to layers of emulsified oil that may be several millimetres thick. Measurements made with Side-Looking Airborne Radar (SLAR), thermal Infra-Red (IR) and Ultra-Violet (UV) can be used to provide useful indications of the relative oil layer thickness in different areas of the oil slick, but these techniques cannot provide an absolute measure of oil layer thickness and hence the volume of oil on the sea at any time. In principle, it might be feasible to consider recovering a series of dispersant-treated slicks at different times to produce a measure of the way in which the oil volume is reduced with time. However, treating an oil slick with dispersant will make it very difficult, or impossible, to quantitatively recover at sea with booms, skimmers or absorbents. The additional mixing energy caused by attempting to recover oil that had not been dispersed by the wave action might cause dispersion and thus artificially increase the apparent dispersant effectiveness.

Accurately measuring the amount of oil remaining a certain time after dispersant treatment at sea is therefore not a feasible route for determining dispersant effectiveness at sea.

2.4.2　Measuring the amount of oil dispersed into the sea

Accurately measuring the amount of oil dispersed into the water by dispersant treatment and wave action is also fraught with several difficulties.

Early attempts at dispersant effectiveness quantification by measuring the dispersed oil concentrations used 'bottle sampling'; taking discrete samples by bottles or Nansen jars (a sampling system used in many studies in the sea). It was soon appreciated that it would be impossible to accurately sample the entire water volume below a dispersant-treated oil slick with enough resolution in space and time to provide an accurate assessment of the total amount of oil dispersed.

These difficulties are caused by the nature of the dispersion process. Dispersant treated oil is most rapidly dispersed by breaking, 'cresting' or near-breaking waves. Individual plumes of dispersed oil are produced by these 'cresting' or breaking wave events. This happens in small areas (perhaps one or two metres wide and only a few metres long) that are localised within the overall area of the oil slick in most sea conditions. The area covered by cresting waves where dispersion is most rapid is transient as the wave breaks and subsequently subsides. Only a very small proportion of the total slick area is covered by cresting waves at any one time. The frequency of cresting waves and fractional area of the sea surface covered by them at any time is related to wind speed and sea-state.

The individual plumes of dispersed oil droplets created by breaking waves are then diluted and dispersed by the turbulence created by wave action within the water column. These individual plumes spread out, horizontally and vertically, as they are diluted into the water column. The dispersed oil concentration within these individual dispersed oil plumes decreases rapidly as the dilution proceeds. The overall, or average, dispersed oil concentration below, and in the water column surrounding, the dispersing oil slick will gradually increase from background levels as the oil is dispersed, but at locations near to the original cresting wave event the dispersed oil concentration will be rapidly decreasing.

In order to produce an accurate 'picture' of dispersed oil concentrations below a dispersant-treated oil slick, there would have to be bottle sampling at a resolution sufficient to capture the individual dispersion events and the overall dispersed oil concentration increase. This would require sampling at every metre or so in all three dimensions under the slick (length, width and depth), and this would need to be rapidly repeated to keep a track of the rapidly diluting individual plumes of dispersed oil. This would give rise to huge numbers of bottle samples needing to be taken and analysed.

The use of UVF (Ultra-Violet Fluorometry)

Ultra-Violet Fluorometry (UVF) can be used to measure the dispersed oil concentration in water. UVF is a technique that exposes the oil in the water to intense UV radiation. Some of the aromatic chemical components in oil will fluoresce (emit UV at a slightly different wavelength) after this treatment and this can be detected by fluorometers. The UVF response produced by an oil is dependent on its composition (aromatics content) and physical form (oil droplet size distribution). The composition of spilled oil (especially crude oils) changes after it has been spilled; the more volatile components evaporate and this will alter the UVF response. Fluorescence is a surface phenomenon; oil droplets emit UV from the surface that has been previously exposed to the intense UV light. Smaller oil droplets have more exposed surface area than larger droplets. The signal produced by a fluorometer therefore needs to be 'back-calibrated' with water samples taken and analysed for quantitative hydrocarbon content by another method.

An advantage of UVF compared to bottle sampling is that the sampling pump (and sometimes the entire fluorometer) can be submerged to a certain depth and then towed through the water column underneath a dispersant treated oil slick. This produces a transect - a line through the water column - along which dispersed oil concentration is continuously measured. Several fluorometers can be used to simultaneously measure dispersed oil concentrations at several depths. This is an improvement compared to taking vast numbers of individual bottle samples, but still does not completely overcome the lack of spatial and temporal resolution needed to produce an accurate quantification of the amount of dispersed oil at any time.

Dispersed oil concentrations that are higher than the background reading are indications that the dispersant is working, i.e. that the oil is dispersing. However, high 'peak' dispersed oil concentration readings are not an unambiguous indication of higher dispersant effectiveness. A particularly high dispersed oil concentration may be recorded if the fluorometer pump (or *in-situ* fluorometer) is towed through an individual dispersed oil plume very shortly after it has been produced by wave action. The initially high dispersed oil concentration will drop quite rapidly as the plume is being dispersed. A UVF transect passing further away from a similar dispersion event and at some time later would record lower 'peak' dispersed oil concentration.

Attempts to integrate the dispersed oil concentrations recorded along transects by UVF into dispersed oil volumes will not be successful because the dispersed oil concentrations at all points under the slick cannot be recorded at the same time. The individual dispersed oil plumes rapidly decrease in dispersed oil concentration as they are diluted to form larger, but more diffuse, plumes. Repeated transects under a dispersant-treated slick may record the same dispersed oil several times and attempts at a mass balance will result in 'double counting' of this dispersed oil, leading to inaccurate mass balances.

2.4.3   Other approaches to dispersant testing at sea

Several approaches have been used to try and overcome the inherent difficulties of measuring dispersant effectiveness at sea.

<u>Continuous release or steady state sea trials</u>

Continuous release experiments, where a continuous stream of oil is released and sprayed with dispersant and then the oil-in-water concentration is measured by UVF have been used by NETCEN in an attempt to produce numerical values for dispersion rate.   This technique avoids the changes with time that occur in a slick; time is essentially 'frozen' by using constant time (which equals drift distance in this technique) after oil release and dispersant treatment.   This technique does overcome many of the problems of trying to determine mass balances at discrete experimental slicks, but this type of sea trial can only be carried out in relatively calm conditions.   Oils cannot be allowed to 'weather' before being treated with dispersant.   In practical terms only the first 15 to 30 minutes of the dispersion process can be monitored. Attempts have been made to relate these numbers to results obtained in the WSL laboratory test method. However, it has not been possible, so far, to derive a commonly accepted relationship between a WSL result and dispersant performance at sea because the technical measure of efficiency cannot be directly translated into an operational measure of dispersant effectiveness.

<u>The use of comparative testing</u>

In the absence of an absolute way to determine dispersant effectiveness at sea, a comparative or relative technique is often used. Most experiments that have taken place with dispersant-treated oil slicks at sea have employed this comparative approach. Two or more oil slicks are laid down on the sea. One oil slick is left untreated as the control slick and the other slick, or slicks, are sprayed with dispersant after a certain period of weathering. The control and dispersant-treated slicks are then monitored by various means, including visual observation and remote sensing techniques.

UVF has frequently been used as an indicator that more rapid dispersion is taking place by recording elevated dispersed oil concentrations under the under the dispersant-treated slick, compared to the dispersed oil concentrations under the control slick. However, for the reasons given in Section 2.3.2, dispersed oil concentrations cannot be directly related to the dispersant effectiveness results obtained in laboratory test methods.

<u>Persistence of a slick as an end-point</u>

Small oil slicks of most crude oils will naturally be broken up and dissipate by the action of the sea. This is often referred to as natural dispersion. Although not identical to the enhanced dispersion caused by the addition of dispersants (small oil droplet creation is not as important as overall slick break-up during natural dispersion), a similar end result is achieved; the coherent oil slicks spreads and is broken up until only traces of sheen are left on the sea surface. In practical terms, the aim of using dispersants is to achieve the same end-point, but to achieve it much more rapidly. The end-point of all but traces of sheen persisting on the sea surface can be used as one indicator of dispersant effectiveness.

Such an experiment may reveal, for example, that the majority of oil in a slick of a particular test oil that had been treated with a particular dispersant (Dispersant A, say), at a nominated treatment rate, was totally removed from the sea surface 2 - 3 hours after dispersant treatment. In the same test at sea it might be that the control slick persisted for two or three days. This should be considered to be a valid result; treatment of the oil with Dispersant A clearly caused relatively rapid dispersion, i.e. it 'worked', but this method does not produce results that can easily be compared with the "percentage of oil dispersed" results obtained from laboratory tests.

The comparison could easily be extended by including another slick of test oil and using another dispersant, Dispersant B for example. Provided that the three oil slicks were laid down almost simultaneously and the two dispersant-treated slicks were sprayed with the same amounts of dispersants at approximately the same time, they will all experience similar sea conditions. If the oil slick treated with Dispersant B persisted for substantially longer after dispersant treatment than the slick treated with Dispersant A, it would then be fair to conclude that Dispersant A was more effective than Dispersant B. There might even be some way of relating the persistence of the dispersant-treated slicks to the dispersant effectiveness results obtained in laboratory tests.

2.5   CONCLUSIONS ON MEASURING DISPERSANT EFFECTIVENESS

Using the information provided in the previous sections, it can be seen that it is not possible to measure the effectiveness of dispersants when used at sea in the same way that is easily achievable in laboratory tests. This is because there are no methods of accurately measuring the amount of oil left on the sea surface, or of measuring the total amount of oil dispersed into the sea. This does not mean that the performance or effectiveness of using dispersants at sea cannot be assessed, it just means that it cannot be measured in an absolute way.

The emphasis in most laboratory test methods has been to measure the proportion of oil volume that is considered to be dispersed. This involves creating a wide range of oil droplet sizes by the application of some shearing action in the laboratory method and then measuring the proportion of the oil volume converted into very small oil droplets that are retained in the water for some period so that they are sampled. This approach produces a range of dispersant effectiveness from 0% to 100%. While this is a technically useful gradation of the relative effectiveness of dispersants, it is not useful for estimating, or predicting, dispersant performance at sea in real oil spill response operations.

Visual and instrumental observations made at previous sea trials and at real oil spill incidents seem to have revealed a more common, and starker, apparent discrimination of dispersant performance. The operational use of dispersants seems to either:

(i)   Work well with the eventual dispersion of the most of the spilled oil;

(ii)   Or dispersants do not appear to work at all, with virtually no dispersion observed.

There have been intermediate cases, but these are few. A complicating factor is the interpretation of visual observations at some incidents that have been contradictory with some observers claiming that the dispersant worked, but other observers adamantly insisting that the dispersant did not work. The visual effects of dispersants on spilled oil can be confusing; not all visible effects of dispersant addition to spilled oil are indicators of subsequent dispersion.

An over-emphasis on quantitative measurement, concentrating on trying to determine the precise proportion of oil volume dispersed, may have concealed a more obvious discrimination in dispersant performance that will be relevant in many cases.

This is not to say that dispersants always appear to totally work (equivalent to 100% result in a particular laboratory test method) or appear not to work at all (equivalent to 0%), but that there can be early and easily visible indications that the initial phase of dispersion is occurring, or that it is not.

The significant difference appears to be in the initial phase of the dispersion process; the action of a breaking or cresting wave passing through the dispersant-treated oil either does, or does not, create a wide distribution of oil droplet sizes. Without the creation of small oil droplets, all subsequent stages of dispersion will not occur.

The visually observed difference is between a dispersant not working to any significant extent and some easily visible degree of dispersion. This might translate into a difference in a laboratory test results of 0% and an intermediate value of 30%, 50% or 70% - this is currently unknown - but it does appear to be a consistent and reliable differentiation of one element of dispersant performance at sea.

A consideration of this approach was used to construct the test matrix for the UK 2003 sea trials. The aim would be to determine the 'break point' between dispersants not working at all (or to any significant degree) and dispersants working to some appreciable degree. This is not a smooth, gradated quantification in dispersant performance that might be easily achieved by a laboratory test method, but since this is currently impossible to achieve at sea, the approach would provide an operationally useful indication of dispersant performance.

Previous sea trials had used a limited number (from 2 to 5) of slicks of relatively large amounts (10 to 50 tonnes) of test oils. In contrast, the 2003 sea trials had the potential to use combinations of four oils, three dispersants and three dispersant treatment rates to produce 36 test oil slicks. Very small oil slicks were used with a volume of only 10 or 20 litres. This approach substantially reduced the environmental risk, complexity and cost of the project.

These sea-trials differed from previous studies conducted at sea in that they used a full spectrum of oil viscosity, dispersant brand and dispersant treatment rate to create a matrix of dispersant performance. The use of these three variables produces a "3-dimensional" matrix of results that allows the 'break point' between dispersants "totally working" to dispersants "not working at all" to be found at the sea-states likely to be encountered.

3. THE 2003 UK SEA-TRIALS

3.1 Objectives

The primary objective of the proposed project is to define the limiting oil viscosity for the use of oil spill dispersants.

This would be achieved by spraying several small oil slicks of four test oils of different viscosity with three dispersants at three different treatment rates and observing the visible effects of dispersant treatment. The aim of the work was to define the limiting oil viscosity for dispersion, that is, the viscosity of oil that caused the dispersants to have no visible indication of dispersant effectiveness.

Because of the small size of the test oil slicks to be used, the effectiveness of the different dispersants and treatment rates were to be judged principally by visual assessment alone.

This assessment would not produce a quantitative measurement of the amount of oil dispersed, or a quantitative measurement of the amount of oil that remained on the sea surface at any time. However, the assessment would indicate whether or not any degree of dispersion was happening shortly after dispersant spraying.

3.1.1 Organisations and personnel involved

The project was funded in direct financial contributions and in-kind contributions of personnel, equipment, vessels and expertise by a consortium of DEFRA (Department for Food, Environment and Rural Affairs), ITOPF (International Tanker Owners Pollution Federation Ltd), MCA (Maritime and Coastguard Agency) and OSRL (Oil Spill Response Limited). Francois Merlin attended as an expert observer as an in-kind contribution from CEDRE.

DEFRA funded some of the project. DEFRA Sea Fisheries Inspectorate staff took part in deliberations on suitable sites for the sea-trials and staff from the Marine and Environment Consent's Unit (who administer the UK Oil Dispersant Approval scheme) attended the sea-trials. DEFRA also facilitated the participation of Robin Law from CEFAS (Centre for Environment, Fisheries and Aquaculture Science) as an expert observer. ITOPF funded some of the work and two ITOPF staff were expert observers. Other ITOPF staff also attended the sea-trials.

The MCA provided funding for a substantial part of the work. The MCA contracted the author of this report to manage the project, plan the required activities, participate in the sea trials, collect, collate and analyse the results and prepare the report. The MCA supplied the MCA *Osprey* for use during the sea-trails and chartered the *Jo-Dan*. OSRL staff with some assistance from Matthew Somerville of BMES (Briggs Marine Environmental Services) adapted the dispersant spraying system and fabricated the oil depositions system. OSRL provided the major vessel, the *Willcarry* under charter from Williams Shipping, for the sea trials.

External observers included Joe Mullins from the US MMS and Ken Trudel from S L Ross Environmental Research.

3.1.2 Location of sea trials

The small-scale sea trials were conducted at a location approximately 10 nautical miles to the south of the Isle of Wight at the end of June 2003. A licence was issued for the deposit of oil at sea at this site by Defra's Marine and Environment Consents Unit as required under the Food and Environment Protection Act 1985. The site is used for Royal Navy mine-sweeping practice and was therefore clear of fishing gear such lobster pots and fixed netting that could have been fouled by oil. The precise site was defined as 1000 yards either side of lines drawn between: 50º 24'N 000º 58'W, 50º 24'N 001º 18.5'W, 50º 24'N 001º 35'W and 500 yards either side of line drawn between: 50º 33'N 000º52.6'W' 50º 24'N 000º58'W

3.1.3 Outline of sea-trial procedures

The personnel involved in the sea-trials were divided into three teams:

(i)   Operations Team

Andy West	OSRL
Matt Simmons	OSRL
Nick Olden	OSRL
Tim Endean	OSRL
Nick Van Horn	OSRL
Abby Findlay	OSRL
Matthew Somerville	BMES
Malcolm Gardiner	Williams Shipping
	Williams Shipping

The OSRL were based on land at Ventnor Towers, Ventnor, Isle of Wight and at sea on board the Williams Shipping *Wilcarry* barge. The OSRL *Tornado* RIB operated out of Bembridge harbour and transferred team members to the *Wilcarry,* which acted as the main vessel for the experiments. On board the *Willcarry* were:

- The test oils and test dispersants and kit to deposit test oils as 1 metre x 20 metre carpets and spray test dispersants at required treatment rates.
- The mechanical recovery equipment: Sidesweep arm, boom, Termite skimmer, 4 IBCs (Intermediate Bulk Containers) and sorbent boom.
- The OSRL *Tornado* and *Sparrowhawk* RIBs. The *Sparrowhawk* RIB was to be used to deploy the UVF to measure dispersed oil concentration under the dispersant-treated test slicks.

(ii)   Expert team

Dave Salt	OSRL
Karen Purnell	ITOPF
Hugh Parker	ITOPF
Robin Law	CEFAS
Francois X Merlin	CEDRE
Kevin Colcomb	MCA
Alun Lewis	Independent Consultant

The members of the expert team were based on land at various hotels in Yarmouth, Isle of Wight and at sea initially on board the *Jo-Dan*, an 11.6-metre angling and diving boat and then on the *MCA Osprey*.

(iii)   Observer Team

Malcolm Peddar	DEFRA
Michael Meekums	DEFRA
Joe Mullins	US MMS
Ken Trudel	S L Ross, Canada
Fionn Molloy	ITOPF
Alexander Nicolau	ITOPF

The members of the observer team were based on land at Sentry Mead Hotel, Madeira Road, Totland Bay which is a couple of miles from Yarmouth and at sea on board the *MCA Osprey* and then the *Jo-Dan* operating out of Yarmouth harbour.

Outline procedure

The procedure of the sea trials was to first lay down a slick of test fuel oil, approximately 1 metre wide and 20 metre long, from near the bow of the *Wilcarry.* This slick was then to be sprayed with dispersant at the required treatment rate from the *Wilcarry* a short distance after it was laid down. The dispersant spray was to be turned on before the oil was deposited onto the sea and turned off after the oil had passed under the spray arm to ensure that all the oil was treated with dispersant.

The apparent effectiveness of the dispersant was to be judged by the expert team using visual observation from a smaller vessel a short period after the oil was sprayed. The UVF fish was then be towed under the slick from the *Sparrowhawk* RIB to measure the sub-surface dispersed oil concentration at 1 to 1.5 metre depth.

Figure 3.   The Willcarry

Figure 4.   MCA Osprey

Figure 5.   Jo-Dan

3.2 MATERIALS USED

3.2.1 Test oils

The four test oils used were IFO-80, IFO-120, IFO-180 and IFO-380 grade fuel oils. These IFOs (Intermediate Fuel Oils) oils were supplied by Esso UK from their refinery at Fawley. IFOs are produced by blending small quantities of various distillates into various refinery residues to produce the required viscosity.

IFOs were used in this work for several reasons:

- Unlike crude oils, the properties of IFOs do not rapidly change when spilled on the sea.
- IFOs are readily available and do not require special shipment due to low flash point.
- IFO-180 and IFO-380 are the typical HFOs (Heavy Fuel Oils) that might be spilled by large ships because they are the most-used bunker fuel oil grades.

IFOs (Intermediate Fuel Oils) are graded by their viscosity at 50ºC; IFO-180 has a maximum viscosity of 180 cSt (centistokes) at 50ºC and IFO-380 has a maximum viscosity of 380 cSt at 50ºC. There is no specified minimum viscosity at 50ºC for a particular IFO grade and the effective minimum viscosity of a particular grade is the maximum viscosity of the IFO grade below it. An IFO-380 grade can therefore have a viscosity of between 180 cSt and 380 cSt at 50ºC and an IFO-180 grade can have a viscosity of between 120 cSt and 180 cSt at 50ºC. In general terms, heavy residues have less value than distillates and IFOs are usually blended to be close to, but not exceeding the specified maximum viscosity for the particular grade. "Heavier", higher viscosity grades of IFOs are cheaper to buy than "lighter", lower viscosity grades.

The viscosity of any oil increases with decreasing temperature. The rate of viscosity increase with reduced temperature is broadly similar, but not exactly the same, for all oils. The Viscosity Index (VI) is a measure of viscosity change with temperature and varies with oil composition. Additionally, many oils exhibit non-Newtonian flow behaviour and the measured viscosity value varies with the shear rate used when to determine it. This effect is less apparent at higher temperatures and low viscosity values, but becomes very evident with high viscosity oils at low temperatures.

Only two grades of IFO oils were used in the majority of the tests and the properties of these two test oils used in the sea trails are contained in Table 3.

| | Density @ 20ºC (gm/ml) | Viscosity (mPa.s or cP centiPoise) | | | |
| | | 15ºC | | 50ºC | |
		@10s^{-1}	@100s^{-1}	@10s^{-1}	@100s^{-1}
IFO-180	0.970	2,075	1925	134	146
IFO-380	0.983	7,100	n/a	314	324

Table 3.   Physical properties of test oils

The specifications limits of IFO grade fuel oils are quite wide and the properties of the particular test oils used on the sea trials should not be considered as being definitive of these grades.

The viscosities at 50ºC of the IFO-180 and IFO-380 oils of 134 and 314 cP are within the maximum viscosity specifications of 180 and 380 cP. The viscosities at 16ºC (the sea temperature at the sea trials) are similar to those of IFO-180 and IFO-380 grades oils previously tested for with dispersants at AEA Technology. In these respects, the oils are typical of fuel oils of the same grade.

However, the composition and therefore physical properties of fuel oils of nominally the same grade can vary over quite a wide range. The maximum permitted Pour Point (the temperature at which an oil just flows when tested in the specified method) for these grades of fuel oils is +30ºC. This is rarely approached by IFO-180 or IFO-380 grades produced from non-waxy crude oils and 'straight-run' (derived from atmospheric distillation) components, but may be approached by fuel oils blended from components of waxy crude oils. If the IFO-180 and IFO-380 fuel oils had a Pour Point significantly above the prevailing sea temperature, they would have become solid when spilled onto the sea, even though they would have had viscosities at 50ºC below the required maximum values.

3.2.2   Dispersants

The three oil spill dispersants used in this work were:

- Agma Superconcentrate DR379
- Corexit 9500
- Superdispersant 25.

Agma Superconcentrate DR379 and Superdispersant 25 constitute about two-thirds of the 1500 tonne dispersant stockpile held by the MCA.

Corexit 9500 is currently not on the UK approved dispersant list, having been withdrawn when the requirement to pass both the 'at-sea' and 'rocky shore' toxicity tests was introduced by Defra in 1997, but is available in other parts of the world and has been extensively studied in laboratory tests. Stocks of Corexit 9500 were held by both the MCA and OSRL before the change in the regulations and this dispersant can be still be used in UK waters, although Corexit 9500 manufactured after the regulation change would not be permitted to be used in UK waters.

3.2.3   Dispersant treatment rates

The three dispersant treatment rates used in this work were DORs (Dispersant to Oil Ratios) of 1:25, 1:50 and 1:100.

A DOR of 1:25 is the typically recommended dispersant treatment rate, but some laboratory studies had indicated that dispersants could still be effective when used at the lower treatment rates. Since this would yield significant cost savings and operational advantages, DOR was included as a variable.

It should be noted that these are 'nominal' treatment rates (and 'nominal' DORs). Dispersant is sprayed onto spilled oil from spraying equipment mounted on boats, ships or aircraft. The amount of dispersant that is deposited on a unit area of an oil slick can be reasonably accurately controlled by suitable system design and operation. The pumps of the spray system will deliver the required flow-rate to the spray arms and the nozzles will be designed to produce an even coverage of dispersant over the width of the spray swath. The speed of the vessel or aircraft will determine how much dispersant is delivered per unit area.

However, oil slicks are of very variable thickness, ranging from sheen that is less than one micron thick, up to layers of several millimetres. The thickness of the oil layer in the slick varies over a very wide range over short distances; areas of thin sheen can be within a few centimetres distance of thick oil patches. The can also be 'holes' – areas of almost 'clean' water- within the overall area of a slick. The actual DOR – the precise ratio of dispersant to spilled oil – will vary over an enormous range within localised areas of the dispersant-treated slick.

3.3   METHODS USED

3.3.1   Oil deposition

The test oils were pumped from IBCs (Intermediate Bulk Containers) on the deck of *Wilcarry* and laid down onto the sea as a 20-metre long strip through the Manta Ray skimmer head as the barge sailed directly into the wind at approximately 2 knots. The oil layer were intended to be approximately 1 metre wide and 20 metres long with a thickness of 0.5 mm for the lower viscosity grades (IFO-80, IFO-120) or 1 mm for the higher viscosity grades (IFO-180 and IFO-380). This was because it would be very difficult (if not impossible) to get thin oil layers with high viscosity oils.

A total of 10 litres oil, pumped out at 30 litres / minute (0.5 litres / sec) for 20 seconds would produce an area coverage of 500 ml/m^2, required to produce a 0.5 mm thick layer of the lower viscosity oils. A total of 20 litres oil, pumped out at 60 litres / minute (1 litre / second) for 20 seconds would produce an area coverage of 1000 ml/m^2, required to produce a 1 mm thick layer of the lower viscosity oils.

The IFO-180 and IFO-380 test oils were pumped out at 1 litre per second for 20 seconds, therefore 20 litres oil deposited on sea. The Manta Ray skimmer head was 780 mm wide, but the test oils produced an irregular width 'carpet' on the sea surface with the oil width ranging from 0.5 or even thinner to 1 metre when it was sprayed with dispersant. With the *Willcarry* moving at approximately 2 knots (~1 metre / sec) the oil layer width and thickness therefore varied over a wide range:

> 1.0 m wide x 20 m long = 20 m^2 and 20 litres = 1.00 mm thick
> 0.7 m wide x 20 m long = 14 m^2 and 20 litres = 1.43 mm thick
> 0.5 m wide x 20 m long = 10 m^2 and 20 litres = 2.00 mm thick
> 0.3 m wide x 20 m long =   7 m^2 and 20 litres = 2.85 mm thick

The speed of the vessel needed to be kept low to prevent the bow-wave from pushing the slick away.

There would have been a maximum of 9 runs for each oil (3 dispersants at three treatment rates to complete the intended test sequence. The total amount of oil required for the sea-trails would have been 9 x 10 litres (90 litres) for 0.5 mm thick slicks and 9 x 20 litres (180 litres) for 1 mm thick slicks.

At the planning stage it became apparent that complementary experimental programmes would probably be conducted if the sea-trials were successful, so Esso UK were asked for approximately 1 tonne of each grade. Esso Fawley refinery supplied this oil.
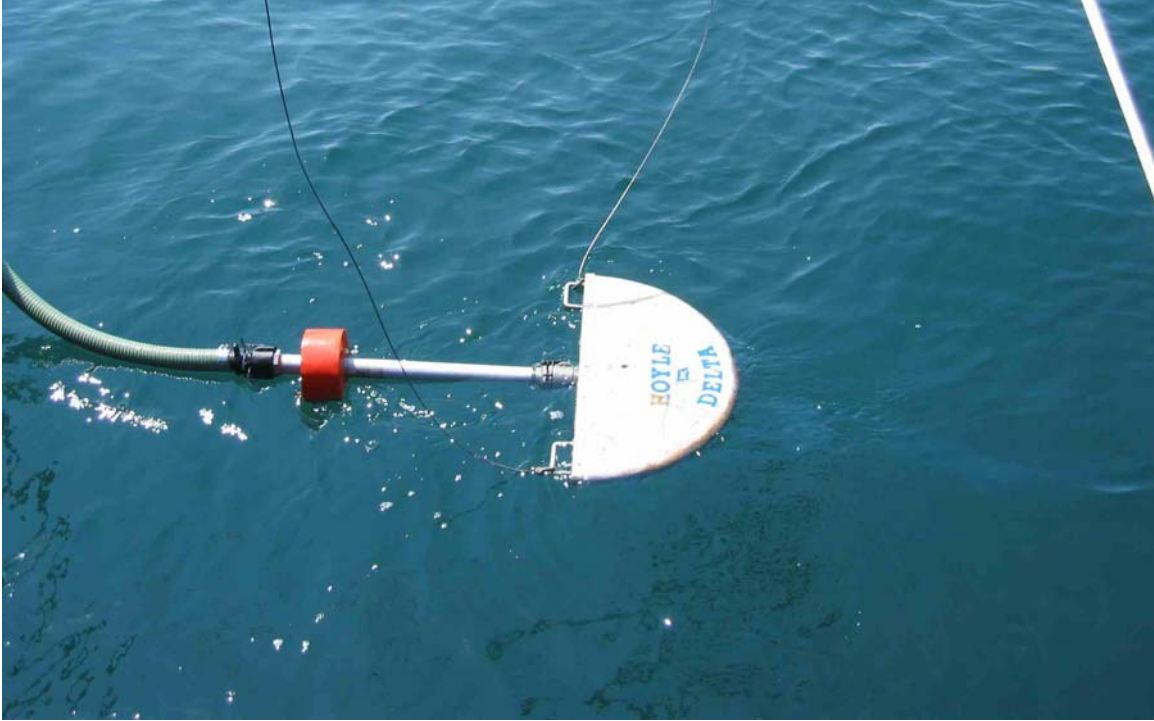
Figure 6   Manta Ray skimmer head used to deposit oil

Figure 7   Modified Boatspray system with a single nozzle used to spray dispersants

3.3.2   Dispersant spraying

Dispersant was sprayed at the required rate onto the oil layer from the modified Boatspray system shortly after it was deposited on the sea. The dispersants were sprayed for longer than oil was deposited, typically 36 seconds, starting before oil was being deposited and finishing after oil had passed below spray nozzle. This was to ensure that no oil was missed by the dispersant.

The dispersant spray was from a single nozzle on 1.5 meter long down tube and spray arm was set 1 metre above *Willcarry* deck. The *Willcarry* has freeboard of 1.7 metres. Therefore, spray nozzle was about 1.2 metres above water. The spray nozzle angle was nominally 90º, given spray width twice that of the spray nozzle height, i.e. 2.4 metres, but was certainly narrower than this, being folded back by the wind and appearing to be about 1.8 metres wide and varying in width as waves passed under.

Nominal dispersant treatment rates, as DORs (Dispersant Oil Ratios), were intended to be 1:25, 1:50 and 1:100.

Three single nozzles, nominally 5, 2.5 and 1.25 litres / minute used and changed as required. Measurements made before the trial showed that these nozzles sprayed 1750, 650 and 400 mls in 20 seconds (87.5 32.5 and 20 mls / sec). With *Willcarry* moving at approximately 2 knots (~1 metre / sec) the amount of dispersant deposited would have been:

$$87.5 \text{ mls / sec over 1.8 metres wide and 1 metre length} = 48.6 \text{ ml / m}^2$$
$$32.5 \text{ mls / sec over 1.8 metres wide and 1 metre length} = 18.0 \text{ ml / m}^2$$
$$20.0 \text{ mls / sec over 1.8 metres wide and 1 metre length} = 11.1 \text{ ml / m}^2$$

The average actual DOR achieved depends on how wide the oil carpet was:

Nominal DOR	1.0 metre wide oil	0.7 metre wide oil	0.5 metre wide oil	0.3 metre wide oil
1:25	1:20	1: 29	1:41	1:58
1:50	1:55	1: 79	1:111	1:158
1:100	1:90	1: 128	1:180	1:257

Table 4.   Effect of oil carpet width on actual treatment rate

The IFO-180 grade fuel oil appeared to spread in an irregular carpet that was approximately 0.5 to 1 metre wide, with an approximate average width of 0.7 metre, but was irregular an fluctuating in width in the wave action.

The higher viscosity IFO-380 formed a generally narrower strip of oil around an average of 0.5 metres wide.

3.4. ESTIMATING DISPERSANT EFFECTIVENESS BY VISUAL OBSERVATION

Because of the current impossibility in quantitatively determining the proportion of oil dispersed or remaining on the sea surface at any time, the major method of assessing dispersant performance used in the sea trials was visual observation.

Visual estimation of the effectiveness of dispersants was used to approve dispersants in the UK before the WSL test method was adopted as the approval test procedure. The 'harbour test' method used a simple rig with a fan-jet to spray a 'carpet' of test oil onto the sea that was 0.3 metres wide. The oil layer thickness was varied by varying the vessel speed. Another spray nozzle delivered the dispersant under test onto the oil layer at several different treatment rates. An agitation board was towed behind the vessel to disperse the oil. A team of observers followed in another vessel and visually assessed the effectiveness of the dispersant. The dispersant was judged to be inefficient if the oil resurfaced behind the agitation board and was judged to be effective if oil did not resurface. The 'break point' between the two conditions was found to be whether or not oil droplets of about 1 mm diameter could be seen on the water surface or in the water column just behind the agitation board. Results from repeated tests using a variety of observers confirmed that the apparently subjective test produced reliable and repeatable results, even with observers who had no previous experience. Testing with this method was discontinued in the mid-1980s when the correspondence between the results and those from WSL method testing was felt to be sufficient.

As stated earlier in this report, visual observations made at previous sea trials and at real oil spill incidents seem to show an easily observed discrimination in dispersant performance, provided that the observer is aware of the relevant visual cues. Dispersants seem to either: work well with eventual dispersion of the majority of the spilled oil or dispersants do not appear to work at all, with virtually no dispersion observed. The significant difference appears to be in the initial phase of the dispersion process; the action of a breaking or cresting wave passing through the dispersant-treated oil either does, or does not, create a wide distribution of oil droplet sizes. Without the creation of small oil droplets, all subsequent stages of dispersion will not occur.

The total rate of dispersion of a treated slick at sea is the time-averaged sum of localised and energetic individual dispersion events. Any method of assessment or measurement of dispersion, be it remote sensing, dispersed oil concentration measurement or visual observation, needs to take this into account. The visual observations would be of only the initial part of the dispersion process.

3.4.1 Visual observations made during dispersant use

It is not possible to quantify the amount of oil that has been dispersed at any particular time by visual observation. However, it is possible to use visual observation to assess whether or not the dispersion process is, or is not, proceeding. It might be thought that the most obvious visual indication that a dispersant is working would therefore seem to be the gradual disappearance of the oil slick with time. However, this is not easy to observe for several reasons:

- It is impossible to estimate the amount of oil on the water surface, or the oil layer thickness, by visual means alone. Although the oil layer thickness causes characteristic effects in very thin oil layers (as described in the Bonn Agreement Colour Code, reference), thicker oil layers looks similar, irrespective of oil layer thickness. A reduction is oil layer thickness from an average of 1 mm to 0.5 mm, or from 0.5 mm to 0.25 mm, as a result of half of the surface oil volume being dispersed will produce no discernible change in appearance.

- The average thickness of surface oil layer will become thinner as some of the oil is dispersed, but this does not happen across the entire slick at a uniform rate. Dispersion occurs most rapidly as breaking (or cresting), or near-breaking, waves pass through the oil slick. The proportion of sea surface covered by cresting waves at a particular instant is proportional to sea-state and therefore wind speed (reference). Only a small proportion of the total area of a dispersant-treated oil slick will be subject to this mixing action at any particular time.

An additional complication is that the addition of dispersant to any oil will cause changes in behaviour and appearance even if the oil is not being dispersed. There are several visual effects associated with dispersant use that are <u>not</u> indicative of a dispersant working:

- A white plume or 'cloud' in the water is dispersant that has washed off the oil. This might be confused with the coffee-coloured (light brown) plume of dispersed oil that is a good indicator of successful dispersant use.

- Dispersant-treated oil often spreads out rapidly across the water surface after treatment. This may be a 'herding' effect caused by dispersant droplets hitting clean water without any oil layer or be genuine rapid spreading of the oil caused by dispersant addition.

- 'Herding' occurs because the surfactants in dispersants exert a stronger spreading pressure across the water surface than spilled oil. The spreading dispersant will cause the oil to be pushed, or 'herded', into a compressed area of a thicker layer. The effect is rapid, but temporary.

- When the surfactants from the dispersant have penetrated into the spilled oil, and in the absence of breaking or cresting waves, the reduction in oil / water IFT will cause the oil to spread out rapidly to a larger area which will be of a thinner oil layer. This enhanced spreading can be thought of as "2-dimensional" dispersion; the oil / water interfacial area can be greatly increased because of the reduction in oil / water IFT. However, in the absence of breaking or cresting waves, the rapid conversion of the oil layer into small oil droplets does not occur.

The visual observation of something happening to the oil after dispersant spraying does not necessarily mean that dispersion is actually occurring.

3.4.2   Short-term visual cues of dispersant performance

Successful dispersion caused by the addition of dispersant and subsequent exposure to cresting, or near breaking, waves will lead to the formation of a plume, or cloud, of dispersed oil droplets in the water column under the dispersant-treated oil. This plume will be relatively small, localised and associated with the cresting wave that caused it to happen.

The most visible signs of dispersion are most evident in the localised, cresting wave locations:

- When a cresting wave passes through an oil slick that has not been treated with dispersant (or through an oil that will not dispersed by the application of dispersant) the surface oil slick is temporarily disrupted. The oil slick is distorted in shape and broken as the white-coloured wave crest passes through. There may be some temporary dispersion in the form of streamers or large oil globules and these will be briefly driven under the water surface, only to re-surface rapidly. The 'clean' water and white-coloured wave crest is normally briefly visible as this occurs.

- When a cresting wave passes through a dispersant-treated slick of an oil that will disperse, the visual appearance is different; a plume or 'cloud' of oil small oil droplets is formed as the crest passes through and this produces brown or black colours in the cresting wave. The plume of dispersing oil gives the tumbling water a brown- or black-coloured appearance and it appears to be more opaque. The plume of dispersing oil droplets can often be seen trailing in the wake of the cresting wave, below the surface in the upper layers of the water column.

Dispersed crude oils appear as a light-brown coloured plume in the water immediately under the oil slick. Plumes of dispersed heavy fuel oils are often more difficult to spot, being black in colour. The dispersed oil plume may, or may not, be easy to see depending on the observation conditions.

The best conditions for observing dispersed oil plumes dispersing into the underlying water are from reasonably close-by (preferably from a boat), soon after the individual dispersion event has occurred (or during the occurrence) and in sunny conditions where the sunlight can easily penetrate into the clear water and be reflected off of the plume. If the oil slick is large or of great thickness, the surface oil layer may obscure the view of any dispersed oil plume. The best observations are often made from very close-by with an almost vertical view of the cresting wave. Viewing from oblique angles, such as those that occur from more than a few metres away when viewing from a low observation height possible in a small boat, is not very useful; reflected light from the sky prevents the viewer from seeing into the water.

3.4.3 Longer-term visual cues of effective dispersant performance

The individual cresting waves will cause a series of individual dispersed oil droplet plumes in the upper layer of the water column and these will slowly be diluted and dissipated at they disperse. The effect over time will be to produce a more diffuse, but larger dispersed oil plume in the body of the water under the dispersant-treated oil slick. For crude oils, this is often a light-brown colour. The dispersed oil will drift under the influence of the currents, while the surface oil slick will move more under the influence of the wind. The diluted dispersed oil plume will become more evident as it drifts from below the dispersing oil slick. The dispersed oil plume will often be visible from boats or ships, and quite often visible from aircraft.

The visual appearance of the dispersant-treated oil that initially persists on the sea surface also gives indications as to whether a dispersant is working. The surface oil will often spread out to form a larger slick of reduced oil layer thickness. As noted above, this is not an unambiguous indicator of dispersant effectiveness; a poorly performing dispersant may cause only this effect without causing dispersion of oil droplets into the water column. However, enhanced spreading can be a precursor of dispersion. The oil will appear to conform more closely to the wave action on the sea surface and the wave-damping effect of the oil will be reduced. More extensive areas of very thin oil layers, sometimes having distinctive rainbow colours, will be observed with time.

3.4.4 Expert observations

Visual observation of the action of dispersants on the test oils would only reveal whether or not the initial phase of the dispersion process was occurring. Although this may not appear as useful as a determination of the proportion or percentage of oil dispersed, it is a very useful indicator of dispersant performance, especially when conducted within the matrix of variables of the sea-trials.

In view of the possibilities of confusion caused by visible effects that are not indicators of dispersion, a panel of experts composed of individuals who have extensive experience of dispersant use at previous sea-trails and at real oil spill incidents was used to conduct this important element of the sea-trial.

The panel of experts consisted of:

- Karen Purnell - ITOPF
- Hugh Parker – ITOPF
- Dave Salt – OSRL
- Robin Law – CEFAS
- Kevin Colcomb – MCA
- Francois Merlin – CEDRE
- Alun Lewis – Independent Consultant

The expert observers were initially on board the *Jo-Dan* and then on the *MCA Osprey.*

The expert observers filled in their observations on a standardised reporting form, specifying the degree of observed dispersion, and other effects, on a four-point scale. The form is shown on page 38.

This form contains four main 'standard phrase' categories and each has a description. The categories and associated definitions were selected to force the observers to concentrate on some characteristics of the dispersion process and to allocate a specific ranking to it. In some ways, a more comprehensive ranking consisting of five or seven categories would have been more useful, but the observation technique could not be practiced prior to the sea-trials, so this simple system was adopted. There was some initial discussion on board the expert observer boat and the use of polarised sun-glasses to see through the reflected sunlight and into the water proved to be very useful. Different observers tended to concentrate on slightly different aspects of the process, but overall the technique proved useful.

The observations only covered the first 10 minutes after the oils had been sprayed with dispersant. The small size of the test slicks made visual observation for longer periods impractical.

The test runs were coded and randomised so that the precise combination of oil, dispersant and treatment rate was unknown to the experts and other observers. The expert observers did not discuss their individual observations and the completed forms were collected after each test.

NAME

………………………………………………..

DATE

………………………………………………..

TIME

…………………………………………………

Rank	Standard Phrase	Description	2 mins	5 mins	10 mins
1	**No obvious dispersion**	Dispersant being washed off the black oil as white, watery solution leaving oil on surface. Quantity of oil on sea surface not altered by dispersant			
2	**Slow or partial dispersion**	Some surface activity (oil appearance altered). Spreading out of oil. Larger droplets of oil (1 mm in diameter or greater) seen rapidly rising back to sea surface, but overall quantity appears to be similar to that before dispersant spraying			
3	**Moderately rapid dispersion**	Quantity of oil visibly less than before spraying. Oil in some areas being dispersed to leave only sheen on sea surface, but in other areas still some oil present.			
4	**Very rapid and total dispersion**	Oil rapidly disappearing from surface. Light brown plume of dispersed oil visible in water under the oil and drifting away from it			

OTHER COMMENTS

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3.4.5 Categories on the expert reporting form

It should be noted that the classification categories are not linear and that there is no zero classification.

The visual observations only apply to the initial stage of dispersion; the almost immediate effects of a cresting wave passing part of the test oil slick or those made within a few minutes after this. The observations were intended to be made over the first 30 minutes, but this was altered to be over only the first 10 minutes following experience gained in the first few tests.

The observations only apply to the initial phase of dispersion and the lack of any visible dispersion (category 1) or visually apparent total dispersion (category 4), or the intermediate categories, only apply to that small portion of the test oil slick that was observed when a cresting wave passed through it. No attempt was made to study the eventual fate of the entire slick.

Category 4 – Very rapid and total dispersion

A category 4 observation does not imply that all of the volume of oil in the test slick had totally dispersed at the time of observation. It should not be considered to be equivalent to 100% in any particular laboratory test method.

The category 4 observation was recorded when the effect of the cresting wave was to cause total dispersion of the limited area of slick that was affected and when a plume of initially dispersed oil was observed in the water below the wave-affected area. No assessment was made to determine whether there was any subsequent resurfacing of some dispersed oil. A category 4 observation indicated that dispersion was certainly occurring, and in the localised area of the cresting wave, appeared to be total.

Given the small sizes of the slicks and the fact that all the oil was treated with dispersant, it is reasonable to assume that the slicks in which rapid localised dispersion was observed (and rated as category 4) would have been almost totally dispersed as all of the slick area was eventually broached by breaking waves.

Category 3 - Moderately rapid dispersion

A category 3 observation indicated that there was partial dispersion, probably larger oil droplets formed with some oil resurfacing or slower dispersion. It was not possible to identify precisely which of these mechanisms dominated – the visual impression was generally of slower or partial dispersion.

Category 2 - Slow or partial dispersion

A category 2 observation indicated that the dispersant had some visible effect, but that it may not have led to significant amounts of dispersion.

Category 1 - No obvious dispersion

A category 1 observation indicates that there were no visible signs of dispersion

3.4.6 Rationale for using visual observations

Visual assessment can never be truly quantitative in that it is not possible to quantify the amount of oil that has been dispersed, nor is it possible to quantify the amount of oil left on the sea surface, at any particular time, by visual observation.

However, more sophisticated techniques suffer from exactly the same problem; it is not possible to accurately measure either the amount of oil that has been dispersed, or the amount of oil that remains on the sea surface, at any particular time. Aerial remote sensing using thermal IR (Infra-Red) cameras cannot accurately quantify the amount of oil on the sea surface. Although there is a distinct difference between the thermal IR 'signature' of thick and thin oil areas, with the thicker oil areas normally appearing slightly warmer than the sea and the thin oil areas appearing slightly cooler than the sea, the relative difference depends on the amount of heat absorbed by the oil from the sunlight and the difference between the air and sea temperatures. Towed UVF (Ultra-Violet Fluorometry) can give a quantitative measure of the dispersed oil concentrations at various points below a dispersant-treated oil slick, but the results cannot be integrated with respect to time and position to give an accurate indication of the amount of oil dispersed at a particular time.

The matrix approach to these sea trials ensured that all possible degrees of dispersion, from 'no dispersion at all' to 'total and rapid dispersion' would occur at different oil / dispersant brand / dispersant treatment rate combinations. The selected test sequence ensured that observers would be able to observe a wide range of dispersant performance. Subsequent analysis of the results from these sea trials showed that the 6 or 7 expert observers independently, and without discussion, recorded very similar observations.

3.5 EXPERIMENTS CONDUCTED

3.5.1 Conditions during the sea-trials

Prior to the sea-trials it had been agreed that certain sea-state and weather criteria would be required for successful and safe completion of the work.

It was concluded that the tests will only be conducted during sea conditions that include breaking waves, i.e. a wind speed of at least 7 to 10 knots. The use of small boats, such as the Sparrowhawk RIB used for fluorometry and the expert and observer boats, dictated that the maximum wind speed that could be experienced was 20 knots. Visibility must be good - no fog, no continuous rain - scattered showers acceptable.

The sea trial was intended to be held over 3 days; Monday 23rd to Wednesday 25th June. However, the wind speeds and sea conditions were not always suitable:

- The sea was too rough for testing on Monday 23rd with wind speeds gusting to 28 knots. Waves were breaking over the deck of the *Willcarry* making deck operations, as required to conduct the sea trials, impossible.

- The sea was then too calm for testing, with a total absence of any cresting waves, on Tuesday 24th.

- Testing with the IFO-80 test oil was started on the Wednesday 25th, but abandoned for safety reasons as the wind speed exceeded 20 knots by midday.

- Testing took place on Thursday 26th and Friday 27th June with wind speeds varying between 8 and 14 knots.

Wind speed - Wednesday 25th June
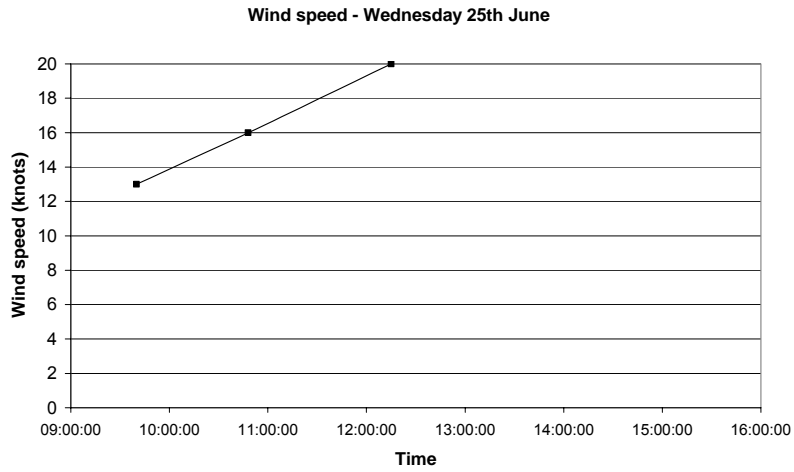
Figure 8.   *Wind speed on Wednesday 26th June*

Wind speed - Thursday 26th June
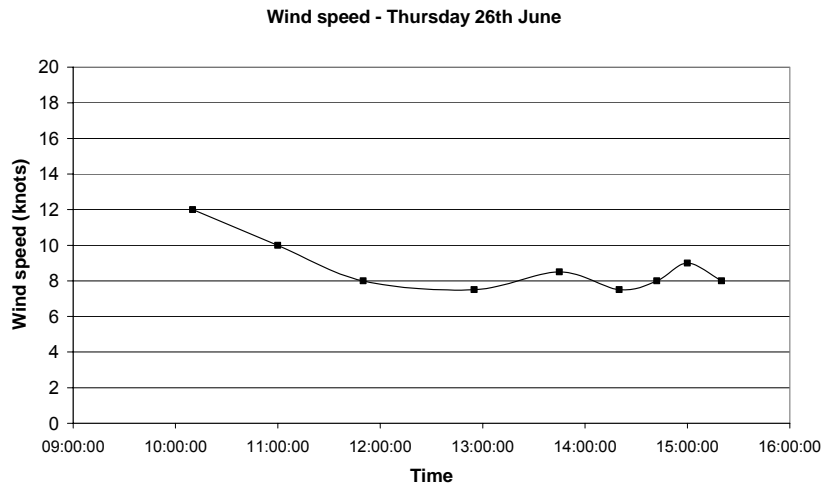
Figure 9.   *Wind speed on Thursday 27th June*

Wind speed - Friday 27th June
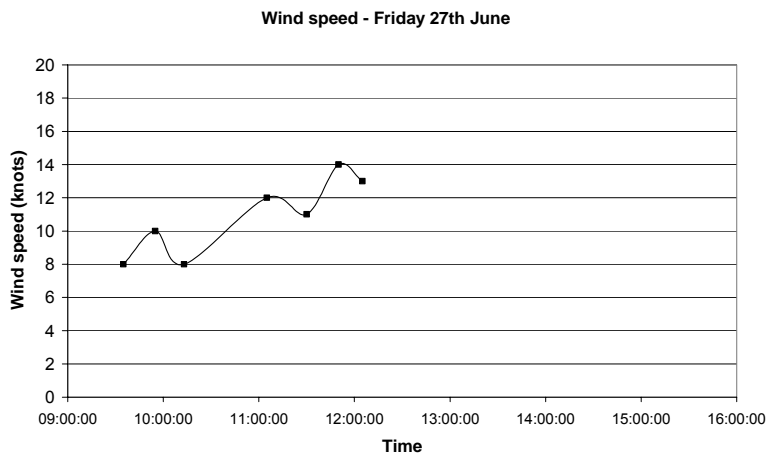
Figure 10.   *Wind speed on Friday 28th June*

Figure 11.   Conditions at midday on the Willcarry on Wednesday 26th June

3.5.2 Tests conducted

A reduced test programme was carried out because of the delay caused by the unsuitable sea conditions and this is shown in Table 5.

Test No.	Time	Oil	Dispersant	Nominal DOR
Wednesday 25th June				
1	09:40	IFO-80	Agma DR 379	1:25
2	10:20	IFO-80	Agma DR 379	1:50
3	10:50	IFO-80	Corexit 9500	1:50
Thursday 26th June				
10	10:10	IFO-180	Corexit 9500	1:25
11	10:25	IFO-180	Corexit 9500	1:50
12	10:40	IFO-180	Corexit 9500	1:100
14	11:00	IFO-180	Agma DR 379	1:25
17	11:30	IFO-180	Superdispersant 25	1:25
15	11:50	IFO-180	Superdispersant 25	1:50
10A	12:15	IFO-180	Corexit 9500	1:25
18	12:55	IFO-380	Superdispersant 25	1:25
50	13:30	IFO-380	Control (no dispersant)	
24	13:40	IFO-380	Corexit 9500	1:25
24A	13:55	IFO-380	Corexit 9500	1:25
18A	14:20	IFO-380	Superdispersant 25	1:25
19	14:40	IFO-380	Superdispersant 25	1:50
23	15:00	IFO-380	Agma DR 379	1:25
25	15:20	IFO-380	Corexit 9500	1:50
60	15:45	IFO-380	Control (no dispersant)	
Friday 27th June				
10F	09:40	IFO-180	Corexit 9500	1:25
14F	09:55	IFO-180	Agma DR 379	1:25
17F	10:15	IFO-180	Superdispersant 25	1:25
18F	11:05	IFO-380	Superdispersant 25	1:25
23F	11:30	IFO-380	Agma DR 379	1:25
24F	11:50	IFO-380	Corexit 9500	1:25
18FA	12:10	IFO-380	Superdispersant 25	1:25

Table 5.   Experiments conducted during sea trial

3.5.3 Nominal and actual dispersant treatment rates

As noted in section 3.3.2, the IFO-180 grade fuel oil appeared to spread in an irregular carpet that was approximately 0.5 to 1 metre wide, with an approximate average width of 0.7 metre, but was irregular and fluctuating in width in the wave action. The higher viscosity IFO-380 formed a generally narrower strip of oil around an average of 0.5 metres wide, but this did vary over a very wide range of at least 0.3 to 0.7 metres, as wave action progressed under the dispersant spray.

The actual amount of dispersant applied to the oil varied with oil layer thickness and therefore width. The estimated actual average dispersant treatment rates for each oil are given in **bold** in Table 6 with a typical range of minimum and maximum given in brackets on either side of the average figure.

Nominal DOR	IFO-180 Average 0.7 metre wide oil	IFO-380 Average 0.5 metre wide oil
1:25	(1:41) **1: 29** (1:20)	(1:58) **1:41** (1: 29)
1:50	(1:111) **1: 79** (1:55)	(1:158) **1:111** (1: 79)
1:100	(1:180) **1: 128** (1:90)	(1:257) **1:180** (1: 128)

Table 6.   Nominal and actual dispersant treatment rates

3.5.4 Observations made from the wing of *Willcarry*

The very low viewing angle from the *MCA Osprey* and *Jo-Dan* made it difficult to observe the dispersion process on some occasions. One of the expert observer, Hugh Parker, transferred to the *Willcarry* to make additional visual observations from the wing of the bridge. This afforded a more vertical viewpoint and observations were made very soon after the test oils were sprayed with the dispersants.

Notes on these visual observations are contained in Table 7.

26th June 2003

10:10	Test 10	Good coverage – complete dispersion
10:25	Test 11	Oil running along side of ship, but well treated. No initial dispersion with black oil past bridge wing but then good dispersion observed aft of the vessel.
10:40	Test 12	Oil drifted away from vessel side but still appeared to have been treated. Black oil visible - difficult to see dispersion.
11:00	Test 14	Dispersant spray atomising following nozzle change – foaming. Good dispersion away from ship.
11:30	Test 17	Dispersant spray atomising & foam in water but coverage appeared to be good. "Tea leaves" difficult to see but last traces appeared to disperse.
11:50	Test 15	Dispersant spray moving from side to side in wind. Oil draped down side of vessel. "Tea leaves" – no dispersion.
12:15	Test 10 A	"Tea leaves" dispersing as oil goes aft of stern.
12:55	Test 18	Tea leaves and dispersion. Dispersion aft in wash.
13:23	Test 50	Sheen & globules in carpet~ 1 metre wide
13:45	Test 24	Along side of vsl. Stringers and puffs of dispersed oil- - black in colour (larger droplets?).
13:55	Test 24 A	Globules & a few stringers. No dispersed oil seen.
14:20	Test 18 A	Globules & larger lumps. No dispersion
14:42	Test 19	Globules – No dispersion
15:00	Test 23	Large chunks Ø = 50 – 100 mm No dispersion
15:20	Test 25	Stringers & globules No dispersion
15:40	Test 60	IFO 380 - no dispersant

27th June 2003

09:35	Test 10 F	"Tea leaves" some dispersed oil early in run.
09:55	Test 14 F	"Tea leaves" dispersing in Patches
10:13	Test 17 F	Complete dispersion
11:05	Test 18 F	Stringers & some dispersion
11:30	Test 23 F	No dispersion Tea leaves, stringers and small globules
11:50	Test 24F	No dispersion Stringers & lumps
12:05	Test 18 FA	No dispersion

Table 7.   Visual observations made from the Willcarry.

Figure 12.   Dispersing oil as seen from the wing bridge of the Willcarry

Figure 13.   Untreated IFO-380 oil as seen from the wing bridge of the Willcarry

3.6   RESULTS OBTAINED

The results that were obtained from the sea trials are contained in Appendix 1. They are presented in table and graphical form (histograms). There was little variation in the visual observations recorded by the individual expert observers; each observer seemed to be seeing the same effects, although there were some slight discrepancies. The observations were also consistent in general trends.

The summarised results are contained in Table 8.

IFO-180 Tests							
Date	Time	Test	Dispersant and nominal treatment rate used	2 minute	5 minute	10 minute	Wind speed (knots)
26/06	10:10	10	Corexit 9500 at 1:25	**4**	**4**	**4**	12
26/06	12:15	10A	Corexit 9500 at 1:25	**3**	**3.2**	**3**	7
27/06	09:35	10F	Corexit 9500 at 1:25	**3**	**3**	**3**	8
26/06	10:25	11	Corexit 9500 at 1:50	**3.2**	**2.7**	**2.3**	12
26/06	10:40	12	Corexit 9500 at 1:100	**2.3**	**2.2**	**1.8**	11
26/06	11:30	17	Superdispersant 25 at 1:25	**1.7**	**2**	**1.8**	9
27/06	10:13	17F	Superdispersant 25 at 1:25	**2**	**2**	**2**	8
26/06	11:50	15	Superdispersant 25 at 1:50	**1**	**1**	**1**	8
26/06	11:00	14	Agma DR 379 at 1:25	**1.5**	**1.8**	**1.4**	10
27/06	09:55	14F	Agma DR 379 at 1:25	**2.2**	**2.8**	**2.5**	10

IFO-380 Tests							
Date	Time	Test	Dispersant and nominal treatment rate used	2 minute	5 minute	10 minute	Wind speed (knots)
26/06	13:45	24	Corexit 9500 at 1:25	**1**	**1**	**1**	8.5
26/06	13:55	24A	Corexit 9500 at 1:25	**1.1**	**1.2**	**1.2**	8
27/06	11:50	24F	Corexit 9500 at 1:25	**3**	**2**	**2**	14
26/06	15:20	25	Corexit 9500 at 1:50	**1.7**	**1.7**	**1.7**	8
26/06	12:55	18	Superdispersant 25 at 1:25	**2**	**2**	**2.3**	7.5
26/06	14:20	18A	Superdispersant 25 at 1:25	**2**	**2**	**2**	7.5
27/06	11:05	18F	Superdispersant 25 at 1:25	**2.5**	**2.2**	**2**	12
27/06	12:05	18FA	Superdispersant 25 at 1:25	**2.7**	**1.2**	**1.2**	13
26/06	14:42	19	Superdispersant 25 at 1:50	**1.4**	**1.6**	**1.4**	8
26/06	15:00	23	Agma DR 379 at 1:25	**1.6**	**1.6**	**1.5**	9
27/06	11:30	23F	Agma DR 379 at 1:25	**1.7**	**1.2**	**1.2**	11

Table 8.   Summarised results

Figure 14.   Dispersant in water under oil that is not being dispersed

3.6.1   Overview of dispersion of IFO-180 grade fuel oil

The IFO-180 fuel oil exhibited a viscosity of just over 2,000 cP at the sea temperature. It appeared to be rapidly and totally dispersed by Corexit 9500 at 12 knots wind speed when applied at a nominal DOR of 1:25 (actual DOR an average of 1:29, varying between 1:41 and 1:21).   The two other dispersants, Superdispersant 25 and Agma Superconcentrate DR 379 were not as effective as Corexit 9500 at the same nominal treatment rate and approximately the same wind speed, but appeared to cause a reasonable degree of dispersion of IFO-180 fuel oil.

There was an effect of wind speed. At lower wind speeds of 7 to 8 knots, Corexit 9500 at a DOR of 1:25 was seen to be less effective, but still appeared to cause moderately rapid dispersion of IFO-180.

There was an effect of dispersant brand. Superdispersant 25 were not as effective on IFO-180 as Corexit 9500, but still caused slow to moderately rapid dispersion at the higher wind speeds of 11 to 12 knots. Agma Superconcentrate DR 379 appeared to be slightly less effective than Superdispersant 25.

There was a marked effect of dispersant treatment rate. A reduction in treatment rate to a nominal DOR of 1:50 (average actual DOR of 1:70, varying from 1:111 to 1:55) caused a significant drop in performance of Superdispersant 25, but not of Corexit 9500. A reduction in treatment rate to a nominal DOR of 1:100 (average actual treatment rate of 1:128, varying between 1:180 and 1:90) caused a slight reduction in the visible effects of Corexit 9500. The other two dispersants were not tested at this treatment rate.

3.6.2   Overview of dispersion of IFO-380 grade fuel oil

The IFO-380 fuel oil used in these tests (which had a viscosity of 7,000 to 8,000 cP at sea temperature) did not appear to be rapidly and totally dispersed by any of the three dispersants when used at any of the treatments rates, ranging from nominal DORs of 1:25 to 1:100 (average actual DORs of between 1:41 and 1:180) at wind speeds of 7 to 9 knots.

There was an effect of wind speed. At wind speeds of 13 - 14 knots, the performance of both Superdispersant 25 and Corexit 9500 used at a DOR of 1:25 (average actual DOR of 1:41, varying between 1:58 and 1:29) improved to produce moderately rapid dispersion of IFO-380. The performance of Agma Superconcentrate DR 379 was less than that of the other two dispersants, but was not tested at the highest wind speeds.

3.6.3 UVF measurements

Some UVF (Ultra Violet Fluorometry) to measure dispersed oil concentrations was undertaken from the Sparrowhawk RIB, although the very small size of the slicks inevitably limited the usefulness of this technique. The weather conditions that prevailed in the early part of the trials were not conducive to small boat operations, either for safety or comfort of the crews and these were suspended a short time into the work.

Further UVF measurements were made with the towed 'fish' deployed from the deck of the *Willcarry*, but because of the small size of the test slicks the results were not conclusive.

Figure 15.   UVF measurements being taken from the Sparrowhawk RIB

3.7   DISCUSSION OF RESULTS

3.7.1   General trends

Since all three dispersants used in the sea trials have ay one time been approved for use in the UK, all three dispersant brands were known to achieve more than the 60% WSL result when tested with the specified 2,000 cP test oil at 10ºC at a treatment rate of a DOR 1:25. The three dispersants showed significant differences in performance at sea, as assessed visually in these sea-trials. The performance of a particular brand of dispersant at sea appeared to be a function of oil viscosity, dispersant treatment rate and prevailing wind speed (therefore sea state).

3.7.2   Effect of dispersant brand, treatment rate and wind speed

The IFO-180 fuel oil used in these tests appeared to be totally and rapidly dispersed by Corexit 9500 used at a nominal DOR of 1:25 at 12 knots wind speed. The other two dispersants (Superdispersant 25 and Agma Superconcentrate DR 379) appeared to be somewhat less effective, but still caused moderate dispersion when use at a nominal DOR of 1:25(actual DOR an average of 1:29, varying between 1:41 and 1:21).

The effects of the higher dispersant treatment rate and the higher wind speed in producing higher dispersant performance were more noticeable for the higher viscosity oil (IFO-380, with a viscosity of 7,000 – 8,000 cP at sea temperature) than for the lower viscosity oil (IFO-180, with a viscosity of approximately 2,000 cP at sea temperature), although the general level of dispersant performance with IFO-380 was low.

3.7.3   Effect of oil viscosity and treatment rate and wind speed

Spraying freshly spilled IFO-180 fuel oil with similar properties to that tested with any of the three dispersants at the recommended rate would appear to be effective (in operational terms) under similar conditions of sea temperature (15ºC) and sea state (wind speed of 12 knots or more).

At a lower wind speed of 7 – 8 knots, Corexit 9500 at a DOR of 1:25 still caused moderately rapid dispersion of IFO-180 and at a DOR of 1:100 (average actual treatment rate of 1:128, varying between 1:180 and 1:90) caused an appreciably lower level of slow and partial dispersion similar to that achieved by Superdispersant 25 and Agma Superconcentrate DR 379 at a nominal DOR of 1:25. Superdispersant 25 at a nominal DOR of 1:50 caused no significant dispersion of IFO-180.

The effectiveness of dispersant treatment of freshly spilled IFO-180 fuel oil with similar properties to that tested is much more dispersant brand dependent and treatment rate dependent at lower wind speeds than at higher wind speeds.

The IFO-380 fuel oil used in these tests (which had a viscosity of 7,000 to 8,000 cP at sea temperature) was not rapidly and totally dispersed by any of the three dispersants when used at treatments rates ranging from nominal DORs of 1:25 to 1:100 at wind speeds of 7 – 9 knots, but moderate dispersion appear to be achieved with both Superdispersant 25 and Corexit 9500 used at a DOR of 1:25 at wind speeds of 13 – 14 knots. Agma Superconcentrate DR 379 did not appear to be effective when used at a nominal DOR of 1:25 at a wind speed of 11 knots.

The apparent effectiveness of dispersant treatment of freshly spilled IFO-380 fuel oil with similar properties to that tested (i.e. with a viscosity of 7,000 - 8,000 cP at sea temperature) will be highly dependent on wind speed (sea state). Sea states associated with wind speeds in excess of 13 – 14 knots (i.e. Beaufort 4 and above) appear to be needed to cause effective dispersion with Superdispersant 25 and Corexit 9500 used at a DOR of 1:25.

3.7.4   The effect of oil viscosity

It should be noted that the different grades of IFO fuel oils were not taken as being typical or representative of all fuel oils of these IFO grades, since Heavy Fuels Oils (HFOs) vary very widely in properties such as Pour Point. It is perfectly possible for an IFO-180 or IFO-380 to have a Pour Point of +20ºC (the grade maximum limit is +30ºC) and therefore to be solid (effectively with infinite viscosity) at 15ºC and yet still conform to the grade viscosity maxima of 180 cP and 380 cP at 50ºC. This could occur with IFOs of any grade produced from waxy crude oils. However, the IFO-180 and IFO-380 fuel oils used in these sea trials were chosen to act as oil viscosity standards; they are representative of any oils that would have an oil viscosity of approximately 2,000 cP and 7,000 – 8,000 cP, respectively, at the prevailing sea temperature.

The sea trials were conducted with freshly spilled fuel oils; there was no time for evaporation of emulsification to occur before the oils were sprayed with dispersant. This was an intentional element of the experimental design and was used to limit the number of variables being studied.

These sea trials have shown that the amount of mixing energy available from waves at the prevailing sea is a particularly important aspect for the successful dispersion of relatively high viscosity oils. It has long been known that the rate of enhanced dispersion of dispersant-treated, initially low viscosity crude oils significantly increases when a significant amount of breaking wave action is present; the estimated rate of dispersion goes through a 'step-change' increase as the wind speed increases to above 7 – 10 knots (Beaufort Force 3). This is borne out by the behaviour of the slicks of IFO-180 treated with dispersants in these sea trials. There was moderate dispersion caused by Corexit 9500 at 8 knots wind speed and much more rapid and visible dispersion at a wind speed of 14 knots.

Dispersant spraying of spilled oils with a viscosity of approximately 2,000 cP at sea temperature is therefore most likely to be effective and rapid when the wind speed is above 10 knots although it is still likely to be effective, although less rapid, at lower wind speeds.

There appears to be a more marked effect with the higher viscosity IFO-380 fuel oil used in these sea trials. There was some transition from very little apparent dispersion at 7-9 knots wind speed, through to apparently moderate dispersion at 12 to 13 knots. This trend may continue, so that there would have been rapid dispersion of the IFO-380 fuel oil at 20 knots or higher wind speed. Unfortunately, although such higher wind speeds were encountered during the intended test period, it was not safe to proceed with the testing which involved relatively small boats that were 10 nm offshore.

There must be an operational upper limit on the wind speed at which dispersants can be used on any oil. A practical limit will be that spilled oil in very rough seas will spend a large proportion of the time being temporarily submerged. This probably occurs at around Beaufort Force 8 or 9 (between 30 and 37 knots mean wind speed), although aerial dispersant spraying operations have taken place, notably at the *Braer* incident, at higher winds speeds. It seem very likely that spilled oils with a similar viscosity to that of the IFO-380 used in these sea trials (7,000 – 8,000 cP at sea temperature) could be rapidly dispersed at winds speeds higher than 13 knots, but below the operational limit of 30 to 37 knots. Dispersant use should therefore still be considered on oils with this viscosity, if there are relatively high wind speeds.

3.7.5   The effect of dispersant brand

Dispersants that all achieve the minimum efficacy level in the WSL test for DEFRA approval purposes are not equivalent in their performance with oils at sea.

The sea trials demonstrated that there are significant differences between the visible effects caused by different dispersant brands; Corexit 9500 was clearly superior in dispersing the IFO-180 oil, dispersing it more rapidly and at lower treatment rates than Superdispersant 25 or Agma Superconcentrate DR 379.

It might be thought that the benefits of a higher performance dispersant would only become apparent when an oil of higher viscosity was to be dispersed. This has certainly seemed the case in some previous laboratory studies; all approved dispersants exhibit a high level of performance with 'easily dispersed', low viscosity oils, but differences are observed as the limiting oil viscosity (of the particular laboratory test) is approached. The results from the sea trial do not appear to confirm this.

Somewhat surprisingly, the differences in apparent dispersion caused by Corexit 9500 and Superdispersant 25 was less marked with the higher viscosity IFO-380 fuel oil, although all dispersants were generally less effective with the higher viscosity oil. Agma Superconcentrate DR 379 exhibited poor performance with the IFO-380 oil. Corexit 9500 and Superdispersant 25 appeared to be equally effective at dispersing the IFO-380.

Corexit 9500 has been shown, in laboratory tests and in some tests at sea, to be particularly effective at 'breaking' emulsions back to the constituent phases of weathered oil and water and then dispersing the oil. Since the IFO oils were treated with dispersant before they could emulsify, this aspect of the dispersant's performance was not evaluated.

Any decision to disperse high viscosity oils should consider any available information on the likely effectiveness of a particular dispersant brand. As described earlier, the results from different laboratory test methods give relative, but not absolute trends. Results from previous laboratory studies are currently being examined – as part of this project - to see whether any consistent trend that confirms the findings of the sea trial can be identified from the results obtained using different laboratory methods.

3.7.6 The effect of dispersant treatment rate

The treatment rates of dispersant, expressed as nominal DORs of 1:25, 1:50 and 1:100, used throughout this summary report are nominal values; they describe the relative proportions of the total amount of oil deposited and the amount of dispersant that was deposited on the nominal oil width of 1 metre. Since the test oils did not all spread out in the same way (different oil viscosity caused different spreading), or form discrete oil 'strips' of even width and thickness, the DOR values are not exactly the ratios of dispersant that were deposited on the oil. The actual treatment rates are shown in Table 6 and summarised in Table 9 for ease of reference.

Nominal DOR	Applied DOR (Minimum) **Average** (Maximum**)**	
	IFO-180	**IFO-380**
1:25	(1:41) **1: 29** (1:20)	(1:58) **1:41** (1: 29)
1:50	(1:111) **1: 79** (1:55)	(1:158) **1:111** (1: 79)
1:100	(1:180) **1: 128** (1:90)	(1:257) **1:180** (1: 128)

Table 9.

Any operational use of dispersants has to use nominal dispersant treatment rates; the amount of spilled oil is rarely known and the oil slick varies greatly in thickness from place to place. Experimental design features ensured that all the test oils were sprayed more accurately with dispersant than could ever be achieved at a real oil spill. Further results analysis will attempt to determine more precise dispersant treatment rates, so that follow-up laboratory studies can be conducted.

In most laboratory test methods, the required amount of dispersant can be added very evenly and precisely to the test oil. The dispersant is added drop-wise to a confined area of oil and is allowed to soak in before the treated oil and seawater are mixed. Some of these test results have indicated that some dispersants can be effective on some oils at a treatment level of a DOR of 1:100 or even 1:200. If dispersants could be used effectively at a quarter or one-eighth of the recommended treatment rates, there would be significant savings in cost and operational complexity.

The results from these sea-trials show that there is the expected effect of dispersant treatment rate; less dispersant is less effective. Only Corexit 9500 appeared to be partially effective when used on IFO-180 at a DOR of 1:100 (average actual treatment rate of 1:128, varying between 1:180 and 1:90). Superdispersant 25 was essentially ineffective when used at a DOR of 1:50 on IFO-180.

Very low dispersant treatment rates of 1:100 or less are not practical when dispersants are used outside of laboratory tests. The dispersant losses caused by wind-drift and the inaccuracies encountered during any dispersant spraying operation at sea mean that greatly reduced treatment rates cannot be recommended for dispersant use.

4. COMPARISON OF THE SEA TRIAL RESULTS WITH RESULTS FROM LABORATORY TESTS

A lot of results on the dispersibility of HFOs using different laboratory methods have been obtained by organisations such as AEA Technology in the UK, CEDRE in France and SINTEF in Norway. Not all of these results are in the public domain, some having been conducted under "commercial-in-confidence" contracts. However, some information is contained in papers that have been presented at various conferences.

4.1 RESULTS FROM TESTING AT AEA TECHNOLOGY

Reports by AEA Technology have been prepared for DEFRA (as MAFF) and for the MCA. The major AEA Technology report for MAFF on this topic was "Developing a dispersant efficacy test for Type 4 dispersants", AEA Technology Report AEAT-5806 and MAFF Project Code AE0811) with the project completed on 04/06/1999.

The major AEA Technology reports for MCA on this topic are:

(i) "Dispersion of emulsified oil at sea" AEA Technology report AEAT-3475 dated June 1998.
(ii) "Dispersion of Emulsified Oils at Sea – Laboratory Study" AEA Technology report AEAT-4347 dated October 1998.
(iii) "A response to heavy fuel oil spills in the UK" AEA Technology Report AEAT-4982 dated March 1999.

4.1.1 IFO-180 grade fuel oil used in sea trials

20 tonnes of IFO-180 grade fuel oil was used in the AEA Technology 1997 sea trials, as described in the first of the AEA Technology reports (AEAT-3475).

The IFO-180 grade fuel oil used in 1997 had been obtained from a different source to that used in the 2003 sea-trials and exhibited a slightly higher viscosity of approximately 2,300 cP at the prevailing sea temperature of 15ºC.

The average wind speed at the 1997 sea trials at the time of the release of the IFO-180 oil onto the sea was 5 m/s (10 knots). The oil was allowed to emulsify on the sea surface for $4^1/_2$ hours, during which time it lost some of the distillate blend components and emulsified to approximately 30% volume water content. The viscosity of the emulsified oil before the initial dispersant treatment was approximately 7,000 cP.

The first dispersant spraying from a DC-3 aircraft resulted in an average dispersant treatment rates expressed as DOR (Dispersant to Oil Ratio), of 1:30. Some of the oil dispersed, but a significant proportion, estimated to be about 50%, remained on the sea surface. The spray aircraft was unable to continue dispersant spraying on the same day for technical reasons and the remaining oil was on the sea surface overnight. During this time it emulsified to a higher degree. Dispersant spraying of the oil after 23 hours on the sea surface at an estimated DOR of 1:14 produced little effect. Further dispersant spraying at the same estimated treatment rate on two further occasions, to produce cumulative DORs of between 1:4 and 1:2 achieved little.

4.1.2   Laboratory results of IFO-180 dispersibility testing

The second AEA Technology report for the MCA, "Dispersion of Emulsified Oils at Sea – Laboratory Study" (AEAT-4347) concentrated on reproducing the weathering of the oil and then testing Corexit 9500 at different treatment rates on the residues and emulsions that had been produced.

The results from laboratory testing using the WSL method on the evaporative loss residues are contained in Table 9, below.

DOR using Corexit 9500	0% evaporation loss	2% evaporation loss	4% evaporation loss	8% evaporation loss
	2,313 cP at 15ºC at 10 s^{-1}	2,633 cP at 15ºC at 10 s^{-1}	3135 cP at 15ºC at 10 s^{-1}	6,008 cP at 15ºC at 10 s^{-1}
1:10	89	90	76	92
1:25	95	86	74	86
1:50	86	80	83	64
1:100	66	77	73	52

Table 9.   WSL results with IFO-180 using Corexit 9500

The IFO-180 grade fuel oil used in the 2003 sea-trails would produce very similar WSL results to those in the above Table. Since there was no significant time for evaporative loss of the distillate component to occur, the results in the first column (0% evaporative loss) are the most relevant.

All WSL results are above the 60% 'pass-mark' with the specified test oil (with a viscosity of 2,000 cP at 10ºC) that is required for UK efficacy approval.

4.1.3   Laboratory results of IFO-380 dispersibility testing

No sea trials have previously been conducted using IFO-380 grade fuel oil.

The AEA Technology report "A response to heavy fuel oil spills in the UK" (AEAT-4982) contains WSL test results from testing IFO-380 grade fuel oils from different sources. Five dispersants were used, including the three dispersants used at the 2003 sea-trials.

The batch of IFO-380 fuel oil, described in this report as being from Milford Haven, had a slightly higher viscosity than the IFO-380 fuel oil used in the 2003 sea trials (Table 10).

The batch of IFO-380 fuel oil, again described as from Milford Haven, and used to produce the 'lightly emulsified' (20% to 25% water content) fuel oils tested to produce the results in "Developing a dispersant efficacy test for Type 4 dispersants" (AEAT-5806) was even more viscous. Since only the emulsified oil was used in the testing contained in the report, the results are of limited relevance to this report.

	Density @ 20ºC (gm/ml)	Viscosity (mPa.s or cP centiPoise) 15ºC @10s^{-1}
IFO-380 used in 2003	0.983	7,100
IFO-380 in AEAT-4982	0.989	10,117
IFO-380 in AEAT-5806	n/a	14,818

Table 10.   Comparison of oil viscosity

The results from the AEAT-4982 report show a wide range of WSL results from the different dispersants at different treatment rates (Table 11).

	Dispersant efficiency on Milford Haven IFO-380 Viscosity 10,117 cP @ 10s^{-1} , Temperature 15°C				
DOR	**Agma DR379**	**Corexit 9500**	**Dasic Slickgone LTSW**	**Dasic Slickgone NS**	**Super dispersant 25**
1:25	26%	51%	53%	22%	63%
1:50	12%	48%	42%	24%	52%
1:100	9%	45%	33%	31%	50%
1:200	-	41%	-	22%	-

Table 11.   WSL results with IFO-380 and several dispersants

4.1.4   The 15% WSL result 'threshold' hypothesis

The AEA Technology reports, and the contents of other reports papers presented at conferences, put forward the hypothesis, based upon an interpretation of results from earlier sea-trials that successful or effective dispersion at sea would be achieved by dispersant and oil combinations that produced WSL results in excess of a 'threshold' 15% value.

There were some caveats; this hypothesis might only hold for wind speeds above 5 m/s (10 knots) and might need to be doubled to a 30% threshold for wind speeds below 10 knots. The single 15% WSL threshold was subsequently modified to a three-zone approach, firstly to "Natural dispersion: $\leq$ 5%; Reduced dispersibility: > 5% and < 15%; Dispersible: $\geq$ 15 %" and finally "$\geq$21%, <21% to >11% and $\leq$11% WSL results" to indicate "effective dispersion, partial dispersion and no dispersion" in the AEAT-4982 report.

Whether these proposed 'threshold' levels of dispersion in the WSL test could be equated to an operationally significant level of performance at sea remained the key question and all these reports stressed that a sea-trial would needed to be held to prove or disprove this hypothesis.

4.2   COMPARISON OF SEA TRIAL RESULTS WITH WSL TEST RESULTS FOR IFO-180 OIL

A direct comparison of all of the 2003 sea trial results obtained with the IFO-180 test oil with the WSL test method results on the similar IFO-180 test oil at the same temperature (15ºC) is contained in Table 12.

Dispersant and nominal treatment rate used	Average actual treatment rate (DOR)	Sea Trial average ranking at 2 mins	Wind speed (knots)	WSL test result (%)
Corexit 9500 at 1:25	1: 29	4	12	95
Corexit 9500 at 1:25	1: 29	3	7	95
Corexit 9500 at 1:25	1: 29	3	8	95
Corexit 9500 at 1:50	1: 79	3.2	12	86
Corexit 9500 at 1:100	1: 128	2.3	11	66
Superdispersant 25 at 1:25	1: 29	1.7	9	-
Superdispersant 25 at 1:25	1: 29	2	8	-
Superdispersant 25 at 1:50	1: 79	1	8	-
Agma DR 379 at 1:25	1: 29	1.5	10	-
Agma DR 379 at 1:25	1: 29	2.2	10	-

Table 12

Only the average observation ranking made at 2 minutes had been used to represent the sea trial result. Only the results from tests using Corexit 9500 were available. As noted earlier, the sea trial results were greatly affected by the wind speed, but there does appear to be some correlation – albeit with very restricted data – for the effect of treatment rate between the sea trial rankings and the WSL test method results at 11 or 12 knots wind speed, as contained in Table 13.

Dispersant and nominal treatment rate used	Average actual treatment rate (DOR)	Sea Trial average ranking at 2 mins	Wind speed (knots)	WSL test result (%)
Corexit 9500 at 1:25	1: 29	4	12	95
Corexit 9500 at 1:50	1: 79	3.2	12	86
Corexit 9500 at 1:100	1: 128	2.3	11	66

Table 13.

The difference between a sea-trial category 4 observation ("Very rapid and total dispersion") and a sea trial category 2 observation ("Slow or partial dispersion") at a wind speed of between 11 and 12 knots is covered by the range of 66% to 95% in the WSL test result.

4.3 COMPARISON OF SEA TRIAL RESULTS WITH WSL TEST RESULTS FOR IFO-380 OIL

A direct comparison of all of the sea trial results obtained with the IFO-380 test oil with the WSL test method results on the similar IFO-380 test oil at the same temperature (15ºC) is contained in Table 14.

Dispersant and nominal treatment rate used	Average actual treatment rate (DOR)	Sea Trial average ranking at 2 mins	Wind speed (knots)	WSL test result (%) Treatment rate (DOR)
Corexit 9500 at 1:25	1:41	1	8.5	48% (1:50)
Corexit 9500 at 1:25	1:41	1.2	8	48% (1:50)
Corexit 9500 at 1:25	1:41	2.3	14	48% (1:50)
Corexit 9500 at 1:50	1:111	1.7	8	45% (1:100)
Superdispersant 25 at 1:25	1:41	2.1	7.5	52% (1:50)
Superdispersant 25 at 1:25	1:41	2	7.5	52% (1:50)
Superdispersant 25 at 1:25	1:41	2.2	12	52% (1:50)
Superdispersant 25 at 1:25	1:41	2.7	13	52% (1:50)
Superdispersant 25 at 1:50	1:111	1.4	8	50% (1:100)
Agma DR 379 at 1:25	1:41	1.6	9	12% (1:50)
Agma DR 379 at 1:25	1:41	1.7	11	12% (1:50)

Table 14.

There are two sub-sets of data within the table; results obtained with wind speeds between 7.5 and 9 knots, and fewer results obtained at wind speeds of between 11 and 14 knots.

There is insufficient data to carry out a statistically significant analysis, but some weak trends are apparent. Category 1 rankings at the sea trial ("No obvious dispersion") and category 2 observations ("Slow or partial dispersion") at 7 to 9 knots wind-speed correlate with WSL results of approximately 50%.

At higher wind-speeds of 11 to 14 knots, observations slightly higher than the category 2 observation ("Slow or partial dispersion") correlate weakly with a WSL result of 50%, but the lone lower average observation result of 1.7 is equivalent to a WSL result of 12%.

4.4 OVERALL COMPARISON OF WSL RESULTS AND OBSERVATIONS MADE AT SEA TRIALS

WSL testing of fuel oils with very similar properties to those used in the sea trials, and with the same dispersants and equivalent treatment rates, produced generally high WSL results, even when the observations at the sea-trials indicated little visible dispersion. WSL results of around 50% were found for combinations of test oil, dispersant and treatment rate that produced only category 1 ("No obvious dispersion") or category 2 ("Slow or partial dispersion") observations at the sea-trials.

Visual observations at the sea-trial showed that, in many of these cases, the test oil was not converted into oil droplets by passage of a cresting wave through the slick. The oil layer was distorted by the wave action and temporarily submerged, but even if the oil was broken up to some degree, it was only into large globules which rapidly resurfaced. In addition, the dispersants were seen to be washed off into the water as a white cloud with the large globules of black oil clearly visible against the white background created by the dispersant in the water.

The behaviour of the oil and dispersant under the influence of mixing at sea is completely different from that which occurred in the WSL test method (and described in Section 2.3.2) to produce the high WSL results.

There were several distinct difference between the behaviour observed at sea and the behaviour in the WSL test method:

(i)   In the WSL test method the dispersant is added to the oil, drop-wise from a syringe, and allowed to soak into the test oil for one minute before the end-over-end rotation of the flask is started. This obviously could not occur at sea, and if the test oil slick was submerged by a wave shortly after it was sprayed with dispersant, the dispersant was seen to be washed off before it had penetrated into the oil.

The soaking period was introduced into the WSL test procedure to improve repeatability. However, it may have also added an effect which is particularly unrealistic for high-viscosity oils.

(ii) In the WSL method the dispersant-treated test oil is mixed into the seawater of the test by a rapid sequence of 60 miniature 'plunging breaker' wave actions as the air and water are displaced as the flask rotates. This provides far more mixing action than was seen to be supplied by the occasional cresting wave passing through the test slicks at the 7 to 14 knot wind speed that prevailed during the sea-trials.

This over-abundance of mixing action may not be critical for low-viscosity oils, such as freshly spilled crude oils, because it might represent a speeding-up of a process that would eventually happen; the prevailing wave action would eventually break up the slick of low-viscosity, dispersant-treated oil into oil droplets that would subsequently be dispersed. This is not the case for higher viscosity oils.

The fuels oils used in the sea-trials, particularly the higher viscosity IFO-380 grade fuel oil, possessed a sufficiently cohesive nature to resist the action of a cresting wave in breaking it up into droplets. The large globules of oil were temporarily submerged, but obviously not dispersed by a single cresting wave. By the time that subsequent cresting waves passed through the oil again, it had more or less recovered its initial physical form and was able to resist the impact of the cresting wave.

It is not possible to say whether it was the wash-off of the dispersant, or whether it was the basic physical characteristic of the oil that prevented subsequent dispersion; both effects are caused by the same factor, the high viscosity of the oil. Nevertheless, the oil did not undergo the first stage of the dispersion process at sea; that of being converted to oil droplets of a wide range of sizes, while it did undergo this process in the WSL test.

(iii)   The results measured in the WSL method is caused by the differences in the buoyancy (rise velocity) of the different sizes of oil droplets produced during the initial, intense mixing phase. Since no obvious oil droplets of any sizes were produced by the cresting wave action on some combinations of IFO-380 test oil and dispersants at sea, the WSL results did not simulate the process that occurred at sea; there was no subsequent "sorting" of the proportion of oil converted into different droplet sizes, because no significant proportion of the oil was converted into oil droplets at sea.

The WSL test method, like any other laboratory test method for testing dispersants, is only a broad simulation of the mixing processes that occur at sea. For its intended purpose of providing a relative result to discriminate between the effectiveness of candidate dispersants for approval purposes, it is probably adequate. The application of the WSL method to high-viscosity, high-density fuel oils has highlighted the limitations of the test method and produces results that can be misleading.

The WSL test method appears to simulate, to some degree, a mixing regime that is more intense than that which occurs in waves associated with 7 to 14 knot wind speeds.

The WSL test method was originally adopted to replace the 'harbour test' method, briefly described in Section 3.4. The significant difference between the 'harbour test' method and the sea-trials described in this report was that the 'harbour test' method used an agitation or 'breaker' board, towed behind the test vessel to provide additional agitation, whereas the UK 2003 sea-trials did not. This is in keeping with the differences in the operational use of dispersants; in the early to mid-1980s, ships spraying dispersant could tow large 'breaker' boards (a series of pallets lashed together), but almost all dispersant spraying operations these days will be conducted by aircraft.

It seems very probable that the WSL method would produce a better correlation with dispersant performance at sea if 'breaker boards' were used. Since it is not feasible to use additional agitation devices, a new correlation between the results of the WSL method and observations at sea should be sought.

4.5 TRANSLATING A WSL RESULT ON FUEL OILS INTO EXPECTED DISPERSANT PERFORMANCE AT SEA

The results of the sea-trial, and the observation methods used in the sea trial, indicate that there is a broad correlation between the visual estimate of dispersion proceeding and the results from the WSL test method:

- A very high WSL test result of above 80% does seem to be an indicator that there will be visibly rapid and apparently total dispersion of fuel oil at sea in wind speeds of at least 11 or 12 knots. The dispersion process will be slower at lower winds speeds of around 8 knots.

- A WSL result of 60% indicates that there will still be a degree of dispersion, but that it may only appear to be partial and will proceed more slowly, particularly at wind speeds of around 7 to 8 knots.

- A WSL result of approximately 50%, or lower, indicates that the dispersion process will be visibly very slow and proceed to a partial extent or that there will be no visible dispersion.

The results indicate that the proposed WSL 'threshold' value of 15% does not discriminate between effective and non-effective dispersion. Under the conditions of the sea trial, a much higher WSL 'threshold' of between 60% and 80% discriminated between visibly very effective (very rapid and nearly total dispersion) and apparently ineffective (slow or partial dispersion). These trends are only strictly applicable to heavy fuel oils of the IFO-180 and 380 grades and in wind speeds of 8 to 14 knots at the sea temperature of 15ºC that was used in the sea trial.

Slower, longer-term dispersion, if it subsequently occurs, was not the subject of these investigations.

5. CONCLUSIONS

1. The sea-trials investigated the part of the dispersion of heavy fuel oils that is easily visible to a trained observer. This initial stage of dispersion is the break-up of a dispersant-treated oil slick into oil droplets under the influence of breaking or cresting waves. This effect was observed to occur with some test oil and dispersant combinations and was observed not to occur with other test oil and dispersant combinations. The observations were reliable and consistently made by observers. This effect was taken as an indicator of subsequent dispersion of the oil on the basis that if it happened, then the subsequent stages of dispersion would occur, but that if it did not occur, then any further dispersion would probably not take place.

2. Under the conditions of the sea trial (with a sea temperature of 15ºC and wind speeds varying between 7 and 14 knots), it was found that the IFO-180 grade test oil could be rapidly and apparently totally dispersed by some dispersants at some treatment rates. It was much more difficult to disperse the IFO-380 grade fuel oil under the same conditions and only slow and partial dispersion was observed in some cases.

3. There were visibly evident differences in the rate and degree of dispersion caused by:

    1. Oil viscosity
        The 2,000 cP at 15ºC IFO-180 grade fuel oil could be rapidly dispersed, but the 7,000 cP at 15ºC IFO-380 grade fuel oil could not be rapidly dispersed.

    2. Wind speed
        The IFO-180 grade fuel oil was rapidly dispersed by a treatment with Corexit 9500 at a nominal DOR of 1:25 at a wind speed of 12 knots, but more slowly at a wind speed of 8 knots.
        There was similar effect with the IFO-380 grade fuel oil; it could be dispersed to a greater degree at a wind speed of 14 knots than at 8 knots, but in both cases there was only an apparently slow and partial dispersion evident by visual observation.

    3. Dispersant brand
        Corexit 9500 was more effective than Superdispersant 25 which was more effective than Agma Superconcentrate DR 379 in dispersing the IFO-180 grade fuel oil. Corexit 9500 and Superdispersant 25 exhibited a low, but similar, level of performance with the IFO-380 grade fuel oil and Agma Superconcentrate DR 379 exhibited a very low level of performance with this oil.

    4. Treatment rate
        Dispersants applied at a nominal treatment rate of a DOR of 1:25 were more effective than when applied at a nominal DOR of 1:50 or 1:100. Only Corexit 9500 exhibited some low level of dispersion of the IFO-180 grade fuel oil when used at 1:100.

The application of dispersants to the IFO-380 grade fuel oil resulted in actual dispersant rates that were approximately half of the intended nominal treatment rates. Nominal DORs of 1:25, 1:50 and 1:100 produced average DORs of 1:41, 1:111 and 1:180.

4. Comparing the results obtained at the sea-trial with IFO-180 and IFO-380 fuel oils, and under the prevailing conditions of a sea temperature of 15ºC and wind speeds of 8 to 14 knots, with WSL test results previously obtained on fuel oils with very similar properties shows that there is a broad correlation between visual observations and WSL test results:

WSL TEST RESULT (%)	VISIBLE EFFECTS
Above 80%	Rapid and total dispersion
60% - 80%	Moderately rapid dispersion
50% - 60%	Slow and partial dispersion
Below 50%	No significant dispersion

The WSL result 'threshold' that discriminates between 'effective' and 'not effective' dispersion for fuel oils at wind speeds of between 8 and 14 knots appears to be approximately 60% to 80%. It is suggested that a WSL results of 60% be used to decide whether visibly rapid dispersion will occur.

5. The results suggest that IFO-180 grade fuel oils could be readily dispersed in summer sea temperatures around the UK provided that the prevailing wind speed is at least 5 to 8 knots.

6. The marked effect of wind speed on the ability of dispersants to disperse these grades of fuel oils suggests that IFO-380 grade fuel oil may be dispersible at higher wind speeds. The precise effect is not known because the sea trials could not proceed with 20 knot winds for safety reasons. However, dispersion of the IFO-380 grade fuel oil did appear to take place with both Corexit 9500 and Superdispersant 25 when used at a nominal DOR of 1:25 (average actual DOR of 1:41) of at 13 knot and 14 knot wind speeds. A high level of dispersion may have occurred with 20 knot winds.

7. The physical state of spilled IFO-380 fuel oil on the sea surface will influence the potential effectiveness of dispersant use. The maximum permitted Pour Point for IFO-380 grade fuel oil is +30ºC. Some IFO-380 fuel oils could therefore be solid at typical UK sea temperatures. Even if they are not solid, many IFO-380 fuel oils will float as lumps and patches of oil that are many centimetres thick. In some circumstances, dispersant spraying will be incapable of delivering sufficient dispersant to cause effective dispersion, or it will be washed off before it can penetrate into the oil.

APPENDIX 1

RESULTS OBTAINED
IN SEA TRIALS

Wednesday 25th June - Test 1: IFO-180 with Agma DR 379 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	10	20	30	10	20	30	10	20	30	10	20	3
K Colcomb				X	X							
R Law				X	X							
A Lewis				X	X							
F X Merlin							X	X				
K Purnell							X	X				
D Salt				X	X							

Wednesday 25th June - Test 2: IFO-180 with Agma DR 379 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	10	20	30	10	20	30	10	20	30	10	20	3
K Colcomb	X											
R Law	X											
A Lewis	X											
F X Merlin				X								
K Purnell							X					
D Salt				X								

Wednesday 25th June - Test 3: IFO-180 with Corexit 9500 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	10	20	30	10	20	30	10	20	30	10	20	3
K Colcomb	X			X								
R Law	X	X										
A Lewis		X		X								
F X Merlin				X	X							
K Purnell				X	X							
D Salt	X	X										

Thursday 26th June - Test 10: IFO-180 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb										X	X	X
R Law										X	X	X
A Lewis										X	X	X
F X Merlin										X	X	X
K Purnell										X	X	X

Thursday 26th June - Test 11: IFO-180 with Corexit 9500 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb					X?	X?	X	X?	X?			
R Law					X	X						
A Lewis					X	X						
F X Merlin					X					X		
K Purnell							X	X	X			

Thursday 26th June - Test 12: IFO-180 with Corexit 9500 at 1:100

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X				X				
R Law						X	X					
A Lewis			X	X								
F X Merlin				X	X							
K Purnell				X?		X	X?					

Thursday 26th June - Test 14: IFO-180 with Agma DR 379 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X?			X?	X	X						
R Law	X		X		X							
A Lewis				X	X							
F X Merlin	X	X										
K Purnell				X	X							

Thursday 26th June - Test 17: IFO-180 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X?		X	X?	X							
R Law				X	X	X						
A Lewis			X	X	X							
F X Merlin				X	X							
K Purnell				X	X	X						

Thursday 26th June - Test 15: IFO-180 with Superdispersant 25 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X	X	X									
R Law	X	X	X									
A Lewis	X	X	X									
F X Merlin	X	X	X									
K Purnell	X	X	X									

Thursday 26th June - Test 10A: IFO-180 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb							X	X	X			
R Law							X	X	X			
A Lewis				X				X	X			
F X Merlin										X	X	
K Purnell							X	X	X			

Thursday 26th June - Test 18: IFO-380 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X	X	X						
R Law				X	X	X						
A Lewis				X	X				X			
F X Merlin				X	X	X?			X?			
K Purnell				X	X	X						

Thursday 26th June - Test 50: IFO-380 no dispersant

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X	X	X									
R Law	X	X	X									
A Lewis	X	X	X									
F X Merlin	X	X	X									
K Purnell	X	X	X									

Thursday 26th June - Test 24: IFO-380 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X	X	X									
R Law	X	X	X									
A Lewis	X	X	X									
F X Merlin	X	X	X									
K Purnell	X	X	X									

Thursday 26th June - Test 24A: IFO-380 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X?	X		X?								
R Law	X	X	X									
A Lewis	X		X		X							
F X Merlin	X	X										
K Purnell	X	X				X						

Thursday 26th June - Test 18A: IFO-180 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X	X	X						
R Law				X	X	X						
A Lewis				X	X	X						
F X Merlin				X	X	X						
K Purnell				X	X	X						

Thursday 26th June - Test 19: IFO-180 with Superdispersant 25 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X	X	X									
R Law				X	X							
A Lewis		X			X							
F X Merlin	X	X	X									
K Purnell				X	X							

Thursday 26th June - Test 23: IFO-380 with Agma DR 379 at 1:25

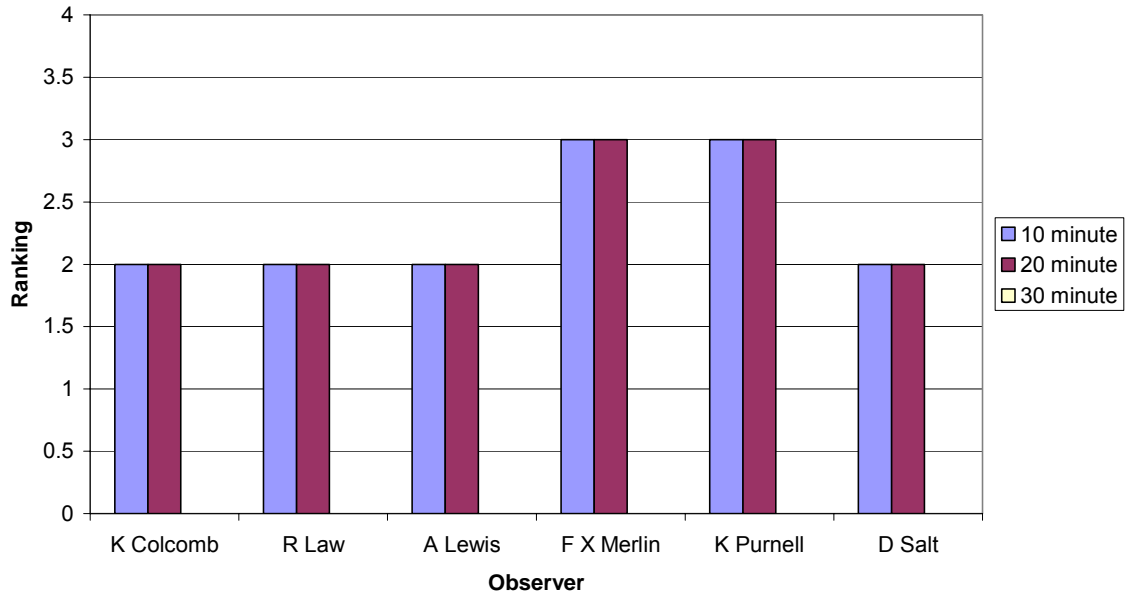| Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X?			X?	X							
R Law				X	X							
A Lewis		X	X	X								
F X Merlin	X?	X	X	X?								
K Purnell	X				X	X						

Thursday 26th June - Test 25: IFO-380 with Corexit 9500 at 1:50

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X	X	X						
R Law				X	X	X						
A Lewis				X	X	X						
F X Merlin	X?	X?		X?	X?							
K Purnell	X	X										

Thursday 26th June - Test 60: IFO-380 with no dispersant

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb	X	X										
R Law	X	X										
A Lewis	X	X										
F X Merlin	X	X										
K Purnell	X	X										

Friday 27th June - Test 10F: IFO-180 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb							X	X	X			
A Lewis							X	X	X			
K Purnell							X	X	X			

Friday 27th June - Test 14F: IFO-180 with Agma DR 379 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X?	X?	X?	X?	X?	X?			
A Lewis				X		X		X				
K Purnell				X				X	X			

Friday 27th June - Test 17F: IFO-180 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb				X	X	X						
A Lewis				X	X	X						
K Purnell				X	X	X						

Friday 27th June - Test 18F: IFO-380 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb					X	X	X?					
A Lewis				X	X	X	X?	X?				
K Purnell				X?	X	X	X?					

Friday 27th June - Test 23F: IFO-380 with Agma DR 379 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb		X	X	X								
A Lewis		X	X	X								
K Purnell	X	X?	X?	X?	X?							

Friday 27th June - Test 24F: IFO-380 with Corexit 9500 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb		X	X				X					
A Lewis					X	X	X					
K Purnell							X	X	X			

Friday 27th June - Test 18FA: IFO-380 with Superdispersant 25 at 1:25

Observer	1 No obvious dispersion			2 Slow or partial dispersion			3 Moderately rapid dispersion			4 Very rapid and total dispersion		
Minutes	2	5	10	2	5	10	2	5	10	2	5	10
K Colcomb		X	X				X					
A Lewis				X	X	X	X?					
K Purnell				X?	X	X	X?					

Test 1

Test 2
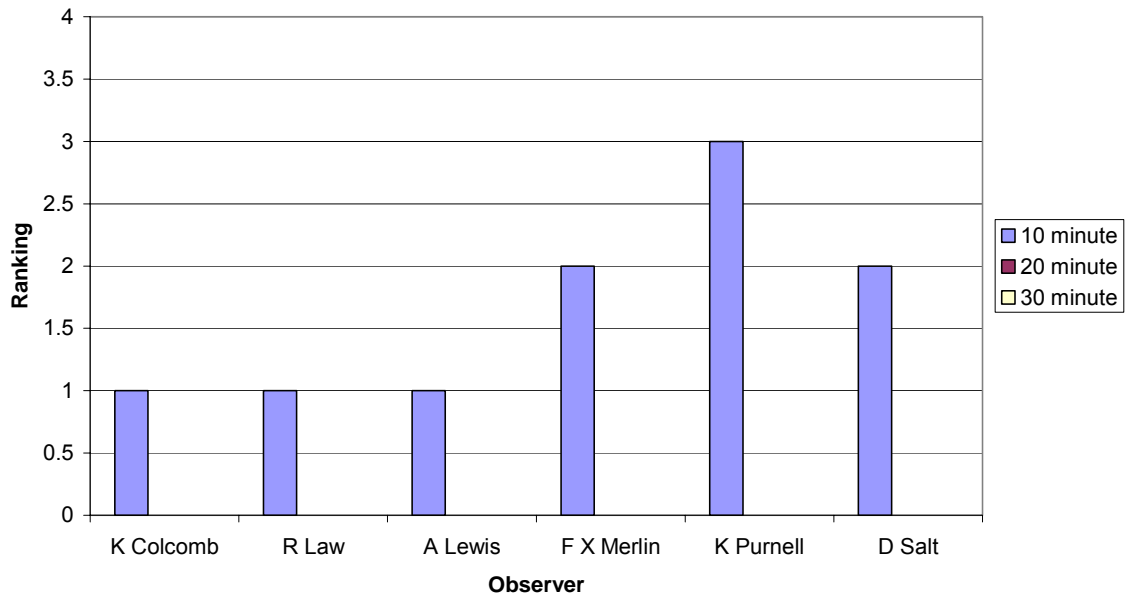
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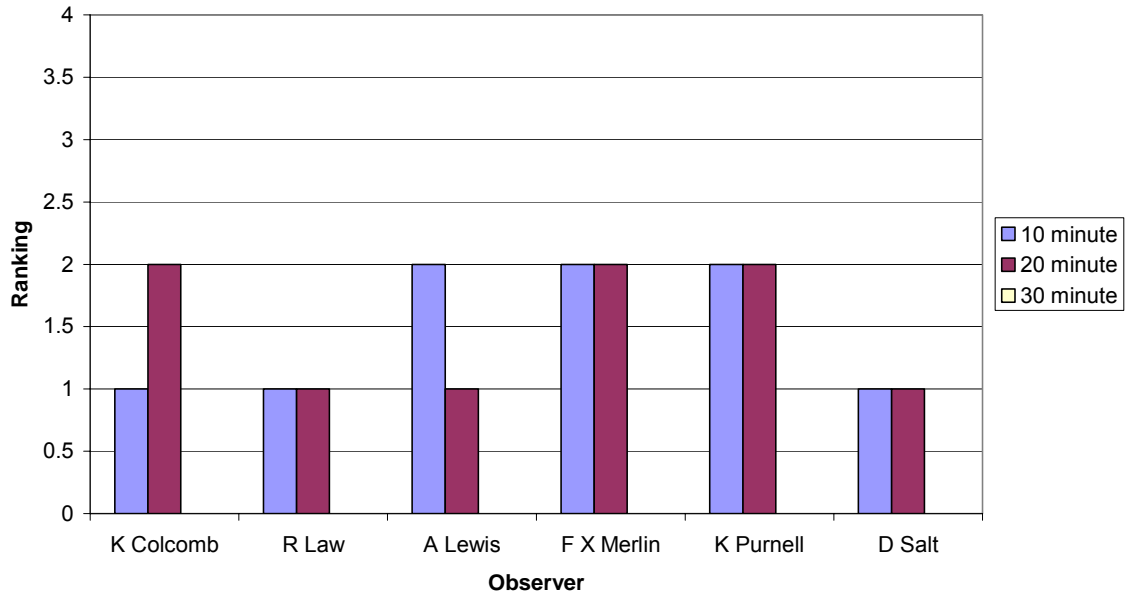
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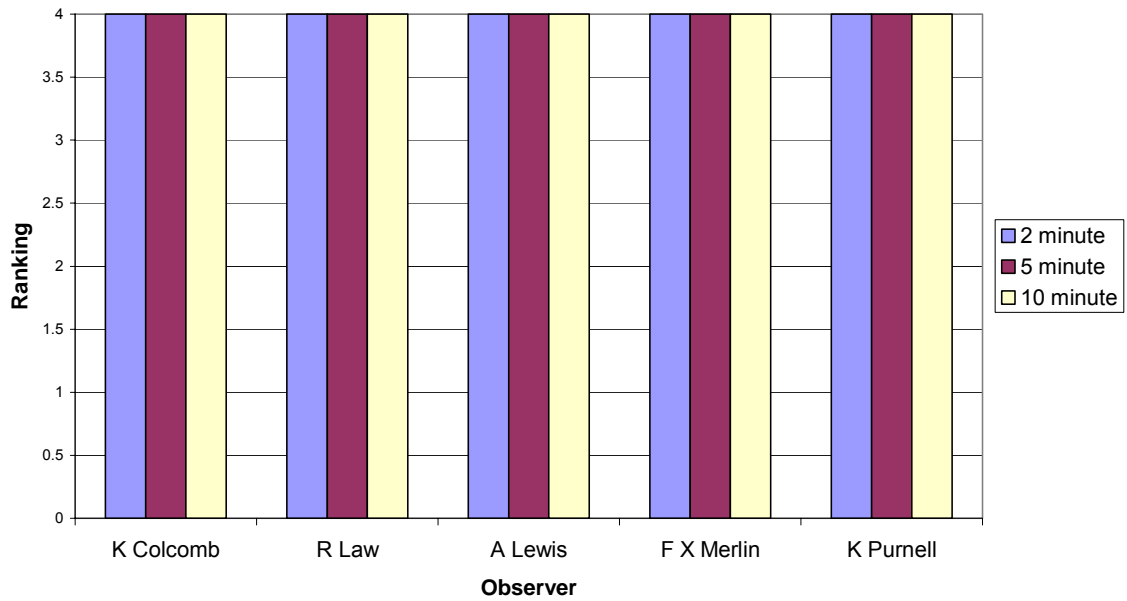
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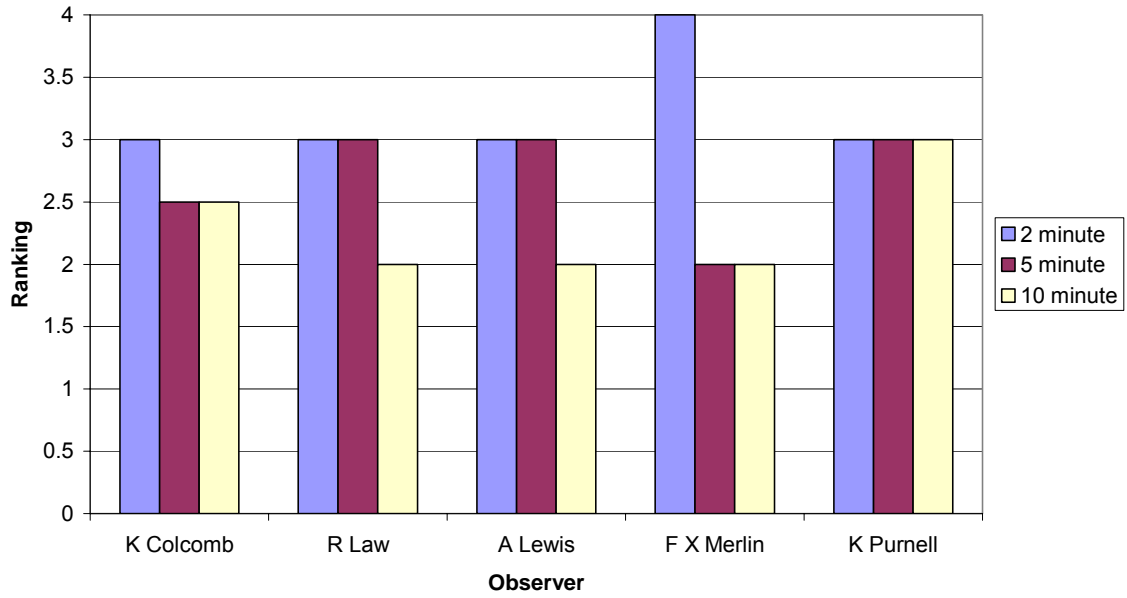
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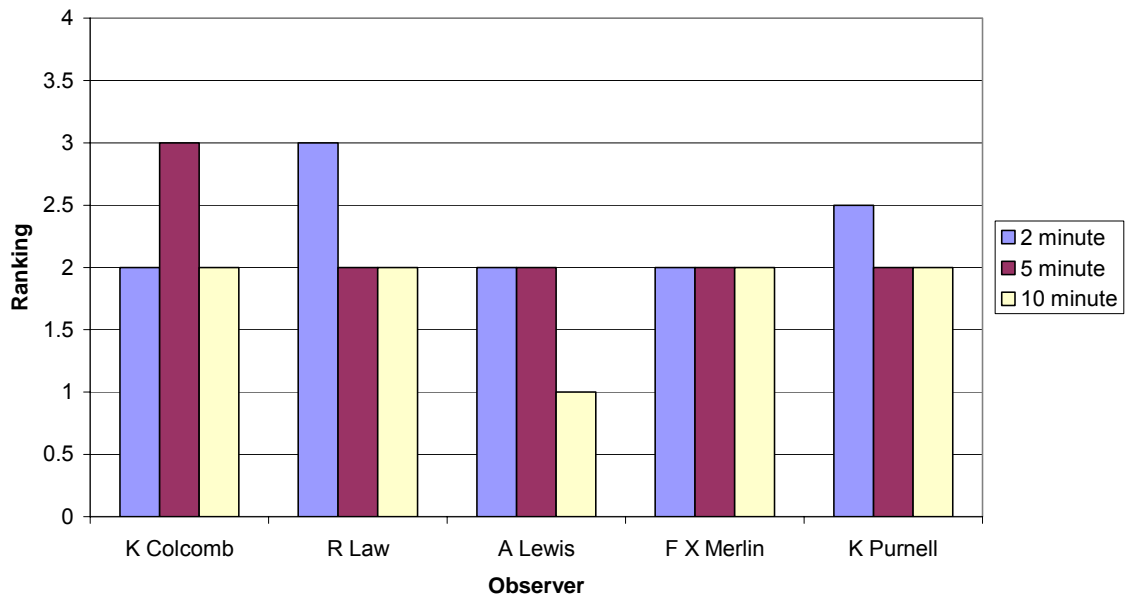
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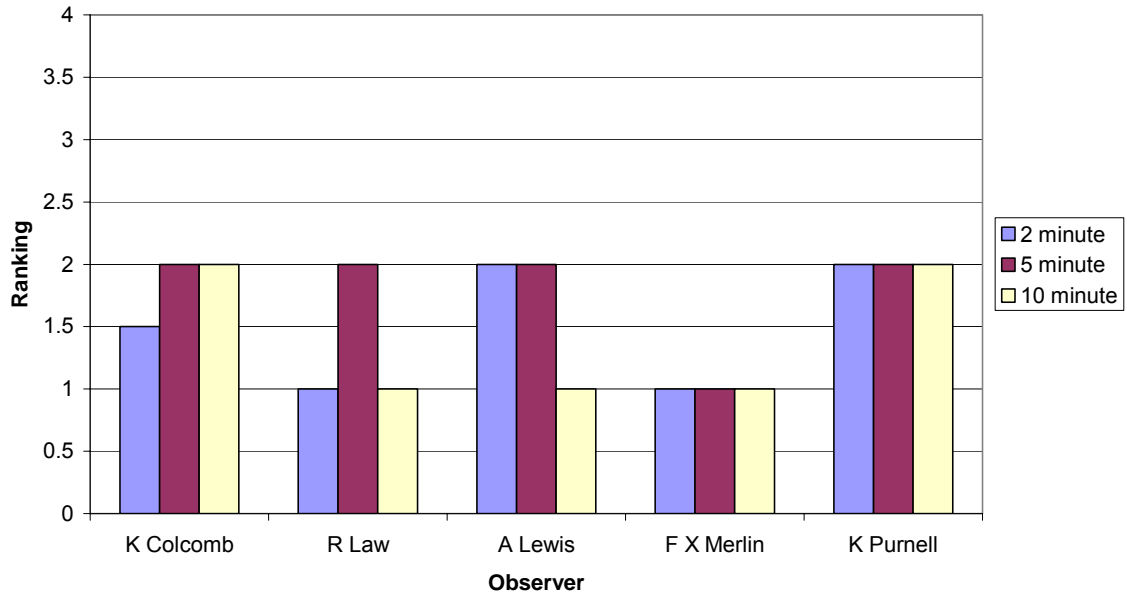
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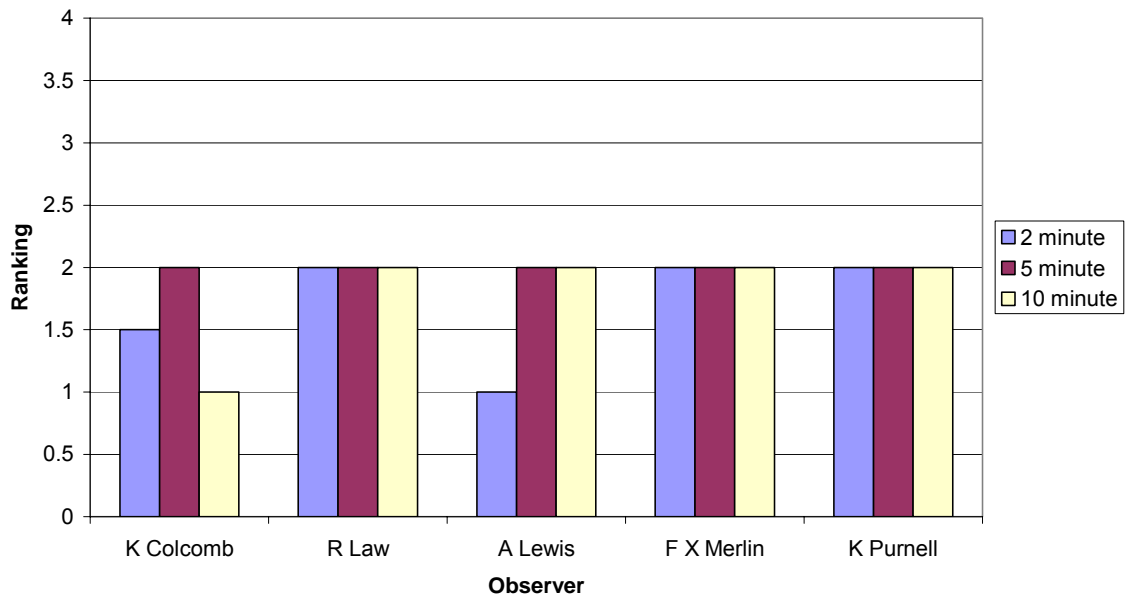
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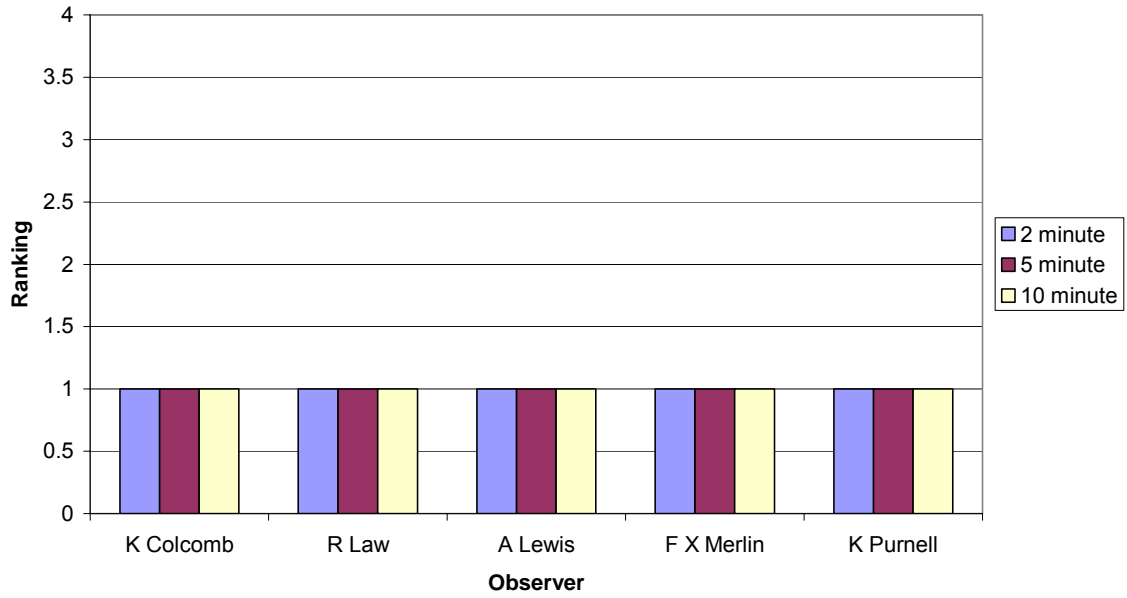
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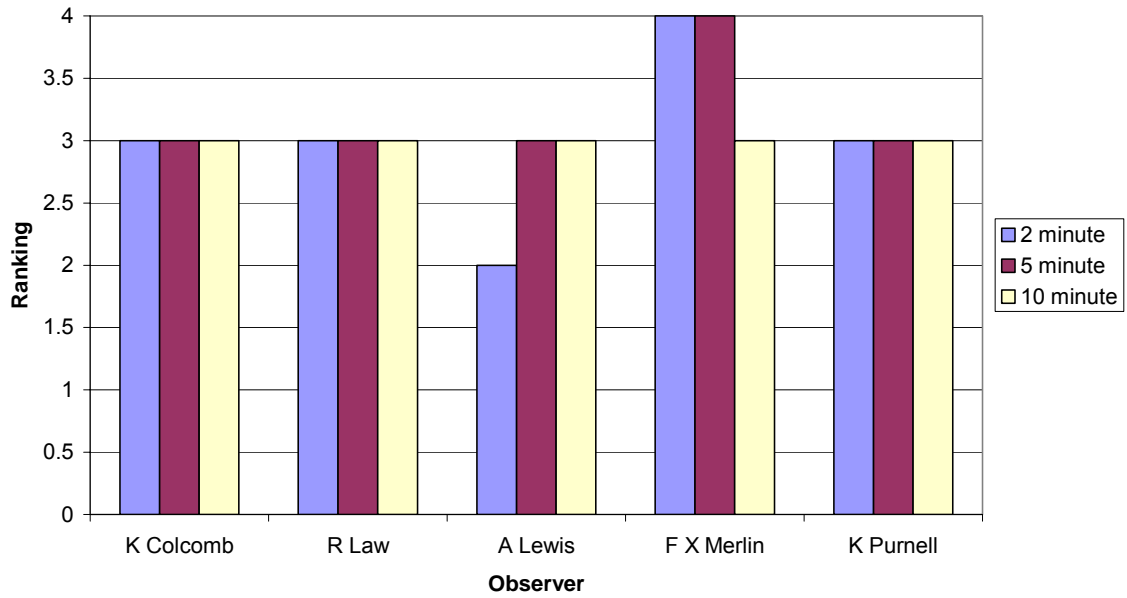
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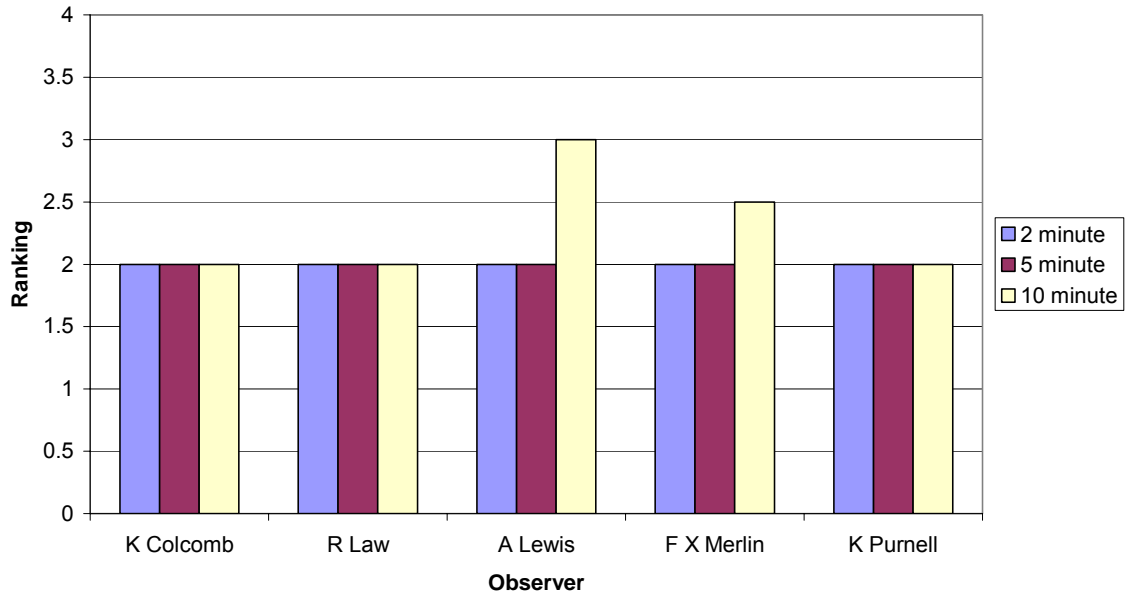
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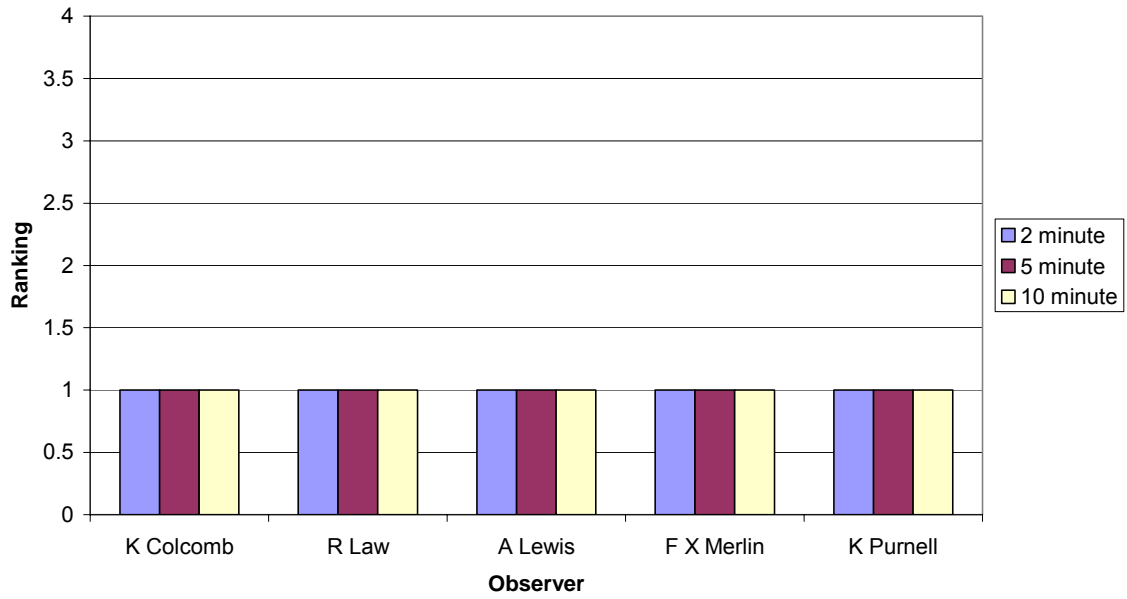
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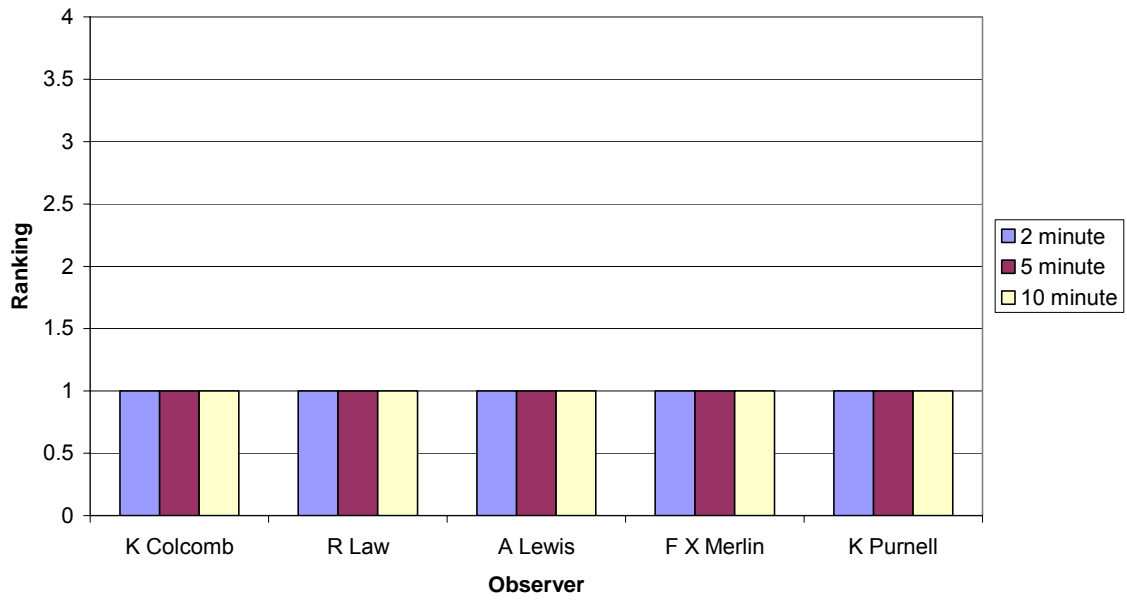
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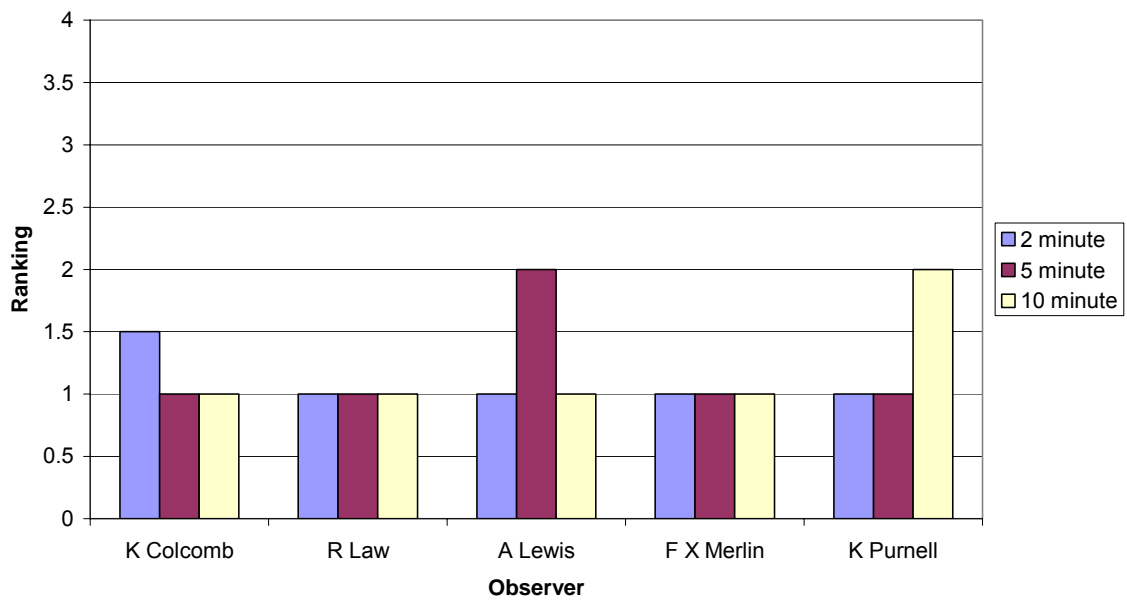
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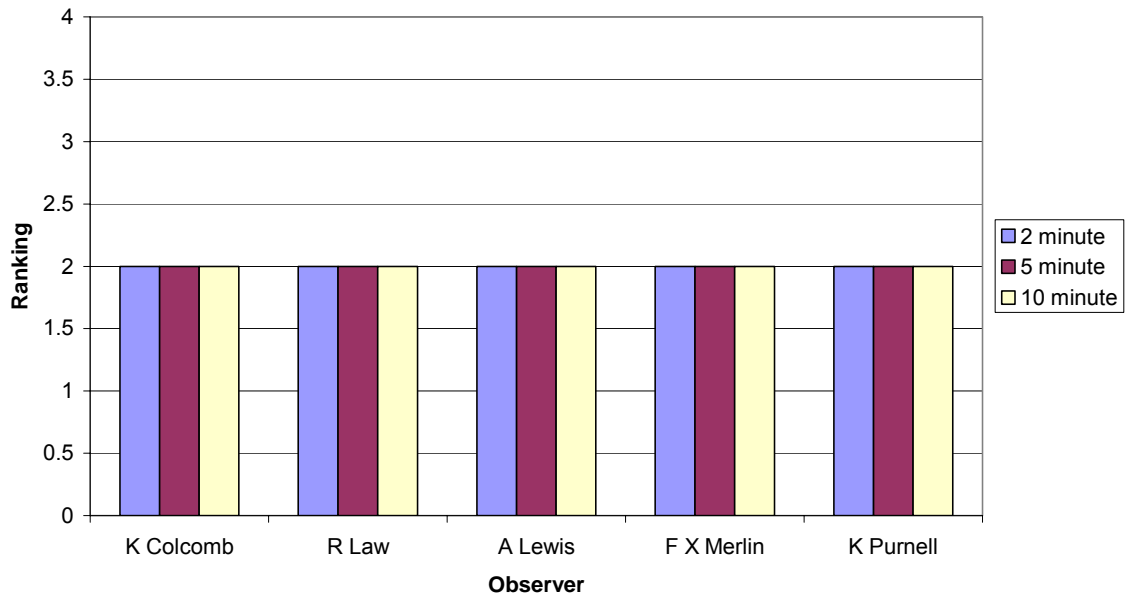
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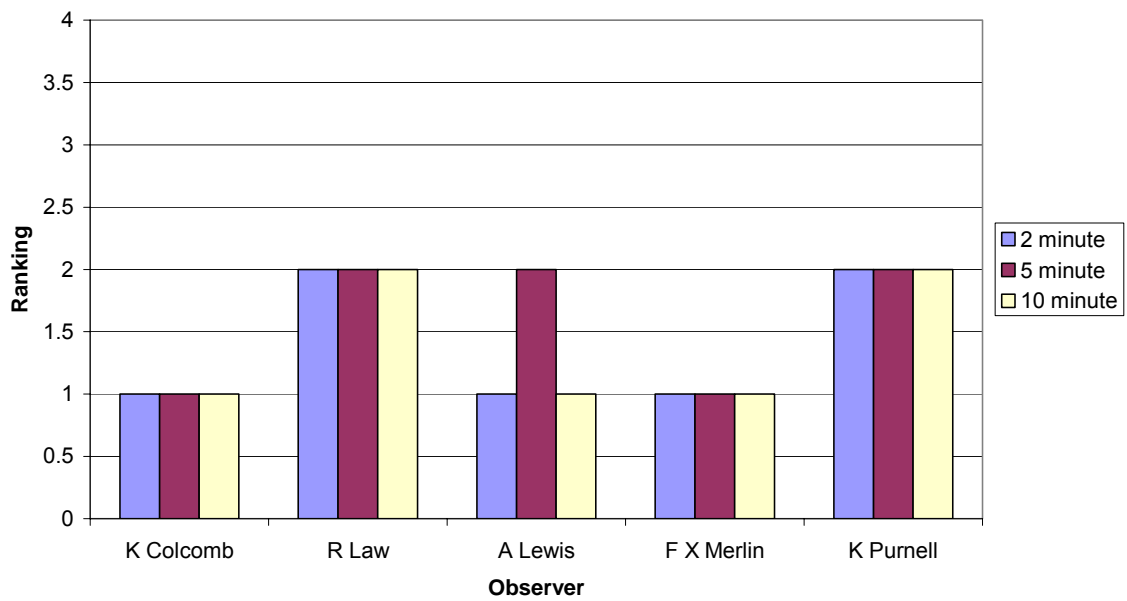
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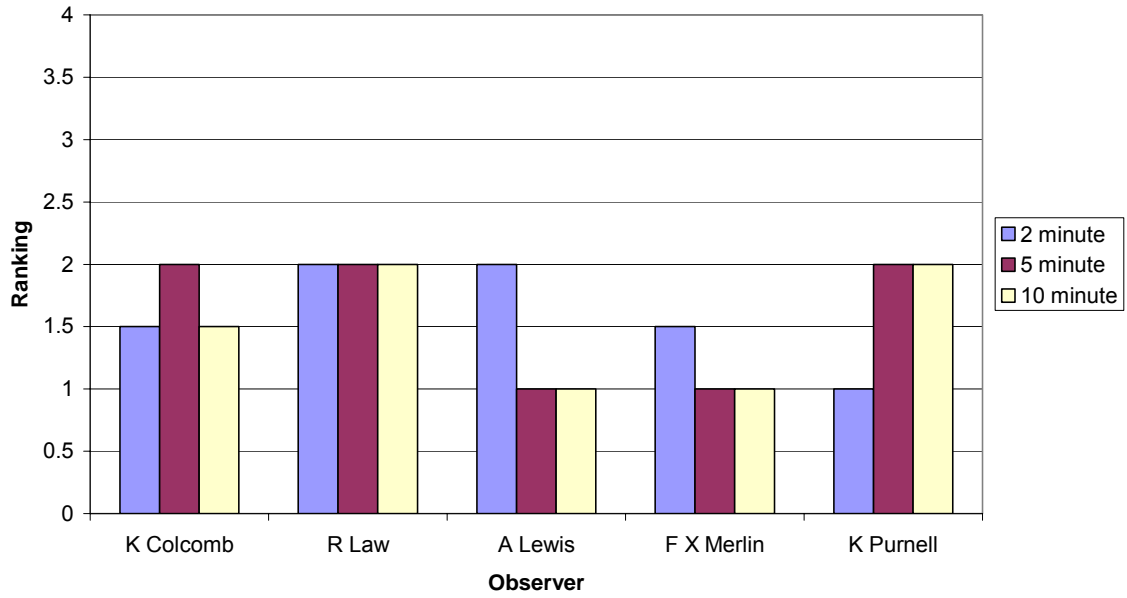
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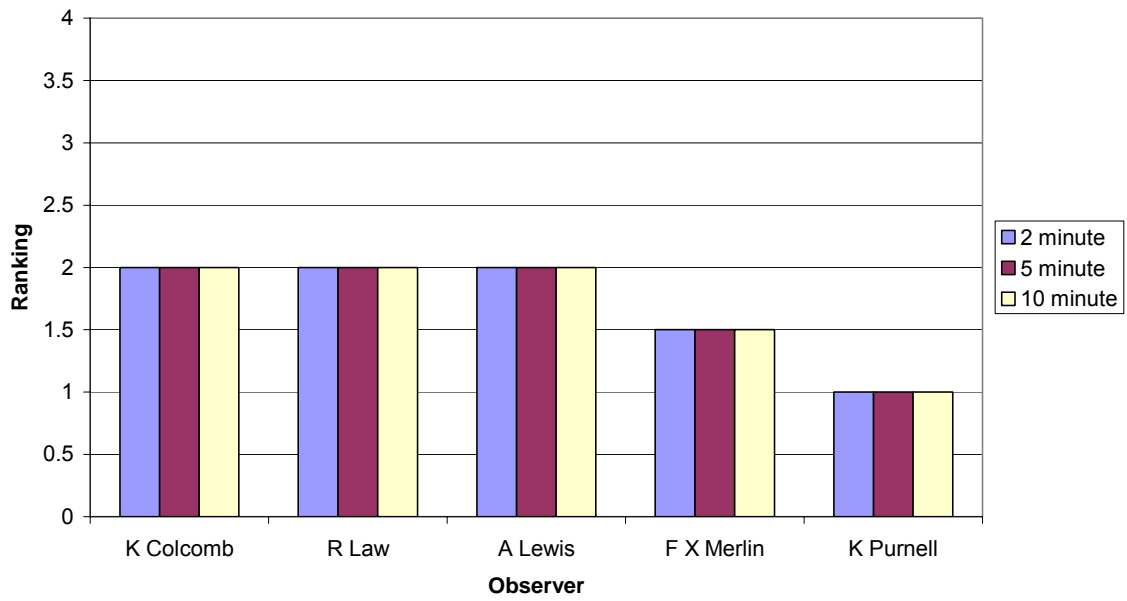
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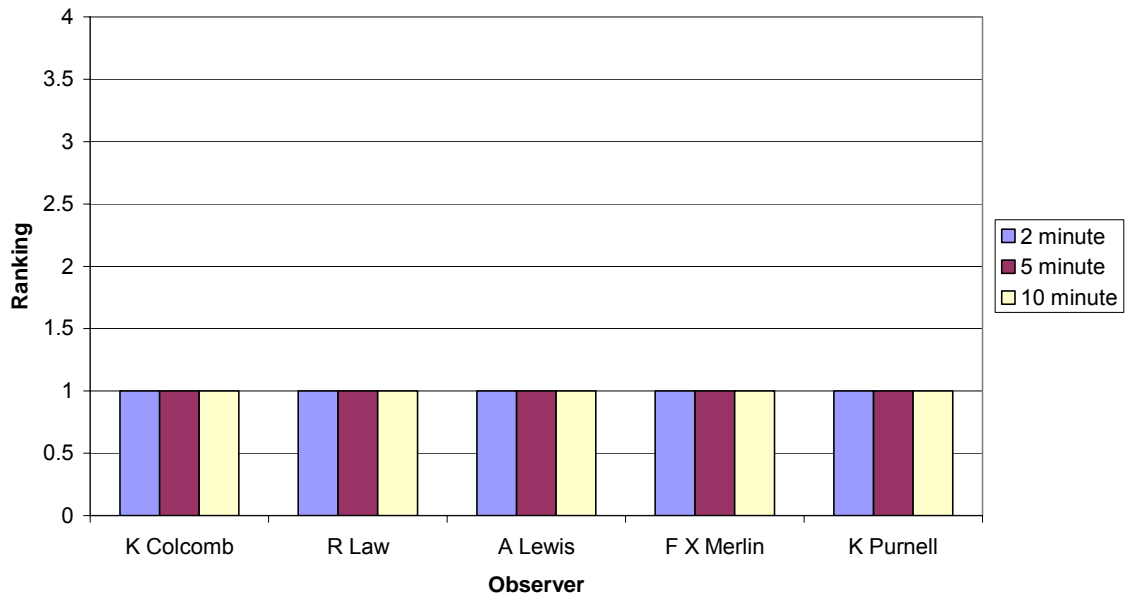
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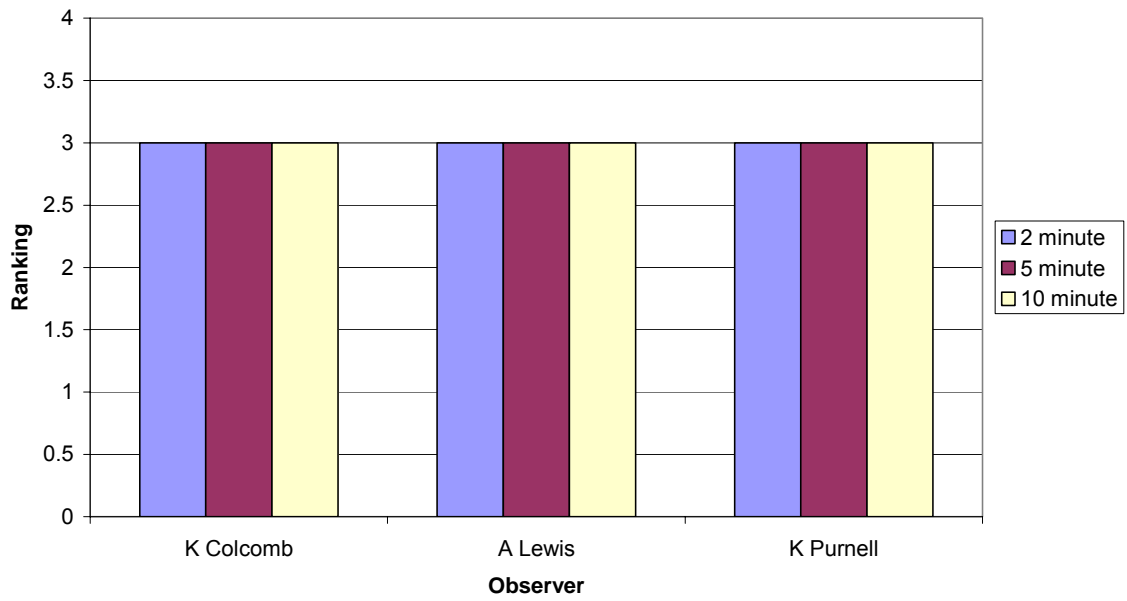
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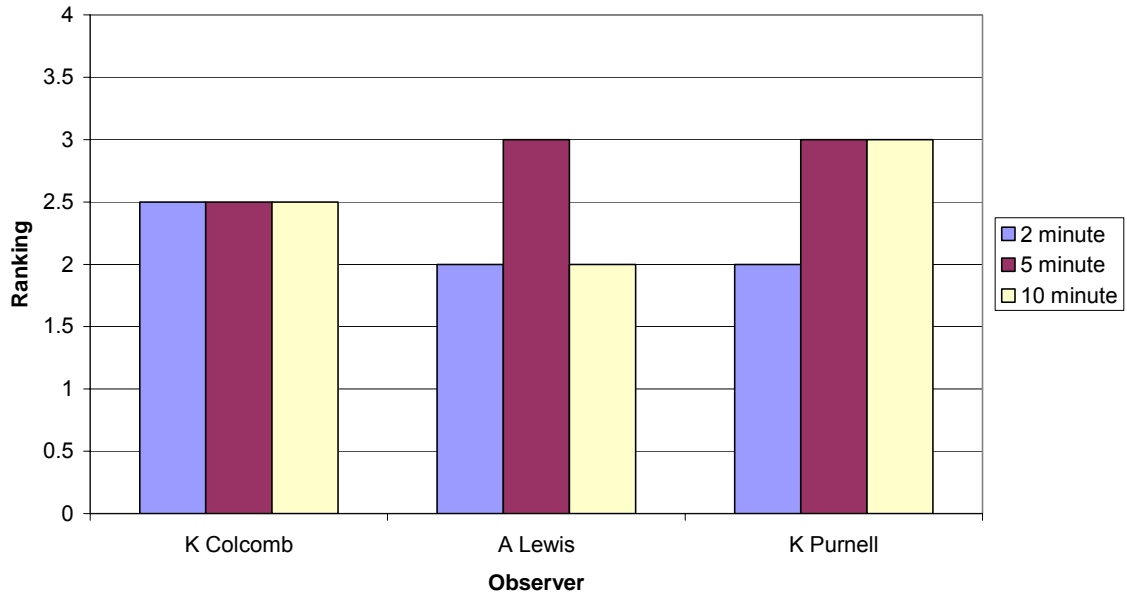
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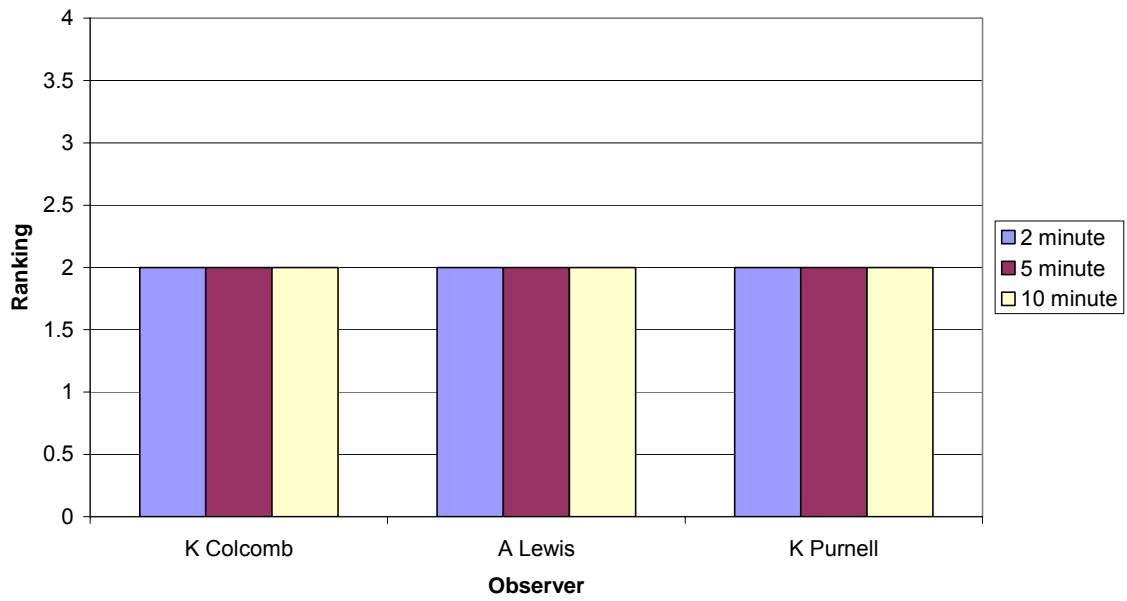
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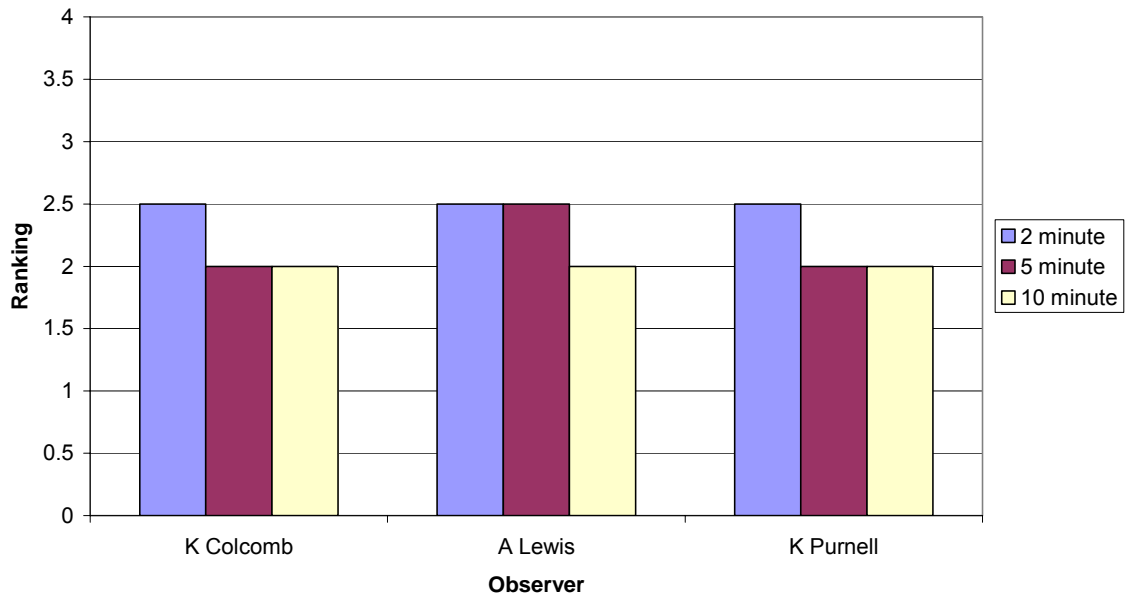
Test 23F

Test 24F

Test 18FA