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9 **State-of-Science for Dispersant Use in Arctic Waters**

10 **Eco-Toxicity and Sublethal Impacts**

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14 **I. Exposure and Exposure Pathways**

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16 **A. General Statement:**

17 A pathway of exposure is the direct physical course a chemical or pollutant takes from its source
18 to the organism exposed (U.S. EPA, 2013). There are four basic pathways of exposure:
19 Inhalation, aspiration, ingestion, as well as external contact (adsorption and absorption). There
20 are unique features in the Arctic environment that will influence these basic pathways of
21 exposure (e.g., physical environment, biological characteristics). In addition, the location of the
22 release; the state of oil (chemically and physically dispersed oil vs. undispersed oil); the type of
23 oil; and the degree of weathering, determine the most significant pathway(s). Exposure is also a
24 function of the organism's life history, distribution and behavior.

25 Adverse effects vary in severity and mechanism and are a function of the exposure pathway, the
26 degree of exposure (both intensity and duration (dose)), the inherent toxicity of the stressor (e.g.,
27 oil, oil component, dispersant and dispersed oil) to the organism, and the sensitivity of the
28 organism (e.g., species, life stage, individual).

29 ***Knowns:***

- 30 1. It is important to identify all the different variables that interact to influence biological effects
31 (i.e., chemical mixture they are exposed to, whether those chemicals are in dissolved or
32 particulate phase, duration and concentration of exposure, pathway of exposure, and timing
33 of exposure relative to life stage/natural history).
- 34 2. Oil is a complex chemical mixture with thousands of constituents that have varying toxic
35 effects, which is not unique to the Arctic.

- 36 3. Measuring Total Petroleum Hydrocarbons (TPH) serves as a general assessment of the level
37 of exposure to whole oil in water; however, measuring Total Polycyclic Aromatic
38 Hydrocarbons (TPAH) will provide a better evaluation of toxicity (NRC, 2003).
- 39 • Studies (NRC, 2003) that summarize existing data indicate that the polycyclic aromatic
40 hydrocarbons (PAHs) are the most toxic of the oil components and that the likelihood
41 of exposure to PAH increases with water solubility. Acute lethality has been associated
42 with low molecular weight compounds (e.g., monoaromatics, naphthalenes); however,
43 other compounds may contribute to toxicity (e.g. heterocyclics).
 - 44 ○ Though analytic capabilities will vary, a standard suite of 50+ PAH analytes has
45 been recommended for forensic chemistry and toxicity evaluations and has been
46 used in Deepwater Horizon (DWH) oil spill (NOAA, 2015) and other oil spills
47 (Boehm et al., 1996). Many laboratories do not currently have the capability for
48 measuring this full analyte list. Nominal concentrations or loadings are not
49 informative (Coelho et al., 2013; Bejarano et al., 2014).
 - 50 ○ When comparing toxicity data on a TPAH basis, it is important to consider that
51 PAH analyte list may vary across studies and that the relative PAH composition
52 varies across oils, which complicate comparability of results (Bejarano et al., 2014).
 - 53 • TPAH alone can be misleading. The composition of the PAH mixture should be
54 determined for all toxicity tests. The most informative laboratory studies are those that
55 include a measure of exposure, assess the exposure (in the water or air, or at the air-
56 water interface), assess the dose (to the organism), and conduct a complete analysis of
57 the oil sample being tested. .
 - 58 • Methods have been developed to help address this complexity (French McCay 2002;
59 Redman et al., 2012).
 - 60 • Toxicity tests that include analysis of PAHs (including homologs), oxy- nitro- PAHs,
61 mono-aromatics, and heterocyclics, are more informative than those with a more
62 limited analyte list.
 - 63 • Chemical detection limits for some standard methods may exceed toxicity thresholds.
64 Typically, lowering the detection limit makes analyses more costly.
- 65 4. When conducting toxicity studies with oil, exposure solutions should be chemically-
66 characterized and measured.
- 67 5. It is important to identify the fraction of oil that is dissolved versus the fraction in droplets
68 (Carls et al., 2008; Carls and Thedinga, 2010; NRC, 2005). There are several methods
69 available for characterizing dissolved and droplet oil fractions (Bennett et al., 1990; Payne
70 and Driskell, 2003; Allan et al., 2012; Wiens, 2013; Letinski et al., 2014).
- 71 6. The exposure pathway and biology of the organism need to be considered to characterize
72 exposure (e.g., exposure pathways that involve dissolved constituents of oil, ingestion or
73 contact with whole oil or particulates contaminated with constituents of oil).

74 7. Dispersants change how oil partitions in the water column. Dispersants alter the exposure
75 concentrations of dissolved components of oil and the size distribution of particulate oil.

76 ***Uncertainties:***

- 77 1. Not all of the constituents in oil or all of the degradation products can be measured.
78 Therefore, it is difficult to determine which of the components of whole oil are causing the
79 toxicological effects, without further development and validation of methods.
- 80 2. While there is some evidence that chemical dispersants alter bioavailability and potential
81 accumulation of PAHs and other oil constituents, relative to mechanically or naturally
82 dispersed oil (Wolfe et al., 1997; Wolfe et al., 1998a; Wolfe et al., 1998b; Wolfe et al.,
83 1998c; Wolfe et al., 1999; Wolfe et al., 2001; Couillard et al., 2005; Mielbrecht et al., 2005),
84 the rate at which this occurs is uncertain.

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86

87 **II. Exposure and Exposure Pathways in Arctic Conditions**

88

89 ***Knowns:***

- 90 1. In general, the pelagic and benthic exposure pathways in the Arctic operate similarly to other
91 marine ecosystems. In contrast, the existence of sea ice may create pathways that are unique
92 to Polar Regions. Consequently, in this section, the focus is on these unique sea ice
93 interactions.
- 94 2. There are potential exposures to dispersants and dispersed oil from three different pathways:
95 • Surface application in open water
96 • Surface application in ice-infested waters
97 • Subsea dispersant application
- 98 3. High levels of spatial and temporal variability in physical and biological parameters in the
99 Arctic might influence exposure and potential effects resulting from dispersed and
100 undispersed oil.
- 101 4. Oil and ice together create a unique biophysical environment that presents unique pathways
102 for exposure.
- 103 • Undispersed oil can pool under, in, or on top of ice. Pooling in between ice floes, leads,
104 polynyas and breathing holes can change exposure duration, concentration, and pathways
105 for organisms.
- 106 • Under-ice communities are unique in their concentration and composition of species,
107 some of which exist nowhere else. This habitat will be exposed to particulate, floating
108 and dissolved contaminants
- 109 ○ Under-ice communities are most similar to benthic habitats “living upside down”.
110 Their algal communities are a seed for the water column and a food resource when
111 pelagic production is low. When the algae slough off, those species go into the

- 112 water column and eventually sink to the sea floor. Some species are ice-obligate,
113 others ice-facultative.
- 114 • There is a unique food web associated with the sea ice; this food web increases the
115 diversity and density of organisms, compared to Arctic open-water and thus the number
116 of species and individuals which could be exposed to undispersed oil and to a lesser
117 extent dispersed oil (e.g., polar cod, ice seals).
- 118 ○ Bacteria, benthic larvae, and protozoa live in brine channels. Krill scrape algae off
119 ice. These are potential pathways for toxic effects and incorporation of
120 contaminants into the food web.
- 121 • Ice undergoes seasonal cycles that can affect the fate and transport of contaminants, and
122 may affect exposure. During freeze up, material can be encapsulated in ice (see Physical
123 Transport and Chemical Behavior, and Degradation and Fate groups).
- 124 • Marine species tend to aggregate at interfaces where oil can collect.
- 125 ○ Marine mammals can be particularly vulnerable to oil in ice openings. Spilled oil
126 may be constrained within openings in the ice, including leads, polynyas, or holes,
127 especially in thick ice (Buist et al. 2011, Nudds et al. 2013), thus exposing marine
128 mammals to concentrated oil (e.g., volatile compounds, dispersed or non-dispersed
129 oil) at the surface-air interface where they breath (Ainley et al. 2003) or access the
130 ice surface (Hammill and Smith 1989). Air volume, respiratory frequency, and time
131 spent at surface vary with species, dive depth and dive duration, but all can be
132 elevated when the animal is recovering from deep or long dives (Reed et al. 1994,
133 Zapol 1987).
- 134 ○ Birds may also be susceptible to oil in leads (e.g., feeding, resting).
- 135 • Grounded contaminated ice is a potential pathway for sediment and shoreline
136 contamination.
- 137 • A thermal bar west of the Mackenzie River to Beaufort Sea attracts semi-salinity tolerant
138 species from rivers where there are high population densities and high productivity.
139 These high-density populations would be susceptible to oil drifting from spills, with
140 greatest vulnerability during the summer season (Carmack and MacDonald, 2002;
141 ADNR, 2014).
- 142 5. Trophic transfer is not a unique exposure pathway, but in the Arctic trophic-chain lengths can
143 be shorter and organisms are lipid-rich. Trophic transfer in invertebrates is more efficient at
144 low temperatures because less energy goes into respiration. This also has implications for
145 vertebrates feeding on invertebrates (Borgå, et al., 2004).
- 146 • Arctic food chains are more dependent on invertebrates that metabolize oil inefficiently
147 leading to potentially greater bioaccumulation (Rust et al., 2004; Barros et al., 2014).

- 148 • Aquatic invertebrates generally show higher bioaccumulation of components of oil such
149 as PAHs compared to vertebrates because of slower biotransformation in invertebrates
150 (den Besten et al., 2003; Meador, 2003).
- 151 6. The Arctic has extensive shallow shelves compared to most other oceans. The pelagic,
152 benthic (pelagic-benthic coupling) and sea ice communities are tightly connected on shelves.
153 The tightness of the connection varies seasonally and spatially (Dunton et al., 2005).
- 154 7. Undispersed oil trapped in ice weathers more slowly and remains persistent in the system in
155 an unweathered state (see Degradation and Fate group). This is also true for oil trapped in
156 deep or shoreline sediments. There is prolonged and delayed potential for physical fouling
157 and exposure because of the encapsulation of oil in ice.
- 158 8. In order to understand effects on Arctic species, the duration and variability of exposure must
159 be considered. There are potentially longer exposure times in and under the ice.
- 160 9. Uptake and metabolism is slowed by lower temperatures, resulting in delayed acute
161 toxicological responses and potentially chronic effects (Chapman and Riddle, 2005).
162 Ultimately, the unique aspects of the Arctic environment (e.g., temperature, UV exposure,
163 and ice) may influence the duration of exposure, dynamics of bioaccumulation, and toxicity
164 that may alter the biological or ecological effects or impacts of a spill.

165

166 ***Uncertainties:***

- 167 1. Exposures are dependent on fate and transport of the contaminants, however, it is unknown if
168 there are unique dispersed oil mixtures that occur in Arctic/super saline environments (e.g.,
169 brine channels) that are different from those in other places. It is also unknown if extreme
170 pycnoclines accumulate contaminants in layers.
- 171 2. The effects of higher trophic web organisms ingesting low trophic web organisms that are not
172 able to metabolize oil, have not been studied. Arctic food webs are different and therefore
173 there is potential for exposure to be different. The effect of oil on Arctic food webs is
174 unknown, but there have been studies for other ecosystems (Neff, 2002; Wan et al., 2007).
- 175 • Because Arctic food chains are lipid-rich, there may be higher rates of
176 bioaccumulation (Meador et al., 1995).
- 177 3. How organisms accumulate oil constituents from oil droplets may be more complicated than
178 simple diffusion kinetics and is poorly understood. The role of ingestion of droplets is
179 uncertain (Hansen et al., 2012).
- 180 4. On the Arctic's extensive shallow shelves, the pelagic, benthic (pelagic-benthic coupling),
181 and sea ice communities are tightly connected (see above). The consequence of this coupling
182 to exposure pathways is uncertain (CSESP, 2014).
- 183 5. There may be exposure pathways related to the biology of Arctic organisms that are still
184 unknown. Because of variable and changing conditions in the Arctic, exposure pathways
185 may change in the future.

- 186 6. Low temperatures and ice are known to influence the exposure pathways, but quantifying
187 these influences is uncertain, which leads to uncertainties about the duration and variability
188 of exposure.
- 189 7. The effects of low temperature on chemical processes and biological effects have not been
190 extensively studied and are uncertain.

191

192 **III. Toxicity of Oil and Dispersed Oil to Arctic Species**

193

194 **A. General Statement:**

195 The known threats of spilled oil include: direct oil contact with the shoreline environment,
196 marine birds, and marine mammals; potential contact with benthic communities, should the oil
197 sink; and toxicological threats to all marine biota from mechanically- or chemically-dispersed
198 oil.

199

200 ***Knowns:***

- 201 1. The addition of chemical dispersants to oil increases: the accommodation of oil (dissolved
202 and particulate oil) in the water by orders of magnitude (Wolfe et. al., 2001; Ramachandran
203 et al., 2004; Carls et al., 2008; Schein et al., 2009; Carls and Thedinga, 2010; Hook and
204 Osborn, 2012; Bejarano et al., 2014; Wise et al., 2014); the volume of water that is
205 contaminated to a given concentration; and the bioavailability of the constituents of oil in
206 water. Dispersants also decrease droplet size and alter oil droplet behavior. The interaction
207 among these changes/processes is dynamic due to weathering, dilution, and biodegradation
208 (see Physical Transport and Chemical Behavior, Degradation and Fate, and Efficacy and
209 Effectiveness documents).
- 210 2. Dispersants and dispersed oil (DDO) are expected to dilute rapidly in the ocean (see
211 Degradation and Fate document). At the air-water interface, oil may continue to be present in
212 concentrations that could affect inhalation and aspiration of air-breathing animals, even after
213 dispersant application.
- 214 3. The effect of exposure duration is different for a surfactant that damages membranes upon
215 contact as compared to PAHs/dispersants that affect lungs rapidly (e.g., acute toxicity) or
216 those that have different mechanisms of toxic action and are gradually accumulated.
- 217 4. While current dispersant guidelines in the United States have protocols to minimize
218 application of dispersant onto wildlife and fish (Alaska RRT Oil Dispersant Authorization
219 Plan, 2014), exposure to DDO can occur. For example, responders would avoid large flocks
220 of birds, but individual birds may be exposed.

221

- 222 5. Only a limited number of toxicity tests have been reported for Arctic species:
- 223 • The acute toxicity of physically and chemically dispersed crude oil and the dispersant
- 224 Corexit 9500A was evaluated for key Arctic species: the copepod (*Calanus glacialis*),
- 225 juvenile Arctic cod (*Boreogadus sadia*), and larval sculpin (*Myoxocephalus* sp.)
- 226 (Gardiner et al., 2013).
- 227 • Some toxicity testing work has been done on Alaskan species with sub-Arctic
- 228 distributions (Moles et al., 1979; Rice et al., 1979; Barrie et al., 1992; Moles 1998; Neff
- 229 and Durell, 2012; Harvey et al., 2013; Camus et al., 2015).

230 **Uncertainties:**

- 231 1. There is very little information on the kinetics of accumulation, distribution, metabolism, and
- 232 elimination of hydrocarbons for Arctic species living at or near freezing (e.g., +1 to -1°C).
- 233 2. While there is limited information about the toxic effects on individual Arctic species, there
- 234 is even less for populations, communities or ecosystems.

235

236 **B. Birds**

237 **Knowns:**

- 238 1. There are several potential pathways of dermal, inhalation, aspiration or ingestion exposure:
- 239 at the surface from slicks of non-dispersed oil, or sprayed dispersant released in the air, and
- 240 swimming through plumes of dispersant and dispersed oil during diving activities (applies to
- 241 birds, otters, fur seals, and all other organisms that occupy pelagic habitats). There is also
- 242 exposure through trophic transfer and parental caretaking of bird eggs and young (Leighton,
- 243 1993; Peterson et al., 2003).
- 244 2. Undispersed oil and its constituents have a high potential to impact birds at the sea surface
- 245 through direct external contact, ingestion, and aspiration/inhalation.
- 246 3. Higher bird densities (e.g., breeding congregations of planktivorous seabirds) in Arctic
- 247 regions increases their proportional risk compared to birds in more temperate areas. High
- 248 densities vary with species, location, and season, but can occur at all times of year.
- 249 4. Chemical dispersants and DDO can disrupt feather structure, causing hypothermia (a harmful
- 250 lowering of body temperature) due to loss of water surface tension and subsequent
- 251 penetration of water or oil to skin, and loss of buoyancy potentially leading to drowning or
- 252 increased energy expenditure (Lambert et al., 1982; Canevari, 1984; Stephenson, 1997;
- 253 Stephenson and Andrews, 1997). This can lead to illness and/or death. In addition, chemical
- 254 dispersants, themselves, will increase water's penetration to the skin, causing many of the
- 255 same physical effects (e.g., hypothermia, loss of buoyancy) (Duerr et al., 2011).
- 256 5. A bird does not need to be completely covered by chemical dispersants or oil in order to
- 257 affect its buoyancy or waterproofing (Jenssen and Ekker, 1991; Jenssen, 1994).

- 258 6. Under controlled laboratory conditions, dispersants alone (Corexit 9527 and 9500) are toxic
259 to bird eggs (Albers, 1979; Wooten et al., 2012) but the relative toxicity of crude oil,
260 dispersant and dispersed oil is dependent on chemical composition, dose, and species
261 affected.
- 262 • Corexit 9527 toxicity to avian eggs (hatchability) was similar to North Slope fresh crude
263 oil; 5:1 and 30:1 oil:dispersant mixtures were more and less toxic, respectively, than
264 crude oil (Albers, 1979).
 - 265 • Albers and Gay's (1982) more environmentally-relevant exposures (using Corexit 9527
266 and oil in penned ponds, with mixtures transferred from hens to eggs rather than applied
267 directly to eggs as in Albers,1979) suggested that chemically dispersed oil will probably
268 pose the same threat as fresh crude, although both treatments demonstrated more toxicity
269 than controls.
 - 270 • Weathered crude oil from the Gulf of Mexico was less toxic to mallard embryos than a
271 mixture of 50:1 oil:dispersant (Corexit 9500) and more toxic than a 10:1 mixture,
272 suggesting that greater proportions of dispersant reduce oil toxicity. All treatments
273 (weathered oil and chemically dispersed oil) were less toxic than fresh crude (Finch et al.,
274 2012).
 - 275 • Finch et al., (2012) suggest that the toxicity differences demonstrated in these studies are
276 due to the reduction of the concentrations of volatile PAHs in weathered oil compared to
277 fresh crude, or the greater toxicity of Corexit 9527 (containing the toxic 2-butoxy
278 ethanol) compared to Corexit 9500.

279 ***Uncertainties:***

- 280 1. There are effects of dispersed oil on feather structure, but there is sparse literature on the
281 extent of the effect of environmentally relevant concentrations of dispersant alone on birds.
282 Albers and Gay (1982) demonstrated that an environmentally relevant mix of oil and
283 dispersant (10:1 fresh crude to Corexit 9527) adhered to bird feathers similarly to fresh crude
284 alone.
- 285 2. There is a lack of toxicity testing, in general, on birds, so we do not have a clear
286 understanding of sub-lethal and indirect impacts such as:
 - 287 • Behavioral effects,
 - 288 • Interactions with migratory behavior,
 - 289 • Organ damage,
 - 290 • Genotoxicity, and
 - 291 • Reduction in prey.

292

293 **C. Marine Mammals**

294 ***Knowns:***

- 295 1. Undispersed oil has a high potential to impact all marine mammals at the sea surface. For
296 example, oil alone is extremely deleterious to polar bears (Ørisland et al., 1981).
- 297 2. Chemical dispersants and DDO can disrupt fur structures (as they do feathers) in sea otters,
298 polar bears, and fur seals, by decreasing water surface tension. This leads to loss of "water-
299 proofing," increased water-logging, and hypothermia (Hurst and Ørisland, 1982; Lipscomb et
300 al., 1993). External oiling may also be an issue relative to hyperthermia in all marine
301 mammals (Williams and Davis 1995).
- 302 3. There are no controlled whole animal studies on the impacts of DDO on marine mammals
303 (Geraci and St. Aubin, 1988). However, there have been studies performed on marine
304 mammals impacted by specific oil spills (Ballachey et al., 1994; Loughlin et al., 1996;
305 Bowyer et al., 2003; Loughlin, 2013; Schwacke et al., 2013; Lane et al., 2015; NOAA,
306 2015).
- 307 4. There have been studies on the impacts of oil alone in controlled conditions on cetaceans
308 (Geraci and St. Aubin, 1988), however, the only Arctic species tested were beluga whales
309 (Geraci and St. Aubin, 1988) and polar bears (St. Aubin, 1990).
- 310 5. Behavioral avoidance of oil by cetaceans did not appear to have occurred in temperate
311 environments, including during the Exxon Valdez oil spill (EVOS) (Matkin et al., 2008) and
312 DWH (Schwacke et al., 2013; Lane et al., 2015; NOAA, 2015).
- 313 6. Four-, five- and six-ring PAHs have the greatest carcinogenic potential (Albers and Loughlin,
314 2003), though these are in relatively low abundance in fresh crude oil.
- 315 7. There have been studies on terrestrial and marine mammals regarding the toxicity of PAHs
316 (Albers and Loughlin, 2003; Malcolm and Shore, 2003). Following EVOS, there were a
317 small number of crude and Bunker C oil toxicity studies done on mink as a model for sea
318 otters (Mazet et al., 2000 and 2001; Schwartz et al., 2004; Mohr et al., 2008) indicating both
319 endocrine and reproductive impacts. In addition, studies of bottlenose dolphins after the
320 DWH oil spill also found both endocrine and reproductive impacts (Schwacke et al., 2013).
- 321 8. There are studies on biological effects using spills of opportunity; however, it is often
322 difficult in those situations to distinguish the effects of dispersants, dispersed oil, and oil
323 alone and there is usually a lack of replication or proper controls for the different exposure
324 groups. Studies of both live animals and stranded animals following the DWH oil spill found
325 that dolphins living in the more heavily oiled areas of Barataria Bay, Louisiana and
326 Mississippi Sound, experienced significant health impacts, poor reproduction, and decreased
327 survivorship as compared to dolphins in non-oiled areas. Three adverse health effects were
328 poor body condition, lung disease and abnormal stress response (Schwacke et al., 2013;
329 Venn-Watson et al., 2013; Lane et al., 2015; Venn-Watson et al., 2015a, Venn-Watson et al.,
330 2015b).

- 331 9. The most important but understudied effects are those on the survivorship and fecundity of
332 the population. This has been evaluated for a few spills of opportunity (e.g., for EVOS
333 Loughlin et al., 1996) and DWH for bay, sound and estuary bottlenose dolphins (Lane et al.,
334 2015, NOAA, 2015). It is often difficult to apply short-term studies on individuals to what
335 can happen over the lifetime of organisms in a population. It is difficult to differentiate
336 effects from exposure to oil versus DDO in individuals undergoing additional environmental
337 influences (Peterson et al., 2003; Matkin et al., 2008).
- 338 10. There is a potential for marine mammals to have chronic exposure to residual oil decades
339 after a spill. For example, Bodkin (2012) documented this for sea otters with respect to
340 Prince William Sound residual oil.
- 341 11. There have been numerous studies on the effects of oil on cultured mammalian cells. One
342 study has been conducted on the effects of oil, dispersants and chemically dispersed oil on
343 the cultured dermal cells of a sperm whale (Schwartz et al., 2004; Wise et al., 2014). Other
344 studies have been conducted where cultured lymphocytes and monocytes from marine
345 mammals have been exposed to oil (Schwartz et al., 2005). However, these may not be
346 representative of the exposure pathways and effects that occur in vivo.
- 347 12. Inhalation of volatile components and aspiration of undispersed and dispersed oil are key
348 exposure and injury risks for cetaceans (Schwacke et al., 2013), pinnipeds (Smith and Geraci,
349 1975; Engelhardt et al., 1977), and sea otters (Lipscomb et al., 1993) all of which breathe at
350 the air-water interface where aerosols, volatiles and oil/dispersant droplets occur. This risk is
351 especially high for cetaceans whose respiratory anatomy and physiology are different from
352 all other mammals. Cetaceans: 1) lack a nasal turbinate to filter air, 2) have deep lung
353 exchange (80-90% of the lung volume with each breathe as compared to 10-20% for
354 humans), 3) may breath hold for long periods of time, and 4) have rich blood supplies for
355 rapid exchange of compounds (Irving et al., 1941; Ridgway et al., 1969; Green, 1972;
356 NOAA, 2015). In addition, their life histories require that they have a functioning lung in
357 order to feed efficiently at depth and migrate in the aquatic ecosystem in which they live.
- 358 13. Surface air-breathing mammals may encounter chemical components of oil at the air-water
359 interface that can cause both toxicity and injury. These components may be released into the
360 air as volatile organic compounds (VOCs), intermediate volatile organic compounds
361 (iVOCs), or semivolatile organic compounds (sVOCs) (de Gouw et al., 2011; Stout, 2015;
362 Haus, 2015; Murphy et al., 2015) and may be present in the air for inhalation or aspiration.
363 Chemical components may also associate with small seawater droplets that can become
364 suspended in the air column (Brock et al., 2011; de Gouw et al., 2011) due to breaking of
365 waves, wind, raindrops, animals breaking the surface, or other disruptions to the air-water
366 interface (primary aerosols). In addition, volatiles and particles in the air can undergo
367 chemical transformations and coalesce to form suspended particulates (secondary aerosols)
368 (de Gouw et al., 2011; Haus 2015; Murphy et al., 2015).
- 369 14. Engelhardt (1977) noted that spilled oil might be expected to interfere with feeding behavior
370 through its effect on baleen function, since the inner aspect of the baleen plates presents a
371 very rough surface. This was supported by laboratory studies (Braithwaite et al., 1983)

372 utilizing baleen from bowhead whales that showed filtering efficiency was reduced by
373 approximately 10 percent when coated with Prudhoe Bay crude oil and reduced by up to 85
374 percent when coated with an oil of higher wax content. Geraci and St. Aubin (1982, 1985)
375 reported similar findings for fin and gray whale baleen, and a temporary inhibition of water
376 flow. St. Aubin et al. (1984) studied baleen from seven species of mysticete whales (minke,
377 right, humpback, gray, fin, sei, and bowhead) and subjected samples to exposure to crude oil,
378 gasoline, and tar but found few consistent impacts to the composition and structural integrity
379 of the plates. They suggested that it was unlikely that transient oil exposure during a spill
380 would deteriorate baleen plates.

- 381 15. For marine mammals, oil/dispersant exposure may be incidental to feeding or may occur
382 directly through ingestion of contaminated prey. Oil on the seafloor may be an exposure
383 pathway for marine mammals that feed in the benthos via digging or eating benthic prey.
384 Marine mammals may also be exposed while feeding on mesopelagic prey throughout the
385 water column and at the surface. The exposure pathway and level is species dependent as a
386 function of the feeding behavior (Bodkin et al., 2012).
- 387 16. With the significant proliferation in tagging technology and diet studies, foraging areas and
388 feeding depths are known for many marine mammals. In addition, prey studies have provided
389 information on prey for some species or stocks of marine mammals. There may be seasonal,
390 inter-annual and decadal changes in prey consumed by these species, and some species (e.g.,
391 baleen whales) have seasonal feeding and fasting periods and locations. Furthermore, some
392 species and prey distributions are changing in the Arctic (Moore and Stabeno, 2015; Kovacs
393 et al., 2011; Stabeno et al., 2012; Moore and Huntington, 2008).

394 ***Uncertainties:***

- 395 1. There are no known studies on toxicokinetics of oil or dispersed oil/dispersants in marine
396 mammals.
- 397 2. There is uncertainty about the extent to which dispersants decrease or increase the risk of
398 exposure and impacts of the volatile oil components at the air-water interface (VOCs,
399 iVOCs, and sVOCs). The behavior of oil and/or dispersant at the air-water interface is
400 critically important to those exposure pathways, but there remain uncertainties about the
401 conditions (e.g. atmospheric and oceanographic) and the impact that biological activity (e.g.
402 marine mammal surfacing and breathing) will have on that behavior.
- 403 3. There is currently no information on dispersant effects on baleen relative to oil effects and
404 there has been a dearth of research on oil and baleen (including dispersed oil/dispersants)
405 between 1980 and 2015. While Braithwaite (1983) examined the effects of Prudhoe Bay
406 crude on baleen, there has been no research reported on the effects of products such as diesel,
407 gasoline or chemical dispersants.
- 408 4. Another concern for baleen fouling is whether oil or dispersed oil alters the way a whale
409 moves through the water, changes feeding efficiency, and/or alters the level of exposure. It is
410 uncertain whether these effects are influenced by environmental parameters (e.g.,
411 temperature and turbulence).

- 412 5. The pathways of oral exposure to oil and the effects of dispersant application on that
413 exposure pathway and dose are uncertain. It is often thought that chronic, long-term oral
414 exposure to PAHs is through ingestion of contaminated prey or from oil/water/dispersant in
415 the water ingested incidental to feeding (Neff and Smith, 1979). There have been no
416 laboratory experiments with oral exposure to oil in marine mammals. The significance of
417 direct exposure to oil and dispersed oil through ingestion of contaminated water and prey
418 while feeding (e.g., cetaceans, pinnipeds and deepwater suction feeders) is unknown. The
419 extent to which aerial and subsea dispersant application move oil into the water column and
420 impact marine mammals and their prey is uncertain.
- 421 6. Uncertainty exists about the impact of DDO on marine mammals because there are currently
422 no biomarkers that distinguish exposure from oil or DDO during actual oil spills.
- 423 7. There are no toxicological studies on the impacts of DDO on Arctic marine mammals.
424 Contributing factors include:
- 425 • There are significant ethical, legal, logistical, and financial challenges to conducting
426 dosing studies that elucidate the impacts of oil/dispersants/dispersed oil on marine
427 mammals.
 - 428 • Targeted toxicological dosing studies will not be practically feasible for most of the
429 Arctic marine mammal species.
 - 430 • The most feasible ways to obtain data may be through spills of opportunity, surrogate
431 whole animal studies (if an appropriate surrogate can be identified for the species of
432 interest), and cell culture-based or ex situ studies (which are often difficult to interpret).
- 433 8. There have been some studies on the impacts of oil on skin, but few that have evaluated the
434 effect of dispersant on transdermal uptake or transport and pathology including what role
435 temperature may play on these processes.

436

437 **D. Fish and Lower Trophic Levels**

438 ***Knowns:***

- 439 1. The amount of data regarding acutely lethal toxicity of dispersed oil to Arctic fish and lower
440 trophic levels is limited compared to the data available on temperate species (NRC, 2005; de
441 Hoop et al., 2011).
- 442 2. The available, but limited, acute lethal toxicity data do not reveal systematic differences in
443 sensitivity between Arctic and non-Arctic fish and lower trophic levels for dispersed oil and
444 oil components (de Hoop et al., 2011; Olsen et al., 2011; Gardiner et al., 2013; Dussauze et
445 al., 2014; Camus et al., 2015).
- 446 3. There are a limited number of studies in other taxa and life stages that show that Arctic
447 species behave similarly to temperate species, when exposed to toxicants (de Hoop et al.,
448 2011; Olsen et al., 2011; Sanchez et al., 2011; Hansen et al., 2014; Camus et al., 2015;).

- 449 4. For fish, at typical application rates for dispersants during an oil spill, potential acute lethal
450 toxicity of chemically-dispersed oil is primarily associated with the dispersed oil and
451 dissolved oil constituents and not with the chemicals in the dispersants themselves (Carls et
452 Al., 2008; Hemmer et al., 2011; Adams et al., 2014a). The bulk of the data is associated with
453 non-Arctic species.
- 454 5. In general, for fish, chemically-dispersed and physically-dispersed oils have similar (within
455 three- to five-fold) acute lethal and sub-lethal toxicities (NRC, 2005; Hemmer et al., 2011;
456 Adams et al., 2014a; Incardona et al., 2014, NOAA 2015) for the dispersants tested so far.
- 457 6. For copepods, chemically-dispersed oil and mechanically-dispersed oil have been shown to
458 have slightly different toxicities (Hansen et al., 2015).
- 459 7. The conclusions in statements 5 and 6 are based on actual measured hydrocarbon
460 concentrations in the water. Toxicity based on loading rates shows greater toxicity in the
461 presence of chemical dispersants because chemical dispersants increase the partitioning of
462 petroleum hydrocarbons in the water (Bejarano et al., 2014).
- 463 8. Dispersants make smaller oil droplets, increasing the surface area-to-volume ratio (Brakstad
464 et al., 2015). This increases the rate at which oil constituents are partitioned in the water
465 column, but does not change the toxicity of those constituents (Carls et al., 2008; Schein et
466 al., 2009; Carls and Thedinga, 2010; Hook and Osborn 2012; Adams et al., 2014a; Bejarano
467 et al., 2014; Incardona et al., 2014; Wise et al., 2014).
- 468 9. Effects driven chemical fractionation points to the 3-5 –ringed alkyl PAH as the predominant
469 cause of oil toxicity to fish embryos (Hodson et al., 2007; Adams et al., 2014b; Bornstein et
470 al., 2014).
- 471 10. Heterocyclics can dominate the toxicity in highly weathered oils when polycyclic aromatics
472 or other lower molecular weight aromatic hydrocarbons have been depleted (Barron et al.,
473 1999; Faksness et al., 2015).
- 474 11. Some sub-Arctic species (e.g., Pacific herring, *Calanus* copepods) can be sensitive to
475 dispersed oil (e.g., at ppb total PAH concentrations) (Duesterloh et al., 2002; Barron et al.,
476 2003; Carls and Meador, 2009; Incardona et al., 2012; Incardona et al., 2014).
- 477 12. Heterocyclics can have similar acute toxicity as PAHs and can be predominant in weathered
478 oil (Barron et al., 1999).
- 479 13. Most standardized toxicity tests (e.g., LC₅₀) measure lethality of older life stages (i.e.,
480 juveniles and adults). There is very limited information for more sensitive larval and
481 embryonic life stages of Arctic species (Gardiner et al., 2013; Olsen et al., 2013).
- 482 14. Data from standard acute LC₅₀ and EC₅₀ tests can miss delayed mortality and other adverse,
483 ecologically-important endpoints that are expressed over a longer period of time
484 (Ingvarsdóttir et al., 2012; Olsen et al., 2013).
- 485 15. Dispersants can alter the integrity and permeability of cell membranes (Cotou et al., 2001;
486 Hook and Osborn 2012; Almeda et al., 2014). This has been shown in bacteria and diatoms.

- 487 The permeability can be increased and the surfactants can damage the integrity of the cell
488 membrane.
- 489 16. The significance of photo-enhanced toxicity in Arctic waters is uncertain, but the following is
490 known:
- 491 • UV radiation is seasonally and spatially (3D) variable (Weatherhead and Morseth, 1998).
 - 492 • Studies prior to and following the DWH spill showed that UV radiation can increase the
493 toxicity of oil to some organisms by 1-2 orders of magnitude (Barron et al. 2003;
494 Incardona et al., 2012; Alloy et al., 2015, NOAA 2015). This has not been tested in
495 Arctic species, though it has been assessed in sub-Arctic, Alaskan species (Pelletier et al.,
496 1997; Barron et al. 2003; Incardona et al., 2012).
 - 497 • There are some existing data on irradiation levels and modeled water clarity in the Arctic
498 (Weatherhead and Morseth, 1998).
- 499 17. There is literature documenting that developing fish embryos are generally very sensitive to
500 low concentrations of crude oil as measured by exposure and internal doses of PAHs (Heintz
501 et al., 1999, 2000; Carls and Meador, 2009).
- 502 • Fish embryos are especially sensitive to oil, regardless of exposure pathway (NOAA,
503 2015).
 - 504 • There is evidence that exposure of embryos to low concentrations of oil can have a
505 population level effect on salmon, but this has not been tested specifically in Arctic
506 species (Heintz, 2007).
- 507 18. There have been fewer sublethal oil and dispersant toxicity studies on invertebrate embryos
508 than on early life stages of fish (Bellas et al., 2008; Saco-Álvarez et al., 2008; Bellas et al.,
509 2013).
- 510 19. There are many endpoints that could be ecologically-important that have not been as well
511 assessed as acute mortality. Evidence from the EVOS shows that sub-lethal exposures of
512 pink salmon embryos to oil severely reduces subsequent survival at sea (Carls and Thedinga,
513 2010).
- 514 • Many protocols for determining whether dispersants can be safely used rely on toxicity
515 tests with larval fish. Protocols have been developed for embryonic stages as part of the
516 DWH damage assessment (NOAA, 2015).
- 517 20. There is some evidence that smaller body size (greater surface area to volume ratio) may
518 cause greater sensitivity to dispersants and dispersed oil.
- 519 • Phytoplankton (Fan and Reinfelder, 2003)
 - 520 • Microzooplankton (Almeda et al., 2014)
 - 521 • Fish embryos and dispersed oil (Incardona et al., 2014)
- 522 21. Recent research from Norway (Sørhus et al., 2015) on the toxicity of oil to haddock eggs
523 indicates that oil droplets stick to the eggs, potentially increasing the exposure of embryos to

524 hydrocarbons. Adhesion of oil to eggs has not been reported for all fish species, but may not
525 be unique to haddock.

526 22. With site-specific information about the oceanographic conditions, specific species,
527 spawning habits, and distribution of eggs and larvae, Vikebø et al. (2015) used a modeling
528 approach to predict the exposure of a species to dispersed and undispersed oil in an Arctic
529 region in northern Norway. Vikebø et al. (2015) model predictions estimate, that under some
530 scenarios, a substantial portion of the young of the year could be exposed to oil in a single
531 event, but that this portion could be moderately reduced by the application of dispersants.

532 23. It is crucial, but currently difficult, to extrapolate from effects on individuals to populations
533 for ecological risk assessment (Chapman 2002; Calow and Forbes, 2003; Van Straalen, 2003;
534 Hendriks et al., 2005; Barnhouse et al., 2007; Forbes et al., 2008; Fodrie et al., 2014).

535 • Some attempts to extrapolate effects of individuals to populations have been made,
536 including Arctic species (Heintz, 2007, pink salmon); but the inputs to the models are
537 based on limited or incomplete data sets.

538

539 *Uncertainties:*

540 1. Standard test species and life stages may not be representative of the most sensitive members
541 and life stages of an aquatic community (Barron et al., 2013). This is true regardless of what
542 test species/life stages are used (now or in the future), as the most sensitive species of an
543 ecosystem may not be known given that it is not practical or feasible to test all existing
544 species and life stages.

545 2. The limited available data suggest certain Arctic species can show a delayed response
546 compared to non-Arctic species following oil exposure (Gardiner et al., 2013; Camus et al.,
547 2015). This may be due to differences in species physiology or exposure temperatures.

548 3. There is limited information about effects of dispersants and dispersed oil on Arctic species,
549 other than acute lethality. Newer techniques (e.g., metabolomics, proteomics, and
550 transcriptomics) can provide highly sensitive information about sub-lethal effects caused by
551 dispersed oil and dispersants in fishes and invertebrates (Lin et al., 2009; Van Scoy et al.,
552 2010; Hook and Osborn, 2012; Van Scoy et al., 2012).

553 4. Photo-enhanced toxicity occurs in other environments, but its significance in the Arctic is
554 uncertain. It is uncertain which organisms and life stages are at risk and how much oil and
555 UV radiation is required to produce significant photo-toxicity in Arctic waters. This
556 uncertainty applies to both dispersed and undispersed oil. Photo-enhanced oil toxicity may be
557 expected in the Arctic due to longer daytime hours in the summer months, as well as reduced
558 stratospheric ozone. However, there are many factors that impact the UV irradiance in the
559 Arctic (e.g., the angle of the sunlight is more extreme which reduces UV radiation intensity)
560 making it difficult to predict the magnitude of photo-toxic effects (Weatherhead et al., 2005).

- 561 5. Some work has been done on larval and juvenile Arctic fish species (McFarlin et al., 2011;
562 Gardiner et al., 2013), but no peer-reviewed research exists on Arctic fish embryos exposed
563 to dispersed crude oil.
- 564 6. There is incomplete understanding of the exposure processes, toxicokinetics, and
565 toxicodynamics at the low temperatures present in the Arctic.
- 566 7. Temperature, pH, and salinity affect chemical uptake and toxicity in some aquatic species
567 (Ramachandran et al., 2006; Whitehead 2013), but it is uncertain how these parameters affect
568 toxicity in Arctic species.
- 569 8. There are aspects of the ecological physiology of Arctic fish relating to cold temperature that
570 may make early life stages more susceptible to the toxic effects of oil (e.g., ion channels that
571 maintain heart rate at extreme cold temperatures, metabolic rate) (DeVries and Eastman,
572 1981; Incardona et al., 2014).
- 573 9. It is uncertain how the characteristics of Arctic ecosystems influence the vulnerability of
574 species to oil. Some examples include:
- 575 • The accumulation of oil under the ice where there is a rich community of organisms.
 - 576 • The near-shore coastal zone of the Beaufort Sea is an area rich in fisheries, marine
577 mammals and birds due to unique oceanographic conditions created by freshwater run-off
578 (Carmack and MacDonald, 2002; ADNR, 2014).
 - 579 • Large aggregations of multiple species at polynas, where there is a potential for oil to
580 accumulate.
- 581 10. The effects on fish hearts of low-dose exposures to PAHs have been demonstrated in
582 temperate fish species. There would likely be similar effects (e.g., cardiac edemas,
583 arrhythmia) in Arctic fish species, but they has not yet been assessed (Incardona et al., 2004,
584 Incardona et al., 2011; Incardona et al., 2014).

585

586 **IV. Overall Summary**

587

588 ***Knowns:***

- 589 1. Environmental conditions in the Arctic (e.g., low temperatures, extreme light cycles, sea ice)
590 may affect the behavior, distribution, and fate of spilled oil, dispersant, and dispersed oil, the
591 extent to which marine biota are exposed to oil and to dispersants, and the effects of those
592 exposures.
- 593 2. Dispersants change exposures to oil in several ways, though these changes are not unique to
594 the Arctic environment:
- 595 • The amount of oil in water
 - 596 • Droplet size

- 597 • Fraction of dissolved vs. particulate
- 598 • The array and relative concentrations of petroleum hydrocarbons that are bioavailable to
599 aquatic species
- 600 3. Most studies of biological effects (individuals) have been on temperate species.
- 601 • There are physiological differences between Arctic and temperate species.
- 602 • The limited numbers of studies on Arctic species show that they respond similarly to
603 temperate species when exposed to toxicants.
- 604 4. There are population- and ecosystem- level differences between Arctic and temperate species
605 and communities. There is information on the population biology of many Arctic species and
606 their ecosystems; however, there is little information on the resiliency of populations to oil
607 exposure.

608

609 ***Uncertainties:***

- 610 1. There are extensive data on the toxicity of dispersants and dispersed oil to several taxa, but
611 fewer data for tests with Arctic species.
- 612 2. A shifting baseline due to changes in Arctic environments complicates our knowledge.
- 613 3. The unique ecosystems and aspects of biology/aggregation due to time of year and life
614 history in the Arctic (that are not found in other regions), create uncertainty in assessments
615 related to dispersed and non-dispersed oil.
- 616 4. For any environment, there will always be uncertainties and unanswered questions regarding
617 the biological effects of oil spills.

618

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