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State-of-the Science of Dispersants and Dispersed Oil in Arctic Waters:

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Chemical dispersants were employed on an unprecedented scale during the Deepwater Horizon (DWH) oil spill in the Gulf of Mexico, and could be a response option should a large spill occur in Arctic waters. The use of dispersants in response to the DWH spill raised concerns regarding the need for chemical dispersants, the fate of the oil and dispersants, and their potential impacts on human health and the environment. Concerns remain that would be more evident in the Arctic, where the remoteness and harsh environmental conditions would make a response to any oil spill very difficult. An outcome of a 2013 Arctic oil spill exercise for senior federal agency leadership identified the need for an evaluation of the state-of-the-science of dispersants and dispersed oil (DDO), and a clear delineation of the associated uncertainties that remain, particularly as they apply to Arctic waters. The National Oceanic and Atmospheric Administration (NOAA), in partnership with the Coastal Response Research Center (CRRC), embarked on a project to seek expert review and evaluation of the state-of-the-science and the uncertainties involving DDO. The objectives of the project were to: identify the primary research/reference documents on DDO, determine what is known about the state-of-the-science regarding DDO, and determine what uncertainties, knowledge gaps or inconsistencies remain

regarding DDO science. The project focused on five areas and how they might be affected by Arctic conditions: dispersant efficacy and effectiveness, physical transport and chemical behavior, degradation and fate, eco-toxicity and sub-lethal impacts, and public health and food safety. The Louisiana University Marine Consortium (LUMCON) dispersants database was used as a source of relevant literature generated prior to June 2008. The CRRC created a database that compiled relevant research thereafter. The six to ten experts on each of the panel were from academia, industry, NGOs, governmental agencies and consulting. Despite the fact that their scientific perspectives were diverse, the panelists were able to generate hundreds of statements of knowns and uncertainties about which all of the members agreed. This required detailed discussion of 1000s scientific papers. While the cutoff date for literature considered was December 31, 2015, the vast majority of the findings are still relevant and most of the uncertainties remain. As the ice in the Arctic diminishes and maritime development and activity increase, these five documents can inform discussions of the potential use of dispersants as a spill response option in both ice-free and ice infested Arctic waters.

INTRODUCTION AND BACKGROUND

Chemical dispersants are a rarely used response option in the United States (U.S.), but are a tactic that may be available to Federal On-Scene Coordinators to combat the effects of spilled oil in certain marine offshore areas (generally >10 m water depth and >3 miles offshore). However, in 2010 chemical dispersants were employed on an unprecedented scale during the *Deepwater Horizon* oil spill in the Gulf of Mexico. The use of dispersants during that spill raised concerns regarding the behavior and fate of the oil and dispersants, and their potential impacts on human health and the environment

Production and transportation of oil occurs in U.S. Arctic waters, and vessel traffic continues to increase due to diminishing ice cover. The risks of oil spills in the Arctic are a concern, especially because the remoteness, distances, and harsh environmental conditions would complicate the response to any oil spill in those waters. Because long-range aircraft can conduct the surface application, dispersants may be an option when mechanical recovery options are not feasible. Nevertheless, considering the use of dispersants in the Arctic would present challenges for decision makers and stakeholders alike.

A 2013 Arctic oil spill exercise for senior U.S. federal agency leadership identified the need to evaluate the state-of-the-science of dispersants and dispersed oil for Arctic waters, and the associated uncertainties that remain,. Considering this, the National Oceanic and Atmospheric Administration (NOAA), in partnership with the Coastal Response Research Center (CRRC) at the University of New Hampshire, and in consultation with the U.S. Environmental Protection Agency (EPA), sought expert review and evaluation of the state-of-the-science (i.e., knowns and uncertainties) regarding dispersant and dispersed oil in Arctic waters. Five panels of scientists were convened beginning in January 2015 to focus on separate topical areas: Dispersant Efficacy and Effectiveness (CRRC, 2017a), Physical Transport and Chemical Behavior (CRRC, 2017b), Degradation and Fate (CRRC, 2017c), Eco-Toxicity and Sublethal Impacts (CRRC, 2018), and Public Health and Food Safety (CRRC, 2019). Initially, the scientists met face-to-face at NOAA's Western Regional Center in Seattle, WA for 10 hours of discussion. Subsequently, the scientists met using an internet meeting site. Each panel met for a minimum of 40 hours of discussions, all facilitated by the CRRC. Panel size varied from approximately 8 to 15 experts, representing governmental agencies, NGOs, industry and academia.

In total, the expert panels read over 3000 peer-reviewed relevant studies and generated over 100 pages of findings. The panel reports were made available to the public and further technical input was solicited. After reviewing the public input, the panels completed the documents. With the exception of two statements, the scientists agreed to the statements the panels developed. The two statements where agreement was not unanimous are noted in the reports. Discussions were lively and the wording of each finding was carefully crafted by the scientists to gain the overall agreement obtained among the panel members.

The documents and other relevant information from each of the panels are at State-of-the-Science of Dispersants and Dispersed Oil (DDO) in Arctic Waters project (url: crrc.unh.edu/dispersant science).

A cutoff date of December 31, 2015 was established for source material to be reviewed by the panels. Additional research published after this date, stemming largely from the *Deepwater Horizon* spill, has added to our knowledge, but was not considered for this project.

The statements in this executive summary are the key findings from the individual panels. Again, it is important to note that the individual documents contain the exact wording to which the panelists agreed and those interested in the context of this summary are encouraged to read the actual documents to explore the details and subtleties of the findings.

It took up to four years to complete some of the documents, especially those on ecotoxicity and sublethal impacts and public health and food safety. This occurred because these topics were the most complex, and there were more publications to review and greater differences in the interpretation and efficacy of the experimental conditions and conclusions among the panelists. During the final two years of the project, the National Academies (NAS) convened a panel of scientists to conduct a study that "assess(ed) the effects and efficacy of dispersants as an oil spill response tool through review and evaluation of domestic and international research reports and results, including both field and laboratory studies"….and "evaluate(d) trade-offs associated with dispersant use, in part through use or review of net environmental benefit analyses conducted for past oil spills" (NAS, 2019). Not only were the scopes of the two efforts on dispersants different, but the approaches were also distinct. For example, the NAS committee had a few experts on each topic acting as one body, whereas the CRRC/NOAA effort consisted of separate panels of several experts on the same topic representing a diversity of perspectives across the oil spill community. Additionally, the NAS report was a book, while the CRRC documents were statements solely addressing the state of science with little introductory or background material.

KEY FINDINGS AND CAVEATS:

- Dispersants do not change the oil chemically. Rather, dispersants increase the oil droplet surface-area-to-volume ratio by reducing oil droplet size, which facilitates hydrocarbon dissolution and other natural weathering processes. The concentration of oil droplets and dissolved constituents will decrease over time with dilution and degradation.
- Dispersants change the behavior of and exposures to oil in several ways, including several that are not unique to the Arctic Environment, by:
    - Increasing the amount of oil in the water column;
    - Reducing the amount of oil on the water surface;
    - Producing a higher concentration of smaller oil droplets in the water column; and
    - Increasing the oil droplets and dissolved constituents in the water column.

  - Dispersants are thereby expected to *reduce* oil exposure to surface/shoreline-associated species and habitats and *increase* exposure of aquatic species and subsurface habitats.

- Dispersants can be applied to the sea surface (from boats and aircraft) and subsurface (injected directly into a leaking subsea source such as a wellhead). The experience with subsea dispersant applications is especially limited—but high profile (i.e., *Deepwater Horizon*). Oil that is dispersed into the water column is less affected by winds and is primarily moved by currents. Floating oil and dispersed oil may move independently and not necessarily in tandem.
- Laboratory studies on dispersants vary due to differences in experimental designs and test conditions, and may not realistically reflect field conditions (e.g., aquarium vs open water).
- Laboratory studies on dispersant toxicity can be difficult to interpret and compare due to differences in exposure protocols, test organisms and endpoints, and the differences between calculated (or nominal) exposure concentrations vs. empirically measured concentrations (these two types of concentrations can be substantially different).
- Uncertainties associated with the behavior and fate of dispersants and dispersed oil increase substantially with the presence of sea ice.
- Uncertainties related to ecotoxicity and potential human effects stem from a basic paucity of research, especially studies that are relevant to the Arctic.
- Oil spills and response operations can negatively affect individual health, public health, mental health, and food safety. These adverse effects are not limited to dispersants.

- Prior to DWH, there was limited research on health implications of dispersants and dispersed oil, and even less in the Arctic. Even after DWH, this area of study has lagged other fields.

KEY FINDINGS: BY INDIVIDUAL EXPERT PANEL

Efficacy and Effectiveness Key Points

- Dispersants will work in cold marine water, but their effectiveness depends on the physical properties of oils, and factors that might influence those properties (e.g., temperature).
- Viscosity is a major physical property that affects dispersibility. Oils become more viscous in cold temperatures.
- Oils that are readily dispersed in temperate regions are expected to remain dispersible in colder regions, if the oil remains a fluid.
- Wave energy is needed to mix the dispersants and promote the dispersion process.
- Ice cover dampens wave energy which is reduces dispersant effectiveness, but transitional conditions, such as those encountered during ice formation, transport and break-up, result in additional types of mixing energy compared to open water.
    - Shearing by small pieces of ice may enhance dispersion by adding near surface mixing energy.
- Artificial mixing energy (e.g. propeller wash) can be used to augment natural mixing.
- Larger dispersed oil droplets may resurface or strand under sea ice due to reduced/dampened wave energy.
- The effectiveness of dispersants and the behavior of dispersed oil in the presence of the many kinds of sea ice is not well known.

- Ice cover and low temperatures may increase the length of time during which oil characteristics are favorable for dispersant use due to reduction in natural weathering processes like evaporation or dissolution.

Physical Transport and Chemical Behavior Key Points

- Dispersants reduce floating oil and increase the amount of oil in the water. Dispersed oil may move independently from surface oil.
- The circulation patterns of Arctic waters are complex, with seasonal influences (e.g., freshwater inputs from large river systems, ice formation and melting) that make oil transport modeling difficult.
- Large river systems introduce freshwater and dispersants are generally less effective in estuarine waters.
- River outputs and glacial till could be significant sources of suspended particulate materials in Arctic waters. When oil encounters organic and inorganic suspended particulate materials it can associate with them to form OMA (oil-mineral-aggregates) or OSA (Oil-Suspended Particulate Matter Aggregates).
- Adding dispersants to surface oil will increase the formation of oil-associated aggregates, given sufficient concentrations of suspended particulate and mixing energy. Once formed, the aggregates are stable structures with unpredictable behaviors.
- There are many forms and stages of sea ice and all forms of ice add complexity to the movement and behavior of the oil.
- The percent cover of sea ice is important
  - Less than or equal 3/10s: Oil and ice move independently
  - Between 4/10s and 7/10s: Transition – Uncertain

  - Greater or equal to 8/10s: Oil moves with the ice

- Oil-ice interactions (e.g., oil trapped within or under ice) are difficult to predict. During ice formation, the denser brine may transport dispersed and dissolved oil constituents to the sea bottom.
- Once oil is frozen into ice, open ocean transport processes are no longer dominant, and the encapsulated oil will move with the ice.
- Oil and dispersant that becomes encapsulated in pack ice can move long distances with the ice and then be released during melting and breakup.

Degradation and Fate Key Points

- Biodegradation is a fate mechanism for dispersants and dispersed oil. However, the impact of chemical dispersants/dispersion on biodegradation is not well characterized.
  - Other breakdown pathways for dispersants include photolysis and oxidation; interactions with organic matter are important to understanding these pathways but are not well studied.
- Hydrocarbon-degrading microbes are ubiquitous, although differences in microbial community structure exist both spatially (e.g., surface, subsea) and geographically (e.g., Arctic, GoM).
  - Distinct chemical compounds within the oil have different degradation rates, with some classes of compounds degrading more rapidly than others and some essentially recalcitrant.
  - Biodegradation of oil is complex and can result in formation of organic metabolites, assimilation as biomass and/or mineralized to CO_2.
- Oil degrading bacteria are present in Arctic nearshore and off-shore environments.

  - Bacteria will actively degrade crude oil in cold (-1°C) Arctic waters.
  - Degradation in the Arctic will occur more slowly that in temperate waters
- Dispersants can enhance biodegradation of oil by increasing interfacial area
- Dispersants cause the formation of oil droplets that are smaller than those formed from physical dispersion alone.
  - By increasing the oil-water-interfacial area, dispersant application can enhance biodegradation of oil relative to that in a slick on the surface.
  - Chemical dispersion has been frequently (but not always) observed to increase oil biodegradation rates over those for physically-dispersed oil.
- Dispersants vary in composition, and different formulations vary in their degradation and fate.
- Many dispersed oil fate studies show contradictory results that may relate to experimental conditions that do not reflect field conditions during a spill.
  - Concentrations of oil used in laboratory studies are often much greater than those expected in spill situations, contributing to uncertainty.
- Sedimentation processes involving OMA/OSA and marine snow, can be situationally important mechanisms for moving dispersed oil from the water column to the benthic environment.
- Surfactants used in dispersants are also found in consumer products and trace surfactant concentrations found in the environment may be unrelated to oil spill response.
  - Although potential sources of surfactants, such as wastewater discharges, are present in the Arctic, it is unknown whether they would hamper the ability to detect chemical dispersants.

Toxicity and Sublethal Impacts Key Points

- Oil is a complex chemical mixture with thousands of constituents with varying toxic effects. The variability and complexity in oil mixtures make predictions of the effects difficult.
- Because not all oil constituents nor all degradation products can be measured, it is difficult to determine what other components of whole oil are also drivers of toxicological effects.
- Routes of exposure to oil include ingestion, inhalation, aspiration, or external contact (adsorption and absorption).
  - External oiling and inhalation/aspiration exposure of birds and marine mammals can be very harmful. Fur and feathers lose their insulating properties and animals can die from hypothermia. Inhalation/aspiration of oil and chemicals affects respiration and can result in pneumonia and other diseases.
  - Surface air-breathing mammals may encounter chemical components of oil at the air-water interface that can cause both toxicity and injury. However, there are no known studies on toxicokinetics of oil or dispersed oil/dispersants in marine mammals.
  - External exposure to dispersants and dispersed oil may result in effects in birds and mammals similar to those for oil alone.
- Toxicity data are very limited for Arctic species. Some fish species and life stages appear to be very sensitive to low level exposures.
- The application of dispersants to floating oil moves some of the oil from the surface and reduces the potential exposure of surface-dwelling species; but temporarily increases

water concentrations by orders of magnitude and can increase exposure to organisms in the water column.

- Dispersants do not change the inherent toxicity of the oil but alter (increase) the concentrations of dispersed whole oil and dissolved components of oil in the water column; thus, increasing biotic exposure to oil.
- Sea ice is a unique habitat; oil and dispersants can radically change the biophysical characteristics of that habitat.
  - Arctic marine mammals rely on the leads between ice floes and breathing holes, where undispersed oil can pool. Birds also use leads for resting and feeding and would be susceptible to the presence of oil. Obligate under-ice communities and food webs could be exposed to dispersed oil in the upper water column.
  - Under-ice communities are unique in their concentration and composition of species, some of which exist nowhere else. This habitat could be exposed to particulate, floating and dissolved contaminants.
  - Bacteria, benthic larvae, and protozoa live in brine channels. Krill scrape algae off ice. These are potential pathways for toxic effects and incorporation of contaminants into the food web.
  - Ice undergoes seasonal cycles that can affect the fate and transport of contaminants and may affect exposure.
- Slow oil weathering and degradation rates in the Arctic may increase environmental persistence, but biological uptakes and metabolisms are also slower in Arctic species.

- In laboratory studies, nominal concentrations or loadings (i.e., calculated but not confirmed by measurement) provide limited data to support the understanding of toxicity and are not informative.

Public Health and Food Safety Key Points:

- Oil spills, dispersants and other response operations have the potential to negatively affect human health and food safety, but rigorous human exposure assessments are difficult to conduct.
- Most of the limited epidemiological research on health implications of dispersants and dispersed oil are from the Deepwater Horizon spill.
- Since dispersants are rarely used, and accidental human exposures are exceedingly rare, and data on background or baseline levels of human exposure to dispersant-related chemicals in the environment are scarce, it is difficult to fully elucidate and reliably disentangle health effects of oil alone, dispersant alone, dispersed oil, stress, or any combination of these.
- People are exposed to the same chemical constituents found in dispersants through other environmental pathways, including low-level residues from consumer products.
- Oil dispersants, as well as oil itself, can cause eye damage, skin irritation and inflammation. Less is known about long-term health implications.
- Human exposure assessments during oil spill response operations are uncommon but many of those studies rely on self-reported exposures and symptoms and reflect health concerns.
- Potential human exposure routes include inhalation, dermal and ocular contact, and ingestion. The extent to which dispersants can modify biological barriers and, thus, alter

permeation of oil-derived chemicals through various routes at different levels of human exposure are unknown.

- There is a range of potential occupational (response workers) and non-occupational exposures to dispersants and dispersed oil. Responders directly handling oil and dispersants or in the immediate vicinity of response and dispersant applications are at greater risk of exposure and adverse effects than the general population, but occupational exposures can be minimized by proper application and the appropriate use of personal protective equipment (PPE).
- During the Deepwater Horizon response, workers who self-reported exposures to oil, dispersants, or other chemicals had a higher incidence of symptoms such as headache, eye and respiratory irritation, and fatigue than workers who did not report exposures.
- Limited exposure data make it difficult to understand health effects. Baseline health information from Arctic populations at potential risk from exposure to oil and dispersants (e.g. Alaskan Natives), including ethnic sensitivities or vulnerabilities is lacking. During an incident, the remoteness and extreme environmental conditions can be anticipated to make rigorous exposure assessments challenging and extremely difficult.
- During the Deepwater Horizon response, the CDC tracked potential short-term health effects related to the oil spill in the affected communities. No trends in illnesses were identified by the multiple surveillance systems used. CDC surveillance did detect some complaints of non-specific symptoms such as throat irritation, eye irritation, nausea, headache and cough.

- Where airborne contaminants, including dispersant components, were monitored, measured concentrations were either below detectable limits or below occupational thresholds.
- None of the 6,000 Deepwater Horizon water samples containing oil-and dispersant-related chemicals measured exceeded U.S. EPA benchmarks for protection of human health following skin contact and incidental ingestion by a swimmer.
  - However, this may be attributable to the elapsed time between application and measurement, and the inherent volatility of the measured compounds.
- Changes in mental health, sometimes long-term, have consistently been observed after natural and technological disasters, including large oil spills and spills where dispersants were not used. Mental health symptoms do not appear to be related to direct chemical exposure but arise from multiple factors including fear of chemical exposure, loss of economic livelihood, and social disruption.
- Toxicological studies on other mammalian species suggest potential concerns for humans.
  - It is unclear how dispersant or dispersed oil exposures used in experimental animal studies, which are often designed to identify hazards to workers with long-term exposure to chemicals in the work place, compare with potential short-term human exposures to dispersants or dispersed oil during oil spills.
- The toxicity of individual constituents of Corexit 9500 and 9527 has been evaluated. However, other commercial dispersant formulations and dispersed oil have not been well-characterized toxicologically in appropriate mammalian models.

- Uncertainty remains regarding adverse human health effects resulting from exposure to chemically-dispersed oil and dispersants, especially with respect to long-term effects (e.g., cancer, reproductive and developmental effects including endocrine disruption, epigenetic changes) and interactions between chemical and non-chemical stressors (e.g., heat, psychosocial stressors).
- Some laboratory experiments with human cells have indicated dispersants are toxic; however, while such assays may serve as initial screens to test for potential chemical toxicity, conditions used in experimental laboratory studies may not reflect route, dose, or duration of exposure encountered in the field.
- Some dispersant formulations have not been characterized toxicologically or environmentally for conditions of use in the field and potential human exposures, particularly as they apply to the Arctic environment.
- Seafood risk assessments are based on estimated consumption rates for potentially exposed populations. National seafood consumption rates, including species consumed and portions of animals consumed, are not representative of consumption by local populations in the Arctic (especially Alaska Natives).
- The seafood safety ramifications of some dispersant formulations are inadequately characterized toxicologically or environmentally under conditions of use in the field and potential exposures, particularly in the Arctic environment.

CONCLUSIONS

The unprecedented use of chemical dispersants on and below the ocean's surface during the Deepwater Horizon oil spill raised all sorts of scientific, public, and political questions. Did we understand how the ingredients and components of the dispersants behave? How toxic are they? What are the potential risks of dispersants and do they outweigh the benefits? We knew the flood of questions would not end when the well was capped; they would only intensify the next time there was a significant oil spill in U.S. waters. What if that spill was in Arctic waters? How would our advice change? NOAA, as the primary scientific adviser to the U.S. Coast Guard, would need to keep abreast of the surge of new information and be prepared to answer those questions. Ten years later, we know a lot more, but many of the scientific, public, and policy questions remain open to debate. The biggest lesson learned is one we already knew. Once oil is spilled there are no good outcomes and every response technology involves trade-offs.

Any decision to use dispersants will need to be made cautiously, combining the best available science with the particular circumstances of an oil spill. In some cases, dispersants may not be the best option, but in other scenarios, there may be a net environmental benefit from using dispersants. Unfortunately, however, once an oil spill occurs, we do not have the luxury of waiting for more research to address lingering scientific and technical concerns. A decision will have to be made quickly and with incomplete information, applied to the situation at the moment. Hopefully, this synthesis will assist responders and decision makers if faced with a major spill in Arctic waters.

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