State of Science for Dispersant and Dispersed Oil (DDO) Use in Arctic Waters

April 5, 2017

Russia WWF

DWH Lessons Learned Conference

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Project Overview

- Three year U.S. Arctic-focused SONS Exercises evaluated potential dispersant use for oil well blowout
  - Underlying questions of science
  - Communicating the decision
- Coastal Response Research Center, a NOAA ORR grantee, led an Arctic dispersant state of the science review with scientific experts
  http://crrc.unh.edu/dispersant_science

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Project Objectives

- Identify primary research / reference documents
- Determine what is known definitively and what uncertainties remain about the state of science of DDO in Arctic
- Provide recommendations on outreach / education materials based on state of science

Approach

- Topics reviewed / discussed by 5 panels
  - Efficacy and Effectiveness
  - Physical Transport and Chemical Behavior
  - Degradation and Fate
  - Ecotoxicity and Sublethal Impacts
  - Public Health and Food Safety
- State of science only

Project Management

- Project Lead: Coastal Response Research Center
- Federal Team: NOAA ORR and U.S.EPA
- Interested Alaska Centric Entities
  - U.S. Dept. of the Interior - Alaska
  - U.S. Geological Survey
  - U.S. Coast Guard
  - Alaska Department of Environmental Conservation
  - Cook Inlet Regional Citizens Advisory Council
  - Alaska Oil Spill Recovery Institute
  - Prince William Sound Regional Citizens Advisory Council

Caveats

- Mostly focused on surface application
- Focus is U.S. Arctic waters
- Conditions considered:
  - Ice free water
  - Ice infested water
  - Full ice cover
- No operations evaluation
- Primarily Corexit 9500/9527 in U.S. and post-DWH research

Document Compilation

- Assembled database of relevant DDO literature
  - Prior to June 2008 - LUMCON database (website)
  - June 2008 - December 31, 2015 CRRC
- Peer review as defined by U.S. federal agencies
- Documents continue to be published beyond December 2015

State-of-Science Documents

- Started with January 2015 workshop for each panel
- Each panel has been having conference calls since then
- Once panel completes document, it is released for public input (~2,500 emails sent)
- Input must include peer-reviewed literature to support comments
- Panels review the public input and make final changes to document
- Documents released as completed, along with database on that topic

Status of Papers by Panel

Topic	Input Period	Document Status	# Responses	Final Expected
Efficacy & Effectiveness	1/22-2/22/2016	Final by panel, addressing input	12	January 2017
Physical Transport & Chemical Behavior	1/22-2/22/2016	Final by panel, addressing input	12	March 2017
Degradation & Fate	4/4-5/4/2016	Final by panel, addressing input	7	March 2017
Ecotoxicity & Sublethal Impacts		Draft completed, in editing before panel review/approval		Public release April 2017
Public Health & Food Safety		Working on Final draft to release for public input		Public release June 2017

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State-of-Science of DDO in Arctic

- **Workshop – communicating the state of science to the public & others**
  - **Will follow completion of state of science papers**
  - **Small workshop with scientists and communication experts**
  - **Recommend types of material that would be most effective for communications to public**

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Knowns

- Environmental factors that impact dispersant effectiveness:
  - Oil type
    - Oils have: different viscosities, weather differently
  - Emulsification
  - Mixing energy
  - Dispersant formulation
  - Dispersant : Oil Ratio (DOR)
  - Water's salinity
  - Potential for dilution (small shallow water body vs. open ocean)
  - Temperature

Goals of Dispersant Application

- Reduce surface slicks
  - Break-up into small droplets that enter water column
    - Less contact for surface species (e.g., birds, marine mammals, turtles)
    - Speed dissolution
    - Speed biodegradation
    - Reduce oil toxicity by dilution
  - For subsea, disperse oil into droplets, so it does not reach surface

Dispersant Application Method

- Surface
  - Aerial (from air)
  - Vessel (on water)
- Subsea injection at wellhead

Efficacy vs. Effectiveness

- Efficacy = how well dispersants work in ideal/controlled setting (e.g., laboratory trial)

- Effectiveness = how well dispersants work under “real-world” conditions

Efficacy vs. Effectiveness

- **Knowns:**
  - If an oil remains fluid in cold waters in the Arctic, it will likely be dispersible if it is dispersible in temperate waters.
  - Subsea dispersant effectiveness in Arctic is likely equivalent to effectiveness in other subsea regions with the same conditions at depth.

Efficacy vs. Effectiveness

- **Uncertainties:**
  - The environment, oil and water systems are very complex, so applying general rules about dispersibility to the Arctic must be done carefully.
    - Ice is a big complicating factor

Efficacy vs. Effectiveness

Temperature

- **Knowns:**
  - Low-medium viscosity oils (<1,000 - 2,000 cP) are readily dispersible in seawater at freezing
  - Dispersion of oil should occur at near freezing temperatures, if oil remains fluid
- **Uncertainties:**
  - Dispersibility of higher viscosity oils

Mixing Energy

- **Knowns:**
  - Ice-free waters: mixing energy impacts equivalent to those in temperate waters
  - Ice-infested waters: ice dampens surface waves energy, slowing dispersion kinetics
    - However, shearing caused by motion of small pieces of ice in non-breaking waves (provides additional near surface mixing energy
  - Propeller wash from ships, including ice breakers, can enable dispersion of oil + dispersant

Mixing Energy

- **Uncertainties:**
  - Limited studies of surface mixing energy for some ice conditions (e.g., frazil ice)
  - Effectiveness of oil dispersion not fully characterized with highly ice-infested waters
  - Effects/interactions of shearing, dampening and reduction of evaporative weathering on oil dispersion not well understood

Dispersant Effectiveness

- **Uncertainties:**
  - Poorly studied topics:
    - Effects of low salinity and hyper-saline water
    - Behavior of oils with viscosities >2000 cP
    - Dispersants other than Corexit
    - Impacts of gas at high subsea pressure

Detection & Monitoring of Effectiveness

- No standard dispersant effectiveness monitoring protocols for ice-infested waters
- Existing quantitative assessment techniques for measuring overall effectiveness have lots of uncertainty

Overall Conclusions on State of Science of Efficacy & Effectiveness of Dispersant Use in Arctic Waters

- Subsea efficacy & effectiveness should be similar in Arctic to elsewhere if same conditions at depth
- Ice in Arctic waters changes the conditions for oil dispersant interactions in ways we do not fully understand

Physical Transport & Chemical Behavior

Physical Transport & Chemical Behavior

- Sea Ice Impacts
  - Brine exuded from ice during ice formation is transported to bottom waters forming a stable boundary layer
    - Dispersant use during this time may enhance transport of dissolved oil constituents to the bottom
  - Ice formation, transport and melting may create additional types of mixing vs. open water

Physical Transport & Chemical Behavior

- **Knowns:**
  - Key point: dispersants do not change oil or its constituents chemically
    - Dispersants impact formation of oil droplets
  - Lots known about droplet size as a function of dispersant use, particularly regarding dissolution of hydrocarbon constituents from droplets
  - Dispersants help reduce droplet size
  - Smaller droplet sizes = higher dissolution and degradation = longer residence time in water column vs. being on surface as a slick

Physical Transport & Chemical Behavior

- **Uncertainties: Droplet size/formation**
  - No models of near surface droplet size distribution for naturally vs. chemically dispersed oil in ice infested waters
  - Lab studies of mixing energy's impact on droplet size distribution do not scale up well to the field
  - Turbulence regimes under ice are not well understood
  - Difficult to predict droplet rise under ice
  - Unknown if resurfaced chemically dispersed oil can be dispersed again when mixing energy added

Physical Transport & Chemical Behavior

- **Knowns:**
  - Open water conditions follow same hydrodynamic principles observed in other regions
  - Unique Arctic factor is when oil frozen in ice
  - Capacity of ice to pool non-dispersed oil increases with under-ice roughness
  - Transport of dispersed oil depends on droplet size, cross-currents, in situ conditions (e.g., density gradient)
  - 3D decrease in concentration (for droplets and dissolved constituents) over time with distance from spill

Transport

- **Uncertainties:**
  - Pooling capacity and transport under ice difficult to predict Transport of surface oil in water with intermediate ice coverage is uncertain
  - Difficult to predict transport and mixing in frazil, grease and slush ice
  - Spreading of dispersant treated oil in ice-infested water is difficult to predict

Oil-in-Ice

- **Knowns:**
  - Experimental field releases have increased understanding of behavior of oil-in-ice
  - Spreading (movement of oil within ice field) is constrained by ice
  - Oil in pack ice will move with the ice unless pack ice is at low concentrations
    - They may move independently of ice
  - Secondary release of oil entrapped in ice occurs at site where ice melts

Oil-in-Ice

- **Knowns (continued):**
  - Fresh ice in leads may emulsify due to wave action; this oil may not be as readily dispersed by chemical dispersants
  - Window of opportunity for surface application of chemical dispersants increases with high ice cover and low air and sea temperature (e.g., less weathering

Oil-in-Ice

- **Uncertainties:**
  - Uncertain how oil is transported when 3/10ths to 8/10ths ice cover
  - Uncertain if oil dispersant mixtures trapped in ice will be dispersed when ice is melted

Oil Weathering

- **Knowns:**
  - Bulk properties of oil frozen into first year ice are much the same as when oil first encapsulated
    - When temperature warms, oil can migrate to surface of ice through brine channels forming melt pools
    - Water soluble oil constituents released into brine and transported with brine to water underneath ice
  - Field trials show weathering in Arctic is slow; dispersant window as long as 7 days

Oil Weathering

- **Uncertainties:**
  - Much uncertainty because of:
    - Limited field data
    - Variation with ice concentration and type
    - Much uncertainty about degree of water-in-oil emulsification, volatilization, dissolution

Testing & Monitoring

- Lab and tank tests are difficult to extrapolate to field
- Field tests best to resolve uncertainties, but difficult to conduct (e.g., permits, control, safety)

Oil-Mineral Aggregate (OMA)

- **Knowns:**
  - Arctic river outputs and glacial till can be significant in OMA formation
  - OMA occurs in cold waters and presence of ice
  - In lab studies, chemical dispersants enhance OMA formation
  - OMA will sink similar to sediment
    - Observed during Deepwater Horizon spill when drilling mud injected as a well control method
  - Lots of work on OMA done by Khelifa (Environment Canada) and Lee (Canada Dept. of Fisheries and Oceans)

OMA

- **Uncertainties:**
  - Formation, behavior and fate of OMA in ice-infested water

Mathematical Modeling

- **Uncertainties/Issues:**
  - Limited empirical data to develop improved predictive models of dispersed oil droplet sizes, dissolution, OMA formation, water-in-oil emulsification for oil spills in ice
  - Modeling movement of oil through brine channels
  - Modeling of oil movement under ice
  - Modeling with higher concentrations of ice
  - Visualization tools do not usually include polar projections
    - Arctic Collaborative Environment (ACE) & NOAA Arctic ERMA do.

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Subsea Release

- **Knowns:**
  - Many aspects of Arctic subsea conditions may be similar to conditions elsewhere
  - In shallow waters, force of rising gas from blowout could break ice
- **Uncertainties:**
  - Effect of gas bubbles from subsea spill and hydrate formation on oil droplet size formation
  - In shallow release, uncertain if oil-water plume will melt ice

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Degradation & Fate

Fate of Dispersants Alone

- Knowns:
  - Dispersant components have different half lives in the environment
    - Affected by environmental conditions
  - Anionic surfactants (e.g., DOSS) biodegrade under aerobic conditions and more slowly anaerobically
    - Most studies are surfactants alone, not dispersant mixtures

Fate of Dispersants Alone

- **Knowns (continued):**
  - DOSS is most studied anionic surfactants and is constituent of the dispersant Corexit
    - In DWH, found in water column up to 4 months after last use
    - In sediments, still present in DWH-oiled sediments (not in natural seep sediments)
  - Direct absorption of sunlight by dispersants is poor
    - Some decay over days by photolysis
    - Natural organic matter (NOM) + sunlight = reactive oxygen species ⟶ may impact dispersant abiotic degradation

Fate of Dispersants Alone

- **Uncertainties:**
  - Because dispersants vary in composition, degradation and fate are not well known
  - Do other sources of surfactants (non-oil spill related) exist in the Arctic?
  - Effect of sunlight, low temperatures, and natural organic matter on dispersant decay/degradation not well understood

Oil Sedimentation

- Oil Mineral Aggregates
  - Discussed in previous section
- Bulky Sinking (e.g., residue after in situ burning)
  - Density of oil mass becomes greater than surrounding water
  - Dispersants not likely used in this case
- Marine Snow

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Marine Snow

- Knowns:
  - Normal aggregation of marine bacteria, phytoplankton, zooplankton that naturally accumulates particles and sinks to bottom
  - During Deepwater Horizon, oil caused microbes and phytoplankton to produce more exopolymer
  - More exopolymer production = more marine snow

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Marine Snow

- **Knowns (continued):**
  - Oil becomes incorporated in marine snow
    - Marine Oil Snow Sedimentation and Flocculant Accumulation (MOSSFA)
  - Found evidence after DWH of major MOSSFA layer on bottom
    - Now buried by subsequent sediment accretion in Gulf of Mexico (GOM)
  - Sediment cores from IXTOC well blowout spill in GOM (1979) show MOSSFA event

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Marine Snow

- **Uncertainties:**
  - How does dispersant use affect marine snow formation?

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Biodegradation of Oil

- **Knowns:**
  - Hydrocarbon-degrading (HD) microbes are ubiquitous
    - McFarlin et al. (2014) Arctic near-shore waters crude oil biodegradation at -1°C
    - Microbial community structure may differ geographically
    - HD microbes found in Arctic waters
  - Microbes degrade dissolved oil constituents and also at oil-water interface

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Biodegradation of Oil

- **Uncertainties:**
  - What actually happens in the field?
    - Few studies
    - Most based on lab not field

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Oil Biodegradation Pathways

- **Knowns:**
  - Oil constituents degrade at different rates
    - Arctic biodegradation pathways follow typical pattern observed in temperate waters
    - Complex microbial consortia degrade different oils (and their constituents) with complementary metabolic pathways
      - Live vs. dead oils
      - Light vs. heavy oils
  - Lab studies show no change in biodegradation sequence with dispersants present

Oil Biodegradation Pathways

- **Uncertainties:**
  - Is biodegradation sequence in anaerobic marine environment consistent?

Factors Affecting Biodegradation

- **Knowns:**
  - Nutrients and trace metal availability important in oil biodegradation rates
    - Lab studies suggest oil biodegradation can become nutrient limited
    - At low oil concentration (dispersed oil), there should be sufficient micronutrients

Factors Affecting Biodegradation

- **Knowns:**
  - Cold-water adapted microbes in deep water exhibit higher degradation rates of oil at lower temperatures than at high temperatures
    - Psychrophilic unique enzyme
    - Arctic water = -1.8ºC to 1.5ºC;
      summer inflows = 8ºC to 12ºC
  - Bioavailability, solubility and physical properties affect observed biodegradation rates
  - Salinity range of Arctic not impediment to biodegradation

Factors Affecting Biodegradation

- <u>Uncertainties:</u>
  - Importance of psychrophiles and psychrotrophs in Arctic oil biodegradation
  - Biodegradation rates in ice uncertain
  - Effect of OMA on biodegradation in Arctic

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Effect of Chemical Dispersants on Oil Biodegradation

- Lots of papers published on this topic, some not scientifically sound and some not representative of environmental conditions
  - Examples:
    - Nominal initial oil concentration (not actually measured)
    - Dispersant concentrations very high >1,000 ppm

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Effect of Chemical Dispersants on Oil Biodegradation

- **Knowns:**
  - 10 µm oil droplets degrade faster than 30 µm oil droplets (Brakstad et al., 2015)
  - Dispersants increase oil-water interfacial area, thus increasing biodegradation of oil droplets vs. slick
  - Chemical dispersion most frequently increased oil biodegradation rates vs. physically dispersed oil
    - Most studies with Corexit

Effect of Chemical Dispersants on Oil Biodegradation

- Caveats to Chemically Dispersed Oil Biodegradation Findings:
  - Often studies used proxy for biodegradation (e.g., increase bacterial numbers)
  - Need multiple lines of evidence (e.g., oil decreases, TEA decreases)
  - Publication bias against negative results
  - Oil spill comparison is usually chemically dispersed vs. oil slick; usually not physically dispersed in environment

Effect of Chemical Dispersants on Oil Biodegradation

- Caveats to Chemically Dispersed Oil Biodegradation Findings (continued):
  - Magnitude of effect varies
  - Lots of factors vary (e.g., temperature, concentration of oil, dispersant vs. particulate, DOR, dispersant type and concentration, oxygen, nutrients)

Effect of Chemical Dispersants on Oil Biodegradation

- Uncertainties:
  - Impacts of droplet size; only 10 µm vs. 30 µm studied
  - Impact of dispersants/dispersion on microbial activity
    - Degrading short-term vs. long-term release and adaptation
  - Lack of realistic field conditions
    - DWH oil concentrations in water typically < 10 ppm

Effect of Chemical Dispersants on Oil Biodegradation

- **Uncertainties (continued):**
  - Order of biodegradation of dispersant components vs. oil constituents
    - Preferential biodegradation?

Ecotoxicity and Sublethal Impacts of Dispersants and Dispersed Oil in Arctic Waters

Out for Public Input June 2017

Public Health and Food Safety of Dispersants and Dispersed Oil in Arctic Waters

Out for Public Input
April 2017

Panel Experts Efficacy and Effectiveness

- Catherine Berg, NOAA
- Robyn Conmy, USEPA
- Ben Fieldhouse, Environment Canada
- Merv Fingas, Spill Science
- Tim Nedwed, ExxonMobil
- Christopher Reddy, Woods Hole Oceanographic Institution
- Ken Trudel, SL Ross Environmental Research Ltd
- Timothy Steffek, US Bureau of Safety & Environmental Enforcement

Panel Experts: Physical Transport and Chemical Behavior

- Christopher Barker, NOAA
- CJ Beegle-Krause, SINTEF
- Robyn Conmy, US EPA
- Thomas Coolbaugh, ExxonMobil
- Merv Fingas, Spill Science
- Ali Khelifa, Environment Canada
- James R. Payne, Payne Environmental Consultants, Inc.
- W. Scott Pegau, Alaska Oil Spill Recovery Institute

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Panel Experts: Degradation and Fate

- Robyn Conmy, US EPA
- Thomas Coolbaugh, ExxonMobil
- Merv Fingas, Spill Science
- Terry Hazen, University of Tennessee and Oak Ridge National Laboratory
- Robert Jones, NOAA
- Samantha (Mandy) Joye, University of Georgia Athens
- Mary Beth Leigh, University of Alaska Fairbanks
- Karl Linden, University of Colorado Boulder
- Kelly McFarlin, University of Alaska Fairbanks
- Scott Miles, Louisiana State University
- Mathijs Smit, Shell Global Solutions International BV
- Mark D. Sprenger, US EPA

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