## DEEPWATER HORIZON INCIDENT: WHAT HAPPENED TO THE OIL?

**An article in five parts by Alun Lewis, Independent Consultant**

Alun Lewis worked at the BP Research Centre in the U.K. from 1967 to 1992 and specialized in oil spill response studies from 1979. He was responsible for the formulation and testing of oil spill dispersants, particularly for use in the Arctic, and developed the Enersperse range of dispersants. Alun was a member of the IP Dispersants Working Group, which prepared the UK Guidelines on the Use of Dispersants in 1986. He also took part in the dispersant sea-trials in the Beaufort Sea in 1986 and in several large scale sea-trials to test dispersants in UK and Norwegian sectors of the North Sea. Leaving BP Research at the end of 1992, he worked for several months as a consultant to Warren Spring laboratory to prepare a report on the sea trials involving sequential aerial application of demulsifiers and dispersants. Alun went to work for SINTEF in Trondheim, Norway in 1993. Once again, the topic of his studies as a Senior Scientist was oil spill response, specializing in the fate and behavior of spilled oil and the use of oil spill dispersants. He participated in many research programs on the "weathering" of spilled oils at sea. These included the development of laboratory procedures to simulate the various oil "weathering" processes that occur at sea. He participated in several large-scale sea-trials from 1994 until 1996 to validate these laboratory techniques and to explore the operational aspects of dispersant spraying from ships and helicopters. He was also keynote speaker and presenter of the dispersant 'white paper' at International Oil Spill Conference in 1997.

Returning to the UK in the middle of 1997, Alun worked with AEA Technology plc at Culham, Oxfordshire as a Principal Consultant. Alun was the project manager for the AEA'97 sea trial project, which was a large sea trial involving dispersant use on Alaska North Slope and Forties crude oils and IFO-180 fuel oil. Alun became an independent consultant in 1998. His specialties are oil spill dispersants, the behavior of spilled oil at sea and the aerial surveillance of oil at sea. He has worked with many clients, commercial and governmental, both in the UK and around the world. He has conducted numerous studies for the UK Maritime and Coastguard Agency. He also organized the 2003 UK dispersant sea-trial in the English Channel. He has participated in many national exercises and training courses. Alun has conducted many National and Regional Dispersant Workshops throughout the world.

---

### PART ONE

It has been six years since the Deepwater Horizon incident and an enormous amount has been written about the various aspects of the oil release and the response. BP funded the Gulf of Mexico Research Initiative (GoMRI) with $500 million over a 10-year period and a very large number of research studies have been conducted. Since 2011, GoMRI has provided $350 million for studies and over 650 papers have been published by GoMRI-funded researchers, including over 100 papers produced in 2016. This effort has not yet answered the obvious questions about what actually happened to the oil that was released into the Gulf of Mexico (GoM), such as:

i. How much oil was released into the GoM?

ii. What happened to the released oil?

iii. How effective were the different oil spill response techniques used?

This paper has been put together to try and assess the current state of knowledge in a way that is easy to comprehend and to highlight what uncertainties remain.

### 1. How much oil was released from the well and how much entered the GoM?

Oil and gas started to be released into the sea at 5,000 feet (1,500 m) water depth after the riser buckled and broke when the Deepwater Horizon sank on April 22nd, 2010. Various measures were used to try and stop the flow or capture the escaping oil before the oil was stopped from flowing on July 15th. The gas and oil flows varied over the 87 days of the release. The amount of oil and gas being released from the subsea wellhead could not be directly measured.

The US Government formed the Flow Rate Technical Group (FRTG) on May 19th 2010 to provide estimates of the flow rates. This team announced on August 2nd that it estimated that a total of 4.9 million barrels of oil has been released from the well. Various academic researchers have also produced their own estimates of how much oil had been released from the well or had entered the Gulf of Mexico, based on various measurements and assumptions.

The amount of oil released was instrumental in determining the fines under the Clean Water Act and was the subject of a prolonged legal case. BP's experts estimated that 2.45 million barrels of oil had been released from the well while the US Department of Justice's experts estimated that 4.19 million barrels of oil had been released. On 15th January 2015, after listening to extensive evidence presented by both sides, Judge Carl Barbier of the US District Court for the Eastern District of Louisiana determined that 4.0 million barrels of oil had been released from the well.

Not all of the oil released from the well entered the waters of the GoM. From June 3rd until the oil flow was stopped, some oil was being collected from the wellhead and pumped to the Discoverer Enterprise. Some oil was also collected and sent to the Q4000 vessel and burnt by flaring. During the legal case, it was eventually agreed by all parties that 810,000 barrels of oil that was released from the well had been recovered directly from the wellhead before it had entered the water. The legally agreed amount of oil that was released from the subsea well into the waters of the GoM was therefore 4 million minus 810,000 barrels, which equals 3.19 million barrels of oil.

3.19 million barrels is equivalent to 134 million US gallons or 507,000 m3 of crude oil. The precise amount of crude oil that was released will most probably never be known, but this value is the legally agreed amount based on a consideration of the evidence available. Some papers use the older estimates or their own estimates and this can create confusion.

## 2. What happened to the oil that was released?

The Deepwater Horizon incident involved a subsea blowout of oil and gas from a HPHT (High Pressure High Temperature) oil well at a water depth of 5,000 feet. Some aspects of the behaviour of the released oil can be understood from past oil spills, but others are particular to a subsea oil well blowout.

### a. Knowledge of the behaviour of oil spilled onto the sea surface

The general behaviour of oil spilled onto the sea's surface from, for example, a damaged oil tanker, has been extensively studied and is well understood. Spilled oil is said to 'weather' and the oil properties and volume change with time at sea. The basic processes are:

i. Spreading: Spilled oil spreads out over the sea surface to form an oil slicks of very uneven thickness, ranging from sheen that is around 1 micron (4 x 10-5 inch) thick up to patches of oil that can be several millimetres (circa 0.1 inch) thick.

ii. Natural dispersion: Some of the oil in the thinner areas of the slick will be subjected to wave action that converts the oil into oil droplets of various sizes in the upper water column. Most of this oil will float back up to the sea surface, but a small proportion will be retained as dispersed oil in the upper water column. Most of this dispersed oil will be biodegraded within a few days by naturally occurring microorganisms in the sea.

iii. Evaporation: The more volatile components from the oil, typically the BTEX compounds (Benzene, Toluene, Ethylbenzene and Xylenes) and short chain hydrocarbons, evaporate into the air leaving an oil residue that is of less volume, but of higher viscosity, on the sea surface.

iv. Water-in-oil (w/o) emulsification: The oil residue that remains on the sea surface may be capable of forming stable water-in-oil emulsions that consist of water droplets within the body of the oil stabilised by the presence of precipitated asphaltenes from the oil. Most crudes oils and residual fuels oils do this, but distillate fuels (gasoline and kerosene) do not. This a physical process requiring wave action and the water content of the emulsified oil will raise slowly to around 75%, thereby increasing the volume of pollutant on the sea surface to four times that of the oil from which it is formed. The viscosity of emulsified oils is much higher than that of the oil residue from which they are formed and the oil becomes persistent on the sea surface as any natural dispersion is supressed.

v. Drifting of oil on the sea surface: The emulsified oil residue drifts on the sea surface under the combined influence of approximately 3% of wind speed and 100% of the prevailing surface currents.

The speed at which these processes occur and the extent to which the physical properties of the oil are altered depend on (a) the properties of the crude oil, and (b) the prevailing conditions, principally temperature and sea state. Several different computer models are available that can forecast the effects of oil 'weathering' and drift trajectory. A typical example would be:

- 10,000 barrels of a light crude oil spilled onto the sea surface would rapidly spread out to form a very large oil slick. About 30% volume, consisting primarily of the BTEX compounds, would evaporate in the first 24 hours on the sea surface. This would leave around 7,000 barrels on the sea surface.
- In moderate sea conditions about 5% of the volume of oil would be naturally dispersed into the sea by wave action, leaving 6,500 barrels of oil on the sea surface.
- Water-in-oil emulsification over the next few days could cause the water content of the emulsion formed to rise up to 75% volume. The volume of emulsified oil would increase to around 25,000 barrels. This emulsified oil would be persistent and some could drift ashore

## b. Knowledge about the behaviour of oil released subsea

Subsea blowouts had not been studied to a great extent before the Deepwater Horizon incident. However, some work had been done, notably the DeepSpill experiments which were conducted in Norwegian waters in 2000 with oil and

gas released at a depth of 844 metres (2,770 feet) and these gave insight to the behaviour of the oil released at the Deepwater Horizon incident. The basic processes are:

- The subsea release of oil and natural gas (methane) the break up the oil into droplets of various sizes in the water because of the intense turbulence of the release. The gas will be in the form of gas bubbles in the water column.
- The gas bubbles will produce a buoyant plume of water that rises quite rapidly through the water carrying the ‘plume’ or ‘cloud’ of oil droplets within it.
- In water deeper than about 500 metres, the natural gas will dissolve into the water due to its solubility at high pressure. The dissolution of the gas will reduce the buoyancy of the rising plume and the ascent will slow.
- The larger oil droplets will then continue their ascent towards the sea surface due to their inherent buoyancy, while smaller oil droplets will remain dispersed in the water at depth.

The properties of the crude oil are less in important in determining the initial fate of the oil than with a sea surface oil spill, but the release conditions, principally the Gas Oil Ratio (GOR), is a very important factor controlling the oil droplet size distribution that is produced at the release. The droplet size distribution determines how much of the released oil is mechanically dispersed and stays in the water column and how much oil eventually reaches the sea surface.

There are several obvious differences between the behaviour of a crude oil released onto the sea surface and oil released subsea:

i. Mechanical dispersion: The natural dispersion of oil caused by wave action at the sea surface is replaced by the much more energetic turbulence caused by the high-velocity release of oil and gas into the sea. This mechanical dispersion can cause a significant proportion of the oil released to never reach the sea surface. Instead, the oil would be dispersed into the water column at depth where the majority of the oil would be biodegraded over the next days and weeks.

ii. Evaporation replaced by dissolution: As the crude oil is underwater and not in contact with the air there will be no evaporation of the more volatile components from the oil directly into the air. However, being present as a plume or cloud of small oil droplets in the water there is a high oil/water contact area that enables partially water soluble oil compounds to rapidly dissolve into the sea. The most volatile compounds in the oil, the BTEX compounds, are also the most water soluble. The BTEX compounds, plus some other compounds, dissolve into the sea.

iii. Water-in-oil emulsification suppressed: The dispersion of the oil into oil droplets with a wide range of sizes is not suitable for the slow incorporation of water droplets to form water-in-oil emulsions while the oil is in the water column. However, oil that reaches the sea surface would then start to behave as if it had been released there. There will be some further loss of volume by evaporation of the volatile components that remain in the oil into the air (although a high proportion will have already been lost by dissolution into the water column). This leads to changes in oil composition that allows stable oil-in-water emulsions to be formed.

There is insufficient information available to provide an example of the fate of oil release from a ‘typical’ subsea oil and gas blowout.

**PART TWO**

## 2 c. The US Federal Government Oil Budgets

A US Federal Government interagency team, led by the Department of the Interior (DOI) and the National Oceanic and Atmospheric Administration (NOAA), developed a tool called the Oil Budget Calculator to estimate what probably happened to the oil at the *Deepwater Horizon* incident. This group published two 'Oil Budgets'; one of 4 pages on August 4th, 2010 and a more comprehensive 217-page report, Oil Budget Calculator - *Deepwater Horizon*, on November 23rd, 2010. The fate of the oil released from the wellhead was divided into several categories as described in Figure 1.

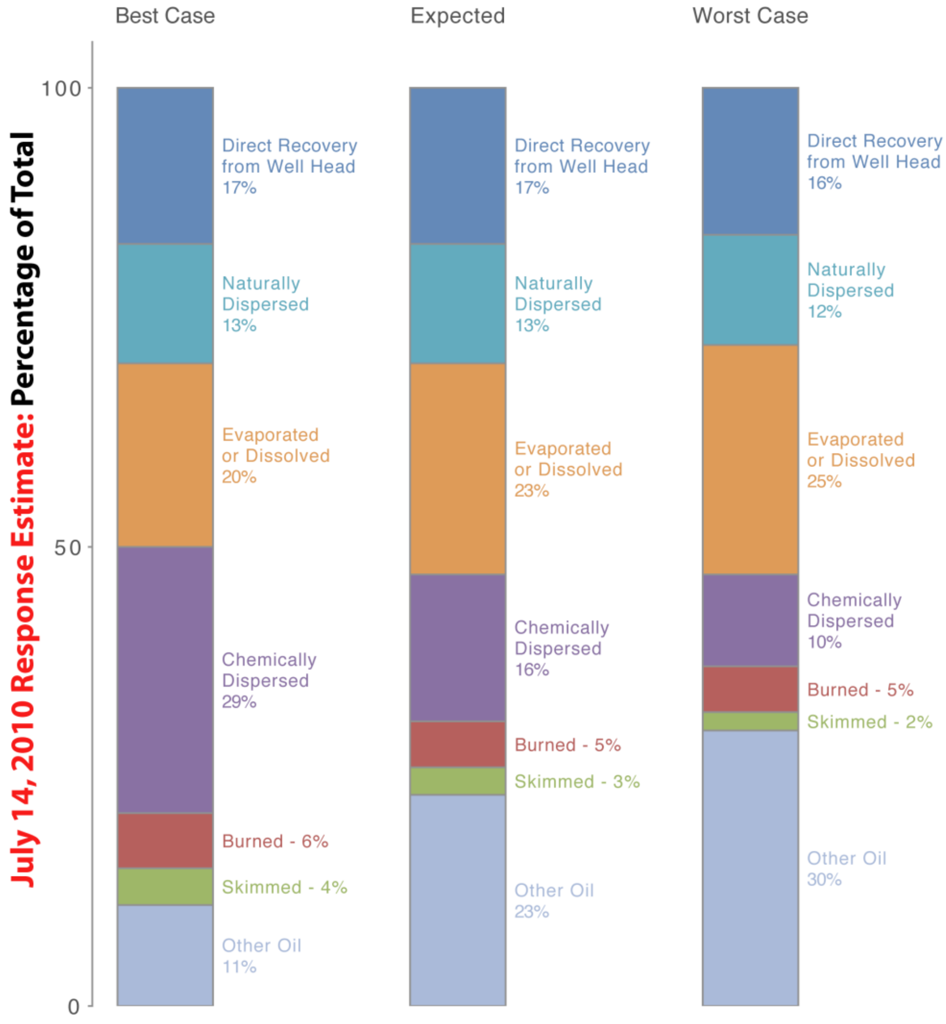



*Figure 1. Oil Budget Calculator estimates published on 23rd November 2010*

The amount of oil estimated to have been released from the well was 4.94 (±10%) million barrels, to give 4.75, 4.94 and 5.14 million barrels for the three cases. This was significantly higher than the 4.0 million barrels eventually agreed by the legal process.

- Only the amount of oil directly recovered from the wellhead was a known value of 820,000 barrels and represented 16% to 17% of the total amount of oil released from the well.
  <u>All of the other values are estimates based on the opinions of a panel of experts.</u>
- The estimated proportions of the total amount of oil released that were subject to the natural processes of natural dispersion and evaporation / dissolution were within reasonably narrow limits; 12% to 13% to naturally dispersed oil and 20% to 25% for evaporation or dissolution. The estimates of the amount of oil burnt or skimmed during the response are also within narrow limits; 5% to 6% for burning and 2% to 4% for skimming.
- The estimated proportion of the total amount of oil that was released that was dispersed by the use of dispersants, both subsea dispersant use and on oil on the sea surface, has the widest range; from 29% (1,400,000 barrels) to 10% (500,000 barrels) with an 'expected' value of 16% (770,000 barrels).

- The calculations within the Oil Budget Calculator report show that the subsea use of dispersant accounts for approximately 75% of the oil estimated to have been "Chemically dispersed" with the remaining 25% being due to dispersant use on oil on the sea surface.
- The report notes "*Given the limited nature of the field data, the best that could be done was to estimate effectiveness using the experience and knowledge of dispersant experts. Unfortunately, reaching consensus among the experts was not possible.*"

- The uncertainty in the other estimates of oil fate generated a residual category of "Other" oil that was estimated to have been between 11% and 29% of the estimated total amount of oil released from the well.
  - This "Other" oil category included oil "*that becomes tar balls, forms surface slicks, sinks due to sedimentation, remains in the surf zone or impacts the shore and is subsequently cleaned up.*" Clean-up operations recorded the volume of oily debris that was recovered during shoreline clean-up. However, no estimates were made of the proportion of oil in this debris, so it was not possible to estimate of this amount with the Oil Budget Calculator.
  - Computer simulations reported in 2014 estimated that the amount of oil that came ashore was from 10,000 tonnes (70,000 barrels) for the 'best case', 22,000 tonnes (154,000 barrels) for the 'expected case' and 33,000 tonnes (231,000 barrels) for the 'worst case'. These values represent only 1.5%, 4.5% and 3.1% of the total amount of oil that was released from the well.

The longer-term oil fate processes of photo-oxidation and biodegradation were not considered in the Oil Budget Calculator.

It should be noted that the amounts of oil in the different categories in the Oil Budget are expressed as percentages of the total amount of oil estimated to have been released from the well. 820,000 barrels of oil were recovered directly from the wellhead, did not enter the water and therefore was not subject to the natural processes of dispersion and evaporation / dissolution or the response actions. Table 1 presents exactly the same volume estimates, but expressed as percentages of the amount of oil that was estimated to have entered the water. The volumes calculated are the same, but the percentages have increased as a proportion of the lower total amount of oil.

| **Estimated total amount of oil that entered the water (millions of barrels)** | **Best case** | **Expected case** | **Worst case** |
|---|---|---|---|
| | **3.93** | **4.12** | **4.32** |
| **Fate category** | **% of total oil in sea** | **% of total oil in sea** | **% of total oil in sea** |
| Naturally dispersed | 16 | 15 | 15 |
| Evaporated or dissolved | 24 | 29 | 30 |
| Chemically dispersed | 36 | 19 | 12 |
| Burned | 7 | 6 | 6 |
| Skimmed | 5 | 4 | 3 |
| Other | 13 | 27 | 35 |

*Table 1. Oil Budget Calculator estimates as percentages of the amount of oil that was estimated to have entered the water*

The Oil Budget Calculator used statistical techniques designed to minimise the uncertainty implicit in the wide range of different opinions expressed by the panel of experts on different aspects. The Oil Budget Calculator report states that the estimates of dispersant effectiveness may well have been low:

- "*The emphasis was on getting a conservative answer so as not to underestimate clean-up requirements. In terms of response, this translates into using conservative estimates for clean-up efficiency, particularly with regard to skimmer efficiency and dispersant success.*"
- *"The Oil Budget Calculator is believed to be sufficiently accurate to meet the needs of the Deepwater Horizon spill response. Thus, while it may have underestimated dispersed oil, it predicted sufficient amounts of subsurface oil as to encourage a large-scale water-sampling program."*

It is important to note that the estimates in the Oil Budget are not based on any measurements that were made at the time; they are estimates made by a panel of experts and some have a wide range of uncertainty.

Alternative methods of calculation using the same input data lead to higher estimates of the amount of oil dispersed by dispersant use and a reduction in the amount of oil in the "Other" oil category. Laboratory studies conducted since the Oil Budget Calculator estimates were made have indicated that the amount of oil dispersed by subsea dispersant use was higher than that estimated, even with the 'Best case' assumption.

**PART THREE**

## 2 d. "Other" oil, "Residual" oil and "missing" oil in the Oil Budget and oil deposition on the sea floor

The earlier version of the Oil Budget presented at the White House on August 4th, 2010 with the title "BP Deepwater Horizon Oil Budget: What Happened to the Oil?" contained the following pie chart (Figure 2):

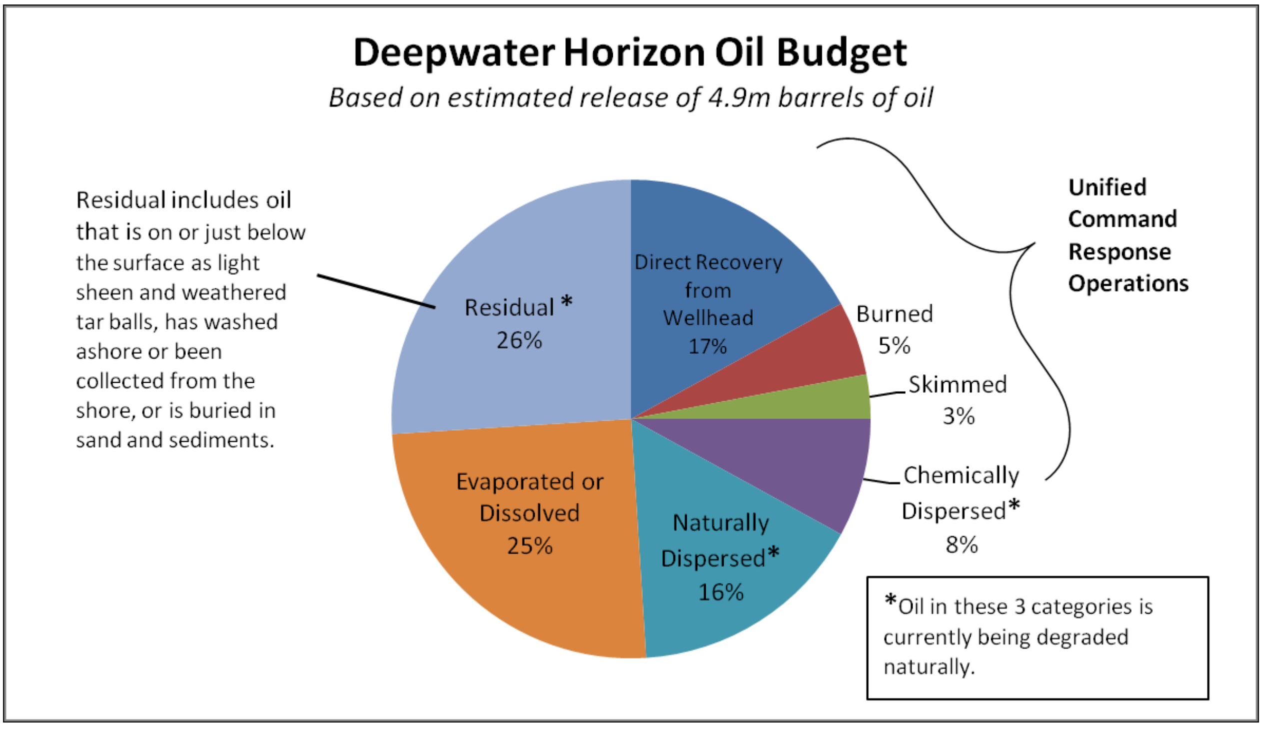



*Figure 2. Pie chart from August 4th, 2010 Oil Budget*

The "Residual" oil in this pie-chart became "Other" oil in the later (November 23rd) version of the Oil Budget. Another change was the increase in the amount of oil estimated to have been dispersed by the use of dispersants from 8% in this pie-chart to 16% with a range of 10% to 29% in the later version.

Although the explanation of what the "Residual" oil category consisted of is included in the graphic, some people interpreted this as indicating that the oil that the oil was 'unaccounted for' or 'missing'. There was a great deal of speculation as to where the 'missing' oil might be and attention turned to the sea floor. Press reports of sediment sampling during a research cruise by RV *Oceanus* in September 2010 stated that "*Dr Samantha Joye describes seeing layers of oily material — in some places more than 2 inches thick — covering the bottom of the seafloor.*" Dr. Joye also took part in a dive in the U.S. Navy's deep-ocean research submersible *Alvin* in December 2010 and said that she saw "*about three to four inches of material.*" These early reports of thick layers of oil or oily material on the seabed have not been confirmed by subsequent investigations.

Several scientific papers have presented evidence that some highly weathered and extensively biodegraded residue from the oil has been deposited on the sea floor at low concentrations over wide areas, most often incorporated into the surface layers of the sediment. The chemical compounds detected, such as hopane, are the most recalcitrant (resistant to biodegradation) in the oil. The hopane concentration in the 'fresh' crude oil is 69 parts per million (ppm). Several papers have 'back calculated' from the amounts of hopane detected on the sea floor to propose that a lot more 'fresh' crude oil was originally deposited. With a hopane content of 69 ppm, 1 gram of hopane is equivalent to 14.8 kg of 'fresh' crude oil. On this basis, it has been claimed that 7% - 8% or more (some estimates have ranged up to 30%) of the total amount of oil released into the GoM has been deposited on the sea floor. However, this proposed explanation ignores the effects of biodegradation of dispersed oil which was well established long before the *Deepwater Horizon* incident.

One apparent difficulty in proposing the sinking of 'fresh' crude oil is the density difference between the crude oil and seawater. The density of the fresh crude oil released from the subsea well was 0.875 gm/ml and the density of seawater in the GoM is around 1.025 gm/ml. The fresh crude oil would not sink unless some other material or mechanism was involved. Oil dispersed as very small oil droplets in the water column can be almost neutrally buoyant because of the small droplet size, but oil alone does not sink.

It has been hypothesised that marine snow interacted with the oil to cause deposition on the sea floor. Marine snow is a well-known phenomenon that NOAA defines as: *"Marine snow is a shower of organic material falling from upper waters to the deep ocean. As plants and animals near the surface of the ocean die and decay, they fall toward the sea floor, just like leaves and decaying material fall onto a forest floor. In addition to dead animals and plants, marine snow also includes faecal matter, sand, soot, and other inorganic dust. The decaying material is referred to as "marine snow" because it looks a little bit like white fluffy bits."*

Several scientific papers have been published over the last 4 years that describe laboratory experiments that are claimed to mimic the conditions that prevailed at the *Deepwater Horizon* incident and claim to demonstrate that marine snow was involved in the deposition of oil on the sea floor. However, incubating oil in a sealed bottle with a low volume of seawater for prolonged periods in a laboratory does not accurately simulate the dispersion, dilution and biodegradation of dispersed oil that occurred at the incident.

The role of marine snow in the possible deposition of crude oil on the sea floor has attracted considerable academic interest, but remains a possible hypothesis and not a conclusive explanation at this time.

## 2 e. Biodegradation of dispersed oil

Oil dispersed into the water column by any process - natural dispersion by wave action, mechanical dispersion by the turbulence of a subsea oil and gas release or by the use of dispersants (subsea or on oil on the sea surface) - will undergo three processes; initial dispersion into the water column, dilution to low concentrations in the water and eventual biodegradation.

Oil droplets in the water column are rapidly colonized by petroleum-degrading microorganisms that occur naturally in ocean environments. All of the world's oceans have natural hydrocarbon seeps and oil degrading microbes are found in all marine environments. Most of the chemical components of crude oil has only limited water solubility and the microorganisms must inhabit the interface between the oil and the water to biodegrade the oil. Oil dispersed as small droplets has a much greater oil/water interfacial area than an oil slick floating on the sea surface.

The microorganisms use the oil as a source of energy to grow and reproduce. The different chemical compounds in crude oils will be biodegraded at different rates and to different extents by naturally-occurring hydrocarbon-degrading microorganisms. Linear chain alkanes will be most rapidly biodegraded (within days), followed by the single-ring aromatic compounds and then by branched chain alkanes and cycloalkanes which can take weeks to be biodegraded. Many complex branched, cyclic, and aromatic hydrocarbons, which otherwise would not be biodegraded individually, can be oxidized through co-metabolism in an oil mixture due to the abundance of other substrates that can be metabolized easily within the oil. The ultimate fate of the majority of oil that is biodegraded is to be eventually converted into carbon dioxide and water via a series of intermediates.

Some very heavy oil compounds, such as asphalt or bitumen, are very slow to biodegrade and have high enough densities that could cause them to sink to the seabed. These recalcitrant residues are biologically inert and are non-toxic or practically non-toxic.
When dispersants are used on an oil slick drifting on the sea surface, the dispersed oil will initially be present as discrete plumes of dispersed oil under the areas of the slick where breaking waves have passed through. These will be rapidly diluted into the underlying upper water column to a depth of 10 or 20 metres. Any recalcitrant residue left after biodegradation will be deposited very diffusely over a huge area of seabed

and the low concentrations will be undetectable amongst in the other components of marine snow that will have been deposited.

The oil dispersed at the *Deepwater Horizon* incident, by mechanical dispersion and by subsea dispersant use at the source of the release, was continuously generated for a period of 87 days. The dispersed oil at a water depth of 1,200 metres drifted to the south-west with the prevailing current. The dispersed oil would have been progressively biodegraded as it drifted, but it was being continuously replenished with 'fresh' crude oil from the ongoing release. This seems to have produced a strip of detectable deposited recalcitrant oil residue on the seabed below the drifting dispersed oil. The traces of the recalcitrant oil residue has been interpreted by some people as indicating that the 'fresh' crude oil was deposited and then biodegraded, but a more logical explanation is that only the recalcitrant residue was deposited after extensive biodegradation of dispersed oil while in the water column.

# PART FOUR

## 3. Estimating the effectiveness of oil spill response methods

One of the apparently most simple questions that can be asked about the largest oil spill response effort ever, conducted at the *Deepwater Horizon* incident (at a cost of $14.3 billion), is also the most difficult to answer. That question is:

**How much good did the oil spill response methods undertaken at the *Deepwater Horizon* incident actually do?**

The difficulties involved in answering this question apply to any oil spill response.

### a. Effectiveness of response as the reduction in amount of damage that would have been caused

The aim of any oil spill response method is to minimise that damage that could be caused by the spilled oil. At an incident where oil spill response had been undertaken, such as the *Deepwater Horizon* incident, assessing how effective any oil spill response actions had been on this basis would therefore require:

i. Estimating how much damage would have occurred if the response had not been undertaken and
ii. Comparing that with what damage had actually occurred when response was undertaken.

This produces the obvious problem of trying compare the consequences of events that had not occurred (no response) with those that had occurred (response).

The NRDA (Natural Resource Damage Assessment) process conducted in the US under OPA 90 concluded that the damage caused to the natural resources by the *Deepwater Horizon* incident required $8.8 billion to restore. In the NRDA context, the *Deepwater Horizon* incident includes everything that occurred and that includes the largest-ever oil spill response operation ever mounted anywhere in the world. The NRDA process required very extensive and expensive studies to arrive at this conclusion and even then, some doubt about the accuracy of this assessment remains. Establishing the scale of damage that would have been caused in the hypothetical case of no response being undertaken would apparently require equally extensive and costly studies. It is therefore not possible that the 'baseline case' of no response will ever be established for what could have happened at the *Deepwater Horizon* incident.

### b. Effectiveness of response as the percentage of oil removed from the sea surface

Past experience has shown that the most severe and long-lasting damage caused by spilled oil has been to sensitive coastal resources, such as saltmarshes, mangroves and mudflats, that are impacted by spilled oil drifting ashore. The underlying assumption of all oil spill response techniques conducted at sea is that the aim should be to remove as much of the spilled oil from the sea surface before the oil can drift ashore. Protective booming close to the sensitive resources can act as a 'last line of defence'.

The oil on the sea surface can be removed by being:

- Recovered from the sea surface by the use of booms and skimmers for subsequent disposal.
- Burned at sea with ISB (In-Situ Burning).

- Dispersed into the water column by the use of dispersants. In the case of the *Deepwater Horizon* incident, dispersants were also used subsea at the source of the release to prevent oil from reaching the sea surface by dispersing it into the water column before it could reach the sea surface.

The assumption that removing oil from the sea surface prevents the oil from drifting ashore is valid, but without sophisticated modelling and accurate long-range weather forecasting it is not possible to know where the oil removed from the sea surface by response actions would have drifted ashore. The severity of ecological damage done by spilled oil depends on the sensitivity of the shoreline resource impacted. If a particularly sensitive resources, such as salt marshes or mangroves, are impacted the ecological damage will be more severe and long-lasting than if less sensitive resources, such as tourist beaches, are impacted - although the socio-economic cost may still be high.

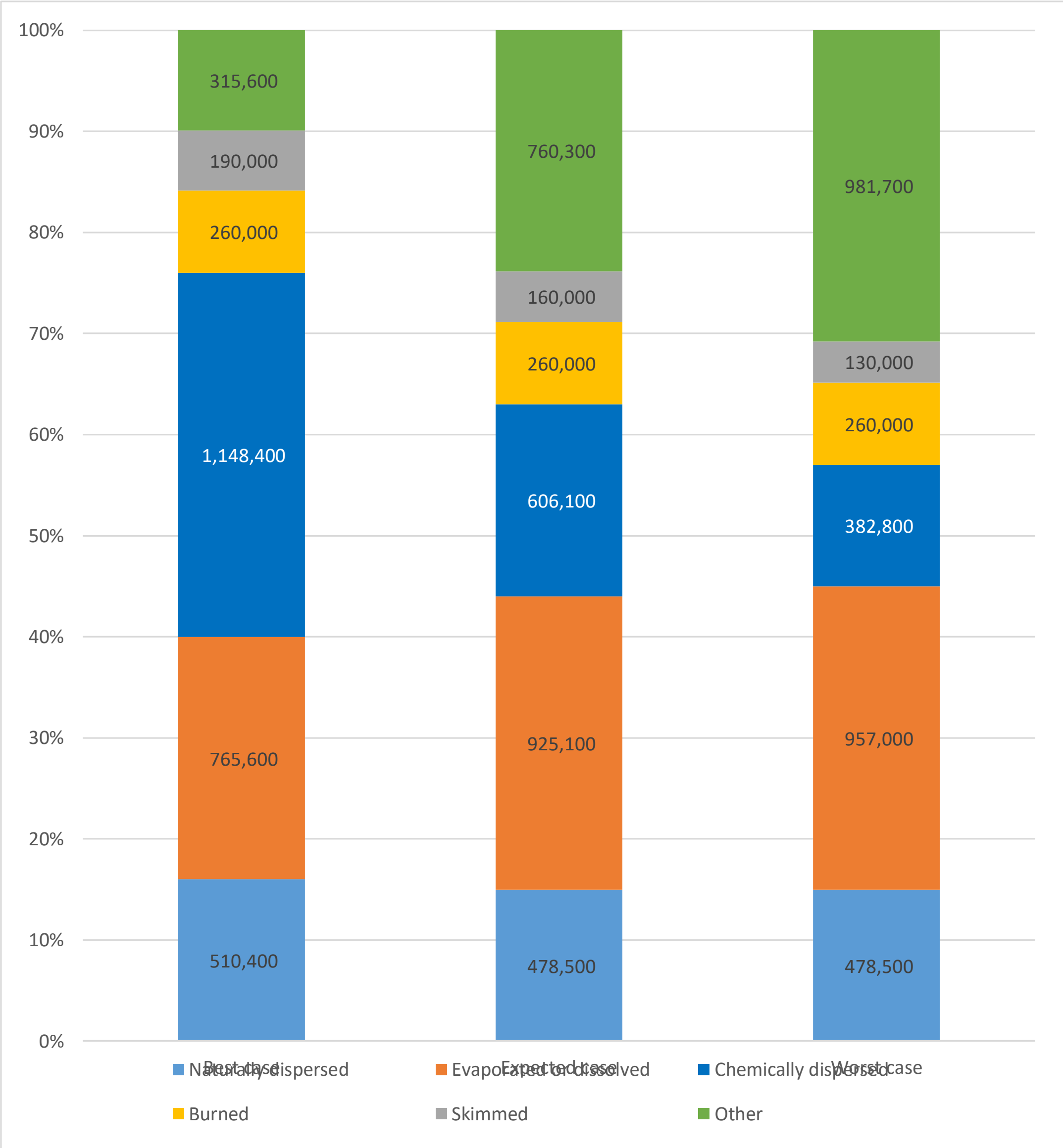



*Figure 3. Oil Budget Calculator estimates as percentages of the legally agreed amount of oil that was estimated to have entered the waters of the GoM*

Despite this limitation and in the absence of any other agreed method of assessing response effectiveness, the proportion or percentage of oil removed from the sea surface by response actions has been used to indicate response effectiveness.

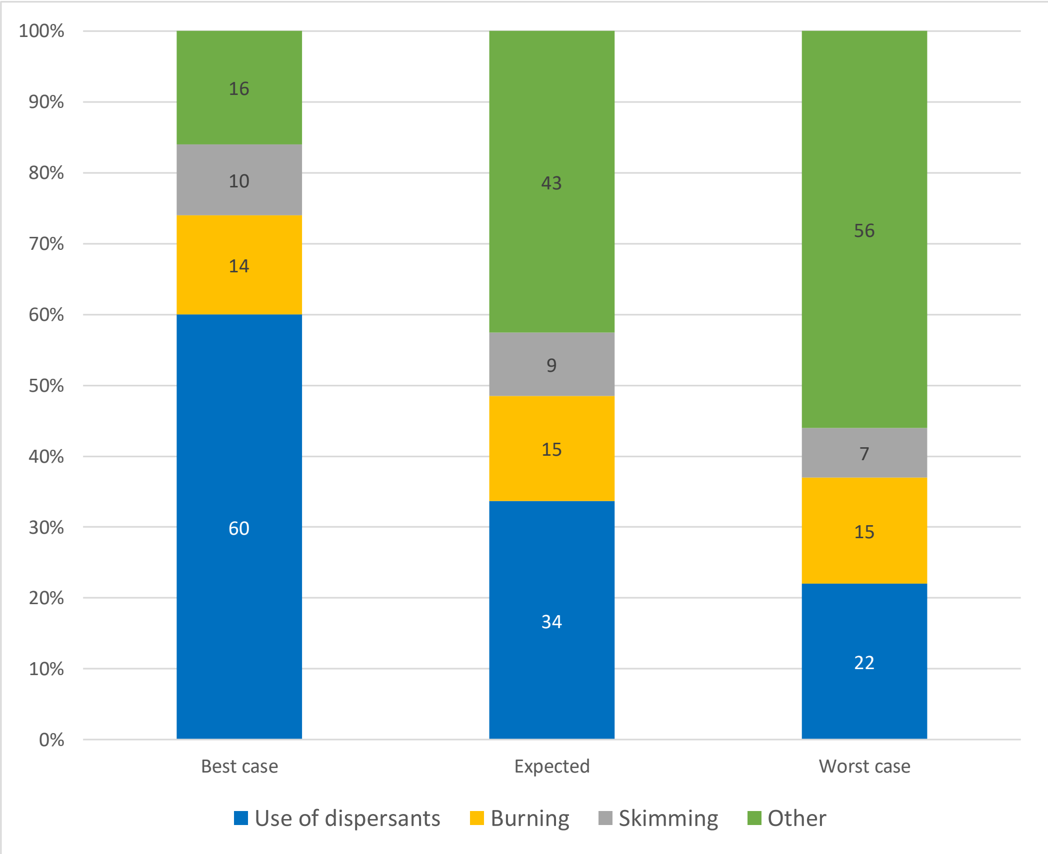
The estimates made by using the Oil Budget Calculator for the fate of the oil that entered the waters of the GoM, previously presented in Figure 1 are presented again in Figure 3, but with the amounts included and adjusted to reflect the legally-agreed amount of 3.19 million barrels of oil that entered the waters of the GoM.

Using the numbers in this Figure, it might initially seem that any response method is of only limited effectiveness. Burning removed 260,000 barrels, about 8% of the total amount of oil and skimming removed 130,000 to 190,000 barrels, equivalent to 3% to 5%. The percentage of the oil dispersed by dispersant use, with an expected value of 19% (606,100 barrels) and a range of 12% (382,000 barrels) to 36% (1,148,400barrels), is relatively high.

However, natural dispersion (including mechanical dispersion at the release source and natural dispersion of oil caused by wave action on the sea surface without dispersant addition) plus evaporation / dissolution had already removed 40% to 45% of the total amount of oil released from the sea surface, or prevented it from reaching the sea surface. That amount of oil would never have been available for response on the sea surface. Only 60% to 55% of the total amount of oil that entered the water was available for response.

In terms of the amount of oil that was available for response, the percentage effectiveness of the different response methods could be expressed as is shown in Figure 4. The 'percentage effectiveness' numbers for all response methods are proportionally higher, but the basic numbers from which they are calculated are the same.

*Figure 4.*




*Response 'effectiveness' as percentage of oil available for response*

As noted earlier, the amount of oil that came ashore at the *Deepwater Horizon* incident has been estimated by computer simulations to be 10,000 tonnes (70,000 barrels) for the 'best case', 22,000 tonnes (154,000 barrels) for the 'expected case' and 33,000 tonnes (231,000 barrels) for the 'worst case'. These values represent only 2.2%, 4.8% and 7.2% of the total amount of oil released into the sea. This is only a small fraction of the total amount of oil, but the oil contaminated up to 2,000 km of shoreline and the NRDA settlement allocated over $4.3 billion (plus a 10% contingency), over half of the total $8.8 billion, for shoreline restoration

## PART FIVE

### 3. Estimating the effectiveness of oil spill response methods (continued)

#### c. What would have happened if no response were undertaken?

The essence of any oil spill response actions is to reduce the amount of oil that would come ashore, compared to the case of no response being undertaken. It is obvious that if no response had been undertaken at the *Deepwater Horizon* incident, more oil would have reached the sea surface or remained on the sea surface.

Figure 5 illustrates the scale of the no response condition with the amounts of oil estimated to have been removed from the sea surface by response now being place in the 'Other' oil category.

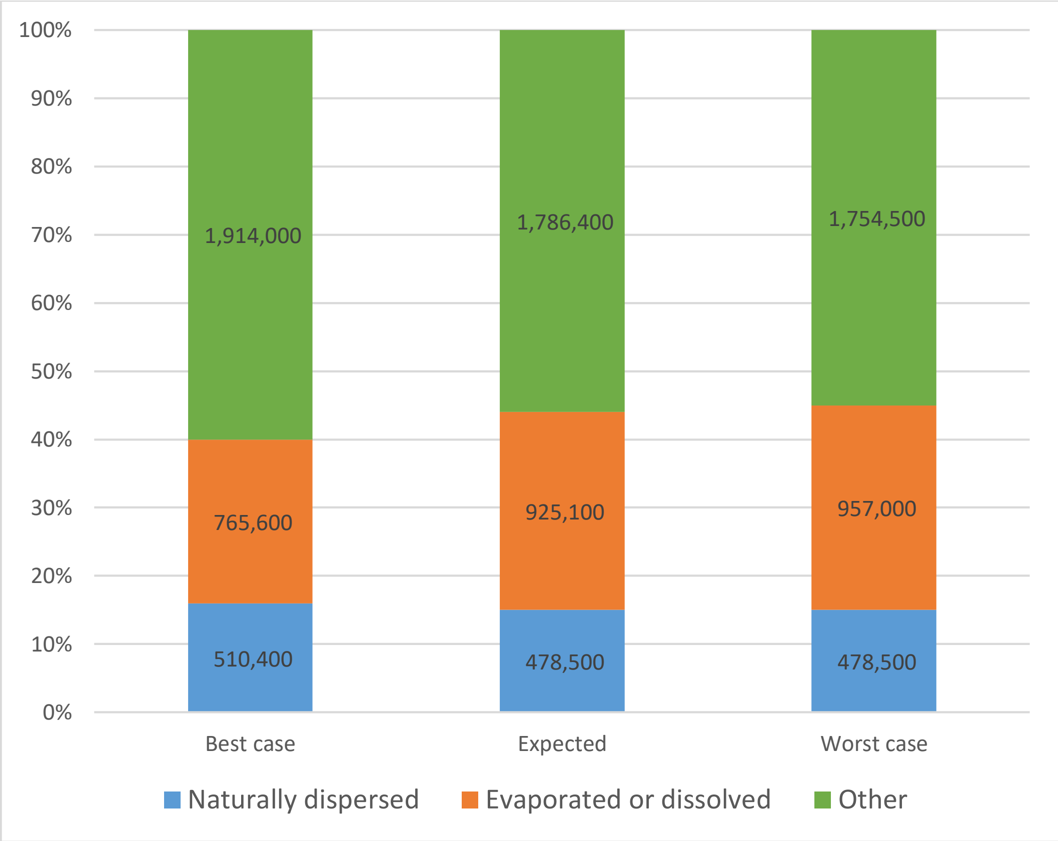



*Figure 5. The 'no response' case as percentages and amounts oil that entered the water*

The amount of oil that was estimated to have some ashore at the *Deepwater Horizon* incident was approximately 20% to 23% of the amount of oil estimated to be in the 'Other' oil category. Using this proportion to estimate the amount of oil that would have come ashore in the case of no response produces amounts of 366,000 to 412,000 barrels; a range of from 2 to 6 times as much oil as was estimated to have come ashore with the response actions that were conducted.

Further oil drifting onto an already heavily oiled shoreline may not cause additional damage. However, given the fluctuations in wind and currents on a local scale, more oil drifting ashore is likely to impact a greater length of shoreline or lead to lightly oiled areas suffering heavier contamination and this would result in additional impacts.

However, as described earlier in section 2a, this would most probably not have been the 'end of the story.' One very visual aspect of the *Deepwater Horizon* incident was the different colours of the 'oil' on the sea surface. The relatively 'fresh', unweathered oil was very dark brown while the weathered and emulsified oil was a vivid orange colour. Experiments conducted at the time, and confirmed by later studies, showed that the crude oil released from the well needed to lose about 40% to 45% of its volume by evaporation before it could form a stable water-in-oil (w/o) emulsion.

In the absence of any response, further evaporative loss of the more volatile oil components to the air would have slowly occurred from the oil on the sea surface, resulting in an approximate total of 55% of the oil volume released into the water being removed by natural processes. Approximately 45%, or 1.75 million barrels, of the oil would have remained on the sea surface. Once a stable w/o emulsion could be formed, the water content would rise to 65% or more, thus trebling the volume of pollutant on the sea surface to produce approximately 4.2 to 4.3 million barrels of emulsified oil. The volume of emulsified oil would therefore have been approximately one-third more (135%) of the original amount of oil that entered the water. Some of this emulsified oil would have been eventually and naturally dispersed into the water column, but a lot would have remained as persistent oil on the sea surface and some would have drifted ashore.

These calculations indicate that it is likely that around 5 times (with a range of 4 to 14) more of emulsified oil would have come ashore on the coastlines of the GoM, if no response had been carried out at the *Deepwater Horizon* incident.

## 4. Conclusions

The *Deepwater Horizon* incident occurred under the intense glare of publicity by all aspects of the media and the oil release continued for 87 days. The largest-ever oil spill response operation was mounted with intense political pressure and media interest. A prolonged legal process was undertaken to resolve several aspects. A very extensive NRDA process estimated the damage caused to natural resources and the cost required to restore these resources. An extensive follow-up programme of academic research is still continuing.

Despite all of these activities, there continues to be some uncertainty about some aspects of the incident.

i. It has been legally determined that 4 million barrels of oil were released from the well and that 3.19 million barrels of oil entered the waters of the GoM. This is, of course, a compromise of different views and opinions.

ii. The fate of the oil has stimulated a great deal of academic research, but definitive answers have yet to be found. In several instances, laboratory experiments with patently unrealistic conditions have yielded erroneous results.

iii. Some pieces of information, for example an accurate assessment of precisely how much oil came ashore, will never be known. Experiments that aim to simulate the conditions that occurred at the *Deepwater Horizon* incident may eventually be able to provide more certainty about precisely what happened

iv. The US Federal Government produced the Oil Budget Calculator and this paper has used the same approach to estimate how effective the oil spill response actions were, in terms of the estimated amounts of oil and their fate with and without response. More sophisticated computer modelling would undoubtedly produce more sophisticated answers, but in the absence of some basic inputs of known values, some uncertainty will always remain.

v. Dispersant use, both subsea and on oil on the sea surface, altered the outcome in a significant way, but there is still a high level of uncertainty about how much oil was dispersed by dispersant use. The Oil Budget Calculator estimated that between 0.4 million and 1.1 million barrels of the oil that entered the sea was dispersed. These estimates were intentionally conservative and it is likely that the actual amount is towards the upper end of this range. It is therefore likely that between 19% and 36% (or higher) of the oil that entered the seas was dispersed and subsequently biodegraded to a very substantial degree. In terms of the oil available for response, these percentages rise from 34% to 60%.

vi. Using the same logic, burning removed 8% of the oil and skimming removed 5% of the total amount released into the sea or 15% and 9%, respectively, of the oil that was available for response.

vii. If no response had been conducted, the amount of oil on the sea surface would have been from twice to six times higher. Burning or dispersing the oil before water-in-oil emulsification of the oil could occur prevented a very large amount of emulsion from being formed. It is estimated that at least 5 times (and perhaps 14 times) more of emulsified oil would have been formed if no response had been undertaken. This cannot be directly translated into the amount of emulsified oil that would have come ashore, but is indicative of the effectiveness of the response actions that were carried out.

Despite all the uncertainties, all the available evidence indicates that the spill response effort, primarily led by dispersant use, substantially reduced the amount of surface oil and in doing so made a large contribution to mitigating the spill’s impact.