Determine the Relative Efficiency of Various Surface Chemical Dispersant Delivery Techniques/Systems

Final Report

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LIST OF ACCRONYMS

API	American Petroleum Institute
BSEE	Bureau of Safety and Environmental Enforcement
DOR	Dispersant-to-oil Ratio
EPA	Environmental Protection Agency
FOSC	Federal On-Scene Coordinator
GOM	Gulf of Mexico
NCP	National Contingency Plan
NEBA	New Environmental Benefit Analysis
RRT	Regional Response Teams
SIMA	Spill Impact Mitigation Assessment
SMART	Special Monitoring of Applied Response Technologies
VMD	Volume Mean Diameter
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

In the event of an offshore oil spill, several responses are available to mitigate the hazards and environmental impact of the released oil, including mechanical containment and recovery (booms, skimmers), surface/in-situ burning, and the release of chemical dispersants. Chemical dispersants are applied to oil spilled in bodies of water in order to break down the oil into relatively small droplets that will disperse into the surrounding water. The use of chemical dispersants increases the surface area of the oil-water interface, which enhances the natural biodegradation process of the petroleum hydrocarbons. Prior to the use of chemical dispersants in spill response operations, personnel require information regarding the anticipated effectiveness of the chemical dispersant under various environmental conditions and the relative efficiency of various surface chemical dispersant delivery techniques/systems so an effective and timely response can be planned and implemented.

National Response Teams and Regional Response Teams utilize federal, state, tribal, and local government representatives to develop procedures and policies for oil spill responses in different areas within the United States. These policies and contingency plans may address situations on how chemical dispersants should or should not be used, including the environmental and coastal impact tradeoffs of dispersant use, and may preauthorize the use of chemical dispersants by the Federal On-Scene Coordinator. The Federal On-Scene Coordinator may authorize the use of non-preauthorized chemical dispersants with the concurrence of the Environmental Protection Agency (EPA) and in consultation with the Department of Commerce and Department of Interior. In order to effectively produce policies prior to oil spills and make timely response decisions for use of chemical dispersants, all involved response personnel must have accurate knowledge of the most effective and efficient chemical dispersant delivery systems available. Therefore, there is a need to develop a technology selection process that can be used to evaluate the relative efficiency of different chemical dispersant delivery systems as a function of spill characteristics, environmental conditions, and delivery system capabilities.

The information in this report assesses how to determine the relative efficiency of different chemical dispersant delivery technologies with the intent of improving the operational decision-making process for effective and efficient chemical dispersant delivery under different oil spill scenarios. This evaluation was conducted through the completion of the following tasks: a technology literature review, industry survey, gap analysis, technology efficiency qualification, and a technology selection process through the creation of a decision tree. The information gathered during these tasks is described in full detail in this report, and has been used to generate an interactive decision tree that can be used as a tool to select the most appropriate chemical dispersant delivery technology based on a set of key spill and environmental parameters. This decision tree tool has been developed by Southwest Research Institute and can be employed by Bureau of Safety and Environmental Enforcement (BSEE) and spill responders to identify the most-suitable chemical dispersant delivery system based on conditional parameters.

1. INTRODUCTION

In the event of an offshore oil spill, several responses are available to mitigate the hazards and environmental impact of the released oil, including mechanical containment and recovery (booms, skimmers), surface/in-situ burning, and the release of chemical dispersants. Chemical dispersants are applied to oil spilled in bodies of water in order to break down the oil into relatively small droplets that will disperse into the surrounding water. The use of chemical dispersants increases the surface area of the oil-water interface, which enhances the natural biodegradation process of the petroleum hydrocarbons. Prior to the use of chemical dispersants in spill response operations, personnel require information regarding the anticipated effectiveness of the chemical dispersant under various environmental conditions and the relative efficiency of various surface chemical dispersant delivery techniques/systems so that an effective and timely response can be planned and implemented.

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To improve operational decisions through a technology selection process for chemical dispersant technologies, the relative efficiency of different chemical dispersant delivery platforms and spray systems was assessed through the completion of a literature review, industry survey, gap analysis, technology qualification, and technology selection process. The order in which these tasks were accomplished was as follows:

1. ***Literature Review*** – A literature search was conducted to identify the intended function of different chemical dispersant delivery platforms and technologies and the operating conditions that could affect their efficiency. Standard, industrial, and academic literature databases were used to search for research papers or publically available data on various surface dispersant delivery platforms and technologies, spill characteristics, and weather conditions that could be encountered during an oil spill.
2. ***Industry Survey*** – An industry survey was conducted to identify both the common best practices and current industry standards on chemical dispersant delivery that are not publically available in the literature.
3. ***Gap Analysis*** – Gaps between the capabilities of current technologies and platforms and the intended need for future effective chemical dispersant delivery systems were identified, where recommendations to fill in these knowledge gaps are presented.

These gaps were identified based on the information collected under the literature review and industry survey. The gap analysis aids in determining the limitations of the technology selection process.

4. ***Technology Qualification*** **–** A quantifiable set of parameters was developed that can be used to assess the relative efficiency of various chemical dispersant delivery systems. The technology qualification aids in determining the best delivery platform based on a spill scenario needed for the technology selection process.
5. ***Technology Selection Process*** **–** A method for evaluating the relative efficiency of different technologies was created via an interactive decision tool that can be used to identify the most suitable delivery system based on environmental and spill conditions. This was generated using the information gathered and developed from the previous tasks.

A visual representation of the order in which these tasks needed to be accomplished to successfully create the interactive decision tree is shown in Figure 1-1.

Figure 1-1. Task Progression

The five steps required to generate the technology selection process were to conduct a literature review, industry survey, gap analysis, technology qualification, and technology selection process.

The information gathered and developed during these tasks has been summarized in the successive sections of this report in the order in which they were conducted.

2. LITERATURE REVIEW

The following section summarizes the high-level findings from the literature review that was conducted to characterize the function of different chemical dispersant delivery technologies and their intended operating environment, identifying factors that could affect different technologies effective delivery of chemical dispersants. The literature review is the first task completed in order to develop a technology selection process as identified in Figure 2-1. A list of references can be found in Section 8.

Figure 2-1. First Task in Developing a Technology Selection Process
The literature review is the first task completed in the process to create an interactive decision tree.

2.1 Chemical Dispersants

Chemical dispersants are chemicals that are a combination of one or more surfactant and one or more solvent. When chemical dispersants are applied on an oil slick using surface application techniques, the solvent will carry the surfactant toward the oil-water interface. The surfactant will then reduce the interfacial surface tension between the two fluids. When mixing energy occurs, such as with wave motion, the reduced interfacial tension will allow small droplets to break off the oil slick, which will disperse into the surrounding water. The creation of these small droplets increases the surface area of the oil-water interface, which enhances the rate at which the microbial degradation of the oil occurs.

Several factors can influence the ability of a chemical dispersant to break up an oil slick. Some of these factors are identified in Table 2-1.

Table 2-1. Factors that Influence Chemical Dispersant Effectiveness
Several factors and their associated properties.

FACTOR	PROPERTY
Formulation	Chemical composition
Oil properties	Viscosity, density, chemistry
Environment	Mixing energies, salinity, temperature
Application	Dosage, coverage

Although many possible combinations of parameters can affect chemical dispersant effectiveness, an overall consensus amongst the industry indicates that in order for the applied chemical dispersant to effectively break the spilled oil into small droplets, several actions must occur:

- The surfactant must be applied to the oil with the most suitable ratio of surfactant to oil,
- The surfactant must properly mix with the oil to reduce the interfacial tension,
- Additional mixing energy must be applied to form oil droplets, and
- The droplets must not recoalesce significantly.

All these activities are dependent on both the delivery method and the environmental conditions at the time of the chemical dispersant application. Chemical dispersant effectiveness is traditionally assessed using a qualitative efficacy approach, and although many parameters influence chemical dispersant effectiveness, some correlations have been developed that quantify the relative effectiveness of a chemical dispersant [Ufford 2014].

Before a chemical dispersant can be applied to a specific area, careful considerations of various environmental conditions must be evaluated. This requires planning activities that will aid in a successful chemical dispersant delivery in an effective time frame. The decision-making processes used for this are known as the New Environmental Benefit Analysis (NEBA) and Spill Impact Mitigation Assessment (SIMA). These decision-making processes can be used to choose the best response option and are discussed in detail in Appendix A.

The use of chemical dispersants is dependent on whether the spill occurs in a pre-authorized or pre-approved area, a case-by-case area, or an excluded chemical dispersant application area. Having an area pre-approved for chemical dispersant use is intended to allow the Federal On-Scene Coordinator (FOSC) to make a timely response. The only requirement for the type of chemical dispersant used in these pre-approved areas is that the chemical dispersant must be included on the National Contingency Plan (NCP) Schedule.

In the U.S., there is a regulatory requirement to have a stockpile of chemical dispersants for quick mobilization and delivery for spill cleanup [API TR 1148 2015]. The two chemical dispersants that have been tested, approved, and are part of the stockpiles are Corexit EC 9500A and Finasol OSR52. In order to be approved in the U.S., a chemical dispersant must obtain an effectiveness value of 45% or greater, compared to a controlled test, before it can be added to the U.S. EPA NCP Schedule for chemical dispersant stockpile [OSRL 2018].

2.2 Chemical Dispersant Delivery Systems

There are two main chemical dispersant delivery systems for surface applications. Chemical dispersants can be applied either on the sea surface using aerial (i.e., fixed-wing or helicopter) or by boat (i.e., vessel) mounted systems. Regardless of the chosen chemical dispersant delivery system, the capability of each system is dependent on the following characteristics defined below:

- **Swath** is the effective surface area that can be covered by the delivery system.
- **Application/dosage rate** is the volume of the sprayed product by the surface area covered by the spray.
- **Coverage rate** is the surface area covered by the spray divided by the total time required to spray the chemical dispersant.
- **Encounter rate** is the area of oil that can be sprayed in a specific time and is determined by multiplying the vessel or aircraft speed by the width of the spray deposited on the slick surface.
- **Payload** is the carrying capacity of the delivery system.
- **Flow rate** is the rate at which the chemical dispersant is being released out of the spray system.

- **Droplet size** or **volume mean diameter** is the ideal chemical dispersant droplet size that is produced by the spray system.
- **Chemical dispersant-to-oil ratio (DOR)** is the amount of chemical dispersant that should be applied to a specified amount of oil.

Aerial spraying is the most widely used application approach since it allows the chemical dispersant to be applied neat (i.e., undiluted) and has larger swath widths in comparison to other delivery platforms [Fingas 2011]. Chemical dispersant application from an aircraft can be accomplished using either helicopters or fixed-wing aircraft, typically using spray systems designed specifically for chemical dispersant application.

Helicopters can be used for smaller oil spills, spills less than 12.5 miles from the shore [ASTM F1737 2015], or offshore spills where they can take off from and land on the rig platform. For oil spill response, helicopters can be equipped either with spray arms or with underslung buckets that can be filled with chemical dispersants. The limiting factor for using helicopters is that they are only capable of single-pass applications due to small payload capacities.

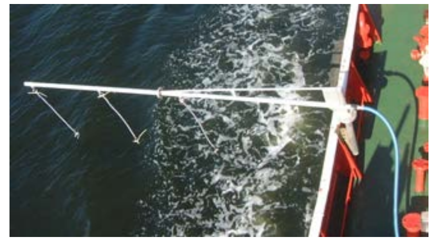
Small fixed-wing aircraft also have a limited payload capacity, and are limited in transit speeds and travel distances before needing to refuel. Large fixed-wing aircraft have a higher chemical dispersant carrying capacity and typically a larger swath than other delivery platforms. Large aircraft can also travel longer distances and at higher speeds and will reach the spill location faster than smaller aircraft or helicopters. The use of aircraft for applying chemical dispersants should not exceed aerial speeds greater than 188 knots due to the creation of excessive wind shear [ASTM F1737 2015]. This has a strong effect on the chemical dispersant droplet size and could affect the ability of the chemical dispersants to effectively break up the oil slick.

Similar to some aerial applications, boats are normally equipped with spray systems for applying chemical dispersants. Spray systems consist of tanks used for chemical dispersant storage, a gasoline or electric power source, a pump, metering and control valve equipment, spray arms, and nozzles. These systems convert the chemical dispersant into a spray that can be deposited on the oil slick. Some advantages and disadvantages of different spray systems are identified in Table 2-2.

The spray arms are normally equipped with multiple nozzles, which help evenly distribute the chemical dispersant onto the oil slick. The individual nozzles should also be spaced so that they overlap as the spray contacts the oil [Fiocco & Lewis 1999]. The size of these spray arms will vary, where large vessels can have individual spray arms that can be 39 feet in length, while smaller vessels tend to have smaller spray arms that will go up to 20 feet [Fiocco & Lewis 1999].

Table 2-2. Characteristics of Various Spray Equipment [Nuka 2005]

Some advantages and disadvantages are identified for the different types of spray equipment available for chemical dispersant application.

SYSTEM	ADVANTAGES	DISADVANTAGES	EXAMPLE IMAGE
Spray arm (diluted)	Uniform dosage across swath, wide range of adjustment possible for vessel speed and dosage without changing nozzles.	Heavy piping suspended over side of vessel, loss of chemical dispersant effectiveness due to dilution prior to application, limitation of swath due to arm length.	 Multiple nozzle spray arm [DESMI, 2011]
Spray arm (neat)	Uniform dosage across swath, most effective use of chemical dispersant.	Fine droplets easily blown off target due to wind, limitation of swath due to arm length, small nozzles tend to clog easily, need to change nozzles to adjust vessel speed and dosage.	 Hand lance spray arm and pump [Markleen 2017]
Fire monitor	Covers 3-4 times area of boom systems, droplets less sensitive to wind, rugged enough to withstand permanent installation, can be permanently mounted without interfering with other operations.	Variations in dosage swath, sight loss of chemical dispersant effectiveness due to dilution prior to application.	 Fire monitor [NauticExpo 2017]
Ducted fan	Can cover 3-4 times area of boom systems, no loss of effectiveness due to dilution before application	Very wind sensitive, need to change nozzles to vary dosage or vessel speed.	 Ducted fan [ETCEMS 2017]

The droplet size of the applied chemical dispersant is important to its overall effectiveness in breaking up the oil slick. Droplets that are too small can be blown off target by the wind, and droplets that are too large may break straight through the oil slick without efficient mixing into the oil. The droplet size is driven by many factors, which include:

- Viscosity
- Density
- Surface tension
- Exit velocity from nozzle/orifice
- Nozzle diameter
- Chemical volatility

Based on past studies, a chemical dispersant is optimally effective at breaking up the oil when the volume mean diameter (VMD) of the chemical dispersant that is being sprayed is between 300 – 700 µm in size [ASTM F2465 2005]. Chemical dispersant droplet VMD generated from spray equipment can be determined using different measurement techniques, such as with laser particle or laser scattering instrumentation and water/chemical sensitive coated cards [ASTM F1738 2015].

A fire monitor is a single-point spray system that injects chemical dispersant into the water stream using differential pressure or with an eductor. When using a fire monitor, the typical chemical dispersant concentrations that can treat a larger area than typical spray arm systems due to swath width [ExxonMobil 2008]. Similar to a fire monitor, a ducted fan is a single-point spray system that can apply a similar chemical dispersant concentration.

A large boat can carry a significant amount of chemical dispersant and can remain spraying the chemical dispersant on the slick for prolonged periods. Boats also have the ability to stay at the spill location overnight, but must be cautious during rough weather or sea conditions. The transit speeds of larger ships, however, are typically slower in comparison to other platforms and they may not be able to reach the spill location in the window of opportunity during which chemical dispersant application would be most effective. Smaller boats can achieve relatively higher transit speeds, but carry less chemical dispersant. These vessels can be useful for chemical dispersant application for near-shore spills [Fiocco & Lewis 1999]. Regardless of boat size, they have an added benefit in aiding chemical dispersant effectiveness, where the wake of the vessel can produce additional mixing energies that help enhance dispersion.

Table 2-3 summarizes the average payload and coverage capabilities for different delivery systems. Table 2-3 shows that the larger aircraft tend to have high payload capacities and coverage rates when compared to other delivery approaches. Table 2-3 also shows that even the larger helicopters cannot carry as much chemical dispersant as would a supply ship, but have a much higher coverage rate than any of the vessel platforms. In addition to payload capacity and coverage, the advantages and disadvantages, including their weather limitations, of each system should be taken into consideration for response decision-making purposes, as outlined in Table 2-4. The top-level considerations for both aircraft and boat response options are identified in Table 2-5.

Table 2-3. Chemical Dispersant Payloads and Coverage for Different Delivery Systems [Nuka 2005]

Larger aircraft tend to have higher payload capacities and coverage rates as compared to other types of chemical dispersant delivery platforms.

PLATFORM	CHEMICAL DISPERSANT LOAD (LITERS)	COVERAGE (HECTARE/HOUR)	COVERAGE (HECTARE/DAY)
Small boat	1,000	10	80
Small ship	3,000	20	160
Supply ship	10,000	30	240
Small helicopter	700	170	280
Large helicopter	2,000	280	800
Agricultural spray plane	400	170	270
DC–3	4,500	540	2,400
DC–4	8,000	840	4,800
DC–6	11,000	1,010	7,330
C–130 (Hercules)	13,000	1,010	8,670

Table 2-4. Advantages and Disadvantages of Different Chemical Dispersant Delivery Systems [ExxonMobil 2008]

Each delivery system platform has its own advantages but also weather and application limitations.

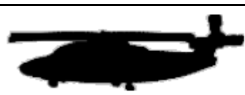
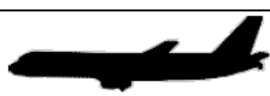
APPLICATION METHOD	WEATHER LIMITATIONS	ADVANTAGES	DISADVANTAGES
 Vessels/boats	5 – 19 knot winds 1 – 10 ft waves	• Good control • Can provide mixing energy	• Limited to small spills • Smaller swath width
 Single-engine airplane	16 – 19 knot winds 7 – 10 ft waves	• Relatively inexpensive • Can land on field	• Limited to smaller spills • Applies chemical dispersant neat only
 Medium-sized helicopter	16 – 27 knot winds 7 – 16 ft waves	• Highly maneuverable • Can land almost anywhere	• Relatively expensive • Applies chemical dispersant neat only
 Large multi-engine airplane	27 – 43 knot winds 16 – 23 ft waves	• High payload • High coverage rate	• Very expensive • Requires runway • Applies chemical dispersant neat only

Table 2-5. Considerations for Surface Chemical Dispersant Delivery Options [Coolbaugh et al. 2017]

The advantages and disadvantages for all surface chemical dispersant application approaches should be considered before a response option is chosen.

	AERIAL CHEMICAL DISPERSANT USE	BOAT CHEMICAL DISPERSANT USE
Advantages	• Can treat a large area of the slick in a relatively short period of time • Faster transit times	• Widely available systems that are simple to operate and able to stay on station • Greater ease of verification of chemical dispersant effectiveness
Disadvantages	• Application reliant on accurate slick spotting • Larger aircraft not as suitable for small surface slicks	• Limited area of treatment • Slow transit times • Not suitable during heavy weather/rough sea states
Logistical considerations	• Requirements for permits • Management of flight hours • Identification of suitable operation bases • Refueling and reloading • Use of spotter aircraft while targeting the slick	• Support from aircraft or other aerial observation system required • Potential long transit time to site during restaging • Chemical dispersant supply replenishment potentially challenging for offshore

2.3 Oil Properties

Oil spills or discharges can occur at any point during the life cycle of the petroleum being explored, produced, or transported, hence, the oil composition can vary greatly. Although oil compositions are different, they can typically be classified as being light, medium, or heavy crudes, where:

- Light crudes will evaporate to a significant degree.
- Medium crudes will have different aromatics, saturates, resins, and polar compounds.
- Heavy crudes and fuel products will have lower volatility but a higher viscosity.

Independent of oil type, the oil properties that influence spill behavior and ultimately chemical dispersant use is indicated in Table 2-6. These properties should be taken into consideration during response planning.

Table 2-6. Oil Properties That Influence Chemical Dispersant Use

Oils are comprised of different constituents that affect how they behave once spilled in the environment, limiting certain spill response options.

PARAMETER	EFFECT
Crude Oil/Product Type	Light, medium, and heavy crudes will undergo different behavior under similar environmental conditions, and can potentially limit chemical dispersant use. Hydrocarbon compounds can vary greatly in oils with the same °API, where the oil will behave differently under the same spill scenario.
American Petroleum Institute (API) Gravity	High °API fluids are more likely to evaporate or to be dispersed, while low °API fluids tend to have higher viscosities and are harder to disperse.
Viscosity	Dispersion of oils with high viscosities is limited, where an oil viscosity of 10,000 cSt is considered unaffected by chemical dispersants [IPIECA 2015].
Pour Point	Oils with larger pour points can solidify in cold environments, eliminating the need for chemical dispersant use.
Flash Point	Oils with high flash points (i.e., lighter crudes) tend to naturally disperse or evaporate in a short time frame, but present a safety concern with its combustibility properties.
Solubility	Most petroleum hydrocarbons have low water solubility, except for lighter crudes, which can have higher solubility (i.e., readily dissolves in water) and often cannot be removed by mechanical recovery.

2.4 Weathering

The term weathering refers to a wide variety of physical, chemical, and biological processes that spilled oil undergoes in the environment over a defined period of time. As oil weathers, its chemical properties change. However, the severity of this change is dependent on the type of oil that is spilled and the weather conditions during and after the spill. Although the outcome of oil weathering is condition specific, several general physical property changes are observed:

- Density will increase as the light fractions of the oil evaporate.
- Density decreases linearly with increasing temperature.
- Viscosity increases exponentially with decreasing temperature.
- Both the density and viscosity of the oil will increase if the oil emulsifies.
- Surface and interfacial tension tend to increase slightly when weathering processes occur.

The types of processes and their high-level effect on using chemical dispersants as a spill response option are described in Table 2-7.

Table 2-7. Weathering Parameters that Affect Chemical Dispersant Use

The variety of physical, chemical, and biological processes affects the fate of the spilled oil.

PARAMETER	EFFECT
Evaporation Rate	The loss of oil due to evaporation may increase the viscosity of the remaining oil spilled, directly affecting the amount of DOR needed and the chemical dispersant dosage.
Natural Dispersion	Light oils or oil slicks undergoing high mixing energy from the sea state may naturally disperse, thus, eliminating the need for chemical dispersant use.
Emulsion	Emulsion increases the density, viscosity, and volume of the spilled oil, which directly affects the amount of DOR needed and chemical dispersant dosage.
Dissolution	Dissolution increases the toxicity level of the surrounding environment, but this amount is typically small since the properties in the oil that are capable of dissolution evaporate relatively quickly.
Biodegradation	Biodegradation is a slow process in relation to other weathering processes and typically has minimal impact on oil spill behavior within the window of opportunity.
Photo-oxidation	Photo-oxidation can alter oil properties due to the effects of sunlight, resulting in by-products that may be resins, which can either be soluble and dissolve into water or cause an emulsion to form.
Sedimentation	Sedimentation (i.e., oil sinks towards the sea floor) can increase in the density of the oil due to weathering and/or interaction with suspended sediments and make tracking and recovery of the oil difficult.

2.5 Slick Movement

Oil slick movement is highly dependent on the type of the oil that is spilled and the weather conditions during and after the spill. The main considerations for determining slick movement include the following:

- Wind and sea conditions that affect spill behavior and oil spill response countermeasures.
- Slick spreading.
- Slick drift characteristics.
- Slick thickness and volume estimation.

Weather is recognized as being an important factor in predicting spill behavior, and can be described using the relationship between wind speed and the associated sea condition, often known as the Beaufort scale [Singleton 2008]. The Beaufort scale is a quantitative identifier, numbered 0 through 12, for environmental wind conditions and its associated sea condition. A table indicating the corresponding wind speed and wave heights for specified Beaufort scale numbers can be found in Appendix B. A high Beaufort scale number is indicative of higher sea energies and increases chemical dispersant effectiveness. However, high sea energies can also promote oil weathering, where some oils may become non-dispersible after a certain time frame. The limit for effective chemical dispersant treatment is considered to be above a Beaufort 7 sea state. Additionally, when chemical dispersants are applied at low wind speeds, oil dispersion will be low since there is low turbulent mixing. However, the chemical dispersants will tend to stay with the oil and a more rapid dispersion of the slick will occur when the wind speed increases.

At a Beaufort state 6, a small craft advisory will be issued indicating that smaller boats and aircraft should not be operated due to unsafe weather conditions. A small craft advisory is a type of warning issued by the National Weather service in the U.S., and is normally put into effect when winds have reached, or in 12 hours are expected to reach, a speed marginally less than gale force [NWS 2017]. A small craft advisory may also be issued when ice exists that could be hazardous to small boats. The National Weather Service does not specifically identify what constitutes as a small craft, although the U.S. Coast Guard informally defines this as boats whose total length is less than 33 feet [Braesch 2009].

The spreading of oil is said to occur in three different phases [Fay 1971], but spends a majority of the time spreading due to the influence from the viscosity of the oil. Research has been accomplished defining the area characteristics of these phases for different oil types [Karman 1940, Fay 1969 & 1971, Blokker 1964]. Correlations for estimating slick spread or surface area can be found in Appendix B.

In addition to their natural tendency to spread, oil slicks move along the water surface primarily by surface currents and winds. The rate and degree at which oil weathers will affect its "wind-drift" factor, or the tendency of the oil to move due to the wind and sea state. These property changes will also affect the ability of the oil to disperse both naturally and with the aid of applied chemical dispersants. A general rule of thumb is that if the wind speed is less than approximately five knots, then the slick generally moves at a rate that is 97% of the surface current and approximately 3% of the wind speed. If the wind is more than 11 knots, and the slick is in open sea, wind predominates in determining the slick movement [Fingas 2011]. The slick wind-drift factor will also change over time, since the spill initially will be a large cohesive film, but will eventually break apart into smaller patches.

The slick thickness is a relatively important parameter to quantify, since it dictates the correct chemical dispersant dosage or DOR. Oil slicks are not uniformly thick, and are dependent on the volume of oil spilled, oil properties, and environmental conditions. This affects the chemical dispersant application approach since thick areas of oil most likely need to be treated using a multiple passes of spray application before the chemical dispersants are effective. At present, there is no reliable and practical method for measuring spill thickness over large areas. However, as first-order approximation, about 90 – 95% of the oil spill volume can be assumed to be contained within 5 – 10% of its area [Ross et al. 2001]. The most common method to estimate the slick thickness is by a visual color representation of the oil on the surface of the water. Appendix B shows a method for determining both the slick thickness and the spill volume based on the observed color and area of the spill. It is noted that this table is a basic tool for approximating slick thickness, since different crudes or weathering may lead to deviations in the predicted visual representation of the slick.

2.6 Window of Opportunity

The concept of window of opportunity relates to the prediction of the best time period for effective chemical dispersant delivery [Fingas 2011]. As time progresses after the initial spill, the oil will become more weathered and less dispersible. Therefore, it is ideal to predict a time window for chemical dispersant application so that it is most effective. Currently, the best correlations for predicting the window of opportunity have been developed by Khelifa and Fieldhouse [2014], shown in Equation 1 and Equation 2.

For $0 \leq \mu_{15} \leq 33.468$ cP

$$\mathrm{TW} = 8.754\mathrm{C_f}\left(\frac{\mu_{15}}{33.468}\right)^{-3.4201} \tag{1}$$

For $33.468 \text{ cP} \leq \mu_{15} \leq 10{,}000$ cP

$$\mathrm{TW} = 8.754\mathrm{C_f}\left(\frac{\mu_{15}}{33.468}\right)^{-0.3556} \tag{2}$$

In Equation 1 and Equation 2, TW is the window of opportunity measured in hours and μ_{15} is the dynamic viscosity of the oil measured at 15ºC. Here, C_f is a correction factor, and is defined in Equation 3.

$$\mathrm{C_f} = 1.48\left(\frac{\mathrm{V}}{1{,}000}\right)^{0.25}\left(\frac{10{,}000}{33.468}\right)\mathrm{e}^{0.573\left(\frac{\mathrm{T}}{23}\right)}\mathrm{e}^{-0.97\left(\frac{\mathrm{W_S}}{12}\right)} \tag{3}$$

In Equation 3, the temperature of the air or water, T, is measured in ºC, the wind speed, Ws, is measured in knots, and the oil volume, V, is measured in barrels (bbl). These time-window correlations have been validated for 24 different GOM oils and provide a model prediction for a time window for spill scenarios that have a volume of 1,000 – 10,000 barrels, cross winds up to 15 knots, temperatures between 13ºC and 29ºC, and an oil viscosity up to 10,000 cP.

It is noted that these correlations for predicting the window of opportunity for oil dispersion do not account for the differences between types of chemical dispersants, treatment rates, energy mixing, or the effect of emulsion, since the validation tests were conducted in a controlled test environment. As a result, these correlations may predict shorter time windows than what occurs in the field. Of the hundreds of different oils produced, most appear to be light and easily disposable when they are fresh. Modeling studies of the weathering characteristics of 28 different GOM oils suggested that the majority, approximately 85%, appeared to have windows of opportunities longer than a few days. [Trudel et al. 2001].

2.7 Monitoring Chemical Dispersant Effectiveness

With the increase in use of chemical dispersants and the advancement of application technologies, the need for a protocol to monitor chemical dispersant effectiveness has increased. The purpose of monitoring protocols is to determine if the applied chemical dispersant is effective at breaking the oil slick into droplets. To address the need for effectiveness monitoring, federal oil spill experts and responders generated guidelines, known as Special Monitoring of Applied Response Technologies (SMART), to assist the Unified Command for decision-making purposes for in-situ burn and chemical dispersant response operations [USCG et al. 2006]. SMART does not directly address health and safety factors of response personnel, but rather attempts to balance feasible and operationally efficient monitoring using scientific principles.

According to the SMART operations, chemical dispersant effectiveness is primarily monitored either by visual observations from a trained individual or by oil concentration measurements at the spill site. The choice of chemical dispersant monitoring will vary based on application; therefore, SMART recommends three different tiers of monitoring. These tiers are described in Table 2-8.

Table 2-8. SMART Protocol Observation Tiers

SMART protocol recommends three different successive tiers for monitoring the effectiveness of chemical dispersants.

TIER	DESCRIPTION
Tier I – Visual Observations	Visual observations by a trained observer provide a general qualitative assessment of chemical dispersant effectiveness. Visual monitoring may be enhanced by advanced sensing instrumentation (i.e., thermal imaging).
Tier II – On-Water Monitoring for Efficacy	To confirm visual observations real-time, water-column monitoring at a single depth, and water-sample collection for later analysis (i.e., fluorometry) are conducted.
Tier III – Additional Monitoring	To expand on water monitoring to meet information needs, water-column monitoring at multiple depths, the use of a portable laboratory or additional water sampling may be conducted.

For Tier 1 observations, the effectiveness of the chemical dispersant is visually indicated by the formation of a yellow-to-coffee-colored plume of dispersed oil. This colored plume can normally be identified from ships or by spotter aircraft. The oil concentration is difficult to measure in the water column, over a large area, and at regular measurement time intervals. After chemical dispersants are identified as being effective on the spill, it is also difficult to determine how much oil is left on the water surface, as there are no methods currently available for measuring oil slick thickness, and the oil subsurface can move in a different direction and at a different rate than the oil slick observed on the surface [Fingas 2011].

2.8 Oil Spill Modeling

Currently, multiple models exist for oil slick movement, oil weathering, plume dispersion, and spray drift. The purpose of these models is to provide tools to adequately assess what the state of the oil spill is at any given time and to identify the response of a spray system in the environment. These models are based on a variety of conditions and parameters, where some can contain first-order models, higher-order models, or empirical correlations based on laboratory testing. A high-level overview of some of the available oil spill and spray models is presented in Appendix C.

3. INDUSTRY SURVEY RESPONSES

The following section summarizes the findings from the industry survey that was conducted to collect information related to chemical dispersant delivery technologies and best practices. The industry survey is the second task completed in order to develop a technology selection process as identified in Figure 3-1.

Figure 3-1. Second Task in Developing a Technology Selection Process
The industry survey is the second task completed in the process to create an interactive decision tree.

3.1 Summary of the Industry Survey

Industry experts were interviewed to collect information related to current chemical dispersant delivery technologies to determine how these technologies successfully apply chemical dispersants and to identify common best practices that are not publically available in the literature. These industry experts largely fit in three categories: responders, equipment manufacturers, and government entities. Other key contacts that were interviewed included subject matter experts from operating companies or consultants. The survey questions that were sent to the industry contacts are located in Appendix D.

The information obtained in this process was critical in identifying the unpublished knowledge gaps and existing practices in the chemical dispersant delivery field. The overall industry response indicated the following:

- Chemical dispersant technology is reasonably well understood and more public outreach is needed to demonstrate that chemical dispersants can be effective at mitigating coastline impacts from large offshore oil spills.
- When a spill occurs, a tradeoff study is normally conducted in which the benefits and impacts of using dispersants, mechanical recovery, or conducting no spill response at all are weighed. This tradeoff study is conducted based on parameters such as spill size, oil type, spill location, weather conditions, and environmental/costal impact to determine the most effective response method.
- The communication of spill properties to responding authorities still needs improvement and developing chemical dispersant technologies for cold water environments is still of interest.

Interview responses for each contact group are summarized in the subsequent sections, where the information gathered from the other points of contact is integrated into the three categorical sections.

3.1.1 Responders

Eight oil spill response organizations were contacted for an interview. Four responses were received, where a summary of all responses is provided below:

- All response agencies indicated that within the last four years, on average, there have been 10 to 15 oil spills per year in the Gulf of Mexico (GOM) that required the activation of a response team to evaluate the response required to manage the oil spill impact to the environment. In 2017, there were 17 oil spill incidences in the GOM that required the activation of an oil spill response team. Most spills are remediated using mechanical recovery techniques. Typically, chemical dispersants may be used for very large spills from pipelines or tankers and if they are a sufficient distance from environmentally sensitive areas.
- Increasing the flow of information on spill properties and utilizing spill response models would greatly improve chemical dispersant response. Each spill is unique and many parameters are considered (oil type, location, active spill, etc.) when making the decision on the use of chemical dispersants.
- An in-depth Net Environment Benefit Analysis (NEBA)/Spill Mitigation Impact Assessment (SIMA) analysis is needed and should be used to determine which response methods will be deployed.
- When used promptly, chemical dispersants are very effective in mitigating coastal hazards. However, proximity to sensitive coastal areas, shallow waters, and weather patterns complicate chemical dispersant delivery.
- SMART protocols are effective for monitoring chemical dispersant effectiveness. Advanced instrumentation was utilized in the Deepwater Horizon spill, such as Volatile Organic Compound (VOC) and subsea plume droplet size measurements.

3.1.2 Equipment Manufacturers

Eight equipment manufacturers were contacted. Six responses were received, where a summary of the key information from the responses is provided below:

- Equipment manufacturers provide a wide range of delivery technologies for aerial and boat systems. However, boat spray systems are the most commonly requested equipment.
- Manufacturers provide manuals describing the proper operation and maintenance practices of their equipment. However, the end user is ultimately responsible for regular maintenance.
- Equipment qualification is driven by the request of a customer and can include in-house testing against standards, customer driven requirements, or independent testing.
- Chemical dispersant delivery technology is not being actively developed. Minor improvements are incorporated when users provide feedback to the manufacturers.
- It is unknown to these equipment vendors, and those individuals who are not heavily involved with the oil spill industry, whether scheduled training exercises and regulatory inspections of equipment are conducted through unannounced exercises with response agencies. It is noted, however, that the BSEE Oil Spill Preparedness Division (OSPD) currently conducts governmental-initiated unannounced exercises and training verification. These exercises are intended to evaluate a response team under a spill

scenario exercise and to assess the operator's preparedness. These exercises occur no less than once every three years [30 CFR 254 2011].

3.1.3 Government Entities

Three government agencies were contacted for an interview. Responses were received from all contacts, where a summary of the responses is provided below:

- Regional Response Teams (RRTs) usually have a decision on whether they are able to use chemical dispersants in a non-pre-approved region within six hours of the spill.
- Non-technical aspects, such as regional politics, can weigh heavily on the decision-making process.
- Public outreach efforts on chemical dispersant use should be expanded to communicate the effectiveness and safety aspects of chemical dispersants for oil spill response.
- Aerial application is usually preferred due to fast rate of response and large swath areas.

4. GAP ANALYSIS

This section summarizes the gap analysis conducted on the different chemical dispersant delivery technologies, their intended function, and common practices. Eleven gaps were identified using information from the literature review and the industry survey responses. These gaps and suggested roadmaps to fill these gaps are discussed in the subsequent sections. The gap analysis is the third task completed in order to understand the limitations of the technology selection process as identified in Figure 4-1.

Figure 4-1. Third Task in Developing a Technology Selection Process
The gap analysis is the third task completed in the process to create an interactive decision tree.

A high-level description of why each of the eleven topics is considered a gap is described below:

1. **Slick Thickness Estimation –** Current slick thickness estimation is subject to human bias or is determined by a local measurement, which does not directly correlate to an average value for the entire slick thickness.
2. **Oil-Weathering Correlations –** Current oil-weather correlations are developed based on physical processes that are independent from on one another or have not been adequately validated.
3. **Chemical Dispersant Application in Cold Environments –** Chemical dispersants and chemical dispersant spray systems are currently not designed for cold environments.
4. **Windows of Opportunity Predictions –** Current window of opportunity predictions only take into account a limited amount of oil properties in their estimate, are based on tests conducted in a laboratory setting, or do not take into account differences between dispersant types or oil weathering effects.
5. **Standards for Testing Technologies Effectiveness –** A standardized testing methodology that confirms the accuracy and uncertainty of the efficiency of the technologies is currently not documented. It is also unknown how often standards are updated with the most relevant information.
6. **Equipment Maintenance Practices –** It is unknown if equipment maintenance activities are routinely being completed. In addition, manufacturers do not often receive feedback from responders on how their equipment is functioning.
7. **Laboratory Versus Field Testing** - The results from laboratory testing does not necessarily relate closely to the expected effectiveness of the technology in the field, creating varying degrees of success for equipment performance.
8. **Biodegradability Chemical Dispersant Testing –** The U.S. currently does not require biodegradability testing on the chemical dispersants that are stockpiled.

9. **Monitoring Chemical Dispersant Effectiveness** - Current determination of chemical dispersant effectiveness at breaking up oil is subject to human bias or is determined by a local measurement.
10. **Technical Advisor and FOSC Communication** - Spill properties and current weather conditions are not being communicated in an efficient time frame between the FOSC and personnel at the spill site.
11. **Education for Regulators and General Public –** There is still limited understanding by the general public and government agencies on the use of chemical dispersants as an emergency spill response option.

4.1 Slick Thickness Estimation

The accurate estimation and measurement of slick thickness is crucial for determining effective dosage when applying chemical dispersants. A recent study by U.S. Coast Guard [2014] indicates that SMART protocols, when accomplished by trained individuals, can estimate a slick thickness within reasonable confidence. However, current methods rely heavily on trained operators using visual methods that are qualitative and subsequently subject to human bias. Measurement techniques, such as fluorometry, can provide concentrations of oil in gathered samples at single locations. However, this result does not translate into a representative "average" slick thickness. Real-time imaging (visible or infrared) techniques are currently commercially available for identifying oil slicks. An image processing procedure can be adapted to measure slick thickness in real time, eliminating human interpretation. With better knowledge of slick thickness, chemical dispersant response planning could be improved and the volume of chemical dispersant used in treatment could potentially be decreased.

4.2 Oil-Weathering Correlations

Accurate correlations for estimating the density, viscosity, evaporation, and emulsification of an oil spill over time are essential for estimating a window of opportunity in which chemical dispersants are most effective. However, many oil-weathering correlations simply combine empirical or semi-empirical models through coupling of dependent variables, such as volume of oil remaining, and do not account for the influence of physical processes on one another. While many weathering correlations or tools exist, the majority of these correlations has not been validated or has only been compared to limited field or meso-scale test data. Continuing to develop these tools and refine the models through validation of field or meso-scale type test data will help improve spill response planning and will provide better window-of-opportunity predictions for applying chemical dispersants.

4.3 Chemical Dispersant Application in Cold Environments

With an increase in arctic exploration, the possibility of the need to apply chemical dispersants in these types of cold environments has increased. In the past, chemical dispersants were not designed for application in cold environments, as low temperatures can result in an increase in oil viscosity that decreases chemical dispersant effectiveness. Ice coverage can prevent the spreading of an oil slick, can increase the slick thickness, and can reduce mixing energy at the surface caused by wave movement. To increase the effectiveness and use of chemical dispersants as a spill response method in cold environments, both the chemical dispersant type and delivery technologies should further be developed specifically for the arctic region. Testing has shown that chemical dispersant gels with larger chemical dispersant droplet sizes are effective at dispersing highly viscous oil past what is considered the standard viscosity limitation of 10,000 cSt. Due to higher viscosities and lower mixing energies, the use of chemical dispersant gels should be further investigated using experimental testing for arctic applications [Ufford et al. 2014].

Vessel application technologies can also be improved upon for arctic conditions to promote mixing energy. Due to reduced mixing energy from waves, vessel chemical dispersant application systems can use additional mechanical means to increase the mixing energy at the surface after the chemical dispersant has been applied to the slick. Other technologies, outside of chemical dispersant spray systems, can also be developed and investigated through field testing for their potential to create mixing energy turbulence after chemical dispersant application. Chemical dispersant application systems will also need to be developed to withstand environmental effects from operating in cold temperatures, such as brittle material failure, freezing of equipment, impeded access, and oil trapped by ice. The development of an aerial chemical dispersant application system for arctic environments should also be considered when there is heavy ice coverage, since vessels may have limited access to the spill site with these conditions.

4.4 Windows of Opportunity Predictions

The window of opportunity is a prediction of the best time frame during which chemical dispersants will be most effective in breaking up an oil slick. The correlations that currently do exist for predicting this window of opportunity only take into account a limited amount of oil properties and environmental conditions, such as wind speed and temperature effects. These correlations were also developed based on experimental studies in a controlled test environment and do not account for the differences between types of chemical dispersants, treatment rates, DOR, mixing energy, or emulsion effects. Developing relationships that include available chemical dispersants, treatment rates, and weathering effects for a wide range of oil types should be accomplished through testing to create a more accurate window of opportunity prediction.

4.5 Standards for Testing Technologies Effectiveness

Multiple ASTM standards currently exist for defining the characteristics needed for spray arms, single point, and multiple nozzle systems for both aircraft and boat spray systems. ASTM subcommittees are dedicated to developing and updating these standard documents. To ensure these standards are up to date and contain the most relevant information regarding chemical dispersant delivery technologies, these documents should continue to be reviewed regularly and modified by these subcommittees to include the most relevant information.

Although these standards contain information regarding equipment performance, such as nozzle shear, droplet size distribution, and target dosage, a standardized testing methodology that confirms the accuracy and uncertainty of the efficiency of the technologies are not documented. The addition to the standard of items such as testing protocol, variance between testing approach, success criteria, and uncertainty or error in the test measurement would help define the quality of the technology provided to the end user. Enforcement or audits of the ability of the equipment manufacturer's technologies to meet the requirements outlined in the standard should also occur. These audits will ensure that manufacturers are producing the most effective chemical dispersant delivery equipment.

4.6 Equipment Maintenance Practices

Feedback from survey responses stated that equipment manufacturers will provide manuals and maintenance best practices for the equipment sold to response agencies. These manuals include information on regular maintenance activities that should be performed to ensure that the equipment is functional over its lifespan. Maintenance records are checked during inspections, and records are kept for three years rather than for the lifespan of the equipment. It is also unknown how often these maintenance activities are routinely being completed. To remedy this, routine audits of equipment maintenance should continue to be implemented to ensure proper functionality, and records should be kept for the full lifespan of the equipment.

During the surveying activities, equipment manufacturers agreed that more feedback from the technology users would drive improvements in design. Manufacturers stated that sometimes feedback on equipment performance is provided to them following a spill, but the responding agency's debriefing process does not require this feedback. Having feedback from the response agencies on the performance of the technologies in the field would aid in improving designs for future delivery devices.

4.7 Laboratory Versus Field Testing

Laboratory testing of chemical dispersant delivery technologies is generally not impacted by issues encountered in the field since the environmental conditions can be controlled to a degree. The results from laboratory testing, however, do not necessarily relate closely to the expected effectiveness of the technology in the field, where natural dilution, weathering, emulsions, and other natural processes can occur with the oil spill, creating varying degrees of success for equipment performance. Validating correlations from studies conducted at different testing facilities is challenging as well. To remedy this, chemical dispersant delivery technologies should be tested and validated in field-like conditions, or as close as possible to these conditions, to assess technology performance. The development of success criteria for the ability of the various technologies to perform in both a laboratory setting, outside a proof of concept, and in a field setting is also desirable. If field testing is not a viable option, then efforts should be made to correlate laboratory testing data to a field-like scenario. The long-term effects of this type of testing will alleviate doubt of the effectiveness of the various technologies at chemical dispersant delivery, and will give confidence to the user that the technologies work as intended.

4.8 Biodegradability Chemical Dispersant Testing

Laboratory-based testing on chemical dispersant toxicity is required for chemical dispersants to be approved for stockpiling in the U.S. However, the U.S. does not currently require testing for biodegradability. Some countries, including France, Italy, Greece, and Spain, require biodegradability testing of chemical dispersants. Testing the biodegradability of a chemical dispersant should be required in the U.S. to understand the potential effect on the marine environment in which the chemical dispersant is applied. The chemical dispersant biodegradability testing should evaluate if a chemical dispersant is biodegradable and if it contains any persistent harmful constituents [OSRL 2018]. Experts believe this testing is important for chemical dispersant approval since a chemical dispersant with high biodegradability and low toxicity is preferable. France has a standardized biodegradability test for chemical dispersants using standard NFT 90346 [OSRL 2018]. In order to regulate the biodegradability of chemical dispersants used in the U.S., the French standard for biodegradability testing could be adopted or modified. [EMSA 2016].

4.9 Monitoring Chemical Dispersant Effectiveness

Chemical dispersant effectiveness is currently being monitored by a trained responder using visual and local measurements of small portions of the slick using SMART Protocols. This monitoring approach could however be interpreted differently by separate individuals. Additionally, local measurements using fluorometers or VOC monitors aid with monitoring efforts, but they are limited to smaller areas of the slick, and are not ideal for monitoring larger spills, where the slick can span a large area and vary in thickness. Additionally, the fluorometer readings at a single location are not representative measurements of the entire oil slick, as the thickness is not uniform and various weathering conditions change the oil slick properties, such as oil viscosity and slick location due to drift. Similar to the solution of measuring the slick thickness, the use of imaging techniques with both visible and IR light may aid in an improved quantitative determination of chemical dispersant effectiveness.

4.10 Technical Advisor and FOSC Communication

Feedback from several interviews during the surveying process indicated that the spill properties and current weather conditions are not being communicated in an efficient time frame between the FOSC and personnel at the spill site. This lag or lack in communication is largely due to the remote nature of spill locations (e.g., the lack of a high-speed communications infrastructure or incompatible communication equipment) and the lack of diagnostic equipment at the location to ascertain the slick thickness, weathering, and other pertinent spill properties [U.S. Coast Guard 2014].

A solution to remedy this delayed communication could be to integrate existing models that predict spill transport with current weather and ocean currents tracked by NOAA data servers to predict oil transport. This information can be used by the FOSC as a decision-making tool. Existing decision-making trees contain high-level information to aid regional response team decisions on chemical dispersant use. These documents should also be routinely updated to incorporate the most accurate spill transport models and used by FOSC for the response decision-making process.

4.11 Education for Regulators and General Public

Feedback from survey responses indicated that there is a knowledge gap or misinterpretation in government entities and in the general public of chemical dispersant functionality, safe usage, and overall response planning for their use. Although new research on chemical dispersants has increased understanding of chemical dispersant effectiveness and environmental effects, there is little consensus across all of the literature. This limits the understanding of the general public and government agencies on the use of chemical dispersants as an emergency spill response option.

To improve public education and increase the acceptance level of chemical dispersants, the regional response teams could host public and media outreach events on the use of chemical dispersants. Emphasis should be placed on educating the public and regulators in coastal regions that are most likely to be affected by the spill. The information must be provided in an easily understandable format and should be available for easy public access. Information regarding tradeoffs between the use of chemical dispersants to mitigate coastline impacts based on spill conditions and environmental effects should be emphasized. Flow charts and other tools that provide guidelines on which chemical dispersant delivery method is optimal for particular weather conditions and spill characteristics should also be publically available to all regional response teams. Proof that these tools have been thoroughly researched will allow the responders to justify their decisions in response to the next major oil spill.

5. TECHNOLOGY QUALIFICATION

Based on the technology literature review, industry survey, and gap analysis, a set of parameters have been identified that can be used to assess the relative effectiveness of various chemical dispersant delivery systems based on operating conditions. The technology qualification is the fourth task completed in order to develop a technology selection process as identified in Figure 5-1.

Figure 5-1. Fourth Task in Developing a Technology Selection Process
The gap analysis is the fourth task completed in the process to create an interactive decision tree.

The applicability of the various delivery systems is assessed with respect to specific spill characteristics and environmental conditions. This set of parameters can be organized into three different categories:

1. Parameters that affect the ability of the delivery system to effectively apply chemical dispersants.
2. Environmental parameters that limit the use of certain delivery systems.
3. Parameters that affect the ability of the chemical dispersant to break up the oil.

It is noted that these parameters do not take into account technology availability and mobilization time. The relative efficiency of a chemical dispersant delivery technology describes the ability of the system to effectively apply chemical dispersants. This efficiency can be described as the relationship or the ratio between the output performance of the technology in relation to an ideal performance, as shown in Equation 4.

$$E_S = \frac{P_{technology}}{P_{ideal}} \times 100\% \tag{4}$$

Using this relationship, the best chemical dispersant delivery system for a chosen spill scenario will have the highest percentage value. For an optimal system, an efficiency value of 100% will be obtained. This relative efficiency is a combination of multiple efficiencies and can be calculated using Equation 5.

$$E_S = (E_D \times E_{DIR} \times E_{SR} \times E_{SW} \times E_{VMD} \times E_P \times E_{SH} \times E_{AS} \times E_{TW}) \times 100\% \tag{5}$$

The nomenclature, indicated in Equation 5, is as follows:

- E_D is the efficiency of the system based on the appropriate chemical dispersant dosage
- E_{DIR} is the efficiency of the chemical dispersant injection rate of the system
- E_{SR} is the efficiency of the system based on nozzle shear rate
- E_{SW} is the efficiency of the swath width of the system
- E_{VMD} is the efficiency of the system based on the volume mean diameter of the chemical dispersant

- E_P is the efficiency of the system based on the payload the platform can carry
- E_{SH} is the efficiency of the system based on the chemical dispersant spray height
- E_{AS} is the efficiency of the system based on the air shear from the vessel speed
- E_{TW} is the efficiency of the system based on the window of opportunity

Equation 5 does not represent the efficiency of the applied chemical dispersant to effectively remove the oil, but rather the relative efficiency of a delivery system so a comparison between platforms can be made for a specific spill scenario. Calculating the efficiency in the manner identified in Equation 5 allows each individual parameter to have equal influence on the overall technology efficiency, meaning no parameter has higher influence on the overall calculation than another parameter.

The individual efficiency parameters are described in full detail in Appendix E and are organized into two efficiency calculation categories: those that are equipment specific and those that are based on the delivery approach. If a parameter does not directly apply to the chosen delivery system or technology, the value of said parameter will be 1 when calculating E_s in Equation 5. An efficiency calculation example is also provided in Appendix E.

The environmental parameters that do not directly quantify the efficiency of the delivery system's ability to apply chemical dispersants, but do affect which technology is best suited for a specific condition is discussed in detail in Appendix E. These environmental parameters include the following:

- Precipitation and visibility
- Wind and sea state
- Direction of slick movement
- Ice coverage

Additionally, the parameters that affect the efficiency of the chemical dispersant to effectively disperse the oil are also discussed in Appendix E. These identified parameters do not directly affect the ability of the delivery system to apply chemical dispersants, but they should be taken into consideration for response planning purposes.

6. TECHNOLOGY SELECTION PROCESS

Based on the information gathered and developed during the literature review and industry survey, an interactive decision tree was generated in Microsoft Excel that can be used to identify the most suitable chemical dispersant delivery system based on user input parameters. The technology selection process is the last task completed to develop the interactive decision tree as identified in Figure 6-1.

Figure 6-1. Fifth Task in Developing a Technology Selection Process

The technology selection process is the fifth and final task completed in the process to create an interactive decision tree.

The Excel file is divided into the following three tabs:

1. A tab labeled Flow Chart containing the decision tree.
2. A tab labeled Results ranking the relative efficiency of commercially available chemical dispersant delivery technologies so a comparison between systems can be made.
3. A tab labeled Technology Table containing the currently available chemical dispersant delivery equipment and their characteristics.

These three tabs are discussed in detail in the following subsections. A snapshot image of the entire decision tree, located in the Flow Chart tab, is shown in Figure 6-2, and expanded views of sections of the decision tree are shown in Figure 6-3, Figure 6-4, and Figure 6-5. These images are only to be used as a reference; readers are encouraged to use the Excel file and follow the decision tree step process located in Appendix F while reviewing the following subsections of this report to fully understand the interactive part of the file.

The tree is divided into two main sections, the first one chooses the best delivery platform based on environmental parameters and the second one uses spill characteristics to determine the relative efficiency of the different chemical dispersant spray equipment types. The equipment efficiency, based off the user input parameters, is calculated using Equation 5. The tree is organized in a way that will first eliminate certain platform systems based on the environmental conditions in the first portion of the tree, and then refine which delivery system is most suitable based on the spill conditions in the second portion of the tree. The chronology of the tree is discussed in the successive sections.

It is noted that full weathering effects of the spilled oil are not included during the decision-making process that was used to design this decision tree. Weathering effects are currently not fully and quantitatively defined for all oil types and environmental conditions, therefore, it would be difficult to implement these within this software tool.

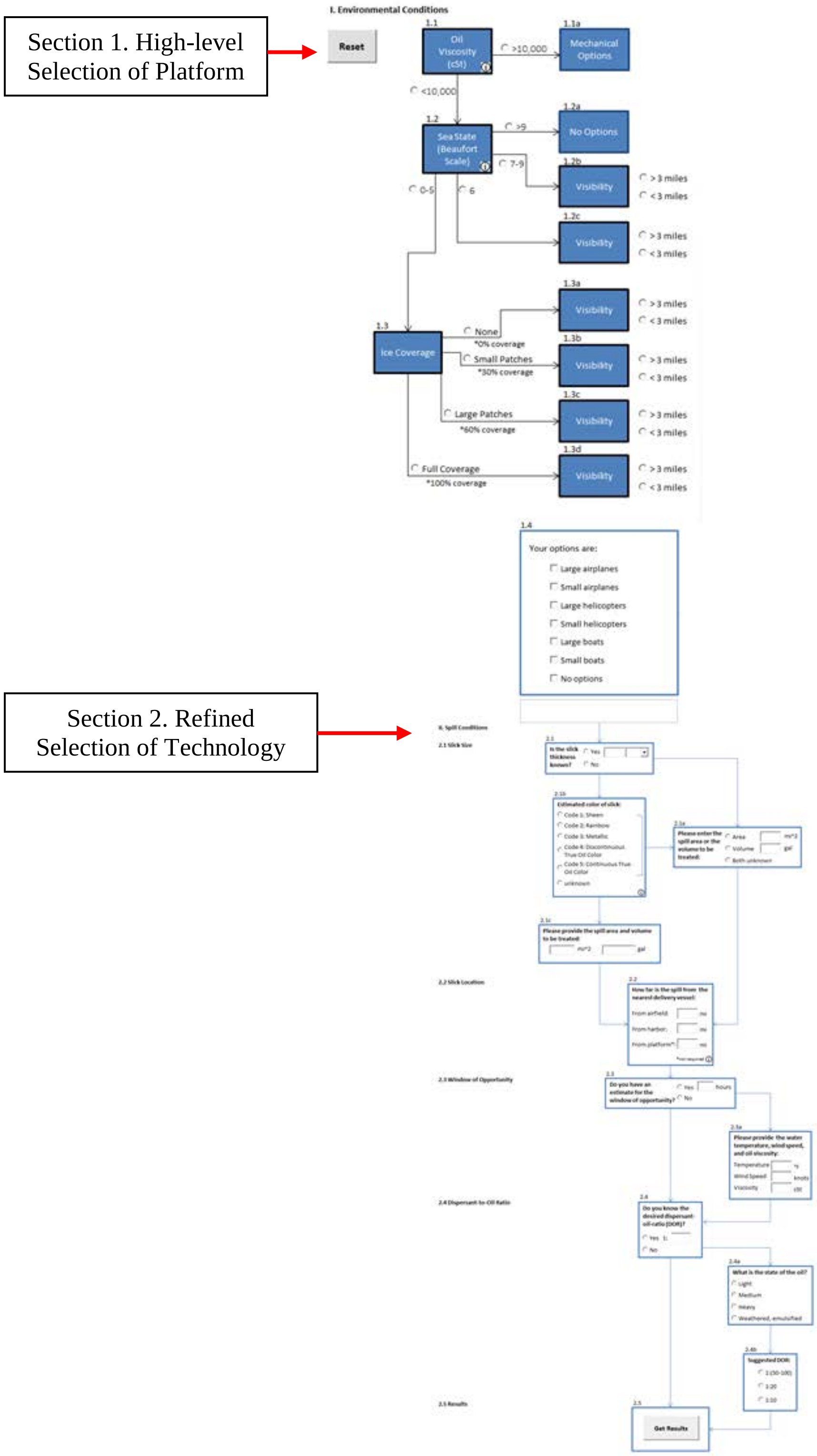


Figure 6-2. Schematic of Interactive Decision Tree

The decision tree is comprised of two main flow chart sections; the first section eliminates unsuitable types of delivery platforms based on environmental conditions, and the second contains parameters that determine the relative efficiency of the chemical dispersant platform.

6.1 Selection of Delivery Platform

The high-level selection of the delivery platform used in the decision tree, labeled I. Environmental Conditions, is shown in Figure 6-3. The steps for selecting the platform are as follows:

1. Select the oil viscosity to ensure chemical dispersants can be used as a response method;
2. Select the sea state based on the Beaufort scale. The sea state will, from a high level, down-select the most appropriate delivery platform between large and small response vessels as well as platform type;
3. Select the ice coverage, if applicable. The chosen ice coverage will also down-select the most appropriate delivery platform between large and small response vessels as well as platform type within the Beaufort scale range;
4. Select the visibility. The chosen visibility down-selects the chosen platform between aircraft and boat platforms as dictated by visual flight regulations [API TR 1148 2015].

Once the visibility is selected, the decision tree will put a checkmark in the box or boxes next to the most appropriate type of delivery platform. The delivery platform options that can be chosen are:

- Large airplanes
- Small airplanes
- Large helicopters
- Small helicopters
- Large boats
- Small boats
- No options

A given scenario may have multiple delivery system outputs. However, these outputs will be ranked according to their relative efficiency within the Results tab of the Excel document after all options in the second section of the tree have been selected.

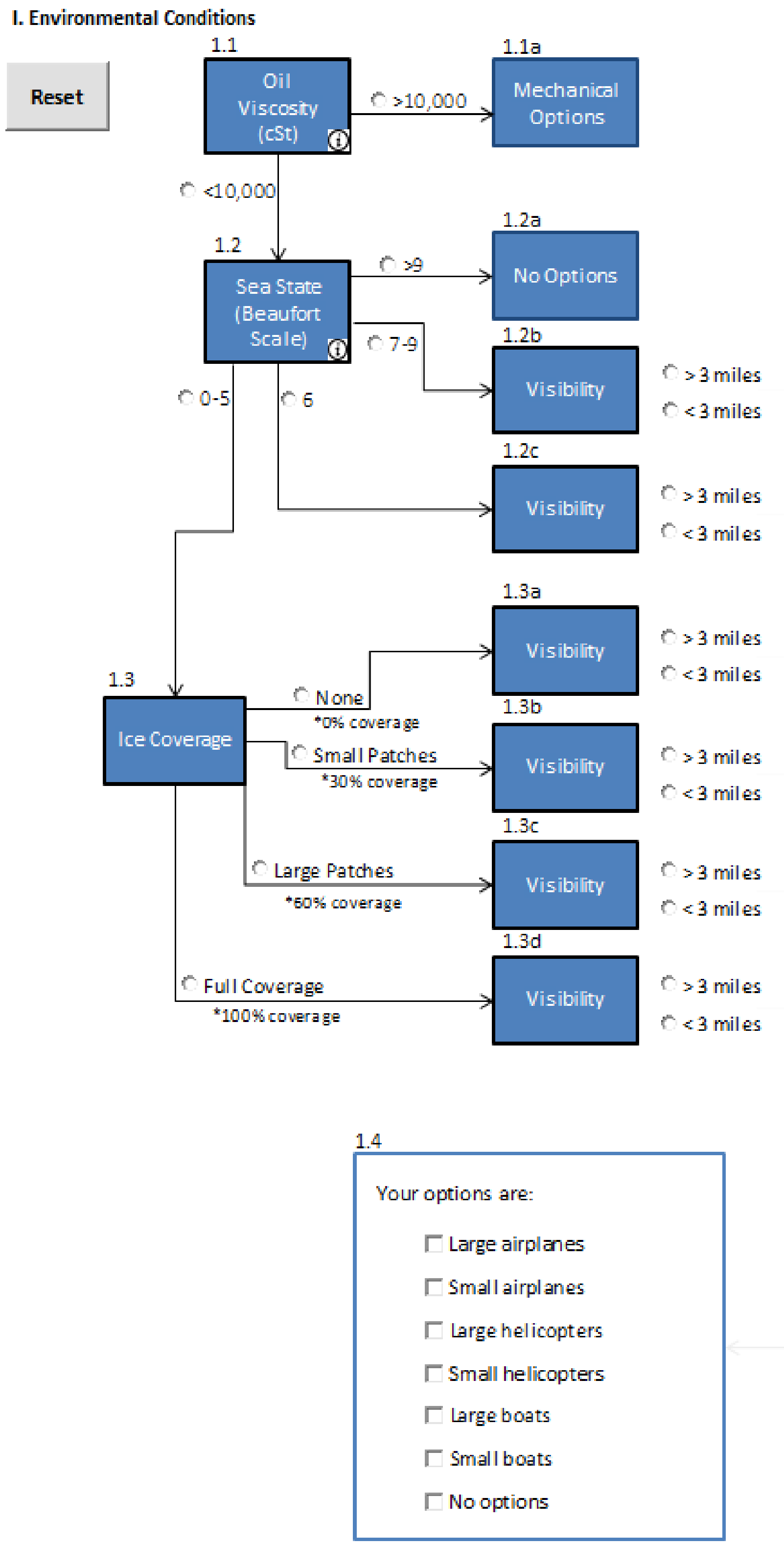


Figure 6-3. High-level Selection of Delivery Platform

The delivery platform is initially chosen based on the oil viscosity, sea state, ice coverage, and visibility.

6.2 Selection of Spill Characteristics

Once the high-level selection of the chemical dispersant platform is chosen, the spill characteristics, identified as II. Spill Conditions in the tree, can be selected or entered by the user, as shown in Figure 6-4 and Figure 6-5. The information entered or estimated in this portion of the tree will calculate the efficiencies of each delivery technology, using Equation 5, refining which is the most suitable chemical dispersant delivery approach for the spill scenario.

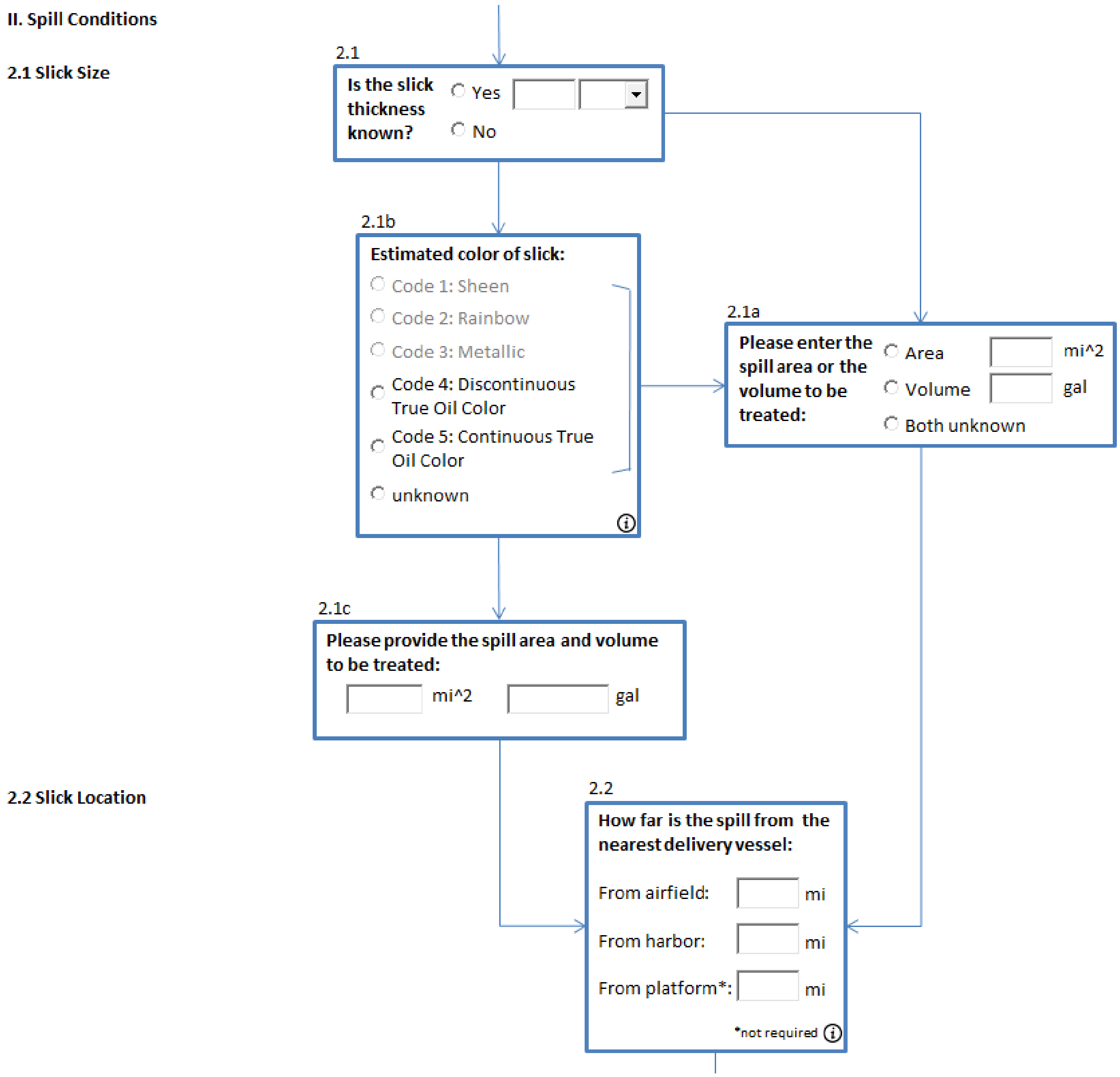


Figure 6-4. Slick Size Selection and Location

In this portion of the decision tree, the user either enters or selects certain parameters to estimate the slick size and enters the location of the spill. The parameters for the slick size include the slick thickness or color, the spill area, and spill volume that will be treated.

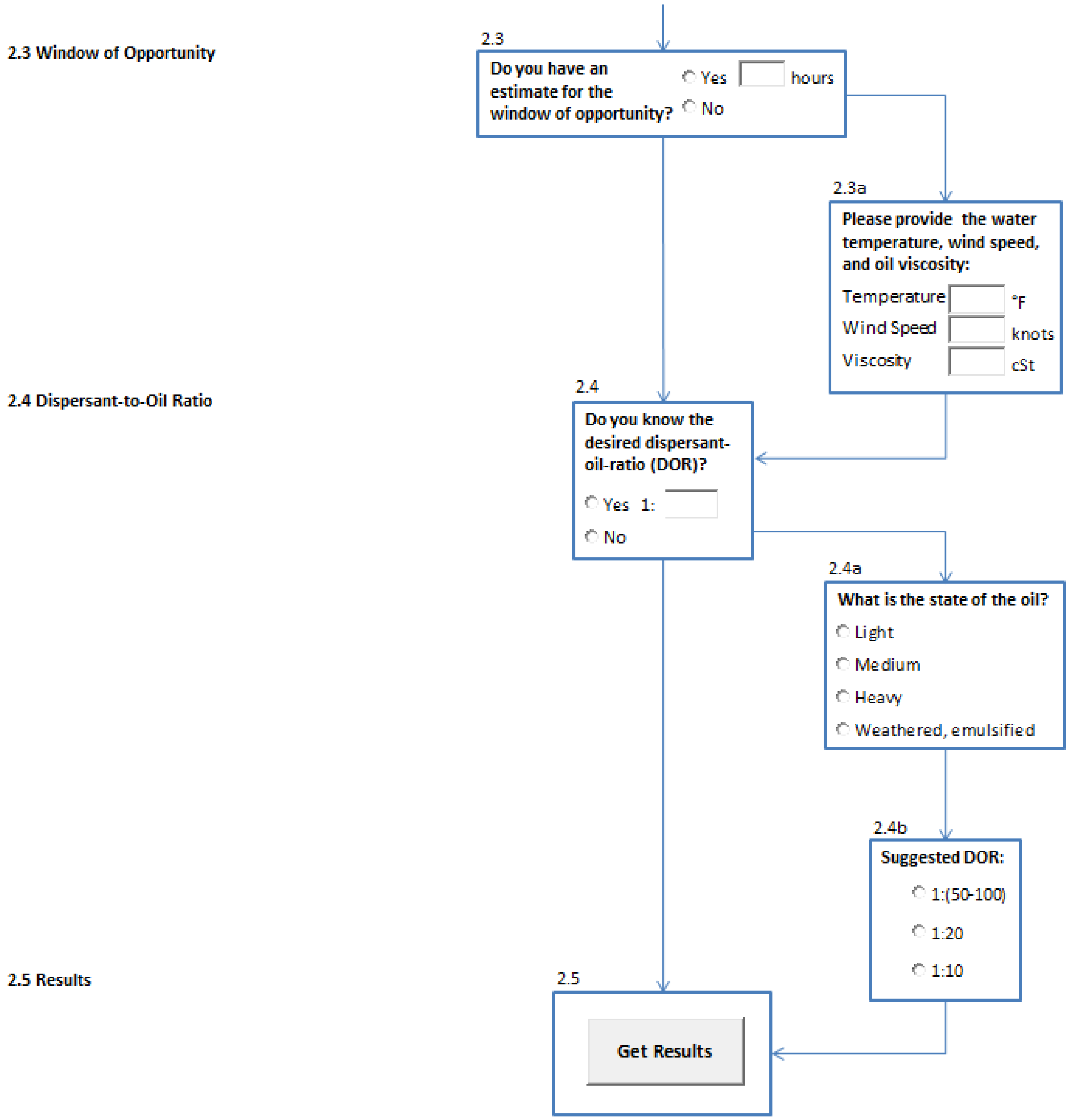


Figure 6-5. Window of Opportunity and DOR Selection

In this portion of the decision tree, the user either enters or selects certain parameters that describe the window of opportunity and DOR.

The next steps that should be followed in the decision tree are as follows:

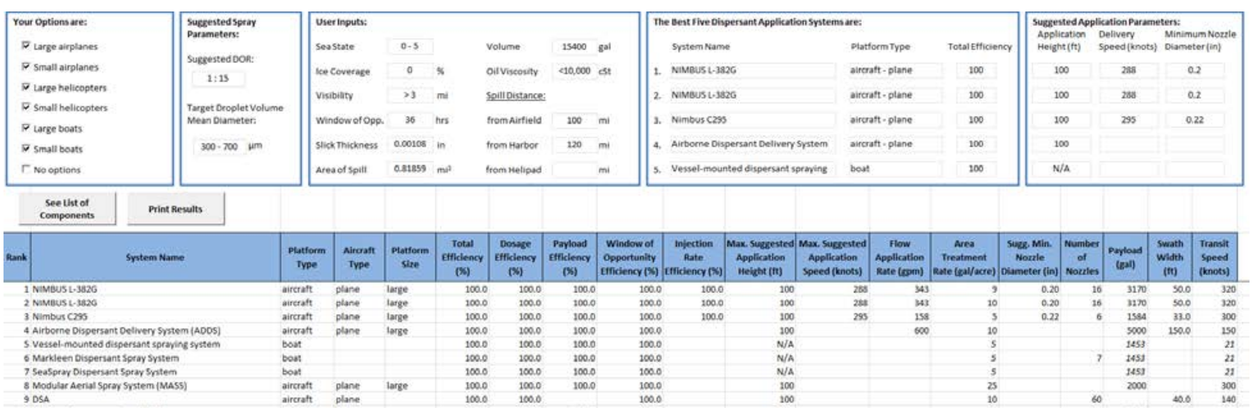
1. Enter the slick thickness or select the color of the slick for a thickness estimation based on the Bonn Agreement Oil Appearance Code [Lewis 2007]. The slick thickness determines the appropriate chemical dispersant dosage and the chemical dispersant injection rate needed from the technology. The decision process assumes that the slick is uniformly thick. It is noted that oil slicks are not uniformly thick and can vary depending on the volume of oil spilled, oil properties, and environmental conditions.

2. Enter or estimate the area or volume of the spill that will be treated by the chemical dispersant delivery platform. The area and volume of the spill that will be treated will determine how much chemical dispersant is needed to be sprayed across a treatment area, which relates to the payload of a platform and swath width characteristics.
3. Enter the distance of the spill from the closest airfield and harbor. If the distance from a platform is known, the user has the option to enter this distance as well. These distances impact which chemical dispersant platform is chosen based on transit speed and the window of opportunity.
4. Enter or estimate the window of opportunity. The window of opportunity relates to the prediction of the best time period for effective chemical dispersant delivery, which also impacts which chemical dispersant platform is chosen based on the transit speed.
5. Enter or estimate the chemical dispersant-to-oil ratio (DOR) based on the oil quality.

Once all values are entered or selected within the tree, the Excel file will estimate and output the efficiencies of the technologies within the Results tab.

6.3 Decision Tree Output Results

The Results tab contains a list of chemical dispersant delivery equipment currently available on the market, including their performance characteristics and calculated relative efficiencies, as shown in Figure 6-6. Based on the user inputs and selections from the decision tree, the file ranks the different systems by their total relative efficiency, with the most efficient platform being given a Rank value of 1. Only chemical dispersant delivery packages are ranked within the Results tab, while individual components such as nozzles or pumps are treated as system accessories that can be added onto a chemical dispersant delivery platform and do not have an efficiency calculation. These system accessories can be found near the bottom of the list of currently available equipment as shown in Figure 6-7.



Rank	System Name	Platform Type	Aircraft Type	Platform Size	Total Efficiency (%)	Dosage Efficiency (%)	Payload Efficiency (%)	Window of Opportunity Efficiency (%)	Injection Rate Efficiency (%)	Max. Suggested Application Height (ft)	Max. Suggested Application Speed (knots)	Flow Application Rate (gpm)	Area Treatment Rate (gal/acre)	Sugg. Min. Nozzle Diameter (in)	Number of Nozzles	Payload (gal)	Swath Width (ft)	Transit Speed (knots)
1	NIMBUS L-382G	aircraft	plane	large	100.0	100.0	100.0	100.0	100.0	100	288	343	9	0.20	16	3170	50.0	320
2	NIMBUS L-382G	aircraft	plane	large	100.0	100.0	100.0	100.0	100.0	100	288	343	10	0.20	16	3170	50.0	320
3	Nimbus C295	aircraft	plane	large	100.0	100.0	100.0	100.0	100.0	100	295	158	5	0.22	6	1584	33.0	300
4	Airborne Dispersant Delivery System (ADDS)	aircraft	plane	large	100.0	100.0	100.0	100.0		100		600	10			5000	150.0	150
5	Vessel-mounted dispersant spraying system	boat			100.0	100.0	100.0	100.0		N/A			5			1453		21
6	Markleen Dispersant Spray System	boat			100.0	100.0	100.0	100.0		N/A			5		7	1453		21
7	SeaSpray Dispersant Spray System	boat			100.0	100.0	100.0	100.0		N/A			5			1453		21
8	Modular Aerial Spray System (MASS)	aircraft	plane	large	100.0	100.0	100.0	100.0		100			25			2000		300
9	DSA	aircraft	plane		100.0	100.0		100.0		100			10		60		40.0	140
10	National Response Corp. (NRC)	aircraft	plane		100.0	100.0	100.0	100.0		100			5			3310		155

Figure 6-6. Decision Tree Results Output

The Results tab in the Excel file will rank the current commercially available technologies' relative efficiencies based on the user selection in the decision tree.

See List of Components | Print Results

Rank	System Name	Platform Type	Aircraft Type	Platform Size	Total Efficiency (%)	Dosage Efficiency (%)	Payload Efficiency (%)	Window of Opportunity Efficiency (%)	Injection Rate Efficiency (%)	Max. Suggested Application Height (ft)	Max. Suggested Application Speed (knots)	Flow Application Rate (gpm)	Area Treatment Rate (gal/acre)	Sugg. Min. Nozzle Diameter (in)	Number of Nozzles	Payload (gal)	Swath Width (ft)	Transit Speed (knots)
	Accessories for Dispersant Delivery Systems																	
	AFEDO 30 Nozzles	component			100.0					N/A		15.9			2		72.2	
	AFEDO 40 Nozzles	component			100.0					N/A		21.2			2		78.7	
	AFEDO 50 Nozzles	component			100.0					N/A		26.4			2		91.9	
	AFEDO 75 Nozzles	component			100.0					N/A		39.6			2		105.0	
	Spray Arms	component		large	100.0					N/A					6		39.4	
	Spray Arms	component		large	100.0					N/A					8		52.5	
	MegaSpray 125	component			100.0					N/A		10					NA	
	MegaSpray 125	component			100.0					N/A		12					NA	
	MegaSpray 150	component			100.0					N/A		22					NA	
	MegaSpray 150	component			100.0					N/A		26					NA	
	MegaSpray 200	component			100.0					N/A		37					NA	
	MegaSpray 200	component			100.0					N/A		44					NA	

Figure 6-7. List of Spray Equipment Accessories

Individual spray components are treated as system accessories that can be added on to a spray package.

Above the list of chemical dispersant delivery technologies, five boxes, which are outlined in blue, show the following outputs to the user:

1. **Delivery Platform Options –** This box contains the best type of delivery platform for the chosen scenario identified in the first portion of the decision tree.
2. **Suggested Spray Parameters –** This box contains the suggested DOR and the droplet size VMD based on the inputs and selected parameters in the decision tree.
3. **User Inputs –** This box contains all the spill conditions based on the user inputs or selections from the flow chart.
4. **The Best Five Chemical Dispersant Application Systems –** This box shows the top five delivery platforms and their associated total performance efficiency based on the user selections on the Flow Chart tab.
5. **Suggested Application Parameters –** This box contains the suggested maximum spraying height, suggested maximum delivery speed for the top five delivery platforms according to the parameters described in current equipment design standards [ASTM F1737, 2015], and a suggested minimum nozzle size in accordance to ASTM F1413 [2013].

Some of the output boxes will remain blank based on the user selected scenario. For example, if they user selects a Beaufort scale of 6, they will not select any ice coverage option. The ice coverage in the user inputs box will then remain blank. Below these five blue-outlined boxes is a button labeled See List of Components. Once this button is pressed, the Excel file will scroll down to the bottom of the technology list and will show the user the additional accessories that are not part of a chemical dispersant delivery system or package, but can be integrated within a delivery platform or used as an add-on component with a delivery system or package, such as nozzles or chemical dispersant pumps. Those technologies not selected as being viable platform options will become less prominent in the table, but will still be available to the user to view. The user can still scroll through all of the technology performance output options based on the chosen spill scenario. Additionally, a button labeled Print Results is located next to the See List of Components button. Once pressed, the results that are shown in the five blue boxes will be displayed in a print preview. These results can then be saved as a PDF file or printed.

Some characteristics of current technologies are not reported by the manufacturer but are required to calculate the total relative efficiency of each system. The decision tree is programmed to assume values for some of the unknown characteristics in order to calculate this relative efficiency. When these assumed characteristics are used to calculate the total relative efficiency, they are italicized in the results table as an indicator to the user. The current decision tree uses the following assumptions:

- **Transit Speed –** If the transit speed of the platform is unknown, the speed is estimated based on publically available data on aircraft or boats of similar size and payload, as described in Section 1. The current transit speed assumptions in the decision tree are 191 knots for a large plane, 118 knots for a small plane, 98 knots for a small and large helicopter, 15 knots for a large boat, and 26 knots for a small boat, respectively. If a plane and boat cannot be categorized as being either small or large, the average of the transit speed for large and small planes and boats is used.
- **Payload –** If the payload is unknown, the payload is estimated based on ASTM F1737 [2015] and publically available data on the payload of chemical dispersant application systems. The current payload assumptions in the decision tree are approximately 1,250 gallons for a large plane, 383 gallons for a small plane, 212 gallons for a helicopter, 2,640 gallons for a large boat, and 264 gallons for a small boat, respectively. If a plane and boat cannot be categorized as being either small or large, the average of the payload for large and small planes and boats is used.
- **Area Treatment Rate –** If the area treatment rate is unknown, the area treatment rate is estimated based on ASTM F1737 [2015]. The current area treatment rate assumption in the decision tree is five gal/acre for all technologies with unknown area treatment rates.
- **Unknown Area or Volume –** If the area or volume of the spill that will be treated by the chemical dispersant delivery platform is unknown, the area is assumed to be one square mile. The volume is then estimated based on this treatment area and the slick thickness value.
- **Missing Parameter** – If any parameter is unavailable from the manufacturer and is missing in the Technology Table, the efficiency associated with that parameter is treated as being 1. Once the Technology Table becomes more complete, these calculated efficiency values will be more accurate and will fully update based on the spill scenario.

If, in the future, these values are reported by the manufacturer, they can be updated by the user in the Technology Table tab, as described in the next subsection, in the Excel file.

6.4 Technology Table

The Technology Table tab contains the currently available chemical dispersant delivery technologies, including their performance parameters. In this portion of the Excel file, the user may update or change any of the information that is provided in this table, such as updating flow rate or swath width of a technology based on future changes from the manufacturer. In addition, the user may add new technologies to the table as they become available on the market or remove old technologies as they become obsolete. This allows the user to update the information as chemical dispersant delivery technologies evolve in the future. When a performance parameter is not known, the cell should be left blank and the decision tree will use the assumed parameters as described in the previous section.

7. CONCLUSION

A qualification selection approach was successfully developed that can be used to determine the relative efficiency of different chemical dispersant delivery technologies under various spill conditions. This was accomplished with an in-depth literature review, industry survey, gap analysis, technology efficiency qualification, and a technology selection process through the generation of an interactive decision tree.

Eleven gaps were identified based on the literature review and industry survey. The reasoning behind these gaps and the suggested roadmaps to fill these gaps are described in full detail in this report. The Industry Survey results provide standard practices for delivery technologies and response agencies, and provide input on the current gaps and a future outlook for chemical dispersant use in oil spill cleanup operations.

A method for calculating the efficiency of the delivery systems has also been developed, where an equation to calculate the efficiency allows the different delivery system parameters to have equal influence on the overall technology efficiency. This relative efficiency calculation was critical for creating the technology selection process via an interactive decision tree. This interactive decision tree has been generated in Microsoft Excel and can be used to identify the most suitable chemical dispersant delivery system based on environmental and spill characteristics. This decision tree can be updated by a user as future chemical dispersant delivery technologies are developed.

The information provided in this report and the interactive decision tree developed as part of this effort, can be used to assess the relative efficiency of different chemical dispersant delivery technologies with the intent of improving the operational decision-making process for effective and efficient chemical dispersant delivery under different oil spill scenarios. This interactive decision tree can be used for a variety of applications. Some of these applications include, but are not limited to, the following:

1. This interactive decision tree can be used to help develop best practices and training scenarios for the surface application of chemical dispersants based on conditional parameters.
2. A technology manufacturer can use this tool to gauge the quality of their equipment based on a defined spill condition. This will allow them to improve upon their existing technologies and develop new technologies based on specific spill and environmental conditions.
3. This interactive decision tree can be used for public outreach purposes, showing the undertakings and tradeoffs that go into the decision-making process for chemical dispersant use and oil spill response.
4. This decision tree can be used for strategic planning of asset locations, in particular with equipment availability and response organization mobility.

Significant findings from this study are summarized below:

- Independent of the delivery system platform, the effectiveness of each system is dependent on swath, application/dosage rate, coverage rate, encounter rate, payload, flow rate, droplet size, and DOR.

- Before a chemical dispersant can be used as an oil spill response method, careful consideration of the various environmental conditions the chemical dispersant is being applied to must be evaluated using NEBA or SIMA.
- Tradeoff studies are normally conducted in order to identify the environmental and costal impacts with using dispersants or other response options for spill cleanup.
- Aerial spraying is the most used chemical dispersant application platform since it allows for chemical dispersants to be applied neat and via a large swath.
- Vessel chemical dispersant application is best used for smaller oil spills, nighttime application, or in cold environments, and the delivery systems are typically equipped with spray arms, fire monitors, or ducted fans to apply the chemical dispersant.
- Independent of oil type, the oil properties that influence spill behavior and response options include oil density, viscosity, pour point, flash point, and solubility. A variety of correlations exists for calculating these properties.
- The weathering of oil refers to a wide variety of processes that include evaporation, emulsification, natural dispersion, dissolution, biodegradation, photo-oxidation, and sedimentation. All of these processes are dependent on the oil constituents and the environmental conditions.
- Oil slick movement is highly dependent on the type of oil that is spilled and the weather conditions during and after the spill. Currently, models exist that predict oil spill fate and movement.
- SMART protocols aid in quantifying chemical dispersant effectiveness, which is typically reported to the incident command by a trained individual from a spotter aircraft or by on-water monitoring.

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APPENDIX A

Net Environmental Benefit Analysis and Spill Impact Mitigation Assessment

Appendix A – Net Environmental Benefit Analysis and Spill Impact Mitigation Assessment

Before a chemical dispersant can be used as an oil spill response method, careful considerations of various environmental conditions the chemical dispersant is being applied to must be evaluated. This requires pre-planning activities, which will help aid in a successful chemical dispersant delivery in an effective time frame. Three high-level questions are normally considered before using chemical dispersants.

1. Is it possible to use chemical dispersants based on the oil physical properties, within the window of opportunity, and with respect to regulatory approval?
2. Will applying chemical dispersant mitigate the potential impact of an oil spill?
3. Is it logistically feasible to apply the chemical dispersant with the most appropriate delivery approach using the provided chemical dispersant stockpiles?

These questions are typically posed in pre-planning activities based on spill scenarios. This decision-making process provides responders with an objective methodology to make justifiable choices and identify the potential limitations of chemical dispersant use. One such response planning approach is to use a Net Environmental Benefit Analysis (NEBA). NEBA is a well-established decision-making process to help make these choices regarding response approaches [Coolbaugh et al. 2017]. NEBA is a four-step process and is described in Table A-1.

Table A-1. NEBA Process

Four major steps are conducted while using the NEBA process to help make decisions about the most appropriate response options.

NEBA STEPS	DESCRIPTION
Evaluate data	The first stage is to consider where the spilled oil is located and where it will drift under the influence of currents and wind - various oil spill trajectory models exist to support this. It is also useful to know how an oil will "weather" as it drifts. This is part of evaluating the available data.
Predict outcomes	The second stage is to assess what is likely to be affected by the spilled oil if no response is undertaken. This may include ecological resources offshore, nearshore and on shorelines, alongside socio-economic resources. Pragmatic, operational considerations should form a very important part of the NEBA process applied to all feasible response options.
Balance trade-offs	The advantages and disadvantages of the potential response options are considered and weighed against the ecological and socio-economic impacts of each to understand and balance the trade-offs.
Select best option(s)	The person concludes with the selection of a response method(s) within oil spill contingency plans that minimizes the impact of potential spills on the environment, and promotes the most rapid recovery and restoration of the affected area.

Additionally, a concept called Spill Impact Mitigation Assessment (SIMA) has also been established as a selection process tool, but is not as widely utilized as NEBA [Coolbaugh et al. 2007]. SIMA is a response selection process that includes both socio-economic considerations as well as environmental impacts, and it has been developed to help facilitate the selection of the most appropriate response options to effectively combat an oil spill [IPIECA Report 593 2017]. SIMA uses a four-stage approach similar to the NEBA approach described in Table A-1. Once the appropriate decision-making process has been followed and the use of chemical dispersants has been determined to be a suitable response option, then the best chemical dispersant application system or approach should be identified.

APPENDIX B

Beaufort Scale, Oil Spread, Slick Thickness and Volume, and DOR

Appendix B – Beaufort Scale, Oil Spread, Slick Thickness and Volume, and Chemical Dispersant-to-Oil Ratio

1.1 Beaufort Scale

The relationship between wind speed and the associated sea condition can be described using the Beaufort scale [Singleton 2008], shown in Table B-1.

Table B-1. Beaufort Scale

The Beaufort scale values correspond to a specific wind speed and wave height.

BEAUFORT NUMBER	WIND SPEED	WAVE HEIGHT	SEA CONDITIONS	DESCRIPTION
0	< 1 knot	0 ft	Sea looks like mirror	Calm
1	1 – 3 knots	0 – 1 ft	Ripples with appearance of scales	Light air
2	4 – 6 knots	1 – 2 ft	Small wavelets	Light breeze
3	7 – 10 knots	2 – 3.5 ft	Large wavelets	Gentle breeze
4	11 – 16 knots	3.5 – 6 ft	Small waves become larger	Moderate breeze
5	17 – 21 knots	6 – 9 ft	Moderate waves	Fresh breeze
6	22 – 27 knots	9 – 13 ft	Large waves	Strong breeze
7	28 – 33 knots	13 – 19 ft	Sea heaps up to form breaking waves	High wind, moderate gale, near gale
8	34 – 40 knots	18 – 25 ft	Moderately high waves of greater length	Gale
9	41 – 47 knots	23 – 32 ft	High waves	Storm/severe gale
10	48 – 55 knots	29 – 41 ft	Very high waves with long overhanging crests	Storm/whole gale
11	56 – 63 knots	37 – 52 ft	Exceptionally high waves	Violent storm
12	≥ 64 knots	≥ 46 ft	Air is filled with foam and spray, exceptionally high waves/devastation	Hurricane force

In Table B-1, the green highlighted areas indicate a Beaufort state where a small craft advisory will be issued.

1.2 Oil Spread

The spreading of oil is said to occur in three different phases [Fay 1971]. Once oil is released at sea, the liquid will spread under the influence of gravity, until the interfacial tension between the oil, water, and air are equal. The spreading then changes from being a gravity-dominated process to a phase strongly influenced by the viscosity of the oil, and finally to a phase that is dominated by surface tension forces [Oebius 1999]. Research has defined the area characteristics of these phases for different oil types [Karman 1940, Fay 1969 & 1971, Blokker 1964]. Table B-2 summarizes these efforts.

Table B-2. Slick Spreading Stages

A slick will undergo spreading in three different phases, where the slick spends most of its time spreading due to viscous action in Phase 2.

PHASE	EQUATION FOR SLICK AREA
1. Gravity phase	$A_{s1} = 1.3\pi(\Delta_F gV)^{\frac{1}{2}}t$ (B-1)
2. Viscous phase	$A_{s2} = 0.96\pi\left(\frac{\Delta_F gV^2}{\nu_{oil}^{\frac{1}{2}}}\right)^{\frac{1}{3}} t^{\frac{1}{2}}$ (B-2)
3. Surface tension phase	$A_{s3} = 2.56\pi\left(\frac{\sigma^2}{\rho_{oil}^2\nu_{oil}}\right)^{\frac{1}{2}} t^{\frac{3}{2}}$ (B-3)

In Table B-2, A is the slick area, V is the oil slick volume, g is the gravitational acceleration, t is the time, ρ_{oil} and ν_{oil} are the density and kinematic viscosity of the oil, and Δ_F is calculated using Equation B-4.

$$\Delta_F = \frac{\rho_{sw} - \rho_{oil}}{\rho_{sw}} \tag{B-4}$$

In Equation B-4, ρ_{sw} is the density of seawater, which will change based on temperature and salinity content. Δ_F is universally taken as 0.23 for all oils [Oebius 1999]. In slick spreading, the first phase occurs quickly, and the third stage occurs with the slick breaking into smaller components. Therefore, the majority of the oil spreading occurs in the second phase, and can, therefore, be roughly calculated using Equation B-2 for any given time t [Mishra & Kumar 2015].

Another correlation that estimates the change in slick area over time is the relationship developed by Sebastiao and Soares [1995] in Equation B-5.

$$\frac{dA}{dt} = k_{sp}\frac{V^{\frac{4}{3}}}{A} \tag{B-5}$$

Equation B-5 is an iterative correlation, where k_{sp} is an evaporation constant and is oil type and weather dependent. For an initial estimation at the time that the oil is spilled, the area can be calculated using Equation B-6.

$$A_o = \pi\left(\frac{k_2^4}{k_1^2}\right)\left(\frac{\Delta_F gV_o^5}{\nu_{sw}}\right) \tag{B-6}$$

In Equation B-6, k_1 and k_2 are empirical constants, with values of 1.14 and 1.45, respectively, Δ_F is calculated using Equation B-4, and ν_{sw} is the kinematic viscosity of the seawater. It is noted that all correlations mentioned were developed under ideal conditions. The slick area will strongly depend on the oil type, weathering, and movement processes, and the use of these correlations may result in a deviation from these predictions.

1.3 Slick Thickness and Volume Estimation

The slick thickness is a relatively important parameter to quantify, since it dictates the correct chemical dispersant-to-oil ratio (DOR). Oil slicks are not uniformly thick and affect the chemical dispersant application approach since thick areas of oil most likely need to be treated using an application of multiple passes of spray before the chemical dispersant takes effect. As a first-order approximation, about 90 – 95% of the oil spill volume can be assumed to be contained within 5 – 10% of its area [Ross et al. 2001]. The most common method to estimate the slick thickness is by a visual color representation of the oil on the surface of the water. Table B-3 indicates these visual observations with approximate thickness.

Table B-3. Estimation of Oil Volume, Slick Thickness, and Area [ExxonMobil 2008]
Characteristics of the slick can be estimated by the appearance of the oil on the surface.

		APPEARANCE					
		Barely Discernible	Silvery Sheen	Rainbow Colors	Darkening Bands of Color	Dull Colors	Light Brown
	Approximate Thickness (μm)	0.05	0.1	0.5	1	3	10
	Area (ft^2)	Gallons					
Estimated volume of oil spilled based on thickness	1,000	< 0.01	< 0.01	0.01	0.02	0.1	0.2
	10,000	0.01	0.02	0.1	0.2	0.7	2.5
	100,000	0.1	0.2	1.2	2.4	7	24.5
	500,000	0.6	1.2	6	12	37	122
	1,000,000	1.2	2.5	12.2	25	73	245
	5,000,000	6	12.2	61	122	367	1,224
	10,000,000	12	24	122	245	734	2,447

Table B-3 also gives a first-order estimate of the spill volume and area determined based on the observed color. It is noted that this table is a basic tool for approximating spill thickness, volume, and area if these parameters are unknown.

In addition to Table B-3, the Bonn Agreement Oil Appearance Code [Lewis 2007] can be used to give a rough estimate of both the slick thickness and volume based on the appearance of the oil on the sea surface. The Bonn Agreement Oil Appearance Code is a sequence of five categories that are organized into different code numbers based on the appearance of the slick, as shown in Table B-4.

Table B-4. Bonn Agreement Oil Appearance Code [Lewis 2007]
Oil slick thickness and volume can be estimated by the appearance of the spill on the sea surface.

Code	Appearance	Slick thickness (μm)	Volume estimate (L/km^2)
1	Sheen (silvery/grey)	0.04 to 0.30	40 to 300
2	Rainbow	0.30 to 5.0	300 to 5000
3	Metallic	5.0 to 50	5,000 to 50,000
4	Discontinuous True Oil Color	50 to 200	50,000 to 200,000
5	Continuous True Oil Color	>200	>200,000

It is noted that different crude oil types or weathering effects may lead to deviations in the visual appearance of the slick. It is important to treat these values as rough estimates and not definitive values. Traditionally, darker portions or patches of the slick are treated first within the spill, as this color indicates that more oil is present at that location.

1.4 Estimating DOR

The DOR range is the amount of chemical dispersant that can be applied to a specified amount of oil. Depending on the chemical dispersant type and delivery platform, the chemical dispersant should be applied either pre-diluted or neat (e.g., undiluted). In general, increasing the ratio of the DOR increases the rate and degree of oil dispersion. For lighter oils, dispersion can occur quickly, while heavier crude oil products may take much longer, especially in calm sea conditions. However, the actual DOR needed depends primarily on two factors: the oil slick thickness and the chemical dispersant application rate. Guidance on the DOR needed for different scenarios is indicated in Table B-5.

Table B-5. DOR Estimation

The amount of DOR needed for oil dispersion is dependent on the oil slick state and mixing energy.

SCENARIO	DOR
Response planning	1:20
Weaker chemical dispersants	1:(20 – 30)
Strong chemical dispersants or high mixing energy	1:(50 – 100)
Heavy, highly weathered, emulsified oils or low mixing energy	1:< 20

APPENDIX C

Oil Spill Modeling

Appendix C – Oil Spill Modeling

Multiple models exist for oil spill slick movement, oil weathering, plume dispersion, and spray drift. These models are based on a variety of conditions and parameters, where some can contain first-order models, higher-order models, or empirical correlations based on laboratory testing. A high-level overview of some of the available oil spill models is presented below.

The Observation Systems Capability Analysis and Review Tool (**OSCAR**) is a three-dimensional dynamic simulation tool for response planning [SINTEF 2014]. This model computes the oil fate, including the environmental effects of oil releases. It also includes response strategies in its simulations. Many of the modules of OSCAR have been developed through lab studies at SINTEF and field studies in temperate and arctic climates. The modules cover advection by currents, wind, and diffusion, as well as weathering (evaporation, dissolution, and dispersion). It includes an oil database with experimental data.

The Spill Impact Model Application Package (**SIMAP**) is an oil fate model that can be used to quantify both the fate and concentrations of spilled oil located below the sea surface, as well as the transportation and weathering effects of the floating oil [French-McCay, 2003, 2004]. This model has been validated against data collected from 20 large oil spills, as well as experimentally designed tests used for result verification.

Automated Data Inquiry for Oil Spills (**ADIOS2**) [Lehr et al. 2002] is an updated oil spill model of the original ADIOS oil spill model. ADIOS2 is a software package that predicts the weathering processes and characteristics of oil slicks. The weathering process includes spreading, evaporation, dispersion, sedimentation, and emulsification. ADIOS2 also contains user oil spill cleanup options, which include the use of chemical dispersants.

General NOAA Oil Modeling Environment (**GNOME**) [NOAA 2018] is a modeling tool that predicts how wind, ocean currents, and weathering processes affect slick drift. This model allows the user to customize the toolkit for different spill scenarios. GNOME also estimates the amount of oil beached, still floating, or evaporated at specific time windows.

The Oil Weathering Model (**OWM**) takes oil laboratory data (i.e., density, viscosity, etc.) from fresh and weathered samples and predicts oil properties at a later time [Brandvik 2012]. It also uses environmental conditions and oil film thickness. Its outputs include oil spill properties such as the viscosity of emulsions, water content, and a time window for use of chemical dispersants. OWM is a submodel within OSCAR.

SIMPAR [Waterstaat 2005] is an all-encompassing oil-weathering model. This software includes complex oil weathering formulations, where the sensitivity of the results are various for different oil spill properties and environmental conditions.

Dose-Related Exposure Assessment (**DREAM**) [Rye 2007] is a three-dimensional software tool that models the environmental effects of plume or complex mixtures transport with different exposures and dosages. This model accounts for physical-chemical processes separately for each fluid phase, which includes dilution and transport, dissolution, volatilization, particulate setting, degradation, and sedimentation.

AERMOD [EPA 2018] is a steady-state plume model that simulates oil dispersion based on a stratified environment, and includes boundary layer turbulence and scaling (e.g., turbulence cascade) concepts. It includes surface and elevated plume sources on simple and complex terrain. It consists of three modules (the steady-state dispersion model, the meteorological data processor AERMET, and the terrain processor AERMAP).

The Industrial Source Complex **(ISC3)** [EPA 2005] model is a steady-state plume model to simulate plume transport. It can be used to assess dissolution under a variety of environmental conditions. The program's long-term mode computes average concentration values on an area of a few hundred square kilometers for a period, such as a season or a year. The short-term mode computes mean concentration values for a period of one or a few hours.

CALPUFF [EPA 2018] is a multi-layer, multi-species turbulent plume dispersion model. It models the effects of dynamic meteorological conditions on plume transport, transformation, and dissolution. CALPUFF can be applied on scales of tens to hundreds of kilometers. It includes algorithms for the terrain, as well as other effects, such as deposition and chemical transformation.

The Estimated Dispersant System Potential **(EDSP)** [BSEE 2016] is a tool developed by BSEE and Genwest Inc. that is designed to help with response planning for chemical dispersant application. It calculates a system-level chemical dispersant application rate based on the application platform (i.e., boat, helicopter), access, and extent of the spill. Unlike some of the other models described here, this tool does not predict oil weathering or the extent of spill over time.

AGDISP™ [CD 2016] was developed by the USDA Forest Service to predict spray drift for agricultural applications, but can be used for chemical dispersant spraying from aerial platforms. It includes detailed algorithms for characterizing the release, dispersion, and deposition over and downwind of the application area. It can be used for boom or aerial application scenarios, including various types of aircraft.

AgDRIFT® [CD 2016] is a modified version of AGDISP, developed through a Cooperative Research and Development Agreement between the EPA, the US Department of Agriculture's Forest Service, and the Spray Drift Task Force. It is used for assessing spray drift conditions for aerial, boom, and air-blast applications.

APPENDIX D

Survey Questions

Appendix D – Survey Questions

1.1 Vendors (Equipment Manufacturers)

1. What chemical dispersant technologies do you currently provide?
2. How do you verify that this equipment works? What testing methods or standards are used? Where has this equipment been tested, and how often is this equipment tested?
3. How do you quantify the effectiveness of your equipment?
4. For your equipment, is there a swath width, droplet distribution, or volumetric mean diameter that is desired?
5. Does your technology have a shelf life? If yes, what is the typical shelf life?
6. What literature, brochures, or other information can you provide?
7. Are most of your products off the shelf (standard), or are they typically customized equipment? What is the average lead-time for ordering?
8. Do you offer training services for the use of your equipment? How often are these used (e.g., upon purchase or yearly)?
9. Are there real-time sensors/monitors to verify the equipment is properly functioning while in operation?
10. When has your equipment been used on a maritime oil spill? Where was it used? How do you know its effectiveness when it was used?
11. What are the suggested maintenance intervals?
12. Who are the typical customers (e.g., coast guard, response entities, or commercial company)?
13. Are you developing any new delivery technologies or any redesign of your current systems?

1.2 Users (Responders)

1. How often does a spill or incident occur that would require your response? How do you determine if the use of chemical dispersants is required?
2. What decisions do you currently employ to acquire/determine the technology to be used in the event of a spill? (e.g., Do you look for how they tested it? Do you look at historical cases/uses?)
3. What is the most prevalent or typical scenario for which you find chemical dispersant use is necessary?
4. Where do you find the current chemical dispersant delivery options lacking in terms of effectiveness?
5. How do you monitor that the chemical dispersant is working/being effective? Is there any other technique used besides the USCG SMART Protocol?
6. What kind of training schedule do you employ?
7. Do you have a list of previous spills, the size of the spill, and what technology was used for cleanup and recovery?

8. What gaps do you see in existing technology? What features are currently not on technologies that you would find effective for response options (e.g., arctic conditions, high sea state, off-nominal conditions, delivery techniques)?
9. Do you give feedback to the vendors? Do they change or modify their technology because of it?

1.3 Government Entities (Unified Command and Field On-Scene Coordinator)

1. What are some key factors in deciding and approving the use of chemical dispersants?
2. What spill characteristics would determine if aerial application or surface application is used?
3. What would you need to know to expedite the decision-making process?
4. How do you monitor that the chemical dispersant is working/being effective?
5. Are there real-time sensors/monitors to verify the equipment is properly functioning while in operation?

APPENDIX E

Efficiency Parameters and Example Calculation

Appendix E – Efficiency Parameters and Example Calculation

1. Efficiency Parameters and Calculations

1.1 Relative Efficiency of Chemical Dispersant Application Systems

The efficiency calculation of specific spray equipment characteristics is described in full detail in the subsequent sections. These parameters are the following:

- Chemical dispersant dosage
- Chemical dispersant injection rate
- Nozzle shear
- Swath width
- Volume mean diameter

1.1.1 Chemical Dispersant Dosage

The chemical dispersant dosage is the amount of chemical dispersant that should be sprayed over a designated area. The ideal chemical dispersant dosage can be calculated using the relationship in Equation E-1 [ExxonMobil 2008].

$$\mathrm{Dosage} = 27{,}200\mathrm{t_s DOR} \qquad \text{(E-1)}$$

In Equation E-1, the ideal Dosage is measured in U.S. gallons (USG) per acre, t_s is the slick thickness in inches, and DOR is the chemical dispersant-to-oil ratio. This calculation assumes that t_s and DOR are known quantities. Appendix B gives guidance on how to estimate these two values if these parameters are unknown. According to ASTM F2465 [2013] and F1737 [2015], oil spray equipment should be able to provide a chemical dispersant dosage between 2 to 100 USG per acre. If the chemical dispersant dosage that the delivery system can produce, $\mathrm{Dosage_{technology}}$, is greater than or equal to the ideal dosage calculated in Equation E-1, then the efficiency from the chemical dispersant dosage, E_D, is 1. If $\mathrm{Dosage_{technology}}$ is less than then the ideal dosage, then E_D can be determined using Equation E-2.

$$\mathrm{E_D} = \frac{\mathrm{Dosage_{technology}}}{\mathrm{Dosage}} \qquad \text{(E-2)}$$

Information provided in ASTM F1737 [2013] has indicated that a dosage in the range of 1 to 10 USG per acre has been sufficient for a majority of the encountered chemical dispersant delivery scenarios.

1.1.2 Chemical Dispersant Injection Rate

The chemical dispersant injection rate (DIR), measured in USG per minute, also called the chemical dispersant flow rate or application rate, refers to the volume of the chemical dispersant sprayed over a period of time. DIR can be estimated using the relationship in Equation E-3 [ASTM F1413 2013].

$$\mathrm{DIR} = 2.33 \times 10^{-3}\mathrm{SU_{application}Dosage} \qquad \text{(E-3)}$$

In Equation E-3, S is the swath measured in ft, $U_{application}$ is the speed of the delivery vehicle while it is applying chemical dispersants in knots, and Dosage is measured in USG per acre. If the DIR of the technology, $\mathrm{DIR_{technology}}$, is greater than or equal to the ideal or needed DIR calculated in Equation E-3, then the efficiency from the chemical dispersant injection rate, E_{DIR}, is 1. If $DIR_{technology}$ is less than then the ideal DIR, then E_{DIR} can be determined using Equation E-4.

$$E_{DIR} = \frac{DIR_{technology}}{DIR} \tag{E-4}$$

This chemical dispersant injection rate efficiency can directly be used to determine the effectiveness of the coverage rate of the chosen platform. Since Dosage is used to calculate $DIR_{technology}$, E_D and E_{DIR} will result in the same efficiency value. If E_D can be determined, then E_{DIR} will be given a value of 1 when calculating the overall efficiency, and vice versa.

1.1.3 Nozzle Shear

The shear rate, measured in sec^{-1}, of the flow exiting the nozzle and a single-point spray system can be calculated using Equation E-5 [ASTM F1413 2013].

$$\text{Shear rate} = 3.9\frac{Q}{D^3} \tag{E-5}$$

In Equation E-5, Q is the average flow rate per nozzle in U.S. GPM, and D is the diameter of the nozzle orifice in inches. According to ASTM F1413 [2013], the mechanical shear rate going through the nozzle should also be low, where a value less than 10,000 sec^{-1} is suggested for aircraft systems, and 2,000 sec^{-1} for boat systems. If the nozzle shear rate is less than 2,000 sec^{-1} for a boat application, the shear rate efficiency E_{SR} is 1. If the shear rate is greater than 2,000 sec^{-1}, then E_{SR} is calculated using Equation E-6.

$$E_{SR} = \frac{2{,}000}{\text{Shear rate}} \tag{E-6}$$

If the shear rate is less than 10,000 sec^{-1} for an aerial application, E_{SR} is 1, if the shear rate is greater than 10,000 sec^{-1}, then E_{SR} is calculated using Equation E-7.

$$E_{SR} = \frac{10{,}000}{\text{Shear rate}} \tag{E-7}$$

1.1.4 Swath Width

Swath width is the effective surface area that can be covered by a delivery system. The efficiency due to swath width can be calculated using Equation E-8.

$$E_{SW} = \frac{SA_{technology}}{SA_{slick}} \tag{E-8}$$

In Equation E-8, $SA_{technology}$ is the surface area that can be covered by the technology in ft^2, and SA_{slick} is the surface area of the slick in ft^2. If multiple passes can be made with the delivery system, then Equation E-8 is multiplied by the associated number of passes, n, as indicated in Equation E-9.

$$E_{SW} = n\frac{SA_{technology}}{SA_{slick}} \tag{E-9}$$

According to ASTM F1413 [2013], the delivery technology should be capable of delivering the chemical dispersant within 10% variance of the width. If SA_{slick} is unknown, it can be roughly estimated by slick color representation similar when assessing slick thickness. Guidance on estimating the volume can be found in Appendix B. It is noted that in common field practice, the entire surface area of the slick is typically not treated, but rather smaller areas or portions of the slick are treated; normally those that are darker in color or have larger thickness.

1.1.5 Volume Mean Diameter

The droplet size distribution of the applied chemical dispersant should have a volume mean diameter (VMD) between 300 to 700 µm in size [ASTM 1413 2013]. If the delivery system can produce a VMD between 300 to 700 µm, then the efficiency from the contribution of VMD, E_{VMD}, is 1. If the VMD is less than 300 µm, then E_{VMD} is calculated using Equation E-10.

$$E_{VMD} = \frac{d}{300} \tag{E-10}$$

In Equation E-10, d is the average size particle or VMD in micrometers. If the VMD is greater than 700 µm, then E_{VMD} can be calculated using Equation E-11.

$$E_{VMD} = \frac{700}{d} \tag{E-11}$$

1.2 Delivery Platform Efficiency Calculation

The efficiency calculation of the parameters that are relative to the chemical dispersant delivery platform is described in full detail in the subsequent sections. These parameters are the following:

- Payload
- Delivery height
- Air shear
- Window of opportunity

1.2.1 Payload

The payload is the chemical dispersant carrying capacity of the delivery system. The efficiency of the payload of a delivery system, E_p, is the relationship between how much chemical dispersant the system is able to hold, $Payload_{technology}$, in relation to the amount of chemical dispersant that needs to be applied, n_d. If n_d is less than or equal to $Payload_{technology}$, then E_p is 1. If n_d is greater than $Payload_{technology}$, then E_p is calculated using Equation E-12.

$$E_P = \frac{Payload_{technology}}{n_d} \tag{E-12}$$

The amount of chemical dispersant needed can be calculated from a known DOR value and a known spill volume.

1.2.2 Delivery Height

The delivery height is the effective height at which a chemical dispersant can be delivered. This height is only considered in aerial chemical dispersant delivery. According to ASTM F1737 [2015], the spray altitude during application should not go beyond the height values indicated in Table E-1.

Table E-1. Chemical Dispersant Spray Altitude for Various Aerial Platforms
Helicopters should not go above 30 ft when applying chemical dispersant, while fixed-wing aircraft should not go above 100 ft.

AERIAL PLATFORM	HEIGHT
Helicopters	30 ft
Small Airplanes	30 ft to 100 ft
Large Airplanes	50 ft to 100 ft

For helicopters, if the spray height is less than 30 ft, then the expected efficiency due to the delivery systems height, E_{SH}, will be 1. If the spray height, H, for a helicopter is greater than 30 ft, then E_{SH} will be calculated using Equation E-13.

$$E_{SH} = \frac{30}{H} \tag{E-13}$$

In Equation E-14, H is the height of the helicopter in ft. For fixed-wing aircraft, if the spray height is between 30 ft to 100 ft for a small aircraft, and between 50 ft and 100 ft for a large aircraft, then the expected efficiency due to the delivery systems height, E_{SH}, will be 1. If the spray height for a fixed-wing aircraft is greater than 30 ft, then E_{SH} will be calculated using Equation E-14.

$$E_{SH} = \frac{100}{H} \tag{E-14}$$

The efficiency calculation for the fixed-wing aircraft does not take into account the lower height restriction and assumes that the aircraft will not fly below 30 ft for the small airplanes and helicopters and 50 ft for the larger airplanes.

1.2.3 Air Shear

The vehicle speed, particularly for aircraft delivery systems, should be optimized so that the droplet sizes of the sprayed chemical dispersant are between 300 µm and 700 µm. This can be accomplished by reducing the air shear created by the difference between the speed of the vessel and the speed at which the chemical dispersant is being sprayed. This differential speed, U_{diff} measured in knots, can be calculated using Equation E-15.

$$U_{diff} = U_{application} - \left(0.409\frac{Q}{D^2}\right) \tag{E-15}$$

In Equation E-15, $U_{application}$ is the delivery system speed, in knots, while it is applying chemical dispersants, Q is the average flow rate per nozzle in U.S. GPM, and D is the diameter of the nozzle orifice in inches. As stated in ASTM F1413 [2013], the differential speed should be less than 188 knots (200 ft/s). If the delivery system is traveling too fast where the differential speed is greater than 188 knots, there is a possibility that the droplets will break up into smaller diameters, creating chemical dispersant volume mean diameters smaller than 300 µm. If U_{diff} is less than 188 knots, then the efficiency due to air shear, E_{AS}, is 1. If U_{diff} is greater than 188 knots, then E_{AS} is calculated using Equation E-16. With aerial applications, chemical dispersants are best applied when flying into the wind.

$$E_{AS} = \frac{188}{U_{diff}} \tag{E-16}$$

1.2.4 Window of Opportunity

The concept of window of opportunity relates to the prediction of the best time period for effective chemical dispersant delivery. This time window for effective chemical dispersant use can limit the platform that is chosen due to vessel speed. The time needed for the application platform to reach the spill site, $t_{technology}$, in hours can be calculated using Equation E-17.

$$t_{technology} = \frac{0.86 L_{travel}}{U_{vessel}} \tag{E-17}$$

In Equation E-17, L_{travel} is the distance the technology needs to travel to the spill site in miles and U_{vessel} is the boat transit speed in knots. If $t_{technology}$ is less than the window of opportunity, TW, measured in hours, then the efficiency based on the window of opportunity, E_{TW}, is 1. If $t_{technology}$ is greater than TW, the E_{TW} is calculated using Equation E-18.

$$E_{TW} = \frac{TW}{t_{technology}} \tag{E-18}$$

An estimation of TW in Equation E-18 is shown in Section 2.6 in the main portion in this document. It is noted that mobilization time is not taken into consideration for the efficiency estimation. This calculation also does not take into account whether the spill occurs in a pre-authorized chemical dispersant use location. For offshore oil spills, helicopters can be used as a delivery platform, if they happen to be available on the rig, and can apply chemical dispersants within the TW since they can easily take off from and land on the rig platform.

1.3 Relative Efficiency from Environmental Conditions

The parameters identified under this section do not directly quantify the efficiency of the delivery system's ability to apply chemical dispersants, but do affect which technology is best suited for a specific environmental condition. These environmental parameters are the following:

- Precipitation and visibility
- Wind and sea state
- Direction of slick movement
- Ice coverage

1.3.1 Precipitation and Visibility

Both precipitation and visibility will affect the chemical dispersant delivery response method. If there is no precipitation present, and there is clear or "good" visibility, then both boat and aerial chemical dispersant platforms can be used. If there is, however, rain or snow, the response method may be limited to boat only, or by utilizing larger aircraft that can withstand heavier downpours. Poor visibility may also limit aerial application, such as with fog. If visibility is poor due to heavy fog, then the platform may be limited to boat application only. Flying is also limited at night. If a chemical dispersant application is needed outside of daylight, then a boat system should be used. Visibility can be quantitatively described in terms of flight limitation of aerial platforms as noted in Table E-1 and with using flight limitations outlined by API TR 1148 [2015].

1.3.2 Wind and Sea State or Environmental Conditions

The wind and sea state can be characterized by the Beaufort scale, which describes the intensity of both the wind and sea condition on a scale of 1 through 12. A high Beaufort scale number is indicative of higher wind and sea energies and increases chemical dispersant effectiveness, where the limit for effective chemical dispersant treatment is considered to be above a Beaufort 7 sea state [Fiocco & Lewis 1999]. When chemical dispersants are applied at low wind speeds, oil dispersion will be low since there is low turbulent mixing. However, the chemical dispersants will tend to stay with the oil and a more rapid dispersion of the slick will occur when the wind speed increases. At Beaufort states of 6 and 7, a small craft advisory is issued, where small boats and aircraft are not permitted to be out at sea or flying, eliminating them as a delivery platform choice when these conditions arise. Different boat and aerial systems have operational weather limitations where they cannot be used for chemical dispersant delivery, as described in the main body of this report in Section 2.2.

1.3.3 Direction of Slick Movement

Slicks will drift due to wind direction and ocean currents. The direction of how a slick will move is mainly due to oceanic currents and tide phases, where only 3% of the movement of a slick is directly a response to wind speed. If the wind is more than 11 knots, and the slick is in the open sea, wind predominates in determining the slick movement [Fingas 2011]. At high wind speeds, chemical dispersant application becomes difficult since the slick tends to drift, and the ability to target the slick location is difficult. The rate the slick will drift is also not constant and will change over time, therefore, the delivery platform must be able to operate in both the wind and sea state, but also be able to effectively apply chemical dispersants while the slick is moving at various speeds.

1.3.4 Ice Coverage

Ice coverage will often limit the type of chemical dispersant application system. Oil will be more difficult to recover in dynamic ice-laden waters due to access limitations. If small patches of ice are present, the use of boats for the delivery platform would be preferred, since they can provide additional mixing energy by churning the surface ice and water to promote dispersion. If there are large amounts of ice coverage that inhibit boat access, aircraft should be used as the delivery platform. Ice coverage can be divided into no coverage, or 0% area covered by ice, small patches, around 30% of the area covered by ice, large patches, around 60% area coverage by ice, and full coverage, 100% of the area covered by ice.

1.4 Parameters Affecting Dispersion of Oil

The parameters identified under this section do not directly affect the ability of the delivery system to apply chemical dispersants, but rather the efficiency of the chemical dispersant to effectively disperse the oil. These parameters and their effect on an oil spill from using chemical dispersants are indicated in Table E-2, and should be taken into consideration for response planning purposes.

Table E-2. Parameters That Affect Oil Dispersion Using Chemical Dispersants
These parameters do not affect the ability of the delivery systems to apply chemical dispersants but should be taken into consideration during response planning.

PARAMETER	EFFECT
Chemical Dispersant-to-Oil Ratio (DOR)	The DOR directly relates to the chemical dispersant dosage a delivery system needs to apply to the slick.
Slick Thickness	The slick thickness dictates the DOR. Oil slicks are not uniformly thick and affect the chemical dispersant application approach, since thick areas of oil will most likely need to be treated with multiple passes of spray application before the chemical dispersants are effective.
Air Temperature	The air temperature can manipulate the weathering of the oil, which can alter the slick thickness and maximum surface area the slick will spread. This affects the effective swath and dosage needed from a delivery platform.
Water Temperature	The water temperature can manipulate the weathering of the oil, largely with emulsion effects and salinity changes, which can alter the slick thickness, viscosity, and maximum surface area the slick will spread. This affects the effective swath and dosage needed from a delivery platform.
Crude Oil/Product Type	Light, medium, and heavy crudes will undergo different behavior under similar environmental conditions, and can potentially limit chemical dispersant use. Hydrocarbon compounds can vary greatly in oils with the same °API, where the oil will behave differently under the same spill scenario.
American Petroleum Institute (API) Gravity	High °API fluids are more likely to evaporate or to be dispersed, while low °API fluids tend to have higher viscosities and are harder to disperse.
Viscosity	Dispersion of oils with high viscosities is limited, where an oil viscosity of 10,000 cSt is considered unaffected by chemical dispersants.
Pour Point	Oils with larger pour points can solidify in cold environments, eliminating the need for chemical dispersant use.
Evaporation Rate	The loss of oil due to evaporation may increase the viscosity of the remaining oil spilled directly affecting the DOR and the chemical dispersant dosage.
Natural Dispersion	Light oils or oil slicks undergoing high mixing energy from the sea state, may naturally disperse, thus, eliminating the need for chemical dispersant use.
Emulsion	Emulsion increases the density, viscosity, and volume of the spilled oil, which directly affects the DOR and chemical dispersant dosage.

2. Efficiency Calculation Example

The following example is provided to demonstrate the method for determining the efficiency of a platform for delivering a chemical dispersant in a hypothetical spill scenario. The values listed below do not pertain to any currently existing chemical dispersant delivery system. The steps shown below will walk the user through the calculations and outline information needed to calculate platform efficiency.

Spill Scenario: An oil spill has occurred about five miles off shore in the Gulf of Mexico (GoM). The spill source was an oil-containing vessel that impacted a structure and released crude oil on the water surface. The estimated spill volume is 100,000 gallons and the estimated spill thickness is 0.001 inches. Both the spill volume and the slick thickness have been estimated based on the slick appearance as indicated in Appendix B. Chemical dispersant use has been authorized by the Federal On-Scene Coordinator (FOSC) given that the prevailing winds and water current may threaten the Louisiana coastline and the effective time window is 24 hours before the oil becomes weathered and is no longer dispersible. The chemical dispersant-to-oil ratio (DOR) needed for this spill has been specified as 1:20.

The following steps will demonstrate how to calculate the relative efficiency of an available aerial delivery platform to apply chemical dispersant to this spill.

Step 1. Gather the Platform Performance Data

Contact the manufacturer or refer to the performance specification of the platform to acquire the relevant parameters needed for this calculation. These parameters and associated values for this example are shown in the Table E-3. Many calculations presented below use empirical relationships; be mindful of the required units in the table and convert them as necessary from the information sources.

Table E-1. Platform Parameters

The platform specifications can be obtained from manufacture data sheets.

PARAMETER NAME	VALUE	UNITS
Vehicle Chemical Dispersant Application Speed	150	knots
Swath Width	60	ft
Chemical Dispersant Injection Rate (DIR)	10	U.S. GPM
Number of Nozzles	8	--
Nozzle Diameter	0.25	inches
Platform Payload	3,000	U.S. gallons
Maximum Platform Coverage in a Day	2,000	ft
Droplet Size at the Nozzle Flow Rate	710	µm
Vehicle Spray Height	50	ft
Transit Distance	5	miles
Vehicle Transit Speed	175	knots

Step 2. Calculate the Platform Dosage or DIR Efficiency

The next step is to calculate the required dosage. The DOR specified is 1:20, or a value of 0.05, when the fraction is divided. The slick thickness was specified to be 0.001 inches. Therefore, the required dosage is calculated from Equation E-19. Note to be mindful of the units since the calculation here uses units of inches for the slick thickness and then converts accordingly using the coefficient defined in the equation.

$$\text{Dosage} = 27{,}200 * t_s * \text{DOR}$$

$$\text{Dosage} = 27{,}200 * 0.001 \text{ inches} * 0.05 = 1.36 \text{ U.S. gallons/acre} \tag{E-19}$$

Calculate the capable dosage of the platform from the specified DIR of the vehicle, swath width, and application speed of 5 U.S. GPM, 60 ft, and 150 knots, respectively using Equation E-20. Note to be mindful of the units since the calculation here uses units of U.S. GPM, ft, and knots and then converts accordingly using the coefficient defined in the equation.

$$\text{Dosage}_{\text{technology}} = 430.1 * \frac{Q}{S * U_{\text{application}}} \tag{E-20}$$

$$\text{Dosage}_{\text{technology}} = 430.1 * \frac{10 \text{ gpm}}{60 \text{ ft} * 150 \text{ knots}} = 0.47 \frac{\text{U.S. gallons}}{\text{acre}}$$

Since the dosage that can be applied by the technology is less than the ideal dosage, the efficiency is calculated using Equation E-21.

$$E_D = \frac{\text{Dosage}_{\text{technology}}}{\text{Dosage}}$$

$$E_D = \frac{0.47}{1.36} = 0.35 \tag{E-21}$$

Since the efficiency due to dosage was estimated, the efficiency due to chemical dispersant injection rate is not included in this calculation and is treated as 1 ($E_{DIR} = 1$).

Step 3. Calculate the Nozzle Shear Efficiency

In this example, the nozzle flow rate is calculated from the maximum flow rate of the platform divided by the number of nozzles. If the platform could supply more chemical dispersant at a specified flow rate than what is required, then the DIR divided by the number of nozzles would be used to calculate the nozzle shear efficiency. For aerial applications, the ideal shear rate should be less than 10,000 sec^{-1}. The nozzle shear rate is calculated via Equation E-22 using the nozzle flow rate and nozzle diameter of 1.25 U.S. GPM (10 U.S. GPM distributed among eight nozzles) and 0.25 inches, respectively. Note that the leading coefficient in this relation requires units of U.S. GPM and inches.

$$\text{Shear rate} = 3.9\frac{\text{Q}}{\text{D}^3} \tag{E-22}$$

$$\text{Shear rate} = 3.9\frac{1.25\text{ gpm}}{0.25\text{ inches}^3} = 312\text{ sec}^{-1}$$

The calculated shear rate is below the ideal aerial shear rate; therefore, the nozzle shear efficiency is treated as 1 (E_{SR} = 1).

Step 4. Calculate the Swath Width Efficiency

The amount of surface area that can be covered using this vehicle platform is determined from the swath width of the platform and coverage area. For a single day application, this platform can cover 2,000 ft. Therefore, the surface area the technology can cover is the swath of the platform multiplied by the distance the platform can cover as shown in Equation E-23.

$$\text{SA}_{\text{technology}} = \text{Swath Width} * \text{Distance Coverage}$$

(E-23)

$$\text{SA}_{\text{technology}} = 60\text{ ft} * 2{,}000\text{ ft} = 120{,}000\text{ ft}^2$$

The total surface area of the slick that needs to be treated was estimated from a spotter aircraft as being 100,000 ft^2. Since the platform is able to cover more area than the effective area of the spill, the efficiency is set to 1 (E_{SW} = 1). The total surface area of the slick can be estimated using the information in Appendix C if it cannot be measured at the spill location.

Step 5. Calculate the Payload Efficiency

The payload efficiency is calculated from the amount of chemical dispersant needed and the required chemical dispersant based on the spill size and DOR. The volume of chemical dispersant required to disperse 10,000 gallons of oil can be computed using the DOR as shown in Equation E-24.

$$\text{n}_{\text{d}} = \text{DOR} * \text{V}_{\text{oil}}$$

(E-24)

$$\text{n}_{\text{d}} = 0.05 * 100{,}000\text{ gallons} = 5{,}000\text{ gallons}$$

The payload efficiency can then be calculated as the ratio of payload to required volume using Equation E-25.

$$\text{E}_{\text{P}} = \frac{\text{Payload}_{\text{technology}}}{\text{n}_{\text{d}}}$$

(E-25)

$$\text{E}_{\text{P}} = \frac{3{,}000}{5{,}000} = 0.60$$

Step 6. Calculate the Volume Mean Diameter Efficiency

The droplet diameter size is a function of the nozzle flow rate. This information can be obtained from the manufacturer. In this example, the volume mean diameter of the chemical dispersant is 710 microns. Since the droplet size is above the expected range of 300 to 700 microns, the efficiency is calculated as shown in Equation E-26.

$$E_{VMD} = \frac{700}{d}$$

$$E_{VMD} = \frac{700}{710} = 0.99 \tag{E-26}$$

Step 7. Calculate the Window of Opportunity Efficiency

The window of opportunity efficiency is dependent on the time it takes for the vehicle to reach the spill site and time specified in this example before the oil is no longer dispersible. In this example, the time it takes the vehicle to reach the spill site is calculated using Equation E-27 where the distance to the spill and the vehicle transit speed are 5 miles and 175 knots, respectively. Note to be mindful of the units as the coefficient here assumes units of miles and knots and then converts accordingly using the coefficient defined in the equation.

$$t_{technology} = \frac{0.86 L_{travel}}{U_{vessel}}$$

$$t_{technology} = \frac{0.86 \times 5 \text{ miles}}{175 \text{ knots}} = 0.02 \text{ hours} \tag{E-27}$$

Since the calculated transit time is less than the window of opportunity, the efficiency of this parameter is set to 1 ($E_{TW} = 1$).

Step 8. Calculate the Spray Height Efficiency

Since this scenario uses an aerial application platform, the spray height efficiency must be calculated. The delivery height of this vehicle is 50 ft, which is less than the 100 ft and greater than the 30 ft required for optimal efficiency, specified in Table E-1. Therefore, the spray height efficiency is 1 ($E_{SH} = 1$).

Step 9. Calculate the Air Shear Efficiency

The differential speed between the airflow around the aircraft and the nozzle velocity is calculated using Equation E-28, where the flow rate and nozzle diameter are 1.25 U.S. GPM (10 U.S. GPM spread over eight nozzles) and 0.25 inches, respectively. Note, the coefficient used in this equation assumes units of knots, U.S. GPM, and inches for the parameters and then converts accordingly.

$$U_{diff} = U_{application} - \left(0.409 \frac{Q}{D^2}\right)$$

$$U_{diff} = 150 - \left(0.409 \frac{1.25 \text{ gpm}}{0.25 \text{ inches}^2}\right) = 142 \text{ knots} \tag{E-28}$$

The required speed differential for optimal air shear efficiency is 188 knots; therefore, the air shear efficiency is set to 1 ($E_{AS} = 1$).

Step 10. Determine the Overall Platform Efficiency

The overall efficiency of this platform is calculated to be 21%, as calculated using Equation E-29.

$$E_S = (E_D \times E_{DIR} \times E_{SR} \times E_{SW} \times E_{VMD} \times E_P \times E_{SH} \times E_{AS} \times E_{TW}) \times 100\% \qquad \text{(E-29)}$$

$$E_S = (0.35 \times 1 \times 1 \times 1 \times 0.99 \times 0.60 \times 1 \times 1 \times 1) \times 100\% = 21\%$$

Steps 1 through 10 can be repeated to calculate the efficiency of a different platform, which then can be compared to the platform above in order to determine which platform is most suited for the spill scenario.

APPENDIX F

Decision Tree Step Process

Appendix F – Decision Tree Step Process

The following subsections describe the process steps for using the interactive decision tree. Note that the interactive portion will only function in Excel if the user has both Macro and ActiveX settings enabled. These can be activated in the Trust Settings in Excel.

1.1 Selection of Delivery Platform

The high-level selection of the delivery platform in the decision tree is labeled I. Environmental Conditions. The first step in the decision tree, starting at location **1.1**, is to decide if chemical dispersants can be used as a response method. This decision can be made by selecting the known oil viscosity that is anticipated during the expected window of opportunity, where the decision is made by the user as follows:

- If the oil viscosity is selected as being less than 10,000 cSt, chemical dispersants can be used and the user should move forward to **1.2**.
- If the oil viscosity is selected as being greater than 10,000 cSt, then chemical dispersants cannot be used as a response option as indicated to the user when clicking on the ⓘ symbol. Consequently, the rest of the flow chart in the Excel file will not be able to be used, and mechanical recovery should be explored as per step **1.1a**.

If chemical dispersants can be used, the second step is to select the sea state at **1.2** in the tree. The sea state will, from a high level, down-select the most appropriate delivery platform between large and small response vessels as well as platform type. For example, if a Beaufort scale of 6 is selected, this would eliminate small airplanes, small helicopters, and boats as a delivery response option. The sea state is described in terms of the Beaufort scale. Clicking the ⓘ symbol at step 1.2 will generate a separate box defining the wind and associated sea conditions of each Beaufort scale number to aid the user. A table indicating these values can also be found in Appendix B. The sea state is divided into four different paths that can be undertaken, where the user can decide the following:

- If the Beaufort scale is selected as being greater than 9, then move forward to **1.2a**, which indicates that no platform option is available for this scenario.
- If the Beaufort scale is selected as being at 6, or between 7 and 9, then move forward to **1.2b** and **1.2c** to select the visibility.
- If the Beaufort scale is selected as being between 0 and 5, then move forward to **1.3** to select the ice coverage, if applicable.

Step **1.2** assumes there is no ice coverage present at a Beaufort scale of greater than 5 due to the high wind and wave height conditions that will be present in the environment, removing ice from the intended application area.

If the Beaufort scale is selected as being between 0 and 5, the next step in the tree is to select the ice coverage at step **1.3**. Similar to the sea state selection, the chosen ice coverage will also down-select the most appropriate delivery platform between large and small response vessels as well as platform type within the Beaufort scale range. For example, boats are preferred over aircraft in cold environments or when ice is present, as this type platform has the ability to promote additional mixing energy. However, access to the spill with a boat may be limited based on how much ice is present. Therefore, aircraft may be the only response platform option for this scenario. The selections for ice coverage are the following:

- Select the None option if there is no ice present, then move forward to **1.3a.**
- Select the Small Patches option if approximately 30% of the area is covered by ice, then move forward to **1.3b.**
- Select the Large Patches option if approximately 60% of the area is covered by ice, then move forward to **1.3c.**
- Select the Full Coverage option if 100% of the area is covered by ice, then move forward to **1.3d**.

If a Beaufort scale of 6, 7 through 9, or 0 through 5 with a chosen ice coverage is selected, the next step in the tree is to choose the visibility. Visibility can be affected by weather conditions, such as precipitation or fog. The chosen visibility down-selects the chosen aircraft delivery platforms based on visibility descriptions in API TR 1148 (2015). Visibility does not directly apply to a boat application platform selection. The options for visibility are divided into the following selections:

- Greater than 3 miles
- Less than 3 miles

Once the visibility is selected, the decision tree will put a checkmark in the box or boxes next to the most appropriate delivery platform in location **1.4** in the tree. Location **1.4** will highlight in a red color to indicate all required selections have been made to provide an output delivery platform. A text box under location **1.4** will provide further instruction to the user, if applicable. Additionally, the options in location **1.4** can be manually selected or deselected to include or remove those platform options in the decision tree results. The delivery platform options are:

- Large airplanes
- Small airplanes
- Large helicopters
- Small helicopters
- Large boats
- Small boats
- No options

A given scenario may have multiple delivery system outputs. However, these outputs will be ranked according to their relative efficiency after all options in the tree have been selected within the Results tab of the Excel document. With each selection, the other tree options will become less prominent, and the selected tree path will highlight red so the user can see a visual representation of the decision path. A Reset button is provided, which once pressed, will remove all user selections from the first portion of the tree.

1.2 Selection of Spill Characteristics

Once the high-level selection of the chemical dispersant platform is chosen in **1.4**, the spill characteristics, identified as II. Spill Conditions in the tree, can be selected or entered by the user. The information entered or estimated in this portion of the tree will calculate the efficiencies of each delivery technology, using Equation 5, refining which is the most suitable chemical dispersant delivery approach for the spill scenario.

The second portion of the tree begins with the user entering the slick thickness in the location of the tree identified as **2.1**. The slick thickness determines the appropriate chemical dispersant dosage and the chemical dispersant injection rate needed from the technology. The options for determining the slick thickness in the tree are as follows:

- If a value is known, select the Yes option and type in the slick thickness in inches or millimeters in the associated box, and move forward to location **2.1a** in the tree. An information box will indicate to the user if a value outside a typical slick thickness range is entered.
- If a value is not known, select the No option, and move forward to location **2.1b** in the tree.

If the slick thickness is not known, then it can be estimated by choosing the associated color of the slick in **2.1b**. The selection options for the visual representation of the slick are as follows:

- Code 1: Sheen (silvery/grey)
- Code 2: Rainbow
- Code 3: Metallic
- Code 4: Discontinuous True Oil Color
- Code 5: Continuous True Oil Color
- Unknown

These code numbers are based on the five categories described in the Bonn Agreement Oil Appearance Code [Lewis 2007]. To aid the user, clicking the ⓘ symbol at step 2.1b will generate a separate box defining the conditions of each Bonn Agreement Oil Appearance Code. It is noted that dispersants are not typically sprayed on oil slicks with appearance codes 1, 2, or 3. However, these codes are included in this tool for information purposes. The decision process assumes that the slick is uniformly thick. It is noted that oil slicks are not uniformly thick and can vary dependent on the volume of oil spilled, oil properties, and environmental conditions. However, this tool can be used for comparison purposes between slick selections by choosing different slick colors or entering different slick thicknesses.

If the slick color cannot be determined and the Unknown option is selected, then the user should move forward to **2.1c** in the tree, which asks the user to input an estimated area in mi^2 and volume in gallons of the portion of the spill that will be treated by the chemical dispersant delivery platform. Once either of these values are entered into the input boxes, the user can move forward to **2.2** in the tree. The area and volume of the spill determine how much chemical dispersant is needed to be sprayed across a spill area, which relates to a platforms payload and swath width characteristics.

If a slick thickness value was entered in **2.1** or a color was selected in **2.1b**, the user should select and enter the area or volume of the spill in **2.1a**. If either of those options is entered into the input boxes, the user can then proceed to location **2.2** in the tree. If both the area and volume are unknown, the Excel file will estimate a volume and area using the conditions specified in the Bonn Agreement Oil Spill Appearance Code [Lewis 2007]. Once the values have been entered into the input boxes, the user can move forward to **2.2** in the tree.

Once the slick size is estimated, the user shall then proceed to input the slick location in location **2.2** in the tree. The slick location will dictate if the chosen platform can get to the spill location within the window of opportunity based on the transit speed of the vessel. The user should enter the following three distances at location **2.2**:

1. The distance from the spill in miles to the closest airfield;
2. The distance from the spill in miles to the closest harbor;
3. The distance from the spill in miles to the closest platform.

The user **must** enter values in the first two input boxes in order to move forward in the decision tree. The user has the option to enter a value into the platform distance input box if known as indicated by clicking the ⓘ symbol. Once the values have been entered in the input boxes in **2.2**, the user can then proceed to enter or estimate the window of opportunity at location **2.3** in the tree. The window of opportunity relates to the prediction of the best time period for effective chemical dispersant delivery, which also impacts which chemical dispersant platform is chosen based on the transit speed. The options for determining the window of opportunity are as follows:

- If a value is known, select the Yes option and type in the window of opportunity in hours in the associated input box, and move forward to location **2.4** in the tree.
- If a value is not known, select the No option, and move forward to location **2.3a** in the tree.

If the window of opportunity is unknown, it can be estimated by the user defining the temperature in °F, the wind speed in knots, and the oil viscosity in cSt in **2.3a**. Once these values have been entered into their respective input boxes, the user can then move forward to location **2.4** in the tree to enter or estimate the desired DOR. The user has the following options for defining the DOR at this location:

- If a value is known, select the Yes option and type in the DOR into the input box and move forward to location **2.5** in the tree. Note that the DOR input entered by the user is the estimated amount of oil treated by one part chemical dispersant.
- If a value is not known, select the No option and move forward to location **2.4a** in the tree.

If the desired DOR is unknown, then it can be estimated by knowing the state of the oil. At location **2.4a**, the user has the following options that can be selected to describe the state of the oil:

- Light
- Medium
- Heavy
- Weathered or emulsified

Once one of these options is chosen, the decision tree will select a suggested DOR based on the user input in location **2.4b** in the tree. These suggested DOR outputs are as follows:

- 1:(50 –100)
- 1:20
- 1:10

Once the DOR is entered at location **2.4** or has been suggested in **2.4b**, then the user can proceed to location **2.5** in the tree. This location contains a button labeled Get Results. When the user clicks on this button, it will automatically take them to the Results tab, where the relative efficiency between platforms can be compared. Additionally, with each selection or value entered into a specified input box, the tree path will highlight red so the user can see a visual representation of the decision path.