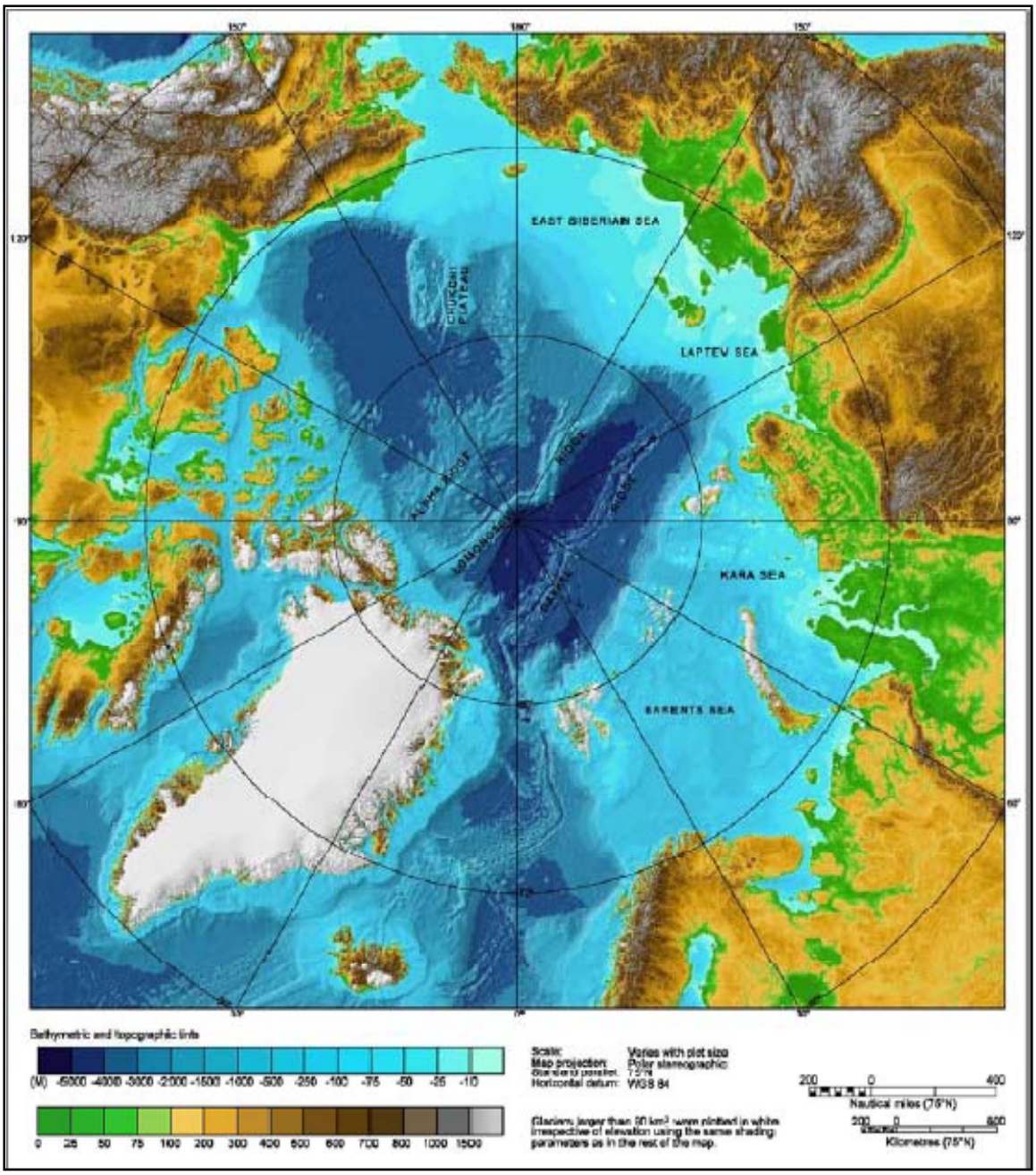
FATES AND EFFECTS OF WATER BASED DRILLING MUDS AND CUTTINGS IN COLD-WATER ENVIRONMENTS

Jerry M. Neff



FATE AND EFFECTS OF WATER BASED DRILLING MUDS AND CUTTINGS IN COLD WATER ENVIRONMENTS

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EXECUTIVE SUMMARY

Objective

The objective of this review is to summarize the current state of knowledge about the composition of water based drilling muds (WBM) and associated drill cuttings, their fates following discharge to the ocean, and their effects on marine organisms and ecosystems. The focus of this review is on effects of drilling discharges from offshore oil and gas exploration and production activities in subarctic regions and in the Arctic region, as defined by the Arctic Council, including Arctic waters of Alaska (the Beaufort and Chukchi Seas), Arctic Canada (the Canadian Beaufort Sea and Arctic Archipelago), Greenland, Norway (the Norwegian and Barents Seas), and the Russian Barents Sea area. Subarctic, cold water environments include Atlantic Canada (Nova Scotia and Newfoundland), the central and northern North Sea (the Norwegian and United Kingdom Sectors), and the Russian Far East (Sakhalin Island). Environmental effects in these cold-water environments are compared to effects in temperate marine environments, such as the U.S. Gulf of Mexico and the southern North Sea.

Offshore Oil and Gas Resources in the Arctic

The demand for energy continues to grow world-wide, far-outpacing the development of alternative, non-fossil energy sources. As new oil and gas discoveries in lower-latitude areas of the globe have declined and the existing reserves are being depleted, the resulting rising fossil fuel prices combined with improvements in technologies for safely developing oil resources in the Arctic have stimulated interest in developing the vast untapped offshore reserves in Arctic regions of the northern U.S., Canada, Norway, Greenland, and Russia.

The United States currently imports nearly 60% of its crude oil. As domestic oil and gas production continues to decline, the U.S. government is developing strategies to decrease our dependence on foreign oil as a critical national security strategy. Part of this strategy is to continue to develop the vast oil and gas resources of Arctic Alaska. The U.S. Geological Survey (USGS) recently estimated that there are vast reserves of discovered and undiscovered oil and gas in the Arctic, more than 80% of them offshore. Most of the undiscovered reserves are in Arctic Alaska, the Canning/Mackenzie River Basin, Canada, and the Russian Barents Sea. The U.S. Minerals Management Service (MMS) has estimated that most of the undiscovered resources in Alaska are in the Chukchi and Beaufort Seas. Both regions contain more undiscovered oil than gas resources.

Offshore Oil and Gas Exploration and Development in the Arctic

The first offshore marine oil wells were drilled in coastal waters of California, the U.S. Gulf of Mexico, the Caspian Sea, and Venezuela in the first three decades of the twentieth century. Offshore oil and gas exploration and development has proceeded at a slower pace in the Arctic region than in more temperate waters. The first offshore drilling in Alaska was in upper Cook Inlet in the early 1960s, followed by exploratory drilling in the Gulf of Alaska in 1975, and in the Beaufort Sea in 1981. The first exploratory drilling in the Canadian Beaufort Sea occurred in 1972 and in the Arctic Archipelago in 1973. Oil exploration in the Barents Sea was initiated in the Russian sector in the 1970s and in the Norwegian sector in 1981. To date, more than 500

exploratory, production, and disposal wells have been drilled in Arctic waters of Alaska, Canada, Norway, and Russia. Drilling wastes were discharged from most of these wells in accordance with strict local environmental regulations.

Offshore oil and gas development in the Arctic has been slow. This is due mainly to the greater technical difficulty and costs of exploiting offshore resources in cold-water marine environments, concerns of local peoples about effects of offshore development on the biological resources of Arctic seas, and regional politics. These problems have lead to development of technological and engineering advances in the design and operation of offshore oil and gas exploratory rigs and production platforms. These innovations have enabled the oil industry to operate safely, efficiently, and with minimal and short-lived harm to the environment, in even the harshest Arctic marine environments.

Concerns about Effects of Offshore Oil and Gas Development on the Marine Environment

Since the late 1960s, the offshore oil and gas industry has attempted to minimize environmental disturbance during their offshore operations. Most of the countries, including all the Arctic countries, exploiting offshore oil and gas resources have developed environmental regulations intended to ensure that offshore exploration and development causes minimal disturbance to the marine environment and its biological resources. The major disturbance during drilling of wells offshore is the discharge of used drilling muds and cuttings. The major disturbance during oil and gas production is discharge of produced water. Monitoring of discharges of drilling muds and cuttings has enabled the industry to identify wastes, waste constituents, and disposal practices that should be restricted or modified to protect the environment. As a result, the types of drilling wastes that regulatory agencies permit for discharge to their marine waters have changed over the years. Toxic ingredients in WBM have been removed and replace with non-toxic additives. Discharge of WBM containing toxic chemicals has been banned, ensuring that ocean discharged used WBM and cuttings will not be toxic to marine organisms. Current discharges and discharge practices, if performed in compliance with environmental regulations, cause little or no disturbance to the marine environment.

Development of Offshore Arctic Oil and Gas Resources

Exploratory drilling offshore usually involves drilling single vertical wells over a large area where geologic prospecting has identified promising geologic formations deep below the sea floor. More than 150 exploratory and delineation wells were drilled offshore in Arctic waters of the U.S. and Canada between 1973 and 2006.

Nearly all oil and gas wells drilled onshore and offshore in the last century were drilled by the rotary drilling process. A drill bit, attached to a hollow drill pipe, is rotated to penetrate the earth, producing crushed rock chips, the drill cuttings. A drilling fluid is pumped down the drill pipe, exiting at the drill bit, to wash the drill cuttings to the surface. An exploratory well usually can be drilled in one to three months. If commercial quantities of oil or gas are identified, the operator may drill several development wells to produce the fossil fuels. The usual practice in the Arctic is to drill several production and injection wells from a single, artificial island, platform, or drill ship, often with subsea completions to minimize the footprint of the production facility on the

sea surface and sea floor. The intent of the overall development design is to safely and cost-effectively maximize production from the reservoir over the productive life of the reserves, with minimum disturbance of the marine environment.

Drilling Muds and Cuttings

The wastes produced in largest quantity during drilling exploratory and development wells are drilling muds and drill cuttings. Three types of drilling muds have been used offshore, water based drilling muds (WBM), oil based drilling muds (OBM), and synthetic based drilling muds (SBM). Only WBM and associated cuttings and SBM cuttings have been permitted for offshore disposal in the U.S., including Alaska. WBM are the only drilling muds being proposed for exploratory drilling in the Beaufort and Chukchi Seas. Therefore, this review is restricted primary to the offshore fates and effects of WBM and associated cuttings.

Modern WBM are composed of a weighting agent, usually barium sulfate (barite), clay or organic polymers, and small amounts of additives suspended in freshwater, seawater, or a saline brine. The WBM ingredients of major environmental concern are metals and petroleum hydrocarbons. Most of the metals are in barite and most of the chromium is in chrome lignosulfonates. EPA (1993) established a limit of 1 mg/kg (ppm) mercury and 3 ppm cadmium in barite added to WBM destined for discharge offshore, effectively reducing the concentrations of all metals in whole WBM. Chromium concentrations have been reduced by replacement of chrome lignosulfonate with chrome-free drilling mud additives. Additional metals have been removed by replacing metal-rich pipe thread compounds with low-metal replacements. Modern WBM containing low-trace metals barite and no chrome lignosulfonates have metals concentrations similar to those in clean, fine-grained marine sediments. Some of the clay in WBM has been replaced with non-toxic natural biological or synthetic organic polymers, reducing or eliminating the need for hydrocarbon lubricants for the drill sting.

Regulation of Drilling Mud and Cuttings Discharges

The U.S., Canada, the North Sea countries, and most other countries with offshore oil and gas resources have strict regulations intended to protect the marine environment from harm from drilling discharges. The U.S. regulates offshore discharge of drilling wastes based primarily on the toxicity of the whole drilling muds to marine organisms. Canada and the North Sea countries regulate drilling discharges based primarily on the toxicity of individual drilling mud ingredients. The different regulatory schemes are equally effective in ensuring that WBM and associated cuttings will not harm the marine environment and its biological resources. All the regulations are extremely conservative (protective of the environment) and ensure that discharged WBM and associated cuttings have a low risk of ecologically significant chemical toxicity in the water column and in sediments

The U.S. EPA regulates discharges to Federal and some state waters with National Pollutant Discharge Elimination System (NPDES) permits. The composition, aquatic toxicity, and discharge rate of drilling muds and cuttings are regulated to ensure that discharges will not harm the marine environment. WBM and cuttings are prohibited from discharge to the ocean if they contain free oil, lubricants, diesel fuel, or other hydrocarbons that form sheen on the water surface. WBM and cuttings can be discharged only if they contain acceptably low concentrations

of metals and petroleum hydrocarbons and if their toxicity is low, as determined by a required marine toxicity test. Therefore, there is no net environmental benefit from prohibiting all discharges (zero discharge) from exploratory drilling if the wastes comply with current EPA effluent limitations guidelines in the NPDES permit.

The current guidelines in Canada for use and disposal of drilling wastes focus on minimization of discharge of petroleum to marine waters. As in the North Sea countries, toxicity testing of proposed new drilling mud additives, rather than whole drilling muds, as is required in the U.S, is used to limit the discharge of toxic chemicals to the ocean. Discharge of OBM cuttings to marine waters of the Canadian Arctic and the northwest Atlantic Ocean is no longer allowed. WBM and cuttings and SBM cuttings can be discharged if they contain only non-toxic ingredients.

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) provides guidance for regulation of discharges from offshore platforms to marine waters of the OSPAR countries, including Great Britain, the Netherlands, and Norway. Ocean discharge of OBM and SBM cuttings was phased out between 1996 and 2007. WBM and cuttings may be discharged if they do not contain hazardous chemicals. The drilling operator is responsible for ensuring that chemicals that are intended for use or discharge offshore have been tested for eco-toxicological properties. All drilling mud chemicals intended for offshore disposal in drilling muds and cuttings must be tested for toxicity, bioaccumulation, and biodegradability.

Norway recently introduced the concept of zero harmful discharge for produced water and drilling waste discharges to Norwegian waters of the North Sea and Norwegian Sea. A stricter zero discharge policy is being evaluated for the Barents Sea. These stricter regulations focus mainly on produced water discharges. The zero discharge concept was extended to drilling wastes, based largely on adverse environmental impacts of more than a decade of routine discharge of OBM and SBM cuttings to the North Sea. The Norwegian government and oil industry are re-evaluating the zero discharge policy for WBM and cuttings, because of the growing evidence that WBM/cuttings discharges cause less environmental harm than the alternative disposal practices.

Ocean Discharge of WBM and Cuttings

During rotary drilling of offshore wells, WBM is pumped down the drill pipe and carries drill cuttings produced by the drill bit back to the drilling rig. WBM is recycled downhole and cuttings usually are washed to remove adhering WBM and discharged to the sea. During drilling of the near-surface, top hole sections, there is no way to return mud and cuttings to the rig and they are deposited directly on the sea floor. The drilling mud for the top hole usually is just a mixture of small amounts of natural clay and barite in seawater. After the riser is in place, drill cuttings containing 5 to 10% adsorbed WBM solids usually are discharged continuously to the ocean at a rate of 53 to 530 gallons/hour during drilling, which occurs about half the time during an exploratory drilling operation. There also are periodic bulk discharges of small amounts of WBM during drilling and a bulk discharge of a larger volume of WBM at the end of drilling.

More than 50 exploratory wells were drilled in the State and Federal waters of the U.S. Beaufort Sea and Chukchi Sea between 1981 and 2002. The exploratory wells were in 18 to 167 feet of

water. Drilling muds and cuttings were discharged from most of these wells directly to the water in the open-water season, or to the surface of the ice or under the ice in the shore-fast ice season. Ocean discharges of WBM and cuttings from several of the Beaufort Sea exploratory wells were monitored. The results of these studies were consistent with the conclusions of the 1983 National Research Council (NRC) report on drilling discharges in the marine environment: disturbance to the marine environment was minor and recovery was rapid.

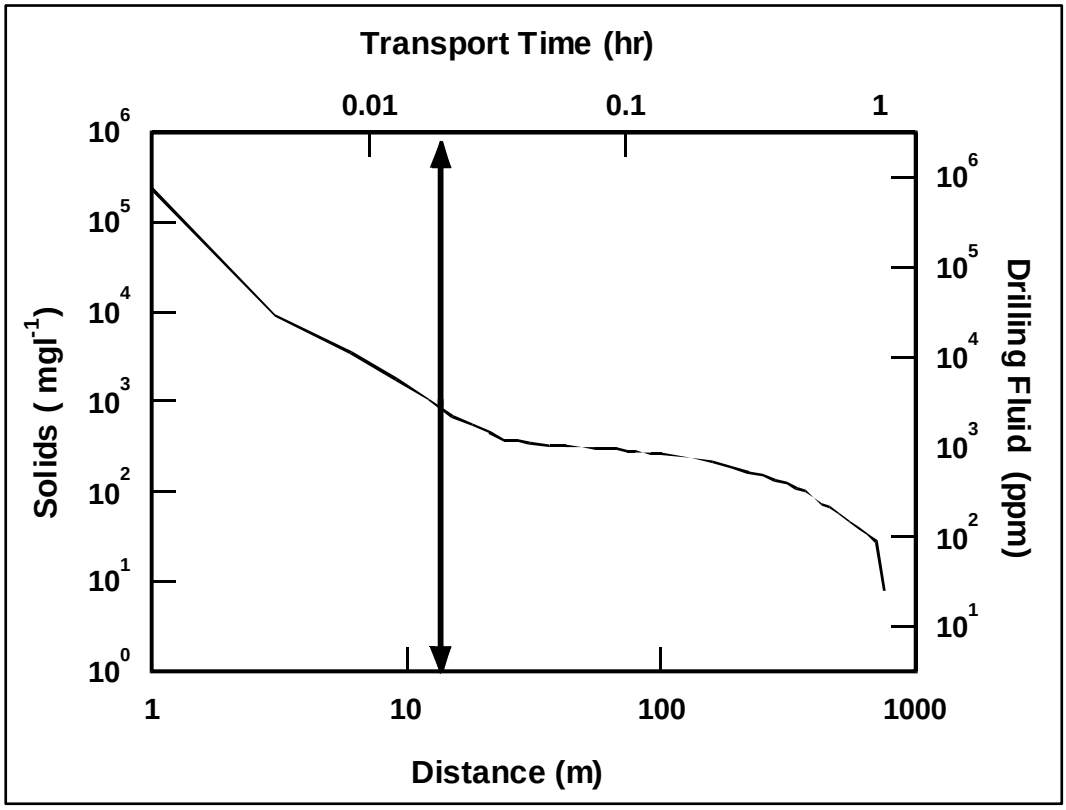
Fates of WBM and Cuttings in the Ocean

When discharged to the ocean, WBM and drill cuttings form a plume that dilutes rapidly as it drifts away from the discharge point with the prevailing water currents. Dispersion models predict that, when WBM and cuttings are discharged to the ocean, the larger particles, representing about 90% of the mass of the mud and cuttings solids, form a plume that settles quickly to the sea floor. About 10% of the mass of the mud solids, consisting of fine-grained clay-sized particles and a portion of the soluble components of the mud, form another plume in the upper water column that drifts with prevailing currents away from the platform and is diluted rapidly in the receiving waters.

Field studies of drilling mud dispersion have been performed in temperate environments and in cold climates, such as Cook Inlet, the Beaufort Sea, Norton Sound, and the Norwegian Sea, and confirm the model predictions. Field studies in temperate and cold-water environments consistently show that drilling waste solids are diluted by up to 30-fold in the discharge pipe and by an additional 1000- to 3000-fold within 100 ft of the rig. Dilution rate increases with increasing current speed. The results of all the field and modeling studies performed between the 1970s and 2009 of dispersion and dilution of WBM and cuttings discharges in the ocean have shown that dilution and dispersion of the dissolved and particulate fractions of the discharges are extremely rapid and completely non-toxic concentrations of mud/cuttings are reached within about 50 feet of the discharge (Figure ES-1).

Figure ES-1 illustrates the predicted concentrations of drilling mud solids in the water column with distance and transport time (the time required for a parcel of fluid moving with the current to reach a particular distance) during a 42,000 gal/hr WBM discharge lasting 1 hour offshore Sakhalin Island, Russia. The solids concentration dropped from 300,000 ppm at the source to less than 8 ppm at 2460 ft and a transport time of 1 hour. The vertical arrows show the distance from the discharge point at which the solids reached 3,000 ppm, corresponding to the toxicity limit for drilling muds in the current Alaska NPDES permit. The solids fell below this concentration within 50 ft of the discharge.

Figure ES-1 Predicted Concentrations of Drilling Mud Solids in the Water Column with Distance and Transport Time



In 1989, the National Research Council concluded, based on a review of results of the modeling and field studies of drilling mud and cuttings solids performed before 1989, that offshore discharges of WBM and associated cuttings will have little or no harmful effects on water-column organisms. The steady decrease in concentrations of metals and hydrocarbons in WBM, required in NPDES permits issued since 1989, has ensured that discharges of WBM and cuttings are completely non-toxic to water column biological communities.

Hydrocarbon concentrations are low in WBM and cuttings that meet current effluent limitations. Most of the hydrocarbons in Beaufort Sea, Barents Sea, and other Arctic sediments, including those from exploratory drilling sites, are from organic-rich sediment layers being drilled or erosion of natural kerogens, peat, and soft coal (lignite) deposits along the coast or rivers emptying into the Arctic Ocean. These hydrocarbons are tightly bound to solid organic particles and are not bioavailable or toxic to marine organisms.

Only barium is present in most modern (after EPA limited mercury and cadmium in drilling mud barite) WBM at substantially higher (>100-fold) concentrations than in fine-grained marine sediments. The other metals in WBM are present at concentrations similar to those in fine-grained marine sediments and most are present as insoluble sulfide mineral inclusions in the nearly insoluble barite. They do not dissolve in sediment pore water or overlying seawater, even under anoxic (low oxygen) conditions. These metals are not bioavailable or toxic to bottom-living animals because of the low solubility of barite and the metal sulfides in seawater and marine sediment pore water.

The traces of mercury sometimes associated with WBM are present as extremely insoluble mercuric sulfide in the barite. The drilling mud mercury cannot dissolve and be converted to toxic methylmercury by sulfide reducing bacteria in sediments, and therefore is not harmful to marine animals.

The only metal usually found in sediments near exploratory drill sites at significantly higher than background concentrations is barium. There are no area-wide trends in metal concentrations in Beaufort Sea and North Sea sediments that could be associated with ocean discharges of WBM and cuttings during drilling of exploration, delineation, and development wells.

The U.S. MMS and the oil industry have been monitoring the effects of drilling activities in the development area of the Alaskan Beaufort Sea for more than 20 years. The monitoring has shown that little metal, mostly barium, and petroleum hydrocarbons accumulate in sediments within a few hundred feet of gravel drilling islands and WBM and cuttings discharges. The increase over background concentrations of barium and occasionally other metals in sediments near drilling operations is insufficient to cause harm to local bottom-dwelling marine invertebrates. Since all these metals are tightly bound to solid particles (barite or clays), they are not bioavailable or toxic to bottom-dwelling marine organisms. Environmentally significant increases in the concentration of petroleum hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAH), in Beaufort Sea sediments have not been detected. Similar results have been reported at drilling sites in the Dutch, United Kingdom, and Norwegian North Sea where only WBM and cuttings were discharged.

Bioaccumulation of Metals and Hydrocarbons from Drilling Discharges by Marine Animals

Bioavailability is the extent to which a chemical can be absorbed (bioaccumulated) by a living organism. Several field and laboratory studies in temperate and cold-water environments have shown that the metals in WBM and cuttings are not bioaccumulated by marine organisms. The metals in WBM and cuttings are not bioavailable because they are present almost exclusively as extremely insoluble inclusions in barite and cuttings minerals. Many field surveys of the concentrations of metals and hydrocarbons in tissues of marine animals from the vicinity of offshore WBM and cuttings discharges in temperate and cold-water marine environments have shown that metals and hydrocarbon concentrations in tissues of marine animals near platforms are similar to concentrations in tissues of the same or similar species well away from and out of the influence of the platforms. If the metals and hydrocarbons in WBM and cuttings discharges are not bioavailable, they do not enter marine food webs and are not harmful to marine organisms and ecosystems.

WBM and Cuttings Chemicals in Arctic Marine Food Webs

Arctic marine food webs, including those in the Beaufort and Chukchi Seas, are relatively simple compared to those in many temperate and tropical climates, with relatively few abundant plants or animals at different trophic levels. The abundance and distribution of large zooplankton, such as adult euphausiids and copepods, upon which bowhead whales feed, are dependent on phytoplankton blooms and, so, vary widely regionally and seasonally. A key species in the Arctic marine food web is the Arctic cod, which feeds on small invertebrates and fish and is

consumed by a wide variety of fish, birds, and marine mammals, including ringed seals and beluga whales. These food webs are important in transferring natural and human-introduced chemical contaminants, including those from drilling discharges, from sediments to top predators in the food web.

Metals and hydrocarbons introduced into the marine environment in WBM and cuttings discharges from offshore exploratory drilling activities are not likely to enter temperate and Arctic, including Beaufort and Chukchi Sea, food webs in ecologically significant amounts. None of the metals and hydrocarbons measured in tissues of Beaufort Sea invertebrates and fish during the MMS monitoring programs were bioaccumulated to higher than background concentrations. Because the drilling mud chemicals are not bioaccumulated, they are not transferred through the marine food web by trophic transfer (predator eating contaminated prey). There is limited evidence of bioaccumulation, but none of trophic transfer or biomagnification (increase in concentration from one trophic level to the next) of metals and hydrocarbons in all the field and laboratory studies performed to date on effects of WBM and cuttings discharges to temperate and Arctic marine environments. Marine animals at all trophic levels near offshore WBM and cuttings discharges to temperate and Arctic marine environments do not contain higher concentrations of metals (including methyl mercury) and petroleum hydrocarbons (including PAH) than the same or similar species from locations distant from drilling discharges. Thus, metals and hydrocarbons from offshore exploration are not entering marine food webs.

Toxicity of WBM Additives and WBM

Environmental regulations in all Arctic countries with offshore oil and gas operations prohibit ocean discharge of drilling wastes that are toxic to marine organisms or may cause environmental degradation. Over the last few decades, the environmental regulatory agencies and the oil industry have substantially reduced the potential harmful effects of drilling waste discharges by decreasing concentrations of metals in barite, identifying and replacing toxic drilling mud chemicals with less toxic alternatives, and prohibiting discharge of some types of waste, such as OBM, SBM, and associated cuttings. Toxicity testing is required to ensure that drilling mud ingredients or whole drilling muds destined for offshore discharge are not toxic. Laboratory toxicity tests reveal that petroleum, particularly the aromatic fraction, and chrome lignosulfonate, contribute most to the toxicity of WBM containing them. The current NPDES permits for all outer continental shelf regions in the U.S, including the Beaufort and Chukchi Seas, prohibit ocean discharge of WBM containing diesel fuel, free oil, or chromate. WBM that meet these requirements are not toxic to marine organisms or ecosystems.

The U.S. EPA requires that WBM destined for ocean disposal have an acute toxicity to mysids (a sensitive shrimp-like crustacean) of less than 3,000 ppm whole drilling mud (toxicity increases as toxic concentration decreases). Although this toxicity limit is very conservative (protective), more than 99% of WBM tested to date have an acute toxicity concentration higher than 3,000 ppm, making the drilling muds completely safe to discharge to the ocean in temperate and Arctic environments.

Many thousands of short- and long-term toxicity tests have been performed on whole WBM and WBM ingredients with a wide variety of freshwater and marine plants and animals, including many species from Arctic and cold-water environments of Alaska, Canada, and Norway. There

was little or no difference in the toxicity of drilling mud ingredients or whole drilling muds to Arctic and temperate species. WBM containing ingredients permitted by current U.S. effluent limitation guidelines or on OSPAR's PLONOR list (List of Substances/Preparations Used and Discharged Offshore That Are Considered to Pose Little or No Risk to the Environment) were non-toxic to all species. These results suggest that ocean discharge of WBM and cuttings in strict compliance with local environmental regulations will not cause toxic effects in water column and sediment-dwelling plants and animals near the discharges.

Ecological Effects of WBM and Cuttings in the Marine Environment

Although laboratory toxicity tests are useful for regulation of WBM discharge, they do not provide sufficient information to predict all the ecological effects in the water column and on the sea floor of WBM and cuttings discharges. Microcosm and field studies near offshore discharges are required to determine marine ecological effects of drilling operations.

Several microcosm and mesocosm studies have been performed over the last three decades in temperate and cold-water marine environments to document the ecological impacts of WBM and cuttings in sediments. WBM and cuttings usually were layered on natural sediments in trays that were supplied with flowing seawater in the laboratory or deployed on the sea floor. These studies consistently show that WBM and WBM cuttings have a low chemical toxicity to marine organisms. When toxicity was identified in the past, it was attributed to petroleum hydrocarbons or chrome lignosulfonate in the mud, both now strictly limited in WBM destined for ocean disposal. Layers of WBM and cuttings in mesocosm trays may bury some of the resident benthic fauna and slow settling of marine invertebrate larvae from the plankton. Longer-term effects are caused by physical disturbance of the sediments by changing sediment texture and causing mild organic enrichment from microbial degradation of organic matter in the cuttings, both resulting in changes in the benthic faunal community.

Field monitoring programs have largely confirmed the conclusions drawn from the laboratory toxicity and mesocosm studies. The results of the limited number of field monitoring studies of effects of WBM and cuttings discharges on Beaufort Sea biological communities have been confirmed by the results of many more comprehensive microcosm and ecological investigations near WBM and cuttings discharge sites in cold water environments of the southern and northern North Sea, the Barents Sea, off Sakhalin Island in the Russian Far East, and in the Canadian Beaufort Sea off the Mackenzie River and off Atlantic Canada. Field studies show that environmental effects of WBM and cuttings discharges are similar in intensity, aerial extent, and duration in temperate and Arctic marine environments.

All the studies show that WBM and cuttings discharges have no or minimal and very short-lived effects on zooplankton communities in the immediate vicinity of the discharge. Effects on benthic macrofaunal and megafaunal communities are minor and nearly always restricted to sediments within about 300 ft of the discharge where drilling waste solids accumulate. There is no evidence of ecologically significant bioaccumulation of metals or petroleum hydrocarbons by marine animals residing or deployed in cages near WBM and cuttings discharges in cold-water or temperate environments. There is no evidence in the field of chemical toxicity of any WBM ingredients. The lack of bioaccumulation or toxicity of drilling waste components assures that

effects of WBM cuttings piles are highly localized within a few hundred feet of the discharge and are not being exported to the local food web.

Ecological effects of WBM and cuttings discharges, when detected, are caused by physical disturbance of the water column and benthic environment. Elevated suspended particle concentrations associated with the discharges may clog the gills or digestive tract of zooplankton or benthic filter-feeding invertebrates. Accumulation of drilling wastes on the sea floor buries some of the immobile benthic fauna. Changes in sediment grain size and texture render the sediments unsuitable for settling and growth of some species, while rendering the substrate more suitable for other species. If the WBM contains biodegradable organic additives, it may stimulate growth of microbial communities in sediment, often leading to depletion of oxygen in the sediments. Anaerobic, sulfate-reducing bacteria may further degrade the organic matter, producing hydrogen sulfide. This process, called organic enrichment, causes changes in the abundance, species composition, and diversity of the benthic community. Organic enrichment is rare in sediments near WBM and cuttings discharges.

Benthic communities in WBM cuttings piles recover quickly, due to a rapid return of sediment texture to pre-discharge conditions, and rapid degradation of the organic matter in the WBM cuttings piles allowing sediment oxygen concentrations to return to normal. The rate of benthic recovery depends on the thickness of mud and cuttings accumulations on the sea floor, and may be slightly slower in cold water than temperate environments, because of longer life cycles and slower recruitment of some benthic fauna.

The physical disturbances to the water column and sediments from WBM and cuttings are similar in character and magnitude to the disturbances caused by natural processes, such as storms, massive inputs of suspended sediments from Arctic rivers during spring breakup, and ice scour. Arctic planktonic and benthic communities are well adapted to seasonal disturbance and recover rapidly from the relatively brief and intermittent disturbances associated with exploratory drilling operations.

1.0 INTRODUCTION

1.1 Objectives of Review

As the pace of oil and gas exploration and development in coastal and offshore waters increased in the 1960s and 1970s, there was growing concern in the United States and other countries with offshore petroleum resources that wastes routinely discharged from offshore platforms during drilling and production operations could cause serious, long-term harm to the marine environment. Regulations intended to protect the marine environment were enacted in many countries. Most encouraged or required research and monitoring activities to document environmental effects of the discharges and to identify mitigating measures to prevent or reduce impacts. Several countries with offshore oil and gas resources, particularly the United States, Canada, and the North Sea countries (The United Kingdom, Netherlands, and Norway), implemented research and monitoring programs in the 1970s to document marine environmental effects of permitted discharges, particularly of drilling muds/cuttings and produced water. Two types of drilling muds were used to drill wells in the 1970s and 1980s - water based drilling muds (WBM) and oil based drilling muds (OBM). Synthetic based drilling muds (SBM) were introduced in 1990 to replace OBM. The U.S never permitted offshore disposal of OBM, SBM, or drill cuttings produced during use of OBM, though some other countries, including Canada, and the North Sea countries, did permit offshore discharge of OBM cuttings. SBM cuttings are permitted for discharge to U.S. Federal waters.

In 1982, The U.S. Bureau of Land Management (the predecessor of the Minerals Management Service: MMS), that had regulatory authority over oil and gas development in Federal waters of the U.S., commissioned the National Research Council (NRC) of the National Academy of Sciences to review all the relevant research on the marine environmental effects of offshore discharge of drilling muds and cuttings, the largest discharges associated with drilling of wells. The NRC (1983) examined all the information available at that time on the environmental fates and effects of WBM and associated drill cuttings discharges and concluded:

> "Based on laboratory and field studies to date, most water-based drilling fluids used on the U.S. OCS have low acute and chronic toxicities to marine organisms, (because of) the expected or observed rates of dilution and dispersal of drilling muds in the ocean after discharge. Their effects are restricted primarily to the ocean floor in the immediate vicinity of and for a short distance down-current from the discharge. The bioaccumulation of metals from drilling fluids appears to be restricted to barium and chromium and is observed to be small in the field."

Based on the NRC study, the U.S. EPA, MMS, and the U.S. oil industry collectively concluded that discharge of WBM and cuttings to Federal waters in strict compliance with existing environmental regulations would not cause lasting harm to the marine environment and its living resources.

Although much of the research and monitoring that NRC (1983) reviewed was from cold-water environments, there has been concern recently in Arctic development areas of Alaska, Canada, and Norway that these cold-water marine environments may be more sensitive than more temperate environments to effects of permitted discharges from offshore platforms. The major

concerns are that chemicals from permitted discharges could bioaccumulate in Arctic marine food webs and harm valued subsistence marine resources, such as fish, marine mammals, and birds, as well as the people who depend on them for food.

The objective of this review is to summarize the current state of knowledge of the composition, environmental fates, and physical and biological effects of WBM and associated drill cuttings following discharge to coastal and offshore marine waters, with emphasis on cold-water environments. The focus of this review is on WBM and associated cuttings because they are the wastes discharged in the largest volumes during exploratory drilling in the Alaskan Beaufort and Chukchi Seas. Other waste discharges during exploratory drilling, including cooling water, gray water and black water (domestic and sanitary waste that undergoes secondary treatment/chlorination or other treatment to comply with permit limitations), are considered harmless if discharged in accordance with EPA permits, and will not be discussed here. This review also will discuss the fates and effects of individual chemical ingredients of WBM in Arctic and subarctic marine ecosystems and animals. SBM cuttings have not been discharged to the Alaskan Beaufort and Chukchi Seas during earlier exploratory drilling and there currently is no plan to discharge them in future drilling operations. Ocean discharge of SBM cuttings is being phased out in Canada and Norway. Therefore, environmental effects of ocean discharge of SBM cuttings will not be discussed here (see Neff et al., 2000, and OGP, 2003 for recent reviews of SBM).

The review covers the following topics, with emphasis on the large amounts of research and monitoring that has been performed in cold-water marine environments of Alaska, Canada, and Norway:

1. Background information about the history of exploration for and development of offshore oil and gas resources, with emphasis on activities off Alaska, Canada, and Arctic regions of Norway and Russia;
2. Short history of technology development for drilling in the harsh conditions of Arctic marine environments;
3. Description of the compositions and physical properties of modern WBM and cuttings, including those proposed for use for exploratory drilling in the Beaufort and Chukchi Seas.
4. Summary of environmental regulations for WBM and cuttings discharges to Alaskan and other U.S. Federal waters, with a comparison to discharge regulations in Canada and the North Sea countries.
5. Review of the relevant scientific literature on the fates of WBM and cuttings following discharge to the ocean, particularly in Arctic Alaska and Canada.
6. Comparison of biological effects, including bioaccumulation and toxicity, of whole WBM and associated cuttings and individual ingredients of modern WBM in Alaskan marine organisms to biological effects in marine animals from cold water marine environments elsewhere in the world.
7. Characteristics of Arctic marine food webs in relation to possible pathways for exposure of valued marine biological resources to chemicals from drilling wastes; and

8. Field studies of the effects of drilling discharges on Arctic and subarctic marine ecosystems and valued marine biological resources.

1.2 A Short History of Offshore Oil and Gas Exploration and Production

1.2.1 Lower Latitudes.

1.2.1.1 The First Offshore Wells

The first recorded offshore marine oil well in the world was drilled in 1897 from a wooden pier extending a short distance into the Santa Barbara Channel at Summerland, California, a short distance southeast of Santa Barbara (Veldman and Lagers, 1997; MMS, 2007a). The well struck high-quality crude oil, spurring construction of 10 piers, each supporting 6 to 20 derricks, within two years of the first offshore discovery. The first offshore well in Europe was drilled in 1923 from a filled area in the bay at Bibi Eibat on the Caspian Sea near Baku, Azerbaijan. The first offshore wells in South America were drilled in 1924 from wooden piles in Lake Maracaibo, an estuary in northern Venezuela. The wood piles were destroyed rapidly by marine shipworms. Drilling from concrete platforms began in 1927 and from steel derricks in 1934.

1.2.1.2 The Gulf of Mexico

Offshore oil exploration in the U.S Gulf of Mexico was initiated in the early 1930s in coastal wetlands of Louisiana (Veldman and Lagers, 1997; MMS, 2007a). The first commercial oil discovery occurred in 1938 in the Creole Field, located about one mile off the Louisiana coast in about 13 ft of water. The first offshore well in Texas also was drilled in 1938 in Galveston Bay. The first successful well out of sight of land was drilled in 1947, 12 miles from shore in the Ship Shoal lease area off Louisiana. This offshore discovery led to rapid expansion of offshore oil and gas exploration and production in the northern Gulf of Mexico. More than 40,000 wells have been drilled in U.S. State and Federal waters of the Gulf of Mexico and there currently are about 3800 offshore structures in the Gulf of Mexico.

Technological developments in rig design and drilling methods have permitted oil and gas exploration to move rapidly offshore in the U.S. Gulf of Mexico. The first well in more than 650 ft (200 m) of water was drilled in 1974 in 700 ft of water off the Mississippi River. The first deep-water (>1000 ft) well was drilled in 1979 in 1025 ft of water in the same area. In 2009, Shell Oil Company installed the Perdido spar production platform in the Great White prospect in the western Gulf of Mexico about 200 miles south of Galveston, TX, in 7817 ft of water. Perdido produces through sub-sea completions and tie-backs from several nearby wells drilled in 8000 to nearly 10,000 ft of water. Perdido began production of oil and gas in March 2010, becoming the deepest-water production facility in the world.

Oil and gas development began offshore in the Mexican Gulf of Mexico in the late 1960s and early 1970s. Petroleo Mexicanos (PEMEX) discovered the giant Ixtoc field in 1974 and the even larger Cantarell field in 1976, both in the Bay of Campeche (Petzet, 2001).

1.2.1.3 The North Sea

Serious exploration for oil and gas in the North Sea began after the 1958 United Nations Convention on the Continental Shelf went into effect (Veldman and Lagers, 1997). The convention set principles for demarcating the North Sea among the five North Sea countries. The first wells were drilled between 1961 and 1963 in the Dutch Sector 15 miles offshore in 45 ft of water. The first discovery was in the United Kingdom Sector in 1965. BP discovered gas in what became the West Sole field in 88 ft of water east of Hull, England. Three additional gas deposits were discovered in the same area within a few months of the first discovery. Phillips discovered the first commercial oil reserves in the Norwegian sector in 1967 in the Ekofisk field about 200 miles southwest of Stavanger, Norway, in the southernmost area of the Norwegian Sector. Ekofisk is still in production today. As of 2004, nearly 500 offshore oil and gas fields have been developed or were under construction off Western Europe, mostly in the North Sea (Westwood and MacFarlane, 2004). Approximately 78 percent of the productive fields are in the UK and Norwegian sectors.

1.2.1.4 Other Offshore Areas

Offshore oil and gas development and production are occurring in many other parts of the world. Other centers of offshore oil and gas development include the Gulf of Thailand, Indonesia, the northwest shelf and Timor Sea off Australia, the east and west coasts of India, the South Atlantic Ocean off Brazil, offshore several countries in north and west Africa, and the Arabian Gulf (Saudi Arabia, Qatar, United Arab Emirates, and Iran).

The pace of offshore oil and gas exploration and development also is increasing in cold-water environments of Alaska, Arctic and Atlantic Canada, the Barents Sea off northern Norway and western Russia, and offshore in the Russian Far East.

1.2.2 Offshore Exploration in the Arctic and Subarctic

The official definition of the Arctic is lands and seas lying north of the Arctic Circle, 66°33' N latitude. The Arctic countries include the United States (Alaska), Canada, Norway, Finland, Russia, and Denmark (Greenland). However, these countries define the Arctic more broadly to include lands and seas south of the Arctic Circle that have physical and climatic conditions similar to those in the Arctic. For example, the United States defines the Arctic as U.S territory north of the Arctic Circle and all U.S. territory north and west of the boundary formed by the Porcupine, Yukon and Kuskokwim Rivers, all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas, and the Aleutian Island chain, but not the Alaska Peninsula. The Protection of the Arctic Marine Environment (PAME) Working Group of the Arctic Council (2009) combines geographic definitions of member countries in its definition of the Arctic region, including marine and coastal areas where mean summer temperatures do not exceed 10°C (50°F) (Figure 1-1). The focus of this review is on offshore oil and gas activities in this region as well as other cold-water areas, such as the Atlantic coast of Canada, the northern North Sea, and the Pacific coast of Russia, where there is substantial offshore oil and gas development.

Figure 1-1 shows a map of the Arctic Region (red line) as defined by the Arctic Council (2009). The Arctic region is defined as that area where the average temperature for the warmest month is below 50°F (10°C).

Figure 1-1 Map of the Arctic Region

1.2.2.1 Alaska

South Central Alaska. Offshore oil and gas exploration and development has proceeded at a slower pace in the Arctic region than in more temperate waters (NRC, 2003). The harsh environmental conditions have made oil prospecting on land and particularly offshore extremely difficult. There also were severe financial and logistic constraints in moving drilling equipment to remote, often ice-covered development sites and then in transporting any oil discovered to market.

Russian settlers learned about oil and gas seeps on the Alaska Peninsula from the indigenous people as early as 1853 (Hershberger, 1982; Veldman and Lagers, 1997). The first wells were drilled on the Iniskin Peninsula on the west shore of Cook Inlet in 1898. The first productive wells were drilled on the shore at Katalla on the Gulf of Alaska south of the Copper River delta in 1902. The Katalla field produced about 154,000 barrels (1 barrel = 42 gallons) of a light crude oil until 1933, when the oil refinery burned down. Several wells were drilled in the Kanatak District on the Alaska Peninsula across the Shelikhov Strait from Kodiak Island in 1923 and 1926 and in the Yakataga District south of Katalla in 1926 and 1927. None of this exploration found commercial quantities of oil.

Significant oil resources were discovered in 1957 near the Swanson River on the Kenai Peninsula west of Cook Inlet, ushering in the Alaska oil boom. Three platforms were drilled in Cook Inlet five years later from small rigs that could not withstand winter conditions in the inlet. Shell, Socal, and Richfield built the first permanent platform designed to withstand the severe environmental conditions of Upper Cook Inlet in 1964. By the late 1960s, 5 fields in the Kenai/Cook Inlet area were producing oil and 9 fields were producing natural gas.

The North Slope. Exploration for oil and gas on the Alaskan North Slope began slowly and, as in southern Alaska, focused initially on oil seeps identified by indigenous people. In 1923, the government withdrew 37,000 mi^2 of the North Slope, extending from the vicinity of oil seeps at Cape Simpson, near Barrow, to the crest of the Brooks Range, from oil exploration and established the Naval Petroleum Reserve #4 (Mull, 1982; National Research Council, 2003). The USGS and the Navy performed some geologic exploration there between 1923 and 1926 and resumed exploration in 1944 (USGS, 2001). Exploratory drilling was not attempted until after the war. Between 1945 and 1955, 37 test wells and 45 core tests were drilled on 18 geologic structures, leading to discovery of a small non-commercial oil field at Umiat and small gas fields at Barrow and Gubik. Spurred by the large Swanson River discovery on the Kenai Peninsula, the oil industry drilled several exploratory wells near the Beaufort Sea coast in 1963 and 1964. Two wells were drilled in the Coleville River delta in 1966 and 1967.

In the winter of 1966, Richfield Oil (later ARCO) and Humble oil (later Exxon) drilled an exploratory well 80 miles east of Umiat. The well was a dry hole. The drill rig was moved 60 miles north to a prospect called Prudhoe Bay State #1, where drilling was initiated in April 1967. Work had to be suspended during the summer thaw and was resumed in November after freezeup. Gas was discovered at 8202 feet. Drilling was continued and oil was discovered deeper in the hole in March 1968. Subsequent delineation of the formation revealed that the Prudhoe Bay field was the largest in North America.

In 1969, 33 wells were drilled along the Beaufort Sea coast east and west of Prudhoe Bay. The wells revealed additional commercial oil and gas reserves at Kuparuk, West Sak, and Milne Point. Construction of the Trans-Alaska pipeline and an oil port at Valdez began in March 1975 and was completed in May, 1977. Oil started flowing through the pipeline in June 1977. More than 15 billion barrels (630 billion gallons) of North Slope crude oil had been delivered to Valdez by early 2009.

Oil and gas exploration on the outer continental shelf (OCS) of Alaska began with the drilling of a continental offshore stratigraphic test (COST) well in the Gulf of Alaska in 1975. An additional 13 COST wells were drilled in other lease areas between 1976 and 1983 (Table 1-1). Several oil companies usually shared funding for drilling these COST wells and shared the geological results.

Shallow State and Federal waters of the Beaufort Sea continental shelf were made available for exploratory drilling through a series of lease sales, beginning in 1979. Thirty-one exploratory wells were drilled in State/Federal lease tracts in the Beaufort Sea between 1981 and 2002 (Wainwright, 2002; NRC, 2003) (Table 1-1, Figure 1-2). The Alaska Dept. of Natural Resources (ADNR, 2007) lists 19 oil and gas fields in State and Federal waters of Alaska. Some of these wells are in State lease tracts in coastal waters (< 3 miles from shore) in the Beaufort Sea.

Table 1-1 lists the exploratory drilling in State/Federal lease tracts offshore Alaska. Data from MMS, Alaska OCS Region, Anchorage, AK.

TABLE 1-1
Exploratory Drilling in State/Federal Lease Tracts Offshore Alaska

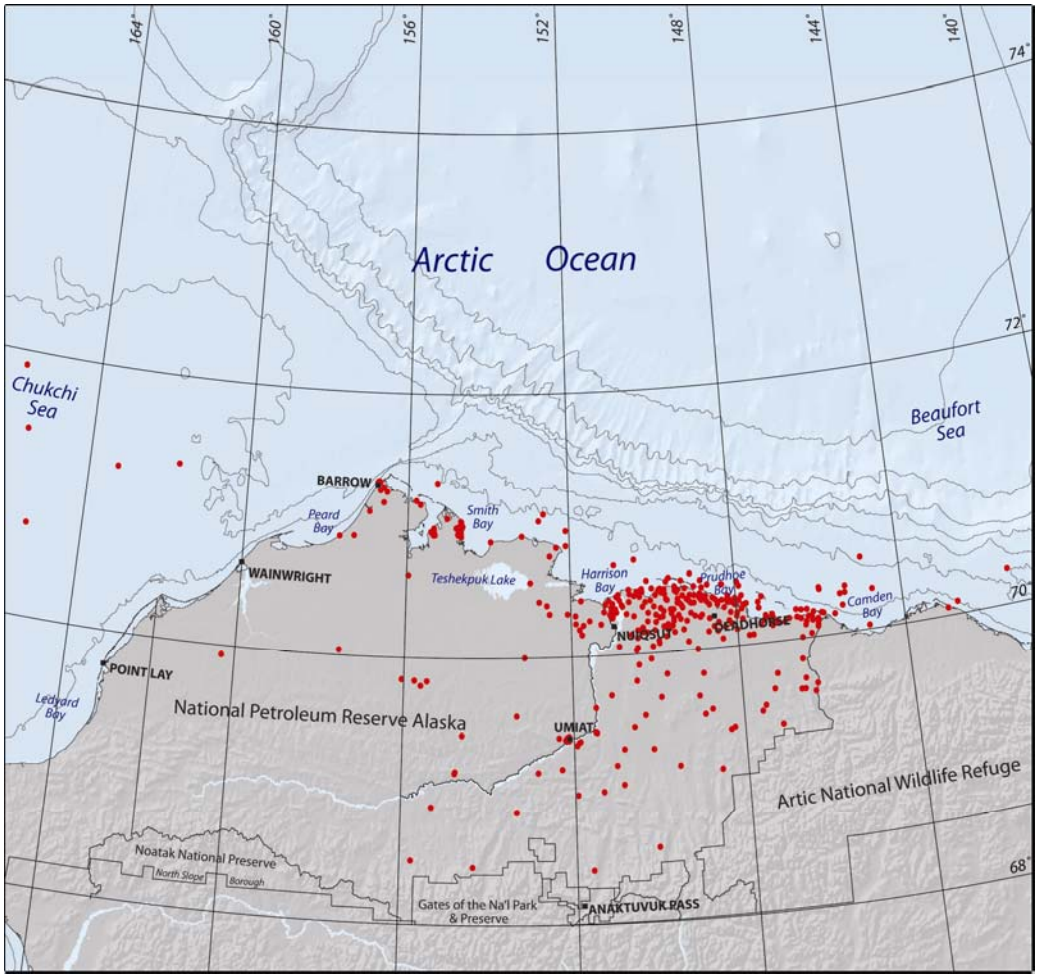
OCS Lease Area	No. Wells	Water Depth	Spud Dates[a]
COST Well[b]	14	ND	1975 - 1983
Beaufort Sea	31	18 – 167	1981 – 2003
Chukchi Sea	5	137 – 152	1989 - 1991
Norton Sound	6	35 – 65	1984 – 1985
Navarin Basin	8	393 – 541	1985
St. George Basin	10	358 – 476	1984 – 1985
Cook Inlet	13	115 – 550	1978 – 1984
Gulf of Alaska	12	184 – 863	1976 - 1983
Total	99	18 – 863	1975 - 2003

[a] The spud date is the date when drilling was initiated.
[b] Continental offshore stratigraphic test (COST) wells were drilled in Gulf of Alaska, St. George Basin (2), Kodiak (6), Cook Inlet, Norton Basin (2), North Aleutian, and Navarin Basin Lease Areas.

Five exploratory wells were drilled between 1989 and 1991 on the Federal outer continental shelf of the Chukchi Sea. An additional 49 exploratory wells were drilled in five other State and Federal lease areas between 1984 and 1991 (Table 1-1). The other lease areas where wells were drilled are Norton Sound, Navarin Basin, St. George Basin, Cook Inlet, and the Gulf of Alaska.

Figure 1-2 is a map of the Alaskan North Slope showing the location for on-shore and offshore wells drilled through 2002. Modified from NRC (2003).

Figure 1-2 Map of the Alaskan North Slope



1.2.2.2 Canada

Mackenzie River Delta and Beaufort Sea. Exploration and development of oil and gas resources in the Canadian Arctic began in 1920 with the discovery of the Norman Wells field, located one degree south of the Arctic Circle adjacent to the Mackenzie River in the Northwest Territories, 900 miles north of Edmonton (Exxon Mobil, 2008). At the time, it was the world's most northern Arctic oil field and, in 1932, became the first commercial oil field and refinery in the Arctic.

Exploratory drilling began farther north in the Mackenzie River delta in 1962 and in the Canadian Beaufort Sea in 1971. The pace of exploration picked up in the 1970s and 1980s (BSStRPA, 2007). There were 53 discoveries of oil and gas between 1970 and 1989, divided roughly equally between the Beaufort Sea and the nearby Mackenzie River delta. The largest offshore oil field, the Amauligak field, was discovered in 1984.

Between 1973 and 1989, 91 wells were drilled in the Canadian Beaufort Sea. Exploration in the Canadian Beaufort Sea ceased in the 1990s, due in large part to the drop in market prices for oil and gas and changes to federal subsidies. The most recent exploratory drilling project was the Devon Paktoa C-60 project with drilling during the winter of 2005-2006 off the Mackenzie River delta (KAVIK-AXYS Inc., 2007). The drilling was from a steel drilling caisson (SDC) with communication with land via an ice road. Forty-nine of the wells in shallow water in the Canadian Beaufort Sea were drilled from artificial ice or gravel islands, steel or concrete-reinforced islands, or SDCs. The SDC used to drill the Paktoa C-60 prospect had been used earlier to drill six exploratory wells in the Alaskan and Canadian Beaufort Seas, including the McCovey well, the last exploratory well drilled in the Alaskan Beaufort Sea. The remaining wells were drilled in deeper waters from floating, ice-resistant oil rigs. Spent drilling muds and cuttings usually were discharged to open waters in the ice-free season and on or under the ice in the winter.

Arctic Archipelago. The first well in the Arctic Archipelago (Arctic Islands) in the Sverdrup Basin, north of 75º N latitude, was drilled on Melville Island in the winter of 1961-1962 (McCracken et al., 2007). This well and two others drilled on Cornwallis and Bathurst Islands during the next two winters were technical successes but dry holes. The first large discovery was in 1969 at Drake Point on Melville Island. The Drake Point gas field, the largest in the Arctic Archipelago, was followed by discovery of additional large gas fields in the islands during the next three years. The first commercial oil discovery was in 1974 at Bent Horn on Cameron Island. There also was a large oil discovery a short distance off Bent Horn at Cisco near Laughheed Island. Crude oil was stored at Bent Horn and, annually from 1985 until the late 1990s, was shipped by ice-breaking tankers to ports further south in Canada.

The gas fields were expected to extend offshore. Because these waters are ice-covered for most of the year, a method was developed to use ice islands (platforms of thickened ice constructed in winter by pumping seawater onto the polar ice pack) as a base for drilling platforms (Eklund and Masterson, 1980). The ice platform design was proven by drilling four stratigraphic test wells in 130 to 300 ft of water in Kristoffer Bay at Ellef Ringnes Island in the spring of 1973. Between 1973 and 1979, 14 wells were drilled in the area from ice islands. Gas was discovered in several of these wells. The first sub-sea completion in the arctic was in 1978 about 0.6 miles east of Melville Island in 180 ft of water. Commercial quantities of oil were discovered in four wells drilled west of Lougheed Island in 1981-1984 (Meneley, 2008).

Atlantic Canada. The first offshore well in Atlantic Canada was drilled eight miles offshore of Prince Edward Island in 1943 (CAPP, 2005). The first exploration permits were issued in the early 1960s and the first exploration wells were drilled in Newfoundland in 1966 and in Nova Scotia in 1967 (Gordon et al., 2000). The first offshore exploratory drilling in Newfoundland occurred in 1971. Several wells were drilled there in the 1970s, but exploration stopped in the early 1980s because of worsening exploration economics due to the severe weather conditions, including icebergs, and poor drilling results.

The first well in Nova Scotia was drilled in 1967 on Sable Island and discovered high-pressure gas. The first wells offshore Sable Island were drilled in 1969 and 1972 and discovered gas. Two additional wells drilled there in the early 1980s also discovered high-pressure gas reservoirs. Gas production from the Sable Island field began in 2000. The first oil discovery was in 1973 in the

Cohasset prospect. Delineation drilling in 1985-1986 showed that the Cohasset/Panuke prospect was commercial.

Exploration on the Grand Banks, a major commercial fishery area southeast of Newfoundland, began in 1966. The first 40 wells on the Grand Banks were dry. Oil was discovered in 1976 in the Hibernia prospect, located about 196 miles southeast of St. John's, Newfoundland, in about 260 ft of water. The Terra Nova and White Rose fields were discovered near Hibernia in the mid-1980s. Hibernia began production in 1997 from the world's largest gravity based system (GBS) platform in 262 ft of water. Terra Nova and White Rose came into production in 2002 and 2005. Both of these projects included subsea completions with production sent to anchored floating production, storage, and offloading (FPSO) vessels (there are no permanent surface facilities). In a subsea completion, the well is drilled from a floating platform and the blowout preventer and production equipment are installed on the sea floor with tie-ins for produced oil and gas to a pipeline or surface storage vessel. The subsea completion can be constructed so that it will not be snagged by fishing gear, as was done for the Snøhvit development in the Barents Sea (Rød, 2009).

1.2.2.3 Other Arctic and Subarctic Areas

Norwegian Sea. The Norwegian Sea extends from about 63° north latitude north to the Barents Sea at about 70° N latitude off the west coast of Norway, including the area around Jan Mayan Island, north of Iceland. Despite the success of Norway, the UK, and the Netherlands in developing the oil and gas resources of the North Sea with minimal environmental effects, there was considerable concern about possible environmental effects, particularly on commercial fisheries, of oil development in the Norwegian Sea. However, in 1979, the Norwegian parliament approved a White Paper recommending initiation of exploration activities north of 62°N latitude (Njå, 2005; Totland et al., 2007). The first discovery was the Midgard well in 1981. This was followed by more than 20 discoveries of oil and gas. Oil production was initiated by Shell Oil Co. from the Draugen field in 1993, followed by the Heidrun field operated by Statoil in 1995. The Norwegian Petroleum Directorate (2009) estimated that the Norwegian Sea contains more than 30% of Norway's undiscovered oil and gas resources.

Barents Sea. The Barents Sea is shared by Norway and Russia. The first exploration license for the Norwegian Barents Sea was awarded in 1979 and exploratory drilling began in 1980 (Hasle et al., 2009). Approximately 70 wells have been drilled to date in the Norwegian Barents Sea. The Snøhvit gas field was discovered in 1984 in about 1000 ft of water 88 miles northwest of the Norwegian coast. The field was developed with 20 production wells and one injection well (for CO_2) and began production of gas and condensate in 2007 (Dahle and Camus, 2007). A plan for development and operation (PDO) was issued in June 2009 for development of the Goliat oil field. The Goliat production facility will consist of a FPSO facility tied to subsea production wells. PDOs are being developed for several other oil and gas fields in the southwestern Barents Sea (Norwegian Petroleum Directorate, 2009).

Exploratory drilling in the Norwegian Barents Sea was halted in 2001 due to concerns about the impact of oil and gas development on fisheries, particularly in the Lofoten area. In 2005-6, the government developed a comprehensive, integrated ecosystem-based management plan for all human uses and activities that allowed exploration for oil and gas to resume in all but restricted

areas of the Norwegian Barents Sea and ocean areas off the Lofoten Islands. The management plan included strict environmental guidelines for fisheries, oil and gas operations, and other activities the area (NME, 2006; Hasle et al., 2009). A similar integrated management plan was issued for the Norwegian Sea in 2009 (NME, 2009). The guidelines for oil and gas operations in the management plans will be discussed in detail below in Section 3

Exploration began in the Russian Barents Sea in the 1970s. More than 100 wells were drilled, leading to discovery of giant gas fields, such as Shtokmanovskoe, Ledovoye, and Ludocskoye. Several smaller fields were discovered farther south in the Pechora Sea. The Russians also discovered two additional giant gas fields in the Kara Sea, east of Novaya Zembla (Austvik, 2006). These fields have been under development since 1992, and the Shtokmanovskoe is considered the largest offshore gas and condensate field in the world (Patin, 1999). There also is a strong potential for additional large gas deposits in the disputed area of the Barents Sea between Norway and Russia, where neither country has drilled to date.

Russian Far East. Russia has identified several promising oil and gas prospects on the continental shelf of the Russian Far East. Most of these undiscovered resources are in the Sea of Okhotsk (including east of Sakhalin Island) and the Russian Bering, Chukchi, and East Siberian Seas. Exploratory drilling began in 1994 and is continuing. As of 1999, more than 20 potential oil- and gas-bearing basins had been identified in these seas (Patin, 1999).

The international oil industry has explored off Sakhalin for the past 30 years and vast oil and gas resources there, estimated at 7 billion barrels of oil and 80 trillion ft^3 of natural gas, have been under development in the Sakhalin-I and Sakhalin-II projects (O'Reilly et al., 2000; Sakhalin Energy Investment Co. Ltd, 2003). Oil and gas production from the Sakhalin I field began in 2005 and full production began in 2009 from the Sakhalin II field (US Energy Administration, 2008).

1.2.2.4 Summary of Offshore Exploration and Development in Cold-Water Environments

As discussed above, the pace of exploration for and development of offshore oil and gas resources throughout the world has lagged behind development of onshore resources. This is particularly true in arctic and sub-arctic environments. This is due mainly to the greater technical difficulty in exploiting these offshore resources, particularly in cold-water environments. There have been extensive technological and engineering advances over the more than 100 years of offshore oil and gas production in the design and operation of offshore oil and gas exploratory rigs and production platforms. These innovations have enabled the industry to operate safely, efficiently, and with minimal harmful environmental impacts, in even the harshest Arctic marine environments.

Since the late 1960s, the offshore oil and gas industry has attempted to minimize environmental disturbance during their offshore operations. Waste management is more difficult during offshore exploration and development than during exploration and development on land. Drilling and production wastes have routinely been discharged to the ocean during offshore operations over the complete history of offshore development. For example, Hartley et al. (2003) identify 2146 development wells at 121 offshore installations and approximately 4000 exploratory and

appraisal wells drilled in the northern and central North Sea through 2001, all of which discharged drill cuttings (some also discharged WBM). More than 40,000 wells have been drilled in the U.S. Gulf of Mexico. Drilling muds and cuttings were discharged from many of the wells in Federal waters.

Most of the countries exploiting offshore oil and gas resources have developed environmental regulations intended to ensure that offshore exploration and development causes minimal disturbance to the marine environment and its biological resources. Monitoring of discharges of drilling muds and cuttings has enabled the industry to identify wastes, waste constituents, and disposal practices that should be restricted or modified to protect the environment. As a result, the types of drilling wastes that regulatory agencies permit for discharge to their marine waters have changed over the years. Current discharges and discharge practices, if performed in compliance with environmental regulations, cause little or no harm to the marine environment, as discussed in detail below.

1.3 Oil and Gas Resources in the Arctic

The extensive geologic prospecting and exploratory drilling in the Arctic over the last 80 years has revealed a strong potential for vast reserves of oil and gas on land and in marine waters throughout the Arctic. As new oil and gas discoveries in lower-latitude areas of the globe have declined and the existing reserves are being depleted, the resulting rising fossil fuel prices combined with improvements in technologies for safely developing oil resources in the Arctic have stimulated interest in developing these vast untapped offshore reserves in Arctic regions of the northern U.S., Canada, Norway, Greenland, and Russia.

In 1991, the U.S. Dept. of Energy (DOE) published a National Energy Strategy (Thomas et al., 1993). The strategy set out two fundamental objectives. The first was to expand U.S. and world oil production capacity and strategic stocks. The second was to reduce U.S. oil consumption through a combination of measures aimed at increasing efficiency, introducing alternative transportation fuels, and aggressive research and development of new energy and oil-conservation technologies. To address the first objective, the National Energy Strategy called for accelerated development of the large oil fields on the North Slope of Alaska. In February of 2009, the Secretary of the Interior announced a four-part strategy for developing a new, comprehensive approach to developing energy resources of the U.S. outer continental shelf (OCS), in response to the President's vision for energy independence for the United States (MMS, 2009). The objective of this strategy was to encourage development of renewable energy resources and oil and gas resources on the Federal OCS, including the Beaufort and Chukchi Seas, in a comprehensive and environmentally sound manner.

The United States currently imports nearly 60 % of its crude oil (API, 2009). As domestic oil and gas production has continued to decline, the U.S. government has increased its call to develop strategies to decrease our dependence of foreign oil as a critical national security strategy, particularly by accelerated development of the vast oil and gas reserves on the North Slope of Alaska (Calder, 2008). These concerns about energy security are shared by the North Sea countries (especially the United Kingdom and Norway) (Powell, 2008), particularly after Russia discovered giant gas fields in the eastern Barents Sea in the 1990s (Patin, 1999) and laid claim to the North Pole in 2007.

The United Nations presented the Law of the Sea Treaty in 1982. Under the treaty, all countries receive exclusive economic rights to any natural resource that is present on or beneath the sea floor out to a distance of 200 nautical miles (230 mi or 371 km) from their shores. This gives the United States, Canada, Norway, Russia, and Denmark (for Greenland) legal claim to extensive areas of the Arctic Ocean floor that might contain valuable mineral (including oil and gas) resources. Each country that ratifies the treaty can extend its claim up to 350 nautical miles (402 mi or 647 km) from shore for those areas that can be demonstrated to be an extension that country's continental shelf. The country must acquire geological data documenting the geographic extent of its continental shelf in order to make a claim for consideration by the UN.

In the summer of 2007, a Russian remotely operated vehicle (ROV) planted a national flag on the seabed below the North Pole during a survey of the Lomonosov Ridge that crosses the Arctic Ocean between the New Siberian Islands and Ellesmere Island, Canada (Powell, 2008). Russia subsequently claimed that the underwater mountains of the Lomonosov and Mendeleev Ridges were extensions of the Eurasian continental shelf and, therefore, should be deemed part of the Russian Exclusive Economic Zone (EEZ) (Baev, 2007). Canada and Denmark are trying to document that the Lomonosov Ridge is an extension of the North American continental shelf. This and other disputes among Arctic countries about who owns the Arctic seafloor has stimulated plans for expanded exploration for oil and gas there.

About 6% of the earth's surface lies above the northern Arctic Circle (66°33' N latitude); this area is divided almost equally among land, continental shelf (defined by Gautier et al., 2009, as extending from the shore to 500 m [1640 ft] water depth), and the deep sea (Gautier et al., 2009). There has been extensive development of Arctic oil and gas resources on land. By 2007, more than 400 oil and gas fields had been developed in the Arctic; most developments were in the West Siberian Basin of Russia and on the North Slope of Alaska (Gautier et al., 2009). These oil and gas fields contain estimated discovered reserves of 40 billion barrels (BBO) of oil, 1136 trillion cubic feet (TCF) of natural gas, and 8 billion barrels of natural gas liquids (sometimes called condensate). These reserves account for about 240 billion barrels of oil and oil-equivalent natural gas (BBOE), which is almost 10 % of the world's known conventional petroleum resources (cumulative production and remaining proven reserves) (USGS, 2008).

By comparison, there has been relatively little offshore oil and gas exploration in the Arctic (Table 1-2). Most of the offshore discoveries there remain undeveloped. The slower pace of offshore development in the Arctic can be attributed to:

- Remoteness from supporting infrastructure and markets, making it difficult and expensive to get any produced oil and gas to shore and to domestic markets;
- Extremely cold temperatures, short day lengths, and foul weather for much of the year;
- The high cost and technical difficulty of safe exploration and development in frequently ice-covered Arctic seas; and
- Concerns of indigenous people about effects of offshore development on culture and environment.
- Environmental litigation and regional politics.

Table 1-2 is a comparison of approximate numbers of exploration wells in the Arctic, compared to those in the U.S Gulf of Mexico.

TABLE 1-2
Comparison of Exploration Well Numbers, Arctic, the U.S. and the Gulf of Mexico

Region	Numbers of Exploration Wells
U.S. Gulf of Mexico	> 10,000
Russia – Barents, Pechora, Kara Seas	> 100
Norway – Norwegian and Barents Seas	~ 80
Canada – Arctic Islands	~ 180
Canada – Beaufort Sea	~ 90
Alaska – Beaufort Sea	~ 50
Alaska – Chukchi Sea	5

Interest in developing these offshore resources has increased in recent years as oil and gas prices have increased, technology developments have allowed exploration, development, and transport of offshore oil and gas resources to be performed safely and efficiently, and strategies for developing these resources with a minimum of environmental disturbance have been developed.

Recently, the U.S. Geological Service (USGS, 2008; Gautier et al., 2009) performed a Circum-Arctic Resource Appraisal (CARA) to estimate the amount of total undiscovered oil, gas, and natural gas liquids resources in the Arctic. They divided the Arctic into 49 assessment units (AU); AUs, also called provinces, are mappable volumes of sedimentary rocks that share similar geologic properties (most oil and gas reservoirs are in layers of sedimentary rock buried below the earth's surface). All assessment units were estimated to contain some undiscovered oil and gas. However, only 25 were predicted to contain sufficient undiscovered reserves to warrant further exploration. These AUs contain an estimated total of 412 BBOE of undiscovered oil and gas resources (Table 1-3), nearly twice the known conventional oil and gas reserves in the Arctic. Approximately 84 % of these undiscovered Arctic oil and gas resources occur offshore.

Table 1-3 is the mean estimated undiscovered offshore oil and gas resources in the Arctic based on the Circum-Arctic Resource Appraisal (CARA). Assessment units are listed in order of total barrels (1 barrel = 42 gallon or 0.159 m^3) of oil and oil-equivalent natural gas (BOE). Refer to Figures 1-3 and 1-4 for locations of Assessment Units (AU). US resources are highlighted. Data from USGS (2008) and Gautier et al. (2009).

TABLE 1-3
Mean Estimated Undiscovered Offshore Oil and Gas Resources in the Arctic

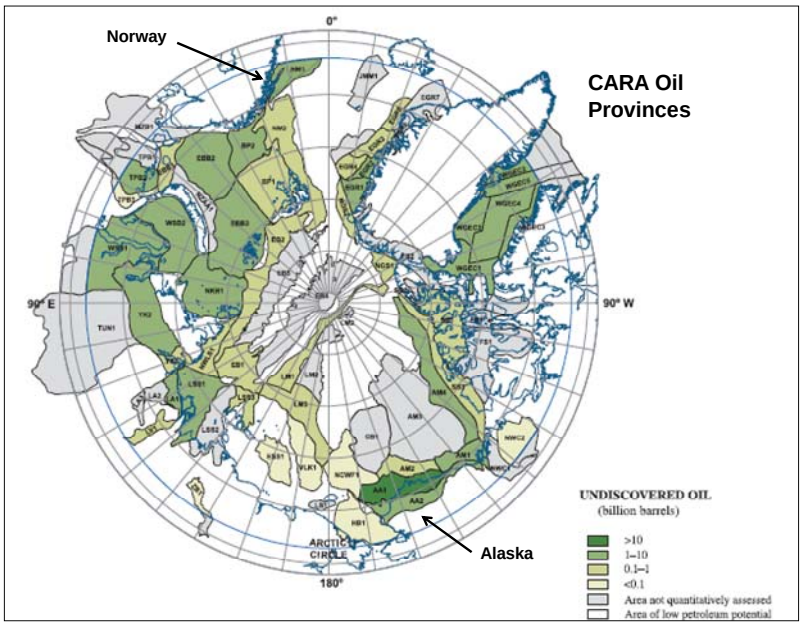
AU Code	Assessment Unit	Country	Oil & NGL (BBO)	Total Gas (BBOE)	Total BOE (BBOE)
WSB	West Siberian Basin	Russia	24.0	109	133
AA	Arctic Alaska	USA	35.9	36.9	72.8
EBB	E. Barents Basin	Russia	8.83	52.9	61.7
EGR	E. Greenland Rift Basins	Denmark	17.0	14.4	31.4
YK	Yenisey-Khatanga Basin	Russia	8.26	16.7	25.0
AM	Amerasian Basin	Canada	10.3	9.48	19.8
WGEC	W. Greenland-E. Canada	Denmark Canada	8.43	8.64	17.1
LSS	Lapdev Sea Shelf	Russia	3.98	5.43	9.41
NM	Norwegian Margin	Norway	1.94	5.38	7.32
BP	Barents Platform	Norway	2.33	4.37	6.70
EB	Eurasia Basin	Russia	1.86	3.25	5.11
NKB	N. Kara Basins & Platforms	Russia	2.20	2.50	4.70
TPB	Timan-Pechora Basin	Russia	1.87	1.51	3.38
NGS	N. Greenland Seared Margin	Denmark	1.62	1.70	3.32
LM	Lomonosov-Makarov	Russia	1.30	1.19	2.49
SB	Sverdrup Basin	Canada	1.04	1.43	2.47
LA	Lena-Anabar Basin	Russia	1.97	0.35	2.32
NCWF	N. Chukchi-Wrangel Foreland Basin	USA Russia	0.19	1.01	1.20
VLK	Vilkiskii Basin	Russia	0.20	0.96	1.16
NWLS	NW Laptev Sea Shelf	Russia	0.29	0.75	1.04
HB	Hope Basin	USA Russia	19.0	108	127
Others	4 Provinces	Russia Canada	0.57	0.63	1.20
Total			134	278	412

NGL natural gas liquids; BMBO billion barrels oil; BBOE Billion barrels of oil and oil-equivalent natural gas.

On an energy-equivalent basis, the Arctic contains more than three times more undiscovered gas than oil. The largest undiscovered oil reserves are in Arctic Alaska, east of Greenland, and the Amerasian (Canning-Mackenzie River, Canada) Basin (Figure 1-3). The largest undiscovered gas and natural gas liquids reserves are in the West Siberian Basin, the East Barents Sea Basin (Russia), and Arctic Alaska (Figure 1-4) (Gautier et al., 2009).

Figure 1-3 shows the Circum-Arctic Resource Appraisal (CARA) AUs (Provinces) with undiscovered crude oil resources. Names of AUs with the highest resource estimates are listed in Table 1-3. From USGS (2008) and Gautier et al. (2009).

Figure 1-3 Circum-Arctic Resource Appraisal AUs with Undiscovered Crude Oil Resources



MMS (2009) recently assessed the current endowment of oil and gas resources on the U.S. OCS. The endowment includes cumulative production, known reserves, future reserves appreciation, and undiscovered, technically discoverable reserves (UTRR). Future reserves appreciation includes known and unknown reserves that may become recoverable with new technologies; UTRR are unknown reserves that can be recovered with current technology.

As expected, the largest reserves in all categories and the largest total endowment are on the Gulf of Mexico OCS (Table 1-4). The second largest is on the Alaskan OCS. Most of the reserves on the Alaskan OCS are in the UTRR category and more than 92% of these undiscovered resources occur on the Beaufort and Chukchi Sea OCS. Mean estimated total UTRR for the Alaskan OCS is 50.1 BBOE, including 26.6 BBO oil and natural gas liquids and 23.5 BBOE of natural gas. The UTRR on the Chukchi Sea OCS is more than twice that on the Beaufort Sea OCS (Table 1-5). Both regions contain more undiscovered oil than gas resources. These vast, untapped fossil

fuel resources need to play an important role in the U.S. goal of energy independence, in conjunction with development of alternative energy sources and energy conservation.

Figure 1-4 shows the Circum-Arctic Resource Appraisal (CARA) AUs (Provinces) with undiscovered natural gas and natural gas liquids resources. Names of AUs with the highest resource estimates are listed in Table 1-3. From USGS (2008) and Gautier et al. (2009).

Figure 1-4 Circum-Arctic Resource Appraisal AUs with Undiscovered Natural Gas and Natural Gas Liquids Resources

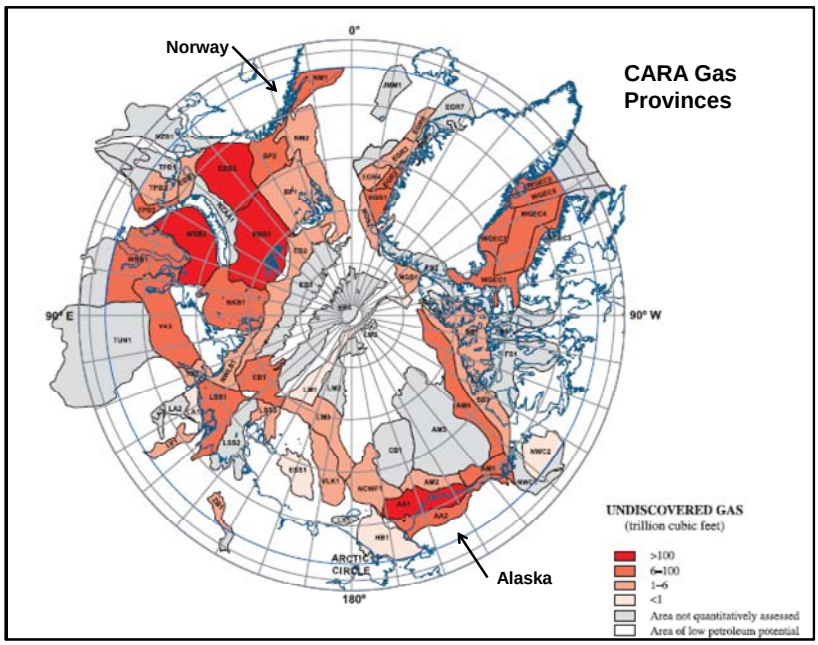


Table 1-4 lists the endowment of oil and gas resources on the Federal outer continental shelf (OCS) of the United States (Usually 3.45 to 230 miles from shore). The endowment includes cumulative production, known reserves, future reserves appreciation, and estimated mean undiscovered, technically discoverable reserves (UTRR). Volumes of oil and natural gas liquids are billion barrels (BBO), of natural gas are billion barrels of oil equivalent (BBOE), and of total reserves are billion barrels oil and natural gas equivalents (total BBOE). One barrel = 42 gallons or 159 liters; there are 5620 ft^3 of natural gas per barrel. From MMS (2009).

TABLE 1-4
Endowment of Oil and Gas Resources on the US OCS

Resource Category		Alaska OCS	Atlantic OCS	Gulf of Mexico OCS	Pacific OCS	Total OCS
Cumulative Production	Oil	0.01	0	13.0	1.06	14.1
	Gas	0	0	27.1	0.23	27.3
	Total	0.01	0	40.1	1.29	41.4
Reserves	Oil	0.03	0	7.06	1.46	8.55
	Gas	0	0	4.90	0.28	5.21
	Total	0.03	0	12.0	1.74	13.8
Reserves Appreciation	Oil	---	---	6.88	---	6.88
	Gas	---	---	5.50	---	5.50
	Total	---	---	12.4	---	12.4
UTRR	Oil	26.6	3.8	44.9	10.5	85.9
	Gas	23.5	6.6	41.4	3.25	74.7
	Total	50.1	10.4	86.3	13.8	161
Total Endowment	Oil	26.65	3.8	71.9	13.0	115
	Gas	23.5	6.6	78.9	3.77	113
	Total	50.1	10.4	150.8	16.8	228

Table 1-5 shows the mean estimated undiscovered, technically discoverable reserves (UTRR) on the outer continental shelf of the Beaufort and Chukchi Seas. Volumes of oil and natural gas liquids are billion barrels (BBO), of natural gas are billion barrels of oil equivalent (BBOE), and of total reserves are billion barrels oil and natural gas equivalents (total BBOE). One barrel = 42 gallons or 159 liters; there are 5620 ft^3 of natural gas per barrel. From MMS (2009).

TABLE 1-5
Mean Estimated Undiscovered, Technically Discoverable Reserves on the Beaufort and Chukchi Seas OCS

Alaska Planning Area	Oil and Natural Gas Liquids (BB0)	Natural Gas (BBOE)	Total UTRR (BBOE)
Beaufort Sea	8.22	4.92	13.1
Chukchi Sea	15.4	13.7	29.1

2.0 OFFSHORE DEVELOPMENT IN THE ARCTIC REGION

Exploration for and development and production of offshore oil and gas resources, particularly in the Arctic, is a large, complex, and long-term undertaking. Offshore oil and gas operations can be divided into three phases: geophysical evaluation, exploration, and development/production. All three phases may occur simultaneously during development of large offshore fields.

2.1 Geophysical Exploration

Geophysical evaluation is performed during the early phases of offshore exploration for oil and gas to help identify subsea geologic structures that may contain economic reservoirs of oil and gas. The most widely used offshore exploration tool is seismic profiling. Seismic profiling is used to identify promising locations for drilling of exploratory wells and sometimes during field development to help delineate a discovery. Additional seismic profiling may be required to identify and map geologic hazards in the sea floor.

Seismic surveys rely on data from the reflection or refraction of low-frequency, high-energy sound pulses directed toward the sea floor (McCauley, 1994; NRC, 2003). The characteristics of the returning sound pulses provide information about geologic strata at different depths below the sea floor and can identify strata with properties favorable for accumulation of oil and gas.

In the past, sounds were produced with explosives. Modern offshore seismic surveys are performed with towed acoustic arrays consisting of air guns, that produce periodic pulses of compressed air of the proper sound frequency and intensity by mechanical means, and sensors that detect the returning echoes. The sound pulses are focused directly downward in a narrow arc toward the sea floor. The echoes returning to the sensor array provide information about the structure of deeply-buried geologic formations. The seismic survey data are used to identify geologic formations that have a structure favorable for accumulation of fossil hydrocarbons. However, exploratory drilling is required to positively identify and delineate sub-seafloor hydrocarbon reservoirs.

Offshore exploration is a high-risk business and the fraction of exploration wells that discover an economic reservoir often is low, even in seismically favorable geologic formations. For example, 41 percent of the 434 tracts drilled on the outer continental shelf of the Gulf of Mexico in 1983 were productive (Farrow, 1990). More than 200 dry holes were drilled over 10 years in oil-prone formations in the North Sea before the first discovery (Kobrin, 1988).

2.2 Exploratory and Development Drilling

As the technology of geotechnical exploration has improved over the last few decades, the ability to identify and characterized potentially productive subsurface hydrocarbon reservoirs has improved substantially. However, drilling is the only way to measure directly the amount of subsurface petroleum and gas; there is no substitute. With modern geotechnical exploration technology, it is possible for industry on the North Slope today to drill for thinner and deeper reservoir targets with fewer wells, smaller drill rigs, and with generation of less liquid and solid waste than it was 20 years ago (Gelb et al., 2006).

Drilling of wells is the main activity in exploration and development. Exploratory drilling involves drilling wells to determine if fossil fuels (oil and gas) are present (OGP, 2003). Each exploratory well usually requires 1 to 3 months to drill. Exploratory wells in U.S. offshore waters usually are vertical wells drilled with WBM, with discharge of WBM and cuttings to the sea. If fossil fuels are discovered during exploratory drilling, additional appraisal and delineation wells may be drilled to determine the vertical and horizontal dimensions of the reservoir and its economic potential.

If commercial quantities of oil or gas are identified, the operator may drill several development wells to produce the fossil fuels. These development wells usually are drilled from a single platform and are deviated in different directions from the vertical to tap different areas of the formation. SBM or OBM may be used and the cuttings may be reinjected, transported to shore, or discharged to the ocean (only SBM cuttings), depending on local regulations and the availability of suitable disposal wells or upland drilling waste handling sites. The number and distribution of the development wells are dictated by the structure of the hydrocarbon-bearing formation, the size of the hydrocarbon accumulation, and the ability of the hydrocarbons to migrate through the formation shales and sandstones. The current practice usually is to drill many production and injection wells from each modern offshore production platform to minimize the footprint of the production facility on the sea floor. The intent of the overall development design is to safely and cost-effectively maximize production from the reservoir over the productive life of the reserves, with minimum disturbance of the marine environment.

2.2.1 Exploratory Drilling

Exploration, delineation, and development drilling are similar, though the facilities from which drilling occurs often are different. Exploratory drilling offshore usually involves drilling single vertical wells over a large area where seismic surveys and other geologic prospecting have identified promising geologic structures.

More than 300 exploratory and delineation wells were drilled offshore in Arctic waters of the U.S. and Canada between 1973 and 2006 (Table 1-2). Most were drilled in water depths of less than 72 ft from bottom-founded drilling structures (e.g., gravel and sandbagged islands, sacrificial beaches, ice islands, the steel casing systems, Molikpaq, and concrete island drilling systems) (Keener and Allen, 2009). Fifty-three wells were drilled in water depths of 61 ft to 260 ft from floating vessels (4 Canmar/Dome conventional drill ships, the round-hulled Kulluk, and a barge). The Kulluk has drilled 12 wells in the U.S. and Canadian Beaufort Seas, and is being considered for use for drilling exploratory future wells in the Beaufort and Chukchi Seas. The Molikpaq was first deployed in the Canadian Beaufort Sea for drilling in shallow (30 to 130 ft) ice-prone waters (Isaacson and Gaida, 1994). It was converted for deep-water development and production and moved to Sakhalin Island, Russia in 1998. Both the Kulluk and Molikpaq were specifically designed to operate safely in heavy ice conditions and allow offshore drilling year-round.

Thirty exploratory wells were drilled over a period of 23 years (1981 to 2002) in State/Federal lease tracts administered by MMS between Barrow and Kaktovik in the Alaskan Beaufort Sea (Table 2-1, Figure 1-2). Records are incomplete on drilling in State lease tracts in waters of river deltas and coastal lagoons and within 3 nautical miles of the barrier islands. At least 33

exploration, delineation, and development wells were drilled in State Lease Sale BF tracts before 1986 (2 wells at Northstar, 6 wells at Niakuk, and 25 wells at Endicott) (Boehm et al., 1987). Several exploratory wells were drilled from gravel pads on or adjacent to barrier islands in state waters (e.g., Endeavor Island, Resolution Island, Challenge Island, Goose Island, and Alaska Island). An additional 5 wells were drilled between 1989 and 1991 over a large area 60 to 140 miles offshore in the northeastern Chukchi Sea (Table 2-2). Three exploratory wells were drilled in 2003 from a gravel island at the Oooguruk prospect located about 5 miles off Harrison Bay in about 5 ft of water.

As discussed in detail below, all of the exploratory and delineation wells drilled to date in the Beaufort and Chukchi Seas were drilled with water based drilling muds (WBM). Drilling muds and cuttings were discharged to the ocean during most exploratory drilling, except when the drilling operation was in shallow water close to shore, allowing transport of drilling wastes to shore on ice roads for onshore disposal. Some non-aqueous phase drilling muds were used for development drilling at Endicott and Northstar and all drilling wastes were disposed of in waste disposal wells at the drill site or transported to shore for onshore disposal (Krieger et al., 2002).

Ocean discharges of WBM and cuttings from several Beaufort Sea exploratory wells were monitored. The results of these studies were consistent with the conclusions of the 1983 National Research Council report (NRC, 1983): disturbance to the marine environment was minor and recovery was rapid. These studies are described in detail below.

Eleven of the exploratory wells in the Beaufort Sea were discoveries, with a potential for development (NRC, 2003). Five of these were significant discoveries: Kuvlum, Hammerhead, Sandpiper, Tern Island/Liberty, and Seal Island/Northstar (ADNR, 2009). Seven producing fields include offshore production (Badami, Endicott, Milne Point, Niakuk, Northstar, Point McIntyre, and Oooguruk). However, all but Endicott, Northstar, Point McIntyre, and Oooguruk are being produced through directional wells drilled from onshore facilities. Both Endicott and Point McIntyre use causeways to support offshore drilling and production facilities. Northstar, the only facility that gathers oil from Federal waters, pumps oil to shore by buried, ice-resistant pipelines and uses winter ice roads for re-supply of materials.

Shell Offshore, Inc. (SOI) plans to drill exploratory wells in the Beaufort Sea on the Torpedo and Sevulliq prospects near the Hammerhead prospect, discovered by Union Oil Co. in 1985-1986. The exploratory drill sites are in approximately 100 ft of water 15 miles north of Flaxman Island off Camden Bay (SOI, 2009). An ice-reinforced drillship, the *Frontier Discoverer*, will be used for exploratory drilling.

Table 2-1 lists in chronological order the exploratory wells drilled to date or planned on the State/Federal lease tracts of the U.S. Beaufort Sea. Several wells drilled on State leases are not included. Data from MMS, Alaska OCS Region, Anchorage, AK. Spud dates for the new wells are tentative because of ongoing litigation.

TABLE 2-1
Chronological Order of Exporatory Wells Drilled to Date or Planned in the U.S. Beaufort Sea

Prospect	Spud Date[a]	Water Depth (feet)	Drilling Unit
Beechey Point	11/1/81	18	Gravel Island
Beechey Point	12/27/81	18	Gravel Island
Tern	5/28/82	21	Gravel Island
Tern	10/16/82	21	Gravel Island
Mukluk	11/1/83	48	Gravel Island
Cross Island	11/2/83	0.5 - 8	Gravel Island
Seal	2/4/84	39	Gravel Island
Antares	11/1/84	49	CIDS[c]
Antares	1/19/85	49	CIDS[c]
Seal	2/22/85	39	Gravel Island
Hammerhead	8/10/85	103	Explorer II Drillship
Harvard	9/2/85	49	Gravel Island
Orion	11/10/85	50	CIDS[c]
Sandpiper/Harvard	2/8/86	49	Gravel Island
Mars	3/12/86	25	Ice Island
Corona	7/28/86	116	Explorer II Drillship
Phoenix	9/23/86	60	SSDC/MAT[d]
Hammerhead	9/27/86	107	Explorer II Drillship
Tern	2/10/87	22	Gravel Island
Aurora	11/2/87	66	SDC/MAT[b]
Belcher	9/5/88	167	Kulluk[e]
Fireweed	10/19/90	50	SCD/MAT[b]
Galahad	9/15/91	166	Explorer II Drillship
Cabot	11/1/91	55	SDC[b]
Kuvlum	8/22/92	110	Kulluk[e]
Kuvlum	7/28/93	96	Kulluk[e]
Kuvlum	9/7/93	107	Kulluk[e]
Wild Weasel	10/13/93	87	Kulluk[e]
Liberty	2/7/97	21	Gravel/Ice Island
Warthog	11/1/97	35	CIDS[c]
McCovey	12/6/02	35	SDC/MAT[b]
Planned Exploratory Wells			
Torpedo	2010	120	Frontier Discoverer Drillship
Sivulliq	2010	108	Frontier Discoverer Drillship

[a] Spud date is the date drilling was started
[b] SDC/MAT, steel drilling caisson or steel drilling caisson/drilling mat unit
[c] CIDS, concrete island drilling system
[d] SSDC/MAT, single steel drilling caisson/drilling mat
[e] Kulluk, an ice-reinforced conical drilling unit (CDU)..

Table 2-2 lists in chronological order the exploratory wells drilled to date or planned on the Federal outer continental shelf of the U.S. Chukchi Sea. Data from MMS, Alaska OCS Region, Anchorage, AK. Spud dates for the new wells are tentative because of ongoing litigation.

TABLE 2-2
Chronological Order of Exporatory Wells Drilled to Date or Planned in the U.S. Chukchi Sea

Prospect	Spud Date[a]	Water Depth (feet)	Drilling Unit
Klondike	7/9/89	141	Explorer III Drillship
Burger	9/22/89	149	Explorer III Drillship
Popcorn	10/14/89	143	Explorer III Drillship
Crackerjack	9/23/90	137	Explorer III Drillship
Diamond	9/7/91	152	Explorer III Drillship
Planned Exploratory Wells			
Burger/Posey (5)	2010	149	Frontier Discoverer
Crackerjack/Karo	2010	137	Frontier Discoverer
SW Shoebill/Karo	2010	150	Frontier Discoverer
Klondike/Devil's Paw	2012	140	Ice-strengthened jackup rig

The Burger exploratory well, drilled in the Chukchi Sea in 1989, discovered gas and condensate resources estimated at 7.6 to 27.5 trillion ft^3 and 0.393 to 1.404 billion barrels, respectively (Craig and Sherwood, 2004). The Klondike exploratory well discovered small oil plays at several depths. Two of the other three wells also discovered small plays of oil. The discoveries were not considered economic at the time, due mainly to low gas prices and logistic constraints in producing and transporting hydrocarbons from this remote area. However, there was considerable interest in the Chukchi Sea planning area in Lease Sale 193, held in February 2008. More than 5000 blocks were leased to 6 oil companies, including blocks in the five prospect areas where exploratory drilling occurred in 1989 to 1991.

Shell Gulf of Mexico, Inc. (SGOMI) and ConocoPhillips Alaska, Inc. (CPAI) are planning to drill new exploratory wells in the blocks they leased in Sale 193 over the next several years. CPAI plans to drill a well at Devil's Paw, a short distance north of the Klondike well drilled in 1989. Shell plans to drill up to five wells, three of them near the 1989 discovery well in the Burger prospect (SGOMI, 2009). The other two wells will be in the Crackerjack and SW Shoebill prospects (Table 2-2).

2.2.2 Development Drilling

Development drilling is a larger undertaking than exploratory drilling. Drilling of offshore production wells in cold-water environments may take place from fixed or floating, ice-reinforced platforms, including drill ships (e.g., Snøhvit in the Norwegian Barents Sea), or from artificial islands in shallow water (e.g., Northstar and Oooguruk in the Alaskan Beaufort Sea).

Several wells may be drilled from each fixed platform, sometimes with additional wells drilled from floating rigs, with subsea completions and tie-ins to the fixed platform. Production may be transported to shore through pipelines or via oil tanker. This is the development strategy currently being used for field development in the Norwegian, Barents, and Alaskan Beaufort Seas. One or two wells can be drilled at a time from a platform, and each well may require a few weeks to six months to drill. Full development of a field may involve one or several platforms, dozens of wells, and may take a few to as many as twenty years. Production may continue for twenty years or more. During production, maintenance drilling is required periodically. In development of a large field, the usual practice is to bring wells into production as they are drilled. Thus, drilling and oil and gas production go on simultaneously from an offshore platform during much of the life of an offshore field. For example, the Ekofisk field in the southern North Sea has been in production since 1971; production and maintenance drilling continue today (NPD, 2009).

Because of these differences, exploratory platforms (sometimes called rigs) and development/production platforms often have markedly different designs. Exploratory rigs usually are smaller than development platforms and, in the Arctic, may include ice islands, artificial gravel islands, and floating ice-resistant structures. The floating rigs can be moved from one drill site to another. The basic rig and platform designs developed for more temperate climates have been modified to withstand the harsh climatic and ice conditions of the Arctic.

Exploratory wells located in shallow water (20 to 50 ft) close to shore in the Alaskan and Canadian Beaufort Seas were drilled from man-made islands constructed from gravel and/or ice or from concrete island drilling system (CIDS) or steel drilling caisson/drilling mats (SDC/MAT) (Table 2-1; Figure 2-1). Gravel islands constructed for exploratory drilling usually are much smaller than those constructed for development/production facilities. Mukluk Island was just over half an acre, compared to five acres for the Northstar production facility and six acres for the Oooguruk drilling island (Figure 2-1). Most of these wells were drilled during the winter when ice was present, and were accessible from shore via ice roads. Further offshore in deeper (50 to 70 ft) water, exploratory wells were drilled from specialized bottom-founded drilling units such as concrete island drilling units (CIDS), single steel caisson systems (SSDC or SDC/MAT), or the single steel drilling caisson (SSDC), a converted tanker that sat on a reinforced steel platform and could be moved, allowing year-round drilling (McCracken et al., 2007) (Figure 2-1). Wells located in deeper water further offshore were drilled during the open-water season using ice-reinforced floating drill rigs such as the 24-sided conical drilling unit, the *Kulluk,* and the drillship *Frontier Explorer* (Figure 2-1).

Development drilling and production in subarctic regions usually are performed from large fixed or floating platforms or drillships. Subsea completions are becoming more common, particularly in deep water. These differences affect the magnitude of physical disturbance of the environment and the options available for management of drilling and production wastes (Farrow, 1990; Veldman and Lagers, 1997; CAPP, 2001; OGP, 2003). Exploratory rigs have a smaller footprint on the sea floor, usually are present at a particular location for a short time, and discharge much smaller amounts of liquid, solid, and gaseous wastes than production facilities. Exploration rigs, especially those several miles from land, also have less capacity to store wastes than production facilities. Drilling wastes from an offshore exploratory rig cannot be reinjected because there is

no reinjection well available at the site. Annular reinjection is not feasible for exploration wells on the Beaufort/Chukchi Sea OCS.

Figure 2-1 shows examples of drilling rigs used for exploratory drilling in Arctic waters of Alaska and Canada. Top left: the Oooguruk drilling island. Top right: the SDC/MAT used to drill the Paktoa-60 well in the Canadian Beaufort Sea. Lower left: the Kulluk drilling unit. Lower right: the *Frontier Discoverer* that Shell plans to use in the Beaufort and Chukchi Seas.

Figure 2-1 Examples of Drilling Rigs Used for Exploratory Drilling in Arctic Waters of Alaska and Canada

Only a few offshore production facilities have been constructed in the Alaskan Arctic Region. The Endicott, Northstar, Point McIntyre, and Oooguruk facilities are the only production facilities currently operating in the U.S. Beaufort Sea. All were constructed on gravel islands. The Liberty prospect will be developed by ultra-extended-reach drilling from and expansion of the existing Endicott satellite drilling island (BPXA, 2007).

Endicott was the first offshore production facility in the Alaskan Beaufort Sea (BPXA, 2004). Endicott is near the Tern prospect discovered and delineated in 1982-1987. The field was developed by BPXA with wells drilled from two man-made gravel islands located in 14 ft of water and connected to the mainland by an elevated causeway. Oil production began at Endicott in October 1987. Production began at Sag Delta North in 1989 and at Eider in 1998 through long-reach deviate wells from Endicott's main production island.

Northstar, the only Arctic development that is partly in Federal waters, was developed from a five-acre man-made gravel island at the site of the Seal Island prospect, discovered in 1984. The

production island is outside the barrier islands about 12 miles northwest of Prudhoe Bay and 6 miles offshore in about 40 ft of water. Island construction began in the winter of 1999-2000. Northstar is connected to onshore oil processing facilities by a double pipeline that was buried 7 to 11 feet below the seafloor to avoid damage from ice scour (PI/Dwights, 2004). First oil production was in 2001.

The Oooguruk facility was completed in 2008 and consists of three main components – an offshore drill site (Figure 2-1), an onshore interconnect and production support facility, and a system of flowlines, power cables, and communications cables connecting the onshore and offshore facilities. The offshore drill site is a six-acre artificial gravel island about 5.6 miles from shore with facilities for development drilling and field operations. Forty horizontal development wells will be drilled from the island, half of them for production and half for water injection.

The Liberty Prospect is inside the barrier islands east of Endicott about 6 miles offshore in Foggy Island Bay, in a water depth of about 22 ft (MMS, 2007b). It is approximately 30 miles southeast of the Northstar development and about 6 miles from the Endicott Causeway, near Tern Island. BPXA drilled the discovery well in the Liberty prospect in 1997. They plan to develop the Liberty Prospect with ultra-extended-reach drilling (uERD) from an expansion of the existing Endicott satellite drilling island (SDI) to about 6 miles offshore (BPXA, 2007). Six wells are planned, four producers and two injectors, in the initial phase of development. The wells will extend 6.4 to 8.1 miles from the drill site and to a vertical depth below the sea floor of about 2.1 miles (BPXA, 2007).

2.2.3 Development in Other Arctic Regions

There are ten fields in production and four fields under development in the Norwegian Sea. Draugen came on line in 1993 and gas production from Ormen Lange, both operated by Shell, began in 2007. Development is just beginning in the Barents Sea. Snøhvit is the only producing field in the Norwegian Barents Sea. The Goliat facility is under development (Norwegian Petroleum Directorate, 2009). There has been limited development to date of the large gas and oil discoveries in the Russian Barents, Pecora, and Kara Seas, because Russia currently is focusing on developing its large resources in Siberia (Austvik, 2006). There is active development of production facilities off Sakhalin Island, in the Russian Far East (SEICL, 2003; US Energy Information Administration, 2008).

Offshore development and production have been delayed in the Canadian Arctic by the high cost, complex regulatory environment, cultural and environmental concerns of the indigenous peoples, short seasons, and environmental concerns regarding building and operation of production and transportation systems to process the fossil fuel and get them to distant markets (CCEI, 2007). The only production in the Canadian Arctic was from the Bent Horn field in the Arctic Islands; crude oil was shipped by tankers from Bent Horn to east coast ports during the short summer shipping season from 1985 to 1996. A single tanker-load of crude oil also was shipped to Japan from the Amauligak well in 1986 following extended production testing. The producing oil and gas regions of Atlantic Canada are not actually in the Arctic Region. There has been extensive oil and gas development there since the mid-1990s. The Hibernia oil field is the largest offshore field in Canada and has been producing since 1997 (CCEI, 2007).

3.0 OFFSHORE DRILLING FOR OIL AND GAS IN THE ARCTIC REGION

3.1 Use and Composition of Drilling Muds

3.1.1 What are Drilling Muds?

The wastes generated in largest quantity during drilling exploratory and development wells are drilling muds (sometimes called drilling fluids) and drill cuttings. Drill cuttings are particles of crushed sedimentary rock produced by the action of the drill bit as it penetrates into the earth. Historically, most oil and gas wells drilled since about 1900 were drilled by the rotary drilling process (Allen, 1981). A drilling mud is an essential component of the rotary drilling process. The Lucas gusher at Spindletop, Texas, was drilled in 1901 with a rotary drill and a drilling mud consisting of a slurry of water, finely-ground rock chips (cuttings) from the hole, and clays from local surface soils. Blowouts, such as that at Spindletop, were common, because of the early state of our knowledge of drilling technology, well construction, and drilling mud formulation. Operators developed and introduced the first specially formulated drilling fluids for rotary drilling in 1913 to help lift the drill cuttings out of the hole and counteract the hydrostatic pressure in the geologic formation being drilled, decreasing the risk of a blowout (Neff, 1982).

Many tens of millions of research and investment dollars have been spent over the last century to improve the performance of drilling muds and to minimize their harmful effects in the environment (Gelb et al., 2006). Hundreds of drilling muds have been developed for rotary drilling, including water, or a mud-in-water slurry, oil, synthetic organic muds, brine-in-oil or synthetic emulsions, mists, and foams (Whittaker, 1985; OGP, 2003). Most modern drilling muds are mixtures of fine-grained solids, inorganic salts, and organic compounds in water or an organic liquid.

There are three major types of drilling muds (sometimes also called drilling fluids):

- **Water based drilling muds** (WBM): formulated mixtures of natural clays, organic polymers, weighting agents, and other additives suspended in fresh or salt water, or a saline brine;
- **Oil based drilling muds** (OBM): drilling muds in which the continuous phase is a refined petroleum product (usually diesel fuel or a low-aromatic mineral oil), in which water, weighting agents, emulsifiers, and other additives are dispersed; and,
- **Synthetic based drilling muds** (SBM): drilling muds in which the continuous phase is a synthetic organic chemical, in which water, weighting agents, salts, emulsifiers, and other additives are dispersed. The most frequently used synthetic chemicals are olefins, paraffins, and esters.

3.1.2 Development of Drilling Muds for Offshore Operations

The earliest drilling muds were WBM, and were composed mainly of clay (mud) and a weighting agent to counteract down-hole pressure. Because they did not perform well under some down-hole conditions, chemicals were added to the basic WBM formula to solve different

down-hole problems. Refined oil, usually as diesel fuel, which is used on offshore rigs for running electric generators and other machinery, often was added to lubricate the drill string and minimize differential pipe sticking or to help free stuck pipe. Adding oil to WBM also helped stabilize the wellbore wall, leading to the development of OBM to drill through difficult shale formations. OBM were widely used for drilling on land and for offshore drilling in some areas of the world. Used OBM usually were not discharged, but were separated from cuttings and returned to shore for reprocessing or disposal. However, cutings generated during drilling with OBM were discharged to the ocean in the North Sea, Canada, and several other offshore exploration and production areas.

Discharge of OBM and associated cuttings to U.S. State and Federal waters was prohibited by OCS order No. 7 in 1969; provisions of the Clean Water Act of 1977 amended this prohibition. The Clean Water Act gave EPA the authority to regulate waste discharges to fresh and marine waters. EPA has never permitted ocean discharge of OBM and OBM cuttings to U.S. territorial waters, limiting the use of OBM for offshore drilling in the US. EPA always has required that OBM and associated cuttings from offshore drilling be returned to shore for reprocessing or upland disposal.

The offshore oil and gas industry is challenged to achieve a balance between minimizing the potential environmental impact of operational waste disposal against project objectives. The cost of waste management is more than just the cost of collecting and disposing of waste streams and operators must consider the long-term liability of environmental and waste management decisions (Morton et al., 2005). The inherent technical advantages over WBM provided by OBM and SBM for drilling difficult deep or deviated wells through shale formations are increasingly being offset by environmental risks and liabilities. Beginning in the late 1970's, it became evident that waste discharges from drilling operations could have undesirable effects on the marine environment. Early field studies showed that environmental effects from discharging spent WBM and cuttings were much less than those associated with ocean discharge of OBM cuttings (NRC, 1983).

Experience in the North Sea revealed that diesel OBM cuttings were toxic and persistent in marine sediments (cuttings piles) near platforms (Davies et al., 1983; Kingston, 1987; Olsgard and Gray, 1995). Diesel was replaced in OBM by low-aromatic mineral oils in an effort to reduce harmful environmental impacts of cuttings discharge. Mineral oil OBM cuttings, even those containing no aromatic hydrocarbons, also were harmful to bottom-living biological communities near platforms. SBM were developed in the early 1990s to provide a less toxic alternative to OBM in an effort to minimize environmental harm from ocean discharge of cuttings (Neff et al., 2000). In SBM, the continuous phase is a low-toxicity, biodegradable, synthetic organic compound, usually an olefin or ester.

However, laboratory and field studies showed that the harmful effects of low-aromatic mineral oil OBM cuttings and SBM cuttings discharges to benthic communities were due primarily to sediment oxygen depletion caused by the biodegradation of the hydrocarbons in muds (Neff et al., 2000). OBM cuttings discharges are no longer permitted in Canada and the North Sea countries. Discharge of SBM cuttings to the North Sea has been phased out.

After several years of laboratory and field studies, the U.S. Environmental Protection Agency (EPA) developed specific regulations to manage the discharge of cuttings from SBM mud systems. The whole used SBM was not permitted for discharge; however, SBM cuttings were permitted for ocean discharge if the concentration of the synthetic chemical on cuttings did not exceed the concentration prescribed in the NPDES permit (6.9 weight % internal olefin or 9.4 weight % ester on wet cuttings). Current general National Pollution Discharge Elimination System (NPDES) permits for Federal waters of the Gulf of Mexico and Alaska allow ocean discharge of SBM cuttings if they meet Effluent Limitations Guidelines (ELG). The EPA regulations stimulated the offshore industry to develop new solids control technologies for the removal of excess SBM from the cuttings prior to discharge. At the inception of the new rules, technology could remove down to approximately 5% retained SBM on the cuttings. Modern technologies can clean cuttings to below about 2% retained synthetic chemical.

Numerous offshore studies worldwide have evaluated the environmental fates and effects of SBM cuttings (Neff et al., 2000; OGP, 2003). They have shown that, if local environmental regulatory practices are followed, environmental impacts are substantially less severe than those from OBM cuttings discharges. In most cases, SBM discharges affect only a slightly larger seafloor area than WBM and cuttings discharges. Recovery of benthic communities from the organic enrichment (sediment oxygen depletion) effects of the SBM cuttings often is rapid (Neff et al., 2005). EPA's decision to continue to allow discharge of SBM cuttings containing low concentrations of adhering synthetic chemical is based in large part on the results of these environmental studies.

Offshore SBM cuttings discharge also is permitted in Canada and the North Sea. However, the Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) (OSPAR, 2000b) issued new guidelines for ocean discharge of organic phase drilling fluids (OPF), including OBM and SBM, cuttings to the North Sea, calling for phase-out of OPF cuttings containing more than 1% adhering organic phase chemicals. This ruling was based in large part on the effects of the long history of routine discharge of OBM cuttings to the North Sea, without consideration of the better environmental performance of SBM cuttings. This effectively meant that no SBM cuttings could be discharged, because the solids control equipment could not meet these new limits. OPF cuttings discharges to offshore waters of OSPAR countries declined gradually to zero in 2005-2007 (OSPAR, 2009a, b).

Because of the high costs and concerns over the possible harmful effects of the ocean discharge of SBM and OBM cuttings enriched in organic matter, there is an ongoing research effort in the U.S., Canada, and the North Sea countries to improve the technical and environmental properties of WBM so that they can be used instead of OBM and SBM to drill difficult offshore formations and be discharged to the ocean or to land with minimal environmental harm. Because only WBM will be used to develop the proposed exploratory wells in the Beaufort and Chukchi Seas, the scientific literature on the fates and effects of OBM and SBM cuttings discharges will not be discussed further in this review. Fates and effects of OBM cuttings discharges have been reviewed by Davies et al. (1989) and of SBM discharges by Neff et al. (2000) and OGP (2003).

3.1.3 Functions of Water Based Drilling Muds

Modern drilling muds have several functions critical to the rotary drilling process. They include (Neff et al., 1987; OGP, 2003):

- **Counteract formation pressure.** The column of drilling mud in the drill pipe and annulus provides a hydraulic head (weight) that counteracts the pressure in the formations being drilled, preventing formation fluids from flooding the well bore, causing a blowout.
- **Remove cuttings from the borehole.** Jets of drilling mud exiting the drill bit carry drill cuttings away from the bit, preventing it from clogging, and convey them to the surface.
- **Suspend solids.** The drilling mud must have sufficient viscosity to suspend cuttings and weighting agent when drilling stops, as during addition of new lengths of drill pipe.
- **Cool and lubricate the drill string and drill bit.** Friction of the rotating drill string heats the drill pipe and, particularly the bit. Circulating drilling mud cools the drill string and lubricates it where contact is made with the formation or casing, at the drill bit, and in curved sections of deviated or horizontal wells.
- **Protect, support, and stabilize the borehole wall.** Some types of formation minerals, particularly shales, are sensitive to water and swell and slough off the side walls into the well bore during drilling, decreasing wellbore quality. WBM may contain additives to minimize shale swelling.
- **Protect permeable zones from damage.** Special drilling mud additives build a filter cake (a low-permeability layer of packed solids) on the walls of the well, preventing drilling mud loss into permeable formations, which may damage the formation and increase drilling costs.
- **Support part of the weight of the drill string.** The steel drill pipe is buoyed in the hole in proportion to the volume and density of the drilling mud displaced by the pipe in the annulus.

3.1.4 Composition of Water Based Drilling Muds (WBM)

WBM is a suspension of particulate minerals, dissolved salts, and organic compounds in freshwater, seawater, or concentrated brine. WBM ingredients can be divided into 16 functional categories (Table 3-1). Each functional category of additives may contain several alternative materials with slightly different properties. Because of strict regulations on the toxicity of WBM destined for offshore discharge (see Section 4), the mud engineer is encouraged to select or develop additives that combine good operational performance with low toxicity. Although more than 1,000 trade name or generic additives have been used in the past for drilling mud formulation, modern WBM rarely contain more than about 10 ingredients; most are added in small amounts to change mud properties to solve specific down-hole problems. Because different additives may be required to drill different sections or through different geologic formations of a well, the total inventory of drilling mud ingredients to drill all sections of a typical Arctic offshore exploratory well usually contains about 20 materials. The ingredients used in modern WBM are the least toxic in their functional category. The most abundant ingredients (other than water) in most WBM are weighting material, inorganic salts (in several functional categories), and a mud viscosifier (usually bentonite clay or a low-toxicity organic polymer) (Figure 3-1).

Table 3-1 defines the functional categories of materials used in WBM, their functions, and provides examples of typical chemicals in each category. From NRC (1983) and Boehm et al. (2001d).

TABLE 3-1
Functional Categories of Materials Used in WBM

Functional Category	Function	Typical Chemicals
Weighting Materials	Increase density (weight) of mud, balancing formation pressure, preventing a blowout	Barite, hematite, calcite, ilmenite
Viscosifiers	Increase viscosity of mud to suspend cuttings and weighting agent in mud	Bentonite or attapulgite clay, carboxymethyl cellulose, partially hydrogenated polyacrylamide (PHPA) & other polymers
Thinners, dispersants, & temperature stability agents	Deflocculate clays to optimize viscosity and gel strength of mud	Tannins, polyphosphates, lignite, lignosulfonates
Flocculants	Increase viscosity and gel strength of clays or clarify or de-water low-solids muds	Inorganic salts, hydrated lime, gypsum, sodium carbonate and bicarbonate, sodium tetraphosphate, acrylamide-based polymers
Filtrate reducers	Decrease fluid loss to the formation through the filter cake on the wellbore wall	Bentonite clay, lignite, Na-carboxymethyl cellulose, polyacrylate, pregelatinized starch
Alkalinity, pH control additives	Optimize pH and alkalinity of mud, controlling mud properties	Lime ($Ca(OH_2)$), caustic soda ($NaOH$), soda ash (Na_2CO_3), sodium bicarbonate ($NaHCO_3$), & other acids and bases
Lost circulation materials	Plug leaks in the wellbore wall, preventing loss of whole drilling mud to the formation	Nut shells, natural fibrous materials, inorganic solids, and other inert insoluble solids
Lubricants	Reduce torque and drag on the drill string	Silicate beads, water-based lubricants, synthetic liquids, graphite, surfactants, glycols, glycerin

Functional Category	Function	Typical Chemicals
Shale control materials	Control hydration of shales that causes swelling and dispersion of shale, collapsing the wellbore wall	Soluble calcium and potassium salts, other inorganic salts, and glycols
Emulsifiers & surfactants	Facilitate formation of stable dispersion of insoluble liquids in water phase of mud	Anionic, cationic, or nonionic detergents, soaps, organic acids, and water-based detergents
Bactericides	Prevent biodegradation of organic additives	Glutaraldehyde, triazine disinfectants
Defoamers	Reduce mud foaming	Alcohols, silicones, aluminum stearate, alkyl phosphates
Pipe-freeing agents	Prevent pipe from sticking to wellbore wall or free stuck pipe	Silicate beads, detergents, soaps, surfactants, water-based lubricants
Calcium reducers	Counteract effects of calcium from seawater, cement, formation anhydrites, and gypsum on mud properties	Sodium carbonate and bicarbonate (Na_2CO_3 & $NaHCO_3$) , sodium hydroxide (NaOH), polyphosphates
Corrosion inhibitors	Prevent corrosion of drill string by formation acids and acid gases	Amines, phosphates, specialty mixtures
Temperature stability agents	Increase stability of mud dispersions, emulsions and rheological properties at high temperatures	Acrylic or sulfonated polymers or copolymers, lignite, lignosulfonate, tannins

3.1.4.1 Weighting Materials

Barite (barium sulfate: $BaSO_4$) is a soft, dense (4.1 – 4.5 g/cm^3) natural mineral that is the most frequently used weighting material in drilling muds of all types (NRC, 1983; OSPAR, 2001). Drilling mud barite used offshore in the U.S. must be at least 92 weight % pure, have a specific gravity greater than 4.2 g/cm^3, contain less than 250 mg/kg soluble alkaline earth elements (as calcium), and 97 weight % must pass through a 75-µm screen, with no more than 30 % smaller than 6 µm in diameter (API, 1993). A slightly lower specific gravity (SG 4.1 – 4.2), high purity barite is replacing the denser barite as supplies of the denser barite diminish. Mineral impurities in barite include quartz (SiO_2), calcite ($CaCO_3$) , celestite ($SrSO_4$) , and hematite (FeO_3), all

abundant natural minerals in marine sediments (Bruton et al., 2006), as well as trace amounts of several metals (Table 3-2), mostly in the form of insoluble metal sulfides.

Figure 3-1 shows an example of the composition of a typical water based drilling mud (WBM) and of the additives to a typical WBM. Organic polymers may be used with or instead of bentonite as viscosifiers in WBM.

Figure 3-1 Composition of a Typical WBM and of Additives to a Typical WBM

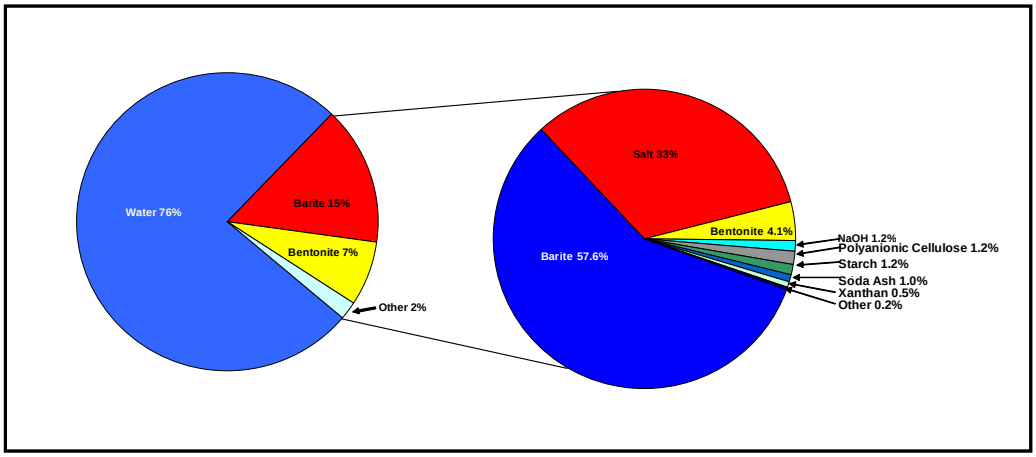


Table 3-2 shows the mean metals concentrations in high-purity drilling mud barite of the types used after 1993 in the U.S and North Sea (EPA set limits of 1 ppm mercury and 3 ppm cadmium in drilling mud barite in 1993), drilling muds from several depth intervals in two offshore, California, exploratory wells, drilled in 1992-1993 (Steinhauer et al., 1994; Phillips et al., 1998), and the range of concentrations in uncontaminated marine sediments (Neff et al., 1987). Concentrations are mg/kg dry wt (parts per million: ppm). Only barium (highlighted) sometimes is present in modern WBM at concentrations substantially higher (>100-fold) than concentrations in clean marine sediments.

TABLE 3-2
Mean Metals Concentrations of High-Purity Barite Used After 1993 in the U.S. and North Sea

Metal	Drilling Mud Barite	Water Based Drilling Mud	Marine Sediments
Arsenic (As)	1 – 2.2	4.4 – 10.0	4.2 - 26
Barium (Ba)	503,000	12,500 – 179,000	1 - 2000
Cadmium (Cd)	0.05 - 0.35	0.84 – 1.75	0.03 - 0.8
Chromium (Cr)	15 - 40	82 - 126	12 - 150
Copper (Cu)	86 - 98	24 - 38	7 - 50
Iron (Fe)	1600 – 24,800	0.002 – 27,000	7200 – 60,000
Lead (Pb)	18 - 318	2.3 - 40	2.8 – 33
Mercury (Hg)	0.05 - 0.44	0.08 – 0.15	0.003 – 0.2
Nickel (Ni)	1.2 – 3.8	39 - 51	6.0 – 48.4
Vanadium (V)	14 – 28	46 - 99	25 - 238
Zinc	35 - 1211	126 - 235	15 - 157

Because of concern about possible environmental effects of metals in drilling mud barite, EPA (1993) established a limit of 1 mg/kg (ppm) mercury and 3 ppm cadmium in barite added to WBM that might be discharged offshore. EPA considered that, by regulating these two metals of particular concern, they also would ensure that concentrations of other metals in barite would be acceptably low. Low trace metal barite is available in the U.S. for drilling muds used and discharged offshore (Bruton et al., 2006). The data in Table 3-2 are for low trace metal barite of the type used after the 1993 EPA guideline and for drilling muds discharged to the Gulf of Mexico, offshore California, Cook Inlet, and the Beaufort and Chukchi Seas.

The EPA guidelines on mercury and cadmium have been effective in reducing metals concentrations in drilling muds. Before 1993, concentrations of chromium, lead, and zinc sometimes were much higher (>100-fold) and concentrations of mercury and cadmium were moderately higher (<100-fold) in WBM than in uncontaminated marine sediments (Neff, 1987, 2005). North Sea drilling muds in particular often contained elevated concentrations of lead and zinc. Elevated chromium concentrations in drilling muds were almost exclusively from chrome lignosulfonate thinners frequently added to drilling muds. The current NPDES permit for offshore exploratory drilling in Alaska prohibits discharge of chromates in WBM and cuttings. Although the chromium in chrome lignosulfonate is in the less soluble and toxic chromic valence state, operators in the U.S. and North Sea countries have voluntarily replaced chrome-based thinners with chrome-free products. The chromium concentration in most modern WBM is similar to that in marine sediments (Table 3-2).

The North Sea countries have been encouraged to replaced high trace metal barite with clean barite or ilmenite (iron titanium dioxide) and have adopted the use of metal-free pipe thread compound to reduce concentrations of lead and zinc in drilling muds. The only element (barium is an alkaline earth element, not a metal) that is present frequently in modern WBM at very high concentrations is barium (as barite weighting agent) (Table 3-2).

Metals concentrations usually were low in U.S. offshore WBM, even before EPA imposed limits of mercury and cadmium in drilling mud barite. For example, the different types of WBM used for exploratory drilling in the U.S. Beaufort Sea between 1979 and 1983 contained low concentrations of cadmium and mercury; some of these drilling muds contained slightly elevated concentrations of chromium, probably from chrome lignosulfonate (Table 3-3).

Concentrations of lead or zinc also were elevated in some drilling muds (Table 3-3). Some of the copper, lead, and zinc in these older WBM, may have come from corrosion inhibitors/sulfide scavengers, such as zinc carbonate and zinc sulfonate, added intentionally to the drilling muds, or from drill pipe dope and drill collar compound, used to lubricate the joints in the drill pipe (Ayers et al., 1980b). Some pipe dope may get into the drilling mud and be discharged with the mud and cuttings. Older types of pipe dope and pipe thread compound contained percent concentrations of metallic copper, lead, and zinc, to ensure electrical conductivity between lengths of drill pipe. These metal-containing components have largely been replaced for offshore drilling with additives that do not contain elevated concentrations of metals (OLF, 2007).

Hematite (iron oxide: Fe_2O_3) occasionally is used instead of barite to prepare a high-density WBM for use in deep drilling (Chénard, 1984). It is a red powder with a density of 5.3 g/cm^3. Mineral impurities in hematite include quartz, rutile, and pyrite.

Table 3-3 list the concentrations of several metals in WBM used for drilling five exploratory wells in the Alaskan Beaufort Sea between 1979 and 1983. The different WBM for Reindeer Island were used at different depth intervals between 5000 and 13,700 ft below the surface. WBM discharged at Mukluk and Tern Island were seawater-lignosulfonate and XC-polymer muds, respectively. The WBM discharged at Sag Delta 8 and Challenge Island was not specified. Concentrations are mg/kg (ppm). Data from NTS (1981, 1982, 1983, 1984).

TABLE 3-3
Concentration of Several Metals in WBM used for Five Exploratory Wells in the Alaskan Beaufort Sea 1979-1983

Type/Location	Barium	Cadmium	Chromium	Copper	Lead	Mercury	Zinc
Reindeer Island							
CMC/Gel	4,400 - 6240	<0.5 - 0.6	28 - 63	6.4 - 10.4	2.4 - 13	0.017 - 0.031	42 - 64
XC-Polymer	720 – 1,170	<0.01 - 1.5	66 - 176	10 - 16	5.6 - 56	0.015 - 0.070	48 - 64
XC-Polymer/Unocal	NA	NA	56 - 125	2.8 - 17	9 - 117	0.028 - 0.217	198 - 397
Lignosulfonate	800 - 7640	<0.01	121 - 172	10 - 12	16 - 56	0.03 - 0.07	49 - 56
Sag Delta 8	60,000	0.28	19.0	19.0	20.0	<0.01	380
Challenge Island	200,000 - 360,000	0.2	590 - 1300	14 - 17	17 - 20	0.04 - 0.08	95 - 140
Mukluk	9,520 - 33,200	0.19 - 0.20	9.2 - 10			0.06 - 0.08	
Tern Island	113 - 259,000	1.7	28 - 37	13	16 - 106	<0.1	130

OSPAR (2004b) has included ilmenite (iron titanium oxide: $FeTiO_3$) on the ***List of Substances/Preparations Used and Discharged Offshore That Are Considered to Pose Little or No Risk to the Environment*** (the PLONOR list) to encourage its use as a replacement for impure barite in drilling muds discharged to the North Sea. Barite was retained on the list to

allow operators the choice of using low trace metal barite or ilmenite as a weighting agent. The PLONOR list is part of a ranking system for the relative environmental hazard of chemicals used and discharged offshore in the northeast Atlantic (see discussion in Section 4). OSPAR made this recommendation because of concern about possible environmental impacts of metals sometimes found in low grade barite. Ilmenite has a density of 4.5 to 5.0 g/cm^3 and usually contains lower concentrations than barite of most metals, though concentrations of some metals, particularly nickel and zinc, may be higher in ilmenite (Fjogstad et al., 2002). However, metals in both barite and ilmenite are present in extremely low-solubility forms that do not leach into seawater where they could bioaccumulate and harm marine organisms (Neff, 2008). Barite is a softer mineral than ilmenite and hematite and, therefore, does not abrade pumps, valves, impellers, mixing equipment, and other components of the drilling mud system, as these alternative weighting agents do. Hematite and ilmenite apparently are not used currently in U.S. offshore WBM.

Large amounts of barite are used in drilling muds, particularly when drilling deep wells or penetrating geopressured strata. The amount of barite added to drilling mud generally increases from about 0.05 lb/gal near the surface to as much as 17 lb/gal near the bottom of a deep well (NRC, 1983). It is possible, by use of barite, to produce a WBM weighing up to about 19 lb/gal, more than twice the density of water (Hudgins, 1991). This weight is used to counteract the pressure of the formation being drilled, preventing a blowout.

The average amount of barite in drilling muds used to drill wells offshore in the U.S. Gulf of Mexico increases with well depth from about 61,200 lbs for wells to a depth below the sea floor of 5,000 ft to more than 800,000 lbs for wells greater than 10,000 ft deep (Boehm et al., 2001d). The average amount of barite discharged from 559 shallow water (<1000 ft) wells drilled in the Gulf of Mexico in 1998 was 583,000 lbs/well (Table 3-4).

3.1.4.2 Viscosifiers and Filtrate Reducers

Clay and/or an organic polymer may be added to drilling mud to maintain the gel strength (viscosity) required to suspend and carry drill cuttings to the surface. Bentonite clay (sodium montmorillonite) and polymer viscosifiers are the second most abundant ingredients in most WBM (Figure 3-1; Table 3-4). Bentonite clay is very abundant in natural marine sediments, representing between 15 and 55 % of the clay fraction (<2 µm grain size) of marine sediments throughout the world (Griffin et al., 1968). Clays similar to those in WBM are major components of the sediments delivered to the Beaufort Sea each spring in river runoff (Rember and Trefry, 2004). The three major rivers between Harrison Bay and Camden Bay (the Sagavanirktok, Kuparuk, and Coleville Rivers) and coastal erosion deliver approximately 6.9 million tons (14 billion pounds) of fine-grained sediments to the coastal Beaufort Sea each year, mainly in a few weeks in the spring. By comparison, the 30 exploratory wells drilled in the Beaufort Sea between 1981 and 2002 (Table 2-1) discharged approximately 2,000 tons (4 million lbs) of WBM and cuttings solids, about 0.3% of the solids delivered to the Beaufort Sea during a few weeks each spring in river runoff and coastal erosion.

Bentonite forms a thixotropic gel in the well bore. A thixotropic gel becomes fluid when stirred or shaken and returns to a semi-solid state upon standing. The sheer from the rotation of the drill string and bit liquefy the bentonite slurry, facilitating mud pumping. When drilling stops, the

bentonite gels, preventing suspended cuttings and barite from settling out and clogging the annulus. A few WBM additives are used to optimize these properties of the clay.

Bentonite also is used as a filtrate reducer (Table 3-1). The clay coats the walls of the well bore with a low-permeability filter cake, decreasing loss of fluids from the drilling mud into the geologic formation. However, more than 75% of formations drilled are shales; shales cause more than 90% of wellbore instability problems (Schlemmer et al., 2003). Many shales, which are sedimentary rocks formed by high-pressure compaction of silt-clay sediments, absorb water from the WBM, causing the shale to swell and disintegrate, damaging the wall of the well. This problem can be solved by use of OBM or SBM. However, if environmental concerns dictate use of WBM, all or some of the bentonite can be replaced by one or a combination of several water-soluble organic polymers, including carboxymethyl cellulose (CMC), xanthan gum, and partially hydrolyzed polyacrylamide (PHPA). Sodium or potassium chloride/PHPA muds have been used extensively in the Gulf of Mexico, Beaufort Sea, Arctic and Atlantic Canada, and the North Sea for drilling difficult expandable shale formations (Schlemmer et al., 2003). Shell and ConocoPhillips are proposing to use salt water/PHPA drilling muds to drill lower sections of their exploratory wells in the Beaufort and Chukchi Seas (SGOMI, 2009; SOI, 2009; CPAI, personal communication).

Table 3-4 lists masses of solid and volumes of liquid drilling mud ingredients discharged to the Gulf of Mexico in shallow (<1000 ft water depth) offshore drilling operations in 1998. From Boehm et al. (2001d).

TABLE 3-4
Masses of Solid and Volumes of Liquid Drilling Mud Ingredients in GOM in Shallow Water in 1998

Functional Category	Total for 559 Wells	Mean/Well
Weighting Materials (lbs)	326,000,000	583,000
Viscosifiers (lbs)	46,500,000	83,200
Thinners, dispersants, & temperature stability agents (lbs)	8,850,000	15,800
Filtrate reducers (solid & liquid) (lbs)	7,700,000	13,800
Alkalinity, pH control additives & calcium reducers (lbs)	13,200,000	23,600
Lost circulation materials (lbs)	11,700,000	20,900
Lubricants (gal)	183,000	327
Shale control materials (liquids) (gal) Shale control materials (solids) (lbs)	1,210,000 6.660,000	2170 1190
Emulsifiers & surfactants (gal)	150,000	268
Bactericides (gal)	850	1.5
Defoamers (gal)	17,000	17000
Scale inhibitors (gal)	584	30
Total solids (lbs)	420,000,000	750,000
Total liquids (gal)	1,560,000	2790

Starch and starch derivatives, such as xanthan gum and guar gum, are polysaccharide polymers derived from plants and are used frequently in WBM (OSPAR, 2001). These water-soluble polymers are used to increase the viscosity and solids carrying capacity of the drilling mud and to reduce shale swelling in the well bore (Hudgins, 1991). Drilling muds containing polysaccharide polymers usually are treated with biocide (disinfectant) to inhibit microbial degradation of the polysaccharides. The biocide currently used most frequently for this purpose is glutaraldehyde, a widely-used disinfectant in hospitals (Miner et al., 2009), that degrades rapidly and is not persistent in the environment. Shell (SOI, 2009; SGOMI, 2009) is planning to use a saturated brine/PHPA WBM with a high pH (~10.5) to drill deeper sections of its exploratory wells in the Beaufort and Chukchi Seas. The combination of high salt and pH will inhibit bacterial growth, reducing or eliminating the need to use glutaraldehyde disinfectant.

3.1.4.3 Thinners and Dispersants

As well depth increases, it is necessary to add more weighting agent to the drilling mud to counteract down-hole pressure. More bentonite or polymer has to be added to support the added weight of the barite and lift it and the cuttings out of the hole. Addition of barite, and bentonite to the mud increases its viscosity, increasing the pressure needed to pump it, increasing the risk of loss of water and drilling solids to the formation. Various thinners or dispersants are added to bentonite WBM to decrease viscosity, improving pumpability. They usually act by binding to the charged surfaces of clay platelets, preventing them from clumping together (flocculate). Lignosulfonates, lignites, and tannins were for many years the most frequently used thinners for offshore bentonite-based WBM. However, modern polymer muds, even those containing some bentonite, usually do not require much thinner.

Lignosulfonates are organic polymers derived from the lignin of wood and are byproducts of the pulp and paper industry (Hudgins, 1991). When bonded with certain inorganic ions, such as chromium, iron, or calcium, at an alkaline pH, they are effective in preventing flocculation of clays. They are most effective at alkaline pH, requiring addition of sodium hydroxide (NaOH). Although chrome lignosulfonates are the most effective thinners, they no longer are used for offshore WBM because of a ban on discharge of chromate in current permits, base on concern about the possible toxicity of the chromium. The chrome in chrome lignosulfonate is in the less soluble and toxic trivalent, chromic state. However, inorganic chromate salts sometimes are added to chrome lignosulfonate muds to stabilize the lignosulfonate at high temperatures in a deep hole. Lignosulfonates also are good emulsifiers and aid in control of fluid loss to the formation. If a lignosulfonate is required to solve a particular drilling problem, one of several chrome-free lignosulfonates can be used.

Chrome lignosulfonates, often including added chromate, are considered the most toxic components of most WBM that do not contain added refined petroleum (Conklin et al., 1983). Therefore, the U.S., Canada, and North Sea oil industries usually replace chrome lignosulfonates with iron or calcium lignosulfonates or other deflocculents, or use polymer viscosifiers that do not require lignosulfonate thinners in WBM for drilling offshore wells (Frost et al., 2006).

Lignite (a soft brown coal), applied as a fine powder, also is used as a clay deflocculation and filtration control agent. An oxidized lignite, called leonardite, composed primarily of degraded humic acids, is used most frequently in WBM (Hudgins, 1991). Leonardite also is a high-quality

soil amendment, used to improve yields of vegetable crops (Burdick, 1965). Humic acids are natural organic components in soils and sediments, formed from natural microbial degradation of plant materials; they have a low aqueous solubility and help to control fluid loss to the formation.

3.1.4.4 Other Drilling Mud Additives

A wide variety of other additives is available for changing the physical/chemical properties of a drilling mud so that it will function optimally during well drilling and will not harm the marine environment if discharged (Hudgins, 1991) (Table 3-4). Only a small number of these additives are still used in WBM; the toxic additives have been eliminated or replaced with non-toxic chemicals to ensure that the WBM will meet the stringent toxicity limitations in the discharge permit.

Sulfonated salts of asphalt or gilsonite (a natural asphaltic material) may be added in small amounts to WBM to control fluid loss to permeable formations. Soltex is a commercial form of sodium asphalt sulfonate that is added to some WBM to stabilize shale formations, reduce permeability of the well bore, and increase lubricity of the drilling mud. Asphalt is derived from the residual fraction produced by refining crude oil. Asphalts are composed mainly of resins and asphaltenes, high molecular weight hydrocarbon polymers that are not soluble or toxic. Because these sulfonated compounds sometimes contain traces of polycyclic aromatic hydrocarbons (PAH) (Stout and Emsbo-Mattingly, 2008) tightly bound to the insoluble organic matrix, they have been replaced in most modern WBM with non-toxic plant or synthetic polymers.

In the past, lubricants, including diesel fuel and vegetable or mineral oils, sometimes were added to WBM to reduce torque and drag on the drill string, particularly when drilling a deviated well. They usually were added periodically during drilling at concentrations between 5,000 and 150,000 mg/L. Occasionally, the drill pipe became stuck in the hole. The mud engineer often attempted to free the stuck pipe by adding a slug or pill of an OBM to the WBM and pumping it into the area where the pipe was stuck. The OBM pill sometimes contained as much as 60% diesel or mineral oil (Neff et al., 1987). After the stuck pipe was freed, the OBM pill usually was recovered and separated from the WBM system and disposed of on land. Sometimes, the OBM pill, representing a small fraction of the total mass of the mud in use, was allowed to mix completely with the WBM.

EPA (1993, 1996) banned the discharge to the ocean of drilling muds containing diesel fuel or free oil. As a result, OBM, diesel fuel, and mineral oil pills are no longer added to WBM destined for ocean disposal. Modern polymer WBM have substantially higher lubricity than standard bentonite (gel) muds, and so lubricants are not required as frequently.

When an OBM is required to solve a particular down-hole problem, the OBM and cuttings are recovered and sent to shore for onshore recycling or disposal. OSPAR Decision 2000/3 (OSPAR, 2003) allows the discharge to the North Sea of cuttings with oil concentrations below 1%. Although new technologies have been developed and are in use that clean the cuttings down to concentrations below this limit (Garland, 2005; OSPAR, 2009a, b), the current practice in the North Sea countries is to replace petroleum-based lubricants in WBM with oil-free alternatives.

Water-soluble emulsifiers often were added to WBM containing hydrocarbon lubricants to disperse the oil in the water phase of the mud (Hudgins, 1991). They included fatty acids, sulfonates, and polyoxylates, some of which may have contributed to the toxicity of the drilling mud. Alkylphenol polyethoxylates (APEO) were used in the past as emulsifiers and cuttings cleaners in North Sea OBM. However, the octylphenol and nonylphenol degradation products of APEOs are endocrine-disruptor toxicants and, for this reason, these emulsifiers were banned by OSPAR and replaced with less toxic products for drilling and production offshore in the North Sea (Getliff and James, 1996). Most modern WBM do not contain high concentrations of insoluble organic compounds, so emulsifiers rarely are needed.

3.1.4.5 Metals

Several metals are present in most WBM (Table 3-2). The metals of greatest concern, because of their potential toxicity and/or abundance in drilling fluids, include arsenic, barium, chromium, cadmium, copper, iron, lead, mercury, nickel, and zinc (NRC, 1983: Neff et al., 1987, 2000). A few of these metals were added intentionally in the past to drilling muds as metal salts or organo-metallic compounds, such as ferrochrome lignosulfonate. Others are present as trace impurities in major mud ingredients, particularly barite and clay (Tables 3-2 and 3-5).

Table 3-5 shows the concentrations of metals in drilling mud bentonite and chrome and ferrochrome lignosulfonate. Concentrations are mg/kg dry wt (ppm). Data from Neff (1982).

TABLE 3-5
Concentrations of Metals in Drilling Mud Bentonite and Chrome/Ferrochrome Lignosulfonate

Metal	Bentonite Clay	Chrome/Ferrochrome Lignosulfonate
Arsenic (As)	0.7	NA
Barium (Ba)	ND - 560	NA
Chromium (Cr)	1.3 - 3.0	925 - 39,100
Cadmium (Cd)	ND - 0.6	ND - 1.4
Copper (Cu)	ND	ND - 11
Iron (Fe)	NA	1250 - 36,700
Mercury (Hg)	ND - 0.2	NA
Lead (Pb)	ND - 22	ND - 10
Zinc (Zn)	31 - 57	1.2 - 17

NA, Not analyzed; ND, Not detected.

The metals that sometimes were present in WBM used before 1993 at concentrations substantially (>100-fold) greater than natural concentrations in marine sediments are barium, chromium, lead, and zinc (Neff, 2005). Mercury and cadmium sometimes also were present at elevated concentrations in U.S., Canadian, and North Sea drilling muds; they were derived primarily from contamination of drilling mud barite (Neff, 2002b; Trefry and Smith, 2003). With wider use of low-trace-metal barite for drilling muds, average mercury and cadmium

concentrations in WBM have declined, though concentrations sometimes are slightly higher than natural concentrations in clean marine sediments.

The most abundant metal in most WBM is barium (an alkaline earth element like calcium and magnesium). Nearly all the barium in drilling mud is from barite ($BaSO_4$) added to the mud to increase its density. Clays and clay-rich shales may contain high concentrations of barium. Barite also may be abundant in fine-grained marine sediments, with concentrations as high as 2000 ppm in some sediments, particularly in deep water.

Iron and aluminum, although present at high (often percent) concentrations in WBM, rarely are more abundant in WBM than in natural silt/clay sediments. Clays are aluminum polysilicates containing variable amounts of iron and alkaline earth elements, such as calcium, magnesium, strontium, and barium. Iron is abundant in marine sediments as insoluble iron oxides or iron sulfides. Barite also often contains elevated concentrations of aluminum and iron.

Frequently in the past, chromium was the only metal other than barium that was detected at elevated concentrations in sediments near drilling waste discharge locations (Neff et al., 1989). When present at elevated concentrations, compared to concentrations in clean sediment, drilling mud chromium is derived primarily from chrome- or ferrochrome-lignosulfonates added intentionally to the mud for viscosity control. Chromate salts often were added to a chrome lignosulfonate mud to stabilize the lignosulfonate at high temperatures. Barite and bentonite clay may also contain traces of chromium. Although EPA has not limited discharge of WBM containing chrome lignosulfonate, it does prohibit discharge of wastes containing sodium chromate or sodium dichromate (EPA, 2006). The oil industry in the U.S and North Sea are voluntarily phasing out use of chrome- and ferrochrome-lignosulfonates in WBM destined for offshore disposal. Chrome lignosulfonates no longer are used in drilling muds on the Norwegian continental shelf (Frost et al., 2006) and will not be used in the WBM for drilling exploratory wells in the Beaufort and Chukchi Seas (SOI, 2009; SGOMI, 2009; CPAI, personal communication).

Most of the other metals sometimes detected in drilling muds are present primarily as trace impurities in barite, clay, or the drill cuttings in the formation penetrated by the drill bit. The most abundant metals in barite are barium, lead, zinc, and iron (Table 3-2); some barites also may contain slightly elevated concentrations of chromium or mercury. Concentrations of all these metals in the high-grade barite used today are similar to those in clean, fine-grained marine sediments.

Lead, zinc, and copper also may enter drilling mud in pipe thread compound (pipe dope) or drill collar dope used to lubricate the threads and promote electrical conduction between pipe sections (Ayers et al., 1980b). The dopes contain several percent metallic metals; some of the dope gets into the drilling mud, contaminating it. These metal-rich drilling chemicals were replaced by metal-free compounds for drilling of production wells in the Snøhvit gas field in the Norwegian Barents Sea (Rød, 2009). This will be the practice for future offshore exploratory drilling in Arctic Alaska.

Sulfide may accumulate in drilling muds from the formation being drilled or from bacterial degradation of organic components, particularly carbohydrate gelling agents, in the mud. The

usual method for removing sulfide from drilling mud is with inorganic sulfide scavengers. These scavengers react with both H_2S and HS^- to produce insoluble metal sulfide salts. The most frequently used sulfide scavengers in drilling muds are iron oxides, zinc oxide, and basic zinc carbonates (OSPAR, 2001; Neff, 2005). These metal salts react with sulfides to form insoluble iron sulfide (FeS_2) and zinc sulfide (ZnS), respectively. These metal-containing substances have largely been replaced for offshore drilling with additives that do not contain elevated concentrations of metals (OLF, 2007). If the sulfides are being produced by sulfide-reducing bacteria in the mud system, the mud may be treated with a disinfectant, such as glutaraldehyde, or sodium chloride concentration and pH may be increased to inhibit bacterial growth.

3.1.4.6 WBM Proposed for Exploratory Drilling in the Beaufort and Chukchi Seas

SOI (2009) has estimated that approximately 22,000 gallons of WBM will be used to drill the Sivullik N and Torpedo N exploratory wells off Camden Bay. SGOMI (2009) also expects to use between 25,000 and 27,000 gallons of WBM to drill each of its planned exploratory wells in the Chukchi Sea. CPAI has not filed its Exploration Plan for the Chukchi Sea, so estimated WBM use is not available. It probably will be about the same as the Shell estimate for their exploratory wells in the Chukchi Sea.

The two Shell Outer Continental Lease Exploration Plans for the Beaufort Sea and Chukchi Sea (SOI, 2009; SGOMI, 2009) and the drilling fluids proposals prepared for Shell by MI SWACO and IFE (MI SWACO, 2009) provide estimates of the types and quantities of drilling muds and drilling mud additives that will be used for exploratory drilling (Tables 3-6 and 3-7).

The first step in drilling each exploratory well in shallow Arctic waters is construction of a mudline cellar (MLC). A 36-in pilot hole is first drilled to about 60 ft. Then, the MLC is constructed to about 40 ft with a 20-foot-diameter drill bit and sediments are washed out of the hole with seawater and an airlift system. The 36-inch bit then drills to 200 to 360 ft to set the 30-inch structural pipe. The 26-in. hole is drilled from below the 30-in structural pipe to approximately 1200 ft with seawater and occasional sweeps of high-viscosity gel mud containing mainly bentonite clay. The remainder of each well is drilled with seawater- or saturated brine-PHPA drilling muds, the composition of which is changed slightly to control conditions in the formations being drilled, mainly by adding more barite weighting agent, as the well is drilled deeper. The main ingredients of a saturated brine/PHPA drilling mud are sodium chloride (table salt), barite, and partially hydrolyzed polyacrylamide polymer PHPA (Table 3-7). A specially-formulated heavy WBM (12 to 13 lb/gal) is kept on the drillship in case unexpected high pressure gas is encountered during drilling of shallow sections of the well.

Several contingency additives are kept on board the drill ship to use, if needed, to solve down-hole problems, such of loss of drilling fluids to the formation, or an increase in the viscosity of the drilling mud due to clay from the formation (Table 3-7). All the chemical additives proposed for drilling and for contingency are natural products or synthetic chemicals that were chosen or developed to combine optimum performance in drilling the formation with characteristics that ensure low toxicity to Arctic marine organisms in the Beaufort and Chukchi Seas.

KCl/polymer drilling muds, similar to those proposed for exploratory drilling in the Beaufort and Chukchi Seas, were used to drill the Tern Island, Reindeer Island, and probably several other exploratory wells in the Beaufort Sea in the early 1980s (NTS 1981, 1983). The KCl has been replaced by seawater or sodium chloride brine because the KCl drilling muds sometimes do not pass the toxicity test required by the NPDES permit. However. KCl is the second most abundant natural salt in seawater and a KCl mud would be diluted to a completely non-toxic concentration by the time it exited the discharge pipe.

Table 3-6 lists the proposed drilling mud program for exploratory wells that Shell plans to drill from the *Frontier Discoverer* off Camden Bay in the Beaufort Sea. Concentrations are in pounds/gallon of WBM. Data from MI SWACO (2009), SOI (2009), and SGOMI (2009).

TABLE 3-6
Proposed Drilling Mud Program for Shell Exploratory Wells, Camden Bay, Beaufort Sea

WBM Type	Depth Interval (ft)	Ingredient	Function	Concentration (lb/gal)
Mud Line Cellar Sweep (20'/36" Interval) (Mud wt 8.6 lb/gal)	0-365	Seawater	Sweep sediment from 36" surface section	--
Seawater/Sweeps (26" Interval) (Mud wt 8.5 lb/gal)	365[a]-1200	Freshwater[b]	Base fluid	---
		MI-WATE	Weighting agent	0.48
		Mi-I Gel	Viscosifier	0.60 – 0.71
		Duo-Vis	Viscosifier	0.02
		Poly Pac-R	Fluid loss control	0.006
		Soda ash	Precipitate calcium	0.006
		Gelex	Viscosifier	As needed for extra viscosity
Seawater/PHPA Mud (17.5", 12.25", 8.5" Intervals) (Mud wt., 10.0-12.5)	1200–10,200	Seawater or brine[c]	Base fluid	---
		MI-WATE	Weighting agent	2.14 – 3.2
		Soda ash	Precipitate calcium	0.006 – 0.01
		Poly Plus RD	Filtration control	0.02 – 0.04
		Duo-Vis	Viscosifier	0.02
		SP-101	Filtration control	0 - 0.05
		Poly Pac UL	Filtration control	0.01 - 0.36
		Caustic soda	Alkalinity control	For a steady 8.5 pH[c]
		Myacide-GA25	Biocide	As needed to control bacteria (~0.005)[c]
Kill Weight Mud (mud wt 12.5-13 lb/gal)	All depth intervals If needed	Seawater	Base fluid	---
		MI-WATE	Weighting agent	3.14
		Mi-I Gel	Viscosifier	0.12
		Duo-Vis	Viscosifier	0.05
		Poly Pac-R	Fluid loss control	0.12
		Myacide-GA25	Biocide	As needed to control bacteria

[a] The mud line cellar (MLC) and the ~220 ft of 36-in hole will be drilled with seawater only.
[b] Freshwater is used initially to speed hydration of the bentonite clay.
[c] Shell may use a saturated brine/PHPA drilling mud at high pH. This mud will suppress bacterial growth, reducing or eliminating the need for biocide. The pH will be lowered to the 8.5 pH limit required by the NPDES General Permit before discharging mud and/or cuttings to the sea.

Table 3-7 lists the chemical composition of additives proposed by Shell for drilling exploratory wells in the Beaufort and Chukchi Seas. Additional contingency additives also are listed. They are stored on the drilling platform to use as needed to solve down-hole drilling problems. Data from MI SWACO (2009).

TABLE 3-7
Chemical Composition of Additives Proposed for Drilling Exploratory Wells in the Beaufort and Chukchi Seas

Additive	Function	Chemical Composition
MI-WATE	Weighting agent	SG 4.1 Barium sulfate ($BaSO_4$)
M-I Gel	Viscosifier	Bentonite clay
Duo-Vis	Viscosifier	Xanthan gum
Gelex	Barite extender, thinner	Polyacrylate/polyacrylamide
Poly Pac R	Fluid loss control	Polyanionic cellulose
Poly Pac UL	Fluid loss control	Low-viscosity polyanionic cellulose
Poly Plus RD	Fluid loss control	Powdered high molecular weight partially hydrolyzed polyacrylamide polymer
SP-101	Fluid loss control	Sodium polyacrylate
Myacide-GA25	Bactericide	25% Glutaraldehyde
Soda ash	Raise pH, precipitate calcium	Sodium carbonate (Na_2CO_3)
Caustic soda	Alkalinity control	Sodium hydroxide (NaOH)
Contingency Additives		
Salt	Increase salinity of base fluid	NaCl
Sodium bicarbonate	pH control	Sodium bicarbonate ($NaHCO_3$)
Lime	Raise pH	Calcium hydroxide ($Ca(OH)_2$)
Citric acid	Lower pH	Carboxilic acid ($C_6H_6O_7$)
Defoam-X	Reduce foaming of fluids	Glycol blend surfactant
Nut Plug	Lost circulation control	Ground walnut shells
MIX-II	Lost circulation control	Ground cellulose, calcium carbonate mix
Tannathin	Thinner, lost circulation control	Oxidized tannin – from tree bark
Resinex II	Lost circulation control	Resinated lignin
Spersene CF	Mud thinner	Cr-free lignosulfonate
Durogel	Viscosifier, filtration control	Disodium pyrophosphate ($Na_2H_2P_2O_7$)

3.2 Drill Cuttings

3.2.1 What are Drill Cuttings?

Drill cuttings are particles of crushed rock produced by the grinding action of the drill bit as it penetrates into the earth (Neff et al., 1987). Drill cuttings range in size from clay-sized particles (~ 2 μm) to coarse gravel (> 30 mm) and have an angular configuration.

3.2.2 Mineral Composition of Drill Cuttings

The chemical and mineral composition of cuttings reflects that of the sedimentary layers being penetrated by the drill. The cuttings separated from drilling muds on an exploratory rig on the Mid-Atlantic outer continental shelf contained about 50% of 4 types of clay, 23% quartz, with the remainder composed of small amounts of six other natural minerals, mostly carbonates (NRC, 1983). Cuttings from wells drilled in the North Sea typically are composed primarily of sandstone and shale (Gerrard et al., 1999). The sedimentary rocks underlying the continental shelf off the Alaskan Beaufort and Chukchi Seas, including the Northstar production facility are predominantly sandstones, containing mainly quartz and small amounts of feldspars (alumino-silicate minerals that make up about 60% of the earth's crust) and clay. Silica and carbonate minerals also are abundant at some depths (MMS, 2006a). Thus, cuttings generated during the proposed exploratory drilling programs probably will resemble the local marine sediments and the sediments being eroded from the coast or transported to the sea by rivers.

3.2.3 Chemical Composition of Drill Cuttings

Drill cuttings contain, in addition to formation solids, small amounts of liquid and solid drilling mud components. The amounts of drilling mud solids that remain attached to cuttings vary, depending on the grain size of the crushed rock from the strata being drilled. Clay sized cuttings are more difficult than larger cuttings to separate from drilling mud. A typical cuttings discharge during drilling with WBM usually contains 5 to 10% drilling mud solids after passage through the solids control equipment on the platform (Ayers et al., 1980b). Modern solids equipment often can reduce WBM solids concentrations on cuttings to 2% or less.

The chemical composition of drill cuttings reflects the geochemistry of the formation being drilled and the amount of drilling mud ingredients adhering to the cuttings at the time of disposal. For example, the metals concentrations in drill cuttings discharged to offshore waters of California are similar to those of the drilling muds used to drill the wells (Table 3-8). Barium is more abundant in drilling mud than cuttings, as expected, because of its abundance in drilling muds. Lead and zinc concentrations in cuttings sometimes are higher than those in the drilling mud, indicating high concentrations in the formation rocks being drilled, or contamination of the cuttings with pipe thread compound. Cuttings collected at Platform Hidalgo in 1998 and 1993-94 had similar metals concentrations, except for lead and zinc, suggesting that the excess metal was from a contaminant, such as pipe dope, in the mud and not from the formation. Most of the metals associated with cuttings are in immobile forms in the rocks from the geologic formations or drilling mud barite and are at concentrations similar to those in nearby uncontaminated surface sediments (Steinhauer et al., 1994; Phillips et al., 1998).

Table 3-8 lists the concentrations of several metals in WBM and drill cuttings from Platforms Hidalgo and Hermosa in the Santa Maria Basin off southern California. Concentrations are mg/kg dry wt. (ppm). From Steinhauer et al. (1994) and Phillips et al. (1998).

TABLE 3-8
Concentration of Several Metals in WBM and Cuttings, Platforms Hidalgo and Hermosa, Southern California

Metal	Hidalgo (1988)		Hildago (1993-94)		Hermosa (1993-94)	
	Drilling Mud	Cuttings	Drilling Mud	Cuttings	Drilling Mud	Cuttings
Arsenic	6.3	10	10	10	9.3	13
Barium	108,000	5200	53,900	15,000	12,500	1180
Cadmium	1.2	2.3	1.2	2.9	1.8	3.6
Chromium	85	152	91	104	84	94
Copper	30	48	24	70	24	56
Lead	19	1930	23	356	40	32
Mercury	0.13	0.10	0.09	0.07	0.06	0.04
Nickel	41	67	39	47	42	17
Silver	0.28	0.54	0.37	0.50	0.39	0.63
Vanadium	71	105	76	100	46	---
Zinc	290	1346	167	664	235	972

Cuttings produced during drilling with WBM may contain small amounts of petroleum hydrocarbons. The hydrocarbons in cuttings generated with WBM may come from spotting fluids and lubricants added to the mud, or from the geologic strata being penetrated by the drill bit. Drilling mud and cuttings from all depths in a well off California contained petroleum hydrocarbons (Table 3-9). At all depths, the drilling muds contained higher concentrations of total petroleum hydrocarbons and lower concentrations of total and individual PAH than the cuttings, suggesting that most of the PAH were derived primarily from the formations being drilled.

The source of the high TPH and PAH in the cuttings from near the surface is uncertain; they may be derived from nearby oil seeps or from kerogens and oil-rich shales penetrated by the drill. Total and individual PAH concentrations in drilling muds and cuttings increased with depth in the well. TPH and PAH compositions in the drilling muds and cuttings from the middle and bottom of the well closely resembled the crude oil in the reservoir and probably were from the hydrocarbon-bearing formation.

Table 3-9 lists concentrations of hydrocarbons in composite samples of WBM and drill cuttings (in parentheses) from three drilling depths in a well on a platform in the Point Arguello Field, California. Concentrations are mg/kg dry wt (ppm). From Steinhauer et al. (1994).

TABLE 3-9
Concentration of Hydrocarbons in WBM and Cuttings, Point Arguello Field, California

Chemical	Surface	Mid-Well	Bottom	Average
Total Petroleum Hydrocarbons[1]	159 (600)	137 (95)	988 (526)	390 (407)
Total PAH[2]	0.87 (2.3)	8.0 (12)	51 (121)	25 (45)
Naphthalenes[3]	0.27 (1.2)	5.4 (8.9)	39 (96)	18 (35)
Fluorenes[3]	ND (ND)	0.38 (0.35)	4.1 (8.2)	2.8
Phenanthrenes[3]	0.34 (0.79)	0.94 (0.64)	4.5 (9.3)	2.8 (3.6)
Dibenzothiophenes[3]	0.03 (ND)	0.71 (0.40)	3.9 (8.1)	1.9 (2.8)

[1] Total resolved + unresolved hydrocarbons.
[2] Total 2- through 5-Ringed PAHs plus alkyl homologues.
[3] Includes parent PAH and alkyl homologues.

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4.0 REGULATION OF DRILLING DISCHARGES

4.1 Regulatory Practices in the United States

Numerous Federal and State laws and regulations govern exploration for and development of oil and gas resources in marine waters of the United States (DOE, 2005), including:

1. **The Outer Continental Shelf Lands Act (OCSLA) and its amendments.** OCSLA is administered by the Department of the Interior, Minerals Management Service (MMS), and covers the territorial seas from the outer boundary of state waters to the edge of the exclusive economic zone (200 nautical miles [370 km]).
2. **The Federal Water Pollution Control Act (commonly known as the Clean Water Act: CWA).** The Environmental Protection Agency or a state environmental agency designated by EPA administers provisions of this act that apply to oil and gas activities in State and Federal waters.
3. **The Submerged Lands Act (SLA)**. The SLA gives coastal states jurisdiction over submerged lands seaward of the coastline to a distance of 3 nautical miles (5.6 km) or 9 miles (16.7 km) for Texas and the west coast of Florida.
4. **The National Environmental Policy Act (NEPA)**. NEPA requires federal agencies to consider environmental impacts in their decision-making process. MMS prepares Environmental Assessments (EA) and Environmental Impact Statements (EIS) for proposed new mineral development and construction activities in Federal waters.
5. **The Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA).** The National Marine Fisheries Service (NMFS), or U.S. Fish and Wildlife Service, depending on the species, administers these acts.
6. **The Coastal Zone Management Act (CZMA).** the CZMA gives coastal states the authority to review and approve exploration, development, and production plans for Federal waters off their shores.
7. **The Clean Air Act (CAA).** The CAA is administered by MMS for offshore air emissions sources.

The most important of these laws with respect to environmental protection for offshore oil and gas operations are OCSLA, NEPA, and CWA.

4.1.1 The Outer Continental Shelf Lands Act (OCSLA)

The OCSLA guides and regulates many offshore oil and gas activities from initial leasing of Federal lands on the US outer continental shelf to emplacement of offshore development and production platforms, pipelines, and floating production, storage, and offloading facilities (FPSO), to final decommissioning and removal of platforms (MMS, 1987). It includes requirements for monitoring of environmental impacts of exploration, development, and production activities.

The Submerged Lands Act of 1953 gave the Federal Government title to submerged lands located on a majority of the continental margin. States were given jurisdiction over any natural resources within 3 nautical miles (3.45 statute miles) of the coastline, except Texas and the west coast of Florida, where jurisdiction extends to 9 nautical miles (10.35 statute miles). The OSCLA

subsequently defined the outer continental shelf (OCS) as any submerged land outside State jurisdiction. In 1983, the government declared Federal jurisdiction over the U.S. Exclusive Economic Zone (EEZ), defined as all waters up to 200 nautical miles (230 statute miles) from the U.S. coastline. The 1994 International Law of the Sea extends the boundaries of the U.S. EEZ slightly further offshore of some coasts of Alaska, the eastern U.S, and the Gulf of Mexico.

4.1.1.1 Leasing

The OCSLA authorizes MMS, to lease submerged lands on the outer continental shelf for the purpose of exploration, development, and production of minerals, including fossil fuels. It authorizes MMS to promulgate any regulations necessary to administer the Act. Under OCSLA, MMS has the authority to suspend or prohibit lease sales and offshore oil and gas operations if MMS or the U.S. Congress determines that continuation of such activities would cause immediate and serious harm or damage to the marine environment or the biological resources it supports. Leasing and development are continuing in four Federal lease areas. Lease sales are planned in the central and western Gulf of Mexico (off Texas, Louisiana, and Mississippi), and in Alaskan State and Federal waters of the Beaufort and Chukchi Seas, the North Aleutian Basin, and Cook Inlet.

The lease itself has environmental restrictions imposed by MMS. Section 250.40(a) of OSCLA states that the lessee "shall take measures to prevent unauthorized discharge of pollutants into offshore waters" and shall not "create conditions that will pose an unreasonable risk to public health, life, property, aquatic life, wildlife, recreation, navigation, commercial fishing, or other uses of the ocean." MMS has the authority to include in lease stipulations restrictions on the rate and location in the water column of drilling mud discharge (if it is permitted by NPDES permit). The lease stipulation may require the operator to obtain MMS approval of the method of disposal of drilling mud and cuttings, sand, and other well solids. However, discharge stipulations usually are included in the NPDES permit issued by EPA.

4.1.1.2 Exploratory Drilling

Most offshore exploratory wells in the Arctic are drilled from artificial islands, stationary, or floating ice-resistant drilling structures. Before drilling begins, the operator is required to submit and obtain approval for an Application for Permit to Drill (APD) that includes detailed information about the drilling program with respect to operational safety and pollution-prevention measures. The APD contains project layout diagrams, design criteria for well control and casing, specifications for blow out preventers, and a drilling mud program. The lessee must demonstrate that it is using the best available technology for evaluation of abnormal pressure conditions and to minimize the risk of an uncontrolled well flow.

4.1.1.3 Development and Production

Development and production drilling also require an APD, which is submitted to MMS with a Development and Production Plan (DPP) and a Development Operations Coordination Document (DOCD). The DPP and DOCD contain environmental impact-related information, such as frequency of boat and aircraft arrivals, wastes generated and their disposal methods, air emissions, and the risk and significance of any impacts on the marine ecosystem. The lessee also

is required to submit an Oil Spill Contingency Plan to MMS that assures that a full response capability exists for commitment in the event of an oil spill. Such a commitment includes specification of appropriate equipment and materials, their availability and deployment time, and provisions for different degrees of response effort, depending on the severity of the spill.

MMS evaluates the proposed activity for potential environmental impacts relative to geohazards and man-made hazards (including existing platforms and pipelines), archaeological resources, endangered species, sensitive biological features and Marine Protected Areas, water and air quality, oil spill response, and other uses of the outer continental shelf. Based on this review, MMS prepares the necessary environmental impact assessment documentation under NEPA.

4.1.1.4 Disposal of Exploration and Production Wastes

There are 3 potential options for disposal of drilling wastes generated offshore during exploratory and development drilling:

1. Discharge to the ocean
2. Underground injection
3. Haul to shore for upland disposal or recycling.

Underground injection. In the U.S., MMS is responsible for regulating waste disposal by injection into subseabed formations in the Gulf of Mexico. Waste injection in Alaska is regulated by EPA and the Alaska Dept. of Environmental Conservation. The requirements are similar in Alaska and the Gulf of Mexico. The operator must receive a permit to inject exploration and production wastes; permits are reviewed and granted on a case-by-case basis. MMS must also approve storage on the platform of naturally occurring radioactive materials (NORM) derived from production wastes. Wastes for injection must be from exploration/development (drilling mud and cuttings) and production (produced water and sand), and must originate on the outer continental shelf. The wastes can be injected as a slurry into the formation or be encapsulated in the well bore upon well abandonment.

The geological formation where disposal is to occur must be below the deepest drinking water aquifer. It must be isolated above and below by impermeable shale layers, and it cannot contain any producing wells. The operator must demonstrate the mechanical integrity of the formation, and must monitor well pressure continuously during injection.

If the well bore of an abandoned well is to be used to encapsulate wastes, the well must not be intersected by faults extending to the sea floor and must not be in an area with mudflows, slumps, or slides. The disposal well must have a cement plug at least 200 ft long both above and below the encapsulated waste. The waste plug must be at least 1000 ft below the sea floor. The Alaska regulations include specific requirements for construction of the plug and monitoring of the well and formation, including mechanical integrity testing.

Drilling muds may be disposed of by annular pumping. Annular injection is only feasible if the injection domain is well known and the casing shoe of the outer casing string is set just above or in the injection zone. The outer casing must be adequately cemented and injection pressure controlled to ensure that the waste is contained within the disposal domain. NORM must be encapsulated in pipe sections and then placed in an abandoned well.

Onshore disposal of exploration and development wastes. The States have the lead role in regulating disposal of exploration and production wastes on land. EPA has declared that exploration, production, and associated wastes are exempt from provisions of the national waste management law, known as the Resource Conservation and Recovery Act (RCRA) (Lyon, 1995). These exempt exploration and production wastes are defined as non-hazardous oilfield waste (NOW) and are exempt from hazardous waste status, except in Louisiana and California. However, as mandated by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the generator of nonhazardous oilfield waste (the company operating the exploration or production facility) has complete liability for the waste stream. If the NOW is not managed and disposed of properly, the waste generator may be designated as a potentially responsible party (PRP) and may be required to pay for a CERCLA cleanup operation. These liability issues are encouraging operators or waste handlers to rely more heavily on deep injection of solid wastes into non-productive formations or into salt caverns. Offshore operators are encouraged by both disposal cost and liability risks to develop WBM that are non-toxic to marine organisms, and offshore discharge practices that minimize effects on the marine environment.

Disposal options are limited for drilling wastes generated during exploratory drilling in remote Arctic offshore environments, such as the Chukchi Sea. Because exploratory wells are drilled far apart, there are no wells nearby where waste drilling muds and cuttings could be re-injected. This separation distance also means that critical geological and geomechanical information on a previously drilled exploratory well cannot be extrapolated to the new well. Thus, there is insufficient definition about the disposal domain making annular injection of cuttings while drilling exploratory wells infeasible. There are no nearby shore-based docking and disposal facilities. There usually is insufficient storage space on the drilling rig or drill ship to store large volumes of used drilling muds and cuttings. Storage on the drill rig and barging of wastes to distant shore treatment facilities pose safety risks to rig and support vessel personnel and increase environmental risks from increased air emissions and vessel traffic. The safest, most environmentally acceptable disposal option is offshore disposal of WBM and cuttings in strict compliance with environmental regulations. There is no net environmental benefit from zero discharge of exploratory drilling wastes that comply with EPA effluent limitation guidelines in the NPDES permit. The Arctic Council (2009) recommended:

> "Discharge to the marine environment should be considered only where zero discharge technologies or reinjection are not feasible. Based upon site-specific biological, oceanographic and sea ice conditions, risk assessment methods should be used to determine whether the discharges should be at or near the sea floor or at a suitable depth in the water column to keep impact on marine life as low as possible. These discharges should be considered on a case-by-case basis."

During development of a new field, shore-based drilling waste handling and disposal infrastructure can be developed and disposal wells can be drilled from the production platform or on shore. This was the strategy used for developing the Northstar prospect. Because Northstar is close to shore and connected to shore by ice roads in the winter, it was possible to truck development wastes to shore for on-shore disposal. Drilling wastes were transported to shore where they were treated and reinjected into on-shore disposal wells. Northstar now has its own drilling waste disposal treatment facility and cuttings re-injection well. Trucking wastes to shore is no longer required. This allows drilling on a year round basis.

4.1.2 The Federal Water Pollution Control Act (CWA)

Discharges to the ocean of drilling muds and cuttings are regulated in the United States by the Federal Water Pollution Control Act (CWA). The Environmental Protection Agency (EPA) or a state environmental agency designated by EPA administers provisions of this act that apply to oil and gas activities in State and Federal waters. Alaska Dept. of Environmental Conservation (ADEC) was granted authority in 2008 to issue National Pollutant Discharge Elimination Program (NPDES) permits.

Sections 402 and 403 of the Clean Water Act require that National Pollutant Discharge Elimination System (NPDES) permits for discharges to the territorial seas, the contiguous zone, and the ocean be issued in compliance with EPA's regulations for preventing unreasonable degradation of ocean waters, as described in its Ocean Discharge Criteria (ODC) for determination of unreasonable degradation (EPA, 1993, 1996). Before a permit can be issued, EPA must produce an Ocean Discharge Criteria Evaluation (ODCE) report that identifies pertinent information and concerns relative to the ODC and exploration/production activities in the area covered by the permit. Based on the OCDE, EPA develops new source performance standards (NSPS) that are intended to protect the receiving water environment from unreasonable degradation. NSPS are guidelines for the best available demonstrated control technologies to be incorporated into new offshore facilities or operations. In developing NSPS, EPA considers the best demonstrated process changes, in-plant controls, and end-of-process control and treatment technologies that reduce pollution to the maximum extent possible (EPA, 1985). The NSPS include effluent limitations guidelines (ELG). The ELG define the types, concentrations, discharge rates, and total quantities of chemicals or substances that can be discharged to navigable waters under the permit. Discharges of wastes from offshore platforms to the ocean must comply with ELG and NSPS in NPDES permits. The current ODC for the current EPA Region 10 permit for Alaska (EPA, 2006) concluded, based on a site-specific risk assessment for the lease areas in the Beaufort and Chukchi Seas, that ocean discharge of drilling muds and cuttings in accordance with stipulations in the permit should be allowed.

EPA develops these ELG and NSPS based on the degree of control that can be achieved using various levels of pollution control technology, e.g., the best available technology (BAT) economically achievable. In establishing ELG, EPA must consider the technologies that are already successfully in use, costs and economic impacts of implementation of the control technologies, and non-water quality environmental impacts of the discharge or alternative treatment technologies or disposal options.

Most discharges of wastes to Federal waters from offshore platforms are covered by general NPDES permits issued by the responsible EPA regions or State environmental agencies authorized by EPA. General permits cover all offshore platform discharges within a designated area, such as Alaska. The current EPA Region 10 general NPDES permit for exploratory drilling (#AKG280000) covers the area of Federal and State waters in the Alaskan Beaufort Sea, Chukchi Sea, Hope Basin, and northern Norton Basin, westward to the US/Russian border. Exploration and development in Cook Inlet are covered by another permit. EPA also can issue a special NPDES permit for a single facility if it determines that geological, environmental, or cultural conditions or requirements at the site warrant specific, usually more stringent, permit conditions.

The current ELG for discharges of WBM, SBM, and OBM and associated cuttings to Alaska waters are summarized in Table 4-1. Discharge of OBM and associated cuttings or SBM has never been permitted in U.S. State or Federal waters. Discharge of WBM and cuttings and SBM cuttings containing refined, mineral, or formation (crude) oil is forbidden. Discharge of WBM and associated cuttings and SBM cuttings is permitted in the current Beaufort/Chukchi Sea general NPDES permit if they do not contain free oil (Table 4-1). There also are limits on the concentrations of mercury and cadmium in drilling mud barite, and reporting requirements for concentrations of chromium VI, silver, thallium, total aqueous hydrocarbons, and total aromatic hydrocarbons.

WBMs and cuttings destined for disposal in U.S. territorial waters must pass an aquatic toxicity test. The toxicity of the suspended particulate phase (SPP) of the water-based mud or cuttings is tested with juvenile mysids, *Mysidopsis (Americamysis) bahia,* (a marine shrimp-like crustacean) in a 96-hour test. Mysids were chosen as the standard toxicity test marine animal because they have been shown to be among the most sensitive to a wide variety of chemicals, including metals and petroleum hydrocarbons, and they can be cultured easily in the laboratory (Anderson et al., 1974; Nimmo and Hamaker, 1982). Mysids of several species are used in different regions where offshore development is occurring in the U.S. to allow for a standard pass/fail criterion. The SPP must have a 96-h median lethal concentration (96-h LC_{50}) greater than 30,000 mg/L (ppm). Since the SPP is a 1:9 dilution of the WBM, the toxicity limitation is equivalent to 3000 mg/L WBM.

WBM with a lower LC_{50} (greater toxicity) are not permitted for discharge. Because the mud or cuttings will have been discharged before the test results are available, exceedences of the toxicity limitation are reported to EPA and future discharges of the same or similar muds are prohibited. The operator usually immediately re-tests a WBM that does not meet the toxicity screen to assure that is is toxic. If the mud is toxic, the operator is required to change the mud formulation so that it will pass the toxicity screen. The drilling mud toxicity criterion is a best available technology (BAT) guideline, intended to control the composition and toxicity of WBM intended for offshore discharge.

During development of ELG, eight generic WBM, representative of the types of drilling fluids used offshore in US waters, were identified and characterized chemically and toxicologically (Ayers et al., 1983) (Table 4-2). All but one of the generic WBM contained drilling solids (cuttings). Modern mud/cuttings separation equipment is more efficient in removing fine cuttings from the mud, affording better control of drilling mud composition and reducing the need to discharge drilling muds during drilling.

Operators are required to use only the eight generic WBM for drilling offshore wells, if they intend to discharge the WBM and cuttings. If the operator wishes to add or substitute a new additive to one of the generic drilling muds, he must perform SPP toxicity tests with the new mud to show that it has a LC_{50} greater than 30,000 ppm.

Table 4-1 lists the current Effluent Limitation Guidelines (ELG) for discharges of drilling muds and cuttings to State and Federal waters of Alaska from offshore oil and gas exploration platforms. From NPDES permit # AKG280000 (EPA, 2006).

TABLE 4-1
Current Effluent Limitation Guidelines for Discharges of Muds and Cuttings for Alaskan OCS

Discharge	Pollutant Parameter	Effluent Limitation
WBM and cuttings	Suspended particulate phase (SPP) toxicity	Minimum 96-h LC_{50}[b] of suspended particulate phase of 3% by volume to the mysid *Mysidopsis bahia*
	Drilling mud and cuttings	No discharge if they produce an oil sheen with the bucket sheen test
	Free oil	No discharge
	Diesel fuel oil	No discharge
	Mercury	Maximum 1 mg/kg dw in stock barite
	Cadmium	Maximum 3 mg/kg dw in stock barite
	Chromium VI	Report concentration in aqueous phase of a WBM sample, once per well
	Silver	Report concentration in aqueous phase of a WBM sample, once per well
	Thallium	Report concentration in aqueous phase of a WBM sample, once per well
	Total aqueous hydrocarbons (TaqH)	Report concentration in a WBM sample, once per well
	Total aromatic hydrocarbons (TAH)	Report concentration in a WBM sample, once per well
OBM and cuttings	Drilling mud and cuttings	No discharge
SBM	Drilling mud	No discharge
Synthetic base fluid (C_{16}-C_{18} internal olefin, C_{12}-C_{14} ester, or C_8 ester)[a]	Mercury	Maximum 1 mg/kg dw in stock barite
	Cadmium	Maximum 3 mg/kg dw in stock barite
	PAH	Maximum 50 mg total PAH/kg in synthetic chemical
	Sediment toxicity	10-day toxicity ratio (synthetic chemical/SBM) <1 in marine amphipod sediment toxicity test
	Biodegradation rate	275-day gas production ratio (gas production of synthetic chemical/gas production of SBM) <1.0 in anaerobic biodegradation test
Drill cuttings associated with SBM	Cuttings	No discharge if cuttings produce a sheen with the bucket sheen test
	Diesel fuel oil	No discharge
	Suspended particulate phase (SPP) toxicity	Minimum 96-h LC_{50}[b] of suspended particulate phase of 3% by volume to the mysid *Mysidoposis bahia*
	Sediment toxicity	10-day toxicity ratio (synthetic chemical/SBM) <1 in marine amphipod sediment toxicity test
	Formation oil	No discharge if detected by the reverse phase method
	Base fluid averaged over all well sections	≤ 6.9% internal olefin (weighted average) or ≤ 9.4% ester (weighted average)
	Total aqueous hydrocarbons (TaqH)	Report concentration in a WBM sample, once per well
	Total aromatic hydrocarbons (TAH)	Report concentration in a WBM sample, once per well

[a] Limitations apply if SBM cuttings will be discharged to the ocean.
[b] 96-hr LC_{50}, the median concentration calculated to cause 50 % mortality.

Bioassays performed by the EPA (1985a,b) with the suspended particulate phase (SPP) of eight generic muds and mysids produced 96-h LC_{50}s ranging from 33,000 mg/L to >1,000,000 mg/L SPP (Duke et al., 1984) (Table 4-3), with similar to results obtained by Ayers et al. (1983). The SPP is produced by mixing 1 part drilling mud with 9 parts water; thus, the median lethal concentration of the drilling muds ranged from 3,300 mg/L to >100,000 mg/L mud added. A KCl-polymer mud had the lowest LC_{50} (was most toxic) but is classified as non-toxic by GESAMP (2002). The results of these tests were used by EPA to set a conservative acute toxicity (LC_{50}) limit for WBM of 3,000 ppm drilling mud added (30,000 ppm SPP) in the current ELG. This is a BAT limit. The drilling mud dilutes so rapidly after discharge that marine organisms encountering the mud plume would not be exposed to 0.3% WBM for more than a few minutes and within a few feet of the discharge pipe. The toxicity of the KCl polymer drilling mud is caused almost exclusively by the KCl. KCl is an abundant natural salt in sea water (390 mg/L) and would not be toxic following even slight dilution with natural seawater; however, operators frequently replace KCl with seawater or a NaCl brine in a polymer mud to assure that the mud complies with the toxicity requirement.

All U.S. offshore operators are required by the NPDES permit to perform suspended particulate phase bioassays on used WBM and cuttings each month during drilling and at the end of the well. Data collected by EPA between 1986 and 1989 showed that 99.9 percent of 10,397 Gulf of Mexico drilling mud bioassays yielded a 96-h LC_{50} in excess of the 30,000 ppm SPP limit (SAIC, 1992). WBM have become less toxic since 1989 because operators have replaced toxic ingredients with less toxic ingredients (e.g., replacing chrome lignosulfonate with chrome-free flocculents). Thus, the vast majority of water based drilling muds used offshore in U.S. waters are not toxic to marine organisms.

Table 4-2 lists the chemical composition of the eight generic water based drilling muds (EPA, 2006).

TABLE 4-2
Chemical Compositions of Eight Generic Water Based Drilling Muds

1. Seawater/Potassium/Polymer Mud		2. Seawater/Freshwater Gel Mud	
Component	lb/gal	Components	lb/bbl
KCl	0.12 – 1.2	Attapulgite or Bentonite Clay	0.24 – 1.2
Starch	0.05 – 0.30	Caustic	0.01 – 0.07
Cellulose Polymer	0.006 – 0.12	Cellulose Polymer	0 – 0.05
XC Polymer	0.006 – 0.05	Drilled Solids	0.5 – 2.4
Drilled Solids	0.48 – 2.4	Barite	0 – 1.2
Caustic	0.01 – 0.07	Soda Ash/Sodium Bicarbonate	0 – 0.05
Barite	0 – 11	Lime	0 – 0.05
Seawater	As Needed	Seawater/Freshwater	As Needed
3. Seawater Lignosulfonate Mud		**4. Lime Mud**	
Components	lb/gal	Components	lb/gal
Attapulgite or Bentonite	0.24 – 1.2	Lime	0.05 – 0.48
Lignosulfonate	0.05 – 0.36	Bentonite	0.24 – 1.2
Lignite	0.02 – 0.24	Lignosulfonate	0.05 – 0.36
Caustic	0.02 – 0.12	Lignite	0 – 0.24
Barite	0.60 – 11	Barite	0.60 – 4.3
Drilled Solids	0.48 – 2.4	Caustic	0.02 – 0.12
Soda Ash/Sodium Bicarbonate	0 – 0.05	Drilled Solids	0.48 – 2.4
Cellulose Polymer	0.006 – 0.12	Soda Ash/Sodium Bicarbonate	0 – 0.05
Seawater	As Needed	Freshwater	As Needed
5. Nondispersed Mud		**6. Spud Mud (slugged intermittently with seawater)**	
Components	lb/gal	Components	lb/bbl
Bentonite	0.12 – 0.36	Attapulgite or Bentonite	0.24 – 1.2
Acrylic Polymer	0.01 – 0.05	Lime	0.01 – 0.02
Barite	0.60 – 4.3	Soda Ash/Sodium Bicarbonate	0 – 0.05
Drilled Solids	0.48 – 1.7	Caustic	0 – 0.05
Freshwater	As Needed	Barite	0 – 0.12
		Seawater	As Needed
7. Lightly Treated Lignosulfonate Freshwater/Seawater Mud		**8. Lignosulfonate Freshwater Mud**	
Components	lb/gal	Components	lb/gal
Bentonite	0.24 – 1.2	Bentonite	0.24 – 1.2
Barite	0 – 4.3	Barite	0 – 11
Caustic	0.02 – 0.07	Caustic	0.05 – 0.12
Lignosulfonate	0.05 – 0.14	Lignosulfonate	0.10 – 0.36
Lignite	0 – 0.10	Lignite	0.05 – 0.24
Cellulose Polymer	0 – 0.05	Drilled Solids	0.48 – 2.4
Drilled Solids	0.48 – 2.4	Cellulose Polymer	0 – 0.05
Soda Ash/Sodium Bicarbonate	0 – 0.05	Soda Ash/Sodium Bicarbonate	0 – 0.05
Lime	0 – 0.05	Lime	0 – 0.05
Seawater to Freshwater Ratio	1:1 approx.	Freshwater	As Needed

OBM and SBM are not permitted for discharge to US State or Federal waters. Because of their high cost, they are recovered and recycled for use in drilling additional wells. However, drill cuttings generated during drilling with SBM are permitted for discharge to Alaskan waters if they meet the ELGs (Table 4-1).

Table 4-3 shows the acute toxicity of the suspended particulate phase (SPP) of 8 generic drilling muds to mysids, ordered from most (lowest LC_{50}) to least toxic. 96-hour LC_{50} (the concentration causing 50% mortality after the specified exposure time) concentrations are mg/L mud added (the SPP concentration is 10 times higher). From Duke et al., (1984). Mixtures with an acute aquatic toxicity >1000 mg/L are considered non-toxic (GESAMP, 2002).

TABLE 4-3
Acute Toxicity of SPP of Eight Generic Water Based Muds to mysids

WBM Type	96-Hour LC_{50}
KCl Polymer Mud	3,300
Lime Mud	20,300
Freshwater Lignosulfonate Mud	30,000
Seawater Lignosulfonate Mud	62,100
Lightly Treated Lignosulfonate Mud	68,200
Non-Dispersed Mud	>100,000
Seawater Spud Mud	>100,000
Seawater/Freshwater Gel Mud	>100,000

If the operator wishes to discharge SBM cuttings, the SBM base chemicals and SBM cuttings must pass a water-column SPP toxicity test, a sediment toxicity test, and a biodegradation test. The sediment toxicity and biodegradation tests are required because SBM cuttings tend to accumulate to higher concentrations than WBM cuttings do on the sea floor and contain higher concentrations of biodegradable organic matter (the synthetic chemical and emulsifiers) that may deplete the oxygen in the sediments (Neff et al., 2000). Because SBM cuttings will not be discharged during the proposed exploratory drilling in the Beaufort and Chukchi Seas, regulations concerning their ocean discharge will not be discussed further here.

General and special NPDES permits may contain additional requirements for drilling mud and cuttings discharges. All permits contain specific requirements for:

- Monitoring frequency for compliance with different ELG;
- Analytical methods for chemicals in drilling fluids and cuttings and toxicity test methods;
- Reporting and record keeping. Results of monitoring activities are submitted periodically to EPA in a Discharge Monitoring Report (DMR); and
- Technical and operational requirements.

In writing a new permit, each EPA region may add special requirements specific to the outer continental shelf region under their jurisdiction. For example, permits for Cook Inlet, Alaska and the Beaufort and Chukchi Seas (Region 10) include the following requirements:

- Rate of drilling mud and cuttings discharge is set on a case-by case basis, based on water depth and ranges from 0 to 42,000 gal/hr (Table 4-4).
- Drilling wastes from no more than five wells can be discharged at one location.
- The operator must prepare and submit a mud plan outlining the types of drilling muds and additives to be used.
- The operator must maintain an inventory of all the drilling mud additives actually used.
- Restrictions are placed on setbacks from sensitive environments and in ice-covered areas.
- The operator must perform an environmental monitoring program to evaluate the impacts of drilling discharges on the marine environment when the authorization to discharge is within 2.5 miles of the prohibited areas identified in the permit.
- Additional monitoring is required for concentrations of barium, cadmium, chromium, copper, mercury, and lead in drilling muds.

Table 4-4 lists discharge rate limitationsa and monitoring requirements for drilling muds and cuttings to the Beaufort and Chukchi Seas. From NPDES Permit No. 280000 (EPA, 2006).

TABLE 4-4
Discharge Rate Limitations and Monitoring Requirements for Muds and Cuttings for Alaskan OCS

Water Depth[b]	Discharge Rate Limitation	Measurement Frequency	Sample Type
0 – 16.3 ft	No discharge	Hourly during discharge[c]	Estimate
> 16 – 65.5 ft	21,000 gal/hr		
> 65.5 – 131	31,500 gal/hr		
> 131 ft	42,000 gal/hr		

[a] Discharge rate limitations do not apply during stable ice conditions.
[b] As measured from mean low low water (MLLW).
[c] The maximum daily limit is the maximum hourly rate during any calendar day within a month.

4.2 Regulatory Practices Offshore Canada

The Canadian regime for environmental regulation of offshore oil and gas operations is even more complex than that in the United States, with several Federal, Provincial, and Inuvialuit authorities, in consultation with the Canadian oil industry and the National Energy Board of Camada (NEBC), collaborating to set regulations and guidelines. The regulatory framework applicable to oil and gas activities is similar in each of Canada's offshore areas. Offshore waste discharge regulations are administered by the Canada-Newfoundland Offshore Petroleum Board under the *Canada-Newfoundland Atlantic Accord Implementation Act*, S.C. 1987, c. 3 and the *Canada-Newfoundland Atlantic Accord Implementation (Newfoundland) Act*, R.S.N 1990, c. C-2 in the Newfoundland and Labrador offshore area. In the Nova Scotia offshore area, oil and gas

activities are administered by the Canada-Nova Scotia Offshore Petroleum Board under the *Canada-Nova Scotia Offshore Petroleum Resources Accord Implementation Act*, S.C. 1988, c. 2 and the Canada-Nova Scotia Offshore Petroleum Resources Accord Implementation (Nova Scotia) Act, S.N.S. 1987, c. 3. The National Energy Board is responsible for regulation of oil and gas operations in the rest of Canada's offshore areas, including the Beaufort Sea and the Arctic Archipelago area under the *Canada Oil and Gas Operations Act*, R.S.C. 1987, c. O-7.

The current Offshore Waste Treatment Guidelines (NEBC, 2002) set guidelines for waste minimization and set limits on air emissions, produced water discharges, drilling muds and cuttings discharges, and handling and disposal of other wastes associated with offshore oil and gas operations in the Canadian north.

4.2.1 Drilling Mud Discharge

The current guidelines for use and disposal of drilling wastes focus on minimization of discharge of petroleum to marine waters (NEBC, 2002). In order to minimize the quantity of oil discharged into the marine environment, operators should use WBM or SBM if possible. SBM base fluids also must have a total PAH concentration of less than 10 mg/kg, be relatively non-toxic to marine organisms, and biodegrade under aerobic conditions. The use of OBM is approved only in exceptional circumstances when the use of WBM or SBM is not technically feasible. Under no circumstances will whole OBM or associated cuttings be discharged to the sea. The Chief Conservation Officer may approve the use of enhanced mineral oil OBM, provided its environmental and safety-related performance is demonstrated to be equivalent to or better than that of SBM. An enhanced mineral oil OBM is a non-water based fluid in which the continuous phase is a highly purified petroleum distillate that has a PAH concentration less than 10 mg/kg.

Each operator should, when applying for authority to drill a well, identify a generic drilling mud composition for each hole section and provide results of aquatic toxicity testing performed according to Environment Canada test method EPS 1/RM/26 (EC, 1992).

The use of SBM or enhanced mineral oil OBM should be limited to wells, or portions thereof, where drilling requirements are such that use of WBM is technically impractical. The base enhanced mineral oil should be non-toxic as determined by a standard aquatic toxicity test for the water soluble fraction of oil (EC, 1985). SBM or enhanced mineral oil OBM remaining from a drilling mud change-over or drilling program completion should be recovered and recycled, reinjected downhole, or transferred to shore in a manner approved by the Chief Conservation Officer and disposed of in a manner approved by local regulatory authorities. Under no circumstances are whole SBM or enhanced mineral oil OBM to be discharged to the sea. Spent and excess WBM may be discharged onsite from offshore installations without treatment. However, operators should develop procedures that reduce the need for the bulk disposal of these muds following either a drilling mud changeover or a drilling program completion.

4.2.2 Selection of Drilling Mud Chemical Additives

The National Energy Board of Canada (NEBC, 2009a,b) recently issued guidelines for selection of chemicals for offshore drilling and production activities in Nova Scotia and Newfoundland, Canada. The guidelines are intended to provide a framework for selection of drilling and production chemicals intended for use and possible discharge in offshore development areas of Canada. The guidelines use an approach similar to that of OSPAR (see below) to identify less toxic drilling mud additives and production chemicals to minimize potential environmental impacts of drilling mud/cuttings and produced water discharges.

Chemical selection is done through a multi-step screening procedure.

Step 1: Propose a chemical for use.

- Collect information on the quantity, intended use, and ultimate fate of the candidate chemical.
    - If information is available, proceed to Step 2.
    - If information is not available, seek alternatives.

Step 2: Is the chemical to be used as a pest-control product (biocide)?

- If the chemical is not to be used as a biocide, proceed to Step 3.
- If the chemical is a biocide, is intended to be used as a biocide, is registered under the Pest Control Products Act (PCPA) for its intended use, and is used in accordance with instructions governing the registered use of the chemical, proceed to Step 4.
- If the chemical is intended to be used as a biocide but is not registered under the PCPA, find a substitute or register the chemical.

Step 3: **Canadian Domestic Substance List (DSL).** (The DSL is a list of substances approved for use in Canada)

- If the chemical is on the DSL, and has not been subjected to a Significant New Activity (SNAc) notice, proceed to Step 4.
- If the chemical is identified as a SNAc, contact Environment Canada to verify how the chemical can be used. If the chemical can be used within the Environment Canada use limitations, proceed to Step 4; if not, seek an alternative chemical.
- If the chemical is not on the DSL and small quantity exceptions below apply, proceed to Step 4.
    - Less than 1000 kg/y for Non-Domestic Substance Lists (NDSL) listed chemicals.
    - Less than 100 kg/y for all other chemicals.
- If not on the DSL and small quantity exemptions will be exceeded, confirm registration or register the chemical under the New Substances Notification Regulations (NDSL), or seek an alternative.

Step 4: Canadian Environmental Protection Act (CEPA) toxic substances. **(**CEPA has a schedule 1 list of substances that are considered toxic and may be proposed for virtual elimination).

- If the chemical or its constituents are not on the CEPA List of Toxic Substances, proceed to Step 5.
- If the chemical and/or any constituents of the proposed substance are listed on the CEPA List of Toxic Substances, ensure use of the chemical is in accordance with CEPA risk management strategies for the substance and proceed to Step 5.
- If the chemical or its constituents are on the Virtual Elimination List, consider alternatives.

Step 5: Discharge to the marine environment.

- If no discharge is intended, accept the chemical for use.
- If discharge is intended, proceed to Step 6.

Step 6: OSPAR pose little or no risk to the environment (PLONOR) list.

- If all the constituents of a chemical are on the PLONOR list, accept the product/chemical for use.
- If one or more of the constituents of a chemical are not on the PLONOR list, continue to Step 7.

Step 7: PARCOM OCNS hazard rating.

The NEBC (2009a,b) recommends use of protocols developed by The UK Centre for Environment, Fisheries and Aquaculture Science (CEFAS) for assessing the hazard of offshore chemicals. CEFAS assigns product ratings for the petroleum industry based on the Offshore Chemical Notification Scheme (OCNS). These ratings are based on the physical, chemical and ecotoxicological properties of products. CEFAS publishes a list of ranked products and their hazard classifications. The assigned hazard groups vary from category A (most hazardous) through E (least hazardous), and hazard quotient color bands from purple (most hazardous), through orange, blue, white, and silver, to gold (least hazardous).

- Operators should select chemicals with the lowest environmental risk where appropriate.
- If there is no OCNS rating, proceed to:
    - Step 8, if quantities of less than 10 metric tons (220,000 lb) per year per installation will be discharged.
    - Step 9, if more than 10 metric tons per year per installation will be discharged.
- If rated in the OCNS as C through E, or color band silver, blue, or white, proceed to Step 9 for further hazard assessment or to Step 10.

Step 8: Is the Microtox $EC_{50}(15)>75\%$?

The Microtox toxicity test was selected as an initial screening test for these Offshore Chemical Selection Guidelines. The concentration of the chemical in the toxicity test mixture must be the same as the intended discharge concentration.

The following Microtox endpoint values should be used to determine the toxicity of a chemical formulation:

- EC50(15) Toxicity
- ≤ 75% Toxic (fails test)
- > 75% Non-toxic (passes test)

A chemical that passes the Microtox test should not be discharged in quantities greater than 10 metric tons per year per installation and for periods greater than two years without a hazard assessment (Step 9).

- If the chemical passes the test, accept the chemical and apply discharge limit of < 10 metric tons per year per installation for a maximum of two years.
- If the candidate chemical fails the test or quantity of discharge exceeds 10 metric tons per installation, or the use period exceeds two years, proceed to Step 9.

Step 9: Hazard assessment.

The hazard assessment process should be documented and conducted in accordance with the UK OCNS models. The OCNS (or equivalent) rating may be re-assessed with the application of site specific information before applying the decision criteria.

- If rated equivalent to C through E, or color band silver or gold, accept the chemical.
- If rated equivalent to A or B, or color band purple, orange, blue, or white, proceed to Step 10.

Step 10: Risk Justification.

If there is no alternative to discharging an A or B chemical, or a color band purple, orange, blue, or white chemical, develop and provide justification that demonstrates to the National Energy Board how discharge of the chemical will meet the objective of the guidelines.

- If justification is acceptable to the Board, accept the chemical for use.
- If justification is not acceptable to the Board, reject the chemical.

The hazard assessment identified in Step 9 follows the protocols in the Harmonize Offshore Chemical Notification Format (HOCNF), required to complete a CEFAS OCNS rating.

1. Identify the chemical composition and physical properties of the chemical.
2. Toxicity tests should be performed with four types of aquatic organisms to determine the toxicity of the substance:
   a. Algae
   b. Invertebrates
   c. Fish, and
   d. Sediment reworker (as required).
3. At a minimum, the data generated above should include details on the analytical protocols followed and should include laboratory quality assurance/quality control information.
4. The interpretation of the toxicity test data should follow OSPAR Convention models used for OCNS ratings to develop:

   a. An equivalent non-CHARM hazard category A through E, or
   b. An equivalent CHARM hazard quotient.
5. The Chemical Hazard Risk Management (CHARM) or CHARM-equivalent hazard quotient HQ can be re-assessed to generate a risk quotient (RQ) if installation-specific information is available, such as flow and discharge rates, and characteristics of the discharge dispersion plume.

The toxicity and HQ (predicted environmental concentration/predicted no effect concentration: PEC/PNEC) values associated with the OCNS ratings are described in Tables 4-5, 4-6, and 4-7.

Table 4-5 lists The Offshore Chemical Notification Scheme (OCNS) hazard quotient (HQ) and color bands[a].

TABLE 4-5
Offshore Chemical Notification Scheme (OCNS) Hazard Quotient and Color Bands

Minimum HQ Value	Maximum HQ Value	Color Banding	
> 0	< 1	Gold	Lowest Hazard ↓ Highest Hazard
≥ 1	< 3	Silver	
≥ 30	< 100	White	
≥ 100	< 300	Blue	
≥ 300	< 1000	Orange	
≥ 1000		Purple	

[a] Centre for Environment, Fisheries & Aquaculture Science (CEFAS) (http://www.cefas.co.uk/offshore-chemical-notification-scheme-assessment.aspx)

Table 4-6 lists The Offshore Chemical Notification Scheme (OCNS) letter grouping[a], from most (A) to least (E) toxic.

TABLE 4-6
OCNS Letter Grouping from Most (A) to Least (E)

Initial OCNS Grouping	Aquatic toxicity (LC_{50}) (mg/L)	Sediment toxicity (LC_{50}) (mg/L)
A	< 1	< 10
B	> 1 – 10	> 10 – 100
C	> 10 – 100	> 100 – 1000
D	> 100 – 1000	>1000 – 10,000
E	> 1000	> 10,000

a These letter groupings are adjusted based on biodegradation and bioaccumulation of the chemical, according to Table 4-7.

Table 4-7 shows the Offshore Chemical Notification Scheme (OCNS) letter grouping adjustment. From CEFAS (2006).

TABLE 4-7
OCNS Letter Grouping Adjustment

Increase by 2 Letter Groups	Increase by 1 Letter Group	Do Not Adjust Initial Letter Group	Decrease by 1 Letter Group	Decrease by 2 Letter Groups
Substance is readily biodegradable and is not bioaccumulated	Substance is inherently biodegradable and is not bioaccumulated	Substance is not biodegradable and is not bioaccumulated OR Substance is readily biodegradable and bioaccumulates	Substance is inherently biodegradable and bioaccumulates	Substance does not biodegrade and bioaccumulates

4.2.3 Drill Cuttings

Drill cuttings associated with the use of OBM are not permitted for discharge to the sea and the alternative disposal method requires approval of the Chief Conservation Officer (NEBC, 2002). Discharge of cuttings drilled with OBM or SBM to the sea is not permitted. The cuttings associated with SBM or enhanced mineral oil OBM can be discharged to sea only after injection is shown not to be technically or economically feasible, and the cuttings are treated with best available technology to a synthetic chemical concentration of less than 6.0 % on wet solids. Operators may discharge untreated WBM and associated cuttings to the sea. The location of such discharges is subject to approval by the National Energy Board.

The locations on offshore installations for the discharge of wastes are subject to the approval of the Chief Conservation Officer and will be determined on a case by-case basis. As a general rule, all drilling mud and cuttings discharges should be below the water or ice surface.

Operators should design compliance and environmental effects monitoring (EEM) programs for each offshore drilling program. The compliance monitoring program should document all waste discharges that undergo treatment in accordance with the guidelines and provide, where practicable, measurements or estimates of absolute quantities of oil and other contaminants in the discharges.

The EEM program should detect and document any adverse environmental effects that may result from offshore drilling and development operations. The results of these monitoring programs will be used by regulatory authorities, in consultation with industry and other interested parties, to determine the continued adequacy of the waste treatment technologies and disposal procedures that are used by operators to achieve the waste concentration limits defined in the guidelines. Both compliance and environmental effects monitoring programs require the approval of the Chief Conservation Officer.

4.3 Regulatory Practices in the OSPAR Countries

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) was presented to the former Oslo and Paris Commissions in Paris on September 22, 1992. The Convention entered into force on 25 March, 1998 and has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland, and the United Kingdom and approved by the European Community and Spain. OSPAR developed environmental guidelines for offshore oil and gas operations in the OSPAR region. The OSPAR countries with offshore oil and gas resources (mainly Norway, the United Kingdom, and the Netherlands) independently apply these guidelines to the unique environmental and political conditions of the regions of the North Sea, Norwegian Sea, and Barents Sea under their jurisdiction.

4.3.1 Regulation of Ocean Discharge of Drilling Wastes

The OSPAR Decisions and Recommendations are to be implemented and enforced by each Contracting Party. Although the principles of the Harmonized Mandatory Control System (OSPAR, 2000a) are followed by all contracting parties, the implementation and requirements to meet the goals differ from one contracting party to another.

Discharges of OBM and SBM are strictly regulated within the OSPAR area. Discharge of diesel based OBM was prohibited in 1984; discharge of OBM as contamination on cuttings (OBM cuttings) was prohibited in the OSPAR area in 1996. SBM have been used rarely in the North Sea after 2001, due to OSPAR Decision 2000/3 (OSPAR, 2003a), in which the requirements for discharges of SBM cuttings were tightened. Paragraph 3.1.6 in OSPAR Decision 2000/3 (OSPAR, 2003a) states that "the discharge into the sea of cuttings contaminated with synthetic fluids shall only be authorized in exceptional circumstances". In reaching a decision on any authorization, "Contracting Parties should apply to the management of organic phase fluids (OPF) (OPF include OBM and SBM-contaminated cuttings):

1. The principles of the Harmonized Mandatory Control System for the Use and Reduction of the Discharge of Offshore Chemicals as set out in the applicable OSPAR Decisions (OSPAR, 2002b, 2004a);
2. Best Available Techniques (BAT) and Best Environmental Practice (BEP) as set out in Appendix 1 of the OSPAR Convention;
3. The waste management hierarchy set out in Appendix 1 to this Decision."

OSPAR Decision 2000/3 (OSPAR, 2003a) states further that:

- The discharge of whole OPF to the maritime area is prohibited. The mixing of OPF with cuttings for the purpose of disposal is not acceptable.
- The discharge into the sea of cuttings contaminated with OPF at a concentration greater than 1% by weight on dry cuttings is prohibited.
- The use of OPF in the upper part of the well is prohibited. Exemptions may be granted by the responsible national authority for geological or safety reasons.

- The discharge into the sea of cuttings contaminated with SBM will only be authorized in exceptional circumstances. Such authorizations will be based on the application of BAT/BEP as set out in Appendix 1 of the Decision.

In other words, discharges of SBM and OBM are prohibited, but competent authorities can, under specific conditions, give a limited discharge permit for SBM cuttings.

OSPAR guidance on chemicals used offshore is managed in Norway by the Norwegian Pollution Control Authority (SFT: Statens Fururensningstilsyn) and in the UK by the Centre for Environment, Fisheries & Aquaculture Science (CEFAS). The following is a brief description of the Norwegian environmental management regime for chemicals used and discharged offshore. The UK and the Netherlands have a similar approach, with minor differences.

All chemicals used offshore by OSPAR Convention countries are subjected to the Harmonized Offshore Chemical Notification Format (HOCNF) (OSPAR, 2000a). SFT (2007) describes some aspects of the application of the HOCNF in Norwegian waters. The most recent description of the application of HOCNF in the UK is ERT (2008). According to the HOCNF, marine ecotoxicological test data (as well as other data) should be available unless the substance is on the List of Substances/Preparations Used and Discharged Offshore that Are Considered to Pose Little or No Risk to the Environment (PLONOR) (OSPAR, 2004b). The requirements and test procedures are described in the Norwegian offshore health, safety, and environment (HSE) regulations; Activities Regulations §56 a (Det Norske Veritas, 2006), and OSPAR Guidelines for Toxicity Testing of Substances and Preparations Used and Discharged Offshore (Reference number: 2002/3) (OSPAR, 2003b).

Based on the intrinsic properties of each substance (described in the HOCNF), the substance will be evaluated for substitution (the OSPAR pre-screening scheme: OSPAR, 2004a). In Norway, chemicals are categorized by a color code based on their intrinsic properties (the activity regulations § 56b) (Table 4-8). This scheme is similar to the 6-color scheme CEFAS uses to characterize the hazard of chemicals used and discharged offshore (Table 4-5). Black and red substances are hazardous (components of special concern), while yellow and green substances are not hazardous, but might cause harm to the environment depending on amounts, time, and place of discharge. Substances in black and red categories have the highest priority for substitution due to their hazardous properties, whereas substances in the yellow and green categories will be evaluated for substitution, if less toxic alternatives are available. For example, barite is being considered for replacement with ilmenite as a weighting agent because some grades of mineral barite contain high concentrations of some metals. However, as discussed above, low trace metal barite is available and ilmenite often contains concentrations of some metals similar to or higher than those in barite. Such evaluations should be carried out every third year.

As shown in Table 4-8, discharge of green chemicals has declined by about 5% in the 10 years from 1997 to 2007; discharge of yellow chemicals has declined by about 30%. The declines in discharge of red and black chemicals have been even greater: 94% for red chemicals and 99.5% for black chemicals. Black and red chemicals used on the Norwegian continental shelf include pipe thread compounds (pipe dope – high metals concentrations), corrosion inhibitors, scale inhibitors, and cement chemicals (OLF, 2007).

4.3.2 OSPAR Guidelines for Toxicity Testing of Substances and Preparations Used and Discharged Offshore

The drilling operator is responsible for ensuring that chemicals that are intended for use or discharge offshore have been tested for eco-toxicological properties. Testing of the individual drilling mud components is required in the OSPAR countries (OSPAR, 2003b). All chemicals intended to be used or discharged offshore in the OSPAR region should be categorized as to relative environmental hazard according to the HOCNF color scheme of SFT (Table 4-8) or CEFAS (Table 4-5). This requirement does not apply to lubricants and chemicals in closed systems that are used in small amounts. The requirement also does not apply to laboratory chemicals, dispersants, and beach-cleaning agents stockpiled on the platform or support vessels to combat oil spills, and to new chemicals during the period of field testing. Only part 1 and 3 of the HOCNF must be completed for substances on the PLONOR list

Table 4-8 lists the color scheme used by the Norwegian Pollution Control Authority (SFT) to classify the relative hazard of chemicals used and discharged offshore in the OSPAR area according to the Harmonized Offshore Chemical Notification Format (HOCNF). From OLF (2007) and SFT (2009).

TABLE 4-8
Color Scheme Used by the Norwegian Pollution Control Authority to Classify Relative Hazard of Chemicals

SFT Color Category	Chemical Characteristics	Discharged (metric tons)	
		1997	2007
Green	Chemical on the PLONOR list	114,778	109,778
Yellow	Unclassified chemicals, not considered hazardous	39,864	11,796
Red	Chemicals recommended for substitution because: Two of three categories: biodegradability < 60%; log $K_{ow} \geq 3$; Toxicity (ED_{50} or LC_{50}) ≤ 10 mg/L Chemicals on the OSPAR taint list Inorganic chemical toxicity (EC_{50} or $LC_{50} \leq 1$ mg/L Biodegradability < 20%	3933	23
Black	Chemicals prioritized for substitution (White Paper No. 25, 2002-2003, Table 8.1), including: Hormone disrupting chemicals Biodegradation < 20%, log $K_{ow} > 5$ Biodegradation < 20%, toxicity (EC_{50} or LC_{50} < 10 mg/L	228	1
Total Discharged		158,803	121,598

Chemicals should be tested for the following ecotoxicological properties:

- Biodegradability
  - For substances that are composed of several chemicals, biodegradability of all organic ingredients should be tested. Several biodegradation tests are available for use.
  - Special methods may be needed for chemicals that are known to be toxic to microorganisms (e.g., biocides).
  - The properties of biodegradation products of substances with moderate biodegradability (equivalent to BOD_{28} from 20 to 60%) also should be evaluated.
  - When evaluating the properties of degradation of substances with moderate degradability, the results of testing of inherent biodegradability may be used together with other available information about the substances. The evaluations should be documented.
- Bioaccumulation
  - For substances that are composed of several chemicals, bioaccumulation potential all organic ingredients should be evaluated.
  - Bioaccumulation testing is required for all organic ingredients with a molecular weight below 1500 g/mol.
  - The chemicals should be tested according to OECD 117 "Partition Coefficient (n-octanol/water), High Performance Liquid Chromatography (HPLC) Method" (OECD, 2004).
  - If OECD 117 gives no result, the chemical should be tested in accordance with OECD 107 "Partition Coefficient (n-octanol/water): Shake Flask Method" (OECD, 1995).
  - Both methods are based on equilibrium partitioning and may not be suitable for some chemicals, such as for surfactants; evaluation of the bioaccumulation potential of these chemicals should be performed empirically.
  - The potential for bioaccumulation presented as partition coefficient octanol/water, Log K_{ow}, may be given as a weighted average.
  - The bioconcentration factor may be used to argue that a substance does not bioaccumulate even if OECD 117 or 107 shows that Log K_{ow} >3, e.g., if the chemical is rapidly metabolized and excreted.

  Note also that organic chemicals with a molecular weight greater than about 600 or a Log K_{ow} greater than about 8 do not bioaccumulate because of their extremely low water solubility or large molecular size prevents them from being bioaccumulated efficiently (Neff, 2002a).

- Acute toxicity

Inorganic and organic chemicals should be tested for acute toxicity. The requirement does not apply to substances/preparations on OSPAR's (2004b) PLONOR list.

According to the HOCNF, marine ecotoxicological test data (and related physical/chemical and biological data) should be available unless the substance is on the PLONOR list. These ecotoxicological test data include tests with a micro-alga (*Skeletonema costatum*), crustacean

(*Acartia tonsa*), and fish (*Scophthalmus maximus* [juveniles]). For substances that are known to adsorb to particles (log sediment organic carbon/water partition coefficient, Log $K_{oc} > 3$) or be deposited in sediments, an additional sediment reworker test with the benthic amphipod, *Corophium* spp, is required.

All chemicals intended for use and discharge offshore should be tested for toxicity. The requirement does not apply if the chemical is:

1. Inorganic and with a toxicity to the other test organisms of EC50 or LC50 ≥ 1 mg/l
2. Organic and with a toxicity to the other test organisms of EC_{50} or LC_{50} ≥ 10 mg/l.

If results from alternative toxicity testing are used, documentation may be presented to SFT for evaluation.

4.3.3 Zero Discharge

4.3.3.1 The Norwegian North Sea

The concept of zero discharge of material from offshore oil and gas facilities to the Norwegian North Sea was introduced in the White Paper No. 58 (1996-1997), "*Environmental Policy for a Sustainable Development – Joint Efforts for the Future*", from the NME (1997). White Paper No. 58 required that new field developments avoid harmful discharges (zero discharge). Discharge practices of existing fields were to be reviewed comprehensively with the aim of implementing measures to meet the zero-discharge goals by 2005. At the time, this did not include activities related to exploratory drilling.

The zero-discharge objective was repeated and enhanced in Norwegian White Paper No. 12 (2001-2002), "*Protecting the Riches of the Sea*" (NME 2002b). This White Paper specified zero-discharge goals for oil, naturally occurring substances in produced water and drilling and production chemicals. Norwegian White Papers No. 24 (2000-2001), No. 25 (2002-2003), and No. 26 (2006-2007),"*The Government's Environmental Policy and the State of the Environment in Norway*", included exploratory drilling wastes, including hazardous chemicals and naturally occurring substances, in the zero discharge strategy (NME, 2002a, 2003, 2007).

The government and the Norwegian oil industry interpreted the zero discharge concept to include a zero environmental harm principle in addition to a goal of eliminating discharge of hazardous chemicals during offshore exploration and development operations: zero harmful discharge (SFT, 1998, 2003; Nilssen and Øren, 2003; Nilssen and Johnsen, 2008; NPD, 2009). SFT has divided chemicals used and discharged offshore into four categories: black, red, yellow, and green (Table 4-8). The zero harmful discharge goal is intended to encourage offshore operators to eliminate or replace environmentally hazardous substances (black and red chemicals) with non-hazardous chemicals in their ocean discharges of drilling wastes and produced water (NPD, 2009). The oil industry is encouraged to develop reliable data on the potential hazards of chemicals that are candidates for offshore use and disposal.

In effect, the zero harmful discharge concept is incorporated in the current U.S. NPDES permits for offshore drilling waste discharges. The ELG in current permits require that operators use generic WBM that have been shown to be non-toxic. If they wish to replace or add a new

additive, they must demonstrate that the additive is not hazardous and does not increase the toxicity of the WBM above the toxicity limitation.

The Norwegian White Papers identified produced water as the most important contributor to environmental harm from offshore oil and gas operations. Marine environmental effects of produced water discharges were a focus of much monitoring and research in the North Sea in the 1980s and 1990s (Ray and Engelhardt, 1992; Reed and Johnson, 1996; Neff, 2002a). The North Sea offshore oil industry, lead by StatoilHydro, developed an ecological risk based produced water environmental management tool in 2000, the Dose related Risk and Effect Assessment Model (DREAM) (Johnsen et al., 2000; Reed and Hetland, 2002) as a tool for produced water environmental management. DREAM includes the Environmental Impact Factor (EIF) as a tool for quantitative risk assessment of discharges of complex mixtures to the marine environment. In 2007, DREAM was extended to include discharges of drill cuttings to the marine environment: separate EIFs were calculated for the water column and seabed (Singsaas et al., 2008; Smit et al., 2008b). Most operators on the Norwegian continental shelf use DREAM to help meet zero harmful discharge goals for drilling waste and produced water discharges. The suitability of DREAM for managing discharges of drilling muds and cuttings is still under investigation (Altin et al., 2008; Rye et al., 2008; Reed and Rye, 2010).

4.3.3.2 The Norwegian Barents Sea

The first licenses in the Norwegian Barents Sea were awarded in 1979, and exploration drilling started in 1980. However, the environmental impact statement that formally opened the southern part of the Barents Sea for petroleum exploration was not produced until 1988. So far, approximately 70 exploratory wells have been drilled in the area.

There has been considerable variability in interest of the oil industry and concern by local stakeholders, particularly the fishing industry and native peoples, concerning developing offshore oil and gas resources in the Norwegian Barents Sea, particularly the Lofoten Islands area, since the first exploration licenses were awarded there (Hasle et al., 2009). Although 70 exploratory wells have been drilled in the Norwegian Barents Sea, Snøhvit, operated by StatoilHydro, is the only producing field and the Goliat facility, operated by Eni Norge, still is under development (NPD, 2009). As in Arctic Alaska and Canada, the slow pace of development has been caused by a combination of the harsh environmental conditions and remoteness from markets, making activities extremely expensive with high human health and safety risks, and opposition from local stakeholders, based on the perception that the marine ecosystem of the Arctic is highly sensitive to human disturbance.

For example, exploratory drilling in the Norwegian Barents Sea was initiated in 1980 and Snøhvit was discovered in 1984. Development of the large gas field was approved in 1982 and production began in 2007. The Snøhvit field is in 1020 to 1115 feet of water and consists of 19 production wells and a single injection well (for CO_2) that are subsea completions (no structures on the sea surface), that do not damage and are not damaged by commercial fishing gear (NPD, 2009). The produced natural gas, natural gas liquids, and condensate are transported to the production facility on Melkøya Island through a 100-mile pipeline, where it is converted to liquefied natural gas for tanker transport to markets further south. This facility is a model for future offshore developments in the Arctic, possibly including the Chukchi Sea.

The slow progress of development in the Barents was due in part to environmental concerns. There was a sudden halt in exploration activity in the Norwegian Arctic in 2001, triggered by the general elections. The halt came as the result of a scientific dispute about possible effects on fish reproduction of endocrine-disrupting chemicals detected in some samples of produced water discharged to the ocean, mainly in the UK sector of the North Sea (Hasle et al., 2009). Recent studies have shown that produced water from some UK and Norwegian platforms in the North and Norwegian Sea contained low concentrations of high molecular weight alkylphenols, well-known endocrine disrupters (Boitsov et al., 2007; Balaam et al., 2009). These phenols apparently were derived from breakdown of alkylphenol polyethoxylate (APEO) demulsifiers and detergents that were used widely on platforms for produced water treatment and rig wash (Getliff and James 1996; Jacques et al. 2002). However, Sundt et al. (2009) found that concentrations of alkylphenols required to cause endocrine disruption in cod in the laboratory were more than an order of magnitude higher than concentrations measured in the ocean near produced water discharges.

APEOs have been detected in OBM cuttings piles in the UK sector of the North Sea and in water overlying the piles (CEFAS, 2001, URS, 2002). However, octyl phenol and nonyl phenol, the most endocrine disruptive phenols in APEOs, were not detected in the piles or the overlying waters. Ten cuttings piles were assayed for evidence of endocrine disruption and none was found (Hartley et al., 2003). Thus, there is a negligible risk that marine animals near offshore production facilities will suffer endocrine disruption from drilling waste and produced water discharges.

Stakeholders feared that if petroleum resources were found in the Lofoten-Barents Sea area, there would be pressure to develop and produce them. It was envisaged that discharge of produced water from production operations could threaten important fisheries in the Lofoten area; actually stakeholders were concerned that there was not conclusive scientific evidence that produced water discharges would not harm fisheries (Hasle et al., 2009). In response to these perceived but unfounded risks to the Barents Sea ecosystem, the new government initiated a regional environmental and socio-economic impact assessment for petroleum activity in the Lofoten–Barents Sea area (NMOE, 2003), as the basis for a comprehensive management plan for the area (Norwegian Ministry of Environment, 2006).

The impact assessment reopened some areas, with the exception of areas considered especially vulnerable to oil spills, in the southern Barents Sea for year round oil and gas development activity. The excluded areas included the polar front, the marginal ice zone, the coastal zone out to 22 miles from shore, and the Lofoten area where there is an important traditional seasonal cod fishery. A decision to reopen some areas off Lofoten was postponed until a revision of the plan in 2010.

Norwegian Report No. 8 (2005-2006), "*Integrated Management of the Marine Environment of the Barents Sea and Sea Areas off the Lofoten Islands*", is the first regional management plan for the Barents Sea and northern Norwegian Sea areas (NME, 2006). The objective of the plan is to establish holistic, ecosystem-based management of the activities in the Barents Sea–Lofoten area. Fisheries, shipping, and the offshore oil and gas industries in the area should be managed within a single context: that the total environmental pressure from activities should not threaten the structure, functioning and productivity of the ecosystems, after

taking into consideration additional external impacts (climate change, long range transport of hazardous chemicals, etc) (Vik Green, 2007; Pinturer et al., 2008).

The plan has closed some particularly sensitive fisheries areas to oil and gas activities. Exploration and production activities can continue where licenses have already been awarded and the development of additional resources in existing production license areas will be permitted but under a strict regulatory policy of zero discharge (Pinturer et al., 2008). The zero discharge policy focused mainly on produced water discharges, because these were perceived to pose the greatest risk to the Barents Sea environment. However, for political reasons, drilling and other discharges were included. Requirements of the zero discharge policy with respect to drilling operations include:

- Drilling muds and drill cuttings must be reinjected or taken ashore for treatment.
- Drilling muds and drill cuttings from the top hole section may be discharged if
    - The discharge does not contain hazardous substances (black or red category)
    - The drilling activity is in an area where there is a low risk of physical harm to bottom-living biological resources.
- Discharge of fluids to the sea from well testing is prohibited; down-hole testing or collection of test fluid is required.

There is considerable controversy among the government, stakeholders, and the oil industry about what discharges are covered by the zero discharge goal and whether zero discharge is the most environmentally protective solution for protecting the Barents Sea marine environment. It can be argued that this precautionary approach directed towards marine discharges may not necessarily provide the best overall environmental solution in terms of net environmental benefit versus cost. Reinjection of produced water and transport of drilling muds and drill cuttings for onshore disposal have energy and environmental costs resulting from higher exhaust gas emissions (longer stand-by operations and transport to shore) and substantially greater vessel traffic in the exploration and production areas. Lifecycle analysis should be conducted to cover the impacts throughout the whole chain of operations including effects on water, air, and land quality, and on human health and safety (Paulsen et al., 2003; Pinturier et al., 2008; Gundersen, 2009; Hasle et al., 2009).

Particularly contentious is the zero discharge rule for WBM and cuttings. The Norwegian oil industry recommends a full evaluation of different approaches to management of drilling wastes (Garpstad, 2006):

- Use a holistic approach – evaluations must be done to ensure that measures implemented do not cause adverse effects in other areas.
- Is it right to take cuttings drilled with non-toxic WBM to shore?
- Which is better – small amounts of hazardous substances versus large amounts of substances with low potential for environmental harm? – WBM with discharge versus OBM and SBM with reinjection or transport to shore?
- Energy consumption, emissions to air, additional wastes, etc. must be taken into account.
- Choosing the best chemicals (for environment or for drilling effectiveness?) for mud additives – How should this be documented and credit be given?

- There is a limit to cost-benefit analysis, especially when we cannot see any environmental effects of drilling discharges.

StatoilHydro set a zero discharge goal in developing Snøhvit (Rød, 2009). The strategy included reduction of the amount of WBM used and cuttings generated and replacement of black and red chemicals with green and yellow chemicals (Table 4-8). This resulted in a 44 % reduction of total chemical additives discharged and an 82 % reduction in discharge of yellow chemicals. Only an estimated 18 g of red chemicals and no black chemicals were discharged (Table 4-9).

Table 4-9 lists planned and actual discharge of drilling chemicals during development drilling at the Snøhvit field in the Norwegian Barents Sea. Mass of chemicals is in metric tons (1 metric ton = 1.02 U.S. tons). From Rød (2009).

TABLE 4-9
Planned and Actual Drilling Chemicals Discharges during Development, Snøhvit Field, Norwegian Barents Sea

SFT Hazard Category[a]	Planned Discharge	Actual Discharge
Green	21,537	4047
Yellow	477	88
Red	0	0[b]
Black	0	0

[a] Green is considered non-hazardous (PLONOR); potential hazard increases from yellow, to red, to black (Table 4-8);
[b] An estimated 18 grams of red substances were discharged.

5.0 FATES OF WBM AND CUTTINGS DISCHARGES TO THE OCEAN

5.1 Drilling Offshore Wells

Offshore and onshore exploratory and development wells are drilled by the rotary drilling process. In rotary drilling, the well is drilled with a rotating drill bit to which downward force is applied. The drill bit is fastened to and rotated by a hollow steel drill pipe, referred to as the drill string, through which the drilling fluid is pumped to the drill bit (Figure 5-1). The drilling fluid is pumped down the drill pipe, exits through holes in the drill bit, and returns to the surface in the annulus, the space between the drill pipe and the drill casing or rock wall of the drilled hole. Rotation of the drill bit at the bottom of the hole breaks off small chips of rock, called cuttings, deepening the hole. The drilling mud exiting the drill bit suspends the cuttings and carries them up the annulus to the surface where they are separated by the solids control equipment on the drill rig for disposal.

The first step in drilling an offshore exploratory well in shallow Arctic waters, after the offshore drilling unit is in place, is construction of a mudline cellar (MLC). A MCL may not be needed for drilling in water depths greater than about 300 ft, because of the low risk of bottom scour by ice at these depths. A 36-in pilot hole is first drilled to about 60 ft. Then, the MLC is constructed to about 40 ft with a 20-foot-diameter drill bit that resembles a disc harrow. Stiff clays and large rocks are cut and pushed toward the center of the bit where sediments are pulled to the surface using an air lift system. Rocks are caught in a tool run into the pilot hole that also guides the bit keeping the MLC straight. The 36-inch bit then drills to about 200 ft to set the 30-inch structural pipe (Figure 5-2). The MLC is intended to ensure that the top of the wellhead and blowout preventer are located well below the maximum ice keel-scour depth. The maximum estimated depth of ice scour in the more ice-prone Chukchi Sea drilling area is about 6 ft below the sea floor (SGOMI, 2009). The cuttings are swept out of the MLC and upper section of the 36-inch hole by seawater. The drilling muds and cuttings from drilling the MLC and near-surface hole are vacuumed through a hose from the MLC and deposited directly on the sea floor around the MLC. Similarly, the 26-in hole section is drilled in three stages starting with an 8.5-in pilot hole that is enlarged to 26-in. A drilling riser (the pipe that connects the blowout preventer on the sea floor to the drilling deck and encloses the drill pipe) connects the top of the 30-in structural pipe to the diverter system on the drillship, but only seawater is used, along with periodic sweeps of a high-viscosity drilling fluid containing clay or a viscous organic polymer, for hole cleaning. This fluid is not returned to the drillship since it is so diluted it cannot be saved and recycled. Cuttings from this hole section are also deposited near the MLC on the surface of the seafloor.

Drilling wastes from the other hole sections cannot be returned to the drilling rig until the 20-in conductor casing, blowout preventer, and riser are installed. When the 20-in conductor casing is cemented in place and the riser is installed, drilling mud and cuttings are carried up the annulus between the drill pipe and the riser wall to the drilling floor on the rig (Figure 5-1).

Figure 5-1 is a diagram of the drilling mud circulation system on an offshore drilling rig. The inset shows drilling mud circulation at the drill bit. Modified from ECOMAR (1978).

Figure 5-1 Drilling Mud Circulation Diagram on an Offshore Drilling Rig

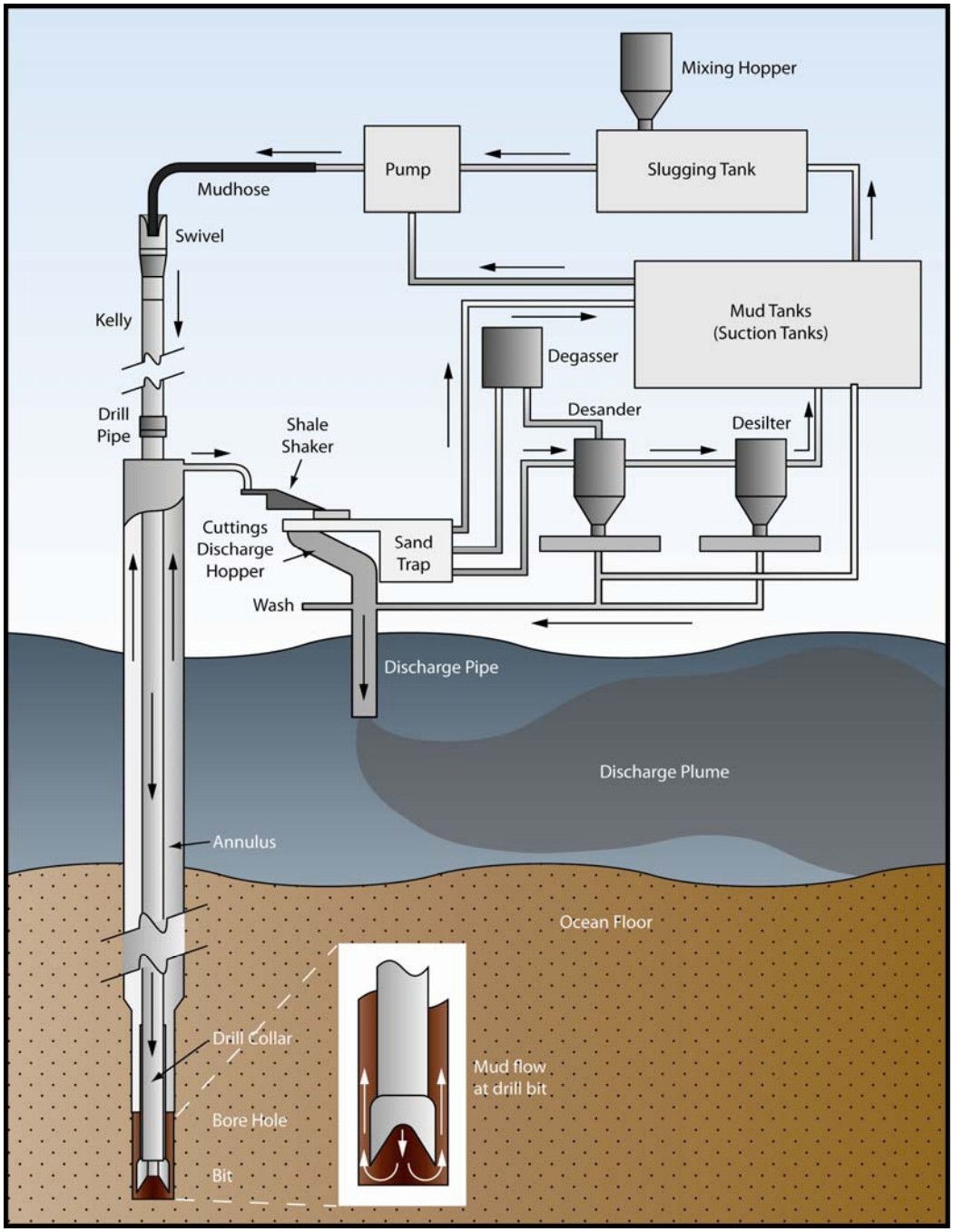
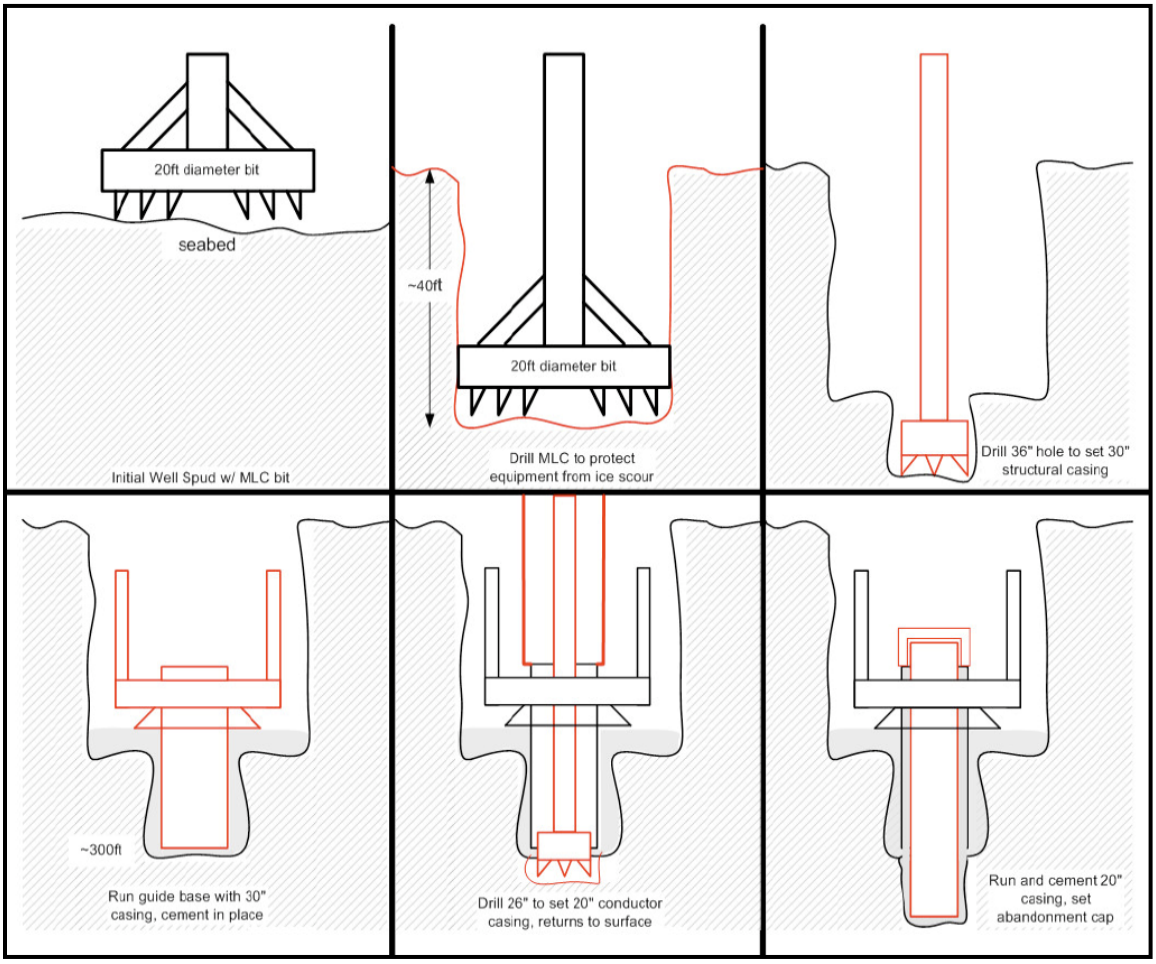


Figure 5-2 shows the top-hole sequence proposed for drilling exploratory wells in the Beaufort and Chukchi Seas. The MLC is drilled to protect the wellhead and blowout preventer from ice scour. From Dyer (2008).

Figure 5-2 Top-hole Sequence Proposed for Exploratory Wells to be Drilled in the Beaufort and Chukchi Seas



5.2 Drilling Mud and Cuttings Separation

The drilling mud and cuttings are separated on the rig. The cleaned WBM usually are returned to the mud tanks for recycling down-hole. Eventually, they are altered by exposure to high temperatures and pressures in the well or by dilution with water and clay-sized cuttings particles. Then they are discharged to the ocean, re-injected into a disposal well, or barged to shore for upland disposal (Puder and Veil, 2007). Drill cuttings usually are treated to remove as much of the drilling mud as possible and are discharged to the ocean or barged to shore for upland disposal, depending on local infrastructure and environmental regulations.

Drilling muds containing cuttings are circulated through several separation devices on the rig to separate the drill cuttings particles from the drilling mud (NRC 1983; Neff et al., 1987). Mud/cuttings separation is based on the difference in particle size of WBM and cuttings

(Figure 5-3). Most WBM solids are clay-sized particles; most cuttings particles are coarser. The coarser, sand/gravel-sized cuttings particles are removed by the shale shakers. The solids that pass through the shale shaker screens may be disposed of as is or passed to hydrocyclones and, occasionally, decanting centrifuges, where finer particles are removed. However, hydrocyclones and decanting centrifuges are not efficient in selectively removing fine cuttings solids from bentonite-based WBM, because the target cuttings for these devices are in the size range of the barite and clay fractions of the WBM. A typical cuttings discharge during drilling with WBM contains 5 to 10% WBM solids. Most of the water-soluble ingredients of WBM, such as carboxymethyl cellulose (CMC) and partially hydrogenated polyacrylamide (PHPA), remain with the WBM phase; a small amount adsorbs to the cuttings particles.

The solids control system usually removes more than 75% of the cuttings from a WBM, unless the cuttings are composed mainly of silt-clay sized particles (CAPP, 2001). The remaining 25% of cuttings, mostly clay-sized particles, tends to increase the viscosity of the mud. When drilling a clay-rich formation with a bentonite WBM, mud viscosity sometimes is controlled by dilution (addition of make-up water) of the drilling mud returning from the shale shaker to maintain an optimum bentonite concentration and viscosity. This WBM management strategy requires frequent bulk discharges of drilling mud to manage the total mud volume on the rig.

SOI (2009) and SGOMI (2009) plan to use a pair of centrifuges downstream of the shale shakers to control the buildup of low-density solids in the mud system. Centrifuges are effective in removing most of the fine solids. Because there will be a need to continually add mud to the mud system as the hole depth and volume increase, there will be some dilution through the addition of seawater and mud chemicals.

Alternative viscosifiers, such as cellulose and polyacrylamide polymers perform better than bentonite in clay-rich formations. Seawater/polymer WBM are used frequently for offshore drilling of clay-rich formations in the Arctic, permitting less mud dilution and less frequent discharge of WBM during drilling.

5.3 Ocean Discharge of Drilling Muds and Cuttings

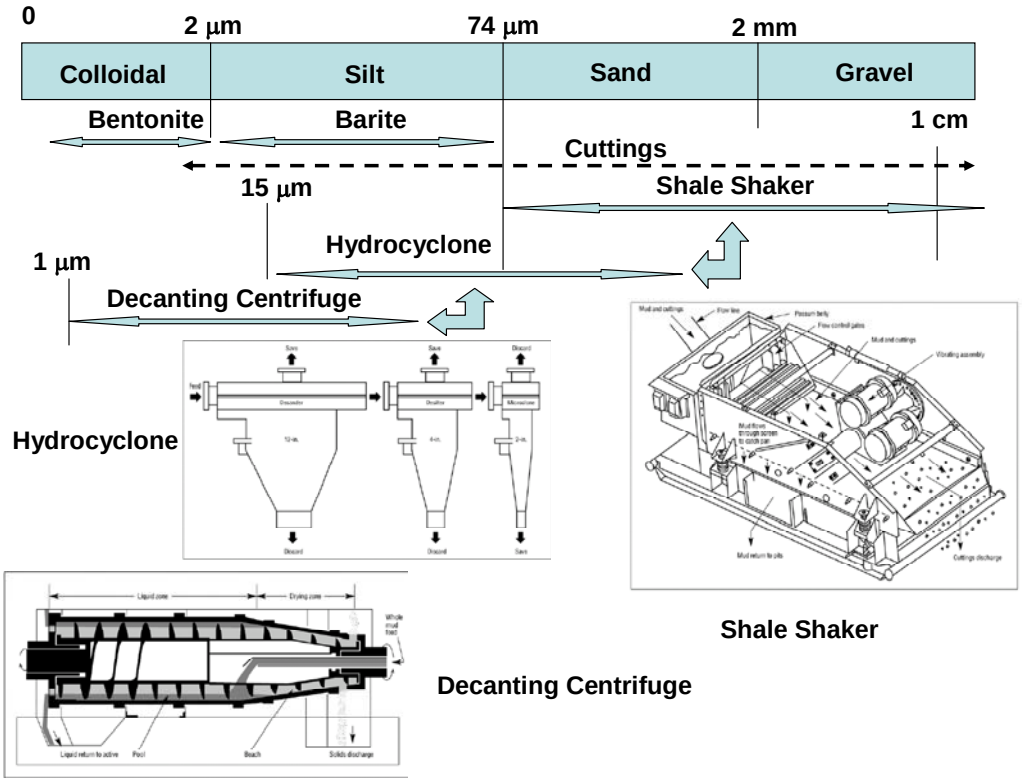
5.3.1 Offshore Drilling Mud and Cuttings Discharge Practices

Offshore discharge is limited to those drilling muds and cuttings that meet the local regulatory requirements. As discussed above, only WBM and associated cuttings and SBM cuttings are permitted for disposal to Federal waters of the US, if they meet ELG requirements. As discussed above, used WBM and associated cuttings also may be permitted by local regulatory authorities for discharge to the North and Norwegian Seas and marine waters of Canada; ocean discharge of SBM cuttings, but not SBM, also may be permitted in some cases. The current NPDES General Permit #AKG280000 (EPA, 2006) for the Beaufort and Chukchi Seas allows discharge of SBM cuttings if they meet ELG requirements.

Figure 5-3 shows that the separation of WBM and cuttings is mainly based on particle size and relies on shale shakers, hydrocyclones, and occasionally a decanting centrifuge. Most cuttings are sand/gravel-sized and are easily recovered on the shale shaker. However, silt- and clay-sized

cuttings are difficult to separate from the barite and bentonite in WBM; hydrocyclones and centrifuges may be required. Modified from CAPP (2001).

Figure 5-3 Equipment Used for Separation of WBM and Cuttings based on Particle Size



An exploratory well usually takes about 1 to 3 months to drill, depending on environmental conditions, mechanical problems encountered during drilling, and hole depth below the sea floor (Gettleson, 1980). Actual drilling occurs only 30 to 50 % of the time during a typical exploratory drilling operation. Drilling is halted periodically to add a length of drill pipe, during well logging, and when the drill string has to be pulled to change the bottom hole assembly, repair damaged drill string components, or replace the drill bit. Drilling muds are not circulated and cuttings are not generated or discharged during these drilling interruptions.

During drilling, the cuttings recovered from the solids control equipment usually are flushed with seawater into a central discharge pipe (shunt line) that releases the cuttings just above or below the sea surface (CAPP, 2001). Depending on the design of the drilling rig, discharges also may occur through the moon pool in the center of the vessel or through a discharge caisson. Occasionally, the responsible regulatory agency may require that the shunt line extend to near the sea floor in order to protect reef structures extending well above the sea floor from burial (e.g., near the Flower Gardens Banks in the western Gulf of Mexico).

The current EPA NPDES General Permit requires that mud and cuttings from drilling of the top hole be discharged onto ”the surface of the seabed”. All other wastes will be routed through the discharge caisson on the drillship. The caisson on the *Frontier Discoverer* is a 15-in metal tube that ends at the bottom of a sponson about 20 ft below mean sea level. Drilling wastes are diluted about 30-fold with seawater as they pass down the caisson.

If permitted by the NPDES permit, WBM are discharged, usually from the mud settling pits, to the ocean intermittently during drilling. Small discharges usually occur every 1 to 2 days and last less than 5 to 20 minutes (Neff et al., 1987; Steinhauer et al., 1992). There may be a bulk discharge of as much as 53,000 gallons of used WBM at the end of drilling, particularly following drilling of an exploratory well. Bulk discharges also occur when the mud engineer needs to substantially change the composition of the drilling mud or when the volume of drilling mud increases to the capacity of the mud pit on the platform. These bulk discharges usually last less than 1 hour, unless this would exceed the discharge rate limitation in the ELG. Drill cuttings containing 5 to 10% adsorbed WBM solids usually are discharged continuously to the ocean at a rate of 53 to 530 gallons/hour during drilling, which occurs about half the time during an exploratory drilling operation (Neff et al., 1987).

The current NPDES Permit No. AKG280000 for the Beaufort and Chukchi Seas (EPA, 2006) sets a discharge rate limitation for drilling muds and cuttings based on water depth at the discharge site, except during stable ice conditions (Table 4-4). Mud and cuttings discharges are not permitted to less than 16 ft of water. The permitted discharge rate increases from 21,000 gal/hr for discharges to 16 to 65.5 ft of water to 42,000 gal/hr for water depths greater than 131 ft. The proposed exploratory wells in the Beaufort and Chukchi Seas are at water depths ranging from 120 ft (Beaufort Sea, Torpedo) to 149 ft (Chukchi Sea, Burger C and SW Shoebill). Mud and cuttings discharge rate limitations for these exploratory wells range from 31,500 to 42,000 gal/hr and should be attained easily.

For example, used WBM from the mud pits and cuttings from the different solids control devices were discharged intermittently from a COST well drilled in 1977 at a water depth of about 200 ft in Cook Inlet, AK (Dames and Moore, Inc., 1978; Houghton et al., 1980b) (Table 5-1). Discharges from the shale shaker were continuous during drilling. Discharges from the sand traps, desanders, desilters, and centrifuges were made intermittently when sufficient solids had accumulated in these devices. Used WBM discharges were made periodically when the mud tanks filled or when the mud system had to be changed (e.g., during cementing operations). There also was a bulk mud discharge at the end of the well. Discharge rates ranged from about 40 gal/hr to as much as 30,000 gal/hr and each discharge lasted one minute to about three hours. All discharges were flushed down the discharge pipe with seawater, effectively diluting the solids before they reached the ocean. The discharge pipe was 20 inches in diameter and extended about 50 ft below the water surface.

The solids control equipment discharges contained up to about 7.5% drilling mud solids, 1 to 50% cuttings solids, and the remainder water. The drilling mud discharges contained 15 to 20% mud solids (Table 5-1). The mud and cuttings solids were diluted substantially with mud make-up water and flush water before exiting the discharge pipe.

Table 5-1 lists the estimated water based drilling mud (WBM) and cuttings discharge rates and volumes to Cook Inlet, AK, from an exploratory well drilled in 200 feet of water in 1977. From Dames and Moore (1978) and Houghton et al. (1980b).

TABLE 5-1
Estimated WBM and Cuttings Discharge Rates and Volumes to Cook Inlet from Exploratory Wells, 1977

Discharge Source	Volumetric Composition	Discharge Frequency	Discharge Rate (gal/hr)	Flush Rate (gal/hr)[a]
Shale Shaker	50% cuttings 7.5% mud solids 42.5% water	Continuous during drilling	40 – 80	20,000
Desander	25% sand 75% water	2-3 hr/day during drilling	125	1250
Desilter	22.5% silt 2.5% mud solids 75% water	2-3 hr/day during drilling	675-715	1700
Centrifuge	1% mud solids 99% water	1-3 hrs as required	1250	170
Sand Trap	20% sand 7.5% mud solids 72.5% water	Every 2-3 days	3700 gal in 2-10 minutes	22,000
Sample Trap	15% dry mud & cuttings solids 85% water	Every 2-3 days[b]	630 gal in 5-10 minutes	22,000
Mud Tank for Dilution	10-15% mud solids 85-90% water	Less than 3/well	≤ 8400 gal @ 29,500 gal/min	22,000
Mud Tank for Cementing	10-15% mud solids 85-90% water	3-6 times/well[b]	20 min @ 40 gal/min	22,000
Mud Tank, End of Well	10-15% mud solids 85-90% water	1/well[b]	≤ 3 hr @ 29,500 gal/min	22,000

[a] The discharge pipe is flushed continuously with seawater, even when there is no drilling.
[b] No discharge during drilling.

5.3.2 Volumes of Drilling Muds and Cuttings Discharged Offshore

5.3.2.1 Discharges Practices

The total volumes of drilling mud and cuttings discharged during offshore drilling of exploratory and development wells depend on the depth of the well, the hole diameters chosen, the types of geologic formations being drilled, the type of drilling equipment used, and the efficiency of the solids control equipment used. These factors vary widely for different offshore drilling operations. Drill hole diameter decreases with depth of the well, decreasing the volume of drilling mud used and cuttings generated. Hinwood et al. (1994) estimated that the total volume of drilling mud and cuttings generated increased with well depth below the sea floor from approximately 132,000 gallons of drilling mud and 34,000 gallons of cuttings for a 2600-foot well to approximately 440,000 gallons of drilling mud and 117,000 gallons of cuttings for an 18,000-foot well. The volume of WBM discharged usually is larger for exploratory than for development wells. During development, several wells usually are drilled during a relatively short period of time from a platform and drilling mud used for one well can be reformulated and used for the next well.

The NRC (1983) estimated the ranges of WBM and drill cuttings discharge volumes from offshore exploratory wells as 211,000 to 1,320,000 gallons and 132,000 to 265,000 gallons, respectively. Ayers et al. (1980a) carefully measured the volumes of WBM and cuttings discharged from an exploratory well drilled to a depth of 16,300 ft on the mid-Atlantic outer continental shelf as 1,300,000 gallons of WBM and 219,000 gallons of drill cuttings. Drilling mud viscosity for this well was managed by dilution, as described above, accounting for the large volume of used WBM discharged, most of which was seawater.

A total of 420 million gallons of drilling mud ingredients (excluding seawater) were discharged to the Gulf of Mexico in 1998 during drilling of 559 wells, most of them development wells (Table 3-4). This represents 750,000 gal/well of mud solids and 2800 gal/well of liquid additives.

Between the end of 1986 and early 1989, 39 development wells were drilled to about 13,000 ft below the sea floor from three platforms in the Point Arguello Field off southern California. Approximately 276,000 gallons of used WBM and 72,000 gallons of drill cuttings were discharged from each well (Steinhauer et al., 1992, 1994).

5.3.2.2 Discharges to Cold-Water Environments

WBM and cuttings discharge data are available for 3 of the 91 exploratory wells drilled in the Canadian Beaufort Sea (Friesen, 1980). These wells were drilled between 1973 and 1975 from artificial ice islands and WBM and cuttings were discharged under the ice. The total drilling waste discharged from each of the drilling islands ranged from 539,000 gallons to 1,000,000 gallons. Many other wells were drilled with OBM offshore in the Canadian Arctic; cleaned cuttings were discharged and the spent OBM were returned to shore. OBM cuttings discharges from 4 wells ranged from 28,500 to 77,700 gallons (Chénard et al., 1989). The volume of drilling wastes usually is smaller when OBM or SBM are used, because there is less erosion of the well bore through sloughing of water-sensitive shales and the used organic-phase drilling muds are not discharged (Neff et al., 2000).

More than 50 exploratory wells were drilled in the State and Federal waters of the U.S. Beaufort Sea and Chukchi Sea between 1981 and 2002. Information on drilling mud and cuttings discharge methods and volumes is available for 16 of these (Table 5-2). The Beaufort Sea wells were in 18 to 167 feet of water. Drilling muds and cuttings were discharged from most of these Beaufort and Chukchi Sea exploratory wells directly to the water in the open-water season, or to the surface of the ice or under the ice in the shore-fast ice season. The Beachy Point well was drilled from a near-shore gravel island in 18 ft of water. The muds and cuttings from this well were transported to shore over an ice road and disposed of at Prudhoe Bay by injection into a disposal well. The five Chukchi Sea exploratory wells drilled in 1989-1990 were in deep water (137 to 149 feet) and far from shore (60 to 140 miles), so transport to shore for disposal would have been cost-prohibitive, dangerous, and harmful to the environment. WBM and cuttings from these Chukchi Sea wells were discharged to the ocean.

The total estimated volume of drilling mud and cuttings discharged from each of these wells ranged from about 211,000 gallons to 668,000 gallons (Table 5-2). If it is assumed that the average discharge from Beaufort Sea wells was 400,000 gallons and the average discharge from Chukchi Sea wells was 210,000 gallons, the total volume of drilling mud and cuttings discharges to the Beaufort and Chukchi Seas in the 21 years of exploratory drilling was 13 million gallons. By comparison, volumes of drilling muds and cuttings discharged from four exploratory wells in the Canadian Beaufort Sea between 1973 and 1977 ranged from 306,600 to 101,000,000 gallons (Friesen, 1980; Crippen et al., 1980).

To put these discharge rates in perspective, the total combined average flow of the three largest rivers emptying into the Alaskan Beaufort Sea (the Kuparuk, Sagavanirktok, and Coleville Rivers) is between 1.5 and 21 trillion gallons/week (Rember and Trefry, 2004; Trefry et al., 2009), most of it during the few weeks of spring breakup. Thus, the total volume of drilling mud and cuttings discharged to the Beaufort and Chukchi Seas in more than 20 years is only a very small fraction of the volume of freshwater containing large amounts of suspended sediment discharged from rivers into the Beaufort Sea each week.

SOI (2009) and SGOMI (2009) filed outer continental shelf lease exploration plans for exploratory drilling in the Beaufort and Chukchi Seas. The plans contain estimates of the composition and volume and discharge rates of WBM and cuttings from each proposed well (Table 5-3). As discussed above, the MLC and surface sections of the wells will be drilled with seawater, with occasional sweeps with a light spud mud, if needed (Table 3-6). Cuttings, possibly containing a small amount of spud mud solids, mainly barite and bentonite, will be deposited directly onto the sea floor around the well site. The estimated volume of cuttings deposited directly on the sea floor during drilling of the top hole ranges from 129,000 to 146,000 gal/well (Table 5-2).

Deeper sections of the well will be drilled with a brine/PPHA drilling mud that will be returned to the surface carrying drill cuttings. The cuttings will be passed through the solids control system to remove WBM and discharged to the ocean through a discharge caisson. The rate of cleaned cutttings discharges during drilling will range from 1600 to 4600 gal/day during the approximately 29 days required to drill the deeper sections of each well. There may be a few bulk discharges of used WBM during drilling and a large discharge at the end of the well if another well is not going to be drilled that year. If another well is planned, the WBM remaining

in the mud storage tanks may be saved, reconstituted, and used for the additional well, if possible. The estimated maximum total amount of used drilling mud that may be discharged ranges from 116,000 to 210,000 gal/well (Table 5-3).

Table 5-2 shows the estimated volumes of water based drilling mud and cuttings discharged to the Alaskan Beaufort and Chukchi Seas from exploratory wells for which information is available from Exploration Plans.

TABLE 5-2
Estimated WBM and Cuttings Volumes Discharged to Beaufort and Chukchi Seas during Exploratory Drilling

Prospect	Date	Water Depth (ft)	Drilling Unit	Discharge Method	Estimated Volume (Gal)
Alaskan Beaufort Sea					
Beachy Pt.	1981	18	Gravel island	Cuttings hauled to shore, injected[d]	420,000
Tern	1982/1987	21	Gravel island	To water per NPDES permit	630,000
Fireweed	1990	50	SDC/MAT[a]	To water per GP AKG284100	420,000
Antares	1984/1985	49	CIDS[b]	To water per GP	294,000
Mars	1986	25	Spray ice island	To sea ice per GP	374,000
Mukluk	1983	48	Gravel island	To water under ice per NPDES permit	294,000
Harvard	1985	49	Gravel island	To water or on ice per NPDES permit	374,000
Sandpiper	1986	49	Gravel island	To water or on ice per NPDES permit	374,000
Belcher	1988	167	Kulluk[c]	Per GP; method not specified	668,000
McCovey	2002	35	SDC/MAT[a]	To sea ice surface per GP AKG2842005	248,000
Liberty	1997	21	Gravel/ice island	To sea ice surface per GP	458,000
Warthog	1997	35	CIDS[b]	To sea ice surface per GP	403,000
Alaskan Chukchi Sea					
Popcorn	1989	143	Explorer III[c]	To water	210,000
Crackerjack	1990	137	Explorer III[c]	To water	210,000
Burger	1989	149	Explorer III[c]	To water	210,000
Klondike	1989	141	Explorer III[c]	To water	210,000

[a] SDC/MATT = Steel drilling caisson or steel drilling caisson/Mat drilling unit;
[b] CIDS = Concrete island drilling unit;
[c] These are ice-reinforced drilling rigs;
[d] This exploratory well was drilled in winter when the gravel island was attached to shore by an ice road. Cuttings were transported to Prudhoe Bay for reinjection. Drilling muds were stored on the gravel island and reinjected into the well at the end of drilling.

As discussed above, drilling wastes from Shell's planned exploratory drilling programs in the Beaufort and Chukchi Sea will be discharged from the *Frontier Discoverer* through a 15-in diameter disposal caisson that is positioned vertically on the side of the drill ship and extends to about 20 ft below the sea surface. Drilling wastes will be discharged into the caisson, which is open at both ends, and will be diluted by an estimated 30-fold before they enter the sea. The estimated maximum volume of used WBM and cuttings that will be discharged into the caisson ranges from 169,000 to 357,000 gal/well (Table 5-3). Larger estimated volumes of drilling muds and cuttings will be discharged from the Chukchi Sea than the Beaufort Sea exploratory wells, because the planned depth below the sea bed of the Chukchi Sea exploratory wells is greater than that for the Beaufort Sea wells.

Table 5-3 lists estimated drilling mud and cuttings discharges from exploratory wells being proposed by SOI (2009) and SGOMI (2009) for the Beaufort and Chukchi Seas. Each well is expected to require about 36 days to drill.

TABLE 5-3
Estimated WBM and Cuttings Discharges from Proposed Shell Exploratory Wells, Beaufort and Chukchi Seas

Prospect	Drill Cuttings Surface Section[a]	Water Based Drilling Mud[b]	WBM & Cuttings Deeper Section[c]	Total Discharge
Beaufort Sea - Camden Bay				
Sivulliq	146,000	116,000	53,000	315,000
Torpedo	143,000	121,000	58,000	322,000
Chukchi Sea				
Burger	129,000	185,000	122,000	435,000
Crackerjack	133,000	210,000	147,000	490,000
SW Shoebill	139,000	199,000	136,000	474,000

a Surface section is drilled with seawater and cuttings are deposited directly on the seafloor at rates of 26,000 to 29,000 gal/day for about 5 days/well.
b Bulk WBM discharges average 3400 to 4000 gal/day for Beaufort Sea wells and 5800 to 6600 gal/day for Chukchi Sea wells. If multiple wells are drilled in a season, WBM in the mud tanks will be used for the next well.
c Cuttings discharge rates from the solids control equipment on the rig are 1600 to 1800 gal/day for Beaufort Sea wells and 3800 to 4600 gal/day for Chukchi Sea wells.

5.4 WBM and Cuttings Dispersion in the Ocean

When discharged to the ocean, WBM and drill cuttings, which are slurries of particles of different sizes and densities in water containing dissolved salts and organic chemicals, form a plume that dilutes rapidly as it drifts away from the discharge point with the prevailing water currents. Dissolved components in the plume dilute rapidly by turbulent mixing (eddy diffusion) of the receiving waters. Particles in the plume also dilute and are dispersed in different ways depending on their sizes and densities. Buoyant particles (density less than that of the receiving waters) float to the surface and are carried away in the direction of wind-driven surface currents. Denser particles sink as they drift away from the discharge site, the rate of sinking depends on particle size and density relative to seawater density at different depths in the water column. The density of seawater increases with increasing depth (pressure) and decreasing temperature. Drilling waste particles may sink to and accumulate at a water depth where the density of the water and particles is the same. The rate of mixing and dispersion of WBM and cuttings depends on the physical and chemical properties of the discharge, the rate and frequency of discharge, and the salinity, the level of turbulent mixing, and stratification of the receiving waters (Gettleson, 1980).

WBM and cuttings are composed of a slurry of particles with a wide range of grain sizes and densities. Clay, silt, and most cuttings solids have densities of about 2.3 to 2.65 g/cm3; drilling mud barite has a density of 4.1 to 4.3 g/cm3 (Nedwed, 2004; Bruton et al., 2006). Particle diameter has a greater influence than density on the rate of settling of WBM and cuttings particles. Drilling mud solids, including silts, clays, and barite, have diameters ranging from less than 1 to about 75 µm (Figure 5-3). Unflocculated clay and silt-sized particles, including bentonite and barite, in a WBM settle in calm water at rates ranging from about 0.005 ft/hr for bentonite clay to about 2 ft/hr for barite and small cuttings particles (Brandsma and Sauer, 1983c). However, bentonite clay particles in a WBM usually flocculate (clump together) upon a 5- to 10-fold dilution in seawater (Muschenheim and Milligan, 1996; Curran et al., 2002). The clay floc is a loose aggregate of clay particles that may include barite particles. These aggregates settle more rapidly than unflocculated silt and clay. The coarser cuttings particles sink rapidly to the bottom. Cuttings particles, which span a size range from clay to gravel (Figure 5-3), settle in seawater at rates of about 0.0003 to 50 ft/hr (Nedwed, 2004).

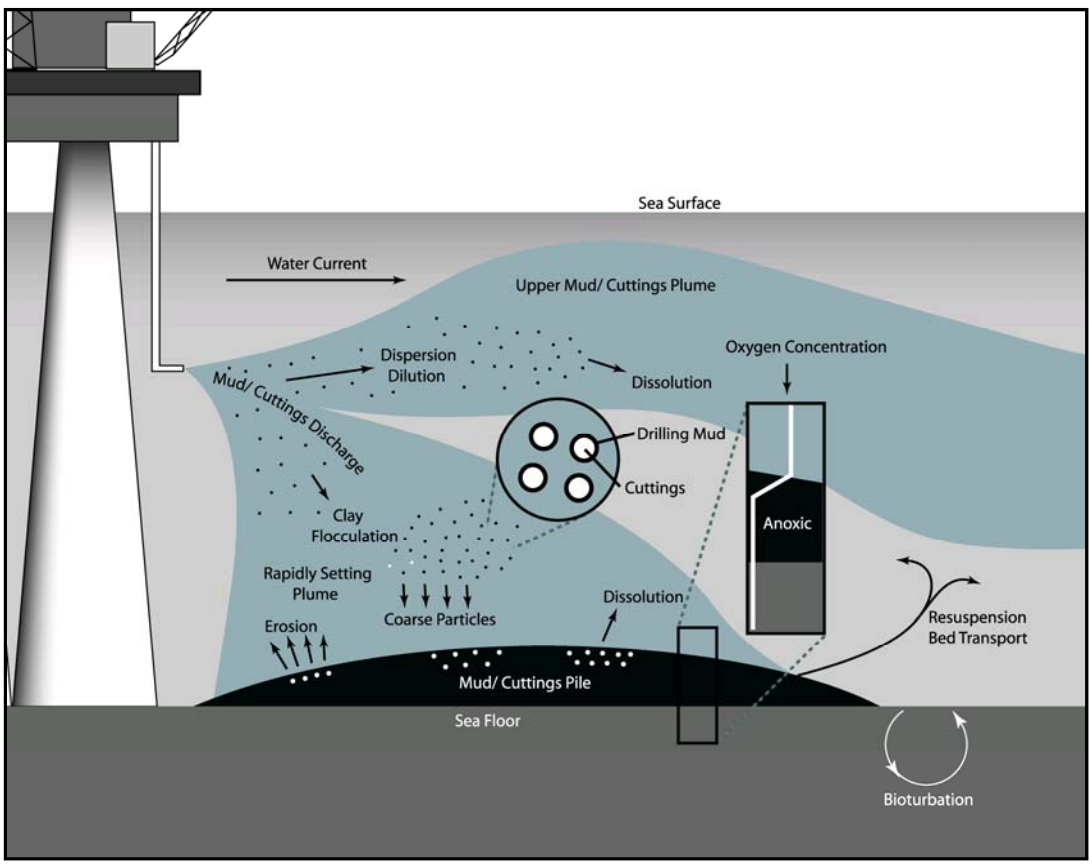
Observations of discharges from shale shakers indicate that the large cuttings particles fall almost straight to the bottom, with adsorbed fine-grained drilling mud solids washing free during the descent. Flocculated clay/barite particles drift downward more slowly. The fine-grained drilling mud solids and cuttings particles form a plume that is diluted rapidly by convection and turbulent mixing as it drifts away from the discharge pipe with the prevailing water currents (Gettleson, 1980).

Drilling mud fate and dispersion models have helped characterize the behavior of the drilling mud and cuttings plume. The models predict that, when WBM and cuttings are discharged to the ocean, the larger particles, representing about 90 % of the mass of the mud solids, form a plume that settles quickly to the sea floor (or until the plume entrains enough seawater to reach neutral buoyancy). About 10 % of the mass of the mud solids, consisting of fine-grained unflocculated clay-sized particles and a portion of the soluble components of the mud, form another plume in the upper water column that drifts with prevailing currents away from the platform and is diluted

rapidly in the receiving waters (Ayers, et al., 1980a; Brandsma et al., 1980, Brandsma and Sauer, 1983c; National Research Council, 1983) (Figure 5-4). The fine-grained solids in the upper plume settle slowly over a large area of the sea floor.

Figure 5-4 illustrates dispersion and fates of WBM and cuttings following discharge to the ocean. The WBM forms 2 plumes, an upper plume, usually representing ~ 10 % of the mass of discharged solids, containing fine-grained unflocculated solids and dissolved components of the mud, and a lower, rapidly-settling plume containing dense larger-grained particles, including cuttings, and flocculated clay/barite particles. The WBM solids undergo dispersion, dilution, dissolution, flocculation, and settling in the water column. If the WBM contains a high concentration of organic matter, the cuttings pile may become anaerobic near the surface. The cuttings pile is altered by redox cycling, bioturbation, and bed transport.

Figure 5-4 Dispersion and Fates of WBM and Cuttings Following Discharge to the Ocean



Field observations have shown repeatedly that drilling mud disperses rapidly after discharge. Field studies of drilling mud dispersion have been performed in temperate environments, including the Gulf of Mexico (Ayers et al., 1980a, 1982; Trefry et al., 1985), the Atlantic Ocean (Ayers et al., 1980b), and the Pacific Ocean (Ray and Meek, 1980, O'Reilly et al., 1989), and in cold climates, such as Cook Inlet (Houghton et al., 1980b), the Beaufort Sea (Miller et al., 1980; NTS, 1981, 1983), and Norton Sound (ECOMAR, 1983). The concentration of drilling mud and cuttings in the plumes was measured as rhodamine dye concentration (dye was mixed with the

effluent before discharge), light transmittance, acoustic back-scatter, or total suspended solids concentrations. The dye measures the dilution of the liquid phase of the discharge; transmittance measures primarily dispersion of clay-sized particles; acoustic backscatter and total suspended solids analysis measure primarily dispersion of coarser particles. The three measurements usually do not correlate well, indicating that the three phases of the plume diluted and dispersed at different rates (Trefry et al., 1985). In most cases, the dye dilutes faster than the suspended solids do. Transmittance changes in an irregular fashion, due to heterogeneity in the size distribution and shape of clay-sized particles and the non-linear relationship between suspended clay concentration and light transmittance.

The results in all cases were quite similar, showing rapid dispersion and dilution of drilling mud and cuttings after discharge. Representative results (Table 5-4) demonstrate dilution (measured as the ratio of suspended solids concentration in the drilling discharge to suspended solids concentration in the ambient water) by a factor of 100 within 20 to 30 ft. Discharges usually are diluted by 10- to 30-fold in the discharge pipe, so actual dilution within 20 to 30 ft is 1000- to 3000-fold. High-rate discharges disperse more slowly than low-rate discharges; this observation may be the basis for discharge rate limitations in NPDES permits (EPA, 2006). In areas where water current speeds are high, such as Cook Inlet, AK, dilution of drilling mud and cuttings discharges is very rapid; discharges from an exploratory drilling rig in Cook Inlet were diluted by 10,000-fold within 300 ft of the rig (Houghton et al., 1980b). Dilution factors for cuttings discharges, which usually are composed primarily of large particles that settle rapidly and are made at low discharge rates, are higher than for bulk WBM discharges.

Below-ice discharges of drilling muds and cuttings in the Beaufort Sea tend to disperse more slowly than discharges to open water (NTS, 1981). However, onto-ice discharges tend to disperse more rapidly than those to open water, probably because the discharged material enters the ocean slowly as the ice melts, and often is diluted by freshwater overflow from rivers onto the ice during the spring breakup (NTS, 1982).

Measurements of water quality during drilling fluid discharges indicate that only light transmittance and suspended solids concentration deviate noticeably from normal values within the discharge plume. Ayers et al. (1980a) showed that temperature, salinity, and dissolved oxygen concentrations were at normal values within 150 ft of a drilling mud discharge point, the closest distance sampled. However, concentrations of particulate aluminum, barium, chromium, iron and lead were slightly elevated in the upper water column for a distance of up to 1500 ft down-current from the drilling mud discharges on the Tanner Bank off southern California (Ray and Meek, 1980), in the Gulf of Mexico (Trefry et al., 1985; Pierce et al., 1985), and on the outer continental shelf off New Jersey (Ayers et al., 1980b). These metals are present in drilling wastes as insoluble components of clay and barite particles in the wastes. As discussed above, most of the chromium in drilling muds used offshore in the 1970s and 1980s was associated with chrome lignosulfonate, a mud thinner. Pierce et al. (1985) showed that the chromium in a used chrome lignosulfonate drilling mud is associated with a low molecular weight organic material; when the drilling mud is discharged to the ocean, nearly all the chromium is adsorbed or complexed with the particulate phase, mainly the silt/clay fraction, in the less toxic Cr III valence state. Chrome lignosulfonate WBM are no longer used for offshore drilling in the U.S., Canada, and the North Sea.

Table 5-4 lists representative field measurements of the dilution of drilling discharges in temperate and cold-water marine environments.

TABLE 5-4
Representative Field Measurements of the Dilution of Drilling Discharges in Temperate and Cold Water

Location	Type of Discharge	Amount Discharged (gal)	Discharge Rate (gal/hr)	Distance From Discharge (ft)	Observed Dilution Factor
Temperate Marine Environments					
Gulf of Mexico[a]	Drilling mud	10,500	11,600	20	96
	Drilling mud	10,500	11,600	150	42,000
	Drilling mud	16,300	42,000	150	1,660
Mid-Atlantic[b]	Mud/cuttings	9240	11,600	50	2274
	Mud/cuttings	21,000	21,00	50	210
Tanner Bank, CA[c]	Drilling mud	unknown	3200	245	9,920
Platform Eva, CA[d]	Drilling mud	11,300	22,500	245	725
Cold-Water Marine Environments					
Cook Inlet, AK[e]	Drilling mud	634	not specified	3000	46,000
	Drilling mud	1700	not specified	2700	22,000
	Drill Cuttings	Continuous	2.6	100	38,000
	Drill Cuttings	Continuous	2.6	400	143,000
Tern Island, Beaufort Sea, AK[f]	Drilling mud	Unknown	3500	98	700
	Drilling mud	Unknown	3500	1600	18,000

[a] Ayers et al. (1982); [b] Ayers et al. (1980b); [c] Ray and Meek (1980); [d] O'Reilly et al. (1989); [e] Houghton et al. (1980b); [f] NTS (1983).

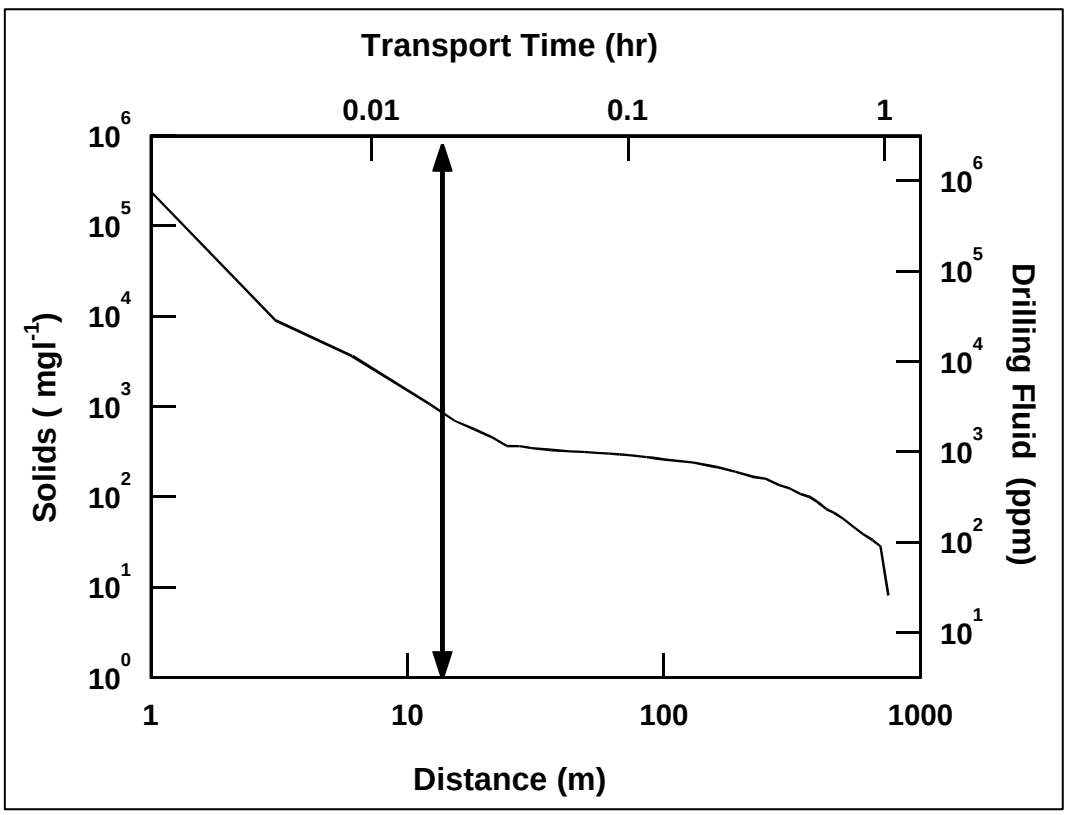
WBM and cuttings dispersion modeling confirms the rapid dispersion and dilution of WBM and WBM cuttings in the receiving water environment. Most modeling is performed with the Offshore Operators Committee (OOC) Drilling Mud Discharge Model (Brandsma and Sauer, 1983a,b, 1992) that has been validated extensively (Nedwed, 1994; Nedwed et al., 2004; Smith et al., 1994) and used frequently by the oil industry and government regulators (EPA and MMS) to predict the fates of drilling muds and cuttings discharges to the ocean.

Ayers (1994) used the OOC mud and cuttings model to predict the dilution and fate of a one-hour WBM discharge at a rate of 42,300 gal/hr to offshore waters of Sakhalin Island in the Russian Far East. The predicted drilling mud plume extended for more than 2000 ft down-current at the end of the discharge (Figure 5-5). The predicted suspended solids concentration in

the plume dropped from 300,000 mg/L (parts/million: ppm) at the source to less than 8 ppm at 2500 ft after a transport time of one hour. The plume was diluted by 1000-fold within about 10 minutes of discharge at a distance of about 300 ft from the platform. The U.S. aquatic toxicity regulatory limit for WBM is 30,000 ppm suspended particulate phase (equivalent to 3,000 ppm drilling mud). The concentration of WBM in the plume dropped below this safe concentration within about two minutes of the discharge about 50 ft down-current from the platform. Thus, marine organisms that may become entrained in or swim through the WBM discharge plume are unlikely to be harmed by it.

Figure 5-5 shows predicted concentrations of drilling mud solids in the water column with distance and transport time (the time required for a parcel of fluid moving with the current to reach a particular distance) during a 42,000 gal/hr WBM discharge lasting 1 hour offshore Sakhalin Island, Russia. The solids concentration dropped from 300,000 ppm at the source to less than 8 ppm at 2460 ft and a transport time of 1 hour. The vertical arrows show the distance from the discharge point at which the solids reached 3,000 ppm, corresponding to the toxicity limit for drilling muds in the current Alaska NPDES permit. The solids fell below this concentration within 50 ft of the discharge. From Ayers (1994).

Figure 5-5 Predicted Concentrations of Drilling Mud Solids in the Water Column with Distance and Transport Time

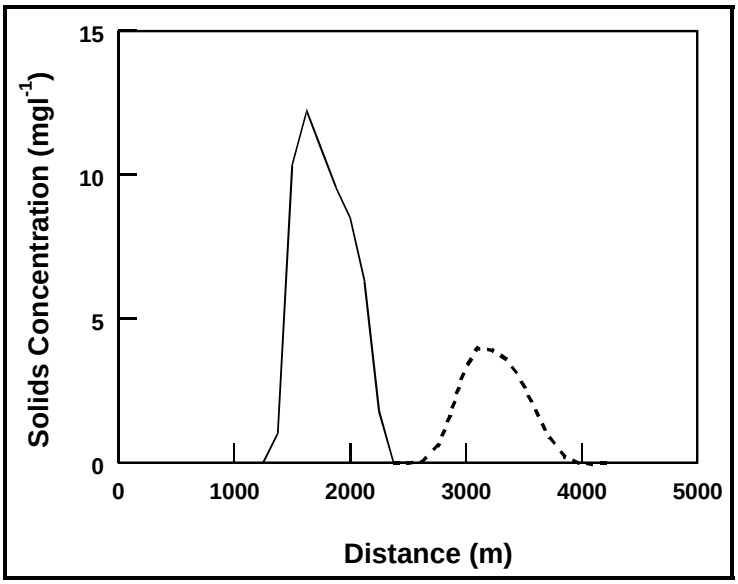


The plume drifted away from the source and continued to dilute after the discharge ceased (Figure 5-6). Two hours after the discharge ended, the maximum predicted suspended solids concentration was 12 ppm, corresponding to dilution by a factor of 26,000. Four hours after the discharge, the solids concentration had dropped to a maximum of 4 ppm corresponding to

dilution by a factor of 78,000. At these low concentrations, the contribution of the drilling mud discharge to the total suspended solids concentration could not be distinguished from natural background concentrations of suspended solids.

Figure 5-6 shows predicted water column concentration of drilling fluid solids at 2 hours (solid line) and at 4 hours (dashed line) after the end of a 1 hour discharge at a rate of 42,000 gal/hr. From Ayers (1994).

Figure 5-6 Predicted Water Column Concentrations of Drilling Mud Solids at 2- and 4-hours



Voparil (2009) recently used the OOC Drilling Mud Dispersion Model to predict dispersion of WBM and cuttings in the water column and their deposition on the sea floor of the Beaufort and Chukchi Seas. The modeling study was performed to aid in the assessment of potential effects on the marine environment of planned exploratory drilling activities in Federal waters of the Beaufort and Chukchi Seas.

Exploratory drilling off Camden Bay in the Beaufort Sea is expected to occur during open water/loose ice conditions during the summer and early fall, with a temporary halt in activities during the fall bowhead whale migration through the area. At this time of year, the water column is stratified, with surface water temperatures and salinities of about 39 to 60°F and 27 to 30 parts per thousand, respectively, grading to about 33°F and 31 parts per thousand below 65 ft water depth. Water circulation during the open water season is controlled primarily by wind direction and river discharges and is primarily to the west (Weingartner, 2006; Weingartner et al., 2005b). Current speeds range from about 4 cm/sec during calm weather to about 89 cm/sec during frequent storms. Suspended sediment concentrations in the water column range from 0.1 to 4 mg/L in calm weather to 50 to > 100 mg/L during storms with greater than 20-knot winds (Trefry et al., 2004; Trefry and Trocine, 2009).

Exploratory drilling in the northeastern Chukchi Sea is expected to occur between July and the middle of September. At this time of year, the water column is stratified, with surface

temperatures and salinities of about 37 to 40°F and 30 parts per thousand, grading to about 30 to 35°F and 32 to 33 parts per thousand below 100 ft water depth (Weingartner et al., 2005a). Current speeds range from about 4 cm/sec during calm weather to about 60 cm/sec during frequent storms. Suspended sediment concentrations in the region of exploratory drilling are expected to be lower than those in the drilling area in the Beaufort Sea.

Voparil (2009) modeled the dispersion of a saltwater/PHPA WBM and cuttings discharged from the 1000 to 14000-ft sections of the well (Table 3-6) at a rate of 3200 to 65,000 gal/hr vertically through a disposal caisson to 17 ft below the sea surface. The discharge is diluted by approximately 30:1 in the caisson. The model predicted that the drilling muds and cuttings discharges would be diluted to less than 100 mg/L between 100 and 300 ft from the discharge and essentially to background in less than 1000 ft down-current from the discharge (Table 5-5). Even after the large-volume bulk discharge of WBM at the end of drilling at the Burger prospect, suspended solids were diluted to about 150 mg/L 300 ft down-current from the discharge. The plume containing more than 1 mg/L above background of suspended sediments extended less than 3300 ft from the discharge, with the highest concentration of suspended sediments at about 65 to 80 ft below the sea surface (Figure 5-7). The plume is diluted to background suspended particulates concentration in less than two hours after the discharge.

Table 5-5 shows estimated suspended solids concentrations (mg/kg) in the WBM and cuttings plume at different distances down-current from a discharge from exploratory drilling operations in the Beaufort and Chukchi Seas. Results of modeling of the bulk drilling mud discharge at the end of drilling in the Burger prospect in the Chukchi Sea are included. Plume dispersion was modeled under oceanographic conditions typical of the discharge sites during the summer and fall when drilling is expected to occur. From Voparil (2009).

TABLE 5-5
Estimated Suspended Solids Concentration in Mud and Cuttings Plume at Different Distances

Distance (feet)	Beaufort Sea		Chukchi Sea			
	Torpedo	Sivulliq	SW Shoebill	Crackerjack	Burger	Burger WBM only
0[a]	38,290	40,250	42,200	42,200	42,200	284,900
3	5540	7027	2437	2459	2437	3207
9	1440	2040	577	676	705	1040
32	373	387	162	163	214	504
98	130	114	90	89	176	388
328	41	41	32	34	40	168
984	7	7	5	5	6	46

[a] Suspended solids concentration at exit from discharge caisson.

The results of all the field and modeling studies performed between the 1970s and 2009 of dispersion and dilution of WBM and cuttings discharges in the ocean have shown that dilution and dispersion of the dissolved and particulate fractions of the discharges are extremely rapid. The National Research Council (1989) concluded, based on a review of results of the modeling

and field studies of drilling mud and cuttings solids performed before 1989, that offshore discharges of WBM and associated cuttings will have little or no harmful effects on water-column organisms. This conclusion is based on the rapid dilution in the water column (Table 5-6) and low toxicity (measured as the chronic no observed effects (NOEC) concentration) to marine organisms of WBM and cuttings. Even if a WBM had a chronic toxicity of 10 mg/L (ppm), dilution would reduce the WBM concentration to well below this concentration within 30 minutes of discharge, assuming a current speed of 10 cm/sec. A 1000-fold dilution would occur in less than one minute.

Figure 5-7 shows the predicted suspended solids plume from the SW Shoebill exploratory well in the Chukchi Sea. The left diagram shows a lateral view of the plume during a high-volume drilling mud discharge. The right diagram shows a crossection of the plume at different times after the discharge. From Voparil (2009).

Figure 5-7 Predicted Suspended Solids Plume from SW Shoebill Exploratory Well in the Chukchi Sea

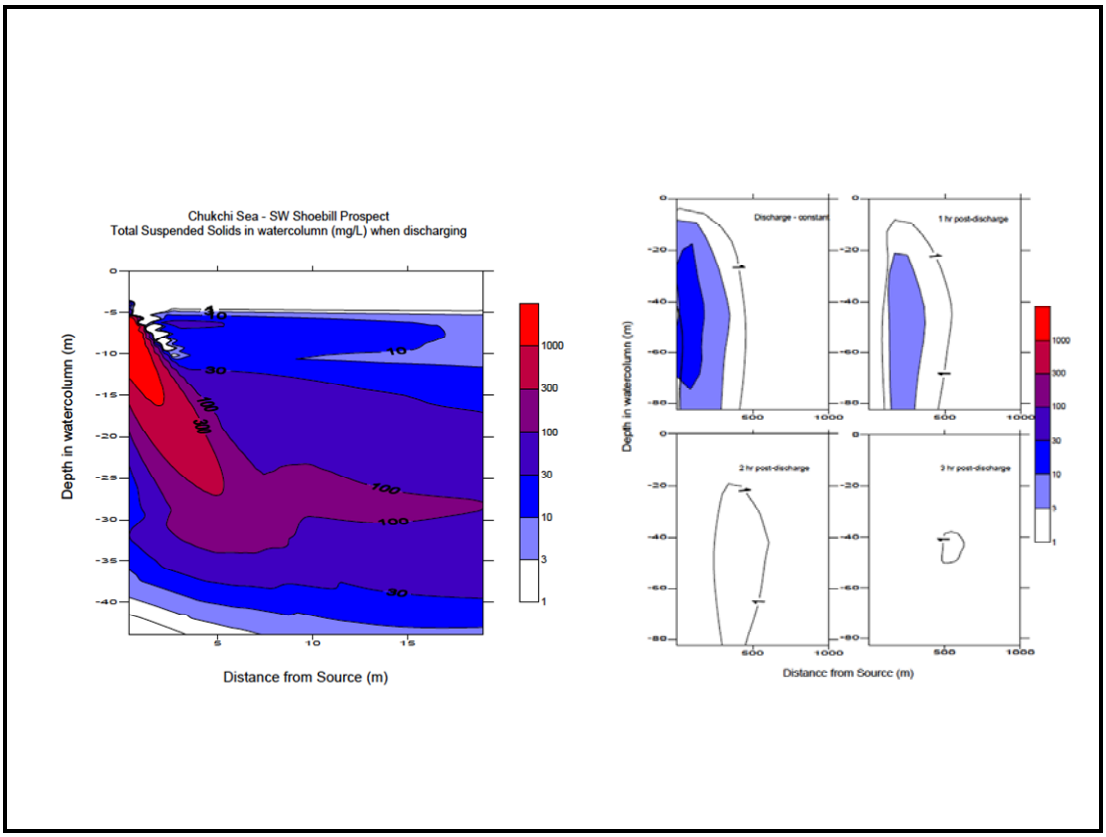


Table 5-6 lists the estimated transport time and distance for dispersion of discharged WBM required to obtain chronic no-effect (NOEC) concentrations, based on laboratory acute, chronic, and sublethal effects studies (See Section 6). From NRC (1989).

TABLE 5-6
Estimated Transport Time & Distance for Dispersion of WBM to obtain Chronic No-Effect Concentrations (NOEC)

Chronic No Effects Concentration (ppm)	Dilution factor required	Transport Time (min)	Distance (ft) at current speed of 10 cm/sec in 5 & 15 min		Percent Frequency
			5 min	15 min	
1000	1000	0.45	4.5	13.4	52
100	10,000	11.1	110	328	94
10	100,000	29.8	292	876	100

No measureable adverse effects on the water column environment of routine WBM and cuttings discharges have been measured, because discharges of small amounts of materials are intermittent and take place only during drilling operations spaced over a few to several months (NRC, 1983; Neff, 2005). Drilling mud solids do not increase to high concentrations in the water column, affect only small parcels of water, and dilute to background rapidly. Periodic, minor increases in the turbidity and suspended particulate material concentrations in the upper water column during mud and cuttings discharges will not have an environmentally significant effect on phytoplankton, zooplankton, and pelagic animal communities in the vicinity of the drill rig (National Research Council, 1983).

Therefore, the focus of more recent offshore WBM and cuttings discharge studies has been on accumulation of drilling mud and cuttings solids on the sea floor. Some of these studies do contain a water column component (e.g., Rye et al., 2008) that confirms the conclusions of the plume dispersion studies.

5.5 Accumulation of WBM and Cuttings Solids in Sediments

All WBM solids and drill cuttings, including adsorbed water-soluble drilling mud ingredients, eventually settle to and accumulate on the sea floor. The distance from the platform and the depth of the solids accumulation (the cuttings pile) depend primarily on the compositions, amounts, and rates of drilling solids discharges, current speeds and directions at different depths in the water column, density stratification in the water column, and water depths. In high-energy environments, such as Lower Cook Inlet, AK (Houghton et al., 1980b), Tanner Bank off California (Ray and Meek, 1980), and Georges Bank off Massachusetts and Nova Scotia (Neff et al., 1989; Hannah and Drozdowski, 2005), little drilling mud and cuttings accumulates on the sea floor near the drill site and deposited solids are quickly swept away by bottom currents. In lower-energy, deep-water environments, such as the mid-Atlantic outer continental shelf (Ayers et al., 1980b; EG&G Environmental Consultants, 1982) and the Grand Banks off Newfoundland (Hannah and Drozdowski, 2005), much of the mud and cuttings may settle on the bottom within a short distance of the platform and persist there because residual currents are weak and storm-driven currents do not extend to the bottom. Water depth at the discharge site often has a large effect on the rate of drilling solids accumulation and persistence on the sea floor (Boothe and Presley, 1989). Storm-wave- or current-induced bed transport in shallow water tends to resuspend and disperse accumulated mud and cuttings solids. Frascari et al. (2000) monitored WBM and cuttings accumulations around a drilling platform in 50 ft of water in the Adriatic Sea east off Italy and found that discharged solids accumulated near the platform during the

relatively calm summer season and were dispersed over a wide area during the stormy winter months.

Open water and below ice discharges of drilling mud and cuttings to the shallow Beaufort Sea are dispersed rapidly, with only particle flocs persisting at the benthic boundary layer (the water/sediment interface) (NTS, 1981, 1983). The greatest dispersion occurs in deep water environments where water currents are high at all water depths and drilling wastes are discharged near the surface. This combination of conditions occurs in deep channels of the southern Barents Sea near the site of the Snøhvit development (Lei et al., 1994).

Shunting was used during development of the gas resources at some facilities in the High Island Lease Area, near the Flower Gardens Banks off Texas/Louisiana (CSA, 1985; Kennicutt, 1995). Shunting was used here to protect the coral reefs at the top of the bank from suspended solids associated with the discharged mud and cuttings. Drilling mud and cuttings were shunted in a discharge pipe and discharged within about 10 m of the sea floor. When shunted to near the bottom, the mud and cuttings solids accumulated in a large pile directly under and in a small area near the end of the shunt pipe. Shunting prevents wide dispersal of the discharged solids, so elevated concentrations of mud and cuttings ingredients are localized near the point of discharge. This practice was effective near the Flower Garden Banks in preventing mud and cuttings solids from spreading to and depositing on the sensitive coral reef community at the top of the bank. However, it did result in a localized accumulation of a large amount of solids and associated drilling mud chemicals in a small area on the sea floor near the end of the discharge shunt pipe. The cuttings pile reached a height of about 6 to 9 ft and a diameter up to 70 ft. The size of the cuttings pile decreased rapidly due to settling, compaction, and water current erosion. There was no visible evidence of the cuttings pile on the sea floor within a few years of completion of drilling.

By comparison, many cuttings piles in the North Sea are more than 3 ft deep (Hartley et al., 2003). This is because, historically (until the mid-2000s), all or the deeper sections of most oil wells in the North Sea were drilled with OBM or SBM. OBM and SBM cuttings often were shunted to just above the sea floor at many large, multi-well North Sea developments (Bell et al., 2000). OBM and SBM cuttings, being “oil-wet”, tend to clump and settle rapidly as large particles over a small area near the platform, often producing a deep cuttings pile directly below the discharge pipe (Neff et al., 2000). They do not disperse readily and so tend to be more persistent than WBM cuttings piles.

Video surveys were performed recently at Arctic exploratory drilling sites in the Tornerose prospect in 1300 ft of water in the Norwegian Barents Sea 34 miles east of the Snøhvit development and at the Laggan prospect in 1970 ft of water in the Faroe-Shetland Channel west of Shetland Island (Jones et al., 2006, 2007; Serpent Project, 2007). Following drilling of the top hole, the only section from which large amounts of drilling mud and cuttings were discharged, visible accumulations of cuttings were scattered on the sea floor out to about 165 ft from the Tornerose drill site (deeper sections of the well probably were drilled with SBM and the cuttings were not discharged). The sea floor was completely covered with a thin layer of cuttings in a radius of about 80 ft from the drill site. The depth of the cuttings pile ranged from 13 to 19 inches within 30 ft of the drill pipe to less than 0.4 inches at 80 ft and less than 0.05 inches at distances greater than 80 ft. The cuttings pile sediment had a slightly higher concentration of

silt+clay, but a similar concentration of total organic carbon than the pre-drilling surface sediments. The only metal present in the cuttings pile at higher concentrations after drilling than before was barium. The barium concentration increased by up to 40-fold in sediments within 30 ft from the drill site. Concentrations of the other metals analyzed (cadmium, chromium, copper, lead, and zinc) did not change.

Visible accumulations of drilling mud and cuttings were larger at the Laggan prospect site where several wells had been drilled with WBM. Complete coverage of the sea floor to a depth up to 3 ft with drilling waste solids extended to about 300 ft from the well site, probably from drilling of the top hole section. Scattered, thin patches of mud and cuttings extended to more than 800 ft in the direction of weak current flow. The cuttings pile sediments were finer than those of the adjacent undisturbed sea bed. Minor biological effects on bottom-living marine animals of deposited drilling waste solids near the two drilling sites were attributed to burial and changes in sediment texture.

Modeling studies have tended to confirm the direct observations of drilling waste accumulation on the sea floor. Lie et al. (1994) modeled deposition of drilling mud and cuttings discharged during exploratory drilling in the southern Barents Sea. They then verified the model predictions by sampling drilling solids accumulation on the sea floor after drilling. The well was drilled in 1215 ft of water on the southern slope of the Bear Island Channel about 40 miles northwest of the Snøhvit production facility. As is the current practice in the Beaufort Sea, drilling mud and cuttings from the top hole section were discharged directly to the sea floor and their fate was not modeled. The deeper sections of the well were drilled with a KCl/polymer WBM and WBM and cuttings were discharged to the ocean through a discharge pipe that opened 50 ft below the sea surface. The average grain size of waste drilling muds ranged from 0.006 to 0.028 mm (silt/clay); the average size of drill cuttings particles ranged from 0.3 to 1 mm (sand) in the deeper sections and <0.063 to 10 mm (silt to coarse sand) at shallower drilling depths. Water current speeds at the site during the monitoring activity ranged from 3 to 46 cm/sec at a depth of 165 ft to 5 to 33 cm/sec 8 ft above the sea floor.

The solids discharge was modeled as 3 fractions, based on density: drill cuttings, high density drilling mud solids (barite), and low density drilling mud solids (sand, silt, clay). The total amounts of drilling solids discharged from the platform during the exploratory drilling campaign were 85,900 gallons of cuttings, 23,000 gallons of barite, and 7925 gallons of silt/clay. It was assumed that solids with a settling velocity less than 0.13 cm/sec would not reach the sea floor within the modeled deposition radius (30 miles). Table 5-7 shows the predicted distribution of the remaining (denser) solids on the sea floor around the drill site. More than 50% of the cuttings accumulated within 1600 ft of the discharge; more than 99% of the drilling mud solids settled more than 3300 ft from the discharge. The maximum predicted thickness of the barite layer was less than 1 µm, with an average thickness of 0.05 µm within 3300 ft of the rig. The depth of the drill cuttings layer also was thin, with only a few patches of cuttings exceeding a depth of 0.1 mm (0.004 inches).

Table 5-7 lists post-drilling modeling of the distribution of drill cuttings, drilling mud barite, and drilling mud less-dense particles (clay) in surface sediments around an exploratory drilling rig in 1215 feet of water in the southern Barents Sea. The values are percent of total settleable particles (settling velocity > 0.13cm/sec) within different radii of the rig. From Lie et al. (1994).

TABLE 5-7
Post-drilling Modeling of Drill Cuttings, Barite and Clay Particles in Exploratory Well drilled in 1,215 ft of Water

Radius	Percent Settling Drilling Mud and Cuttings Particles Within the Radius		
	Drill Cuttings	Drilling Mud Barite	Drilling Mud Clay
820	25	0.05	0.03
1640	56	0.2	0.2
3280	67	1	0.7
16,400	82	22	18
32,800	90	47	42
164,000	100	100	100

The post-drilling sediment and sediment trap monitoring generally confirmed the modeling results. Patches of barite up to 0.5 to 0.6 µm thick were detected by analysis of barium concentrations in surface sediments before and after drilling. Mean barium concentrations increased from 101 mg/kg (ppm) before to 111 ppm after drilling. Mean sediment grain size also was larger after than before drilling, possibly indicating the accumulation of drill cuttings. However, concentrations of all other metals analyzed in sediments (cadmium, copper, iron, mercury, lead and strontium) remained at pre-drilling background concentrations. The wide dispersion of discharged WBM and drill cuttings was attributed to the relatively great water depth and the strong water currents at all depths in the water column.

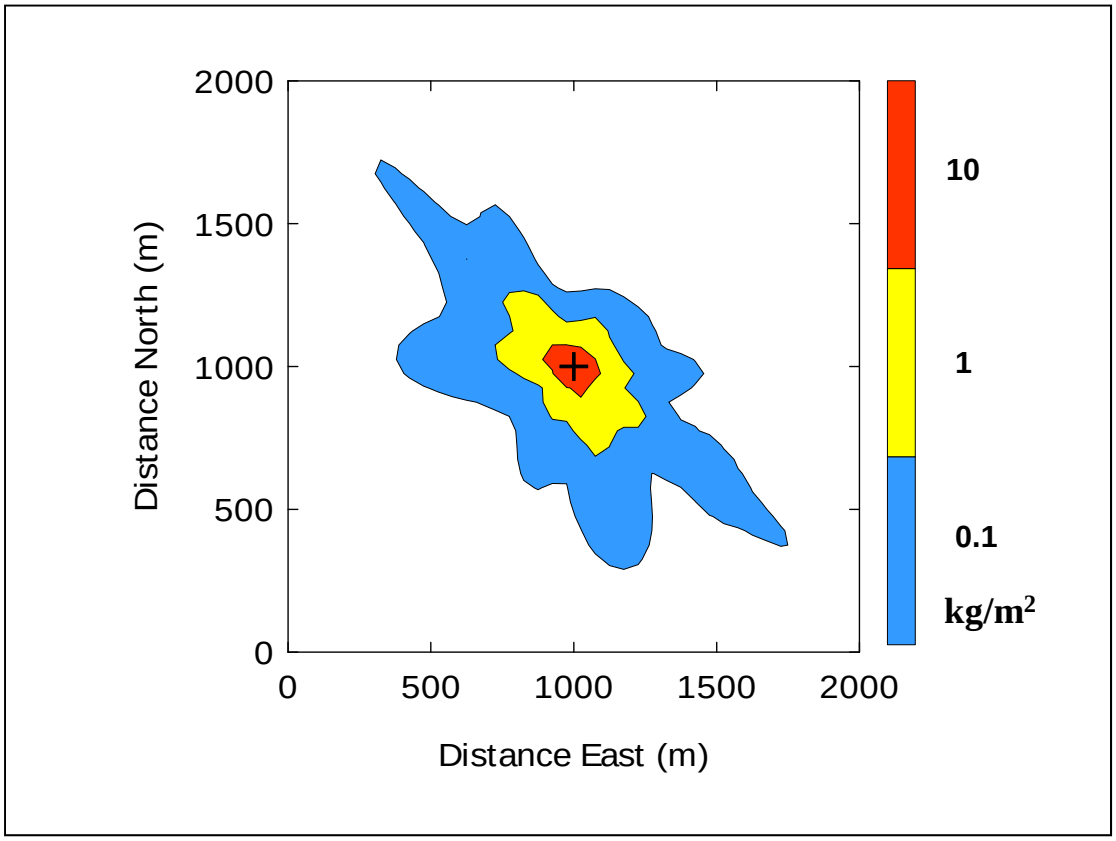
Fluxes of drilling mud solids to the sea floor were modeled near 3 production platforms on the outer continental shelf off southern California, based on drilling mud and cuttings discharge data collected during drilling and accumulation of barite (from discharged drilling muds) in sediment trap arrays deployed at several locations 0.3 to 4 miles from the platforms (Coats, 1994; Hyland et al., 1994). During peak drilling activity, maximum predicted fluxes of drilling solids to the sea floor occurred within 0.9 miles of the platforms and ranged from 0.008 to 0.01 lb/ft^2/day, less than 2 % of the total natural particulate flux into the sediment traps. The discharged drilling mud and cuttings were spread up to 4 miles from the platforms by strong water currents with an average speed of 1.5 cm/sec. Although more than 10 million gallons of drilling muds and cuttings were discharged from the 3 platforms during the 2 years of monitoring, there was little net deposition of drilling waste solids in local sediments, as indicated by the small increase in sediment barium concentration over the discharge period.

Smith (2003) modeled the dispersion and deposition of WBM and WBM cuttings in deep water (Figure 5-8). The solids settled and accumulated over a wide area of the sea floor, mostly along the axis of the net tidal current ellipse. The predicted maximum loading of drilling waste solids on the sea floor was 132 lb/ft^2 in a small area adjacent to the platform. Most of loading near the platform probably was from the direct returns to the seafloor during drilling of the surface hole before the top-hole casing and riser were installed. The direct returns consist primarily of natural near-surface sediments from the drill site and a small amount of spud mud solids. A spud mud, containing a small amount of clay and barite in seawater (Table 3-6), usually is used during drilling of the top-hole. Lighter loadings to about 0.02 lb/ft^2 in sediments extended to about 1000 m from the platform. Predicted increments in sediment barium concentration (from drilling mud barite) ranged from nearly 20,000 ppm near the platform to about 30 ppm where sediment loading with waste solids was 0.02lb/ft^2. The drilling waste accumulated on the bottom to a maximum estimated depth of about 1.6 inches.

Muschenheim and Milligan (1996) performed video of surveys of a drilling site in 100 ft of water on the Scotian Shelf off Atlantic Canada. Video surveys conducted immediately after drilling revealed visible flocs of particulate matter in the benthic boundary layer of the sea floor extending up to 1.25 miles from the drilling platform. A second survey performed 7 months later revealed 1 or 2 small deposits of visible particles but not the extensive coverage observed in the earlier study. High resolution color video images obtained during another field survey revealed dark flocculated material on the sea floor up to 9 miles from a production platform during development drilling (Cranford et al., 2001). Highest concentrations were near the platform, suggesting that the flocs were from drilling discharges. However, they did not collect and analyze the flocs to determine if they were from the drilling discharges. The platform was the geographic center of a water column turbidity field that could have been natural or enhanced by accumulation of flocculated drilling waste particles. Analysis of the bottom current speeds indicated that they were sufficiently energetic to resuspend the fine-grained particles, including those deposited during drilling, explaining why they were not detected in a later survey. The flocculated sediment particles were alternately resuspended and deposited during each tidal cycle, particularly during storms. Lyne et al. (1990) measured extensive sediment resuspension and movement, even at more than 300 ft, during storms on nearby Georges Bank, indicating that bottom flocs are a natural feature of shallow-water ocean environments.

Figure 5-8 shows modeled distribution and loading of WBM and cuttings solids on the sea floor following drilling mud and cuttings discharges to offshore waters. Maximum loading of the sea floor with drilling solids was about 64 kg/m^2 (13.2 lbs/ft^2), representing a thickness of solids of about 1.5 inches. The increment in barium concentration in the cuttings pile is approximately 30 ppm. From Smith (2003).

Figure 5-8 Modeled Distribution of WBM and Cuttings on the Sea Floor following Discharges to Offshore Waters

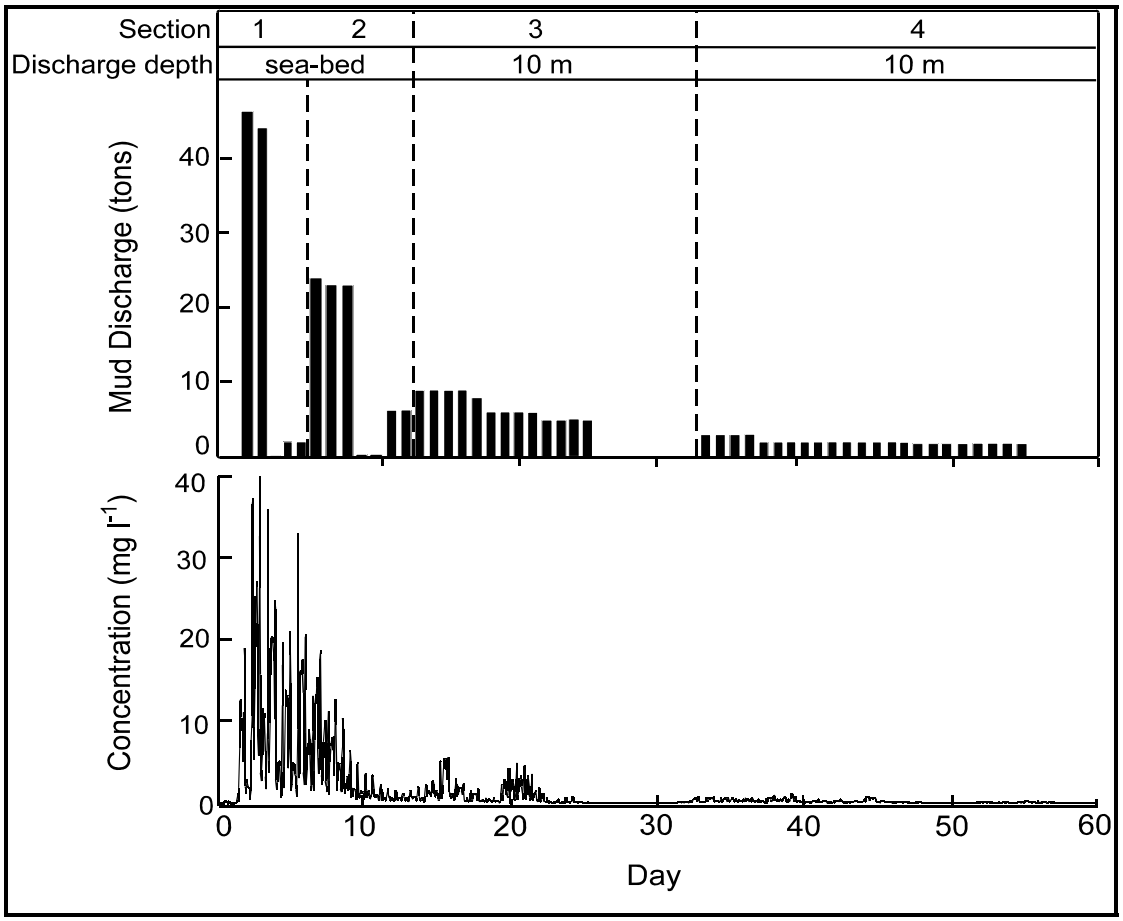


Andrade and Loder (1997) and Hannah et al. (1995, 2006) used the results of these physical oceanographic and drilling waste dispersion and deposition studies to evaluate plume descent models for drilling waste discharges and for development and application of a novel model, called the Benthic Boundary Layer Transport (BBLT) model, for drilling waste dispersion and drift in the benthic boundary layer. The plume descent model simulations have confirmed rapid initial dilution of discharged solids, but have also indicated that the fraction reaching the benthic boundary layer can vary substantially, depending on the local physical and oceanographic features, such as currents, stratification, water depth, and sediment types, at the discharge site.

Simulations for the Canadian Northeast Peak of Georges Bank predict that regional and temporal variations in physical oceanographic processes have a large influence on the potential zone of influence of discharged drilling wastes (Gordon et al., 2000). Estimated concentrations of drilling solids in the benthic boundary layer varied seasonally based on changes in bottom current speeds and turbulent mixing. During drilling of a well, predicted floc concentrations in the benthic boundary layer varied over short time scales and were highest during drilling of the top hole sections (Section 1, lasting about 5 days) when discharge volumes were highest and discharged directly to the sea floor; concentrations were low during later mud and cuttings discharges (Figure 5-9).

Figure 5-9 shows top: Hypothetical WBM discharge scenario for the first 60 days of exploration drilling on the Northeast Peak of Georges Bank. Bottom: Example of predicted near sea floor WBM floc concentrations near one of the hypothetical exploratory drilling sites on Georges Bank, as predicted by the BBLT model. Adapted from Gordon et al. (2000) by Cranford et al. (2001).

Figure 5-9 Hypothetical WBM Discharge Scenarios and Predicted Near Sea Floor Floc Concentrations, Georges Bank



Hannah and Drozdowski (2005) used the BBLT model to evaluate the influence of oceanographic conditions on deposition and persistence of drilling waste flocs at the benthic boundary layer near actual or proposed oil and gas development sites on 3 banks on the outer continental shelf of Atlantic Canada: Georges Bank, Sable Island Bank, and the Grand Bank, all important commercial fisheries areas. The three banks have different current and turbulent mixing regimes that affect dispersion and deposition of drilling waste flocs. Water column mixing energy (current speeds and turbulence) is greatest on the northeast peak of Georges Bank, lowest on the Grand Banks, and intermediate at the North Triumph prospect on the Sable Island Bank. Based on model outputs for typical oceanographic and meteorological conditions on the three banks, Georges Bank is the least likely to experience large particle fluxes from drilling discharge, with predicted near-bottom floc concentrations about an order of magnitude lower than those at North Triumph and a factor of 20 to 50 lower than those at Hibernia on the Grand

Banks. Highest floc concentrations at North Triumph and Hibernia are expected during the summer. Concentrations of flocs composed of a fine clay/barite mixture and measured as particulate barite concentrations, were highly variable over short time scales and ranged from less than 0.1 µg/L to more than 100 µg/L (Hannah et al., 2006). Background concentrations of barium (as barite) in the ocean usually are in the range of 0.05 to 1.0 µg/L; the concentration is higher in areas of high primary productivity (Neff, 2002). The concentrations measured by Hannah et al. (2006) are only about 10-fold above natural concentrations and are below concentrations required to depress feeding and growth in juvenile scallops, the most sensitive species to drilling muds (Cranford et al., 2003), during chronic exposure. Because of the predicted intermittent exposure to drilling mud flocs near platforms during drilling, it is unlikely that discharge of WBM and cuttings to waters of the three Canadian fishing banks will have any effect on bottom-dwelling marine animal populations.

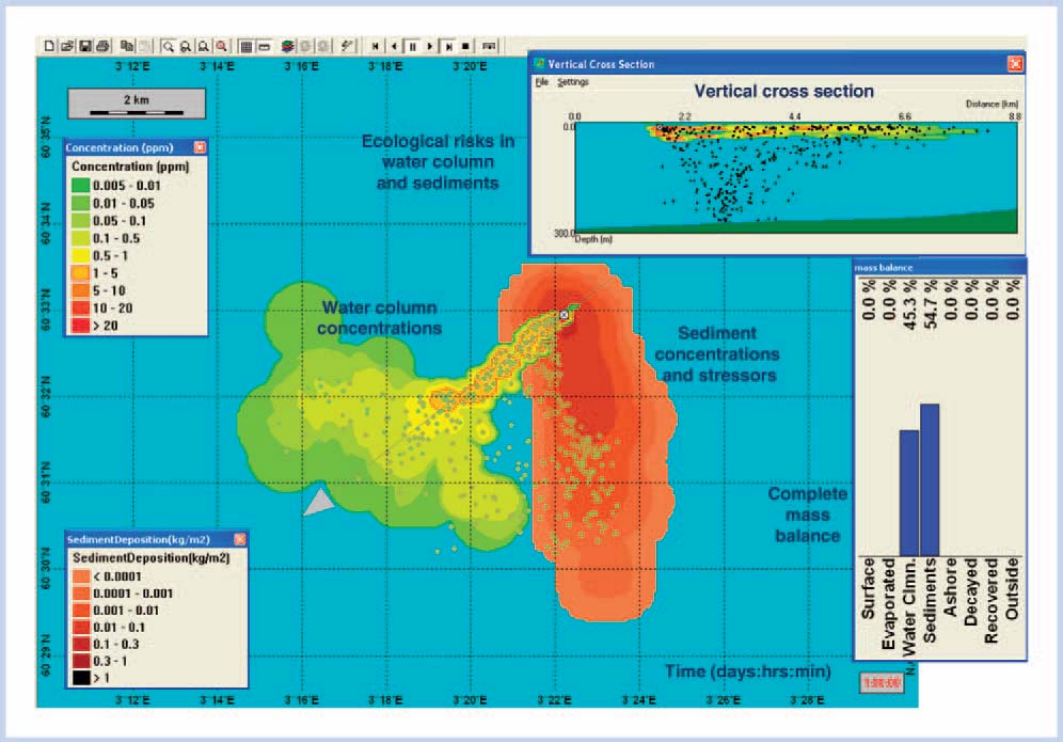
The results of this Canadian modeling effort are not inconsistent with the results of other modeling efforts. Floc-associated mud and cuttings solids at the sediment boundary layer would not be sampled adequately by conventional sediment sampling methods and most existing models do not adequately consider the behavior of flocculated solids. However, the BBLT model has not been validated by sampling and analysis of drilling solids flocs collected at the benthic boundary layer during drilling discharges. Therefore, it is uncertain if the model is accurately predicting elevated (above natural background) concentrations of drilling waste flocs.

As part of the Environmental Risk Management System (ERMS) program to develop risk-based management tools for drilling waste and produced water discharges to the ocean, Rye et al. (2006, 2008) developed a fate and effects model for drilling discharges. The model predicts the fate of the drilling discharge in the water column, including near-field mixing, plume motion, far-field mixing, and transport. The model also estimates the risk to bottom-dwelling marine animals of physical and toxicological effects from exposure to deposited drilling solids. The model currently is undergoing field verification.

Results are presented as a three-dimensional visualization of the concentration fields of solid and dissolved chemicals in the discharge plume in the water column, and deposition of drilling mud and cuttings solids on the sea floor (Figure 5-10). The particles in the model are spread in the water column by ocean currents and turbulence (after the termination of the near-field plume phase). The rate and pattern of solids deposition on the sea floor is determined mainly by the settling velocities of drilling waste particles of different sizes, water column stratification, and current speeds and directions at different depths in the water column. The model also can predict the concentrations of drilling mud and cuttings chemicals (metals and hydrocarbons) in the plume and in seafloor sediments.

Figure 5-10 shows the output of the ERMS risk based drilling mud fate and effects model (DREAM). The model predicts the trajectory and concentrations of solids in the water column, the pattern and concentrations of solids on the sea floor, and environmental impact factors for solids in the water column and sediments. From Rye et al. (2008).

Figure 5-10 Output of Risk-Based DREAM Model



5.6 Accumulation of Chemicals from WBM and Cuttings in Sediments Near Offshore Platforms

5.6.1 Hydrocarbons in Sediments Near Offshore Drilling Platforms

It was common practice in the past, but is less common today, to add diesel fuel or mineral oil to WBM to aid in lubricating the drill string or to aid in freeing stuck pipe. Drill pipe occasionally becomes stuck to the sides of the well bore. This can be caused by swelling or sloughing of shales in the bore-hole wall, during drilling of a deviated well, or unequal pressures in the borehole that can cause “differential sticking”. Lubricating agents or a slug of OBM often were used in the past to decrease the friction and free the pipe. The current practice, and the one that will be used if necessary when drilling exploratory wells in the Beaufort and Chukchi Seas, is to use water based lubricants, silica beads, or other non-toxic substances (Table 3-1). If these methods fail, then the pipe may have to be cut off, and a side track well drilled. The current NPDES permit prohibits ocean discharge of oily muds and cuttings. The oily pill around the stuck pipe section and associated cuttings usually are isolated from the WBM system and disposed of by an alternative means. However, a small amount of oil may get into the WBM system and be discharged with it. The well also may penetrate strata containing oil-rich shales, peat, or kerogens, containing hydrocarbons. These hydrocarbons are tightly bound to insoluble particles and have a low bioavailability to marine organisms. Cuttings from these sections sometimes are discharged if they do not form an oil sheen on the sea surface. Hydrocarbons from these cuttings will accumulate in sediments near the rig.

Hydrocarbon concentrations in these cuttings piles are much lower than those in cuttings piles formed from OBM and SBM cuttings discharges (Davies et al., 1989; Neff et al., 2000). Cuttings piles from multiwell platforms in the North Sea contain elevated concentrations of total hydrocarbons (THC) and polycyclic aromatic hydrocarbons (PAH) if the wells were drilled with OBM or SBM and the cuttings were discharged (Table 5-8). If OBM or SBM cuttings were not discharged, hydrocarbon concentrations in the cuttings piles were low. A frequent practice in the North Sea was to drill the top hole sections with WBM and drill deeper sections in shale formations with OBM or SBM. Discharge of OBM and SBM cuttings has been phased out gradually in the North Sea since the late 1980s, with zero discharge of OBM and SBM cuttings achieved in 2007. WBM cuttings are considered non-hazardous and are still discharged to the North Sea, because of the phase out of OBM and SBM cuttings discharges, THC concentrations in North Sea cuttings piles have decreased by up to 70 % since 1978 (Jensen and Noland, 2006; Renaud et al., 2008).

Table 5-8 lists the concentrations of hydrocarbons and metals in cuttings piles at four production platforms that used different types of drilling muds and discharged cuttings to the North Sea. The top hole usually was drilled with WBM and lower sections were drilled with OBM or SBM. Only WBM were used at Frig. Concentrations are mg/kg dry wt (ppm). Data from Park et al. (2001) and Westerlund et al. (2001).

TABLE 5-8
Concentrations of Hydrocarbons and Metals in Cuttings Piles at Four North Sea Production Platforms

Chemical	Production Platform and Types of Drilling Muds Used			
	Beryl A	Maureen A	Ekofisk 2/4 A	Frig
	WBM/OBM	WBM/OBM/SBM	WBM/SBM	WBM
THC[a]	57,000	17,000	24,000	82
PAH[b]	13	0.82	1.0	0.05
Benzo(a)pyrene	0.07	0.003	0.01	0.002
Arsenic	17	8.6	10.5	4.11
Barium[c]	468	35,000	476	1441
Cadmium	0.74	2.0	0.85	0.67
Chromium	51	93	32	70
Copper	67	93	72	11
Lead	291	157	195	21
Mercury	0.56	2.44	0.24	0.03
Nickel	32	55	35	7.7
Zinc	316	1100	377	43

[a] THC = total extractable hydrocarbons;
[b] PAH = total polycyclic aromatic hydrocarbons (16 analytes);
[c] Some samples were analyzed by methods that do not recover total barium; actual concentration may be higher (Hartley 1996).

The sources of the hydrocarbons in WBM and cuttings can be identified in environmental samples by their hydrocarbon signatures. Diesel fuels, mineral oils, and oil-rich sediment layers contain characteristic saturated and aromatic hydrocarbon fingerprints that that can be identified

in environmental samples by suitable fingerprinting methods (Boehm et al., 2001c; Stout and Emsbo-Mattingly, 2008).

Drill cuttings containing low concentrations of TPH and PAH were discharged to the outer continental shelf at the Point Arguello Field off California during drilling of 39 wells from 3 platforms (Table 3-9). Although there was a slight increase in TPH concentrations in sediments near platform Hidalgo during drilling (from a mean of 49 ppm to 93 ppm), there was not a significant increase in the mean concentration of total PAH in the sediments (Table 5-9). TPAH concentrations in sediments over 4 years before to 1 year after drilling ranged from 0.01 to 0.3 ppm; most of the PAH, particularly in the pre-drilling nearfield samples, were biogenic (perylene), derived from transformation of natural plant material in oxygen-free sediments, probably from shallow subsurface sediment layers penetrated by the drill (Venkatesan, 1988; Silliman et al., 1998), pyrogenic (from combustion), or petrogenic (from nearby oil seeps).

Table 5-9 lists the mean concentrations of hydrocarbons and metals in surface sediments from nearfield (0.9 to 0.4 miles) and farfield (1.4 to 1.6 miles) around platform Hidalgo off southern California before, during, and after drilling mud and cuttings discharges. Concentrations are mg/kg dry wt (ppm). From Hyland et al., 2004).

TABLE 5-9
Mean Concentration of Hydrocarbons and Metals in Surface Sediments, Hidalgo Platform, Southern California

Chemical	Nearfield			Farfield		
	Before	During	After	Before	During	After
THC	49	93	50	41	93	67
TPAH	0.29	0.07	0.03	0.08	0.08	0.02
Arsenic	9.7	11	9.7	6.7	6.8	6.8
Barium	764	970	888	789	872	853
Cadmium	0.56	0.62	0.58	0.59	0.61	0.58
Chromium	124	120	123	131	127	139
Copper	15	16	15	16	14	15
Lead	14	13	14	17	15	14
Mercury	0.067	0.085	0.054	0.075	0.088	0.063
Nickel	40	39	40	44	42	43
Silver	0.13	0.09	0.08	0.13	0.09	0.08
Vanadium	54	48	51	63	53	54
Zinc	75	76	74	66	63	63

THC = Total petroleum hydrocarbons by GC-MS; TPAH = Total 2 through 5-ring aromatic hydrocarbons by GC-MS (Steinhauer et al., 1994).

Similar observations were made during drilling of several exploratory wells on Georges Bank off New England (Neff et al., 1989a; Phillips et al., 1987). Although diesel fuel was added to the WBM for one well to free stuck pipe and about 140 gallons of diesel fuel was discharged with

waste drilling mud (Phillips et al., 1987), there was only a slight increase in TPH and total PAH concentrations in a few sediment samples near the discharge site after drilling. TPAH concentrations in sediments near the rig never exceeded the range of background aromatic hydrocarbon concentrations for outer continental shelf sediments from the region (Boehm and Farrington, 1984), and returned rapidly to pre-drilling concentrations shortly after completion of drilling.

Trefry and Trocine (2009) performed a predrilling monitoring survey in the Camden Bay area where Shell Offshore, Inc. hopes to drill two exploratory wells. Concentrations of TPH and TPAH in surface sediments throughout the area were in the range reported throughout the Beaufort and Chukchi Sea OCS, and other offshore areas in Alaska and the Barents Sea (Table 5-10). However, sediments from a single station at the site of the Hammerhead exploratory well, drilled in 1985, contained TPH and TPAH concentrations higher than the range for the regional background concentrations. A sediment core collected at the Hammerhead site contained a mean of 1.2 ± 0.82 mg/kg dry wt (ppm) TPAH, with the highest concentration (3.5 ppm) in the surface sediment layer. About 20% of the PAH in the sediment with the highest TPAH concentrations was perylene, a natural biogenic PAH. Sediments 50 ft or farther from the drill site contained only slightly elevated TPAH concentrations, well within the regional background TPAH concentration range reported in several studies (Figure 5-11). Most PAH assemblages in surface sediments throughout the Beaufort Sea, including the Mackenzie delta area of Canada, and in the Barents Sea, are enriched in perylene. The PAH composition of the drill-site sediments and the regional sediments is consistent with combined petrogenic (petroleum, coal, kerogen, peat), biogenic (perylene), and combustion (mainly 4- 5-ring PAH) sources. Some of the petroleum PAH also could have been from any of the many oil seeps along the Beaufort Sea and Barents Sea coasts, but most probably came from erosion of coastal and inland peat and coal/kerogen by storm waves and spring floods from local rivers.

The sediment core from the Hammerhead drill-site also contained higher concentrations of barium, chromium, and lead than sediments at other Camden Bay locations. The highest concentration of barium was below 2.5 inches in the core, whereas the highest concentration of TPAH, chromium, and lead were in at the surface of the sediment core. Barium (as barite) tends to behave differently than the metals and organic compounds not associated with the solid barite when discharged WBM and cuttings settle to the bottom, possibly explaining the different distributions. Nevertheless, it is uncertain if the TPAH, barium, chromium, and lead were derived from the drilling muds and cuttings discharged at Hammerhead more than 20 years ago. Sediments from the Sagavanirktok and Canning Rivers are enriched in TPAH, chromium, and lead, but not barium (Steinhauer and Boehm, 1992), so some of the surface sediments at the Hammerhead drill site may have come from river sediments. The drill-site PAH must have been sequestered or tightly bound to sediment particles, or they would have been biodegraded by sediment bacteria, abundant in Beaufort Sea sediments (Braddock et al., 2004), in the 24 years since drilling occurred. Much of the PAH probably are bound to oil-rich shales, kerogen, or peat associated with river sediments and cuttings from the top portions of the well (Boehm et al., 2001a). Some of the PAH also could be from lignite and gilsonite additives to the WBM. Lignite and gilsonite are natural hydrocarbon materials (soft coal and asphaltic material). They contain traces of PAH (Stout and Emsbo-Mattingly, 2008) that are tightly bound to the organic matrix of these fossil materials and, so, are very persistent but not bioavailable or toxic to marine organisms (Rust et al., 2004). Steinhauer and Boehm (1992) Yunker et al., (1991, 1995), and

Naidu et al. (2003, 2006) and Elmquist et al. (2008) have concluded, based on the abundance of perylene in sediments from sites with and without a past history of exploratory drilling, that most of the PAH in Beaufort Sea, Barents Sea, and other Arctic sediments, including those from drill sites, comes from erosion of peat, coal, and black carbon (all of which closely resemble the lignite and gilsonite WBM additives) deposits along the coast or rivers emptying into the Arctic Ocean. PAH in sediments from the Norwegian and Russian regions of the Barents Sea also have been derived in part from eroding natural deposits of kerogens, oil shales, and coals (Dahle et al., 2003; Elmquist et al., 2008; Boitsov et al., 2009). These tightly bound PAH have a low bioavailability and, therefore, are not toxic to marine plants and animals (Rust et al., 2004; Neff et al., 2005).

Table 5-10 lists concentrations of total PAH in marine sediments from the Beaufort Sea, elsewhere in Alaska, and the world.

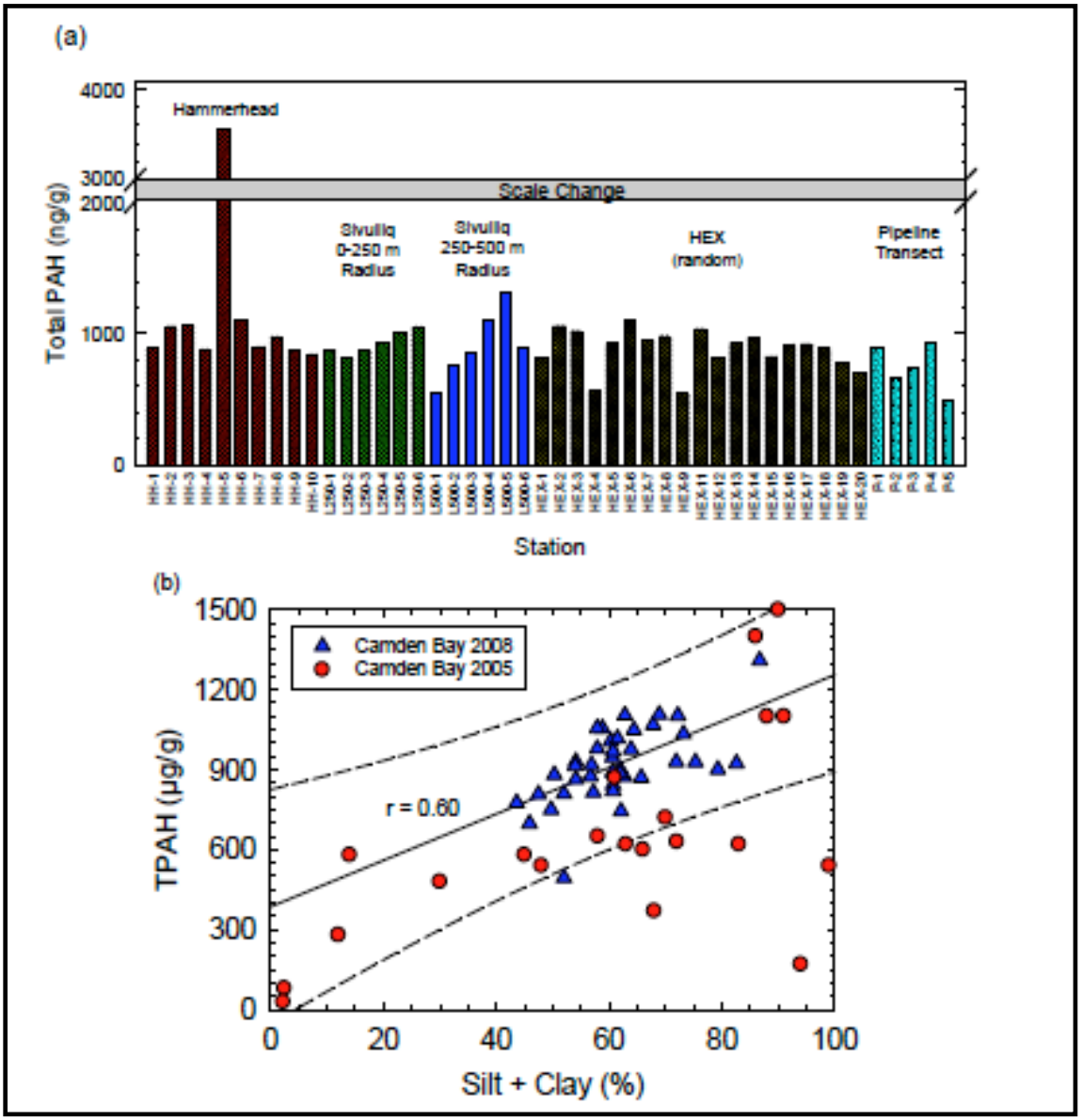
TABLE 5-10
Concentrations of Total PAH in Marine Sediments from Beaufort Sea, elsewhere in Alaska, and the World

Location	Total PAH (mg/kg: ppm)	Reference
Beaufort Sea Surface Sediments	0.03 - 1.8	Brown et al., 2010
Beaufort Sea Sediment Cores (2 - 12 cm)	0.30 - 2.95	Brown et al., 2010
Camden Bay, Beaufort Sea, Except Hammerhead	0.49 - 1.3	Trefry and Trocine, 2009
Camden Bay, Beaufort Sea, Hammerhead Area	0.84 - 3.5	Trefry and Trocine, 2009
Beaufort Lagoon, E. Beaufort Sea	0.03 - 0.71	Naidu et al., 2006
Elson Lagoon, W Beaufort Sea	0.008 - 3.2	Naidu et al., 2003
Beaufort Sea	Offshore: 0.17 - 1.03 River mouths, 0.05 - 0.70 Coastal peat, 0.04 - 0.62	Steinhauer and Boehm, 1992
Mackenzie River Delta, Canadian Beaufort Sea	Means[a], 1.9 - 4.6	Yunker et al., 1995
Mackenzie River	Mean, 0.45	Elmquist et al., 2008
Prince William Sound, AK 82 - 763	0.24 - 1.8	Page et al. (1996)
Cook Inlet and Shelikof Strait, AK	0.001 1.1	Hyland et al. (1995); Boehm et al. (2001b)
Georges Bank and Gulf of Maine, MA, ME	0.001 - 0.54	Boehm & Farrington (1984); Larson et al. (1986)
Continental Slope and Rise off New England	0.01 - 0.10	Venkatesan et al., 1987
Barents Sea	N. Barents mean, 0.56 S. Barents mean, 0.34	Yunker et al., 1995
E Barents Sea	Means, 0.08 - 0.54	Dahle et al., 2003
SW Barents Sea	0.02 - 0.36	Boitsov et al., 2009

[a] Mean TPAH for sediments from the main channels (highest concentrations), nearshore, and offshore (lowest concentrations) locations of the MacKenzie River delta area, Canada.

Figure 5-11 shows the concentrations of total PAH in sediments collected from the Camden Bay area in 2008. (a) TPAH concentrations in all sediments, except those from a single station (HH5) at the site of the Hammerhead exploratory well, were in the range of regional background concentrations for the Beaufort Sea sediments, and (b) were correlated with the % silt+clay in the sediments collected in Camden Bay in 2005 by Brown et al. (2010) and in 2008 by Trefry et al. (2009).

Figure 5-11 Concentrations of Total PAH in Sediments from Camden Bay Area, 2008



This conclusion seems to be confirmed by results of monitoring around several exploratory wells drilled between 1996 and 1998 off eastern Sahkalin Island off the Pacific coast of Russia (O'Reilly et al., 2000). WBM (mostly seawater/polymer muds similar to those used for Beaufort Sea drilling) containing < 0.025 to 75 mg/kg (ppm) TPH were used to drill the wells and were discharged with cuttings to the sea. The drill cuttings contained similar or slightly higher concentrations of TPH. Steinhauer et al. (1994) also reported that cuttings contained higher concentrations of TPH and TPAH than the WBM used to drill wells off southern California (Table 3-9). These results confirm that organic-rich sediments at several levels in the well often contain fossil hydrocarbons.

5.6.2 Metals in Sediments Near Offshore Platforms

5.6.2.1 Forms of Metals in Sediments Near Offshore Drilling Platforms

The metals composition of WBM and cuttings resembles that of natural marine sediments (Tables 3-2 and 3-8). However, concentrations of some metals sometimes are significantly higher in drilling muds and mud/cuttings discharges than background concentrations in uncontaminated marine sediments (Tables 3-2 and 5-9). Barium, chromium, lead, and zinc are the metals most frequently present in WBM at higher concentrations than those in uncontaminated fine-grained marine sediments. Barium is the only metal in modern WBM (complying with the ELG limiting mercury and cadmium concentrations in drilling mud barite) that frequently is present at concentrations substantially higher (>100-fold) than in fine-grained marine sediments.

Barium (from drilling mud barite) usually is the most abundant metal in WBM and cuttings. Concentrations of dense, insoluble barite often are extremely high in WBM (spud muds used to drill the near-surface hole often contain little or no barite). Because of its abundance in drilling muds, barium is used frequently as an indicator of dispersion and accumulation of drilling mud solids in sediments. Barium actually is a tracer of only the most abundant solid ingredient in most drilling muds: barite. Other drilling mud ingredients may have different dispersion and deposition patterns than barite and, therefore, may have a different distribution and persistence in sediments near drilling mud and cuttings discharges (CSA, 2004).

Natural marine sediments and the cuttings themselves also contain barium. Barium is the fourteenth most abundant element in the continental crust of the earth with an average concentration in soils and sediments of about 400 ppm dry wt and a range from less than 1 ppm to at least 2,000 ppm (Trefry, 1982). Barium concentration in sediments usually is inversely related to sediment grain size. Coarse-grained carbonate and silicate sediments, such as those on Georges Bank, a fishing bank off the U.S. New England coast, often contain less than 100 ppm barium, whereas, fine grained sediments, rich in clay minerals, such as many near-shore sediments in the Beaufort and Chukchi Sea (Trefry and Trocine, 2009) and deep sea sediments (Robin et al., 2003), may contain more than 1,000 ppm barium. Most of the barium in marine sediments, even those not containing drilling mud barite, is in solid clay-sized particles of barite and aluminosilicate clays (Robin et al., 2003). Barium concentrations greater than about 2,000 mg/kg in fine-grained soils and sediments may indicate the presence of drilling muds or cuttings.

The natural barite and clay-associated barium in sediments and that introduced as drilling mud barite have a low solubility in seawater (~ 0.08 ppm: Burton et al., 1968), because of the high natural concentration of sulfate in the ocean. Because it is nearly insoluble in seawater, barium has a low bioavailability and toxicity to marine organisms.

The other metals sometimes present in drilling muds at higher concentrations than in marine sediments, usually are associated with barite or bentonite (Tables 3-2 and 3-5). The exception is chromium that, in the past, was present in drilling muds as chrome or ferrochrome lignosulfonate. All the chromium in a used drilling mud, even that added as chromate (Cr VI), is reduced to the trivalent (Cr III), chromic valence state. Less than 1 % of the total chromium in WBM and cuttings from exploratory wells drilled in the Beaufort Sea in 1980 was the toxic

chromate (NTS, 1982). Trivalent chromium salts and Cr III-organic complexes have low solubilities in seawater, limited mobility in seawater and marine sediments, and are not toxic to marine animals (Neff, 2002a, 2008).

Commercial barite contains micro-inclusions of barium feldspar, galena (lead sulfide), pyrite (iron sulfide), sphalerite (zinc sulfide), manganese sulfides, quartz, silicate minerals, and phosphate minerals (Ansari et al., 2001; Crecelius et al., 2007). Copper, lead, mercury, zinc, and probably cadmium are associated with sulfide mineral inclusions. Mercury and lead also are present as sulfide inclusions (Crecelius et al., 2007). The zinc sometimes added to drilling mud as a sulfide scavenger, reacts with the sulfide and is converted to zinc sulfide. These metal sulfides have an extremely low solubility and mobility, particularly in anoxic, sulfidic sediments where some of the barite dissolves (Trefry, 1998; Shimmield and Breuer, 2000; Crecelius et al., 2007; Neff, 2008). The metals in pipe dope and pipe thread compound that sometimes get into the mud and cuttings are present as solid metal granules. These solid metals are quite stable in the alkaline conditions in sediments and any metal dissolving is rapidly precipitated as solid carbonates or sulfides.

The metals in barite are relatively immobile and non-bioavailable to bottom-living animals because of the low solubility of barite and metal sulfides in seawater and marine sediments. The solubility of barite in marine sediments and drill cuttings piles is controlled by sulfate concentration in sediment pore water (Monnin et al., 2001). As sediment oxygen is depleted by microbial degradation of organic matter, sulfate reducing bacteria use sulfate as an alternate electron source and generate sulfide that combines with and precipitates sediment metals (Hartley et al., 2003). If barite concentration in sediments is high, it can serve as a source of reducible sulfate for sulfate reducing bacteria (Ulrich et al., 2003), releasing dissolved barium into the pore water (Phillips et al., 2001). Efficiency of bacterial sulfate reduction from barite is extremely low. Much of the barium released into sediment pore water by the activity of sulfate reducing bacteria diffuses upward to the oxic layers of the sediment or into the overlying water column, where it precipitates with the natural sulfate in the oxygenated water phase (Paytan et al., 2002). Thus, barite is highly persistent in marine sediments and drill cuttings piles.

Trefry et al. (1986) and Trefry (1998) have shown that even under hypoxic or anoxic conditions that occur frequently in sediments near offshore platforms, very little barite dissolves. Shimmield et al. (2000) reported a maximum concentration of 450 μg barium/kg sediment of dissolved barium (in sediment pore water) just below the surface of the Beryl A cuttings pile in the North Sea. This conécentration exceeds the seawater solubility of barium, estimated at 37 to 52 μg/L, depending on temperature, salinity, and sulfate concentration (Chow and Goldberg, 1960; Church, 1979). Much of the barium in cuttings pile pore water probably is present as complexes with pore water dissolved or colloidal organic matter or as precipitated microscopic crystalline and amorphous barite particles (Hartley et al., 2003). Bulk sediment at this depth in the pile contained more than 50,000 mg/kg total particulate barium. Thus, barite may dissolve slowly into pore water of anoxic, sulfidic sediments, the rate controlled by the low solubility of barium in marine waters.

Little dissolved, uncomplexed barium escapes from the sediment into the overlying water column; most precipitates as barite, despite the fact that continental shelf bottom seawater is under-saturated with respect to barium sulfate (Church and Wolgemuth, 1972; Monnin et al.,

1999; Rushdi et al., 2000; Trefry and Trocine, 2009). The barite under-saturation of seawater indicates that barite dissolution is very slow in sulfate-rich seawater. In any case, dissolved barium, at the concentrations at which it can occur in seawater or sediment pore water, is not toxic to marine organisms (Neff and Sauer, 1995; Neff, 2002a).

The long-term fate of metals introduced to sediments as solid sulfides, as occurs when drilling muds and cuttings are deposited on the sea floor, depends on the stability of metal sulfides in the sediments (Trefry, 1998). The stability of sulfides in sediment depends on the oxidation/reduction (redox) potential (Eh) and pH of the sediment. Typical redox potentials (Eh) in marine sediments range from +100 mV (oxidizing) to –400 mV (reducing); Eh decreases as oxygen concentration decreases. pH usually is in the range of 7 to 8 (neutral or slightly alkaline). Sulfide minerals are extremely stable under reducing conditions (Eh below about 0 mV) and neutral or alkaline pH. The Eh of continental shelf and slope sediments, where most production platforms occur, usually decreases to below 0 mV at a depth of about 5 to 50 cm below the sediment surface (Presley and Trefry, 1980). The sediments become increasingly reducing below this thin oxidize surface layer and sulfates are reduced to sulfides. Dissolution of barite under reducing conditions where sulfate concentrations are low does not result in dissolution of metal sulfide inclusions in the barite (Trefry et al., 1986; Trefry, 1998; Crecelius et al., 2007).

The redox potential discontinuity (RPD: where Eh falls to 0 mV) usually is less than 1 cm below the surface in mud and cuttings piles on the outer continental shelf near offshore platforms in the Gulf of Mexico and off southern California where fouling organisms falling off submerged platform structures cause organic enrichment in the sediments, leading to oxygen depletion. Schaanning et al. (1996) showed that most metals associated with anoxic sediments of cuttings piles do not dissolve from the barite and leach into sediment pore water and are not bioavailable to benthic marine animals.

The metal of greatest concern in the U.S. with respect to possible harm to marine ecosystems is mercury (Neff, 2002b, 2008; Trefry and Trocine, 2009). Virtually all the mercury in WBM is in the form of mercuric sulfide (the least soluble metal sulfide) in drilling mud barite. Even under oxidizing conditions (Eh > 0 mV), mercuric sulfide is extremely stable and does not dissolve rapidly, particularly if the concentration of sulfate is high, as is the case in marine sediments (Trefry, 1998). Thus, mercury in metal sulfide inclusions in barite from deposited drilling muds and cuttings is highly stable and insoluble in sediments near offshore platforms (Neff, 2008). It is not bioavailable to marine organisms (Neff, 2002b; Trefry and Smith, 2003).

The most toxic forms of mercury are methylmercury and dimethylmercury. Dissolved inorganic mercury can be converted to methylmercury and dimethylmercury by several groups of bacteria, mostly sulfide reducers, at and just below the RPD in sediments (Baldi, 1996; Neff, 2002b). Monomethylmercury is more stable and persistent than dimethylmercury in natural surface waters and sediments (Stum and Morgan, 1996); Dimethylmercury degrades rapidly and rarely is detected in marine sediments. Methylmercury is bioavailable to marine animals and is persistent in tissues of marine organisms. It is highly toxic to all bacteria, fungi, plants and animals.

Although mercuric sulfide can be methylated to methylmercury by sediment bacteria, the speed of this transformation is only one one-thousandth that of methylation of the mercuric ion (Fagerstrom and Jernelov, 1971). Methylation of mercuric sulfide requires the oxidation of the

sulfide to sulfate (Gavis and Ferguson, 1972), which can occur only when the concentration of dissolved sulfide is low. Thus, mercuric sulfide tends to be quite stable in anoxic marine sediments, particularly in the presence of high concentrations of sulfate and sulfide, as is the case where much of the mercury in the sediment is present in sulfide mineral inclusions in barium sulfate (barite) particles in the sediments. Barite also is a poor substrate for sulfate reducing bacteria because of its extremely low solubility (Karnachuk et al., 2002). Trefry and Smith (2003) showed that there is no relationship between the concentration of barite in sediments near offshore platforms in the Gulf of Mexico and the concentration of methylmercury in sediments. Thus, the mercury in barite is not toxic to marine animals and is not transformed to toxic methylmercury.

5.6.2.2 Concentrations of Metals in Sediments Near Offshore Platforms

Temperate Environments. Concentrations of metals, most of them associated with barite, also may be elevated above background concentrations in sediments containing drilling muds and cuttings. However, true background concentrations of most metals in sediments are geographically extremely variable and are not well understood for most locations. The problem of establishing a background concentration and range for uncontaminated marine sediments is due in part to the difficulty in quantitatively extracting all the metal from a sediment. For example, most extraction methods do not dissolve all the barium from barite and, therefore, tend to underestimate concentrations of barium in drilling muds/cuttings and sediments (Hartley, 1996). Other metals also are difficult to extract quantitatively from sea water, salt-rich drilling muds, cuttings, and marine sediments (Terzaghi et al., 1998). The high salt concentration in these samples causes interference in analysis by conventional methods, often resulting in overestimation of actual concentrations. Therefore, it is difficult to compare metals concentration data generated by different, particularly older, analytical methods to establish the background concentrations of metals in sediments and estimate the increment in metals concentrations due to drilling muds and cuttings deposition.

Concentrations of one or a few metals, particularly barium, chromium, lead, and zinc, sometimes are elevated above expected background concentrations in sediments near an offshore drill rig (Table 5-9), and the excess metals (over background concentrations) probably were derived from the drilling discharges (Boothe and Presley, 1985, 1989: Neff et al., 1989a; Steinhauer et al., 1994; Sheahan et al., 2001; Pozebon et al., 2005). The only metal usually found in sediments near exploratory drill sites at concentrations substantially above background is barium. When drilling is from an artificial gravel island, elevated metals concentrations after drilling may be from erosion of the island material (Crippen et al., 1980).

Boothe and Presley (1985, 1989) estimated the mass balance of several metals in sediments within 1600 ft of six exploration and production platforms in the western Gulf of Mexico. A small fraction (<1.5% inshore and <12% offshore) of the barite used and discharged from the platforms was identified as excess barium in sediments within 1600 ft of the platforms. The remainder probably was swept away by storm-induced bed transport. There were significant increases above background in concentrations of zinc (5- to 10-fold) and mercury (4- to 7-fold) in sediments at two offshore platform sites. The amounts of excess zinc and mercury in the sediments were inversely correlated with distance from the platform and directly correlated with the excess barium in sediments, indicating that the excess metals probably were associated with

drilling mud solids. Although there was a relationship between concentrations of the other metals examined (Cd, Cr, Cu, Pb) and barium in sediments, concentrations of these metals were not elevated significantly above background in sediments near the drilling sites.

About 2.73 million gallons of WBM and cuttings were discharged to the ocean during drilling of seven wells from Platform Hidalgo in the Point Arguello Field off California (Steinhauer et al., 1992, 1994; Hyland et al., 1994). The WBM and cuttings discharged from the platform contained several metals at higher concentrations than in local sediments (Table 3-8). Concentrations of most metals in sediments near the platform were similar before and after the drilling discharges (Table 5-9). Concentrations of only barium were elevated slightly during and for a short time after drilling.

Concentrations of barium in surface sediments within about 410 ft of three platforms monitored by Phillips et al. (1998) decreased between 1991 and 1995 (Figure 5-12). Barium concentrations increased slightly in subsurface sediments collected 820 to 3280 ft from platform Hidalgo over the same time period, probably by bed transport from closer to the platforms.

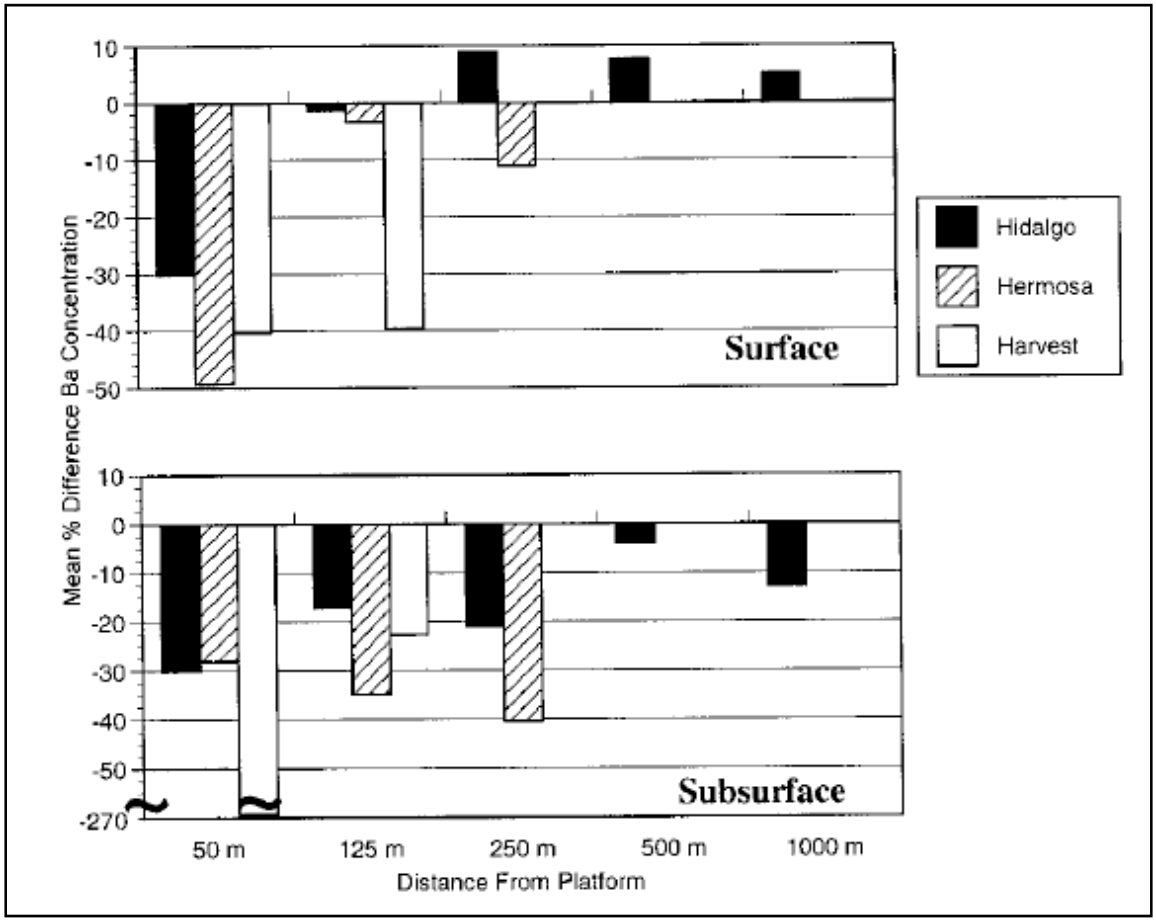
Neff et al. (1989b) reported similar results for sediments near eight exploratory drilling rigs on Georges Bank off the New England coast. Barium and chromium were the only metals present at higher than background concentrations in sediments near the platforms. Slightly elevated concentrations of barium were detected in the silt-clay fraction (representing only a few percent of these sandy sediments) of sediments up to 40 miles down-current from one of the drilling rigs. Excess chromium was detected only in the fine fraction of sediments near the drilling rigs. The estimated half-life of excess barium in the sandy sediments near the exploratory rigs was 0.4 years. Loss of fine-grained barite from sediments probably was caused primarily by storm-induced bed transport and downward percolation through the sandy sediments.

Park et al. (2001) and Westerlund et al. (2001) summarized hydrocarbon and metal concentrations in North Sea cuttings piles near production platforms that had discharged large amounts of WBM, SBM, and OBM cuttings for many years (Table 5-8). Concentrations of most metals were lower in WBM cuttings piles (exemplified by Frig) than in OBM/SBM cuttings piles. Barium was the only metal that was present at an elevated concentration, compared to clean marine sediments, in the cuttings piles sediments at most platforms.

Elevated concentrations of barium were detected in fine grained sediments in depositional areas of the Skagerrak, an arm of the North Sea between Norway and Denmark (Lepland et al., 2000). The barium apparently was derived from drilling mud barite discharged to offshore waters of the southern North Sea, lending support to the hypothesis that drilling mud and cuttings solids can be dispersed over large areas by ocean currents. The nearest oil production field, the Ekofisk Field, is more than 60 miles west of the Skagerrak. As discussed above, Lie et al. (1994) reported that barite from WBM and cuttings discharged from a deep-water drilling rig in the southern Barents Sea was dispersed over a large area and deposited as a very thin coating on the sea floor.

Figure 5-12 shows mean percent difference in barium concentrations in surface and subsurface sediments adjacent to three platforms off southern California between 1991 and 1995. From Phillips et al. (1998).

Figure 5-12 Mean Percent Difference in Sediment Barium Concentrations at 3 California Platforms, 1991 and 1995



Cold-Water Environments. Concentrations of metals in Beaufort and Chukchi Sea sediments have been monitored frequently during the last three decades as part of MMS and oil industry monitoring programs. Tables 5-11 and 5-12 summarize sediment metals data collected between 1984 and 2008 at a large number of locations throughout the Beaufort Sea. Most samples were collected distant, in time and space, from exploratory drilling activities, so the concentrations can be considered to represent the natural background**.**

Grain size distribution and concentrations of organic carbon and trace metals are variable in sediments in coastal and offshore waters of the western Beaufort Sea. Trefry et al. (2003) reported that nearly all samples of surface sediments and age-dated cores contain natural concentrations of several metals, with metal/Al ratios that have been constant for many decades. Metal concentrations in river-suspended matter entering the Beaufort Sea in spring runoff compare well with metal concentrations in coastal and offshore sediments. Overall, the constancy of metal/Al ratios in river-suspended

sediment, the surface layers of bottom sediments, and deeper, older layers in bottom sediments show that anthropogenic inputs of trace metals have not significantly elevated metals

concentrations in sediments in areas of offshore oil exploration and production in the coastal Beaufort Sea.

Table 5-11 lists concentrations of arsenic, barium, cadmium, chromium, and copper in sediments collected throughout the Alaskan Beaufort Sea between 1984 and 2008 and in WBM used in the Beaufort Sea for exploratory wells between 1979 and 1982. Concentration ranges are mg/kg dry wt (ppm).

TABLE 5-11
Concentrations of Some Metals Collected in Beaufort Sea Sediments, 1984 and 2008, and in WBM, 1979-1982

Year(s)	Arsenic	Barium	Cadmium	Chromium	Copper	Reference
Beaufort Sea Sediments						
1984-86	---	128-704	0.06-0.27	22-89	7.6-30	Crecelius et al. 1991
1993	10-43	---	0.06-0.43	77-110	11-63	Valette-Silver et al. 1999
1997-99	7-16	116-569	0.11-0.27	13-63	7-27	Naidu et al. 2001
1999-01	1.0-23	142-863	0.03-0.75	13-104	3.6-46	Trefry et al. 2003
1999-02[a]	4.2-28	155-753	0.03-0.82	13-104	3.6-50	Brown et al. 2010
2001-2	15-31	525-631	0.14-0.20	91-188	31-37	Naidu et al. 2003
2003	6.9-20	329-649	0.08-0.45	56-84	16-55	Naidu et al. 2006
2004-06	4.7-25	142-863	0.03-0.77	15-100	3.9-46	Brown et al. 2010
2008	9.5-22	456-714	0.16-0.31	59-96	15-27	Trefry & Trocine, 2009
2008[b]	10-21	585-18,300	0.15-0.24	73-135	21-53	Trefry & Trocine, 2009
Water Based Drilling Muds - Beaufort Sea - 1979 - 1982						
1979-82	---	520-36,000	<0.2-1.8	17-1300	1.5-88	NTS 1981, 1982, 1983

[a] Brown et al. (2010) summarizes data for 1999 to 2002 of the MMS ANIMIDA Program; Trefry et al. (2003) summarizes data for 1999 to 2001 for the same program.
[b] Surface sediment samples collected near the Hammerhead exploratory drilling site in Camden Bay in 2008.

Concentration ranges of metals in WBM used and discharged offshore in the Beaufort Sea between 1979 and 1982 are also included in Tables 5-11 and 5-12 for comparison. The only metals in historic Beaufort Sea WBM that sometimes are present at higher concentrations than those in Beaufort Sea sediments are barium, chromium, lead, and zinc. There are no area-wide trends in metal concentrations that might be associated with ocean discharges of WBM and cuttings from more than 50 exploration, delineation, and development wells. Concentrations of barium, chromium, copper, and lead in some samples collected near the site of the Hammerhead exploratory drilling site, drilled in 1985/6 were higher than metals concentrations elsewhere in the Camden Bay area. As with sediment PAH (Table 5-9), concentrations of these four metals

were slightly elevated over a small area at the drill site. There was no evidence of spread of metals over a larger area of sediments in the 24 years since drilling. Thus, the concentrations of sediment metals summarized in Tables 5-11 and 5-12 can be used as background concentrations for comparisons with metals concentrations in sediments collected near historic exploratory drill sites shortly after drilling.

Table 5-12 lists concentrations of mercury, nickel, lead, vanadium, and zinc in sediments collected throughout the Alaskan Beaufort Sea between 1984 and 2008 and in WBM used in the Beaufort Sea for exploratory wells between 1979 and 1982. Concentration ranges are mg/kg dry wt (ppm).

TABLE 5-12
Concentrations of Other Metals Collected in Beaufort Sea Sediments, 1984 and 2008, and in WBM, 1979-1982

Years	Mercury	Nickel	Lead	Vanadium	Zinc	Reference
Beaufort Sea Sediments - 1984 - 2008						
1984-86	---	---	5.7-19	37-142	37-123	Crecelius et al. 1991
1993	0.04-0.15	21-75	11-26	---	65-160	Valette-Silver et al. 1999
1997-99	0.008-0.02	7-34	6-15	24-117	18-96	Naidu et al. 2001
1999-01[a]	0.003-0.11	---	2.8-22	27-173	15-136	Trefry et al. 2003
1999-02[a]	0.003-0.20	6.0-48	3.2-22	27-173	15-157	Brown et al. 2010
2001-02	0.05-0.10[b]	45-52	16-26	147-211	114-146	Naidu et al. 2003
2003	0.005-0.09	26-54	11-29	87-136	48-111	Naidu et al. 2006
2004-06	0.003-0.11	6.9-46	4.3-20	87-156	64-108	Brown et al. 2010
2008	0.03-0.08	---	9.9-18	87-156	64-108	Trefry & Trocine 2009
2008[c]	0.04 - 0.06	---	14 - 49	113 - 131	64 - 108	Trefry & Trocine 2009
Beaufort Sea Water Based Drilling Muds - 1979 - 1982						
1979-82	<0.01-0.08	44-88	16-106	160-235	130-380	NTS 1981, 1982, 1983

[a] Brown et al. (2010) summarizes data for 1999 to 2002 of the MMS ANIMIDA Program; Trefry et al. (2003) summarizes data for 1999 to 2001 for the same program.
[b] Concentration of methylmercury ranged from 0.00001 to 0.00013 ppm. [c] Surface sediment samples collected near the Hammerhead exploratory drilling site in Camden Bay in 2008.

Crippen et al. (1980) studied the effects of exploratory drilling from an artificial gravel island on the sediment environment of the Canadian Beaufort Sea. Netserk F-40 Island was constructed in about 30 ft of water from local barrow material consisting mainly of medium sand to fine gravel (1/16 to 3/4 inches). Drilling from the island extended from November 1975 until May 1976 during which time, approximately 307,000 gallons of drilling muds and cuttings were discharge under the ice about 15 ft from the island. A low quality grade of barite, containing elevated concentrations of arsenic, cadmium, mercury, and zinc, was used in the WBM. The drilling mud contained 1950 ppm zinc, 820 ppm lead, and 13 ppm mercury, most of it from the barite. Slaney and Co. (1977) performed an initial survey of the site about 3 months after completion of drilling

and Crippen et al. (1980) performed another survey in August 1977, 15 months after drilling. Much of the gravel island had eroded away by the time of the August 1977 survey.

One of the objectives of both surveys was to evaluate accumulation of metals from the drilling discharges in sediments near the gravel island. Concentrations of barium, cadmium, and chromium, but not mercury, were elevated above background levels in sediments within 985 ft of the gravel island at the time of the first survey, 3 months after completion of drilling (Slaney and Co., 1977). However, Crippen et al. (1980) reported that concentrations of all six metals, including mercury, were elevated in sediments near the island 15 months after drilling (Table 5-13). Although the drilling muds used at Netserk contained elevated concentrations of the six metals, it is probable that the metals, particularly mercury, contamination of the sediments was mainly from the barrow material eroded from the island after drilling and not from the discharged drilling muds and cuttings.

Table 5-13 lists concentrations of six metals in sediments before and 15 months after exploratory drilling at Netserk F-40, an artificial gavel island in the Canadian Beaufort Sea and concentrations in benthic invertebrates collected at different distances from the island 15 months after drilling. Tissue concentrations were converted to dry wt by multiplying by five. Concentrations are mg/kg dry wt. From Crippen et al. (1980).

TABLE 5-13
Concentrations of Six Metals Before and 15 Months After Exploratory Drilling at Netwerk F-40, Canadian Beaufort

Metal	Surface Sediments		Infaunal worms and clams	Epifaunal Isopods
	Before Drilling	15 months After Drilling	15 Months After Drilling	
Arsenic	9.9 (5.2 - 21)	> 12 - 23	7.5 (1.0 - 13)	4.5 (1.5 - 10.5)
Cadmium	1.0 (0.7 - 1.6)	2.1 - 5.9	12.5 (3.0 - 13)	4.5 (3.0 - 7.0)
Chromium	15 (6.4 - 22)	70	7.5 (0.5 - 28.5)	6.0 (0.5 - 19.5)
Lead	20 (10.5 - 24.5)	466	7.0 (0.5 - 18.5)	9.5 (2.0 - 17.0)
Mercury	0.07 (0.02 - 0.11)	> 6	0.25 (<0.05 - 2.45)	0.05
Zinc	116 (56 - 131)	1360	165 (25 - 210)	105 (85 - 130)

Snyder-Conn et al. (1990) monitored persistence of metals in sediments near three exploratory drilling sites in Sefansson Sound along the central coast of the Alaskan Beaufort Sea. The wells were drilled between 1981 and 1984 adjacent to Cross Island, Alaska Island, and Goose Island, the latter an artificial gravel island constructed in 1982, and WBM and cuttings were discharged either to open water or on the ice in 1 to 9 ft of water near the drilling sites. Sediments near each site and at four reference sites were collected in 1985, 1 to 4 years after completion of drilling. The four reference sites were located at similar water depths in areas in the vicinity with no history of drilling activities.

Concentrations of five metals typical of those in WBM and cuttings were measured in all sediment samples (Table 5-14). Unfortunately, the authors provided no quality control data for

their metals analysis and the methods used probably underestimated total aluminum and barium concentrations and overestimated concentrations of other metals. Boehm et al. (1987) analyzed sediments collected in the same areas as the reference and drill site sediments analyzed by Snyder-Conn et al. (1990). The Boehm et al. (1987) data were rigorously quality controlled. Barium, chromium, lead, and zinc concentrations in area-wide sediments measured by Boehm et al. (1987) in 1984 through 1986 were higher than those measured by Snyder-Conn et al. (1990) in reference site sediments in 1985, indicating that the latter investigators probably underestimated actual metals concentrations in all sediments. The poor quality of the analytical data make interpretation difficult; however, Snyder-Conn et al. (1990) decided that the methods were adequate to determine semi-quantitatively if there was an increase in sediment metals concentrations due to drilling discharges.

Table 5-14 lists mean and range of concentrations of 6 metals typical of those found in WBM and cuttings in sediments adjacent to 3 shallow-water exploratory drilling sites (3 to 9 ft of water) and 4 reference sites in Stefannson Sound, Beaufort Sea. All sediment samples were collected 1 to 4 years after completion of drilling. Concentrations are mg/kg dry wt (ppm). From Snyder-Conn et al. (1990).

TABLE 5-14
Mean and Range Concentrations of Six Metals in WBM and Cuttings, Stefannson Sound, Beaufort Sea

Metal	Reference (4)	Cross Island	Alaska Island	Goose Island
Aluminum	3730 (2170 - 5260)	5877 (1475 - 13,000)	3124 (1870 - 5950)	4746 (3615 - 7265)
Arsenic	3.6 (2.0 - 4.7)	4.0 (2.8 - 5.2)	3.8 (2.6 - 5.0)	5.2 (3.6 - 7.2)
Barium	53 (23 - 74)	1809 (778 - 5015)	1977 (770 - 6605)	90 (23 - 344)
Chromium	8 (4 - 11)	92 (5 - 331)	9 (4 - 20)	11 (8 - 18)
Lead	0.6 0.1 - 2.2)	24 (ND - 75)	8.6 (ND - 33)	0.9 (ND - 6.4)
Zinc	39 (20 - 55)	136 (16 - 359)	52 (22 - 150)	58 (43 - 97)

The concentration of aluminum in all sediments was low compared to concentrations in sediments from elsewhere in the Beaufort Sea (10,000 to 72,600 ppm) (Trefry and Trocine, 2009). This may be an analytical artifact, as discussed above, or it may be an indication that the sediments in Stefansson Sound are sandy and contain little clay. However, most sediments in Stefannson Sound are silts and clays derived from river runoff (Boehm et al., 1987; Trefry et al., 2009). Concentrations of aluminum and arsenic were not higher in sediments near the three drill sites than at the four reference sites. Concentrations of three or four of the other metals were slightly higher in some sediment samples collected adjacent to Cross and Alaska Islands, but not Goose Island, than in sediments from the four reference stations. Concentrations of these metals

usually were slightly elevated in sediments within 100 ft of the drill sites and decreased with distance from the sites. Some of the excess metals probably were from the drilling discharges.

Only barium was present in the drill site sediments at a concentration more than three times higher than the highest concentration in uncontaminated sediments from the Beaufort Sea (Tables 5-11 and 5-12). Thus, some metals from drilling discharges to shallow waters of the Beaufort Sea do accumulate in sediments and are relatively persistent there, in agreement with several studies in temperate marine environments. These increments in sediment metals concentrations are unlikely to be harmful to benthic plants and invertebrates in Stefannson Sound, because, as discussed above, all the drilling mud metals are present in solid, inert forms. The drilling discharges themselves could cause a temporary disturbance by burying the benthos. This ecosystem is adapted to such disturbance from the spring floods from the four rivers emptying into the sound (Trefry et al., 2009). Although long-term disturbance from these shallow-water discharges is unlikely, the current NPDES permit for Alaska prohibits discharge to shallow waters less than 5 m (< 16.5 ft) depth (Table 4-4).

A similar study was performed in 1981 and 1982 near three on-ice drilling waste disposal sites in the same area of the Beaufort Sea (NTS, 1982). Sediments were collected at distances ranging from 328 to 5250 feet from the discharge sites before and after gravel island construction and several months after drilling waste discharges. The disposal sites were at Endeavor Island Sag Delta 7 in 9.5 to 11.5 ft of water, Resolution Island Sag Delta 8 in 3 to 6 ft of water, and off the shore of Challenge Island in 8 to 9.5 ft of water. Concentrations of six metals, chosen because they were thought to be abundant in WBM or because they were on the EPA list of priority pollutant metals, were monitored.

Metals concentrations in sediments were similar before and after gravel island construction at Endeavor and Resolution Islands (Tables 5-15 and 5-16). Barium was the only metal with concentrations substantially higher in most sediment samples from the Endeavor and Resolution Island discharge sites after drilling. Barium concentrations in Challenge Island sediments before discharge were higher than those after discharge (Table 5-17). Barium concentrations were elevated in a few pre-and post-construction sediment samples from all 3 discharge sites. There were slight, but not environmentally significant, increases in the concentrations of chromium at Endeavor Island, cadmium at Resolution Island, and chromium, lead, and zinc at Challenge Island in a few sediment samples collected after discharge (Tables 5-15, 5-16, and 5-17).

Table 5-15 lists concentration ranges of metals in sediments 328 to 5250 ft from the Endeavor Island and Sag Delta 7 drilling waste disposal site, before and after gravel island construction and several months after on-ice disposal of WBM and cuttings discharges. Concentrations are mg/kg dry wt (ppm). From NTS (1982).

TABLE 5-15
Concentration Ranges of Metals in Sediments, Endeavor Island and Sag Delta 7 Disposal Sites

Metal	Pre-Construction (July, 1980)	Post-Construction (Dec/Jan 1989-81)	Post-Discharge (August, 1981)
Barium	<500	<500 - 12,000	180 - 5800
Cadmium	0.8 - 1.6	0.8 - 3.7	0.6 - 1.7
Chromium	4.3 - 11	4.5 - 14	6.2 - 110
Copper	3.9 - 18	4.1 - 26	5.9 - 22
Mercury	<0.01 - 0.06	0.02 - 0.10	<0.02 - 0.03
Lead	9.7 - 19	9.9 - 27	13 - 22
Zinc	26 - 71	24 - 130	39 - 100

Concentrations of all metals except barium were within the range of background concentrations for Beaufort Sea sediments (Tables 5-11 and 5-12) in all pre- and post-discharge sediments, with a few exceptions. Concentrations of cadmium were about three times the background concentration range of 0.06 to 0.82 ppm in single post-construction and post-discharge sediment samples from Endeavor and Resolution Islands. The cadmium may have come from the gravel island construction material. The source of the pre-discharge excess barium is not known, but may have been from the island gravel, as was the case for the Mukluk Island drilling site (NTS, 1985).

Table 5-16 lists concentration ranges of metals in sediments 328 to 5250 ft from the Resolution Island and the Sag Delta 8 drilling waste disposal site, before and after gravel island construction and several months after on-ice WBM and cuttings discharges. Concentrations are mg/kg dry wt (ppm). From NTS (1982).

TABLE 5-16
Concentration Ranges of Metals in Sediments, Resolution Island and Sag Delta 8 Disposal Sites

Metal	Pre-Construction (July, 1980)	Post-Construction (Dec/Jan 1989-81)	Post-Discharge (August, 1981)
Barium	<500 - 500	<500 - 3700	140 - 1500
Cadmium	1.1 - 1.5	1.6 - 2.2	1.5 - 4.7
Chromium	5.8 - 11.7	6.0 - 9.7	5.9 - 10
Copper	3.9 - 19	4.1 - 13	5.8 - 21
Mercury	<0.01 - 0.05	<0.01 - 0.04	<0.02 - 0.04
Lead	13 - 19	2.3 - 20	14 - 21
Zinc	29 - 69	13 - 70	38 - 75

Table 5-17 list concentration ranges of metals in sediments 328 to 5250 ft from the Challenge Island disposal site, before and several months after on-ice WBM and cuttings discharges. Concentrations are mg/kg dry wt (ppm). From NTS (1982).

TABLE 5-17
Concentration Ranges of Metals in Sediments, Challenge Island Disposal Site

Metal	Pre-Discharge (Dec/Jan 1989-81)	Post-Discharge (August, 1981)
Barium	550 - 21,000	49 - 1000
Cadmium	0.06 - 1.2	0.7 - 1.7
Chromium	3.0 - 10	4.0 - 22
Copper	3.5 - 9.5	3.0 - 15
Mercury	<0.01 - 0.34	<0.02 - 0.05
Lead	2.0 - 9.4	8.3 - 73
Zinc	22 - 41	23 - 73

Two exploratory wells were drilled at Tern Island, a man-made gravel island in 22 ft of water east of Stefannson Sound, in May and October 1982. Approximately 117,600 gal of drilling wastes were discharged from Tern Island well #1, 29,400 gal on the ice in June, 42,000 gal to open water in July, and 46,200 gal in August. NTS (1983) monitored the fate of metals discharged in drilling wastes in August. Post-construction samples were collected after the June and July discharges; post-discharge samples were collected after the August discharges. Samples were collected at stations northwest and southeast (the direction of the predominant current flows) at 164, 328, and 656 ft from the discharge; reference sediment samples were collected 984 ft northeast of the discharge.

Concentrations of barium in sediments were elevated, compared to concentrations in reference sediments. in post-construction and post-discharge samples collected 164 ft northwest of the discharge site (Table 5-18). Barium concentrations also were elevated in some sediments collected at 164, 328, and 656 ft northwest of the discharge site and in post-discharge sediments collected during the post-discharge survey at 164 to 656 ft northwest of the discharge site. The maximum increment in sediment barium was about 65-fold. Concentrations of chromium and lead were similar in all sediment samples, indicating no increment due to drilling discharges. Thus, only barium concentrations increased in down-current sediments from drilling discharges.

Table 5-18 lists concentration ranges of metals in sediments 164 to 656 feet NW and SE (direction of net current flow) and 984 ft NE from the disposal site at Tern Island, before and several months after open-water WBM and cuttings discharges. Concentrations are mg/kg dry wt (ppm). From NTS (1983).

TABLE 5-18
Concentration Ranges of Metals in Sediments, Tern Island Disposal Site

Metal	Post-Construction (July 28, 1982)	Post-Discharge (September 23-24, 1982)
164 Feet NW & SE of Discharge Site		
Barium	100 - 3770	19 - 6380
Chromium	18 - 25	16 - 20
Lead	14 - 18	13 - 16
328 Feet NW & SE of Discharge Site		
Barium	74 - 270	38 - 3060
Chromium	18 - 27	16 - 21
Lead	15 - 18	13 - 17
656 Feet NW & SE of Discharge Site		
Barium	30 - 110	56 - 1300
Chromium	13 - 19	17 - 26
Lead	12 - 20	14 - 19
Reference Site 984 NE of Discharge Site		
Barium	57 - 230	120 - 190
Chromium	13 - 21	16 - 18
Lead	13 - 19	13 - 17

The Mukluk Island exploratory drilling island was constructed of gravel during the summer of 1983. The island was located in Harrison Bay, about 28 miles northwest of Oliktok Point in 48 ft of water. Drilling of the Mukluk #1 well occurred between November 1983 and January 1984, during which approximately 122,200 gal of WBM and 103,000 gal of drill cuttings were discharged through a discharge pipe below the ice to 9 ft above the sea floor. The drilling mud used for most of the well resembled a generic seawater lignosulfonate drilling mud (Table 4-2). Seafloor sediments were collected for metals analysis in Sept 1983, before drilling and in August 1984 after drilling was completed (NTS, 1985). The island gravel also was sampled for metals analysis before drilling. Barium and zinc were chosen for monitoring because their concentrations in the drilling muds were 300 times and 11 times higher than in pre-discharge site sediments. Concentrations of cadmium, chromium, lead, and mercury were similar in drilling muds and sediments.

Concentrations of barium were elevated in post-discharge sediments up to 650 ft west and 325 ft north of the discharge site (Table 5-19). Zinc concentrations were similar in sediments collected before and after discharge. The gravel island construction material contained higher

concentrations of barium than the local pre-discharge sediments; some of the excess barium in both pre- and post-discharge sediments could have come from erosion of the gravel island.

Table 5-19 lists concentrations of barium and zinc in sediments collected 164 to 3280 ft from the drilling mud and cuttings discharge pipe on Mukluk Island before and after drilling waste discharge. Concentrations are mg/kg dry wt (ppm). From NTS (1985).

TABLE 5-19
Concentrations of Barium and Zinc in Sediments, Mukluk Island Before and After Drilling Waste Discharge

Metal	Pre-Discharge (Sept. 1983)	Gravel Island (Sept. 1983)	Post-Discharge (Aug. 1984)
Barium	250 - 1050	1300- 1450	250 - 2850
Zinc	26.9 - 81.2	14.5 - 17.7	16.3 - 76.4

The most recent exploratory well drilled in the Beaufort Sea was drilled by Devon Canada Corp. at the Paktoa-60 prospect in about 40 ft of water off the Mackenzie River delta. The well was drilled from the SDC/MAT (steel drilling caisson/with lower MAT unit). The SDC is a converted 662-ft oil tanker that has been fitted with lower skirts of cold hardened steel on the bottom that protect the SDC from sliding by providing a broad ice-resistant base. (Figure 2-1). The SDC had been used to drill six exploratory wells in the Alaskan and Canadian Beaufort Sea between 1982 and 2002. Drilling extended from December 2005 to March 2006 and resulted in the discovery of a large oil reservoir. A monitoring program was performed before, during, and after drilling.

The post drilling monitoring program was conducted from August 25-28, 2006, five months after completion of drilling and included sampling and analysis of sediments and benthic amphipod crustaceans at an array of stations located around the drill site at about 330 and 1650 ft. Sediment and amphipod tissue samples were analyzed for five metals (aluminum, cadmium, iron, mercury, and lead), and total and individual alkanes and PAH. Samples of drilling muds and cuttings also were analyzed. The drilling muds used for the well were seawater/KCl/polymer muds (Generic mud #1; Table 4-2) that varied mainly in the amount of barite weighting agent added (Table 5-20).This drilling mud system closely resembles the KCl/polymer mud system evaluated and recommended in the current NPDES permit for the Beaufort and Chukchi Seas (EPA, 2006).

The drilling mud and cuttings contained relatively low concentrations of all metals, total extractable hydrocarbons (TEH), and PAH (Table 5-21), compared to the WBM and cuttings associated with drilling wells off California (Table 3-8). The high concentrations of aluminum and iron indicate that the drilling mud and cuttings contained high concentrations of clay minerals, probably mainly bentonite clay and formation shales. Mercury and cadmium concentrations are well below the limit placed by the US EPA on concentrations of mercury and cadmium in drilling mud barite. The concentration of lead in the drilling mud and cuttings is in the range found in uncontaminated nearshore marine sediments, 5 to 30 mg/kg (Neff, 2002a). Hydrocarbon concentrations are comparable to those in nearshore Beaufort Sea sediments (Table 5-10).

Concentrations of metals in sediments collected near the Paktoa-60 drill site five months after drilling were low (Table 5-22) and comparable to those in sediments from the Alaskan Beaufort Sea (Tables 5-11 and 5-12). Mean concentrations of mercury, lead, cadmium, and hydrocarbons were slightly elevated in post-drilling sediments compared to pre-drilling sediments. This was attributed to higher chemical concentrations in sediments collected directly below the moon pool on the SDC and at the site of drilling mud and cuttings disposal along the side of the SDC. The moon pool is the open shaft on a drill rig through which the riser and drill string descend to the sea floor. Cuttings from the surface hole and some deck drainage accumulate in the moon pool. Sediments from all stations 330 ft or more from the drill site contained background concentrations of metals and hydrocarbons.

Table 5-20 lists composition of the WBM used to drill the Paktoa-60 exploratory well in the Canadian Beaufort Sea in 2005-2006. All ingredients are classified as non-toxic. Data from KAVIK-AXIS (2005).

TABLE 5-20
Composition of WBM used to drill Paktoa C-60 Exploratory Well, Canadian Beaufort Sea, 2005-2006

Additive	Function	Composition	Concentration in Mud (lb/gal)
Barite	Weighting agent	BaSO4	To maintain mud density at 15-17 lb/gal
Potash	Salt	KCl	0.29
Bentonite	Viscosifier	Natural clay	0.25
Alcomer 74P	Thinner, fluid loss control	High MW acrylate copolymer	0.05
Staflo XL	Fluid loss control	Polyanionic cellulose	0.04
Desco CF	Thinner, fluid loss control	Cr-free sulfomethylated tannin	0.05
NeXan	Viscosifier	Xanthan gum biopolymer	0.02
pH buffer	Control pH	Hydrated lime, Ca(OH)2, sodium bicarbonate, NaHCO3	0.01
Caustic	Conrol pH	NaOH	0.004-0.008

Table 5-21 lists concentrations of five metals, total extractable hydrocarbons (TEH) and total polycyclic aromatic hydrocarbons (TPAH) in whole drilling mud collected on Feb. 12, 2006 and in drill cuttings collected on Jan. 16 and Feb. 5, 2006 from the SDC during drilling of the Paktoa-60 well in the Canadian Beaufort Sea. Concentrations are mg/kg dry wt (ppm). From KAVIK-AXYS Inc. (2007).

TABLE 5-21
Concentrations of 5 Metals, THE and TPAH in Drilling Mud, Paktoa C-60 in 2006

Chemical	Whole Drilling Mud	Drill Cuttings
Aluminum (Al)	6000	10,000
Cadmium (Cd)	0.46	0.47 - 0.56
Iron (Fe)	12,500	22,700 - 24,500
Mercury (Hg)	0.11	0.04 - 0.08
Lead (Pb)	20	18-19
TEH	660	140 - 740
TPAH	1.8	2.3

Table 5-22 lists concentrations of total organic carbon (TOC) five metals, total alkanes and total polycyclic aromatic hydrocarbons (TPAH) in sediments located under the moon pool on the SDC and from several stations located 300 and 1650 ft from the Paktoa-60 drill site in the Canadian Beaufort Sea. Concentrations are mg/kg dry wt (ppm). From KAVIK-AXYS Inc. (2007).

TABLE 5-22
Concentration of TOC, 5 Metals, Alkanes and TPAH in Sediments Under Moonpool, Paktoa C-60 Drill Site

Chemical	Post-drilling (Mean ± SD)	Post-drilling (Range)	Pre-drilling (2002)
TOC (%)	1.16 ± 0.30	0.33 - 1.44	1.3 ± 0.17
Mercury (Hg)	0.07 ± 0.014	0.06 - 0.12	0.056 ± 0.008
Lead (Pb)	34 ± 37	15 - 164	22 ± 3.6
Cadmium (Cd)	0.37 ± 0.25	0.23 - 1.39	0.30 ± 0.04
Iron (Fe)	31,000 ± 9000	11,000 - 42,000	40,000 ± 4000
Aluminum (Al)	49,000 ± 17,000	10,000 - 68,000	NA
Total alkanes	12.6 ± 12.5	3.0 - 66.8	12.7 ± 0.08
TPAH	4.42 ± 3.62	2.5 - 19.8	3.47 ± 0.05

These studies of WBM and cuttings discharges from exploratory drilling in the Beaufort Sea are consistent in showing that little metal, mostly barium, accumulates in sediments within a few hundred feet from WBM and cuttings discharges. There may be small increases in concentrations of other metals in sediments near some discharge sites. The increase over background concentrations of barium and occasionally other metals in sediments due to drilling waste discharges are insufficient to cause harm to local bottom-dwelling marine invertebrates. Since all these metals are tightly bound to solid particles (barite or clays), they are not bioavailable or toxic to bottom-dwelling marine organisms. The bioavailability and toxicity of WBM and ingredients of WBM are discussed in the next section.

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6.0 BIOLOGICAL EFFECTS OF WBM AND CUTTINGS IN THE OCEAN

6.1 Bioaccumulation of Drilling Mud and Cuttings Ingredients in Marine Organisms

6.1.1 Bioavailability of Metals from WBM and Cuttings

Bioavailability is the extent to which a chemical can be absorbed (bioaccumulated) by a living organism by active (biological) or passive (physical or chemical) processes (Neff, 2002a). A chemical is said to be bioavailable if it can move through or bind to a permeable surface coating (e.g., skin, gill epithelium, gut lining, cell membrane) of an organism (Newman and Jagoe, 1994). Bioavailability of metals and hydrocarbons from sediments (cuttings piles) can be divided into two components: environmental accessibility and environmental bioavailability.

Environmental accessibility is a measure of the fraction of the total chemical that is in a form or location in the environment that is accessible for bioaccumulation by organisms. Metals of all forms buried in deep layers of sediment or cuttings have a low accessibility to marine organisms living in or on surface layers of the cuttings pile or in the overlying water column. As discussed above, the metals in cuttings piles are present primarily as insoluble inclusions in barite, clay, and rock cuttings particles. These solid metals are not bioaccessible. A small fraction of the total metal is in apparent solution or colloidal suspension (adsorbed to dissolved organic matter or very fine particles) in the pore water of the cuttings pile (Shimmield et al. 2000). If the cuttings pore water is accessible to marine organisms, or is mixed up into the overlying water column by sediment disturbance, some of the dissolved and colloidal metals in it may be in bioavailable forms and may be bioaccumulated by marine organisms.

Environmental bioavailability depends on the interactions of a marine organism with its environment. Exposure occurs at the interface between environmental media (water, sediment, and food) and permeable biological membranes of the marine organism in contact with the different media. Environmental bioavailability is controlled by the relative amount of permeable epithelia in contact with the different environmental media, the duration of contact, and the physical form of the chemical in the environmental medium. Dissolved, free metal ions, some metal-organic complexes, and low molecular weight organo-metal compounds (e.g., methylmercury, arsenobetaine) are the most bioavailable forms of most metals to marine organisms (Neff, 2002a).

The most bioavailable fraction of metals in deposits of WBM and cuttings on the sea floor is that dissolved in the pore water or loosely complexed with particles. Deuel and Holliday (1998) fractionated the metals in a WBM into lightly-adsorbed/dissolved fractions and tightly bound, insoluble fractions and concluded that most of the total metals was in organic/sulphide complexes or the residual fraction, both considered inaccessible for bioaccumulation by marine organisms (Table 6-1). Nearly 50 % of the lead and more than 20 percent of the cadmium, chromium, and zinc in the WBM sample were in the iron and manganese oxide fractions that dissolve under oxygen-free (anoxic) conditions in sediments, releasing adsorbed metals.

However, most of the metals released from the iron and manganese oxide particles when the oxides dissolve in anoxic sediments quickly precipitate as sulfides and remain unavailable.

Table 6-1 lists percent distribution of metals among geochemical fractions in a WBM. From Deuel and Holliday (1998).

TABLE 6-1
Percent Distribution of Metals amoung Geochemical Fractions in a WBM

Fraction	Arsenic	Barium	Cadmium	Chromium	Lead	Zinc
Exchangeable	2.7	0.9	4.2	0.9	0.5	1.0
Carbonate	3.2	1.1	3.6	7.3	14.3	13.0
Fe-Mn Oxide	16.0	0.8	21.1	34.0	49.3	33.1
Organic/Sulfide	3.7	0.9	27.7	17.3	9.0	36.2
Residual	74.4	96.3	43.4	40.4	27.0	16.7

Note: Mobility and bioavailability decrease in the order exchangeable > bound to carbonate > bound to Fe-Mn oxides > organic matter/sulfide complexes > residual fraction. The organic/sulfide and residual fractions are considered non-bioavailable.

As discussed above, most of the metals not associated with the Fe/Mn oxides are present primarily in drilling mud barite in the WBM. They are associated with sulphide mineral inclusions (mainly sphaelerite: zinc sulphide) in the barite and are not soluble in near-surface, oxygenated layers of sediment or in anoxic marine sediment pore waters (usually high in dissolved sulphide) (Trefry et al., 1986; Neff, 2002a,b; Neff, 2008). The distribution of metals in different geochemical fractions of North Sea cuttings pile sediments is similar to that described by Deuel and Holliday (1998) for U.S. WBM (Westerlund et al., 2001, 2002). About 17 percent of the lead and 36 percent of the nickel in North Sea cuttings piles are in potentially bioavailable forms.

Crecelius et al. (2007) measured the dissolution of several metals from drilling mud barite into fresh- and sea-water and several pH buffer solutions. Neff (2008) used these data to estimate the maximum concentrations of metals from barite in solution in the pore water of a WBM cuttings pile. The concentration of a metal in solution in pore water can be estimated based on the concentration of barite in the cuttings pile, the fraction (mg metal/mg barite) of the metal in barite, and the distribution coefficient (K_d) for the metal between the barite and water phases (K_d = metal concentration in barite/metal concentration in water in equilibrium with the barite). The estimated concentrations of dissolved metals in the pore water of a cuttings pile containing a typical concentration of barite (5700 mg/kg: the concentration of barite in the mud/cuttings from mid-depth in a well drilled at Platform Hidalgo off California: Steinhauer et al., 1994), were very low and well below the chronic water quality criteria for the metals (Table 6-2). Thus, drilling muds containing barite that meets EPA ELG (≤ 1 ppm mercury and ≤ 3 ppm cadmium in barite), would not be harmful to sediment-dwelling marine animals.

Terzaghi et al. (1998) measured the concentration of five metals (arsenic, cadmium, chromium, copper, and lead) in 0.5 M acetic acid extracts (i.e., the exchangeable fraction) of seven samples of WBM, similar to the U.S. generic WBM, used in Italian drilling operations in the Mediterranean Sea. They estimated Kd values that were remarkably similar to those reported

here. Only chromium had a lower Kd in whole drilling mud than in barite. This is because chromium lignosulfonate was used as a clay thinner in the Italian WBM. As discussed above, chrome lignosulfonate in waste WBM is slightly soluble (Neff et al. 1987). Because of the bioavailability and toxicity of chromium in WBM, chrome and ferrochrome lignosulfonates are rarely used today in WBM destined for offshore disposal.

Table 6-2 shows estimated concentrations of several metals dissolved in the pore water of a cuttings pile containing 3355 mg/kg barium (5700 mg/kg barite). Concentrations in water are µg/L (parts per billion) and are compared with EPA chronic water quality criteria values for sea water (EPA, 1992, 1998). Concentrations of metals in the barite are in mg/kg and are U.S. values from Table 3-2. The barite is similar to that proposed for used by Shell for WBM for exploratory drilling in the Beaufort and Chukchi Seas. Data from Neff (2008).

TABLE 6-2
Estimated Concentrations of Several Metals Dissolved in Pore Water of Cuttings Pile

Metal	Concentration in Barite	Kd	Concentration in Pore Water	Chronic Water Quality Criterion
Cadmium	0.03	8.71	0.02	9.3
Chromium	11	251	0.25	50[a]
Copper	9.7	25.1	2.2	3.1
Mercury	0.12	199,526	2.9 x 10-6	0.025[b]
Lead	7.8	79.4	0.56	8.1
Zinc	8.6	31.6	1.6	81

[a] As chromate (CrO4-2); [b] As methyl mercury ((CH3)Hg).

The Terzaghi et al. (1998) data indicate that only a small fraction of the metals associated with a typical WBM is in the exchangeable, readily bioavailable fraction of the drilling muds. However, if the cuttings contain a large fraction of organic matter, clay, or water-sensitive shales, much of the metal desorbing from the mud will rapidly adsorb to the organic matter or clay mineral fraction of the cuttings, decreasing metal bioavailability.

6.1.2 Bioaccumulation of Metals from Barite and WBM

6.1.2.1 Laboratory Studies

Studies With Warm-Water Species. Solid metals and metal salts associated with barite, clay, and cuttings particles are not readily bioaccumulated by animals living in close association with the cuttings pile; the metals are not passed efficiently through marine food chains (Neff, 1987a; Neff et al., 1989b,c; Leuterman et al., 1997; URS, 2002). When accumulated, the metals often are not assimilated into the tissues, but remain in the tissues as insoluble, inert concretions, probably of the original barite particles (Jenkins et al., 1989), where most of the metals in drilling muds are sequestered.

Neff et al. (1989b), Leuterman et al. (1997), and Schaanning et al. (2002) performed laboratory studies to evaluate the bioavailability to several species of bottom-living marine animals of several metals in different grades (purities) of drilling mud barite in sediments. Some of the marine animals accumulated small amounts of one or more of arsenic, cadmium, copper, lead, mercury, nickel, and zinc during chronic exposure to high concentrations of the barites containing the highest concentrations of metals. Lead was the only metal in impure grades of barite that was bioaccumulated to potentially toxic concentrations in tissues of marine animals in the experiments preformed by Leuterman et al. (1997). Trefry et al. (1986) showed that some lead is leached into solution from barite in the slightly acid environment of the digestive tract of marine animals. Most modern U.S. and North Sea barites contain low concentrations of lead (Table 3-2); barite samples used by Leuterman et al. (1997) contained unusually high lead concentrations.

Correlation analysis of the relative concentrations of the metals in the tissues of the test animals and in the barite samples indicated that most of the metals apparently accumulated were still associated with barite particles, probably as unassimilated solid particles in the gut. It is probable that some of the metals apparently bioaccumulated by the marine animals were actually still associated with fine particulate barite or other sediment particles in the gut and gills, as was shown for clams exposed to drilling muds discharged offshore California (Jenkins et al. 1989). Marine invertebrates can take up fine particles into vacuoles in gut epithelial cells by pynocytosis. The metals associated with the particles remain in the vacuoles and are not actually assimilated by the animal. These sorbed, particulate metals are toxicologically inert (Nott and Nicolaidou, 1989, 1990, 1993, 1994). Neff et al. (1989b) and Leuterman et al. (1997) concluded that metals associated with drilling mud barite have a low bioavailability to marine organisms that might come in contact with discharged drilling fluid solids.

Most of the exchangeable metals associated with WBM (representing less than 5% of the total metals in the WBM: Table 6-1) probably leach into the water column during settling of a WBM through the water column and dilute to natural background concentrations within a short distance of the discharge (Trefry et al., 1986; Neff, 1991). Thus, concentrations of bioavailable metals in pore water of a sediment containing deposited drilling mud solids probably would be much lower than used in these investigations. Neff (2008) estimated the relative amounts of metals associated with drilling mud barite that dissolve into the water column during settling of discharged WBM through the water column and into sediment pore water after the WBM settles on the sea floor. Estimated concentrations of all barite-associated metals dissolved in pore water of sediments containing deposited WBM barite were extremely low and well below published chronic water quality criterion values (Table 6-2).

Similar results have been obtained in laboratory studies in which marine animals were exposed to WBM in sediments. Neff et al. (1989c) exposed lobsters and flounder for up to 99 days in large seawater tanks to sediments contaminated with WBM solids. Some of the test animals also were fed polychaete worms that had been contaminated by exposure to WBM solids. Concentrations of barium and chromium, the two most abundant metals in most WBM used at the time, were measured at different times during the exposure. Lobster and flounder accumulated small amounts of barium, but not chromium, from the contaminated sediments. Flounder, but not lobsters, exposed simultaneously to contaminated sediments and food accumulated slightly more barium than those exposed to contaminated sediments alone. Neither

species accumulated chromium from contaminated food. It is probable that much of the barium apparently bioaccumulated by the lobsters and flounder was present as unassimilated barite particles in the digestive system. Chromium, mostly from chrome lignosulfonate, probably was in the low solubility trivalent state and was not very bioavailable. These experiments show that there was very little food chain transfer and no biomagnification of barium and chromium from drilling muds in marine animals.

A joint URS, Dames and Moore, and TNO team (URS, 2002) performed a similar laboratory bioaccumulation experiment with OBM cuttings from two platforms in the North Sea. The results of their studies were similar to those discussed above for WBM and WBM cuttings. The only evidence of a statistically significant metal accumulation by marine animals in OBM cuttings was for lead. The lead concentration was high in the OBM cuttings and its concentration increased in worms, mussels, and turbot during the exposure. None of the benthic marine animals bioaccumulated mercury from the mercury-contaminated drilling mud cuttings. The OBM cuttings contained 0.13-0.19 μg/g dry wt. mercury, compared to less than 0.005 μg/g in the reference sediment. These mercury concentrations are typical for drilling muds and cuttings discharged in U.S. and North Sea waters and clean natural sediments, respectively. The results of this study are in agreement with those of Neff et al. (1989b,c), Leuterman et al. (1997), and Schaanning et al. (2002) that the metals associated with drilling mud ingredients and cuttings have a low bioavailability to marine animals. Lead appears to be the only metal that is bioavailable in some cuttings piles. This lead may come from the pipe dope and pipe thread compound that sometimes gets into the drilling wastes. Because of concern about metal contaminantion from pipe dope and pipe thread compound, the offshore oil industry is voluntarily replacing metal-rich pipe dope with products that have low metals concentrations (OLF, 2007).

During the exposure, turbot (a flatfish) fed on the polychaetes in the mesocosm tanks (URS, 2002). The biomagnification factor (BMF) of the metals by turbot was estimated as the ratio of the concentration in the turbot tissues to the concentration in the food. BMFs ranged from <0.01 to 0.42, indicating that biomagnification was not taking place. These results confirm those of Neff et al. (1989c) that there is little trophic transfer and no biomagnification of metals from drilling mud and cuttings in benthic environments.

Studies With Cold-Water Species. Northern Technical Services measured bioaccumulation of several metals by amphipods from the XC-Polymer/Unocal WBM being used to drill the Reindeer Island COST well off Prudhoe Bay in the Beaufort Sea. The drilling mud contained metals concentrations similar to those in other types of WBM from other sources (Table 3-3). The amphipods were exposed to a 20% mixture of the drilling mud in seawater for five days. At five days, half the animals were sacrificed for analysis and half were placed in clean flowing sea water to measure loss of accumulated metals. The amphipods accumulated small amounts of copper and lead but not chromium, mercury, or zinc during exposure (Table 6-3). The amphipods lost some of the accumulated copper and lead during 12 hours in clean seawater. This study shows that the bioavailability of metals from an Arctic WBM is low. Most of the accumulated metal is released rapidly following return of the amphipods to clean seawater, indicating that excess metal probably was present in an unassimilated state in the gut or adsorbed to external body surfaces.

NTS (1981) also exposed several species of Beaufort Sea fish to 4 to 17% mixtures of the WBM that were used to drill the COST well at Reindeer Island. There was little indication of bioaccumulation of any of the metals by any of the fish (Table 6-4). Fourhorn sculpin may have accumulated a small amount of chromium and iron from the CMC/Gel/Resinex WBM and chromium from the XC/Polymer WBM. Saffron cod may have accumulated a small amount of iron from the CMC/Gel WBM. Both fourhorn sculpin and saffron cod are demersal (bottom-feeding) species and may have accumulated iron from ingestion of sediment. Iron is extremely insoluble in oxygenated seawater; the iron probably was present in the gut as inert particles. The chromium may have come from the chrome lignosulfonate thinner in the WBMs. Although chrome and ferrochrome lignosulfonates were used in most WBM between the 1970s and 1990s, they are no longer used for WBM destined for ocean disposal.

Table 6-3 lists concentrations of metals in Beaufort Sea amphipods (*Onisimus* sp.) before and after exposure to a 20% mixture of XC-Polymer/Unocal drilling mud for five days, and after return to clean seawater for 12 hours. Metals concentrations are mg/kg dry wt (ppm). From NTS (1981).

TABLE 6-3
Concentration of Metals in Beaufort Sea Amphipods Exposed to 20% Mixture of XC Polymer

Exposure	Chromium	Copper	Mercury	Lead	Zinc
Unexposed	2.7	5.1	0.07	11.9	123
5 Days	2.7 - 3.6	8.0 - 9.3	0.05 - 0.07	11.8 - 13.6	107 - 137
5 Days & 12 hr Purge	3.0 - 3.2	6.9 - 7.1	0.04 - 0.05	10.2 - 12.3	110 - 114

Table 6-4 lists the bioaccumulation of six metals by four species of Beaufort Sea fish during exposure for four days to different doses (% WBM in seawater) of four WBM used to drill the Reindeer Island COST well. Concentrations are mg/kg dry wt (ppm). From NTS (1981).

TABLE 6-4
Bioaccumulation of Six Metals by 4 Beaufort Sea Fish Species Exposed to WBM used in Reindeer Island Well

WBM Type[a]	Dose (%)	Cadmium	Chromium	Copper	Iron	Lead	Zinc
Fourhorn Sculpin (Myxocephalus quadricornis)							
A	0	0.32-0.79	0.11-0.95	3.8-6.0	48-61	0.8-4.0	95-134
	4.0	0.54-0.90	1.9-4.8	5.3-6.0	132-192	2.5-5.0	106-153
B	0	0.76	0.12	4.87	59	3.1	131
	5.0	0.88	0.86	5.4	59	3.9	124
Broad Whitefish (Coregonus nasus)							
B	0	ND-1.0	0.14-1.7	1.7-3.4	33-76	2.4-7.9	89-152
	17	0.16-0.43	0.96-1.8	1.8-3.5	36-56	4.2-7.7	78-120
B	0	0.18-0.4	0.63-1.1	2.2-2.6	34-67	0.4-6.4	84-101
	7.7	ND-0.45	1.2-1.6	2.4-3.0	36-74	ND-6.7	85-141
Saffron Cod (Eleginus gracilis)							
C	0	ND-0.01	1.7	6.0-6.4	64-80	3.2-3.5	95-109
	17	0.26-0.54	1.42-2.0	4.0-6.6	48-72	3.0-4.1	70-86
C	0	0.74	1.7	4.9	95	5.0	100
	17	0.1-0.37	1.6-2.8	3.9-6.7	72-122	2.4-6.6	94-128
Arctic Cisco (Coregonus autumnalis)							
D	0	0.30-1.0	0.53-5.0	2.6-4.5	40-69	1.6-4.0	85-153
	15	0.13-0.47	1.1-1.3	3.1-3.4	60-72	3.3-3.9	86-112

[a] A - CMC/Gel/Resinex mud; B - XC/Polymer mud; C - CMC/Gel mud; D - Lignosulfonate mud.

Tornberg et al. (1980) measured bioaccumulation of cadmium, chromium, lead, and zinc by amphipods (*Onisimus* sp. and *Boeckosimus* sp) during exposure for up to 20 days to several dilutions of XP-polymer WBM that were being used to drill wells at Prudhoe Bay in 1979. Mean metals concentrations in control amphipods were 0.3 ppm cadmium, 3 ppm chromium, 9.7 ppm lead and 85.8 ppm zinc. Maximum concentrations of metals in amphipod tissues occurred after 15 to 20 days of exposure and there was no dose/response relationship in bioaccumulation. Maximum concentrations of metals during exposure to three concentrations (5, 10, and 15% WBM in water) were 1.7 ppm cadmium, 5.3 ppm chromium, 20 ppm lead, and 140 ppm zinc. Some of the tissue metal probably was in the gut in an unabsorbed form. Highest tissue concentrations were in amphipods that were exposed to the 5 or 10% doses, suggesting that the high doses inhibited feeding or slowed passage of food through the gut. This may explain the observation that concentrations of chromium and lead were above expected background concentrations (Table 6-5) in control and exposed amphipods. Both lead and chromium are abundant in Beaufort Sea sediments.

Table 6-5 lists concentration ranges of several metals in fish, amphipods, and clams collected in the Beaufort Sea between 2000 and 2006 as part of the ANIMIDA and cANIMIDA Programs, compared to the National Status and Trends (NS&T) median concentration ranges for mussels or oysters collected in U.S. coastal waters between 1986 and 2003 (From O'Connor and Lauenstein, 2006). Concentrations are µg/g dry wt (ppm). From Neff et al. (2009).

TABLE 6-5
Concentration Ranges of Several Metals in Beaufort Sea Fish, Amphipods and Clams, 2000-2006

Metal	Fish	Amphipod	Clam	NS&T Medians
Silver (Ag)	0.01 – 0.35	0.8 – 4.0	0.04 – 0.13	---
Aluminum (Al)	---	96 - 1200	98 - 2200	---
Arsenic (As)	0.55 – 16	4.0 – 17	8 - 16	8.1 – 9.6
Barium (Ba)	0.30 – 47	7.4 - 59	7 - 40	---
Berylium (Be)	---	0.01 – 0.03	0.03 – 0.08	---
Cadmium (Cd)	0.01 – 0.37	0.3 – 2.4	0.53 – 13	2.1 – 2.9
Cobalt (Co)	---	0.6 – 2.9	0.8 – 4.0	---
Chromium (Cr)	0.04 – 3.8	0.18 - 1.86	0.91 - 5.15	---
Copper (Cu)	1.1 – 21	41 - 210	7.0 - 24	(8.0 – 10)[a] (91 – 140)[b]
Iron (Fe)	19 - 1200	100 - 950	770 - 3600	---
Mercury (Hg)	0.02 – 0.5	0.02 – 0.19	0.0 – 0.13	0.09 – 0.11
Manganese (Mn)	---	10 - 71	47 - 640	---
Nickel (Ni)	0.03 – 4.4	0.8 – 6.7	1.92 – 5.34	1.6 – 2.2
Lead (Pb)	0.01 – 2.6	0.05 – 0.7	0.18 – 1.9	0.63 – 0.98
Antimony (Sb)	---	0.01 – 0.04	0.01 – 0.06	---
Tellurium (Tl)	---	0.01 – 0.03	0.01 – 0.03	---
Vanadium (V)	0.05 – 5.1	0.5 – 3.4	1.3 – 6.9	---
Zinc (Zn)	36.0 – 120	54 - 170	62 - 130	(110 – 140)[a] (1600 – 2400)[b]

[a] Mussels; [b] Oysters

6.1.2.2 Field Studies

Field Studies in Temperate Environments. Field studies confirm that only small amounts of a few metals are sometimes bioaccumulated from drilling muds and cuttings by benthic marine

animals. Attempts to correlate elevated sediment concentrations of barium, occasionally chromium, and rarely zinc, cadmium, lead, and mercury near drilling sites with an increase in the concentrations of metals in tissues of resident benthic or demersal (i.e., bottom-living) fauna sometimes show a correlation between increases in barium concentrations in sediments and tissues. Bioaccumulation of other metals, particularly mercury, from drilling muds and cuttings on the sea floor rarely is observed; in most cases where a small increase in metals concentrations was reported in sediments and tissues of marine organisms near a platform, review of the data revealed sampling or analytical problems that confounded interpretation of the results (NRC, 1983; Neff , 1987a; Hinwood et al., 1994).

Because mud- and cuttings-associated metals have a low bioavailability, they do not enter the local food web and do not get passed though the food web to fishery species consumed by man (Neff, 1987a, 2002a,b; Neff et al., 1989b,c). When accumulated in the tissues of sediment-dwelling marine animals, they usually are excreted slowly or sometimes remain in the tissues as insoluble, inert concretions, probably of the original barite particles (Jenkins et al., 1989). In the few cases where there is some indication of metals bioaccumulation during and shortly after drilling, metals concentrations in tissues return to background levels shortly after cessation of drilling discharges.

There have been several surveys of the concentrations of metals in tissues of marine animals from the vicinity of offshore platforms (Neff et al., 2000; Neff, 1987a, 2002b). In nearly all cases, these surveys have shown that metals concentrations in tissues of marine animals near platforms are similar to concentrations in tissues of the same or similar species well away from and out of the influence of the platforms. Thus, the metals discharged from platforms in drilling muds and cuttings that are deposited in nearby sediments have a low bioavailability to marine animals.

In 1984, Jenkins et al. (1989) measured concentrations of barium in sediments and tissues of clams collected at five locations 390 to 4900 ft down-current from an exploratory drilling rig about three miles offshore in 240 ft of water in the Santa Barbara Channel off southern California. Sampling occurred about one month after completion of drilling. Approximately 450,000 gal of WBM, containing about 1.9 million lbs of barite (about 1.1 million lbs of barium) were discharged during the four months of drilling.

Barium concentrations in sediments decreased with distance down-current from the rig from 17,000 ± 1500 ppm at 390 ft to 1200 ± 181 ppm at 4900 ft. Concentrations of barium were significantly higher in soft tissues of two species of clams (*Clyclocardia ventricosa* and *Pectinaria californiensis*) collected 390 and 1200 ft from the rig after drilling than in pre-discharge samples. Clam tissues were homogenized and split into several subcellular fractions. More than 97 % of the total barium in tissues was in an insoluble granular fraction. This granular fraction probably included barite particles adhering to gills and gut walls as well as barite particles accumulated in vacuoles in epithelial tissues. Thus, little of the barium from drilling mud barite was actually assimilated into the tissues of the clams. As discussed above, most of the metals in drilling muds are present as insoluble inclusions in barite particles. Thus, most of the metals that appear to be bioaccumulated during exposure to drilling mud and cuttings actually have not been assimilated into the tissues, but persist as inert barite particles on and in tissues.

The fates and effects of drilling discharges from an exploratory well drilled in about 350 ft of water off Atlantic City, N.J. in 1979 were studied intensively (Mariani et al., 1980; Menzie et al., 1980; Gillmor et al., 1981, 1982; Maurer et al., 1981 EG&G Environmental Consultants, 1982). The study focused on effects of drilling discharges on the benthic environment in the immediate vicinity of and out to a distance of two miles from the rig. A zone approximately 490 ft in diameter of drilling discharge accumulation was observed immediately after drilling just south of the drill site. Concentrations of barium in surface sediments were elevated to greater than 1000 ppm after drilling compared to 148-246 ppm before drilling. Sediment barium concentrations decreased with distance from the drill site, indicating that the barium probably was from drilling mud barite. Concentrations of other metals were not elevated in sediments near the rig after drilling.

Some samples of mixed species assemblages of brittle stars, mollusks, and polychaetes collected near the rig two weeks and one year after completion of drilling operations contained elevated concentrations of barium and chromium in their tissues in comparison to concentrations in animals collected before drilling. A reported increase in mercury concentration in mollusk, brittle star, and polychaete samples collected two weeks after drilling (Mariani et al., 1980) was later found to be in error (EG&G Environmental Consultants, 1982). Although concentrations of barium and chromium were elevated by up to 10-fold in polychaetes and brittle stars two weeks and a year after drilling, tissue concentrations were not correlated to concentrations in sediments where the benthic invertebrates were collected. Thus, there was little bioaccumulation by benthic invertebrates of metals from discharged drilling muds and cuttings.

Concentrations of barium and chromium, but not other metals were slightly elevated in the fine-grained fraction of sediments (representing about 5 % of sediment mass) near exploratory drilling operations on Georges Bank after drilling (Neff et al., 1989a). However, metals concentrations in sea clams *Arctica islandica* collected from surface sediments near the drilling rigs were in the normal range for bivalve mollusks (Phillips et al., 1987). There was no correlation between concentrations of barium in sediments and in bivalve tissues. Concentrations of other metals were variable in bivalve tissues and there was not as significant difference in the concentration of any metal in clams from reference and rig sites.

Mauri et al. (1998) measured concentrations of several metals in tissues of two species of bivalve mollusks, *Mytilus galloprovincialis* and *Corbula gibba*, from platform legs and sediments adjacent to a gas platform in the Adriatic Sea eight years after completion of drilling. The distribution of lead, copper, and chromium in sediments indicated a probable origin from drilling mud and cuttings discharges. Zinc and aluminum in sediments probably were primarily from sacrificial anodes on platform structures. Bivalves from platform legs and nearby sediments contained higher concentrations of lead, copper, and zinc than bivalves distant from the platform, suggesting metal bioaccumulation from platform sources. The authors identified sacrificial anodes on submerged metal platform structures as the main source of the excess metals in bivalve tissues. Thus, laboratory and field studies are consistent in showing that there is a very limited bioavailability of metals from drilling muds and cuttings to marine animals.

Cripps et al. (1999) reported that mussels (*Mytilus edulis*) collected from the surface of cuttings piles in the Norwegian Sector of the North Sea contained higher concentrations of several metals in soft tissues than mussels from uncontaminated marine areas of the North Sea. The mussels

were part of the biofouling community on submerged platform structures and probably became detached from the platform and settled to the bottom on the cuttings piles. The metals in the mussel soft tissues could have come from the metal platform structures to which they had been attached, from produced water or other waste discharges, or from the cuttings piles themselves. Thus, these observations, though suggestive that metals in cuttings piles are somewhat bioavailable, do not provide solid proof of such bioavailability. Mussels have for many years been collected from platforms offshore southern California for sale to restaurants. Subsamples of all batches of mussels are routinely analyzed for metals and hydrocarbons and are always found to be cleaner than mussels collected inshore (J.P. Ray, personal communication).

Field Studies in Coldwater Environments. The Arctic Nearshore Impact Monitoring in the Development Area (ANIMIDA) Program and its continuation (cANIMIDA), sponsored by MMS, included measurement of metals and hydrocarbons in sediments and tissues of marine animals at several locations in the area of historic exploratory and development drilling along the central Alaskan Beaufort Sea coast (Neff et al., 2009; Brown et al., 2010). Data for the vicinity of the Northstar development were compared to data for other areas from Harrison Bay in the west to Camden Bay in the east in an effort to determine if there were any effects of the construction and operation of the Northstar production facility on the marine environment. The Northstar production facility was constructed in 1999-2000 on an artificial island on the remains of the old Seal Island where Shell drilled exploratory wells in 1984 and 1985. The facility is located seaward of the barrier islands about six miles offshore in about 40 ft of water. Drilling muds and cuttings were not discharged to the Beaufort Sea during development of the Northsar facility. Initially, all wastes were trucked to shore over an ice road for on-land treatment and disposal. Subsequently, a reinjection well was drilled on the gravel island for disposal of development wastes. Oil production began in 2001.

The results of the six years of ANIMIDA/cANIMIDA sampling indicate that there were no significant inputs of metals and hydrocarbons to the ocean waters and sediments from development and production at the Northstar facility. Concentrations of metals and hydrocarbons varied within the normal range in sediments and marine animals from Arctic marine environments. These data can be used as reference (background) concentrations for comparison with metals and hydrocarbon concentrations in sediments and marine animal tissues from the vicinity of Arctic marine exploration and development activities. The sediment metals and hydrocarbon data are summarized in Tables 5-10, 5-11, and 5-12. The tissue metals data are summarized in Table 6-5. Hydrocarbon concentrations in tissues of invertebrates and fish collected in the ANIMIDA/cANIMIDA program will be discussed in Section 6.1.3.

Concentrations of most metals are similar in tissues of the three taxa of marine animals surveyed: fish, amphipods (crustaceans), and clams (mollusks) (Table 6-5). Fish muscle tissue contained lower concentrations of cadmium and higher concentrations of mercury than the crustaceans and mollusks did. Copper concentrations were higher in the crustaceans than in the other two taxa, probably because most marine crustaceans use copper-containing blood pigments. All tissue metals concentrations for which data are available agree well with the ranges of median concentrations for metals in mussels or oysters collected in U.S. coastal waters between 1986 and 2003 in the National Status and Trends Program (O'Connor and Lauenstein, 2006).

Crippen et al. (1980) studied the effects of exploratory drilling from Netserk F-40 Island, an artificial gravel island in the Canadian Beaufort Sea. The well was drilled with WBM containing a low quality grade of barite that contained elevated concentrations of several metals. Slaney and Co. (1977) performed an initial survey of the site about 3 months after completion of drilling and Crippen et al. (1980) performed a second survey in August 1977, 15 months after drilling. Much of the gravel island had eroded away by the time of the August 1977 survey.

An objective of both surveys was to evaluate bioaccumulation of metals from the drilling discharges by resident marine animals. A total of 42 samples of a mixed assemblage of infaunal worms and clams and of epifaunal isopods from the area around the drill site were collected during the August 1977 survey and analyzed for the 6 metals. Mean concentrations of all metals in the sediment samples were slightly elevated after drilling compared to concentrations in sediments before drilling (Table 5-13). Tissue metals concentrations also were slightly elevated 15 months after drilling compared to metals concentrations in the same species beyond the influence of the island (Table 6-6) or those collected in the ANIMIDA program west of the Netserk F-40 site (Table 6-5). However, there was no correlation between concentrations of any metals in sediments and tissues of the marine invertebrates. A few samples of clams from four stations near the island contained slightly elevated total mercury concentrations (to 2.45 ppm), but sample size was small, increasing analytical error, particularly for mercury. Concentrations of chromium and lead in clams and isopods and zinc in clams also were higher than measured in similar species in the ANIMIDA area. As with the tissue mercury data, this may have been an analytical error, because it is difficult to avoid contamination of tissues with these metals during laboratory processing and analysis. Although the drilling muds used at Netserk contained elevated concentrations of the six metals, it is probable that the metals, particularly mercury, contamination of the sediments was mainly from the barrow material eroded from the island after drilling. Thus, the Crippen et al. (1980) study confirmed the observations of others that metals associated with drilling wastes have a low bioavailability to arctic marine animals.

NTS (1981) monitored experimental on-ice discharges of several types of WBM to the Beaufort Sea during drilling of an exploratory well at Reindeer Island in 1979. The drilling muds contained elevated (compared to local sediments) concentration of several metals. They also collected and analyzed marine macroalgae and invertebrates from reference sites and the site of the experimental drilling mud discharge eight and 12 months after the discharges. Concentrations of most metals were higher in the plants and animals from the reference site than in those from the discharge site. However, concentrations of barium and chromium were higher in the tubes of polychaete worms and in tissues of a soft coral (*Eunephyta rubriformis*) from the discharge site. Amphipods maintained in live boxes contained slightly higher concentrations of copper at the disposal site than at the reference site. All other metals concentrations were similar in the two groups of crustaceans. These results show again that drilling mud metals have a low bioavailability to Arctic marine plants and animals.

Table 6-6 lists mean and range in parentheses of concentrations of six metals in sediments before and 15 months after exploratory drilling at Netserk F-40, an artificial gavel island in the Canadian Beaufort Sea and concentrations in benthic invertebrates collected at different distances from the island 15 months after drilling. Tissue concentrations were converted to dry wt by multiplying by five. Concentrations are mg/kg dry wt. From Crippen et al. (1980).

TABLE 6-6
Concentrations (Mean and Range) of 6 Metals Before and After Exploratory Well Drilling, Netserk F-40 Gravel Island

Metal	Surface Sediments		Infaunal worms and clams	Epifaunal Isopods
	Before Drilling	15 months After Drilling	15 Months After Drilling	
Arsenic	9.9 (5.2 - 21)	> 12 - 23	7.5 (1.0 - 13)	4.5 (1.5 - 10.5)
Cadmium	1.0 (0.7 - 1.6)	2.1 - 5.9	12.5 (3.0 - 13)	4.5 (3.0 - 7.0)
Chromium	15 (6.4 - 22)	70	7.5 (0.5 - 28.5)	6.0 (0.5 - 19.5)
Lead	20 (10.5 - 24.5)	466	7.0 (0.5 - 18.5)	9.5 (2.0 - 17.0)
Mercury	0.07 (0.02 - 0.11)	> 6	0.25 (<0.05 - 2.45)	0.05
Zinc	116 (56 - 131)	1360	165 (25 - 210)	105 (85 - 130)

NTS (1982) performed a similar bioaccumulation study at Endeavor Sag Delta 7 and Resolution Sag Delta 8 exploratory drill sites. Concentrations of barium in sediments increased at these sites after drilling (Tables 5-11 and 5-16). They measured concentrations of barium, cadmium, chromium, copper, mercury, lead, and zinc in tissues of kelp (*Laminaria solidungula*), isopods (*Saduria entimon*), and four horn sculpin (*Myoxocephalus quadricornis*) from the vicinity of the discharge sites before island construction, after island construction, and after drilling waste discharge. Although there were seasonal changes in concentrations of all metals in the plants and animals, there were no increases in metals concentrations that could be attributed to drilling discharges.

NTS (1982) also monitored metals concentrations in sediments (Table 5-17) and in tissues of amphipods (*Onisimus* sp. and *Boekosimus*), isopods, and unidentified snails near the Challenge Island disposal site before and after drilling waste disposal. Although the concentrations of barium, lead, and zinc in sediments were higher after discharge, there were no increases in tissue metals concentrations that could be attributed to the drilling discharges.

The Devon Canada monitoring program performed in August 2006 following drilling of the Paktoa-60 well in the Canadian Beaufort Sea included an assessment of bioaccumulation of metals and hydrocarbons by benthic amphipods (KAVIK-AXIS, 2007). Benthic amphipods (tentatively identified as *Onisimus glacialis*) were collected with two- to three-hour deployments of baited traps at five locations near the drill site and at a reference location away from influence of the drilling activities. The amphipods were analyzed for the same four metals (aluminum was not measured in amphipods) and hydrocarbons as were analyzed in site sediments and drilling muds (Tables 5-21 and 5-22).

Concentrations of all four metals were similar in post-drilling and reference amphipods and slightly higher in reference amphipods collected in the Beaufort Sea in 2002 (Table 6-7). Highest concentrations of lead and iron and lowest concentration of mercury were in amphipods collected near the site of the grey water discharge from the SDC. The concentrations of mercury and cadmium in the Paktoa-60 drill site amphipods were in the range of concentrations reported

for the Alaskan Beaufort Sea (Table 6-5). Mean lead and iron concentrations were higher, becasue of elevated concentrations in samples collected near the grey water discharge site. Concentrations of the other metals and hydrocarbons were in the range of those for Canadian and Alaskan Beaufort Sea amphipods. The slightly elevated concentrations of iron and lead in the amphipods probably is associated with ingested, unassimilated fine-grained particles, possibly from the grey water, in the gut of these benthic carnivores/detritivores. KAVIK-AXIS (2007) concluded that there was no evidence of bioaccumulation of metals from drilling wastes by the amphipods.

Table 6-7 lists concentrations (mean, standard deviation, and range) of four metals, total alkanes, and total polycyclic aromatic hydrocarbons (TPAH) in tissues of amphipods (*Onisimus glacialis*) collected at six stations near the Paktoa-60 drill site in August 2006, five months after drilling. Concentrations are mg/kg dry wt (ppm), converted from wet wt by multiplying by five. From KAVIK-AXYS (2007).

TABLE 6-7
Concentrations of 4 Metals, Alkanes and TPAH in Amphipods, Paktoa C-60 Drillsite, August, 2006

Chemical	Post-drilling (Mean±SD, Range)	Reference	Beaufort Sea 2002 (Mean±SD, Range)
Mercury (Hg)	0.10 ± 0.038 (0.06 - 0.17)	0.10	0.05 ± 0.008 (0.04 - 0.06)
Lead (Pb)	1.0 ± 0.55 (0.35 - 1.9)	0.85	0.6 ± 0.35 (0.70 ± 0.90)
Cadmium (Cd)	0.70 ± 0.15 (0.45 - 0.85)	0.90	0.70 ± 0.25 (0.45 - 0.90)
Iron (Fe)	1655 ± 785 (615 - 2820)	1635	895 ± 470 (185 - 1115)
Total alkanes	31.5 ± 33.5 (18.5 - 43.5)	16.5	8.5 ± 2.5 (5.45 - 10.3)
TPAH	0.20 ± 0.10 (0.10 - 0.30)	0.20	0.12 ± 0.07 (0.05 - 0.20)

6.1.3 Bioaccumulation of Hydrocarbons from WBM and Cuttings

Relatively little information is available about the bioavailability of organic compounds from WBM and WBM cuttings. Petroleum hydrocarbons, particularly PAH, are the organic compounds sometimes present in WBM and associated cuttings that could pose a risk of bioaccumulation and toxicity to marine communities near the discharge. Because WBM and WBM cuttings contain low concentrations of saturated and aromatic hydrocarbons, unless contaminated with formation hydrocarbons or a petroleum based lubricant, there have been no laboratory studies and only few field studies of bioaccumulation of saturated and aromatic hydrocarbons from WBM and cuttings. If Shell encounters formation hydrocarbons during

exploratory drilling, the mud and cuttings will be recovered and treated to remove the hydrocarbons or transported to shore.

There have been several laboratory and field studies in the North Sea of bioaccumulation of petroleum hydrocarbons from OBM cuttings and synthetic chemicals from SBM cuttings. The results of these studies were described by Hartley et al. (2003) and show that, although OBM and SBM cuttings contain orders of magnitude higher concentrations of hydrocarbons and synthetic chemicals than WBM and WBM cuttings do, there was very little bioaccumulation by marine mollusks, polychaete worms, and fish. The hydrocarbons in North Sea cuttings piles are degraded very slowly by hydrocarbon degrading bacteria, indicating that the hydrocarbons have a low bioavailability, explaining the lack of bioaccumulation by marine animals. These observations strengthen the conclusion that hydrocarbons, including PAH, associated with WBM and cuttings on the sea floor do not pose a hazard to marine animals and ecosystems.

Neff et al. (2009) measured concentrations of PAH in tissues of invertebrates and fish in the drilling area of the Alaskan Beaufort Sea (Tables 6-8 and 6-9). There were no clear regional differences in PAH and saturated hydrocarbon concentrations in amphipod, clam, and fish tissues. Animals from the vicinity of the Northstar development contained similar TPAH concentrations to those to the east of Northstar, including the Liberty prospect and Camden Bay, where Trefry and Trocine (2009) detected high sediment TPAH concentrations at the site of the Hammerhead exploratory drill site. Thus, these tissue PAH concentrations can be considered background concentrations for the region.

Table 6-8 lists the mean, standard deviation, and range of concentrations of total polycyclic aromatic hydrocarbons (TPAH) and total saturated hydrocarbons (TSHC) in soft tissues of amphipods (*Anonyx nugax*) and clams (*Astarte montagui* and *Cyrtodaria kurriana*) collected from the Beaufort Sea in 2000, 2002, 2004, 2005, and 2006 as part of the MMS ANIMIDA/cANIMIDA Program. Concentrations are mg/kg dry wt (ppm). Data for 2000 and 2002 were converted from wet wt. by multiplying by five, based on ~80% moisture. From Neff et al. (2009).

TABLE 6-8
Concentrations of TPAH and TSHC in Beaufort Sea Amphipods and Clams, 2000, 2002, 2004, 2005 and 2006

Hydrocarbon	Year	Amphipods		Clams	
		Mean ±SD	Range	Mean (SD)	Range
TPAH	2000	0.086 ± 0.018	0.060 – 0.12	0.090 ± 0.054	0.037 – 0.20
	2002	0.096 ± 0.042	0.055 – 0.18	0.080 ± 0.048	0.048 – 0.18
	2004	0.068 ± 0.033	0.040 – 0.14	0.096 ± 0.053	0.043 – 0.17
	2005	0.025 ± 0.014	0.008 – 0.05	0.038 ± 0.015	0.022 – 0.05
	2006	0.060 ± 0.030	0.020 – 0.012	0.14 ± 0.041	0.10 – 0.18
All Years			0.008 - 0.18		0.037 - 0.18
TSHC	2000	55.8 ± 45.3	0 – 130	6.0 ± 8.6	0 – 22.0
	2002	113 ± 71.8	23.5 – 260	14.1 ± 1.39	12.5 – 16.0
	2004	444 ± 8.54	29.8 - 54.1	26.8 ± 14.4	0.68 – 39.7
	2005	31.6 ± 18.4	5.17 – 67.1	1.51 ± 0.52	1.03 - 2.23
	2006	63.0 ± 57.1	13.7 – 249	12.6 ± 2.41	10.2 – 15.0
All Years			0 - 260		0 - 39.7

Table 6-9 lists the range of concentrations of total polycyclic aromatic hydrocarbons(TPAH) in the whole tissues of six species of fish collected between 2004 and 2006 from coastal waters of the Alaskan Beaufort Sea as part of the MMS ANIMIDA/cANIMIDA Program. Concentrations are mg/kg dry wt (ppm). From Neff et al. (2009).

TABLE 6-9
Concentration Ranges of TPAH in 6 Beaufort Sea Fish Species, 2004 and 2006

Fish Species	Concentration Range TPAH
Arctic cisco (Coregonus autumnalis)	0.004 - 0.040
Least cisco (Coregonus sardinella)	0.017 - 0.059
Broad whitefish (Coregonus nasus)	0.022 - 0.046
Humpback broad whitefish (Coregonus pidshian)	0.003 - 0.024
Arctic char (Salvelinus alpinus)	0.020 - 0.075
Arctic cod (Boreogadus saida)	0.034 - 0.092
Arctic flounder (Liopseta glacialis)	0.008 - 0.053
Fourhorn sculpin (Myxocephalus quadricornis)	0.006 - 0.063

The Arctic amphipods from the Beaufort Sea analyzed by KAVIK-AXIS (2007) and Neff et al. (2009) contained 0.02 to 0.3 ppm TPAH (Tables 6-7 and 6-8). This concentration range is orders

of magnitude lower than TPAH concentrations measured in Arctic amphipods (*Eurythenes grylius*) collected northeast of Svalbard in the Norwegian Barents Sea (Svendsen et al., 2007), indicating that the concentrations in Beaufort Sea amphipods are at background levels, compared to some other locations. The Svalbard amphipods are scavengers like the amphipods sampled in the Beaufort Sea and contained a mean of 2.6 ± 2.2 ppm TPAH (range 0.6 to 4.5 ppm). Dahle et al. (2009) reported the highest concentrations of TPAH in the Arctic in sediments collected southeast of Svalbard (probably not the location where Svendsen et al. (2007) sampled) and suggested that PAH were from weathering of coal-bearing formations. The PAH assemblage in Svalbard sediments was dominated by 2-3-ring alkyl-naphthalenes and alkyl-phenanthrenes, whereas the PAH assemblage in the amphipod tissues was dominated by 4-5-ring chrysenes through benzo(a)pyrene. Thus, the source of the PAH in the Svalbard amphipod tissues is unclear, but could be weathered residues of seep oil, coal, or kerogens.

All the Beaufort Sea fish species contained lower concentrations of TPAH than the amphipods and clams did (Tables 6-8 and 6-9) (Neff et al., 2009). Fish have an active metabolic system that rapidly biodegrades and excretes bioaccumulated PAH; the amphipods have a lower level of this enzyme system and clams have very little activity (Neff, 2002a), accounting for this difference. TPAH concentrations were similar in all eight fish species, although some are anadromous/estuarine and are exposed seasonally to peat-derived PAH in the rivers; others, including the fourhorn sculpin and Arctic flounder, are demersal and remain close to sediments, some of which, as discussed above, contain slightly elevated concentrations of saturated and aromatic hydrocarbons. The arctic cod is a keystone species in the Arctic food web throughout the world; it does not bioaccumulate PAH to higher concentrations than the other species examined.

Saturated hydrocarbons were measured only in amphipods and clams. Their concentrations were much higher than those of the TPAH in the invertebrate tissues. Many of the saturated hydrocarbons in tissues are from natural biogenic sources. The much higher concentrations of total saturated hydrocarbons in amphipods than in clams is due to the presence of very high concentrations of pristane, a hydrocarbon derived from phytoplankton and accumulated to high concentrations by calanoid copepods (the favorite food of bowhead whales). The amphipods accumulate the pristane from their diet of dead plankton detritus that is constantly settling to the bottom in the Arctic. Arctic cod also feed heavily on zooplankton and contain high concentrations of pristane. The presence of high concentrations of pristane (not abundant in sediments) and low concentrations of PAH in amphipod tissues is a strong indication that the PAH and saturated hydrocarbons that are present at elevated concentrations in Arctic sediments have a low bioavailability to marine invertebrates and fish. This includes the elevated concentrations of hydrocarbons that were found in sediments at the Hammerhead and Paktoa-60 drill sites. As discussed above, the PAH in these sediments are tightly bound to the particles of peat and kerogen in these sediments and are not bioavailable to hydrocarbon-degrading bacteria or to marine animals and, therefore, are very persistent in sediments.

Payne et al. (1985) and Phillips et al. (1987) examined saturated and aromatic hydrocarbons by UV fluorescence and gas chromatography/flame ionization detection in sediments, sea clams *Arctica islandica,* and flounder *Paralichthys oblongus* from the vicinity of exploratory wells on Georges Bank off the New England coast. One of the exploratory rigs had added diesel fuel to WBM to free stuck pipe and had discharged WBM containing approximately 100 L of diesel.

Concentrations of saturated and aromatic hydrocarbons were low in sediments, clams, and fish. Sediments near the rigs contained less than 1 ppm total aromatic hydrocarbons (mainly PAH), consistent with background concentrations in this region (Boehm and Farrington, 1984). There was no evidence that the two benthic/demersal marine animals bioaccumulated any hydrocarbons from the drilling discharge.

Sjøgren et al. (1989) measured concentrations of several petroleum hydrocarbon classes in livers of Atlantic cod *Gadus morhua* from the immediate vicinity of North Sea platforms discharging either WBM and cuttings or OBM cuttings, and compared concentrations to those in cod collected more than six miles from the nearest discharge (Table 6-10). TPH concentration was similar in livers of fish from all three locations. However, PAH and decalins concentrations were higher in livers of fish from the vicinity of the WBM- and OBM-discharging platforms. Livers of fish from the vicinity of the WBM-discharging platforms contained lower concentrations of PAH and decalins than livers of fish from the vicinity of the OBM-discharging platforms. Alkylcyclohexane concentrations were similar in livers of fish from the WBM-discharging and reference platforms. These results indicate that PAH and decalins (2-ring saturated hydrocarbons), probably from petroleum, are bioavailable near production platforms in the North Sea. It is probable that most of the hydrocarbons were derived from produced water and other discharges from the platforms. Decalins and PAH are abundant in many North Sea produced waters and are readily bioaccumulated by mussels and fish deployed in cages within a few miles of the platforms (Durell et al., 2006; Neff et al., 2006; Førlin and Hylland, 2006). Thus, the PAH in the cod probably came primarily from the produced water. The main concern of regulators and the local stakeholders with respect to zero discharge policy in the Norwegian and Barents Sea is the discharge of produced water containing PAH and endocrine disrupting alkyl phenols, not the discharge of WBM and cuttings (Nilssen and Johnsen, 2008).

Table 6-10 lists the mean and range (in parentheses) of concentrations (µg/g dry wt: ppm) of several hydrocarbon classes in livers of Atlantic cod *Gadus morhua* collected within 800 ft of platforms in the Norwegian North Sea that were discharging WBM and cuttings or OBM cuttings and from more than 10,000 m from discharging platforms (Reference). From Sjøgren et al. (1989).

TABLE 6-10
Concentrations of Hydrocarbons in Atlantic Cod Livers, Norwegian North Sea with WBM and OBM Discharges

Hydrocarbon Class	WBM	OBM	Reference
THC[a]	978 (820 – 1110)	928 (510 – 1890)	880 (560 – 1170)
NPD[b]	0.40 (0.08 – 0.69)	1.80 (0.44 – 3.2)	0.06 (0.004 – 0.11)
C5-C6 Decalins	12.0 (8.3 – 18)	16.4 (1.0 – 65)	5.5 (1.4 – 15)
C8-Alkylcyclohexanes	2.7 (1.7 – 3.6)	6.8 (0.11 – 26)	1.6 (0.4 – 3.1)

[a] Total hydrocarbons measured by GC/FID.
[b] Polycyclic aromatic hydrocarbons, including naphthalene, phenanthrene/anthracene, and dibenzothiophene and their C1-C3 alkyl homologues measured by GC/MS.

The Devon Canada monitoring program performed in August 2006 following drilling of the Paktoa-60 well in the Canadian Beaufort Sea included an assessment of bioaccumulation of hydrocarbons by benthic amphipods (KAVIK-AXIS, 2007). Concentrations of total alkanes,

essentially the same as total saturated hydrocarbons (TSHC), in the amphipods from the vicinity of the drill site ranged from 18.5 to 43.5 ppm, compared to a range of 5.45 to 15.5 ppm in amphipods from reference sites (Table 6-7). The only drill site amphipods with elevated total alkane concentrations were those collected near the moon pool of the SDC. The alkane fraction in these amphipods was dominated by pristane, a primarily biogenic alkane produced by marine phytoplankton. It is probable that these alkanes came from the sediments (cuttings) from the top hole of the well. Although the total alkane concentrations were significantly higher in amphipods from the discharge site than in those from reference areas, all concentrations were in the lower part of the range reported by Neff et al. (2009) for amphipods from the Alaskan Beaufort Sea (Table 6-8).

Concentrations of TPAH in amphipods from the vicinity of the drill site ranged from 0.1 to 0.3 ppm, only slightly higher than the range in amphipods from the reference sites (0.05 to 0.20 ppm) (Table 6-7). The PAH assemblage in the sediments in the region of the Paktoa-60 drill site and in the entire area off the Mackenzie River and in tissues of drill site and reference amphipods was dominated by perylene, a natural diagenic PAH, probably derived from slow decay of plant matter in anoxic sediments to form peat and kerogen. Thus, the amphipods did not biaccumulate PAH from the drilling discharges from the SDC at Paktoa-60.

These field studies are very consistent in showing that saturated and aromatic hydrocarbons in WBM and WBM cuttings discharged to the ocean have a very low bioavailability to marine animals. If the hydrocarbons in WBM and cuttings discharges are not bioavailable then they will not enter the marine food chain and do not have the potential to be harmful to marine organisms and ecosystems.

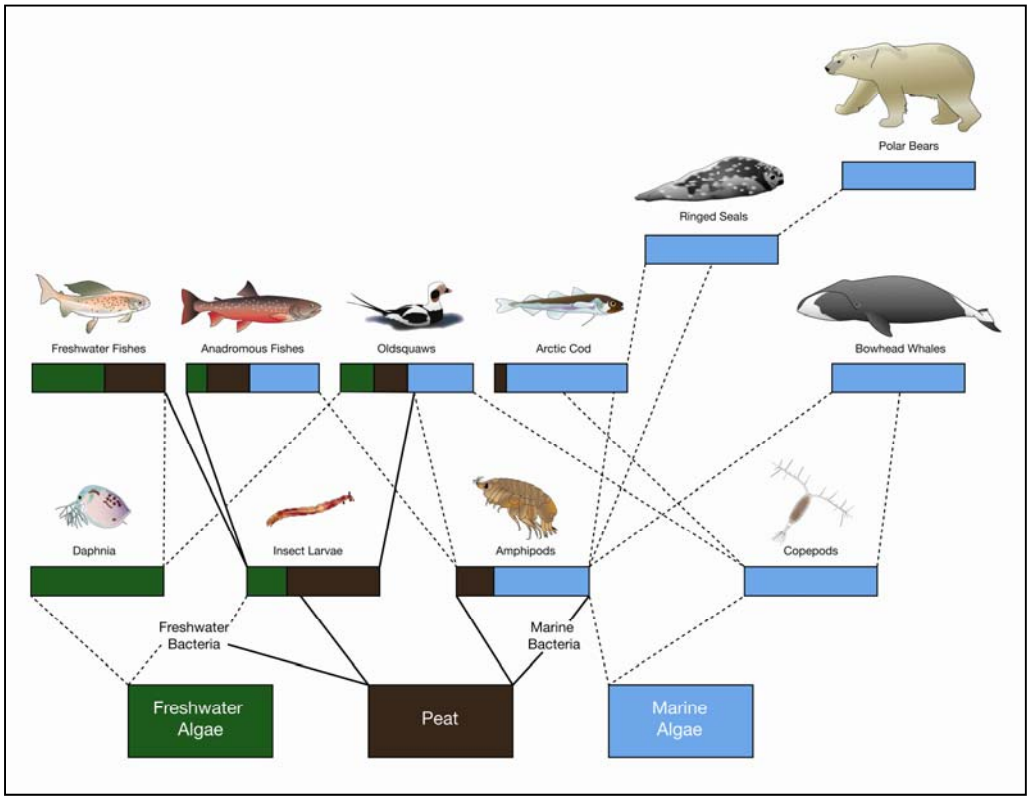
6.1.4 Distribution of Metals and Hydrocarbons in Arctic Marine Food Webs

6.1.4.1 The Chukchi and Beaufort Sea Food Webs

The harsh marine environment of the Chukchi and Beaufort Seas, with wide seasonal variations in light intensity, ice cover, freshwater input from rivers, and nutrient concentrations, results in wide seasonal cycles of primary production, and simple, seasonally variable food webs (Walsh et al., 2005). Food web structure and carbon flow on the continental shelf of the Alaskan Beaufort and Chukchi Seas are different in the nearshore (in bays or inside the barrier islands) and offshore environments and are weakly linked (Figure 6-1). For example, although terrestrially derived peat makes a substantial contribution to available particulate organic carbon (POC) in the nearshore marine environment (left side of Figure 6-1), it contributes much less to offshore organic carbon fluxes (right side of Figure 6-1) (Schell, 1983; Dunton et al., 2006). Arctic cod in Beaufort Sea lagoons may derive up to 70 percent of their carbon from terrestrial carbon (mostly peat); offshore populations derive most of their carbon from zooplankton (Dunton et a., 2006).

Figure 6-1 shows a generalized food web structure showing the sources of organic carbon, including peat, in the Alaskan Beaufort Sea coastal ecosystems. The shading of the rectangles below each taxon shows the relative contribution and pathway of carbon from freshwater algae, terrestrial peat, and marine algae in the food web. Food chain structure grades from near-shore, freshwater/estuarine on the left to offshore marine on the right. Modified from Schell et al. (1982) .

Figure 6-1 Generalized Food Web Structure with Sources of Organic Carbon, Alaskan Beaufort Sea

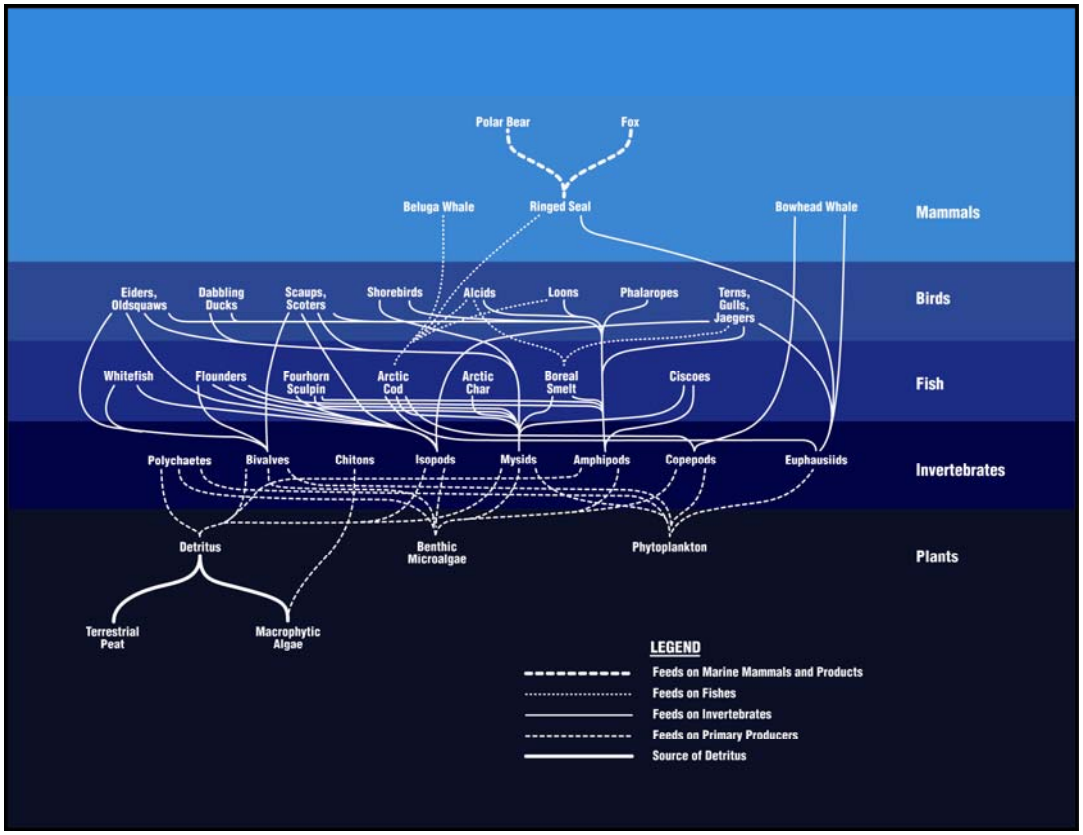


The Beaufort and Chukchi Sea food webs are relatively simple compared to those in many temperate and tropical climates, with relatively few abundant taxa at each trophic level (Figure 6-2). Nutrients to support primary production in the Alaskan Beaufort and Chukchi Seas are derived primarily from inflows from the Bering Sea, Anadyr Water (from the Russian Chukchi Sea), the Canadian Beaufort Sea, and upwelling from the Arctic Basin (Dunton et al., 2003a,b, 2004). Primary production is pelagic (phytoplankton), epontic (living on the underside of sea ice), and benthic (micro- and macro-algae living on the sea floor). The epontic community along the seasonal ice edge may contribute substantially to overall pelagic production. Epontic microalgae support diverse communities of ice-associated meiofauna that help support spring zooplankton blooms (Carey and Montagna, 1982).

Primary production, measured as chlorophyll a concentrations in surface waters, is lower in the Beaufort than in the Chukchi Sea (Dunton et al., 2003a,b, 2004). Near-shore areas east of Barrow and off the Coleville River have the highest primary production in coastal and continental shelf waters of the Beaufort Sea. This probably is caused mainly by the large flux of organic carbon into the Beaufort Sea from rivers (Yunker et al., 2005; Elmquist et al., 2008; Holmes et al., 2008).

Figure 6-2 shows a diagram of the Beaufort/Chukchi Sea food web model, showing carbon pathways from terrestrial peat and primary production to top keystone species of marine birds and mammals. Modified from MMS (1990).

Figure 6-2 Diagram of Beaufort/Chukchi Sea Food Web with Carbon Pathways to Top Species of Marine Birds and Mammals



The Chukchi Sea continental shelf is a highly productive marine ecosystem (Dunton et al., 1989; Feder et al., 1989; Moran et al., 2005). Particulate organic carbon (POC) produced by primary producers (phytoplankton) or in runoff from land may be consumed by primary consumers (mostly zooplankton), or exported to sediments or off the shelf (Wasserman et al., 2003; Moran et al., 2005). In the nutrient rich northeastern Chukchi Sea, the fraction of primary production that is exported from the water column to the underlying sediments increases from about 15% in the spring to about 32% in the summer (Moran et al., 2005). The POC also supports blooms of zooplankton communities, dominated by calanoid copepods and euphausiids that are consumed by Arctic cod and bowhead whales (Figure 6-3). POC in sediments supports development of a rich benthic fauna that supports benthic feeders, such as walrus, some ice seals, gray whales, and many species of demersal fish, and results in strong benthic/pelagic coupling of nutrients (Figure 6-1). Sediments in the northeast Chukchi Sea and in several areas of the Beaufort Sea, as far east as the McKenzie River delta contain high concentrations of organic matter from marine and terrigenous sources. This organic matter tends to sequester metals and hydrocarbons and is ingested by benthic fauna; however, the highly humic organic matter tightly binds the metals and hydrocarbons, lowering their bioavailability to benthic fauna, even those that ingest peat carbon, limiting bioaccumulation and trophic transfer of these constituents in the Beaufot and Chukchi Sea food webs.

POC flux to the benthos probably is lower in the nutrient-depleted Beaufort Sea (Dunton et al., 2003a,b, 2004, 2006). Because of the lower POC flux, benthic biomass in the Beaufort Sea

(average 33 g/m^2) is much lower than that in the Chukchi Sea (average 167 g/m^2) (Dunton et al., 2003a,b, 2004). Sediments in the Beaufort and Chukchi Seas contain organic matter from both marine and terrestrial sources (Yunker et al., 2005; Hemes and Benner, 2006; Holmes et al., 2008). As discussed above, much of the terrigenous organic matter is delivered to the Beaufort Sea in outflows from large Canadian and Alaskan rivers and from coastal erosion and often is enriched in metals and hydrocarbons.

Griffiths and Thompson (2002) identified three zooplankton communities in waters out to 200 m off the eastern Alaskan Beaufort Sea (Camden Bay and eastward to the Canadian border). Copepods are dominant in all three communities, accounting for 50 to 75% of the total zooplankton biomass. Three species represent more than 85% of the total copepod biomass: *Calanus hyperboreus, C. glacialis,* and *Limnocalanus macrourus.* These calanoid copepods, particularly the large lipid-rich adults, are the primary food of bowhead whales in the eastern Beaufort Sea. Calanoid copepods, primarily *Pseudocalanus,* are abundant under the sea ice during winter and early spring; they are replaced in early summer by cyclopoid and harpacticoid copepods, hydrozoans, amphipods, larvaceans and larval stages of planktonic and benthic invertebrates (Horner and Murphy, 1985).

Euphausiids (*Thysanoessa inermis* and *T. raschii*) are much less abundant than calanoid copepods in the eastern Beaufort Sea. However, they are seasonally abundant in the Chukchi Sea and western Beaufort Sea. Euphausiids are transported by deep-water currents from the Bering Sea, through the Chukchi Sea to waters off Barrow, and then into the western Beaufort Sea (Berline et al., 2008). They are the main prey of bowhead whales that aggregate in the northeast Chukchi Sea and off Barrow during the fall migration.

The abundance and distribution of zooplankton is extremely variable in different seasons and years. Total zooplankton wet biomass in waters of the eastern Alaskan Beaufort Sea ranges from 170 to more than 383 mg/m^3 in different years; biomass is greater at depths of more than 10 m than at the surface (Griffiths and Thomson (2002). Wet biomass of zooplankton can be as high as 3,500 mg/m^3 in dense patches. The feeding threshold (the lowest concentrations that stimulates feeding) for bowhead whales may be as high as 800 mg zooplankton wet biomass/m^3 of seawater (Griffiths et al., 2002; MMS, 2006b), highlighting the importance of dense zooplankton patches to bowhead whales.

These primary consumers are preyed on by a variety of secondary consumers (carnivores), including several species of anadromous and marine fish, marine birds, and marine mammals, including some ice seals (e.g., ringed, ribbon, and bearded seals) and baleen whales (bowhead and gray whales) (Figure 6-3). Other marine fish, birds, and mammals consume primarily fish; polar bears consume primarily other marine mammals, particularly ringed seals. Crustaceans, such as copepods, euphausiids, amphipods, isopods, and mysids, are abundant in coastal, estuarine waters where they are preyed upon heavily by several species of fish (Table 6-11). Many of the coastal fish in the Beaufort Sea feed primarily on small fish, particularly arctic cod (Frost and Lowry, 1984).

Table 6-11 lists anadromous and marine fish collected for cANIMIDA Program (Neff et al., 2009) from coastal waters of the Beaufort Sea and their food preferences. Data from Thorsteinson and Wilson (2006) and Craig et al. (1984).

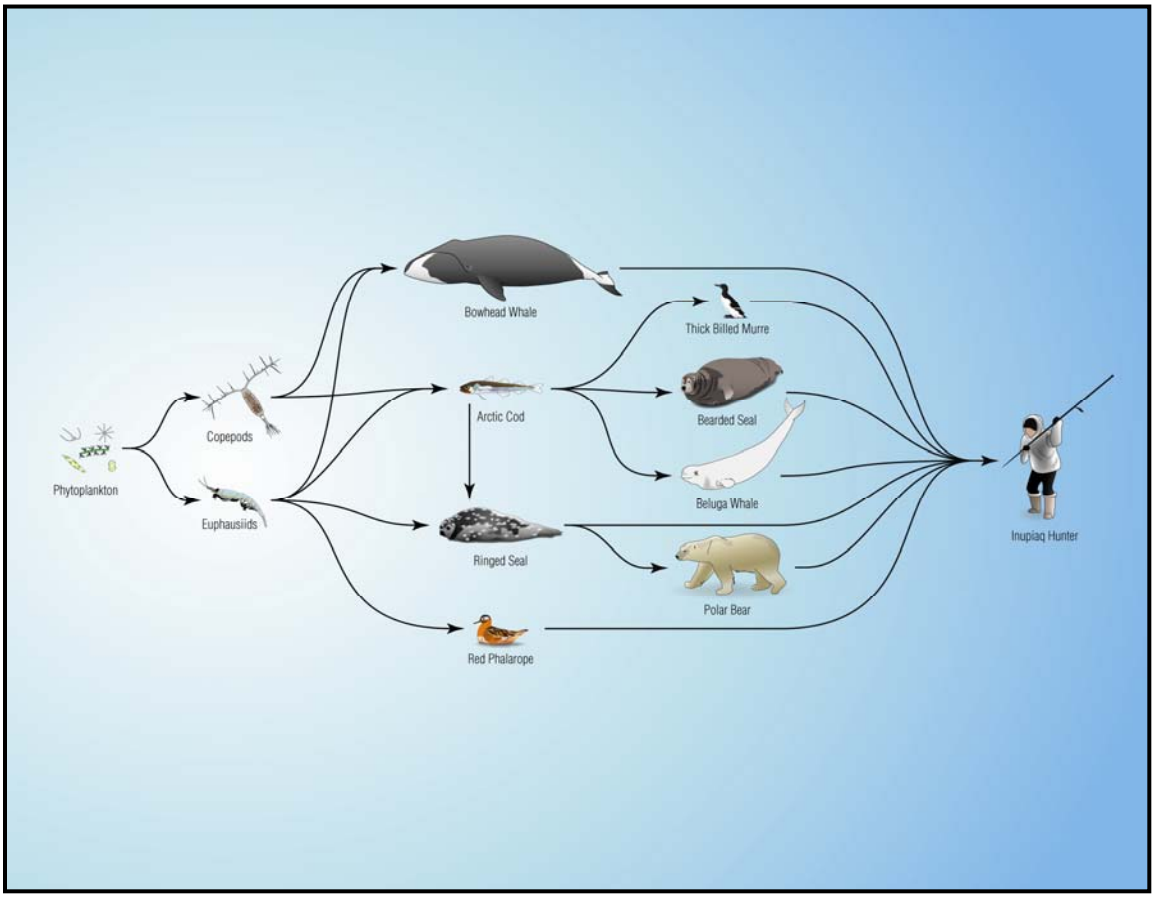
TABLE 6-11
Food Preferences, Anadromous and Marine Fish, Alaskan Beaufort Sea Coastal Waters

Common Name	Scientific Name	Food Preferences
Marine Fish		
Arctic cod	Boreogadus saida	Mysids, amphipods, copepods
Four horn sculpin	Myxocephalus quadricornis	Amphipods, isopods, polychaetes
Arctic flounder	Liopseta glacialis	Demersal & benthic crustacea, polychaetes
Anadromous Fish		
Arctic char	Salvelinus alpinus	Mysids, small fish
Arctic cisco	Coregonus autumnalis	Mysids, larval & juvenile fish
Least cisco	C. sardinella	Mysids, amphipods
Broad whitefish	C. nasus	Chironomids, amphipods
Humpback broad whitefish	C. pidschian	Chironomids, amphipods

Arctic cod (*Boreogadus saida*) is considered a keystone species in all Arctic marine ecosystems, including the Barents, Beaufort, Chukchi Sea marine ecosystems (Lowry and Frost, 1981; Bradstreet et al., 1986). They are a major link between lower trophic level benthic and pelagic primary consumers and upper trophic level apex consumers, such as several species of marine birds, seals, and mammals (Tables 6-12, 6-13, and 6-14; Figure 6-1 and 6-3). They consume primarily gammarid amphipods, copepods, mysids, and epontic zooplankton, and are consumed by many marine birds (including black kittiwakes, arctic terns, thick-billed murres, black guillemots, and glaucous gulls) and marine mammals (including ringed, harp, and bearded seals, walrus, beluga whales, and narwhals).

Figure 6-3 shows the importance of zooplankton and arctic cod in the Arctic pelagic food web leading to mammalian consumers, including man. Based on Macdonald et al. (2005).

Figure 6-3 Arctic Pelagic Food Web with Emphasis on Zooplankton and Arctic Cod on Mammalian Consumers



Bowhead whales and some marine birds and seals also rely on marine crustaceans, particularly copepods and euphausiids, for food. (Tables 6-12, 6-13, and 6-14; Figures 6-1, 6-2, 6-3). The amphipods, mysids, and isopods that are such important foods for many fish, birds and mammals, consume primarily smaller benthic crustaceans and polychaetes, diatoms, and peat (Craig et al., 1984) (Figures 6-1 and 6-2).

Bowhead whales feed on pelagic euphausiids, copepods, mysids, hyperiid amphipods, and occasionally small fish (Lowry and Frost, 1984; Richardson et al., 1995; Lowry et al., 2004). They feed throughout the Alaskan Beaufort Sea during both the spring (eastward) and fall (westward) migrations between the Bering/Chukchi Seas and the Canadian Beaufort Sea. They feed less during the spring than the fall migration (Lowry et al., 2004). Carroll et al. (1987) reported large numbers of bowheads feeding near Point Barrow during the 1985 spring migration. The dominant prey in the whale stomachs were calanoid copepods and euphausiids. They also feed extensively during their fall, nearshore migration through the Alaskan Beaufort Sea to northeastern Chukchi Sea (Lowry et al., 2004). Landino et al. (1994) reported a large aggregation of bowhead whales feeding near Point Barrow in late October 1992. Calanoid copepods were the dominant prey in stomachs of bowhead whales collected off Kaktovik (eastern Beaufort Sea) and euphausiids were the dominant prey in whales collected off Point Barrow (western Beaufort Sea) (Table 6-12).

Table 6-12 lists the diet composition (% of stomach contents) in arctic cod, bowhead whales, beluga whales, and ringed seals in the Alaskan Beaufort Sea. From Frost and Lowry (1984) and Lowry and Sheffield (2002).

TABLE 6-12
Diet Composition in Arctic Cod, Bowhead and Beluga Whales and Ringed Seals, Alaskan Beaufort Sea

Prey	Arctic Cod	Bowhead Whales		Beluga Whale	Ringed Seal		
		E. Beaufort	W. Beaufort		Nov-Mar	Apr-Jun	Aug-Sep
Isopod						16	
Hyperiid Amphipod	1				0 – 17		44
Gammarid Amphipod	12					32	
Copepod	50	60	8				
Euphausiid	3	37	92			20	21
Mysid	20	1				19	
Arctic Cod	5			80	75 - 90	6	30
Other Fish		1		10			
Misc.	9	1		10		7	5

Table 6-13 lists the diet composition (% of stomach contents) in black kittiwakes, red phalaropes, sabine's gulls, and arctic terns feeding in nearshore and offshore waters of the Alaskan Beaufort Sea. From Frost and Lowry (1984).

TABLE 6-13
Diet Composition in Black Kittiwakes, Red Phalaropes, Sabine's Gulls and Arctic Terns, Alaskan Beaufort Sea

Prey	Black Kittiwake		Red Phalarope	Sabine's Gull		Arctic Tern	
	Offshore	Nearshore	Offshore	Offshore	Nearshore	Offshore	Nearshore
Hyperiid Amphipod	1	67	1	54	6	1	
Gammarid Amphiopd		14	49		49		31
Copepod			11				
Euphausiid			5	13	4	35	23
Mysid		11	13		24		
Shrimp	1			3			
Mollusks							
Arctic Cod	95	5		13	4	64	20
Other Fish			1				12
Misc.	3	3	20	17	13		14

Table 6-14 lists the diet composition in long-tailed ducks, common and king eiders, thick billed murres, black guillemots, and glaucous gulls feeding in nearshore and offshore waters of the Alaskan Beaufort Sea. From Frost and Lowry (1984).

TABLE 6-14
Diet Composition in Long-tailed Ducks, Common & King Eiders, Thick-billed Murres, Black Guillemots and Glaucous Gulls, Alaskan Beaufort Sea

Prey	Long-tail Duck	Comm. Eider	King Eider	Thick-bill Murre	Black Guillemot	Glaucous Gull	
	Nearshore	Nearshore	Nearshore	Offshore	Offshore	Offshore	Nearshore
Isopod		83	89				12
Hyperiid Amphipod				1		1	1
Gammarid Amphipod	23	1	2				
Copepod							
Euphausiid	17						13
Mysid	20	15					
Shrimp							
Mollusks	22	1	2				
Arctic Cod				99	100	17	60
Other Fish							
Misc.						75	

Lee and Schell (2002) compared carbon isotopes in zooplankton to those in bowhead whale muscle and estimated that 10 to 26% of annual bowhead feeding activity in the fall was in the eastern and central Alaskan Beaufort Sea, between Prudhoe Bay and the Canadian border. Lee et al. (2005) evaluated isotope data for whales harvested in the spring and fall in the Beaufort and Chukchi Seas and concluded that the Beaufort/Chukchi Sea bowhead population acquires the bulk of its annual food intake from the Bering-Chukchi Sea system. Thompson et al. (2002) estimated that they may obtain approximately 2.4% of their annual energy requirements feeding in the eastern Alaskan Beaufort Sea (Flaxman Island to the Canadian border). This probably is an underestimate although bowheads feed extensively in the Alaskan Beaufort Sea, the times, extent, and locations of feeding vary widely from year to year. The variation is due in large part to variations in the temporal and spatial distribution of dense patches of zooplankton upon which the whales depend, which are controlled by ocean conditions (Asjian et al., 2009).

Beluga whales (*Delphinapterus leucas*) migrate annually through the Alaskan Beaufort Sea, usually further offshore than bowhead whales, between summer feeding areas in the Canadian Beaufort Sea and wintering areas in the Bering Sea. They feed heavily on pelagic and demersal

fish (Treacy, 2002). The dominant prey of beluga whales, because of its abundance in offshore waters, is the arctic cod (Table 6-12; Figure 6-2 and 6-3).

Some ice-associated seals, such as the bearded seal (*Erignathus barbatus*) and ribbon seal (*Phoca faciata*), which feed in coastal waters of the Beaufort Sea in some seasons, feed heavily on benthic invertebrates and demersal fish, such as shrimp, crabs, arctic cod, and sculpins (Wynne, 1997). Ringed seals (*Phoca hispida*), the principal food of polar bears, are common in all seasons in the Beaufort Sea. Their diet varies seasonally from primarily isopods, amphipods, euphausiids, and mysids in spring during retreat of the sea ice, to amphipods, euphausiids, and arctic cod during the summer open-water season, to primarily arctic cod during the winter when the seals occupy the sea ice (Table 6-12) (Figure 6-3).

The protected spectacled eider (*Somateria fischeri*) and king eider (*Somateria spectabilis*) that breed along the Arctic coastal plain from Barrow to the Canadian border, feed primarily on benthic isopods and mysids, and small numbers of mollusks that they gather in shallow coastal waters (<30 m) (Dau and Kistchinski, 1977; Frost and Lowry, 1984) (Table 6-14). Several species of marine birds in the Alaskan Beaufort Sea, including black kittiwakes, arctic terns, thick-billed murres, black guillemots, and glaucous gulls, feed heavily on arctic cod that, in turn, feed mainly on mysids, copepods, and amphipods (Frost and Lowry, 1984) (Tables 6-13 and 6-14; Figure 6-1, 6-2, and 6-3). The copepods that are the principal foods of bowhead whales also are consumed by red phalaropes, Sabine's gulls, arctic terns, long-tailed ducks, and glaucous gulls (Tables 6-13 and 6-14, Figure 6-3).

6.1.4.2 Contaminant Sources in Alaskan Arctic Waters

Metals and hydrocarbons are natural ingredients of the Alaskan Beaufort and Chukchi Sea environments. Large amounts of metals and hydrocarbons enter the Beaufort Sea each year associated with suspended particles in river runoff (Yunker et al., 1991, 1995; Steinhauer and Boehm, 1992; Trefry et al., 2003; Rember and Trefry, 2004). Additional metals and hydrocarbons enter coastal waters and sediments of the Beaufort Sea from dry and wet deposition from the atmosphere. The arctic aerosol over northern Canada and Alaska contains relatively high concentrations of metals, PAH, SHC, and other persistent organic pollutants (POPs) (Matsumoto et al., 1998; Muir et al., 1999; Cheng and Schroeder, 2000). Climate change in the arctic is changing wind patterns, changing the patterns and masses of contaminants deposited to the Arctic seas from aerosols (Macdonald, et al., 2005).

Metals also may enter coastal and offshore waters of the Beaufort Sea from coastal and offshore oil and gas operations (Steinhauer and Boehm, 1992; Trefry et al., 2003). The major sources of metals in Beaufort Sea sediments associated with oil development activities are causeway and drilling island construction and drilling mud and cuttings discharges (NTS, 1982; Naidu et al., 2001; Neff, 2002b, 2005). Island construction material usually has a metal concentration similar to that of natural soils and sediments, but sometimes may contain elevated concentrations of some metals (e.g., Crippen et al., 1980).

As discussed above, the metals that are of greatest concern because of their potential toxicity and/or abundance in drilling muds and cuttings include barium, chromium, cadmium, copper, lead, mercury, and zinc. Only barium is present frequently in modern WBM and cuttings solids

at concentrations significantly higher (> 100-fold) than concentrations in clean marine sediments (Neff, 2005). However, most of the metals that, in the past, were present at high concentrations in drilling muds, were present as insoluble sulfide inclusions in drilling barite and were not bioavailable to marine animals (Neff, 2008). Use of clean, low trace metal barite has reduced the concentrations of these metals to the range of background concentrations in clay-sized sediments. Chromium was abundant in chrome lignosulfonate drilling muds in the past; the chromium was associated almost exclusively with the chrome or ferrochrome-lignosulfonate thinners and chromate salts added to heat-stabilize the lignosulfonates and protect drill sting components from corrosion (e.g., sodium chromate). However, chrome lignosulfonates have been replaced with chrome-free thinners in WBM used and discharged offshore in North America and northern Europe. Corrosion protection now is provided by less toxic organic corrosion inhibitors.

PAH also have natural and anthropogenic sources (Neff, 2002a). The major sources of the complex PAH assemblages found in most soils and sediments are combustion soot and fossil hydrocarbon mixtures (peat, coal, and petroleum). PAH from these sources enter the Beaufort Sea in petroleum spills and in river runoff and aerial deposition. As discussed above, a major source of PAH in marine sediments throughout the Arctic is diagenic (early degradation/fossilization) plant material, such as peat, kerogens, immature bitumen, and lignitic coals (Yunker et al., 1995; Steinhauer and Boehm, 1992; Naidu et al., 2006; Elmquist et al., 2008; Boitsov et al., 2009). These PAH-rich materials reach the Arctic Ocean in coastal erosion and river runoff.

Oil development and production activities on the North Slope also may contribute additional PAH to coastal waters of the Beaufort Sea. In the past, the major sources of PAH inputs to the environment from oil and gas activities were permitted discharges of drilling mud/cuttings and produced water (Neff, 2002a, 2005). However, produced water, pumped to the surface with oil and gas from the hydrocarbon reservoir, is not discharged to coastal or offshore waters of the Alaskan Beaufort Sea. All produced water generated from offshore oil facilities is transported by pipeline to shore and re-injected as water-flood for enhanced production or is reinjected into a non-productive geologic stratum. Some offshore facilities also have their own reinjection wells.

Water based drilling muds are the only ones that have been used for offshore exploratory drilling in the Beaufort Sea. The current NPDES permit for Alaska allows discharge of WBM and cuttings to federal waters of the Beaufort and Chukchi Seas if they meet ELG. OBM and SBM have been used to drill offshore production wells in the Beaufort Sea. The mud and cuttings were transported to shore where the non-aqueous drilling muds were processed and recycled and the cuttings reinjected into wells designed to handle these types of wastes. Transport and offsite disposal of drilling wastes from offshore exploratory drilling usually is not environmentally beneficial from a holistic standpoint. As discussed above, water based drilling muds and cuttings, if used and discharged in accordance with regulations, contribute only small amounts, if any, of metals and hydrocarbons to the local marine environment. The metals and hydrocarbons associated with the WBM and cuttings have a low bioavailability and, very little, if any, enter the local food web.

PAH also are emitted to the atmosphere by flaring waste gases at production platforms or gas-treatment facilities. Approximately 162,000 million standard cubic feet (mscf) of waste gas was

flared at Northstar in 2004 (AOGCC, 2005). The PAH concentration in the flare exhaust is not known. Hydrocarbons, including PAH, may also be emitted in diesel exhaust and fugitive emissions from petroleum production, treatment, storage, and transportation facilities. Accidental drilling mud/cuttings, petroleum, and wastewater releases also are a potential source of PAH to the Beaufort Sea.

6.1.4.3 Metals and Hydrocarbons in the Arctic Food Web

Metals and hydrocarbons introduced into the marine environment from offshore exploratory drilling activities are not likely to enter the Beaufort and Chukchi Sea food webs in ecologically significant amounts. None of the metals and hydrocarbons measured in tissues of Beaufort Sea invertebrates and fish during the MMS ANIMIDA/ cAMIMIDA Monitoring Program bioaccumulated to higher than background concentrations (Tables 6-5, 6-8, and 6-9). These chemicals, with the possible exception of mercury (as methylmercury), are not known to biomagnify (Neff, 2002a). However, if they are bioaccumulated, they can be transferred through the marine food web by trophic transfer. A chemical biomagnifies if it is bioaccumulated to ever higher concentrations as it passes through the food chain; in trophic transfer, the concentration remains the same or decreases at each trophic step (Neff, 2002a). There is limited evidence of bioaccumulation, but not of trophic transfer or biomagnification in all the field and laboratory studies performed to date and discussed above on WBM and cuttings discharges to the marine environment.

There are substantial data on concentrations of metals and PAH in tissues of marine invertebrates, and less data for fish, collected near exploratory and development drilling operations in U.S. and North Sea waters. Some of these data are summarized in Table 6-3 through 6-10. There is a growing body of scientific literature on concentrations of metals and organochlorine chemicals (e.g., pesticides and polychlorinated biphenyls: PCBs) in tissues of higher trophic level marine animals, such as marine birds and mammals, from cold-water environments. In most cases, these animals were not collected in the immediate vicinity of active drilling operations, so it is not possible to identify sources of contaminants in their tissues. The organochlorines are not from drilling operations; in most cases, they enter the Arctic environment in long-range transport in the atmosphere (MacDonald et al., 2005).

There are no reliable data on the concentrations of PAH in tissues of marine mammals in the Arctic. There is a single publication that includes concentrations of PAH in eggs of common eider ducks from the vicinity of Prudhoe Bay, AK. Franson et al. (2004) measured concentrations of several metals in blood and eggs and PAH in eggs of common eiders nesting between Spy Island and Flaxman Island along the Beaufort Sea coast near Prudhoe Bay, AK. Concentrations of all metals and PAH were low in the eider eggs, comparable to concentrations in eggs of other marine birds from elsewhere. PAH concentrations were orders of magnitude lower than those causing sublethal effects or mortality when injected into bird eggs. Thus, common eiders and their eggs are not contaminated with metals and PAH in an area of massive oil and gas development along the coast of the Alaskan Beaufort Sea.

Because marine mammals and birds can rapidly metabolize and excrete accumulated PAH, most investigators assume that it is not useful to measure PAH concentrations in tissues of marine mammals (Muir et al., 1999). Biomarkers of exposure (e.g., cytochrome P450 mixed oxygenase

activity: CYP1A) have been used as an indicator of exposure of marine birds and mammals to PAH (Fossi et al., 1995, 1997). Beluga whales sampled off the Mackenzie River delta contained elevated CYP1A activity in several tissues, indicating exposure to PAH or other inducting chemicals (Wilson et al., 2005). However, these biomarkers are not specific to PAH and response is influenced by a variety of biological and environmental factors. Therefore, there are no reliable data on possible exposure of cold-water marine birds and mammals to PAH from ocean disposal of WBM and cuttings.

Dehn et al. (2005) measured concentrations of five metals in selected prey species of marine birds and mammals in the Arctic (Table 6-15). Wet-weight concentrations of most metals, except mercury, were higher in these prey species than in the higher trophic level animals in development areas of the Alaskan and Canadian Beaufort Seas (Tables 6-5 and 6-7). Total mercury (THg) concentrations are in the expected range. Dehn et al. (2005) did not measure mercury in arctic cod. Jaeger et al. (2007) reported about 0.02 ppm wet wt total mercury in muscle and 0.01 ppm total mercury in liver of Arctic cod from the Barents Sea. Methylmercury concentrations in Arctic cod liver ranged from 0.004 to 0.017 ppm wet wt.

Table 6-15 lists the range of concentrations of metals in tissues of selected prey species of Arctic seals. Concentrations are mg/kg wet wt (ppm: can be converted to approximate dry wt concentration by multiplying by five). Data from Dehn et al. (2005).

TABLE 6-15
Concentration Ranges of Metals in Selected Prey Species of Arctic Seals

Species	Cd	Cu	Se	Zn	THg
Arctic Cod (Boreogadus saida)	0.10-0.26	4.11-6.71	2.74-3.31	63.0-92.0	-
Zooplankton (Unsorted)	0.04-0.44	0.11-2.93	0.15-0.67	13.4-47.5	0.001-0.01
Amphipods[a] (Gammaridae)	0.87	39.50	1.96	89.5	-
Isopods (Saduria spp.)	0.13-1.60	41.1-107	1.94-5.44	51.2-87.9	0.004-0.01
Sculptured shrimp[a] (Sclerocragnon boreas)	9.15	36.20	1.24	50.60	-

[a]Only one sample analyzed.

Campbell et al. (2005) reported similar concentrations of total mercury in mixed zooplankton from the Northwater Polynya in Baffin Bay, Canada, to those reported by Dehn et al. (2005). Earlier, Joiris et al. (1997) reported that concentrations of total mercury were lower in zooplankton from the Barents Sea (0.09 - 0.12 ppm dry wt) than in those from the North Sea (mean, 0.32 ppm dry wt). Jaeger et al. (2007) did not detect mercury in copepods and euphausiids (*Meganychtophanes norvegica, Thyasoessa inermis, Thermisto libellula, and*

Calanus hyperboreus) from the Barents Sea. These zooplankton are the main foods of bowhead whales in the Canadian and Alaskan Arctic.

Concentrations of most metals are similar in liver, kidney, muscle, and epidermis of several species marine mammals from different Arctic environments (Table 6-16). The metals of greatest concern in Arctic food webs are cadmium and mercury; therefore, there are more data for these metals. In general, metals concentrations are lower in different organs of bowhead whales than in organs of polar bears, seals, and toothed whales (belugas). However, the concentration of cadmium often is higher in kidneys of bowhead whales and walrus than in kidneys of the seals and beluga whales. Concentrations of selenium and zinc are quite variable in organs of all species examined. Total mercury concentrations frequently are quite high in liver of polar bears, ringed seals, and beluga whales, but not bowhead whales.

Table 6-16 lists concentration ranges of metals in liver, kidney, muscle, and epidermis tissues of several Arctic marine mammals. Concentrations are mg/kg wet wt (ppm: can be converted to approximate dry wt concentration by multiplying by five). Data from Dehn et al. (2005, 2006a,b).

TABLE 6-16
Concentration Ranges of Metals in Liver, Kidney, Muscle and Epidermis Tissue of Several Arctic Maring Mammals

Location	Tissue	Cd	Cu	Se	Zn	MeHg	THg
Polar Bear (Ursa maritimus)							
Barrow, Alaska	Liver	0.10-1.22					1.50-54.3
	Kidney	1.40-19.6					1.56-45.9
Svalbard Norway	Liver	<0.1-1.2					0.10-6.00
	Kidney	0.30-19.0					0.50-21.0
Ringed Seal (Pusa hispida)							
Barrow, Alaska	Liver	0.01-11.8	4.50-30.0	0.34-25.8	28.5-77.4	0.01-0.50	0.06-16.5
	Kidney	0.01-50.7	2.06-25.6	0.91-5.81	16.4-80.9	0.01-0.16	0.05-1.06
	Muscle	0.01-1.87	0.93-7.97	0.19-0.99	13.2-53.1	0.01-0.38	0.01-1.06
Holman, Canada	Liver	1.20-18.1	2.28-19.4	3.56-39.6	27.3-55.7	0.28-0.88	1.48-72.0
	Kidney	4.54-77.1	3.62-20.2	2.31-4.59	28.5-76.6	0.11-0.70	0.79-3.71
Bearded Seal (Erignathus barbatus)							
Barrow, Alaska	Liver	0.57-33.6	9.64-39.6	0.75-23.2	36.8-81.0	0.004-0.5	0.64-20.4
	Kidney	1.30-94.5	3.38-7.84	2.83-9.35	25.1-69.5	0.001-0.1	0.21-1.50
	Muscle	0.01-0.42	0.54-1.94	0.45-1.37	16.7-87.9	0.001-0.1	0.01-0.09
Walrus (Odobenus rosmarus)							
Bering Strait	Liver	0.29-25-9					0.08-11.1
	Kidney	0.83-106					0.07-1.75
Canada	Liver	0.03-41.0					0.01-5.68
	Kidney	0.03-131					0.07-0.74

Bowhead Whale (Balaena mysticetus)							
Barrow, Alaska	Liver	0.03-50.9	1.09-204	0.06-4.19	6.99-135		0.001-0.6
	Kidney	0.01-64.0	0.76-7.94	0.23-3.21	9.07-56.3		0.001-0.2
	Muscle	0.01-0.61	0.47-1.07	0.08-0.77	9.47-74.1		0.00-0.05
	Epidermis	0.01-0.07	0.25-0.70	0.24-1.42	10.5-28.8		0.00-0.04
Beluga Whale (Delphinaperus leucas)							
Pt. Lay, Alaska	Liver	0.05-7.05	4.90-157	0.93-113	18.5-53.2	0.19-3.89	0.28-72.5
	Kidney	0.46-20.4	1.29-2.92	1.65-10.8	24.0-49.3	0.07-0.67	0.10-12.3
	Muscle	0.01-0.21	0.41-1.51	0.20-1.26	16.3-66.7	0.13-2.40	0.13-3.27
	Epidermis	0.01-0.02	0.23-0.83	2.66-32.9	12.5-160	0.06-1.48	0.03-1.52

Concentrations of metals are very unevenly distributed among different organs and tissues of bowhead whales (Table 6-17). Highest concentrations of cadmium, copper, selenium, and zinc are in the kidney or liver. Zinc, an essential metal, also is elevated in muscle and heart. Highest concentrations of mercury are in heart, tongue, and epidermis. All metals concentrations are in the typical range for human foods. Only cadmium in kidney, eaten by local people only in small amounts, approaches concentrations that could be a health threat to people who consume bowhead whales (O'Hara et al., 2006). Actually, concentrations of cadmium are as high or higher in kidneys of several other marine mammals, particularly walrus (Table 6-16). Mercury concentrations are quite low in all tissues and organs of bowhead whales.

Table 6-17 lists the range of concentrations of selected metals in tissues and organs of bowhead whale (*Baleana mysticetus*) collected by subsistence hunters near Barrow, Alaska. Concentrations are mg/kg wet wt (ppm: can be converted to approximate dry wt concentration by multiplying by five). From O'Hara et al. (2006).

TABLE 6-17
Concentration Ranges of Selected Metals in Tissues and Organs of Bowhead Whales, Barrow, Alaska

Organ/ Tissue	Cd	Cu	Se	Zn	Hg
Kidney	0.47-70.2	1.13-2.20	0.77-2.04	12.7-57.2	0.003-0.18
Liver	0.28-42.2	3.08-8.96	0.50-1.79	23.6-65.1	0.01-0.19
Muscle	0.007-0.212	0.36-0.76	0.13-0.25	24.7-62.8	0.003-0.04
Heart	0.03-3.64	0.90-1.36	0.24-0.92	21.8-30.3	0.006-0.031
Intestine	0.04-1.52	0.45-1.47	0.18-0.63	14.3-31.7	0.004-0.014
Tongue	0.005-0.22	0.11-0.35	0.045-0.18	1.10-15.7	0.003-0.046
Blubber	0.009-0.015	0.10-0.16	0.06-0.14	0.70-1.16	0.005-0.008
Epidermis	---	0.22-0.72	0.39-0.86	9.88-18.7	0.004-0.037

There is particular concern about mercury in Arctic marine food webs (Jaeger et al., 2007; Macdonald et al., 2005). Mercury concentrations in marine waters in much of the Arctic are higher than concentrations in temperate and tropical waters due in large part to deposition of metallic and inorganic mercury from long-range transport and deposition from the atmosphere (Figure 6-4) (Skov et al., 2004; Macdonald et al., 2005; Outridge et al., 2008). There is no evidence that significant amounts of mercury are coming from oil operations around Prudhoe Bay (Snyder-Conn et al., 1990) or from offshore drilling operations, as discussed at length above.

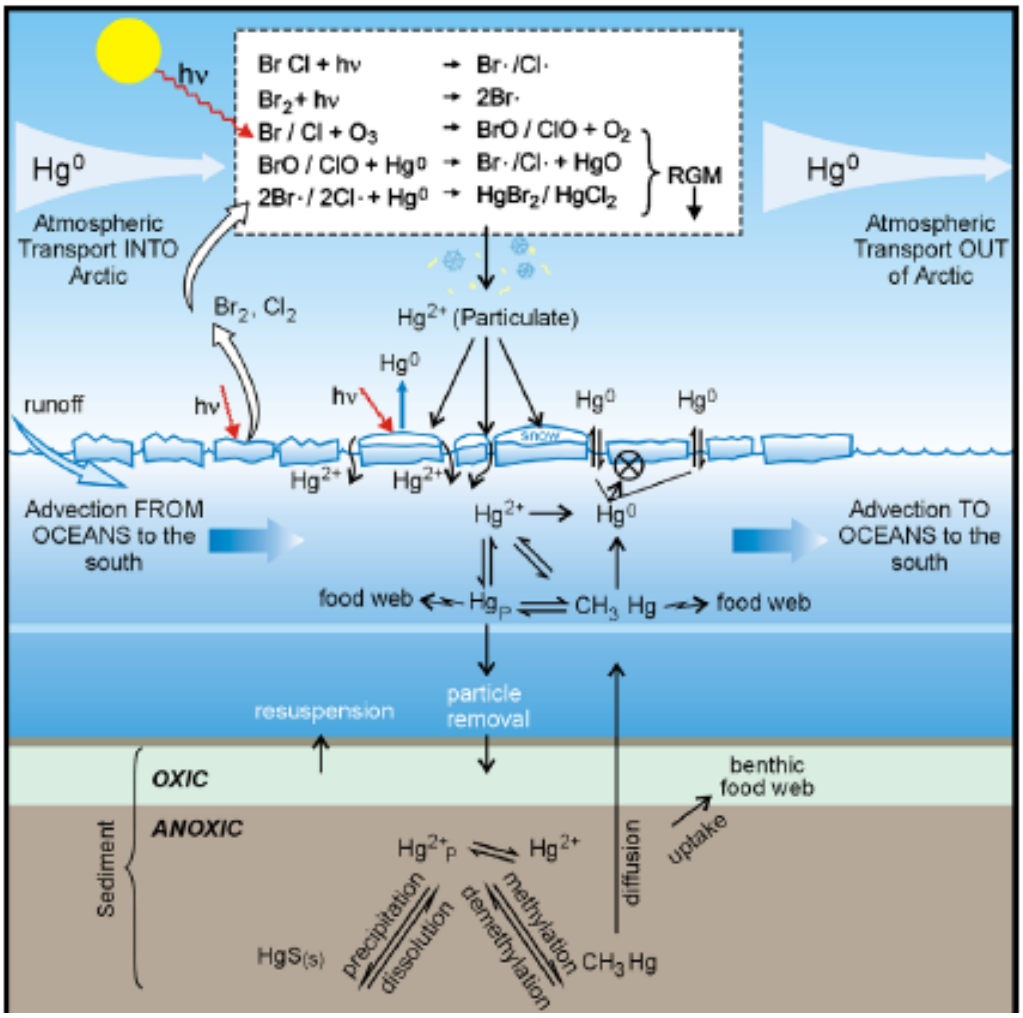
Table 6-18 is an example of the distribution of total and methyl mercury in the lower trophic levels of the nearshore Beaufort Sea food web (Semmler, 2003). There is a large increase in total mercury concentrations from the ambient water to phytoplankton. The apparent bioconcentration factor (BCF: concentration in consumer/concentration in prey) for the transfer from water to phytoplankton is 28,400 and 24,000 for total mercury and methylmercury. The BCF for subsequent trophic steps is between 1.4 and 7. Of course, the trophic linkages between zooplankton and higher trophic levels are uncertain.

Concentrations of total mercury are high in marine birds from the Arctic. Figure 6-5 shows the concentrations of total mercury in liver and muscle of several species of marine birds from the Barents Sea. Total mercury concentrations are higher in liver than in muscle of all species. Highest total mercury and methylmercury concentrations are in liver of northern fulmer. Total and methlymercury concentrations are lowest in little auk. The relative concentration of methylmercury tends to increase with trophic level; however, the fraction of total mercury that is methyl mercury decreases at higher trophic levels. Mercury is complexed with selenium in the liver of marine birds and mammals and accumulates there in insoluble, presumably inert granules. The fraction of total mercury that was methylmercury ranged from about 40 % in northern fulmer to 88 % in little auk.

Figure 6-4 is a schematic diagram illustrating the mercury cycle in the Arctic. The chemical processes initiated by light radiation after polar sunrise are listed in the inset box at top right. The mercury cycle in lakes and oceans is illustrated. Mercury methylation is mediated almost

exclusively by sulfate-reducing bacteria in suboxic layers of sediment. From Macdonald et al. (2005).

Figure 6-4 Arctic Mercury Cycle Schematic Drawing



Methyl mercury represents a small fraction of total mercury in liver, kidney, and muscle of ringed seal, bearded seal, and beluga whale from the Arctic Ocean north of North America (Table 6-16). Woshner et al. (2001) reported that methylmercury (0.49 ± 0.42 mg/kg wet wt) represented about 3% of total mercury (13.2 ± 12/4 mg/kg wet wt) in liver of Alaskan polar bears. Mercury tends to accumulate as insoluble mercury/selenium granules in liver of fish-eating marine mammals, such as beluga whales, but not in lower trophic level feeders, such as bowhead whales (Woshner et al., 2002). Thus, plankton feeders, such as baleen whales rarely accumulate mercury to high concentrations.

The concentration of mercury in tissues of toothed whales, such as belugas, is highly variable geographically (Figure 6-7). The Cook Inlet beluga stock has a much lower concentration of liver mercury than other stocks do. Mercury and selenium concentrations tend to covary, indicating that some of the mercury is present as inert mercury/selenium granules in the liver.

The low concentrations of mercury and other metals, such as cadmium, in belugas from Cook Inlet, where intensive oil and gas development has occurred for decades, indicates that the oil and gas operations are not a major source of metals in these higher trophic level marine mammals.

Table 6-18 lists the concentrations of mercury and methylmercury in surface seawater (dissolved), mixed phytoplankton, mixed zooplankton, amphipods (*Anonyx* sp.), clams (*Astarte* sp.), and fish (average for Arctic char, Arctic cisco, Arctic flounder, fourhorn sculpin, and humpback broad whitefish from the coastal Beaufort Sea. From Semmler (2003).

TABLE 6-18
Concentration of Mercury and Methylmercury in Seawater and Several Species, Coastal Beaufort Sea

Sample Type	Concentration (ng/g dry wt: ppb)[a]			Bioconcentration Factor[b]
	Mean SD	Range	N	
Total Mercury				
Surface seawater[c]	0.69 ± 0.12	0.50 - 0.90	38	-
Phytoplankton	19.6 ± 13.4	11.2 - 39.7	4	28,400
Zooplankton	55.4 ± 30.7	29.6 - 105	8	2.8
Amphipods	78.0 ± 28.2	46.4 - 117	8	1.4
Clams	53.5 ± 18.4	42.6 - 80.9	4	2.7
Fish	106.2± 64.2	30.0 - 266	20	1.9
Methylmercury				
Surface seawater[c]	0.025 ± 0.01[d]	<0.02 - 0.046	15	-
Phytoplankton	0.60 ± 0.56	0.22 - 1.24	3	24,000
Zooplankton	4.25 ± 1.94	2.21 - 6.66	6	7.1

[a] Concentrations of dissolved total mercury and methylmercury in seawater are ng/L (parts per trillion);
[b] Bioconcentration factor is the concentration in consumer divided by the concentration in prey (or water for phytoplankton);
[c] Salinity varied from 14.5 to 32 ppt;
[d] Average and SD were determined using the method detection limit (MDL) as the concentration for samples in which methylmercury was not detected above the MDL.

Biomagnification of total mercury in marine food chains usually is attributed to selective accumulation and retention of methylmercury. Mason et al. (1995a,b, 1996) showed that the preferential bioaccumulation of methylmercury in pelagic marine food webs occurs primarily at the level of phytoplankton. Phytoplankton are able to bioaccumulate both inorganic mercury and methylmercury from water. The inorganic mercury binds to cell membranes of the plants in a relatively non-bioavailable form, whereas the methylmercury accumulates in the cytoplasm. Zooplankton that feed on phytoplankton assimilate more methylmercury than inorganic mercury. Marine animals that feed on the zooplankton also assimilate more methylmercury than inorganic mercury; they also are able to eliminate inorganic mercury more rapidly than methylmercury from their tissues, facilitating the greater accumulation of methylmercury, particularly at higher trophic levels in marine food webs.

Figure 6-5 shows the mean concentrations of total mercury (TotHg) in liver and muscle of northern fulmar, glaucous gull, black-legged kittiwake, Brunnich's guillemot, and little auk from the Barents Sea. Concentrations are mg/kg dry wt (ppm). Error bars are ± 1 standard error (SE). From Jaeger et al. (2007).

Figure 6-5 Concentrations of Total Mercury in Liver and Muscle of Several Barents Sea Bird Species

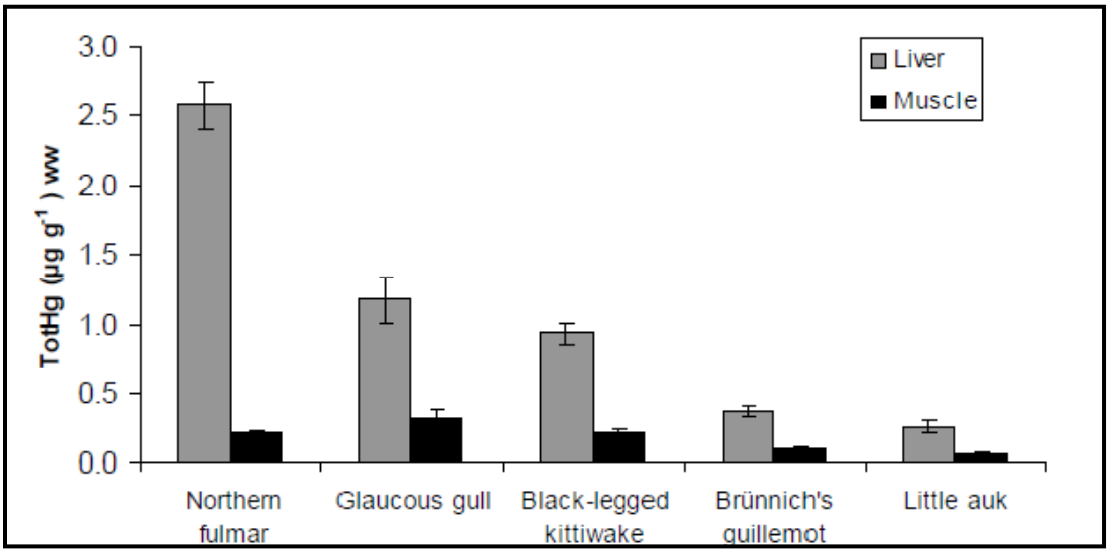


Figure 6-6 shows the mean concentrations of total mercury (TotHg) and methylmercury (MeHg) in liver from northern fulmar, glaucous gull, black-legged kittiwake, Brunnich's guillemot and little auk. Concentrations are mg/kg wet wt (ppm). Error bars are ± 1 standard error (SE). From Jaeger et al. (2007).

Figure 6-6 Concentrations of Total Mercury and Methylmercury in Livers of Several Barents Sea Bird Species

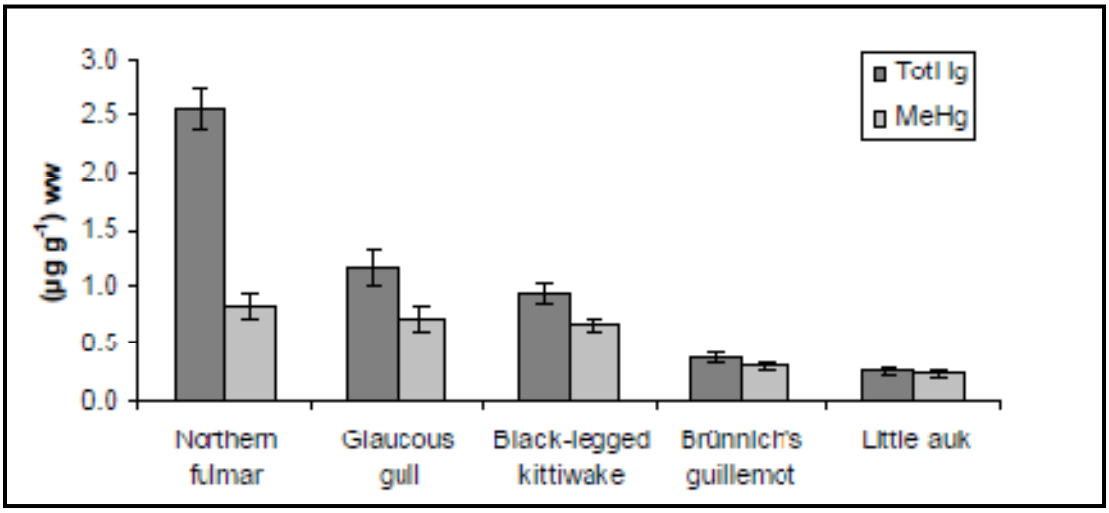
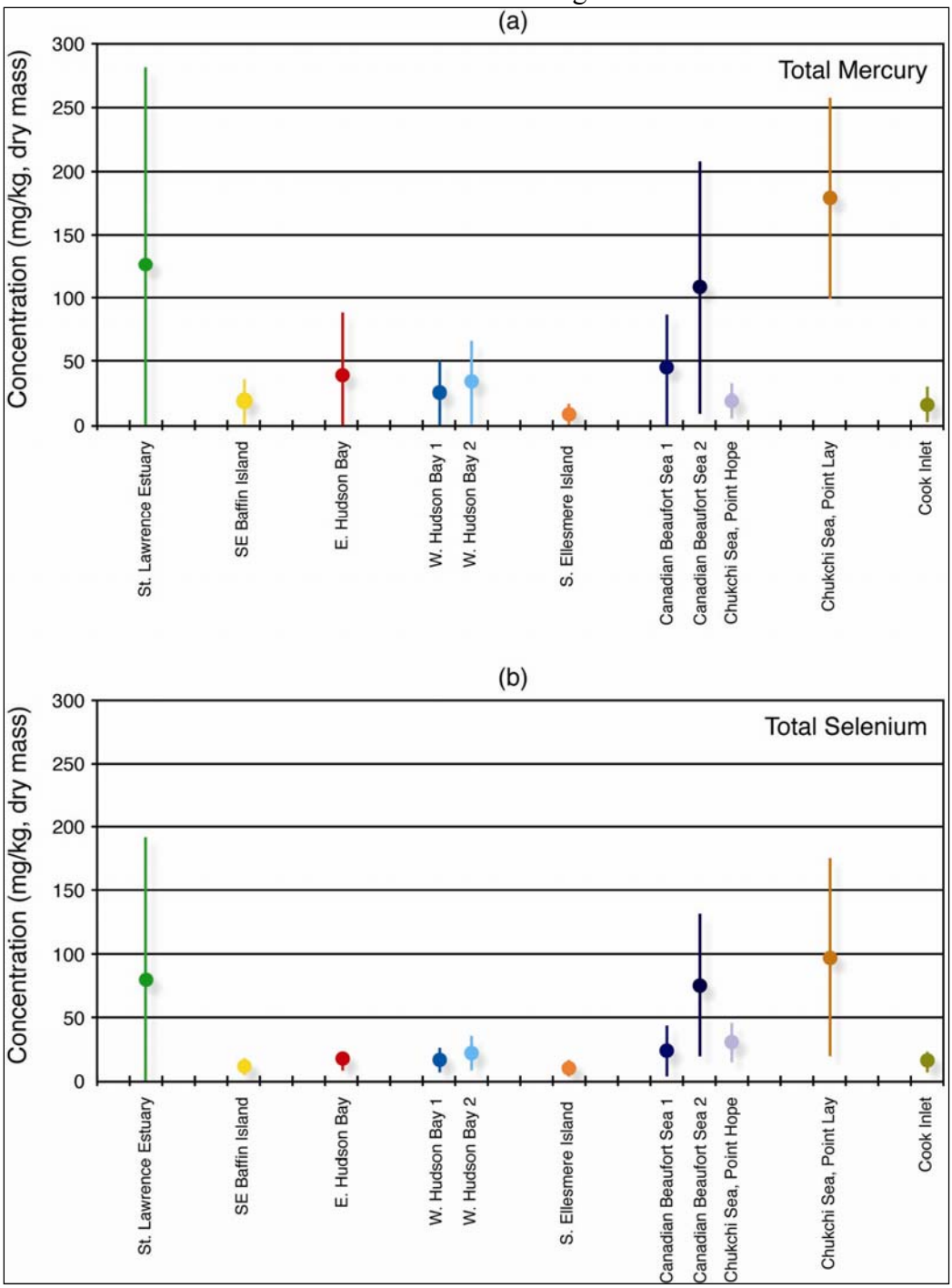


Figure 6-7 shows the concentration of mercury (a) and selenium (b) (mean ±1 SD) in liver tissue of Cook Inlet beluga whales compared to concentrations reported in the livers of other North

American populations and stocks of belugas. The standard deviation for each mean (●) is indicated by a vertical bar. Geographic locations, dates of sample collections, and numbers of animals are shown on the X axis. From Becker et al. (2000).

Figure 6-7 Concentrations of Mercury and Selenium in Livers of Cook Inlet Beluga Shales v. Other Beluga Stocks



Less than 3.5 percent of the total mercury in Beaufort Sea coastal water is methylmercury (Semmler, 2003). Methylmercury in the water column and in tissues of marine organisms is derived from microbial methylation of inorganic mercury in suboxic layers in the water column and sediments (Rolfhus and Fitzgerald, 1995; Gagnon et al., 1996). The methylmercury in Beaufort Sea coastal water probably is from upwelling offshore near the edge of the pack ice (Semmler, 2003) and from runoff from melting permafrost soils containing a large inventory of mercury and methylmercury from aerial deposition and methylation in suboxic layers of frozen soil (Macdonald et al., 2005, 2009). Naidu et al. (2001) suggested that methylmercury in Beaufort Sea sediments could be mobilized into the overlying water column during sediment reworking by ice gouging, storm-induced sediment erosion and resuspension, and bioturbation. This is possible.

As discussed above, the mercury associated with WBM and cuttings is in an insoluble form as mercuric sulfide inclusions in drilling mud barite. Although deposition of WBM and cuttings on the sea floor may cause oxygen depletion in near-surface layers of sediment, rendering the sediments suboxic (low oxygen concentration), there is no evidence that mercury associated with the cuttings pile is methylated and released from the cuttings pile to the overlying water (Neff, 2002b; Trefry et al., 2007). Thus, cuttings pile mercury does not get into the Arctic food web.

Much of the mercury in marine sediments is complexed with dissolved and particulate organic matter in the sediments (Neff, 2002b). The remaining inorganic mercury forms strong, stable complexes with iron oxyhydroxides in oxidized surface layers. In oxidized layers of marine sediments, where most biological activity occurs, concentrations of solid iron and manganese oxides are very high (usually several percent) and most of the mercury not complexed with sediment organic matter is adsorbed to the solid oxides. However, if the sediments become anoxic, the iron oxyhydroxides dissolve, releasing adsorbed metals, including mercury. The inorganic mercury released from oxyhydroxides at the redox potential discontinuity (the location in the sediment column where Eh is about 0 mV) in sediments is bioavailable for bioaccumulation and methylation by sulfate reducing bacteria. However, as redox potential decreases further, particularly in marine sediments rich in sulfate, the mercury precipitates as insoluble, nonbioavailable mercuric sulfide. Thus, mercury methylation seems to occur at the highest rates and methylmercury concentrations are highest in the narrow band of the redox potential discontinuity in the sediments where the mercury can form slightly soluble mercury-sulfide complexes. Any disturbance that moves the RPD toward the sediment-water interface tends to increase the rate of flux of methylmercury from sediment to the water column. Thus, physical disturbance of the sediment surface or a reduction in oxygen concentration at the sediment-water interface caused, for instance, by a decrease in photosynthesis in the water column during low-light conditions in winter or a seasonal increased flux of organic carbon to surface sediments from the water column (Macdonald et al., 2005), can lead to an increased flux of methylmercury into the overlying bottom water. As discussed above, the mercury in drilling mud barite is completely immobile in both oxidized and anoxic layers of sediment and, so is not mobilized by sediment disturbance.

The percent of total mercury that is methylmercury increases from 3 % in phytoplankton, to 7.6 % in zooplankton, and more than 90 % in arctic cod (Semmler, 2003), indicating that methylmercury is preferentially biomagnifying in this part of the Beaufort Sea food chain. Methylmercury was not measured in bowhead whale liver; because of the high selenium/total

mercury ratio, most of the mercury in bowhead liver probably is present as an insoluble mercury-selenium complex (Dehn et al., 2006a). Three to 10% of the total mercury in ringed seal and polar bear liver is methylmercury; the remainder probably is present as mercury-selenium complex (Woshner et al., 2001, 2002). Mercury concentrations in liver are much higher than those in other tissues of marine mammals. Thus, much of the methyl mercury accumulated from zooplankton by bowhead whales and from arctic cod by beluga whales and ringed seals is demethylated and stored as a mercury-selenium complex, probably solid mercuric selenide, primarily in the liver (Khan and Wang, 2009). Thus, the apparent biomagnification of mercury in the trophic step from water-breathing prey to air-breathing predator is the result of assimilation of bioavailable methylmercury and chemical transformation of methylmercury and sequestration as solid mercuric selenide.

7.0 TOXICITY OF WATER BASED DRILLING MUDS TO MARINE PLANTS AND ANIMALS

7.1 Regulatory Limits for WBM Toxicity

Requirements for toxicity testing of drilling muds and drilling mud ingredients differ in different regions of the world. Drilling mud and cuttings toxicity testing requirements for the United States, Canada, and the North Sea (OSPAR) countries were discussed above in Section 4 of this review. In the United States, WBM of eight generic types (Table 4-2) are screened for offshore disposal based on toxicity testing of a suspended particulate phase (SPP) of whole drilling mud with mysids, small shrimp-like crustaceans. The WBM are permitted for discharge if they have an acute toxicity greater than 3,000 mg/L mud added (Table 4-3). If a new additive is added to a generic WBM, the WBM must be retested to assure that it meets the toxicity limitation. Additional toxicity and biodegradation testing is required in the U.S. for SBM cuttings (Table 4-1).

In Canada and the OSPAR countries, candidate individual drilling mud ingredients are tested with three or four species of marine plants and animals. Chemicals that are on the List of Substances/Preparations Used and Discharged Offshore that Are Considered to Pose Little or No Risk to the Environment (PLONOR) are approved without further testing. Toxicity data are required for chemicals not on the PLONOR list. Drilling mud chemicals are approved in Canada if they have an aquatic toxicity greater than 10 mg/L and a sediment toxicity greater than 100 mg/L (categories C, D, and E in Table 4-6). If the chemical has a higher toxicity (lower median lethal concentration), the chemical is not approved unless justified by a risk analysis. Drilling mud chemicals are approved in the OSPAR countries if they are in the green (PLONOR) or yellow (not considered hazardous) categories (Table 4-8). Red and black chemicals are considered hazardous and guidelines recommend elimination from drilling mud formulations and replacement with yellow or preferably green chemicals. The Russian regulatory approach is similar to that in Canada and the OSPAR countries (Patin, 1999); however, there is little information about how these regulations are applied.

As discussed above in Section 4.3.3.1, The North Sea offshore oil industry is developing an ecological risk based environmental management tool for drilling mud and cuttings discharges, the Dose related Risk and Effect Assessment Model (DREAM). DREAM calculates the Environmental Impact Factor (EIF) as a tool for quantitative risk assessment of drilling mud and cuttings discharges to the marine environment. Separate EIFs are calculated for each drilling mud ingredient for the water column and seabed (Singsaas et al., 2008; Smit et al., 2008b). The objective of applying the EIF concept to drilling mud and cuttings discharge management is to identify additives that could pose an ecological risk, so they can be replaced with non-toxic (PLONOR) chemicals and, thereby, help meet zero harmful discharge goals for drilling discharges (NPD, 2009).

The different regulatory schemes appear to be equally effective in ensuring that WBM and associated cuttings will not harm the marine environment and its biological resources. All the regulations are extremely conservative (protective of the environment) and ensure that

discharged WBM and associated cuttings have a low risk of ecologically significant chemical toxicity in the water column and in sediments (Jones and Leuterman, 1990; Garland, 2005).

7.2 Toxicity of Water Based Drilling Mud Ingredients

The most abundant chemicals, based on mass, in WBM, other than water, are weighting materials, viscosifiers, various inorganic salts for pH and shale control, and sometimes lost circulation materials (Figure 3-1). These chemicals usually represent more than 90 percent of the mass of additives to the continuous phase of the mud. Most of these chemicals, particularly the ones still in wide used in WBM, are on the PLONOR list or non-hazardous category (category C, D, or E in Canada: Table 4-6, or the yellow category in OSPAR countries: Table 4-8). Table 7-1 summarizes the most abundant PLONOR chemicals discharged by three Norwegian oil companies to the North Sea in 2003. These PLONOR chemicals represent most of the mass of additives in modern WBM (Figure 3-1).

Table 7-1 lists mass discharges (in metric tons/year)[a] of the PLONOR chemicals used most frequently and discharged in drilling wastes to the North Sea in 2003 by three major oil companies. The chemicals are listed in order of mass discharged and represent most of the mass of additives in modern WBM. From Frost et al. (2006).

TABLE7-1
Mass Discharges of PLONOR Chemicals Used in 2003 by 3 Major Oil Companies, North Sea

PLONOR Chemical	Function in WBM	Total Discharge
Barium sulphate	Weighting material	46,616
Sodium chloride	Shale control	45 458
Potassium chloride	Shale control	10,592
Calcium carbonate	Shale control	3985
Bentonite (clay)	Viscosifier, filtrate reducer	3080
Calcium chloride	Shale control	2347
Carboxymethylcellulose	Viscosifier, filtrate reducer	924
Calcium hydroxide	Alkalinity, pH control	534
Xantham gum	Viscosifier, filtrate reducer	530
Monoethylene glycol	Viscosifier, lubricant	434
Calcium oxide	Alkalinity, pH control	289
Graphite	Lubricant	128
Citric acid	Alkalinity, pH control	121
Sodium carbonate	Calcium reducer	67
Polyanionic cellulose	Viscosifier, filtration control	63
Calcium sulphate dihydrate (gypsum)	Flocculant	45.4
Walnut shell	Lost circulation control	7.7
Mica	Lost circulation control	7.7
Cellulose fiber	Lost circulation control	2.9
Starch	Filtrate reducer	1.5

[a] 1 metric ton = 1.02 US tons; NA: No data available.

The drilling mud additives in WBM used to drill the exploratory well at the Paktoa-60 prospect in the Canadian Beaufort Sea were screened according to the predecessor of the current NEBC (2009a,b) guidance (Table 7-2) and PSAC guidance (PSAC, 2005).

Table 7-2 lists the results of screening of WBM additives used or kept in inventory to drill an exploratory well at the Paktoa-60 prospect in the Canadian Beaufort Sea. The 10-step drilling mud screening guidelines from the CNEB (2009) are described in Section 4.2.2. The toxicity rating is in Table 4-6. Additives of the types actually used at Paktoa-60 (Table 5-19) or that Shell plans to used for drilling in the Beaufort and Chukchi Seas (Table 3-7) are highlighted in yellow. From KAVIK-AXYS (2005).

All but one of the drilling mud chemicals used or held in reserve for possible use at Paktoa-60 were PLONOR chemicals (Step 6), classified as non-hazardous by the OCNS Hazard Rating (Step 7), or acceptable based on the PSAC toxicity screen with the Microtox bioassay. The other chemical (Desco CF) was permitted for use in small quantities (Table 5-19). Desco CF is classified by the U.S. EPA as suitable for generic WBM. The glutaraldehyde biocide, although considered slightly toxic in the OCNS ranking scheme, was approved because it degrades rapidly in the drilling mud before discharge and little is discharged. A different brand of the same biocide is proposed for use in small quantities, if needed, to drill exploratory wells in the Beaufort and Chukchi Seas (Table 3-7).

Most of the drilling mud chemicals listed in Tables 7-1 and 7-2 as well as the WBM containing them at approved concentrations would be classified as non-toxic or practically non-toxic to marine organisms according to the revised hazard evaluation scheme (Table 7-3) developed by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2002).

TABLE 7-2
WBM Additives Screening for Chemicals Used or Stored to Drill Paktoa C-60, Canadian Beaufort Sea

Chemical	Pass (Y/N)	Pass Criteria	Toxicity Rating	Discharge Limit (tons/year)
Barite	Y	Step 6 - PLONAR list	E	4750
Bentonite	Y	Step 6 - PLONOR list	E	4750
KC_l	Y	Step 6 - PLONOR list	E	4750
KNO_3	Y	Step 6 - PLONOR list	E	4750
$NaHCO_3$	Y	Step 6 - PLONOR list	E	4750
NAOH	Y	Step 7 - OCNS Hazard Rating	E	4750
Na_2SO_3	Y	Step 6 - PLONOR list	E	4750
Na_2CO_3	Y	Step 6 - PLONOR list	E	4750
SAPP ($Na_2H_2P_2O_7$)	Y	Step 6 - PLONOR list	E	4750
$CaCO_3$	Y	Step 6 - PLONOR list	E	4750
pH buffer	Y	Step 6 - OCNS Hazard Rating	E	4750
Citric acid	Y	Step 6 - PLONOR list	E	4750
Low MW PHPA polymer	Y	Step 7 - OCNS Hazard Rating	E	4750
Anionic acrylamide polymer	Y	Step 7 - OCNS Hazard Rating	E	4750
Xanthan gum	Y	Step 7 - OCNS Hazard Rating		4750
Desco CF (Cr-free sulfomethylated tannin)	TBA[a]	Toxicity evaluation under way	TBA[a]	TBA
Polyanionic cellulose	Y	Step 7 - OCNS Hazard Rating	E	4750
Alkanol/surfactant defoamer	Y	Step 10 - PSAC List >75% @ 0.22 ppm[b]	B	10
Glutaraldehyde biocide	Y	Step 9 - OCNS Hazard Rating	C	750
C-Kit colorant	Y	Step 10 - PSAC List >75% @ 0.22 ppm[b]	B	10
Polymer fluid loss control chemicals	Y	Step 8 - PLONOR list	E	4750
Polyethylene flake fluid loss control	Y	Step 8 - PLONOR list	E	4750
Cellulose fiber	Y	Step 8 - PLONOR list	E	4750
Sawdust	Y	Step 8 - PLONOR list	E	4750
Walnut shell	Y	Step 8 - PLONOR list	E	4750

[a] Passes the US EPA toxicity test requirement for new additives in generic drilling muds (Offshore, 2008). Leuterman et al. (1989) reported a 96-hr LC50 of >1,000,000 ppm with mysids;
[b] Petroleum Services Association of Canada (PSAC) guidelines for toxicity of drilling mud chemicals (PSAC, 2005).

Table 7-3 lists the revised marine water column toxicity classification of GESAMP (2002). Acute toxicities ($LC/EC/IC_{50}$) and chronic toxicity (no observed effect concentration: NOEC) are mg/L (parts per million in water).

TABLE 7-3
Revised Marine Water Column Toxicity Classification of GESAMP (2002)

Toxicity Rating	Acute Toxicity	Chronic Toxicity
Non-toxic	>1000	>1.0
Practically non-toxic	>100 - ≤1000	>0.1 - ≤1.0
Slightly toxic	>10 - ≤100	>0.01 - ≤0.1
Moderately toxic	>1.0 - ≤10	>0.001 - ≤0.01
Highly toxic	0.1 - ≤1.0	<0.001 (1 part per billion)
Very highly toxic	>0.01 - ≤0.1	---
Extremely toxic	<0.01	---

Many thousands of toxicity tests have been performed on drilling mud ingredients with a wide variety of freshwater and marine plants and animals from warm and cold environments. The range of aquatic toxicity of WBM ingredients, some of which are still used frequently in WBM destined for offshore disposal, are summarized in Table 7-4. Some brands of a few of these chemicals are classified as slightly to moderately toxic in the GESAMP (2002) classification (Table 7-3). Most of these toxic additives are no longer used (e.g., ferrochrome lignisulfonate, diesel fuel), or less toxic alternatives are used, usually in smaller quantities (e.g., corrosion inhibitors, detergents, defoamers, emulsion breakers, biocides). Some of the inorganic salts are toxic only to freshwater animals (Table 7-4).

Cold water marine animals are as sensitive to WBM additives as marine animals from warmer climates (Table 7-5). Arctic marine animals were tested with barite, bentonite, and ferrochrome lignosulfonate, because barite and bentonite were, at the time, the WBM additives used and discharged in the largest mass and chrome and ferrochrome lignosulfonates were considered the most toxic component of a WBM that did not contain added oil (Carls and Rice, 1980, 1984). The results for Alaskan species clearly show that barite and bentonite are nontoxic and that ferrrochrome lignisulfonate can be classified as slightly toxic according the GESAMP classification (Table 7-3) in some tests with larvae of dock shrimp. Marine crustacean larvae are considered one of the most sensitive taxa and life stages to chemical toxicity.

Table 7-4 is a summary of acute toxicities, measured as median lethal concentration (LC_{50}) after 48 to 96 hours, of WBM ingredients to marine algae and animals, summarized from the scientific literature. Toxicities are expressed as mg/L (ppm) of the ingredient or a suspended particulate phase of the ingredient (for insoluble solids). Chemicals with an acute toxicity greater than 100 ppm are considered non-toxic or practically non-toxic (Tables 4-6 and 7-3). From Neff (2005).

TABLE 7-4
Acute Toxicity Summary of WBM Ingredients to Marine Algae and Animals

WBM Ingredient	Range of LC_{50} for different species (mg/L)
Weighting Materials	
Barite (barium sulfate: $BaSO_4$)	385[a] - >100,000
Hematite (iron oxide: Fe_2O_3)	>100,000
Siderite (iron carbonate: $FeCO_3$)	>100,000
Viscosifiers	
Bentonite (montmorillonite clay)	9600 - >100,000
Sodium carboxymethyl cellulose (CMC)	500[a] - >100,000
Polyanionic cellulose	60,000 – 100,000
Organic polymers	7800 - >100,000
Xanthan gum	420
Salts for pH and Shale Control	
Potassium chloride (KCl: muriate of potash)	2100[b]
Lime ($Ca(OH)_2$)	70 – 450[b]
Calcite (calcium carbonate: $CaCO_3$)	>100,000
Sodium hydroxide (NaOH: caustic soda)	105 – 110[b]
Lost Circulation Materials	
Mica	>7500
Jellflake® shredded cellophane	>7500
Thinners, Clay Dispersants	
Ferrochrome lignosulfonate	12 – 1500
Chrome lignosulfonate	12200 – 100,000
Chrome-treated lignosulfonate	465 – 12200
Chrome-free lignosulfonate	31,000 – 100,000
Iron lignosulfonate	2100
Modified chrome lignite	20,100
Potassium lignite	>100,000
Carbonox® lignitic material	6500 - >7500
Generic lignite	>15,000

WBM Ingredient	Range of LC_{50} for different species (mg/L)
Sulfomethylated tannin	33,900 - >100,000
Sodium acid pyrophosphate ($Na_4P_2O_7$)	870b - >100,000
Lubricants	
Diesel fuel	0.1 - 1112
Fatty acid high pressure lubricant	3500 - >100,000
Blended organic ester lubricant	10,400 – 49,400
Graphite	86,500
Biocides (Disinfectants)	
Glutaraldehyde (25-50%)	10 - 940
Isothiazolin mixture	200 (160 - 3200)
Paraformaldehyde	31 (20 - 40)
Other Additives	
Corrosion inhibitors (several types)	2.0 – 7000
Ammonium bisulfite corrosion inhibitor	75,000
H2S scavengers (zinc salts)	235 – 7800
Low MW polyacrylate reverse breaker	3500
Polyacrylate scale inhibitor	77,300
Scale inhibitors	>10,000
Flocculant WT-40	5300
Surfactants	40 – 429
Detergents	0.4 – 340
Defoamers	5.4 – 84
Tributyl phosphate surfactant defoamer	5100
Emulsion breakers	3.6 - 930
Oxygen scavenger (sodium bisulfite)	175 – 185

[a] Microalga test; effects probably caused by turbidity.

[b] Freshwater species used in test; salt water species expected to be much more tolerant because of high ionic strength and buffer capacity of seawater.

7.2.1 Barite

Barite is the most abundant solid ingredient in most WBM. Barite is widely accepted as being insoluble and inert as attested by its use for many decades as a contrasting agent for medical x-rays and cat-scans of the human digestive tract.

Many marine toxicity tests have been performed with dispersions of barite particles in seawater. Particulate barite is nearly insoluble (about 80 µg/L) and is essentially inert toxicologically to marine organisms; most bioassays with marine organisms have produced median lethal concentrations greater than 7,000 mg/L suspended barite (Tables 7-4, 7-5, and 7-6). Russian investigators often record a higher toxicity for this and other drilling mud additives (Kasymov & Velikhanov, 1992), probably due to different test methods (Patin, 1999). Barite toxicity to juvenile scallops is caused by clogging of the gills with fine particles (Cranford et al. (1999). Barium (as barite) is toxic to embryos of the crab *Cancer anthonyi* at concentrations greater than 1,000 mg/L (Macdonald et al., 1988). This concentration is 20,000 times higher than the aqueous solubility of barite in seawater, so any adverse effects probably are caused by physical effects of fine-grained barite particles. Barite settles rapidly from the WBM and cuttings plume and concentrations of barite particles in the water column decline rapidly, even in the benthic boundary layer where most bivalves feed, so it is probable that barite does not produce toxic effects in marine animals.

Table 7-5 lists acute toxicity (LC_{50} at the specified time) and sublethal effects (EC_{50}, cessation of swimming at the specified time) of WBM additives to larvae (dungeness crabs and dock shrimp) and adults of amphipods mysids, and fish from Alaska. Concentrations are mg/L in solution or suspension. From Carls and Rice (1980, 1984).

TABLE 7-5
Acute Toxicity and Subletha Effects of WBM Additives to Alaska Marine Species

Additive	Species	Parameter	Value	Reference
Barite	Dungeness crab (Cancer magister)	EC50 (71hr)	3570	Carls and Rice, 1980
		EC50 (96hr)	71,400±27,000	Carls and Rice, 1984
	Dock shrimp (Pandalus danae)	EC50 (119hr)	2520	Carls and Rice, 1980
		EC50 (96hr)	16,000±24,000	Carls and Rice, 1984
	Amphipod (Onisimus sp.)	LC50 (96hr)	>84,000	NTS, 1981
Bentonite	Dungeness crab (Cancer magister)	EC50 (71hr)	4280	Carls and Rice, 1980
		EC50 (96hr))	81,600±50,000	Carls and Rice, 1984
	Dock shrimp (Pandalus danae)	EC50 (119hr)	1720	Carls and Rice, 1980
		EC50 (96hr)	24,800±10,000	Carls and Rice, 1984
Ferrochrome lignosulfonate	Dungeness crab (Cancer magister)	LC50 (144hr)	210	Carls and Rice, 1980
		EC50 (144hr)	150	Carls and Rice, 1980
		LC50 (96hr)	1440±530	Carls and Rice, 1984
		EC50 (96hr)	330±200	Carls and Rice, 1984
	Dock shrimp (Pandalus danae)	LC50 (144hr)	120	Carls and Rice, 1980
		EC50 (144hr)	50	Carls and Rice, 1980
		LC50 (96hr)	290±180	Carls and Rice, 1984
		EC50 (96hr)	110±30	Carls and Rice, 1984
	Mysid (Mysis sp.)	LC50 (96hr)	2650 - 10,000	NTS, 1981
	Fourhorn sculpin (Myxocephalus quadricornis)	LC50 (96hr)	1000 - 6000	NTS, 1981

Table 7-6 lists the toxicity of barium sulfate ($BaSO_4$) to freshwater (FW) and marine (M) plants and animals. Concentrations are mg/L (ppm) of barite in water or as the concentration of a generic drilling mud (Table 4-2) containing barite (*).

TABLE 7-6
Toxicity of Barium Sulfate to Freshwater and Marine Plants and Animals

Organism	96-hr LC50	Reference
(M) Phytoplankton Skeletonema costatum	385 - 1650	EG&G, 1976
(M) Scallop Placopecten magellanicus	>2.5	Cranford et al., 1999
Mixed marine phytoplankton	>Saturated	Alldredge et al., 1986
(M) Copepod Acartia tonsa	590	EG&G, 1976
(M) Coonstripe shrimp Pandalus hypsonotus	>100,000	Dames & Moore, 1978
(M) Mysid Americamysis bahia	>100,000*	Leuterman et al., 1989
(M) Dock shrimp Pandalus danae	16,200	Carls and Rice, 1984
(M) Baltic prawn Palaemon adspersus	76	Kasymov & Velikhanov, 1992
(M) Yellow crab Metacarcinus anthonyi	>1000	Macdonald et al., 1988
(M) Dungeness crab Cancer magister	71,400	Carls and Rice, 1984
(M) Mussel Mytilaster lineatus	109	Kasymov & Velikhanov, 1992
Several fish &invertebrates	>7500	Daugherty, 1951
(FW) Trout Salmo gairdneri	76,000	Sprague & Logan, 1979
(FW) Sailfin molly Mollienisia latipinna	>100,000	Grantham & Sloan, 1975

The toxic responses to barite are due to physical interactions with gills, the gastrointestinal tract, and integument, as opposed to chemical toxicity. In several chronic studies with grass shrimp *Palaemonetes pugio* and substrates heavily contaminated with solid barite, barium, as barite, accumulated in the exoskeleton, hepatopancreas, and muscle tissue (Brannon and Rao, 1979; Conklin et al., 1980). In addition, barite ingestion caused damage to epithelial tissue of the gut. Starczak et al. (1992) did not find any adverse effects on fecal production, growth, and tube production in adult polychaete worms *Mediomastus ambiseta* living in barite-covered sediments. The polychaetes migrated out of patches of 100% barite.

Barite mixed with sediments or as a layer on the sediment surface interfered with but did not prevent recruitment of several planktonic larvae of polychaetes and mussels to the sediments (Tagatz and Tobia, 1978; Cantelmo et al., 1979; Tagatz et al., 1980; Starczak et al., 1992). It also caused short-term changes in benthic community structure (Tagatz et al., 1978). Fewer species and individuals colonized sediments covered by a thin layer of barite compared to control

sediments. They attributed these effects to alterations of sediment texture by the dense, fine-grained barite, rendering the substrate unsuitable for some species and more suitable for other species settling as larvae from the plankton.

Cranford et al. (1999) exposed juvenile sea scallops *Placopecten magellanicus* to suspensions of 0.5 and 2.5 mg/L (ppm) barite in a flowing seawater system for 28 days. Survival at both doses was similar to that among controls. However, scallops exposed to both barite concentrations had lower gonad growth than control scallops did and, at the higher dose, digestive gland weight was significantly different from control. Control water was unfiltered Bedford Basin sea water that probably contained much lower natural suspended matter concentrations than benthic boundary layer water (water at the sediment/water interface) on Georges Bank where the scallops were obtained (Parmenter et al., 1983), possibly affecting the results of this study of effects of suspended particulate matter on scallops. As discussed above, Hannah et al. (2006) found barium concentrations only slightly elevated above natural background in the benthic boundary layer of Canadian fishing banks during exploratory drilling. Barite concentrations were below concentrations required to depress feeding and growth in juvenile scallops during chronic exposure (Cranford et al., 2003).

Barite in WBM apparently affected the scallops less than pure solid barite did. Acute and chronic exposure of scallops to 100 mg/L water based drilling mud had no significant effect on survivorship or growth (Cranford et al., 1998). Leuterman et al. (1989) showed that barite did not affect the acute toxicity of any of the generic drilling muds in the SPP toxicity test required by EPA (Table 7-6). It is probable that concentrations of suspended barite, clay, or drilling mud particles increased in the exposure water during the chronic flow-through toxicity tests, so the scallops were actually exposed to higher than the nominal suspended solids concentration late in the test when most effects were observed. The effects of barite were similar to those of bentonite clay and probably were caused by physical damage to delicate gill epithelial membranes and interference of the suspended particles with feeding efficiency in this active filter-feeding mollusk. Au et al. (2004) reported that chronic exposure to suspended sediments at concentrations frequently found in estuarine environments cause gill damage in juvenile grouper (a fish).

Clams *Cerastoderma edule* that were exposed to 1-3 mm of a barite mud mixture for 12 days experienced coagulated and shortened gill cilia. In some extreme cases the gill structure disintegrated, probably caused by clogging and abrasion by the fine barite particles. There was 100% mortality within 12 days (Barlow & Kingston, 2001). Benthic animals would never be exposed to a layer of pure barite near a WBM and cuttings discharge. The barite adsorbs strongly to the other drilling mud and cuttings particles, decreasing its potential to do damage to gills.

Dissolved barium, as barium acetate, at concentrations of 0.1 and 0.9 ppm inhibited embryonic development, particularly shell calcification, and resulted in development of abnormal embryos, in mussels *Mytilus californianus* (Spangenberg and Cherr, 1996). Barium was introduced into exposure media as barium acetate, because it was the only form of barium that did not precipitate in seawater at concentrations of 10,000 µg/L or less in 48 hours. The median concentration (EC50) causing developmental effects was 0.2 ppm, about 10 times the natural dissolved concentration in seawater. Complexation with organic acids slowed the rate of barium precipitation. At exposure concentrations above 10 ppm, where rapid precipitation of barite

occurred, the toxicity of the barium acetate to the mussel embryos decreased with increasing concentration, suggesting that it was barium ion or dissolved barium acetate that was causing toxic effects, not barite particles.

This study and three others have reported effects on embryos of marine invertebrates from exposure to barium, either in solution, complexed with organic acids, or as suspended barite (Schatten et al., 1985; Higashi et al., 1992; Cherr et al., 1993). These tests usually were performed in small containers with small volumes of water and high concentrations of embryos. It is possible that, under these conditions, sufficient dissolved or complexed barium was present at the membrane surfaces of the embryos to compete with calcium and strontium (both abundant in seawater) for cellular biochemical reactions involving calcium cofactors (e.g., membrane permeability, microtubule function, and metamorphosis) (Tamm and Tamm, 1990; Ilan et al., 1993). Alternatively, sulfate excreted through the epithelia of the embryos may have caused precipitation of barite on the outer surface of the embryos, resulting in the observed toxic effects. Effects of this type are much less likely in the receiving water environment where barium supersaturation is rare and dispersion and dilution rapidly decrease concentrations of barite particles and dissolved/complexed barium. Planktonic larvae are never exposed for several minutes at a time to elevated concentrations of dissolved barium in a drilling mud plume.

7.2.2 Bentonite Clay

Bentonite (sodium montmorillonite clay) is naturally occurring, insoluble clay that usually is considered non-toxic. It has been used in WBM for more than 100 years to provide viscosity to suspend barite and cuttings, as well as for filtration control. Clay has largely been supplemented with or replaced by alternative viscosifiers and filtrate reducers that perform better in difficult shale formations. The replacement viscosifiers and filtration reducers are natural or synthetic polymers, such as CMC and PHPA (Table 3-1). Both bentonite and the polymers have a low toxicity to marine animals.

Bentonite is non-toxic as defined by GESAMP (Table 7-3) in 96-hr acute toxicity studies with LC_{50}s ranging from 9,600 - >100,000 ppm for freshwater and marine animals (Table 7-7). Leuterman et al. (1989) showed that bentonite, modified bentonite, and attapulgite clays do not increase the toxicity of generic drilling muds. However, Carls and Rice (1984) reported that bentonite can be slightly toxic to larval marine crustaceans during the first few hours of exposure, while the clay-sized solids are in suspension. Once the clay settles to the bottom, no further effects are observed.

Suspended clays cause toxicity mainly by clogging gills or other sensitive surface membranes with fine particles, or by decreasing light penetration into the water column (for marine plants). Filter-feeding bivalve mollusks, adapted to clear waters, seem to be most sensitive. Cranford et al. (1999) exposed juvenile sea scallops *Placopecten magellanicus* to suspensions of 2 mg/L and 10 mg/L bentonite for up to 68 days. Chronic exposure to both doses significantly reduced respiration rate and scope for growth. As with barite, effects were clearly caused by interference with filter feeding. The scallops recovered quickly following return to clear water.

Toxic responses that occur as a result of physical disturbance include abrasion, erosion, or clogging of respiratory surfaces (Sprague and Logan, 1979). Suspended bentonite is toxic to

microalgae, *Skeletonema costatum,* at levels of 9600 ppm. This effect can be attributed to the shading effect of the bentonite clay suspension, reducing the penetration of sunlight into the water, reducing photosynthesis in the alga.

Table 7-7 lists the acute toxicity of bentonite clay to freshwater (FW) and marine (M) plants and animals. Concentrations are mg/L (ppm) or as the concentration of a generic drilling mud (Table4-2) containing bentonite at the expected use rate (*).

TABLE 7-7
Acute Toxicity of Bentonite Clay to Freshwater and Marine Plants and Animals

Organism	96-hr LC 50	Reference
(M) Alga Skeletonema costatum	9,600	EG&G, 1976
(M) Oyster Crassostrea virginica	>7500	Daugherty, 1951
(M) Copepod Acartia tonsa	22,000	EG&G, 1976
(M) Mysid Americamysis bahia	>100,000*	Leuterman et al., 1989
(M) Dock shrimp Pandalus danae	24,800	Carls and Rice, 1984
(M) Coonstripe shrimp Pandalus hypsinotus	>100,000	Dames & Moore, 1978
(M) Dungeness crab larvae Cancer magister	81,600	Carls and Rice, 1984
(FW) Sailfin molly Mollienisia latipinna	>100,000	Wallen, 1951

7.2.3 Other Viscosifiers and Filtrate Reducers

Bentonite has been supplemented or replaced by organic polymers as viscosifiers and filtrate reducers in many modern WBM. PHPA, CMC, and guar gum are examples of polymers frequently used as viscosifiers and filtrate reducers in WBM. They are biodegradable.

7.2.3.1 Carboxymethyl Cellulose (CMC) and Related Cellulose Polymers

CMC and related methyl, ethyl, and polyanionic celluloses are linear polysacccharide polymers made from natural plant cellulose. The number of carboxymethyl and other carbon side groups and total chain length are varied to serve different functions (Caenn and Chillingar, 1996). They often are used with clay and synthetic polymers as viscosifiers and filtrate reducers and are considered non-toxic. In fact, CMC and related cellulose polymers are used frequently as emulsion stabilizers and thickeners in commercial soups, sauces, and ice cream.

The proposed drilling program for the Beaufort and Chukchi Seas includes high molecular weight polyanionic cellulose (Poly Pac R) viscosifier and a low-viscosity polyanionic cellulose (Poly Pac UL) filtration reducer (Table 3-7). The polymer muds used to drill the Paktoa-60 well contained a polyanionic cellulose (Staflo XL) (Table 5-19). There are limited data available about the toxicity of CMC to aquatic/marine organisms (Table 7-8). Leuterman et al. (1989)

reported an acute toxicity of several starch- and cellulose-based filtration control polymers to mysids *Mysidopsis bahia* in the range of 78,000 to > 100,000 mg/L of generic drilling muds containing these polymers. Van Ginkel and Gayton (1996) reported 96-hr LC_{50}s ranging from 500 to 5000 ppm for freshwater bacteria. phytoplankton, crustaceans, and fish. Thus, these natural organic polymers are non-toxic according to GESAMP (Table 7-3) to all but freshwater phytoplankton; they are practically non-toxic to the algae. These polymers are bound to fine particulates in the WBM, decreasing their toxicity even further.

Table 7-8 lists the toxicity of carboxymethyl cellulose and related natural organic polymers to freshwater (FW) and marine (M) organisms. Concentrations are mg/L (ppm) or as the concentration of a generic drilling mud (Table4-2) containing the polymer at the expected use rate (*).

TABLE 7-8
Toxicity of CMC and Related Natural Organic Polymers to Freshwater and Marine Plants and Animals

Organism	LC 50 (ppm)	Reference
Bacterium Pseudomonas putida	1000	Van Ginkel & Gayton, 1996
(FW) Phytoplankton Selenastrum capricornutum	500	Van Ginkel & Gayton, 1996
(M) Phytoplankton Phaeodactylum tricornutum	>10,000	Terzaghi et al., 1998
(M) Brine shrimp Artemia salina	>10,000	Terzaghi et al., 1998
(M) White shrimp Penaeus setiferus	1925	Chesser and McKenzie, 1975
(FW) Water flea Daphnia magna	5000	Van Ginkel & Gayton, 1996
(M) Mysid Americamysis bahia	7800-29,000*	Leuterman et al., 1989
(FW) Zebrafish Danio rerio	2500	Van Ginkel & Gayton, 1996

7.2.3.2 Xanthan Gum

Xanthan gum is a natural polysaccharide, produced by fermentation of glucose or sucrose by the bacterium *Xanthomonas campestris*. It has a complex structure and molecular weight in excess of 1 million daltons. Like CMC, it is widely used to stabilize emulsions and thicken salad dressings, soups, and ice cream (Davidson, 1980).

It also is used to increase the viscosity of drilling muds. There are many commercial brands of xanthan gum, varying mainly in molecular weight. The brand used for WBM for the Paktoa-60 exploratory well (Table 5-19) and planned for the seawater/PHPA drilling muds that will be used for drilling in the Beaufort and Chukchi Seas (Table 3-7) is Duo-Vis. Like CMC, this natural microbial polysaccharide is non-toxic or practically non-toxic according to GESAMP (Table 7-3). Acute toxicity ranges from 207 to more than 1000 ppm (Table 7-9). Addition of xanthan gum to WBM does not affect the toxicity of the drilling mud (Leutedrman et al., 1989). Because xanthan gum tends to complex with solids in WBM, there is no risk that concentrations of this natural polymer would ever reach potentially toxic concentration in a drilling mud plume.

Xanthan gum and cellulose-based natural polymers are sufficiently soluble that they do not accumulate in cuttings piles. These high molecular weight, water-soluble polymers do not bioaccumulate in marine food webs; their molecular size is larger than can permeate biological membranes and their low octanol/water partition coefficients indicate that they have little affinity for accumulation in biological lipids.

Table 7-9 lists the toxicity of xanthan gum to freshwater (FW) and marine (M) plants and animals. Concentrations are mg/L (ppm) or as the concentration of a generic drilling mud (Table4-2) containing xantham gum at the expected use rate (*).

TABLE 7-9
Toxicity of Xanthan Gum to Freshwater and Marine Plants and Animals

Organism	LC 50 (ppm)	Reference
(M) phytoplankton Skeletonema costatum	207	MI SWACO Product Information
(M) phytoplankton Phaeodactylum tricornutum	> 400	Terzaghi et al., 1998
(M) Mysid Americamysis bahia	757,000*	Leuterman et al., 1989
(FW) Water flea Daphnia magna	>1000	Hudgins, 1994
(M) Copepod Acartia tonsa	259	MI SWACO Product Information
(M) Brine shrimp Artemia salina	291	Terzaghi et al., 1998
(FW) Trout Oncorhynchus mykiss	420	Sprague & Logan 1979
(M) Turbot Scophthalamus maximus	>1000	MI SWACO Product Information

7.2.3.3 Synthetic Organic Polymers

Many synthetic organic polymers have been developed and approved for several functions in WBM. They have a simpler chemical structure than the bio-polymers, usually consisting of a straight-chain carbon backbone with short side chains depending on the intended use. The polymers used for drilling mud viscosity control and fluid loss control usually are anionic (carry a negative electric charge). Synthetic polymers of different molecular weights have different functions in WBM: low molecular weight (<1000 daltons) - thinners and deflocculents; medium molecular weight (1000 to 100,000 daltons) - fluid loss control, flocculents, and shale stabilizers; high molecular weight (>100,000 daltons) - bentonite extenders and flocculents (Caenn and Chillingar, 1996). PHPA, used most frequently in WBM as a flocculent or shale stabilizer, is an anionic, medium molecular weight polymer.

Cationic forms of polyacrylates, polyacrylamides, and quaternary amine copolymers sometimes are used for shale stabilization (Samil and Mishra, 2009). Roddie et al. (1999) reported that cationic polymer drilling muds (probably polyamine/polyacrylamide based muds) used in the North Sea were toxic to water column organisms (phytoplankton) but not to benthic

invertebrates. The cationic polymers bind strongly to natural organic matter (humic acids) in sediments, reducing their toxicity. Cationic polymers are more toxic than anionic polymers to marine organisms (Goodrich et al., 1991) and apparently are not used for U.S. WBM.

The WBM proposed for drilling in the Beaufort Sea contain the following synthetic polymers: Gelex, a polyacrylate/polyacrylamide bentonite extender and deflocculent (thinner); Poly Plus RD, a high molecular weight, water-soluble PHPA polymer viscosifier, friction reducer (lubricant), and filtration reducer: SP-101 a medium molecular weight sodium polyacrylate copolymer that is effective in filtration control at high down-hole temperatures. The WBM used to drill the Paktoa-60 well contained Alcomer 74, a low molecular weight anionic acrylate copolymer that functions as a drilling mud thinner. Gelex and Alcomer 74 are low-toxicity replacements for lignosulfonates that have been removed from most offshore drilling muds because of their potential toxicity to marine organisms.

Most of these polymers are based on an acrylate or acrylamide backbone. They are considered to have a low aquatic toxicity and find wide use in various commercial applications, such as drinking water and industrial water clarification and purification, in addition to their uses in drilling muds. The combination of high molecular weight, ionic charge, and high water-solubility allow them to form extremely viscous solutions. Viscosity can be varied by changing molecular weight or charge density. Their limited toxicity to aquatic animals is due to the high viscosity of polymer solutions that clogs the gills of aquatic animals. The ionic charge on the polymer also can influence its toxicity. Cationic polymers are quite toxic to freshwater animals because they bind to the negatively-charged sites on fish gills (Biesinger and Stokes, 1986). Anionic polymers, such as most of those used in WBM, do not bind to membranes and are much less toxic to freshwater animals. Both cationic and anionic polymers have a relatively low toxicity to marine animals because of the high ionic strength of seawater.

Viscosity and charge density of acrylic polymers decrease steeply with dilution of the drilling mud plume in seawater, causing the polymer to flocculate, bind to suspended clays, and settle rapidly to the bottom. Thus, these polymers have a very low toxicity to water column organisms in the field and are bound in sediments in a non-toxic form. Like the biopolymers discussed above, these synthetic polymers have no potential to bioaccumulate in aquatic food chains, because of their high molecular weights and aqueous solubilities (Horticultural Alliance, 2009).

There is concern that polyacrylamide polymers may degrade during use or after disposal, releasing acrylamide, a suspected carcinogen (California EPA, 2005), to the environment. High molecular weight anionic polyacrylamides, such as PHPA, are manufactured by the free-radical polymerization of acrylamide and an anionically charged co-monomer, such as sodium acrylate. Traces of acrylamide may remain in the final product. Most polacrylamides are highly resistant to microbial attack, though they are sensitive to photo-degradation. The PHPA and other polyacrylates in a drilling mud are not subject to photo-degradation, so, only traces of acrylamide are released in drilling waste discharges. The polyacrylamides biodegrade slowly following discharge to the ocean, particularly if exposed to strong sunlight (Smith et al., 1997; Caulfield et al., 2002). Combined photo- and bio-degradation leads to release of monomeric acrylamide and sodium acrylate. Both chemicals are very soluble and biodegrade rapidly in seawater or soils (Horticultural Alliance, 2009). EPA (2009) estimated that acrylamide degrades completely in river water in 4 to 12 days.

Acrylamide, with a water-solubility of about 2.2 kg/L and a log octanol/water partition coefficient (log K_{ow}) of -0.67, has no tendency to adsorb to sediments or bioaccumulate in the marine food web. The bioconcentration factor (BCF) (concentration in tissues/concentration in exposure water) for acrylamide in fingerling trout following 72-hours exposure was -0.86, indicating that bioconcentration had not occurred (EPA, 2009). The lack of bioaccumulation is due in part to the rapid metabolism and excretion of acrylamide by fish (Waddell et al., 1990). Thus, there is no risk that discharge of WBM containing polyacrylamide polymers to the ocean will result in exposure to and harm from acrylamide in the local food web.

The toxicity of acrylic polymers to aquatic plants and animals is low (Table 7-10). Median toxicity or effects concentrations of the polymers in solution in fresh or sea water ranges from 212 to 14,800 ppm. Freshwater plants and animals are more sensitive than marine species. Addition of a polymer to a generic WBM does not affect the toxicity of the drilling mud. Thus, there is no evidence that acrylic polymer additives to WBM pose an ecological risk to the receiving water environment.

Table 7-10 lists the toxicity to freshwater (FW) and marine (M) plants and animals of different types of synthetic acrylic polymer additives used in WBM. Concentrations are mg/L (ppm) in solution or as the concentration of a generic drilling mud (Table 4-2) containing the acrylic polymer at the expected use rate (*).

TABLE 7-10
Toxicity of Synthetic Acrylic Polymers to Freshwater and Marine Plants and Animals

Polymer Type	Trade Names	Species	LC50/EC50	Reference
Partially hydrolyzed polyacrylamide (PHPA)	EZ-Mud, Poly-Plus, New-Vis	(M) Mysid Americamysis bahia	7800 - >100,000*	Leuterman et al., 1989
High MW Polyacrylamide	---	(FW) phytoplankton Chlorella vulgaris	1000	Horticultural Alliance, 2009
		(FW) Waterflea Daphnia magna	212	Horticultural Alliance, 2009
		(FW) Zebrafish Danio rerio	457	Horticultural Alliance, 2009
Polyacrylamide copolymer	---	(M) Brown shrimp Penaeus aztecus	14,800	Hudgins, 1992
Low MW anionic acrylic copolymer	Therma-Thin, Tackle, New Thin, Mil-Temp, Alcomer 74, Ultracap	(M) Mysid Americamysis bahia	7400 - >100,000*	Leuterman et al., 1989
	---	(M) White shrimp Penaeus setiferus	3500	Chesser and McKenzie, 1975
Low MW acrylamide copolymer	Ultracap	(M) Phytoplankton Skeletonema costatum	298	MI Swaco, 2009
		(M) Copepod Acartia tonsa	1290	MI Swaco, 2009
		(M) Turbot Scophthalamus maximus	>1000	MI Swaco, 2009
		(M) Amphipod Corophium volutator	>10,000	MI Swaco, 2009
Acrylate copolymer	---	(FW) Bluegill Lepomis macrochirus	700	Hudgins, 1991
Medium MW Na polyacrylate	Polyac Plus, SP-101, New-Trol	(M) Mysid Americamysis bahia	>100,000*	Leuterman et al., 1989
Anionic Na-acrylate polyacrylamide	MagnaFloc 156	(FW) Waterflea Ceriodaphnia dubia	218	De Rosemond and Liber, 2004

7.2.4 Biocides

Biocides are disinfectants designed to kill bacteria and fungi. A disinfectant (biocide) may be needed in small amounts in the WBM to prevent microbial degradation of organic chemicals (mainly cellulose, starches, and synthetic polymers) in the mud. Glutaraldehyde is the biocide used most frequently today in polymer WBM. Glutaraldehyde has a wide variety of other applications, including disinfecting cooling water systems and surgical instruments.

Glutaraldehyde was the biocide chosen for use in polymer WBM for the Paktoa-60 exploratory well in the Canadian Beaufort Sea (Table 7-2) and for proposed exploratory drilling in the Beaufort and Chukchi Seas (Table 3-7). It is used in small doses, 50 to 1000 ppm, if needed, depending on the severity of the bacterial contamination. Shell has decided to use a concentrated salt brine instead of seawater for their saltwater/PHPA drilling mud and increase the pH of the mud to about 10.5. These changes will decreased microbial attack on the organic phase of the mud, reducing or eliminating the need for a biocide. Glutataldahyde is destroyed rapidly by reaction with organic matter, including the cell walls of bacteria and fungi and organic additives in the drilling mud and in the receiving waters. Glutaraldehyde kills bacteria, fungi, and viruses by cross-linking anine groups in microbial proteins (Sano et al., 2005). These reactions with organic matter inactivate the glutaraldehyde. If used in amounts just sufficient to control bacterial growth, little glutaraldehyde is discharged. If excess glutaraldehyde is used, some may be discharged with the drilling wastes, where it will be biodegraded rapidly by bacteria and fungi or inactivated by adsorption to organic matter in the ocean. The calculated biodegradation half lives of glutaraldehide in oxygenated and anaerobic freshwater sediments are 10.6 and 7.7 hours, respectively (EPA, 2007). Because of its high water-solubility, low log K_{ow}, and rapid biodegradadation, gutaraldehyde does not readily bioaccumulate in aquatic food webs (EPA, 2007).

Glutaraldehyde is moderately toxic to non-toxic to various freshwater and marine animals with LC_{50}s ranging from >6 to 2200 ppm for several crustaceans (Table 7-4). Because it is much more toxic to bacteria, fungi, and viruses, it is finding wide application in sanitation of freshwater and marine ecosystems. The U.S. Coast Guard is evaluating glutaraldehyde for controlling invasive species in ballast water of ships (USCG, 2004; Raikow et al., 2007). It also is being used in aquaculture to control bacterial and fungus infection of fish eggs and parasite infestations in juvenile fish (Escaffre et al., 2002; Paramá et al., 2005). Five- to 10-minute doses of 200 to 800 ppm glutaraldehyde to early egg developmental stages of gilthead sea bream, Atlantic cod, Atlantic halibut, and sand dab are effective in controlling fungal infections without harming the developing eggs (Escaffre et al., 2002; Kegley et al., 2009).

Because glutaraldehyde is being used as a disinfectant in a wide variety of applications that result in release to freshwater and marine environments, there is a large amount of data available on its toxicity to freshwater plants and animals. Table 7-11 contains a few representative examples of the toxicity of glutaraldehyde in marine and freshwater and marine organisms.

Table 7-11 lists the toxicity to freshwater (FW) and marine (M) animals of glutaraldehyde. Concentrations are mg/L (ppm) in solution or as the concentration of a generic drilling mud (Table 4-2) containing glutaraldehyde at the expected use rate, 200 - 500 ppm (*).

TABLE 7-11
Toxicity of Gluteraldehyde to Freshwater and Marine Plants and Animals

Organism	LC 50 (ppm)	Reference
(M) Mysid Americamysis bahia	45,000*	Leuterman et al., 1989
(M) Postlarval mysid Americamysis bahia	7.1	Kegley et al., 2009
(M) Adult mysid Americamysis bahia	20.6	Kegley et al., 2009
(M) Grass shrimp Palaemonetes pugio	41	Hudgins, 1992
(M) Brown shrimp Penaeius aztecus	1100	Hudgins, 1992
(M) Copepod Acartia tonsa	0.11	Leung, 2001
(M) Barnacle Balanus improvisus	7.9	Leung, 2001
(M) Green crab Carcinus maenus	465	Leung, 2001
(M) Sheepshead minnow Cyprinodon variegatus	31.4 - 40	EPA, 2007
(M) Shell growth, oyster Crassostrea virginica	0.78	EPA, 2007
(M) Coho salmon Oncorhynchus kisuch	3	Leung, 2001
(F) Resting eggs waterflea Daphnia mendotae	55	Raikow et al., 2001
(F) Neonate waterflea Daphnia magna	14	Sano et al., 2003
(F) Adult Daphnia magna	56	Sano et al., 2003
(F) Bluegill Lepomis macrochirus	12 - 23	EPA, 2007
(F) Trout Oncorhynchus mykiss	9.5 - 24	EPA, 2007
(F) Fathead minnow Pimephales promelas	5.4	Leung, 2001

Most freshwater and marine animals have 48 to 96-hour LC_{50}s higher than 5 ppm. Lionel Camus (personal communication) reported that the acute toxicity of glutaraldehyde to polar cod *Boreogadus saida*, a keystone species in the Arctic marine food web, ranged from about 15 to 25 ppm, depending on seawater temperature between 1 and 7°C. Some animals, such as copepods, exhibit sublethal effects during long-term exposure to less than 1 ppm glutaraldehyde. However, the dissolved phase of the drilling mud plume, containing glutaraldehyde and other dissolved additives, dilutes by more than 1000-fold within about 10 minutes and a few hundred feet from the discharge. The glutaraldehyde also biodegrades rapidly in the receiving waters, ensuring that water column animals will not be exposed to potentially harmful concentrations of glutaraldehyde long enough to elicit harmful effects.

Because it does not accumulate in sediments or bioaccumulate in tissues of marine animals, it does not pose a risk to benthic communities. Tagatz et al. (1980) studied the effects of paraformaldehyde, another aldehyde biocide with a toxicity similar to that of glutaraldehyde

(Table 7-4), on recruitment of benthic marine invertebrates to sandy substrates in aquaria receiving a continuous flow of unfiltered seawater. The two doses of paraformaldehyde in the flow-through water, 0.014 and 0.27 mg/L (ppm), did not produce any effects in four major taxa of benthic marine animals in the aquaria. Thus, the benthic invertebrates probably are not sensitive to doses of glutaraldehyde in the range that might be expected near the sea floor a short distance from a shallow-water drilling waste discharge.

Addition of any of the additives discussed above to a generic drilling mud did not significantly increase the toxicity of the drilling mud to marine animals. Parrish et al. (1989) showed that adding one or a combination of several common mud additives to generic drilling muds did not increase the toxicity of the mud as much as predicted by a simple additive toxicity model. Thus, the other ingredients in the drilling mud reduce the toxicity of any additives to the mud.

7.2.5 Inorganic Salts and Metals

Some of the salts added to WBM for alkalinity/pH or shale control are slightly toxic to freshwater plants and animals (Table 7-4). These salts are essential micronutrients for all animals, including freshwater and marine animals. Toxicity of these salts occurs when the animal cannot control the concentration of these ions or the pH in body fluids at excessively high or low concentrations of the ions in the ambient water. Pillard et al. (2000) measured the upper (ion excess) and lower (ion deficiency) toxicity limits of seven of the most abundant ions in seawater to mysids *Americamysis bahia,* sheepshead minnows *Cyprinodon variegatus,* and inland silverside *Menidia beryllina* All three species were most sensitive to variations in concentrations of borate ($B_4O^2{}_7^-$) and potassium (K^+) in seawater. Borate is a natural pH buffer in seawater. The upper limit LC_{50} for potassium ranged from 790 to 1210 mg/L in the three species. The natural concentration of potassium in seawater is about 400 mg/L. A typical KCl/polymer drilling mud may contain up to about 2000 mg/L potassium, explaining why it is the most toxic of the generic drilling muds (Table 4-2). The toxicity of the ions in drilling mud will be removed immediately upon discharge by a few-fold dilution of the drilling mud plume. Because all the inorganic ions in WBM also are present in sea water, there is no risk that marine plants and animals near a drilling mud and cuttings discharge will be harmed by the inorganic ions in the drilling muds.

As discussed above, nearly all the metals in WBM are associated with drilling mud barite. The exceptions are chromium, which, when present at elevated concentrations, is associated with chrome- and ferrochrome-lignosulfonate thinners and the chromate salts added to stabilize the chrome lignosulfonate at high temperature, zinc salts added as sulfide-scavengers, and lead associated with pipe thread compound. These sources of chromium, lead, and zinc in WBM have largely been replaced in modern WBM with alternative, metal-free additives. Cleaner grades of barite, that meet EPA requirements for less than 1 ppm mercury and 3 ppm cadmium in drilling mud barite, are being used. Thus, modern WBM rarely contain bioavailable metals at concentrations significantly higher than those in natural marine sediments (Table 3-2).

The metals in barite are present in extremely low solubility forms, mostly sulfides. The barite itself has a very low solubility in seawater. Barite is extremely stable in oxygenated seawater and sediment pore water that is naturally rich in sulfate, but is slightly soluble in anoxic seawater and sediment pore water where sulfate is likely to be depleted. The metal sulfides in barite are extremely stable in anoxic seawater and sediment pore water in the presence of sulfide.

Therefore, there is negligible risk that environmentally significant amounts of dissolved (the most bioavailable and toxic form of metals) barium and metals will leach into the water column or into sediment pore water from barite in a WBM and cuttings discharge to the ocean.

As discussed above, Crecelius et al. (2007) and Neff (2008) measured and modeled the dissolution of barium and metals from modern low-metals barite (Table 3-2) into the pore water of a WBM cuttings pile containing 5700 mg/kg drilling mud barite. The estimated concentration of all metals except copper in the pore water were an order of magnitude or more lower than the EPA marine chronic water quality criterion values (Table 6-2). Estimated copper concentration in pore water was slightly lower than the criterion value. Copper concentration frequently is high in marine and estuarine sediments (Neff, 2002a). However, most of the copper in the pore water is tightly complexed with natural dissolved organic matter (Douglas et al., 1986; Widerland, 1996). These copper-metal organic complexes are not bioavailable or toxic to marine organisms.

7.2.6 Thinners and Clay Dispersants.

Lignosulfonate is an organic salt that is produced as a by-product of the sulfite pulping process for separation of cellulose pulp from wood during the manufacture of paper (Hollingsworth and Lockhart, 1975). Some chrome and ferrochrome lignosulfonate thinners are slightly toxic to marine organisms (Table 7-4). Because of concern about their possible environmental impacts, offshore operators have replaced the chrome- and ferrochrome-lignosulfonates with less toxic chrome-free lignosulfonate salts, or, more frequently with biological or synthetic polymers, as discussed above. Other clay thinners, such as lignites and tannins, are not toxic (Table 7-4).

7.3 Whole WBM

7.3.1 Effects Testing of WBM

Many laboratory toxicity tests have been performed since the mid 1970s on the acute and chronic toxicity of WBM to freshwater and marine animals. Most of these tests were performed in the United States where discharge regulations require toxicity testing of drilling muds destined for offshore discharge (Table 4-1). By 1983, results had been reported for 400 bioassays with 72 different WBM and 62 species of marine animals from the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Beaufort Sea (NRC, 1983). Nearly 80 percent of the median lethal concentrations (96-h LC_{50}) were greater than 10,000 mg/L (ppm) drilling fluid, considered non-toxic by the GESAMP toxicity classification.

The toxicity tests summarized by the NRC (1983) were performed by many different protocols with different fractions of new (formulated in the laboratory but never used for drilling) and used WBM. A used WBM, particularly a heavily treated mud from a deep hole, is a complex mixture of liquids and solids. Some of the mud ingredients may have degraded or complexed with other ingredients under the high-temperature and pressure conditions in the well, altering their physical form and toxicity. The used mud separates into several fractions that behave differently in the receiving water environment. This behavior makes it extremely difficult to design a toxicity test protocol in which test organisms are exposed uniformly and reproducibly to a drilling mud-seawater mixture of known concentration and that at least roughly simulates the kind of exposure pelagic and benthic organisms might encounter in the vicinity of the drilling mud discharge.

Drilling mud bioassays can serve two purposes: to measure compliance with toxicity limitations in drilling permits and; to predict possible effects on marine organisms in the vicinity of a drilling mud discharge.

In an attempt to do the latter, Neff et al. (1980, 1981) developed test protocols for three drilling mud fractions, based on the approach taken by the U.S. Corps of Engineers (EPA/COE, 1977) to evaluate the environmental impacts of dredged materials. The protocols were modified by EPA (1985a,b,c) for use as standard toxicity tests for WBM destined for ocean disposal (Table 7-12). Subsequently, eight generic WBM (Table 4-2), representative of the types of drilling muds used offshore in U.S. waters, were identified and characterized chemically and toxicologically (Ayers et al., 1983). The mysid (*Americamysis [Mysidopsis] bahia*), a small shrimp-like crustacean, was identified as one of the most sensitive marine animals to many organic and inorganic chemicals, including drilling muds (Anderson et al., 1974; Nimmo and Hamaker, 1982) and was recommended as a suitable marine animal for testing the toxicity of the three fractions. The EPA (1985a,b,c) recommend use of *A. bahia* and the SPP phase test. Jones and Leuterman (1990) and others have recommended using closely-related species of mysids from other regions where offshore oil and gas development is occurring. However, the current NPDES permit for exploratory drilling in the Beaufort and Chukchi Seas still requires that drilling mud toxicity tests be performed with *A. bahia* (EPA, 2006: Attachment 4).The rationale for using the same species for all OCS regions is that the test results can be compared to the toxicity limitation of 3000 ppm drilling mud (30,000 ppm SPP phase).

The toxicity of the three fractions of the eight generic WBM (Table 4-2) was evaluated in several studies. The studies gave highly variable results for the generic drilling muds (Table 7-13). However, the LSP of all eight muds always was more toxic (lower LC_{50}) than the SPP or MAF preparations, if concentration was measured as concentration of drilling mud added. The SPP fraction gave the most consistent results and was more representative than the MAF of exposure in the field (Neff et al., 1980). Most NPDES general permits for offshore discharges from drilling operations require that toxicity tests be performed with the SPP of all drilling muds used and discharged offshore (e.g., NPDES Permit No. AKG280000 for EPA Region 10, including the Beaufort and Chukchi Seas).

Bioassays performed by the U.S. EPA (Duke et al., 1984) with the SPP of eight generic muds and mysids gave 96-h LC_{50}s ranging from 3,300 mg/L to >100,000 mg/L mud added (Table 4-3). A KCl-polymer mud had the lowest LC_{50}, still within the GESAMP (2002) non-toxic range. The results of these tests were used by EPA to set an acute toxicity (LC_{50}) limit for water based drilling muds of 3,000 ppm drilling mud added (30,000 ppm SPP) in the current ELG. This limitation is based on best available technology (BAT), not on estimated risk to the receiving environment.

All U.S. offshore operators are required by the NPDES permit to perform SPP bioassays on used WBM each month during drilling and at the end of the well. If SBM are used and cuttings are discharged offshore, the NPDES permit may require LSP tests with a benthic amphipod. Data collected by EPA between 1986 and 1989 showed that 99.9 percent of 10,397 Gulf of Mexico WBM bioassays with mysids yielded a 96-h LC_{50} in excess of the 30,000 ppm suspended particulate phase limit (SAIC, 1992). Thus, the vast majority of WBM used offshore in U.S.

waters meet the ELG. All the WBM are considered non-toxic or practically non-toxic by the GESAMP (2002) ranking (Table 7-3).

Table 7-12 is an outline of protocols developed to evaluate the toxicity of WBM to marine animals. The current NPDES permit for the Beaufort and Chukchi Seas (AKG280000) requires WBM testing with the suspended particulate phase and mysids *Americamysis bahia*.

TABLE 7-12
Protocols Developed to Evaluate the Toxicity of WBM to Marine Animals

Mud Aqueous Fraction (MAF)
1. A 1:9 volumetric mixture[a] of drilling mud and seawater is stirred thoroughly and allowed to settle for 20 hours. 2. The pH of the resulting supernate is adjusted to that of seawater (7.8- 8.1) with HC_l, if necessary, and the resulting solution (100% MAF) is diluted to the appropriate concentrations and used immediately for the bioassay. 3. The 100% MAF contains the water-soluble and fine particulate fractions of 100,000 ppm mud in water.
Suspended Particulate Phase (SPP)
1. A 1:9 volumetric mixturea of drilling mud and seawater is mixed vigorously for 5 minutes. 2. The suspension is then allowed to settle for 1 hour. 3. The pH and O_2 concentration are measured and adjusted to those of seawater, if needed, and the resulting mixture (100% SPP) is siphoned off for immediate use in bioassays. 4. The SPP resembles the MAF except that the SPP contains a higher concentration of suspended particles.
Layered Solid Phase (LSP)
1. A measured volume of drilling mud is layered over clean natural sediment in aquaria. 2. Seawater is added with minimal resuspension of mud particles. 3. Test animals are added to the aquaria after 24 to 48 hours, and monitored for behavior and mortality for up to 7 to 10 days.

[a] Originally, a 1:4 dilution was recommended (Ayers et al., 1983); however, at this dilution, the WBM does not flocculate, as it does following ocean discharge.

7.3.2 Toxicity of WBM to Coldwater Marine Animals

Many of the WBM bioassays reviewed by the NRC (1983) were with marine plants and animals from cold-water marine environments, including the Beaufort Sea and Cook Inlet. McLeay (1976) measured the toxicity of seven Arctic drilling muds (from the McKenzie River delta area, Canada) to marine invertebrates and fish from British Columbia. The drilling muds were similar to the generic WBM approved by the U.S. EPA. All the muds were non-toxic by the GESAMP ranking (Table 7-14). There was no relationship between the volume percent solids in the muds and their toxicity. The drilling mud with the highest percent solids (Pelly weighted gel

XC/polymer mud) was among the muds with the highest LC_{50}s. In most cases, the two salmonid fish were more sensitive than the invertebrates to the WBM. The fish may be sensitive to clogging of the gills with the suspended solids or gill erosion from the high pH of some muds. The Niglintgak weighted polymer mud had the lowest LC_{50} to the fish and the highest pH (12.0). In a field discharge situation, the pH of the drilling mud plume would decline rapidly to that of seawater because of the high buffer capacity of seawater. Salinity (freshwater or seawater) had little effect on LC_{50}s of drilling muds to rainbow trout. Chum and pink salmon (*Oncorhynchus kita* and *O. gorbuacha*, respectively) were only tested in seawater with Kipnik KCl/polymer drilling mud. The LC_{50}s were in the same range as those for the other fish and invertebrates and this drilling mud.

Table 7-13 lists the range of acute toxicities (96-hr LC_{50}) of three fractions (Table 7-12) of eight generic drilling muds (Table 4-2) reported in several studies[a]. LC_{50} concentrations are mg/L mud added.

TABLE 7-13
Acute Toxicity Ranges of 3 Fractions of 8 Generic Drilling Muds

Drilling Mud Type	MAF	SPP	LSP
KCl/Polymer mud	5800 - >150,000	2500 - 27,140	>1500 - 2577
Seawater/Lignosulfonate mud	28,350 - 88,000	5300 - 62,100	733
Lime mud	39,300 - 100,00	726 - 86,000	92 - 1008
Non-Dispersed mud	>100,000- >150,000	>50,000- >100,000	>1500
Seawater spud mud	>100,000- >200,000	>100,000- >200,000	>100,000
Seawater/Freshwater gel mud	>100,000- >200,000	22,400 - >100,000	263
Lightly treated lignosulfonate mud	>100,000- >200,000	1936 - >200,000	26 - 728
Freshwater lignosulfonate mud	97,240 - >200,000	18,830 - >100,000	459 - 4510

[a] Duke and Parrish (1984); ERCO (1980); Ayers et al. (1983); Duke et al. (1984); EPA (1985a,b,c); Gaetz et al. (1986).

As part of an effluent disposal monitoring study for drilling a stratigraphic test (COST) well at Reindeer Island, in the Beaufort Sea off Prudhoe Bay, Northern Technical Services performed bioassays with several types of WBM used to drill different depth intervals of the well (Tornberg et al., 1980; NTS, 1981). Test mixtures were prepared by adding known volumes of drilling mud to seawater with mixing. The suspensions were not mixed during the bioassay, so the test mixtures resembled a combined suspended phase (SPP) and layered solids phase (LSP) (Table 7-12). Three of the fish species also were exposed to the supernatant fraction of a mixture that had been allowed to settle in an effort to determine if soluble components of the drilling mud contributed to toxicity.

None of the WBM were toxic to the ten species of Beaufort Sea marine animals (Table 7-15). Median lethal concentrations (96-hr LC_{50}) ranged from 32,000 ppm mud added for CMC/gel mud and fourhorn sculpin to >700,000 ppm for CMC/resinex/tannathin/gel mud and polychaete worms and snails. Tornberg et al. (1980) reported that there was a tendency for the 96-hr LC_{50} for mysids and fourhorn sculpin to decrease with greater depth in the well. This was due to the high LC_{50}s (215,000 - 235,000 ppm) of the drilling muds used to drill the upper 6000 ft of the well, compared to the LC_{50}s (60,000 to 100,000 ppm) of the muds used to drill the 11,000 to 12,000 foot section of the well. Drilling muds used in deeper sections of a well usually are more heavily treated than top-hole drilling muds with a variety of additives. The differences in the LC_{50}s were relatively small among the different drilling mud types and the different species of Beaufort Sea fish and invertebrates. Effects probably were caused mainly physical clogging of gills and gut with fine-grained solids, and not from the toxicity of any additives.

Table 7-14 lists the acute toxicity (96-hr LC_{50}) of seven WBM from the MacKenzie River delta, Canada, to seawater-acclimated coho salmon and four marine invertebrates from British Columbia, Canada, and seawater- and freshwater- (in parentheses) acclimated rainbow trout. The volume % solids for each mud is included. Concentrations are µl/L (ppm v/v) of drilling mud added. From McLeay (1976).

TABLE 7-14
Acute Toxicity Ranges of 7 WBMs from the MacKenzie River Delta to Coho Salmon and 4 Marine Species

Drilling Mud (vol % solids)	Rainbow Trout	Coho Salmon	Worm	Clam	Crab	Amphipod
Kipnik KCl/Polymer (6.6)	24,000	29,000	37,000	42,000	53,000	NT
Polar Bear Seawater/Polymer (4)	(130,000)	130,000	220,000	320,000	530,000	230,000
Pelly KCl-XC/Polymer (4)	(34,000)	23,000	41,000	56,000	78,000	14,000
Niglintgak Weighted Polymer (14)	(16,000)	15,000	23,000	10,000	62,000	34,000
Pelly Gel Chemical/XC (6)	(42,000)	39,000	>560,000	>560,000	>560,000	80,000
Pelly Weighted Gel XC/Polymer (22)	(18,000)	190,000	320,000	>560,000	560,000	420,000
Imnak Gel XC/Polymer (11)	(42,000)	24,000	200,000	>560,000	>560,000	>560,000

Rainbow trout Oncorhynchus mykiss; Coho salmon Oncorhynchus kisuch; Clam worm Nereis vexillosa; Soft-shell clam Mya arenaria; Purple beach crab Hemigrapsus nudus; Amphipod Orchestia traskiana.

Houghton et al. (1980a) performed similar bioassay studies with high-density ferrochrome lignosulfonate drilling muds that had been used to drill a stratigraphic test (COST) well in central Lower Cook Inlet, Alaska, in 1977. The drilling muds contained 200,000 to 250,000 ppm barite, 85,600 to 92,700 ppm bentonite, 3200 to 5700 ppm ferrochrome lignosulfonate, and 13 to 16% solids, indicating that they were much more heavily treated than the Beaufort Sea drilling muds. Seven species of marine fish and invertebrates from Cook Inlet were exposed to seawater suspensions (roughly similar to the SPP) of the whole used drilling muds.

The ferrochrome lignosulfonate drilling mud suspensions were not toxic to any of the animals (Table 7-16). The 48- and 96-h LC_{50}s ranged from 3000 ppm for pink salmon fry to >200,000 ppm for amphipods and staghorn sculpins. Thus, these heavily-treated lignosulfonate WBM are ranked as non-toxic to all the Cook Inlet marine animals in the GESAMP ranking system (Table 7-3). The total suspended solids concentrations at the lowest LC_{50} value for the different species ranged from >500 ppm for mysids to 30,000 ppm for sculpins. The suspended solids concentration in the pink salmon fry bioassays was about 1100 ppm. Pink salmon fry and shrimp exposed to the highest concentrations of suspended drilling mud had severe histopathological lesions in the gills. The authors attributed the effects of the drilling mud suspensions on Cook Inlet marine animals to physical damage to respiratory surfaces from the high suspended particulate concentrations.

Table 7-15 lists the acute toxicity (96-hr LC_{50}) of drilling mud-in-seawater suspensions (resembling a SPP/LSP mixture) of several WBM and the supernatant (similar to the MAF) of one WBM used in 1979 for drilling the Reindeer Island stratigraphic test (COST) well in the Beaufort Sea offshore Prudhoe Bay, AK. The used WBM contained 9 to 12% water. Data summarized from Tornburg et al. (1980) and NTS (1981).

TABLE 7-15
Acute Toxicity of Drilling Mud used to drill Reindeer Island COST Well, Alaskan Beaufort Sea

Species	No. Tests	Drilling Mud	96-hr LC50
Amphipod Onisimus sp. Boeckosimus sp.	12	XC/Polymer	221,000 - 381,000
Isopod Sadura entomon	3	XC/Polymer	314,000 - 50,000
	2	CMC/Resinex/Tannathin/Gel	530,000 - >600,000
Polychaete Worm Melaenis lobeni	2	CMC/Resinex/Tannathin/Gel	>600,000 - >700,000
Snails Natica clausa Neptunea sp. Buccinum sp.	2	CMC/Resinex/Tannathin/Gel	>600,000 - >700,000
Mysid Mysis sp.	2	CMC/Gel/Resinex	<60,000 - >70,000
	3	CMC/Gel	>40,000 - 215,000
	4	XC/Polymer	50,000 - 400,000
	1	Supernate from XC/Polymer	>250,000
Fourhorn Sculpin Myxocephalus quadrcornis	2	CMC/Gel/Resinex	40,000 - 70,000
	5	CX/Polymer	50,000 - 215,000
	1	Supernate from CX/Polymer	>250,000
	2	CMC/Gel	32,000 - >120,000
	1	Lignosulfonate	350,000
Broad Whitefish Juvenile Coregonus nasus	2	XC/Polymer	64,000 - 100,000
	1	Supernate from XC/Polymer	100,000 - 170,000
Bros Whitefish 1-year Coregonus nasus	3	XC/Polymer	>77,000 - 370,000
	1	Supernate from XC/Polymer	>250,000
	1	CMC/Gel	>200,000
	1	Lignosulfonate	>100,000
Arctic Cisco Coregonus autumnalis	1	XC/Polymer	Inconclusive
	1	Lignosulfonate	400,000
Arctic Cod Boerogadus saida	1	XC/Polymer	>250,000
	1	Lignosulfonate	>100,000
Saffron Cod Eleginus navaga	1	CMC/Gel	170,000 - 300,000

Table 7-16 lists the acute toxicity of seawater suspensions (similar to the SPP) of high-density ferrochrome lignosulfonate drilling muds used to drill a stratigraphic test (COST) well in Lower Cook Inlet, Alaska, in 1977. Concentrations are µL/L (volumetric ppm) drilling mud added. From Houghton et al. (1980a).

TABLE 7-16
Acute Toxicity of High-Density Ferrochrome Ligno-sulfonate Mud, Strat Test in Lower Cook Inlet, Alaska

Species	Number of tests	48-hr or 96-hr LC50
Coonstripe Shrimp Pandalus hypsinotus	7	32,000 - 150,000
Amphipod Eogammarus confervicolus	4	<10,000 - >200,000
Mysid Neomysis kadiakensisa	5	74,000 - <150,000
Isopod Gnorimosphaeroma oreganensis	1	>70,000
Mussel Modiolus modiolus	1	>30,000
Pink Salmon fry Onchorhynchus gorbuscha	3	3000 - 29,000
Staghorn Sculpin Leptocottus armatus	1	>100,000 - <200,000

[a] Reported as Neomysis integer, but probably N. kadiakensis.

Carls and Rice (1984) investigated the toxicity and sublethal effects of several WBM from Alaska to larvae of six species of marine crustaceans. The drilling muds were new or used muds from Prudhoe Bay and from lower Cook Inlet. All but the Prudhoe Bay muds contained ferrrochrome lignisulfonate. Two drilling mud fractions were tested. Known volumes of drilling mud were mixed vigorously with seawater and the larvae were exposed to the dispersion as it settled. The supernatant (aqueous phase), prepared by centrifugation of the suspension also was tested. Stage I larvae less than three days old were used for all tests. Tests consisted of exposure for four days (96 hours) followed by observation of survival and behavior for an additional two days. The behavioral response was cessation of swimming.

The suspended fraction of used Cook Inlet WBM exhibited lower LC_{50}s and EC_{50}s than the aqueous fraction to larvae of five of the six species of Alaskan marine crustaceans (Table 7-17). Kelp shrimp were more sensitive to the aqueous than the suspended fraction of the mud. However, EC_{50}s of the suspended fraction were lower than those for the aqueous fraction for all six species. The suspended and aqueous fractions of the used ferrochrome lignosulfonate WBM from Cook Inlet are non-toxic to larval crustaceans according to the GESAMP ranking scheme, with one exception. The LC_{50} and EC_{50} concentrations of the suspended fraction to dock shrimp are 600 and 500 ppm, respectively, ranking this mud as practically non-toxic to dock shrimp.

The aqueous fractions of the six WBM were not toxic to larvae of king crab or coonstripe shrimp (Table 7-18). Coonstripe shrimp were slightly more sensitive than king crabs to the aqueous fraction. The lowest LC_{50} and EC_{50} were for coonstripe shrimp exposed to used Cook Inlet WBM. Lowest LC_{50} and EC_{50} for king crab larvae were for new Prudhoe Bay WBM. Carls and Rice (1984) concluded that 88% of the toxicity of used Cook Inlet WBM was caused by suspended solids. Variation in the toxicity of the aqueous phases of the different WBM may have been caused in part by differences in pH.

Table 7-17 lists the median lethal concentrations (144-hr LC_{50}) and median effects concentration (144-hr EC_{50}: immobilization) of the suspended solids fraction (resembling a SPP/LSP mixture) and aqueous fraction (resembling a MAF) of a used Cook Inlet, Alaska, ferrochrome lignosulfonate drilling mud to larvae of six species of marine crustaceans from southcentral Alaska. Concentrations are µL/L (ppm) mud added. From Carls and Rice (1984).

TABLE 7-17
Median Lethal and Median Effects Concentrations of Ferro-chrome Lignosulfonate Mud, Cook Inlet, Alaska

Species	Suspended Fraction		Aqueous Fraction	
	144-hr LC50	144-hr EC50	144-hr LC50	144-hr EC50
King Crab Paralithodes camtchatica	4900	4300	119,000	43,100
Tanner Crab Chionectes bairdi	27,400	<5000	46,900	14,600
Dungeness Crab Cancer magister	7300	2500	54,700	7600
Coonstripe Shrimp Pandalus hypsinotus	2800	<4000	16,300	8800
Kelp Shrimp Eualus suckleyi	11,900	500	5800	2300
Dock Shrimp Pandalus danae	600	500	5800	2300

Table 7-18 lists the median lethal concentrations (144-hr LC_{50}) and median effects concentration (144-hr EC_{50}: immobilization) of the aqueous fraction (resembling a MAF) of six new and used WBM from Cook Inlet, Alaska, to larvae of king crabs and coonstripe shrimp from southcentral Alaska. Concentrations are µL/L (ppm) mud added. From Carls and Rice (1984).

TABLE 7-18
Median Lethal and Median Effects Concentrations of 6 New and Used WBMs, Prudhoe Bay, Cook Inlet and Homer

Drilling Mud	King Crab Paralithodes camtchatica		Coonstripe Shrimp Pandalus hypsinotus	
	96-hr LC50	96-hr EC50	96-hr LC50	96-hr EC50
Prudhoe Bay (new)	80,400	23,900	42,300	30,200
Prudhoe Bay (used)	NT	NT	251,000	266,600
Cook Inlet (used)	119,000	43,100	16,300	8800
Homer (new)	824,000	222,300	159,200	84,300
Homer (used spud)	510,100	217,800	220,800	138,000
Homer (used)	708,400	331,400	383,600	359,000

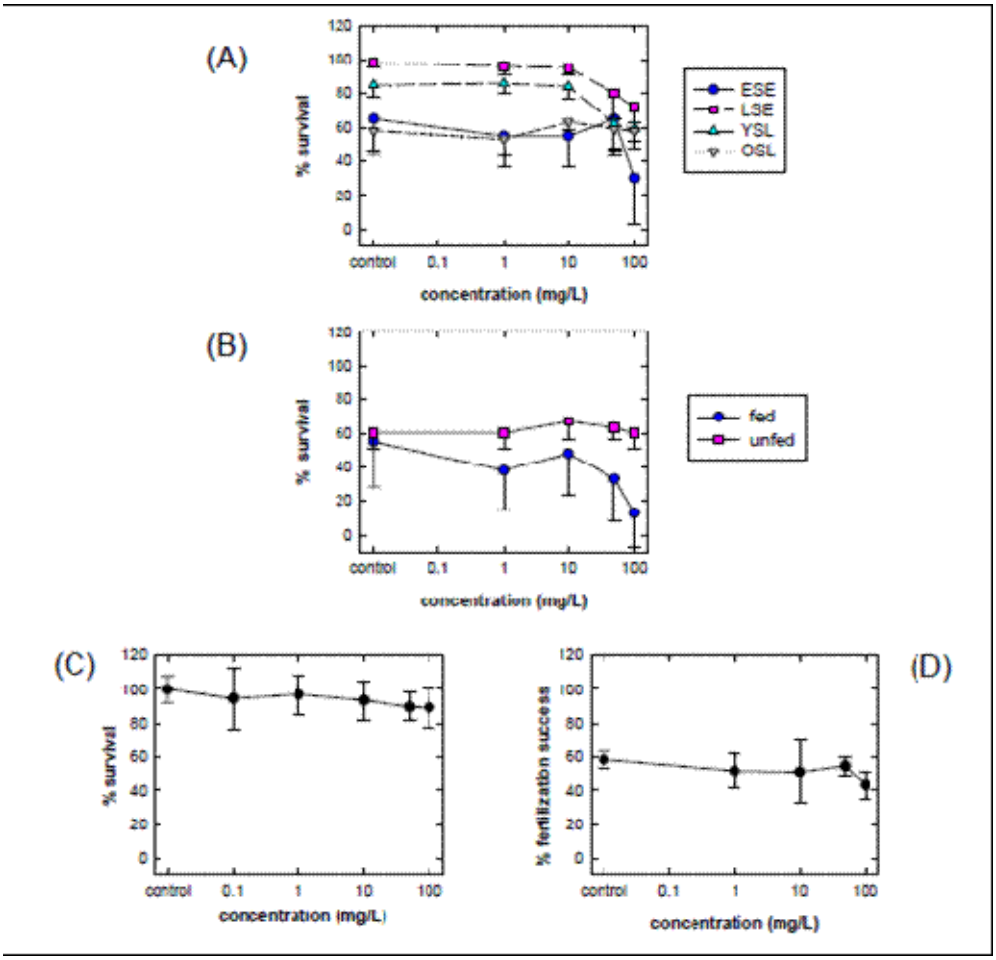
NT Not tested.

Cranford et al. (1998) exposed early life stages of sea scallops *Placopecten magellanicus*, lobsters *Homarus americanus*, and haddock *Melanogrammus aeglefinus* to suspensions of an unidentified used WBM from the Hibernia platform on the Grand Banks off Newfoundland, Canada, for 96 hours. Both WBM and SBM were used and discharged from the Hibernia platform in 1997/1998; the discharges contained an average of 166,000 ppm of total petroleum hydrocarbons (Hurley and Ellis, 2004). Thus, the type of the drilling mud used in these studies is uncertain, but probably was an SBM. There was a slight reduction in survival of three of the four early life stages of haddock, 104 day embryos (ESE), 8-12 day embryo (LSE), 3-7 day larvae (YSL), and 13-17 day, feeding stage larvae (OSL) during exposure to 100 ppm of the drilling mud suspension (Figure 7-1A). The OSL larvae were not affected.

Fed but not unfed lobster larvae had reduced survival after 96 hours exposure to 100 ppm drilling mud suspension (Figure 7-1B). Cannibalism among the lobster larvae precluded attribution of the mortalities to drilling mud exposure.

Figure 7-1 shows the percent survival of haddock (A), lobster (B) and scallop (C) early-life stages during acute exposure (96-h) to suspensions of drilling mud from the Hibernia platform and the percent fertilization success of sea scallop eggs during acute exposure (48-h) of gametes to drilling mud suspensions (D). Four early life stages of haddock were tested: 104 day embryos (ESE), 8-12 day embryo (LSE), 3-7 day larvae (YSL), and 13-17 day, feeding stage larvae (OSL). Error bars are -2 SE for (A) and (B) and ±2 SE for (C) and (D). From Cranford et al. (1998).

Figure 7-1 Percent Survival of Haddock, Lobster and Scallop to Drilling Muds from Hibernia Platform, Canada



There was no effect of exposure on survival of 5- to 7-day veligers of sea scallops (Figure 7-1C) or fertilization success of scallop eggs (Figure 7-1D) at any concentration of the drilling mud suspension. There also was no effect of drilling mud exposure on growth of the larvae. Cranford et al. (1999) subsequently showed that, although low concentrations of suspended WBM, barite, and bentonite clay were not acutely toxic to adult sea scallops, chronic exposure did affect nutrition and growth. The investigators attributed the minimal response of these sensitive early life stages of these cold water marine animals, as well as adults of the filter-feeding scallops, to physical disturbance from the suspended particles.

The results of all these studies of effects of WBM on cold water marine animals are consistent with the conclusion that WBM have little or no chemical toxicity to cold water marine animals and that any effects observed are due primarily to physical effects of abrasion or clogging of gills with suspended solids or burial in fine-grained drilling mud solids. The same conclusion applies to temperate and tropical marine animals. Soegianto et al. (2008) reported that the acute toxicity of the SPP of several used WBM from Indonesia to postlarvae of the tiger prawn *Penaeus monodon* ranged from 30,740 to 78,271 ppm, slightly lower than the toxicity to Arctic crustacean larvae. The SPPs caused gill erosion, probably accounting for much of the toxic effect.

From the beginning of oil and gas development in the North Sea, OBM and later SBM had been used routinely to drill deeper sections of most exploratory and development wells and the oily cuttings usually were discharged to the sea. These cuttings piles were contaminated with petroleum hydrocarbons and supported only depauperate benthic communities (Davies et al., 1983, 1989; Hartley et al., 2003). Effects on benthic communities were much less severe where WBM were used and mud and cuttings were discharged. ERT (2002) performed a toxicity study to indentify characteristics of OBM and SBM cuttings that made them more harmful than WBM and cuttings to the benthos. They collected WBM cuttings samples from two platforms in about 300 ft of water in the Norwegian sector of the central North Sea. They performed bioassays with phytoplankton and benthic amphipods according to standard OSPAR protocols.

Phytoplankton *Skeletonema costatum* were exposed for 72 hours to water extracts of the cuttings, prepared by equilibrating weighed quantities of cuttings with sterile seawater. There was no effect on phytoplankton growth of extract concentrations ranging from 1000 to 10,000 mg cuttings/L seawater. In fact there was some growth stimulation at the highest concentration, indicating that primary nutrients probably were released from the cuttings. Thus, the two Norwegian WBM samples were completely non-toxic to the phytoplankton.

7.3.3 Chronic and Sublethal Effects of WBM

Acute toxicity studies are extremely useful for identifying potentially toxic additives in drilling muds and as a tool for environmental management of the formulation and ocean disposal of drilling muds and cuttings. However, studies of chronic and/or sublethal effects, if performed with environmentally realistic exposure scenarios and concentrations, are better predictors than acute lethal bioassays of the potential effects on the marine environment of drilling mud and cuttings discharges. They also provide insights into the causes of biological effects of drilling discharges.

By the mid-1980s, marine chronic and/or sublethal effects studies with WBM had been performed with more than 40 species of marine animals, including corals, mollusks, crustaceans, polychaete worms, echinoderms, and fish. Many of the studies were with cold-water species from the northeastern United States. Most of these studies were performed with chrome and ferrochrome lignosulfonate WBM, because these were the WBM used most frequently in the Gulf of Mexico, and acute toxicity studies had indicated that lignosulfonate muds containing high concentrations of chromium were the most toxic WBM (NRC, 1983; Neff, 1987a). The U.S. EPA sponsored a comprehensive research program on the composition and toxicity of used WBM in 1977 through 1984 and supplied drilling muds from Mobile Bay, AL, and the on-land Jay field in Florida to several investigators for testing. Several of these drilling muds, including the most toxic ones, contained high concentrations of diesel fuel and chromium (SAIC, 1984) and aren't representative of the WBM discharged today to Federal waters of the U.S.

The responses to sublethal concentrations of whole drilling muds on or in sediments, SPP, and MAF included (Neff, 1987a):

- Altered burrowing behavior and chemosensory responses in lobsters;
- Alterations in patterns of embryological or larval development in lobsters, crabs, sand dollars, starfish, and fish;

- Depressed feeding in larval lobsters, larval crabs, and juvenile hake
- Decreased food assimilation and growth efficiency in mysids;
- Depressed growth and skeletal deposition in corals, starfish embryos, scallops, oysters, and mussels;
- Altered respiration and nitrogen excretion rates in corals, mussels, and lobsters;
- Changes in tissue enzyme activity in crustaceans;
- Histopathology in shrimp and salmon fry;
- Biochemical changes in oysters and scallops; and
- Avoidance behavior in scallops, shrimp, and fish.

Exposure conditions did not closely simulate those the test animal or community might encounter in their natural habitat in most of these chronic and sublethal effects studies. Frequently, exposure concentrations were much higher or the duration of exposure (particularly to unfractionated WBM in the water column or in sediments) was much longer than would occur in the field. In some cases, benthic animals were exposed to whole unfractionated drilling mud layered on or mixed with natural, uncontaminated sediment. As discussed in Section 5.4, considerable fractionation occurs as the drilling mud and cuttings plume descends through the water column unless the drilling wastes are shunted directly to the sea floor. Soluble fractions and unflocculated clay particles usually are transported long distances and diluted to very low concentrations before deposition. Several of the dispersion studies discussed in Section 5-4 have shown that drilling fluids are diluted to very low concentrations in the water column within a short time and distance after discharge. Because discharges are intermittent during drilling, water column animals are at risk of exposure to the rapidly-diluting drilling discharge for short periods of time. Carls and Rice (1984) showed that behavioral responses (depressed swimming activity) of early life stages of Alaskan crustaceans were delayed for 4 to 24 hours after the initiation of exposure to suspensions of Alaskan WBM and mortality was delayed for 48 to 72 hours. Plankton larvae in the field would not be exposed long enough to the drilling mud plume to experience lethal or sublethal effect. Carls and Rice concluded that the responses of the crustacean larvae to WBM were due to physical disturbance from the suspended solids in the mud suspension.

Cranford (2006) summarized several studies of the sublethal effects of WBM, bentonite clay, and barite clay on different life stages of sea scallops *Placopecten magellanicus* from the east coast of Canada. There were no effects of exposure to low concentrations of suspended WBM on hatching of eggs or survival of larvae (Cranford et al., 1998). Low concentrations of suspended WBM, barite, and bentonite were not lethal to adult scallops but did depress metabolism and growth (Cranford et al., 1999). Suspensions of an OBM and three types of SBM, similar to those used at Hibernia, caused greater metabolic and growth depression than the WBM suspension did. Cranford (2006) concluded that growth reductions observed during exposure to all waste types resulted primarily from reduced energy intake through feeding (lower clearance rate) and digestion (lower absorption efficiency). The duration of exposures to suspended WBM solids in these laboratory studies is longer than would occur near an offshore exploratory rig. Sea scallops are adapted to sandy benthic habitats, such as Georges Bank, where suspended sediment concentrations usually are low. In the presence of high suspended silt/clay concentrations, the gills and gut clog with inorganic particles (Cranford, 1995). If exposure was brief, as expected in the field, effects would be minor and rapidly reversible.

Barlow and Kingston (2001) confirmed the observations of Cranford et al (1999) by showing that exposure of the suspension-feeding bivalve *Cerastodera edule* and the deposit-feeding bivalve *Macoma balthica* from the North Sea to low concentrations of suspended barite caused lesions in the gills and gut, probably from abrasion.

Cranford et al. (2003) modeled the potential risk to sea scallop stocks on northeastern Georges Bank during planned exploratory drilling by Canada. Northern Georges Bank supports the largest offshore scallop fishery in the world. The model predicted a potential for 0 to 48 days of growth inhibition during 92 days of exploratory drilling. The wide variation in the predictions was caused by uncertainty about oceanographic conditions and settling velocity and concentration in the benthic boundary layer of drilling solids. Cranford et al. (2003) concluded that this low level of growth inhibition from a single exploratory well would not be significant for the Georges Bank scallop population.

Olla et al. (1982) performed three experiments in which great care was taken to simulate as closely as possible the fractionation that takes place as WBM are dispersed in the water column. They studied the effects of the settleable fraction of a mid-weight chrome lignosulfonate WBM containing 115,000 ppm barium and 380 ppm chromium on the behavior of a model demersal/benthic community of the continental shelf of the northeastern U.S., consisting of sand shrimp *Crangon septemspinosa*, sea scallops *Placopecten magellanicus*, and red hake *Urophysus chuss.* Olla et al. (1982) prepared the settleable fraction by allowing the WBM to settle through a 20-ft vertical column of seawater for one hour. The lower 9 ft of water was collected and passed through the column an additional two times, simulating settling through 59 ft of water. The resulting settleable fraction, containing 10 to 15% WBM solids, was added to the surface of the seawater in large aquaria containing the three species of marine animals and allowed to settle and accumulate on the clean sediment in the aquaria.

The shrimp, scallops, and fish did not respond behaviorally to the presence of the WBM solids on or mixed into the sediments. However, introduction of the settleable solids did elicit immediate and strong, but short-lived reactions. There was increased swimming activity in the scallops and shrimp. The shrimp and fish attempted to avoid the plume of settling solids and then congregated near the water surface. The increased activity persisted for about two to three hours after introduction of the WBM. Normal behavior resumed after the WBM solids settled to the bottom and the water cleared. During the remaining 12 days of the experiment, the fish consumed fewer shrimp, but did not grow more slowly than fish in control aquaria. The scallops and shrimp did not respond to the settled WBM solids. In these more environmentally realistic experiments, demersal/benthic animals responded minimally to the suspended solids from WBM in the water column and did not respond to the WBM solids on the sediments.

Raimondi et al. (1997) performed laboratory studies of the effects of drilling mud discharges from an active production platform off southern California on early life stages of red abalone *Haliotis rufescens* and adult brown cup corals *Paracyanthus stearnsii*. They used results from discharge monitoring studies at the platform (Coats, 1994) to predict environmentally realistic exposure concentrations and durations for abalone larvae in the water column. They predicted that the planktonic larvae would drift through the area of the drilling mud plume for a maximum of about 50 hours and the maximum concentration of suspended solids in the plume would be 10 mg/L of which about 2% (0.2 mg/L) would be drilling mud solids. They also predicted that when

the larvae settle onto a solid substrate, they would be exposed to a drilling mud flux of 200 to 500 mg/m^2/day. Exposure concentrations were set at 0.002 to 200 mg/L, with the highest concentration only possible directly below the discharge.

Fertilization and larval development of red abalone were not affected by exposure to any concentrations of drilling muds. Larvae that were exposed to suspended drilling mud during the precompetent stage (too young to settle naturally), had normal survival to the competent stage and settled normally. Competent larvae (larvae sufficiently developed that they could settle if a suitable substrate or chemical inducer was present) that were exposed to suspended drilling mud also showed normal survival, settlement, and viability. There were significant effects of drilling muds on settlement in three of four exposure regimes. The proportion of surviving larvae that settled successfully increased following exposure to drilling mud for 28 and 52 hours at 9°C. There was a dose-related decrease in successful settlement of larvae exposed to drilling muds for 28 hours at 15°C. Drilling mud exposure did not affect survival of competent larvae. Thus, drilling fluids at realistic exposure concentrations had variable effects on the viability (survival x settlement) of abalone larvae, improving it at low temperature and decreasing it at a higher temperature.

Coralline crusts can chemically induce settlement of abalone larvae. However, if the crusts were first exposed to whole drilling mud suspensions for 28 hours at 9°C, there was a concentration-dependent decrease in larval settlement when larvae were exposed to the mud-contaminated crusts in the presence of suspended drilling muds. Larvae that were first exposed to drilling mud suspensions and then exposed to clean crusts settled normally, indicating that inhibition of settlement was caused by chemical masking or alteration of the substrate and not by a direct response of the larvae to the drilling mud. The environmental significance of this response is unclear. Larval abalone may not be able to settle on hard substrates near platforms where drilling mud solids are settling; however, the larvae would remain competent and be carried by local water currents out of the area of influence of drilling mud discharges where they could settle normally. This type of response is highly species specific and would not be expected in other species of marine planktonic larvae. In addition, the durations of exposure required to cause these effects are greater than would be likely in the water column or benthos near a production platform and the settling substrate would not be exposed to whole drilling mud.

Many corals are sensitive to suspended solids (Dodge, 1982). Raimondi et al. (1997) found that a solitary cup coral responded to exposure to suspended whole drilling mud by decreased survival, increased tissue loss, and overall decreased viability. These effects were elicited following more than two days exposure to 0.02 mg/L to 200 mg/L suspended drilling mud solids, longer than the exposure expected in the marine environment near an exploratory or development drilling operation. Exposure to the lowest concentration reduced viability of the corals by about 40 percent. These effects probably were caused by physical disturbance from the drilling mud solids, and not toxicity of any drilling mud ingredient.

7.3.4 Causes of WBM Toxicity

As expected from the very low toxicity of most individual drilling mud additives (Table 7-4), whole used WBM are non-toxic or practically non-toxic to temperate and cold water species of marine plants and animals (Tables 7-13 through 7-18). Of the major drilling mud ingredients frequently used in the past, only chrome- or ferrochrome-lignosulfonate may be moderately toxic to marine animals (Neff, 1987a; Parrish et al., 1989). The other metals in WBM are associated, almost exclusively, with barite and bentonite and do not contribute to drilling mud toxicity, because of their low bioavailability (Grant and Briggs, 2002; Schaanning et al., 2002; Neff, 2008), as discussed above.

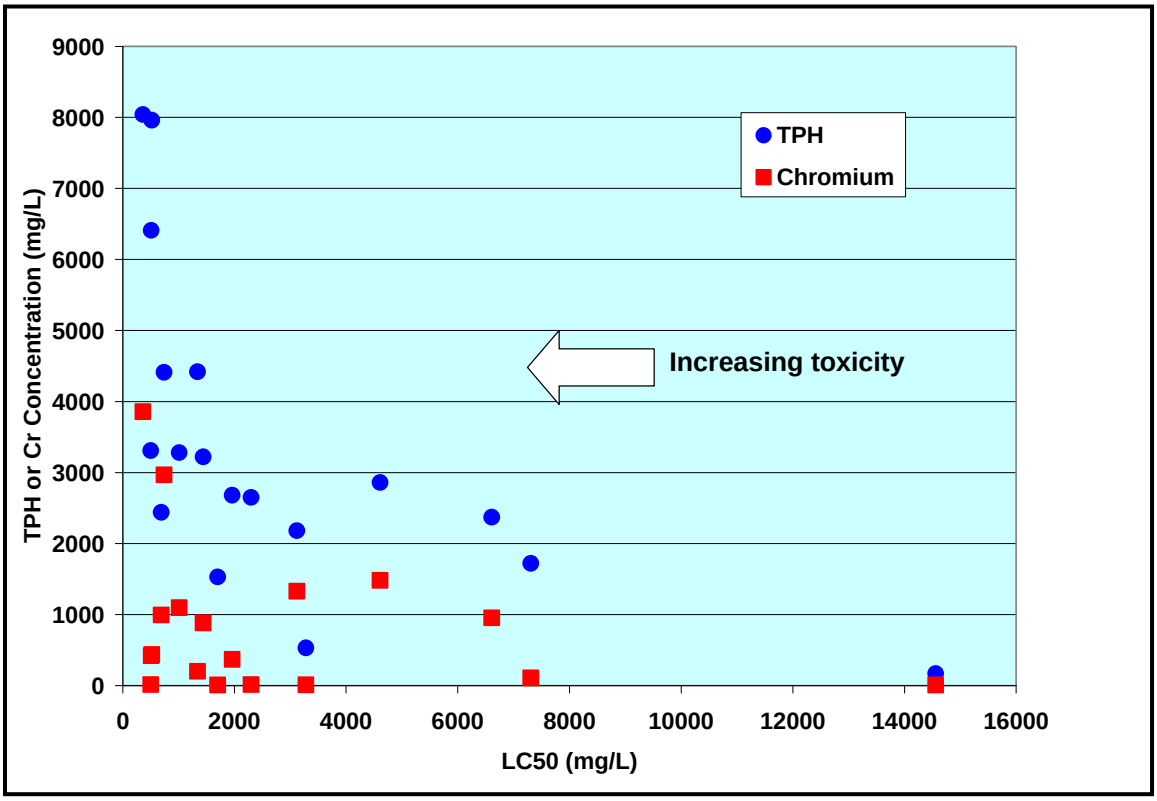
The most toxic minor (based on volumes discharged) additives sometimes used in WBM include diesel fuel, biocides, corrosion inhibitors, detergents, defoamers, and emulsion breakers (Table 7-4). Diesel and mineral oils have been banned from offshore drilling muds in the U.S., Canada, and the OSPAR countries. All the other toxic additives have been largely replaced by less toxic forms for modern WBM, or their use is restricted to emergency situations. The effectiveness of this strategy is attested to by the fact that nearly all WBM used offshore in the U.S meet the very conservative toxicity limitation in the current effluent limitation guidelines (ELG).

Conklin et al. (1983) showed that the toxicity of a WBM could be attributed primarily to chrome only if the chromate plus chrome lignosulfonate concentrations in the mud were very high. Several minor additives, such as zinc-based H_2S scavengers, tributyl phosphate surfactant defoamer, and fatty acid high temperature lubricant are toxic, but usually were not present in used drilling fluids at concentrations high enough to contribute significantly to whole mud toxicity. As discussed above, all these slightly toxic additives have been replaced in modern drilling muds by non-toxic alternative additives.

Diesel fuel or a mineral oil often was added to WBM to improve lubrication or to free stuck pipe in the well (Ayers et al., 1989). The acute toxicity of WBM containing petroleum additives increases as hydrocarbon concentration increases. Conklin et al. (1983) observed a statistically significant inverse relationship between the toxicity to estuarine shrimp of 18 samples of WBM from a coastal drill site in Alabama and the concentrations in the WBM of diesel fuel (the drilling fluids contained between 170 and 8,040 ppm total petroleum hydrocarbons) (Figure 7-2).

Figure 7-2. Relationship between the toxicity to grass shrimp *Palaemonetes pugio* of WBM collected at 18 depths in a Mobil Bay, AL, well and concentrations of chromium and total petroleum hydrocarbons (TPH) in the muds. Based on data from Conklin et al. (1983).

Figure 7-2 TPH or Chromium Concentration in WBM to Toxicity on Grass Shrimp, Mobile Bay, Alabama



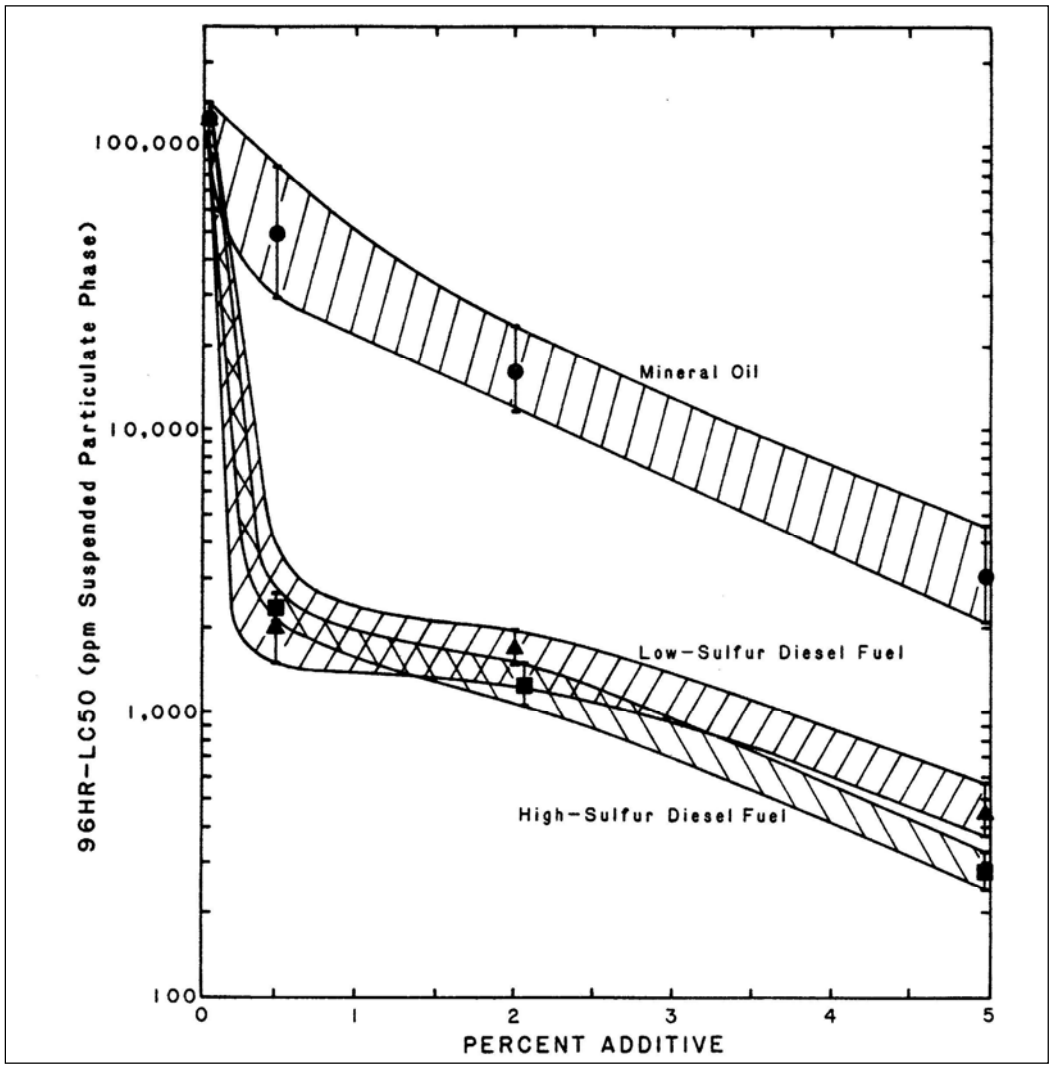
Breteler et al. (1988) showed that petroleum additives to generic WBM No. 8 (Table 4-2) increased its toxicity to water column and benthic marine animals (Figure 7-3). The LC_{50} of the SPP of the generic drilling mud to mysids was 127,000 ppm mud added. Drilling fluids containing a high-sulfur diesel fuel (25 % total aromatic hydrocarbons) were the most toxic, followed closely by drilling fluids containing a low-sulfur diesel

(8.7 % total aromatics). WBM containing 5% low-aromatic mineral oil additive had a toxicity slightly higher than the ELG value (3090 ppm versus 3300 ppm). The solid phase LSP fraction of the WBM containing 5% low-sulfur or high-sulfur diesel was toxic to soft shell clams *Mya arenaria* and grass shrimp *Palaemonetes pugio*. The LSP of the WBM containing 5% high-sulfur diesel also was toxic to the sandworm *Neires virens*. These LSP had high biological oxygen demands, so oxygen depletion of the sediments could have contributed to the toxicity of these muds.

Thus, petroleum, particularly the aromatic fraction, contributes most to the toxicity of WBM containing it. The current NPDES permits for all OCS regions in the U.S, including the Beaufort and Chukchi Seas, prohibit ocean discharge of WBM containing diesel fuel, free oil, or chromate. WBM that meet these requirements are not toxic to marine organisms or ecosystems.

Figure 7-3 shows the effect of addition of low aromatic mineral oil, low-sulfur diesel fuel, or high-sulfur diesel fuel to generic WBM no 8, a freshwater lignosulfonate drilling mud, on the toxicity of the SPP fraction to mysids *Americamysis bahia*. From Breteler et al. (1988).

Figure 7-3 Toxicity Effects to Mysids of Additions of Mineral Oil, Low-Sulfur and High-Sulfur Diesel Fuels to WBM No. 8



The effects of WBM and cuttings on benthic marine organisms probably are caused by, burial, physical disturbance of gill and gut epithelia by the particulate fraction of the mud and cuttings or, indirectly by enrichment of surface layers of the sediment with biodegradable organic matter. Natural microbial communities in sediments digest the organic matter as a source of nutrition, consuming oxygen in the sediments, leading to depletion of sediment oxygen and production of toxic ammonia and sulfide. Changes in sediment texture and depletion of sediment oxygen results in loss of some species of sensitive marine animals and replacement with more tolerant species (Neff, 2005). If disturbance to benthic ecosystems near WBM and cuttings discharges is caused by physical alteration of the local benthic environment and not by toxicity of components of the discharge, area-wide environmental degradation is highly unlikely. The physical disturbances are similar to natural disturbances that most benthic ecosystems, particularly those in the Arctic, experience periodically. Recovery is rapid and there are no toxic chemicals that could be exported from the disturbed area into the wider marine ecosystem and food webs.

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8.0 ECOLOGICAL EFFECTS OF WBM AND CUTTINGS DISCHARGES TO THE OCEAN

Several microcosm, mesocosm, and field studies have been performed over the last three decades in temperate and cold-water marine environments to document the ecological impacts of WBM and cuttings discharges to the ocean. These studies provide valuable information about the causes of disturbance from drilling discharges and the rate of ecosystem recovery.

8.1 Mesocosm Studies

Laboratory or field microcosms and mesocosms are a valuable first step in extrapolating effects of single chemicals or complex mixtures to small groups of a single species in laboratory bioassays to effects on marine benthic or water column communities in the natural environment.

The U.S. EPA sponsored several microcosm studies of the effects of WBM suspensions in the water column or as layers on or mixtures in natural sediments in mesocosm tanks on recruitment of larvae from the plankton to the sediments. Natural unfiltered seawater was pumped through the tanks and recruitment was monitored at several concentrations of WBM in the water column or in sediments. An alternative approach also was evaluated. Trays containing clean or WBM-contaminated sediments were placed on the sea floor and recruitment was monitored for several months. The two methods were compared for assessing potential impacts of WBM on benthic recruitment (Flint et al., 1982; Tagatz and Deans, 1983). There were several significant differences in the characteristics of the communities that developed in the laboratory, in field trays, and in undisturbed natural marine sediments. Flint et al. (1982) concluded that the field sediment trays were superior to laboratory mesocosms for simulating effects of disturbance on benthic communities, whereas Tagatz and Deans (1983) concluded that the laboratory microcosms were easier to manage and were sufficiently similar to the field to allow application of the results to predict effects in the field.

Several experiments with WBM revealed that relatively high concentrations of whole, unfractionated drilling mud layered on or mixed with sandy sediments were required to significantly affect recruitment of benthic invertebrates (Rubinstein et al., 1980, Tagatz et al., 1978, 1980, 1982). Recruitment of some species was depressed severely at all concentrations of applied drilling muds. Other species occurred preferentially in sediments containing drilling muds. These included several species of bacteria and microeucaryotes (ciliates, nematodes, etc.) (Smith et al., 1982), as well as opportunistic species, such as capitellid worms. These effects probably were caused by changes in sediment texture from the added drilling mud or to oxygen depletion from microbial degradation of organic matter in the drilling mud. The increase in the abundance of bacteria and microeucaryotes in the sediments supports the latter hypothesis.

When marine aquaria were supplied with unfiltered natural seawater containing 50 ppm used chrome lignosulfonate drilling mud for eight weeks, numbers of tunicates, mollusks, and polychaetes settling in the sandy substrate or on the walls of the aquaria were significantly lower than the numbers settling in the control aquaria (Tagatz et al., 1982). Several differences in community parameters were detected. These differences could have been caused by physical and/or chemical interference of suspended drilling mud solids with survival or settlement of

planktonic larvae or to accumulation of drilling muds in the sediments over time, which was noted but not quantified, altering sediment texture.

Dow et al. (1990) evaluated the hypothesis that biodegradation of organic matter in drilling mud and cuttings piles on the sea floor contributes to or causes most of the effects on benthic communities. They layered WBM or OBM cuttings on natural sediments in mesocosms. There was only a slight and short-term reduction in the depth of oxygen penetration (the redox potential discontinuity, RPD depth) in sediments containing WBM cuttings, whereas the RPD depth rose to near the sediment surface in sediments containing OBM cuttings and had not returned to normal in one year. Aerobic microbes in surface layers of the sediment biodegraded the organic matter in the cuttings depleting the sediment oxygen. The low concentration of biodegradable organic matter in the WBM cuttings did not support vigorous growth of microbes and there was only a slight decrease in oxygen concentrations in the sediments. The OBM cuttings contained abundant biodegradable organic matter, primarily hydrocarbons, stimulating growth of hydrocarbon-degrading aerobic microbes, leading to oxygen depletion. Anoxic conditions in the OBM cuttings accumulation stimulated anaerobic sulphate-reducing bacteria to produce hydrogen sulphide.

Aerobic and sulphate reducing (anaerobic) bacteria in a WBM cuttings accumulation can use carbohydrates (starch, CMC) and glycols (widely used in North Sea WBM) from WBM solids as an organic carbon source. Most of the organic chemicals in WBM are biodegradable under aerobic conditions (Table 8-1). Organic enrichment and resulting effects on benthic communities of WBM cuttings piles, particularly modern WBM cuttings piles that do not contain high concentrations of petroleum or lignosulfonates, will be much less severe and persistent than in OBM or SBM cuttings piles, because the concentration of biodegradable organic matter is lower.

Table 8-1 lists the rates of microbial biodegradation of several organic components of WBMs used in the Mediterranean Sea. Degradation rates were measured as chemical oxygen demand (COD) and 28-day biological oxygen demand (BOD). From Terzaghi et al. (1998).

TABLE 8-1
Microbial Biodegradation Rates of Organic Components of WBMs used in the Mediteranean Sea

Chemical Product	COD (mg O2/mg OC)	BOD (mg O2/mg OC)	% Degraded in 28 Days
Lignosulphonate	0.92	0.25	27
Modified starch	0.73	0.53	73
Soltex	0.67	0.09	14
XC-polymer	0.83	0.36	43
Mor-Rex	0.99	1.13	>100
Carboxymethylcellulose	0.75	0.50	50
PAC	0.75	0.21	21
Detergent	0.24	0.12	83
Defoamer	3.39	1.08	32

Organic chemicals in settled solids from OBM and SBM cuttings contain thousands of mg/kg total organic carbon, mostly petroleum from OBM and olefins and esters from SBM, with a high chemical oxygen demand (COD) and biological oxygen demand (BOD) (Breteler et al. 1988; Hartley et al., 2003; Neff et al., 2005). Marine sediments and cuttings piles contain populations of aerobic and anaerobic bacteria and fungi that are capable of biodegrading most petroleum hydrocarbons and SBM synthetic chemicals (Leahy and Colwell, 1990). Extensive and long-lasting organic enrichment has been observed in SBM cuttings piles (Neff et al., 2005).

Bakke et al (1986a,b) deployed trays containing natural sediments from which all fauna had been removed in an uncontaminated area of the Oslofjord. Different thicknesses of WBM or OBM cuttings were layered on the sediments to test the suitability of the discharged cuttings as substrates for recruitment and establishment of a benthic community. The thicknesses of cuttings examined ranged from 0.5-12 mm, i.e. representative of the edges of cuttings piles. The trays were left in position for a total of 5.3 years. There was a marked difference in the colonization of WBM cuttings and OBM cuttings. Recolonization of WBM cuttings was good; however, there was an inverse relationship between decolonization of OBM cuttings and the thickness of the cuttings layer.

A 10 mm layer of WBM cuttings had no apparent deleterious effect on benthic decolonization. The same fauna recolonized the sediments containing a 10-mm layer of WBM cuttings as the sediments in the reference trays. However, the depth of the RPD was shallower in the sediments containing WBM cuttings than in the reference sediments. The 10-mm layer of diesel OBM cuttings was colonized by only a few species, dominated by small numbers of the opportunist polychaete *Capitella capitata.* The 10-mm layer of mineral oil OBM cuttings was colonized by a slightly more abundant and diverse assemblage of benthic fauna during the first year. However, the benthic community collapsed within two years. After 64 months, both the diesel and mineral OBM cuttings had only minimal macrofaunal colonization. Similar results were obtained with a 0.5-mm layer of OBM. However, there was some decolonization after four years. The sediments underlying the diesel and mineral oil OBM were reducing, indicating high levels of microbial degradation of organic matter and poor oxygen diffusion through the cuttings layer. This organic enrichment effect was minimal in the WBM cuttings sediments but severe in the OBM cuttings sediments, and probably was the major cause of the differences in recruitment of benthic faunal to the different sediment trays.

Olsen et al. (2007) studied the effects of oily sediment and WBM on benthic infaunal communities from the Barents Sea and Oslofjord, Norway. Undisturbed clean sediments were collected from 1025 ft in the Barents Sea (Arctic) and from 700 ft in Oslofjord (temperate) and placed in microcosms containing local seawater. Slurries of Statfjord (North Sea) crude oil and sediment or an uncharacterized WBM (probably a glycol mud) and seawater were added to the microcosms and allowed to settle on the sediments as a thin layer. Sediment oxygen consumption (SOC: the amount of oxygen consumed/m^2 of sediment) in each microcosm was measured periodically for 21 days. SOC is the sum of abiotic oxidation of chemicals in the sediments and respiration of sediment dwelling microbes and animals. SOC was elevated compared to the control treatment in the high-dose oil treatment and the WBM treatment in Barents Sea sediments. SOC was depressed compared to controls in the WBM treatment in the Oslofjord sediments and unaffected in the oil treatments. Species composition of infauna was unaffected by oil or WBM treatment in either sediment. However, there was a significant

decrease in a few species of infauna in the oil and WBM treatments in both the Barents Sea and Oslofjord sediments. High concentrations of PAH were measured in the sediments and water in the oil treatments. PAH were not measured in the WBM treatments, because they were not expected. Thus, it is not possible to determine if the effects observed in the WBM treatments were caused by hydrocarbons. Olsen et al. (2007) concluded that benthic marine animals from the Arctic were more sensitive to oil and WBM than those from a temperate environment. They also concluded that effects of the oil treatment were caused by PAH and effects of the WBM treatment were caused by burial of the infauna by fine-grained drilling mud particles.

Schaanning et al. (2008) continued the study of effects of drilling muds on benthic processes. They evaluated a glycol-ilmenite WBM from the Barents Sea and a linear olefin-barite SBM from the North Sea. Different amounts of WBM cuttings/seawater slurry were layered on clean marine sediments in 78 cm^2 microcosms and oxygen consumption and nutrient fluxes were monitored for 25 days. In a second experiment, 2 to 5 mm layers of WBM cuttings or SBM cuttings were added to clean sediments in larger 0.1 m^2 microcosms and the benthic communities were monitored for 85 days.

SOC was not affected by different thicknesses of clean sediment layered on natural sediment in the control microcosms during the 25-day experiment. However, there was a positive correlation between the thickness of the WBM solids layer (1 to 65 cm) and SOC at day 9. The highest SOC was about 3-fold the control SOC in the microcosm containing a 26-mm layer of WBM solids. All SOC returned to control values in 25 days. The rate of nitrate consumption was positively correlated with SOC. Release of dissolved silicate from the sediments decreased with increasing depth of the WBM or sediment layer. The sediment under the WBM solids layer turned black during the incubation, indicating that it had become anoxic. Sulfate reducing bacteria and fungi in the WBM layer probably oxidized organic matter, probably glycols, in the WBM, releasing sulfide, which diffused downward and precipitated black iron sulfide in the sediment layer.

Cuttings layers were much thinner in the second experiment and there was no difference in SOC between control and WBM cuttings treatments. However, SOC increased after the first two weeks in the SBM treatment. The increase in SOC corresponded with a decrease in the concentration of synthetic chemical in the cuttings, indicating that the chemical was undergoing microbial degradation.

Benthic communities were quite diverse in all sediments at the start of the second experiment. There were no statistically significant differences among treatments in number of species, number of individuals, Shannon-Wiener diversity, or Peilou's evenness after three months. There also were no statistically significant differences in biomass and community structure parameters among field, control, WBM cuttings, and SBM cuttings treatments. However, abundance of three dominant species did decline and the species composition changed in the cuttings treatments in comparison to the control treatments. These changes were not correlated with SOC or thickness of the oxic layer in the sediments. Schaanning et al. (2008) concluded that effects of the cuttings were most likely related to physical properties, such as shape, sharpness, and size of cuttings particles. This conclusion is in agreement with the conclusions of Smit et al. (2008a) who evaluated the effects of different types of physical disturbance associated with WBM cuttings discharges on benthic communities.

Trannum et al. (2009) performed a microcosm study to clarify the contribution of physical disturbance to the effects of WBM cuttings on benthic communities. Clean surface sediments with natural benthic communities were collected from 135 ft in Oslofjord and placed in 0.09 m^2 microcosms with flowing natural seawater. Natural sediments or 1:1 mixtures of natural sediments and glycol-ilmenite WBM cuttings from the Barents Sea were layered on the sediments to depths ranging from 3 to 24 mm. Chemical and biological parameters were measured periodically during the 193-day (6-month) experiment.

There was a significant decrease in number of species, abundance of individuals, Shannon-Wiener diversity, and biomass of marine animals with increasing depth of WBM cuttings on sediments in the microcosms. The natural sediments had no effect on these biological parameters at any thickness on the sediments. Polychaetes, nemertines, and nematodes were the most affected. There also was a significant positive correlation between WBM cuttings thickness and SOC, and a negative correlation for RPD depth. Layers of 12 and 24 mm of natural sediments on the microcosm sediments had no effect on SOC or RPD depth. This indicates that organic matter in the cuttings was being biodegraded by microbes, resulting in gradual depletion of oxygen concentrations in the underlying sediments. There was a significant correlation between the biological parameters and RPD depth in the WBM cuttings microcosms at day 92, but not at the end of the experiment on day 193. Trannum et al. (2009) concluded that biodegradation of an organic phase, probably glycols, in the WBM cuttings resulted in an increase in oxygen consumption in the cuttings layer, leading to depletion of oxygen in the underlying sediments, as indicated by the reduction of the depth of the RPD layer. This was a classic eutrophication or organic enrichment response (Pearson and Mannvik, 1998) that lead to changes in benthic community in the microcosms. Glycols are much more biodegradable and usually present at higher concentrations than the other organic additives to WBM in Table 8-1, explaining the different results of Bakke et al. (1986a,b) and Trannum et al. (2009).

These microcosm studies are consistent in showing the WBM and WBM cuttings have a low chemical toxicity to marine organisms and ecosystems. Where toxicity is identified, it can be attributed to petroleum hydrocarbons or chrome lignosulfonate in the mud. Deposition of WBM cuttings on the sea floor near a drilling waste discharge results in some burial of the resident benthic fauna and slows settling of marine invertebrate larvae from the plankton. Longer-term effects are caused by physical disturbance of the cuttings from changes in sediment texture and mild organic enrichment from microbial degradation of organic matter in the cuttings. There is no evidence of chemical toxicity in WBM cuttings piles that do not contain elevated concentrations of petroleum hydrocarbons, indicating that effects are localized to the cuttings pile itself and recovery will occur rapidly as the labile organic matter is degraded and removed.

These types of disturbance of the benthic ecosystem occur naturally and are common in coastal and continental shelf environments (Sousa, 2000). Most marine benthic communities, particularly in shallow Arctic seas, are well adapted to physical disturbance and recover rapidly when the disturbance abates (Boesch and Rosenberg, 1981; Cusson et al., 2007).

8.2 Field Studies

Laboratory and microcosm studies, such as those described above, are useful source of data to help make preliminary decisions about whether discharges of drilling muds and cuttings to the ocean may cause ecosystem disturbance. They also provide information that may be useful for decisions about how these ocean discharges should be performed to prevent damage to the environment. If the laboratory studies indicate that there is as low risk that discharge of drilling waste in compliance with environmental guidelines will contribute to environmental degradation, field monitoring programs may be recommended or required to verify this conclusion.

Monitoring programs are of two types: compliance monitoring to ensure that discharges are being performed as prescribed in the permit; and surveillance monitoring, to determine if adverse environmental effects occur and, if they do, their magnitude, aerial extent, and possible migitigative measures.

Norway has required monitoring of the marine environment around all offshore oil and gas production facilities since 1973 (Gray et al., 1999; Jensen and Noland, 2006). The UK (CEFAS, 2001) and Netherlands (Daan et al., 1996) had similar monitoring requirements. In the past, operators were required to submit annual reports on the environmental conditions in the areas being explored or developed. This monitoring was used to detect, map, and assess effects of discharges and provided a technical basis for implementing environmental protection measures where effects were found. The discharges of greatest concern were OBM and SBM cuttings. WBM cuttings were considered to have little long-term impact on the North Sea environment. Therefore, the focus of the monitoring was to map the distribution and concentrations of petroleum hydrocarbons and barite in sediments between 100 and about 2000 m from offshore facilities discharging OBM or SBM cuttings (Neff et al., 2000; Jensen and Noland, 2006).

Most of the benthic monitoring studies did not include an assessment of the effects of drill cuttings on benthic communities. For example, all of the 19 field studies performed in offshore oil fields in the Norwegian sector of the North Sea in 1994 included monitoring of physical and chemical characteristics of bottom sediments, but sediment macrofauna were monitored in only eight of the field studies (Bakke et al., 1996). Ecological studies have been performed at several offshore facilities, mostly those where large volumes of OBM and SBM cuttings had been discharged (Davies et al., 1983, 1989; Daan et al., 1996).

Monitoring program designs were different for different facilities and regions of the Norwegian, UK, and Dutch continental shelf, making it difficult to compare impacts among facilities or regions. The Norwegian pollution control authority issued monitoring guidelines in 1990 for the Norwegian continental shelf (SFT, 1990). After OSPAR (2003a) banned discharge of OBM cuttings in 1996, the focus of environmental management shifted gradually from monitoring benthic impacts of OBM and SBM cuttings to monitoring impacts of water column discharges of petroleum hydrocarbons and other chemicals in produced water (Bakke and Nilssen, 2005). Norway changed its offshore monitoring requirements in 1996 from facility-based monitoring of sediments to a regional monitoring of sediments and the water column (SFT, 1999; Carroll et al., 2000; Jensen and Noland, 2006).

The Norwegian continental shelf was divided by latitude into 11 regions (Table 8-2). Six of the seven regions where exploration and development activities had occurred were monitored every third year. The monitoring activity included measurement of chemicals and biological characteristics in sediments near offshore facilities and regional background stations. Table 8-2 summarizes data for total hydrocarbons and barium concentrations in sediments collected between 1996 and 2006.

Table 8-2 lists the regions of the outer continental of Norway by latitude from south to north. Ranges of total hydrocarbon (THC) and barium concentrations in sediments from reference (R) and oil facility locations (O) for 1996 through 2006[a] are included for the six regions where offshore operations are occurring. Concentrations of THC and barium are mg/kg dry wt (ppm). From Bakke and Nilssen (2005) and Renaud et al. (2008).

TABLE 8-2
THC and Barium Concentrations in Norwegian OCS Regions, 1996-2006

Region	Name	S/N Borders	THC (R & O)	Barium (R & O)
North Sea				
I	Ekofisk	56 - 58°N	(R) 1.3 - 6.8 (O) 0.5 - 6490	(R) 4 - 102 (O) 3 - 7410
II	Sleipner	58 - 60°N	(R) 1.5 - 15.4 (O) 0.5 - 1.8	(R) 4 - 215 (O) 8 - 3940
III	Oseberg	60 - 61°N	(R) 0.7 - 29.9 (O) 0.5 - 18,940	(R) 9 - 482 (O) 11 - 7190
IV	Tampen	61 - 62°N	(R) 0.5 - 8.0 (O) 0.4 - 2500	(R)19 - 479 (O) 3 - 10,750
Norwegian Sea				
V	Møreb	62 - 64°N	---	---
VI	Halten	64 - 66°N	(R) 1.1 - 7.1 (O) 1.2 - 5900	(R) 47 - 228 (O) 83 - 8480
VII	Nordland	66 - 68°N	---	---
Barents Sea				
VIII	Troms	68 - 70°N	---	---
IX	Finnmark	70 - 72°	(R) 1.4 - 4.4 (O) 0.7 - 9.0	(R) 98 - 125 (O) 19 - 945
X	Barents South	72 - 75°N	---	---
XI	Barents North	North of 75°N	---	---

[a] Regional monitoring in Region IX began in 2007.
[b] Field monitoring data are not available for Region V where 19 wells were drilled between 2005 and 2006.

All these regions can be classified as cold-water environments and regions V through X are in Arctic waters of the Norwegian and Barents Seas. Largest discharges of WBM and cuttings were in regions III and IV in the North Sea and VI in the Norwegian Sea (Table 8-3), where more than 200 wells had been drilled between 1996 and 2006. Large amounts of SBM and cuttings were discharged to regions II, III, IV, and VI; discharges of oil and OBM cuttings were lower than those of WBM and SBM cutting and were highest in regions IV and VI. Although discharge of OBM cuttings was banned in the OSPAR area in 1996, there were OBM cuttings discharges in all regions, except V and IX, every year between 1996 and 2006, with largest discharges in regions IV and VI between 2004 and 2006. Discharge of OBM and SBM cuttings to Norwegian waters has been phased out gradually since the late 1980s, with zero discharge of OBM and SBM cuttings achieved in 2007 (Renaud et al., 2008).

Table 8-3 lists the numbers of wells drilled between 1996 and 2006 in seven regions of the Norwegian outer continental shelf and amounts of different types of drilling wastes discharged. Masses are metric tons. From Renaud et al. (2008).

TABLE 8-3
Wells Drilled along with Mud and Cuttings and Barite Volumes Discharged, Norwegian OCS, 1996-2006

Region	Wells Drilled	WBM & Cuttings	SBM & Cuttings	Oil & OBM Cuttings	Barite
I	284	221,348	8838	178	29,917
II	173	401,838	22,938	231	40,242
III	348	1,030218	20,107	296	132,299
IV	456	648,278	146,708	507	144,684
V[a]	19	22,457	0	0	2116
VI	218	579,072	14,102	1485	93,007
IX[b]	10	32,518	0	0	0c

[a] Drilling waste discharges occured only in 2005 and 2006.
[b] Drilling waste discharges occured only in 2004, 2005, and 2006. c Ilmenite was used instead of barite for WBM for Barents Sea drilling (Trannum et al., 2008).

Large amounts of barite were discharged in regions III, IV, VI. The ten wells drilled between 2004 and 2006 in region IX in the Barents Sea were drilled primarily with ilmenite WBM and most of the drilling wastes were transported to shore for disposal (Trannum et al., 2009).

There is a reasonably good relationship between amounts of different drilling mud materials used and discharged in the different regions and the concentrations of THC and barium in sediments near the discharge sites. High sediment THC concentrations occur near facilities in region III and VI where there were large discharges of WBM, SBM, OBM, and cuttings containing large amounts of barite. Sediments in region I contained high concentrations of THC and barium although relatively small masses of drilling wastes were discharged there between 1996 and 2006. Ekofisk and other fields in region I are the oldest developments in the Norwegian North Sea with a long history of discharging drilling wastes and produced water, possibly explaining the high concentrations of THC and barite in sediments near facilities in that region. Sediments

near facilities in region IV also contain high concentrations of THC and barium. This is the location of the Statfjord field, the largest in the North Sea, with the largest volume produced water discharge (Durell et al., 2006). Produced water probably is the source of much of the THC and possibly barium in the sediments near facilities in this area.

The benthic biological communities near facilities in all six regions where monitoring has been performed showed evidence of light to moderate disturbance that seemed to correspond most closely to differences in sediment texture where mud and cuttings solids had accumulated, with a weaker relationship to sediment THC concentration (Renaud et al., 2008).

8.2.1 Temperate Environments

Oil and gas development areas in the North Sea range from temperate in the Dutch sector in the south to cold-water to Arctic in the northern parts of the UK and Norwegian sectors in the north. Monitoring studies have been performed throughout the North Sea, as discussed above. A few of these studies focused on environmental impacts of WBM and cuttings discharges.

Several monitoring programs were performed in the Dutch sector of the North Sea around platforms, most of which discharged OBM cuttings (Daan and Mulder, 1996). A few locations where WBM were used and discharged also were evaluated. Most of the WBM discharges were from single-well sites. Effects on benthic fauna were monitored two months and one year after completion of drilling of each exploratory well with WBM in the Frisian Front area of the Dutch North Sea (Daan and Mulder, 1993). A spud mud and a saturated brine polymer mud were used for drilling and drilling wastes were discharge to the ocean floor at the rig site. These WBM are similar to those that Shell proposes to use for drilling exploratory wells in the Beaufort and Chukchi Seas (Table 3-6). An estimated 1.9 million pounds of drill cuttings solids and 1.7 million pounds of WBM solids were discharged.

An ecological survey performed two months after completion of drilling revealed no measurable adverse effects on the benthic community, even at stations as close as 80 ft from the discharge. Only small amounts of cuttings were detected in sandy bottom sediments, suggesting that the mud and cuttings solids had been transported away from the site and diluted to non-detectable concentrations within two months after cessation of drilling.

The results of the second ecological survey, one year after completion of drilling, were the same. No adverse effects on the benthos were detected, even at stations as close as 80 ft from the former discharge site. In both surveys, the faunal composition was homogeneous throughout the area of former drilling waste discharges. The authors suggest that the lack of detectable effects may have been due to the fact that only one well was drilled at each site, limiting the amount of solids that might accumulate on the sea floor, smothering the local benthic fauna.

Similar results were obtained in another high-energy sandy environment. The MMS sponsored a three-year study of the effects of exploratory drilling on the U.S. southern flank of Georges Bank (Bothner et al., 1986; Phillips et al., 1987; Neff et al., 1989a). The monitoring program was designed to determine the fate and effects on the benthos of exploratory drilling activities. The program included site-specific monitoring around two exploratory rigs in 260 and 460 ft of water and area-wide monitoring of the bank and adjacent continental shelf. Neff (1987) estimated that

a total of approximately 20 million lbs of WBM and 11 million lbs of cuttings were discharged from the eight exploratory wells drilled on Georges Bank in 1981 and 1982. Approximately 140 gal of diesel fuel was discharged in drilling muds from one rig (Phillips et al., 1987).

Small amounts of cuttings were detected in the gravel fraction of sediments within about 650 ft of the rigs being monitored. However, there was no evidence of cuttings piles in bottom photographs. Elevated concentrations of barium, but not the other 11 metals monitored, were detected in the upper inch of sandy sediments near the two monitored rigs after drilling. Maximum increases in barium concentrations in surface sediments between pre-drilling and post-drilling surveys ranged from 5- to 6-fold in sediments within 650 ft of the monitored platforms. Barium concentrations were slightly elevated in surface sediments up to about 3 miles down-current from the rigs. Barium and chromium concentrations were enriched in the silt-clay fraction (representing less than 5% of the total mass of these sandy sediments) of surface sediments near the platforms. Barium, but not chromium, enrichment in the fine fraction extended up to 40 miles down-current from the drilling rigs after drilling. Although and increment in barium concentration, derived from the barite in discharged WBM, was detected, the barium concentrations in the fine fraction remained in the normal range for silt-clay marine sediments (240 ppm before drilling and 1024 ppm after drilling).

The benthic fauna were abundant and diverse throughout the study area during the three years of the study. Some species showed large seasonal fluctuations in abundance, probably due to disturbance of the bottom by severe winter storms, which are capable of causing substantial sediment resuspension and bed transport down to at least 500 ft water depth (Parmenter et al., 1983). However, no changes were detected in benthic communities of Georges Bank that could be attributed to drilling activities.

MMS sponsored a similar multi-year study in the vicinity of development drilling activities on the outer continental shelf off Point Arguello, California (Hardin et al., 1994; Hyland et al., 1994). During the study, a total of 39 wells were drilled and more than 24 million lbs of drilling muds, including 11 million lbs of barite, were discharged from the three platforms monitored. No effects were observed in the soft bottom benthic community. Responses of the hard bottom communities inhabiting rocky outcrops were highly variable, probably representing both seasonal and environmentally-induced changes. Abundances of some species increased and abundances of some others decreased during the period of drilling waste discharges. Changes in populations of only a non-reef-forming coral and a galatheid crab appeared to be correlated with drilling discharges. The effects on the hard bottom community, if they occurred, were not due to chemical toxicity of drilling mud solids. They probably were caused by physical effects of elevated suspended particle concentrations. The authors predicted that recovery from such physical effects probably would begin as soon as drilling mud and cuttings discharges ceased.

Sometimes, there are adverse effects of WBM and cuttings discharges on benthic ecosystems if the discharges are to low-energy, deep-water environments or shallow coastal waters. Benthic surveys were performed immediately before and after and one year after exploratory drilling on the mid-Atlantic outer continental shelf in about 400 ft of water (Maurer et al., 1981; EG&G, Environmental Consultants, 1982; Gillmor et al., 1985). Approximately 4.75 million lbs of WBM and cuttings were discharged. Drill cuttings discharged at this site contained mainly by fine-grain, silt/clay solids (Ayers et al., 1989b). The benthic boundary layer at the site was low-

energy, as indicated by visible evidence of anchor scour marks and a cuttings pile of clay-sized particles one year after completion of drilling. Immediately after drilling, there was a 150-m diameter zone of visible clay-sized cuttings accumulation, up to 3 ft deep, just south of the drilling site. Elevated concentrations of clays were detected on the sediment surface up to 2600 ft from the discharge site.

The abundance of several large, motile predatory species, such as fish, crabs, and starfish, increased near the rig site between the pre-drilling and first post-drilling surveys. These animals probably were attracted to the area by the increased bottom-relief afforded by the cuttings pile, or by the clumps of mussels and other biofouling organisms that had fallen off the drilling rig or anchor chains. The abundance of these animals decreased in the year after drilling.

There was a nearly four-fold decrease between the pre-drilling and first post-drilling surveys in the abundance of animals living in sediments (benthic infauna) near the discharge site. This decline in abundance was the same for the four major taxonomic groups (polychaetes, echinoderms, crustaceans, and mollusks). Although the abundance of polychaetes declined, the composition of polychaete feeding guilds remained essentially unchanged. These declines persisted, but with decreasing severity, for at least one year and, because they were correlated with elevated concentrations of clay in sediments, probably were caused by burial and changes in sediment texture from accumulation of drill cuttings. There was evidence that ecological recovery was occurring in the year after completion of drilling.

There also was evidence of drilling solids accumulations and benthic ecological impacts around a platform about 14 miles off the Texas coast in about 80 ft of water in the Gulf of Mexico (CSA, 1989; Chapman et al., 1991; Carr et al., 1996). Six wells were drilled from the platform and nearly 40 million lbs of WBM and cuttings, including 37 million lbs of barite, were discharged during three years of drilling. An additional four exploratory wells were drilled within the lease blocks. Mean sediment grain size tended to decrease with distance from the platform, suggesting an accumulation of coarse cuttings particles or produced sand. There also were gradients of decreasing concentrations of barium, chromium, cadmium, mercury, and zinc in sediments with distance from the platform.

The benthic macrofaunal community in sediments near the platform was not markedly different from that at reference stations away from the platform. The number of taxa of benthic invertebrates was comparable and the species diversity was greater in sediments within 250 ft of the platform than in sediments farther away. Cluster analysis revealed that the benthic community within 250 ft of the platform was different from that farther away. Biofouling organisms falling from submerged platform structures formed a shelly sand substrate that supported a unique benthic community.

Chapman et al. (1991) and Carr et al. (1996) reported that some sediments near the platform were toxic to benthic organisms in laboratory tests. However, they also observed that the benthic fauna were relatively uniform and diverse throughout the area, showing little or no effects of the drilling discharge accumulations. Thus, the changes in benthic community structure in sediments near the platform were not caused by toxicity of drilling discharge solids at this shallow-water site. As at other temperate climate sites, effects on benthic communities probably were caused by burial, changes in sediment texture, and organic enrichment of the sediments.

8.2.2 Cold-Water Marine Environments

Park et al. (2001) used data from the regional monitoring programs, discussed above (Renaud et al., 2008), for the British and Norwegian North Sea to assess the environmental impacts of representative OBM and WBM cuttings piles. They identified 102 OBM or SBM cuttings piles and 18 WBM cuttings piles. Most of the cuttings piles purported to contain just WBM cuttings also contained OBM or SBM cuttings, so it was not possible to map the zone of impact (>50 ppm THC - the concentration above which there is a risk of benthic effects) of cuttings piles that contained just WBM. Earlier ecological studies had shown that benthic communities usually were disturbed where sediment THC exceeded 50 ppm. In 2001, the area of biological disturbance from all OBM and SBM cuttings piles was estimated to be 1056 km^2 in the UK sector and 549 km^2 in the Norwegian sector of the North Sea continental shelf.

Monitoring also had shown that benthic communities around offshore production facilities recovered after cessation of drilling discharges (Davies et al., 1984; Hartley et al., 2003). Recolinization of OBM and SBM cuttings piles began within one to two years of cessation of discharges as hydrocarbons in the cuttings pile biodegraded. Recolonization of WBM cuttings piles was much more rapid, because concentrations of biodegradable organic matter in the cuttings usually are much lower than in OBM and SBM cuttings piles .

Olsgard and Gray (1995) reviewed the results of 24 field surveys in 14 oil fields on the Norwegian continental shelf that monitored the long-term impacts of and recovery from OBM cuttings discharges from offshore platforms. They used information from a limited number of field studies on environmental impacts of WBM and cuttings discharges to the North Sea for comparison. The authors conclude from their comprehensive review that:

> "Preliminary results from fields using only water-based mud clearly indicate a reduction in environmental contamination and biological impact, compared to effects reported here, for oil-based drill-cuttings."

The authors suggest that the lesser effects of WBM and cuttings than OBM cuttings indicate that the main adverse effects of OBM cuttings are caused primarily by the oil components in the mud adhering to the cuttings. However, they caution that more barite is used in WBM than in OBM. Some of the barite used in the North Sea at the time contained high concentrations of heavy metal impurities. Olsgard and Gray (1995) were concerned that the metals could contribute to adverse environmental effects of the WBM. As discussed above, metals in modern drilling mud barite have an extremely low solubility and bioavailability (Neff, 2008) and are not bioaccumulated by marine animals (Neff et al. (1989b).

Renaud et al. (2008) compared long-term trends in sediment properties, THC and barium concentrations, and benthic community structure at the Ekofisk 2/4 B&K, Statfjord A, and Snorre TLP platforms in the central and northern North Sea (regions I and IV). Ekofisk 2/4 B&K, located in about 230 ft of water in region I, was classified as having a large WBM cuttings pile. About 10% of the total cuttings discharged during drilling of 37 wells since 1974 were OBM cuttings, with most discharges since 1993 of WBM cuttings and possibly some SBM cuttings (Park et al., 2001; Renaud et al., 2008). High concentrations of polychlorinated biphenyls (PCB) have been detected in cuttings piles near North Sea production platforms,

including Ekofisk 2/4 A (Hartley et al., 2003). The PCB may have come from sand-blasting of platform strructures to remove marine antifouling paints containing PCB. Sand-blasting could also be a source of lead and zinc in the cuttings piles.

Statfjord A, located in about 500 ft of water in region IV, is the largest oil field in the North Sea. It has a long history of OBM and SBM cuttings discharges and large produced water discharges, rendering the cuttings pile there among the most heavily contaminated with THC in the North Sea. Snorre TLP is a newer field in about 1000 ft of water in region IV. Little OBM cuttings have been discharged there.

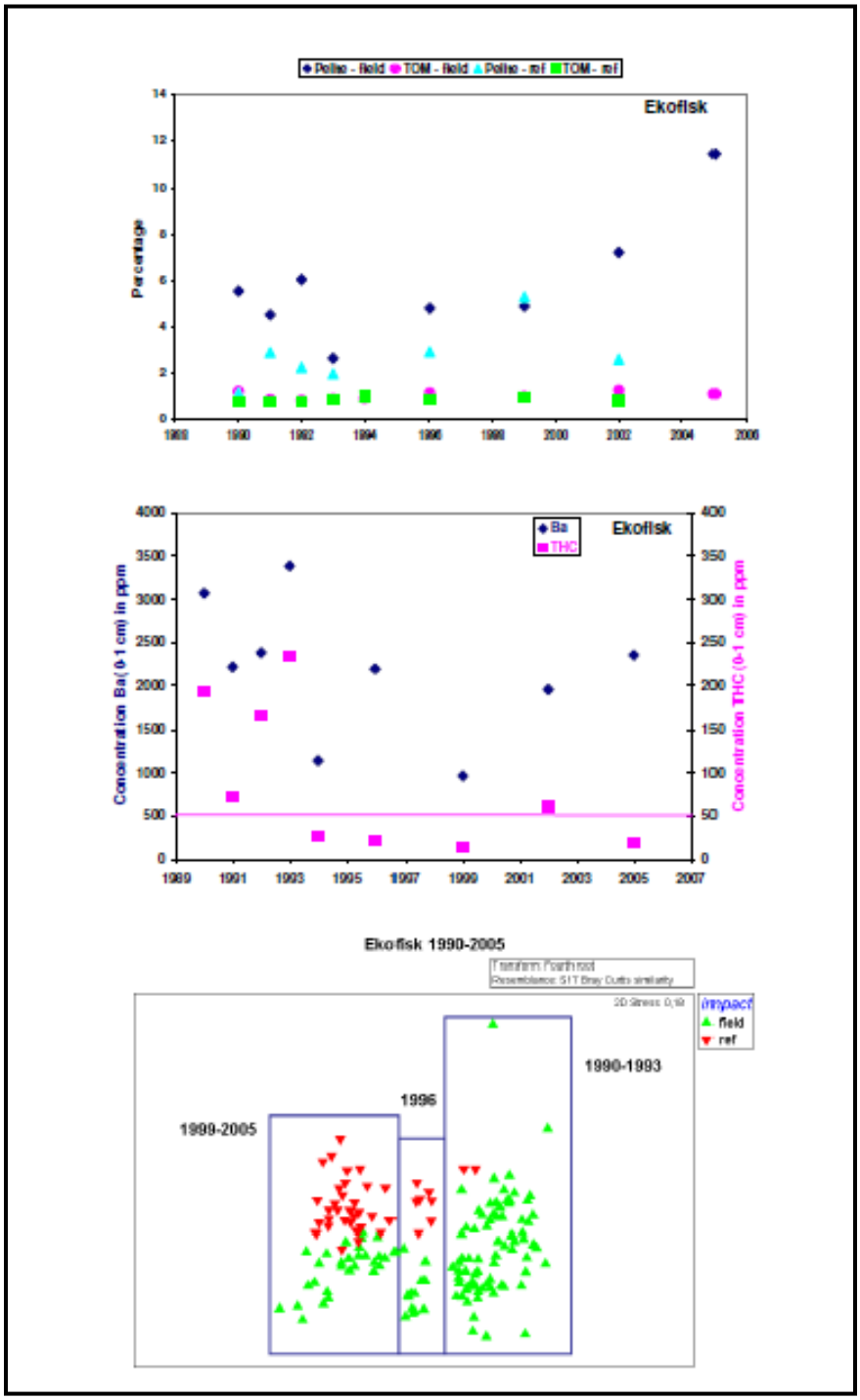
There has been little evidence of a change in pelite (silt + clay) or total organic matter (TOM) concentrations in sediments at Ekofisk after 1990 (Figure 8-1). THC concentrations were high in sediments near Ekofisk in the early 1990s, with mean concentrations up to 234 ppm and a maximum concentration higher than 3000 ppm at a station about 300 ft from the platform in 1992. THC concentrations in sediments declined rapidly after OBM cuttings discharge was banned in 1993 (Figure 8-1). THC concentration has been near or below the predicted no environmental effects (PNEC) concentrations since 1994. Barium concentrations in sediments have not varied much since 1990, ranging from about 1000 to 3500 ppm, indicating that highly insoluble natural and drilling mud barite is persistent in fine-grained sediments.

Benthic faunal community structure was analyzed with a multivariate statistical method, called multidimensional scaling (MDS) that considers the number of individuals and distribution of individuals among the taxa found at each station. The MSD plots show that there was a large inter-annual variation in benthic community structure that was greater than the differences between reference and platform sites (Figure 8-1). There also was a sharp change in community structure in 1996, three years after cessation of OBM cuttings discharges. However, benthic communities at the reference stations always were distinct from those at the platform site.

At Snorre TLP, sediment pelite concentrations were high and tended to increase between 1991 and 2005 at both platform and reference sites. THC concentrations in platform site sediments have remained below 50 ppm since 1991. Mean barium concentrations in platform site sediments have tended to rise gradually from about 2000 ppm in 1992 to about 5500 ppm in 2005. As at Ekofisk, the MSD plots indicated greater variation in benthic community structure among years than between reference and platform sites in any year. However, there were no differences in community structure in any year between reference sites and all platform sites combined. There was a difference for stations located closest to the platform.

Figure 8-1 shows the characteristics of sediments near the Ekofisk B&K platform in the Norwegian North Sea from 1990 to 2005. The surface of the cuttings pile is mainly WBM cuttings. Top: percent pelite (silt+clay) and total organic matter in sediments; Middle: concentrations of total hydrocarbons (THC) and barium in surface sediments (0-1 cm) (the horizontal line is the predicted no effects concentrations - PNEC- for THC; Bottom: multidimensional scaling (MDS) plots for the abundance and diversity of the benthic community. From Reynaud et al. (2008).

Figure 8-1 Sediment Characteristics near Ekofisk B and K Platforms, Norwegian North Sea, 1990-2005



There was little difference in pelite or TOM concentrations at stations near Statfjord A and regional reference stations. The mean THC concentration in the 0-1-cm surface layer of sediment collected near Statfjord A in 1990 was 920 ppm, with a maximum concentration of 6700 ppm. THC concentrations declined in subsequent years, reaching the PNEC concentration in 1999. As

at Ekofisk, this decline probably was due to the ban on OBM cuttings discharges in 1993. However, deeper sediment layers remained heavily contaminated with hydrocarbons from 13 years of routine OBM cuttings discharges.

Mean barium concentrations in surface sediments at Statfjord have remained relatively constant at 2000 to 3500 ppm over the 15 years of monitoring. The MSD plots for 1993 through 2005 show changes in community structure between 1993 - 1996 and 1999 - 2005. Stations 800 and 1640 ft from the platform plotted the farthest from the reference stations in 1993 - 1996. These stations plotted closer to the reference stations in 1999 - 2005. However, benthic communities at reference stations never resembled communities at platform sites, even those 1.25 miles from the platform. The MSD data indicated that there was a strong gradient of decreasing benthic community disturbance with distance from Statfjord A. This disturbance gradient showed some evidence of declining with time after cessation of OBM cuttings discharges, indicating slow recovery of the benthic community.

These temporal studies at three Norwegian platforms with different histories of drilling waste discharges provide insights into causes of disturbance of benthic communities and processes of community change and recovery. The higher concentrations of fine-grained sediments and sometimes TOM at the three platform sites compared to reference sites, indicate that disturbance of sediment texture by deposition of drilling waste solids may have an important role in structuring benthic communities. The results of multiple years of monitoring at the three sites suggest that there are a variety of other factors that contribute to benthic community disturbance near the platforms. Comparison of sediment disturbance at the three platform sites indicates that elevated concentrations of THC in sediments do influence benthic community structure. This effect probably is caused by organic enrichment of surface layers of sediments, leading to sediment oxygen depletion (Trannum et al., 2009).

One of the most important causes of benthic community disturbance on a local scale is the natural spatial and temporal variability in benthic community structure throughout the region (Peterson and Mannvik, 1998; Eckert, 2009). Peterson and Mannvik (1998) reviewed benthic monitoring data from the vicinity of production facilities in the northern North Sea. They concluded that large-scale temporal variability occurs in both the diversity and structure of benthic communities on time scales varying from years to decades. They suggested that broad scale temporal and spatial variability in benthic communities is driven by climate forces that influence overlying water masses, changing pelagic production and benthic/pelagic coupling of nutrients in cold-water continental shelf areas. Benthic/ pelagic coupling is the main source of nutrient flux to the benthos of the entire Arctic continental shelf, including the Chukchi and Beaufort Seas (Moran et al., 2005; Dunton et al., 2006) and is sensitive to natural climate change.

Eckert (2009) reported a similar high variability in marine biological communities in near-shore waters of the Gulf of Alaska. This natural variability, caused primarily by a wide variety of natural and anthropogenic disturbance, makes it difficult to attribute changes in biological communities near offshore facilities or oil spills to the anthropogenic disturbance.

Superimposed on this large-scale variability is heterogeneity of benthic habit characteristics, resulting in heterogeneity in benthic community structure and different responses to local

physical disturbance. Benthic communities have patchy distributions, reflecting small-scale differences in substrate characteristics and local disturbance, such as storm-induced sediment transport and mixing, and ice scour. Marine communities are not static, but instead, are undergoing constant change. The process of change is called ecological succession (Odum, 1969). Succession occurs in an ecosystem following a disturbance that returns the community to an earlier successional state. Because estuarine and nearshore marine ecosystems are continually subjected to natural local and regional disturbance, they never reach the final, long-lived climax state, but are undergoing continuous change. At any given time, a marine ecosystem may be characterized by a mosaic of successional stages representing the evolving spatial pattern since the last disturbance (Gray, 1977; May, 1977; Sousa, 2000). The magnitude and persistence of benthic disturbance from deposition of drilling discharges usually is within the range of natural disturbance, except when the deposited solids contain high concentrations of hydrocarbons (e.g., OBM and SBM cuttings piles). WBM cuttings deposition usually returns the local benthic community to earlier successional states, depending on the severity of the disturbance (e.g., cuttings pile depth), and natural succession returns the benthic community to a stable state rapidly.

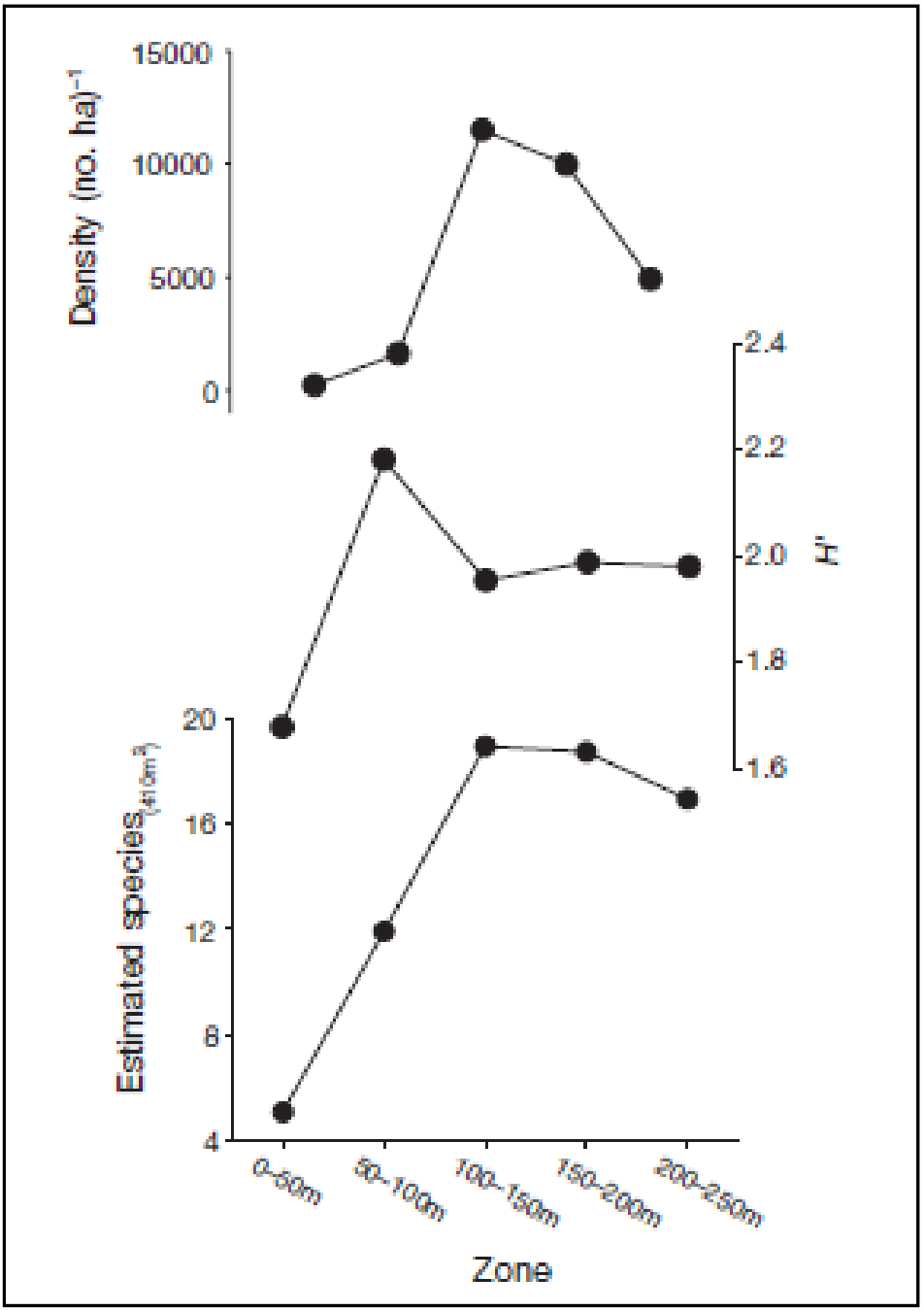
Jones et al. (2006, 2007) performed video surveys from a remotely operated vehicle to assess the impact of exploratory drilling on epibenthic megafaunal communities (large marine invertebrates and fish living on or just above the sea floor) in deep water in the UK sector of the northern North Sea. Monitoring was performed in the Foinaven, Schiehallion, and Laggan fields in 1375 to 1950 ft of water in the Faroe-Shetland Channel west of Shetland Island. Drilling activities and cuttings dispersal at these fields were discussed above in Section 5.5. Apparently, only lightly treated WBM from the top hole sections of the wells were discharged.

The upper slope of the Faroe-Shetland Channel is an unusual deep-sea habitat consisting of a heterogeneous mixture of sediment types with a preponderance of hard cobble and boulder substrates. The benthic communities of this habitat are abundant and diverse and vary with water depth, near-bottom current speeds, and temperatures (Bett, 2001). The epibenthic megafauna play an important role in benthic ecosystem function by transferring organic matter from benthic infaunal production to the overlying water column (benthic/pelagic coupling). The magnitude of benthic disturbance was defined in these studies as the thickness of drilling mud and cuttings on the sea floor.

The Laggan well was drilled in 1950 ft of water (Jones et al., 2006). Physical disturbance from drilling resulted in smothering of the benthos within about 325 ft of the drill site. The most disturbed sediments at Laggen were covered with up to 3 ft of drill cuttings in a zone within 150 to 400 ft from the drill site. Numbers of species, megafaunal density, and diversity were reduced by as much as 92% within 150 ft of the drill site. These community parameters increased with distance from the discharge and were in the normal range within about 300 to 500 ft from the discharge (Figure 8-2). However, there was a highly heterogeneous distribution of megafauna before drilling and beyond the disturbed area after drilling. Thus, it is uncertain how much of the megafaunal community changes observed near the drill site were caused by the drilling disturbance or were a reflection of the natural patchy distribution of different species of megafauna.

Figure 8-2 shows the differences in estimated number of species, megafaunal density, and diversity with distance from drill sites in the Laggan field in 1950 ft of water in Faroe-Shetland Channel in the northern North Sea. From Jones et al. (2006).

Figure 8-2 Estimated Number of Species, Megafaunal Density and Diversity with Distance, Laggan Field, North Sea



The Foinaven field is in about 1665 ft of water and the Schiehallion field is in about 1375 ft of water (Jones et al., 2007). Megabenthic community structure and abundance were different in the three areas, probably due primarily to differences in water depth and substrate characteristics. The Laggen community was dominated by crustaceans, primarily shrimp *Pandalus borealis,* sponges, and echinoderms. The Foinaven community was dominated by crustaceans, especially squat lobster *Munida sarsii*, sponges, and echinoderms. The Schiehallion community was dominated by sponges and echinoderms.

Visible effects on the megafaunal community of disturbance from drill cuttings on the sea floor were difficult to detect at Foinaven and Schiehallion. Sedentary species, such as sponges and sea anemones, were more severely affected by burial, particularly within about 150 ft of the drill sites, whereas motile species such as shrimp, echinoderms, and fish, tended to avoid the cuttings pile at first and then were attracted to it as the sedentary species recovered. Drill cuttings accumulations on the sea floor were visible to a distance of about 150 ft from the drill site at Foinaven. Benthic megafaunal abundance was very low within 150 ft of the drill site, but was in the range of natural abundance at greater distances (Figure 8-3). Sedentary species were more severely affected than motile species. Species abundance increased with distance from the drill site and reached a maximum at 325 to 500 ft from the discharge, declining again at greater distances. Highest species diversity also was at 325 to 500 ft.

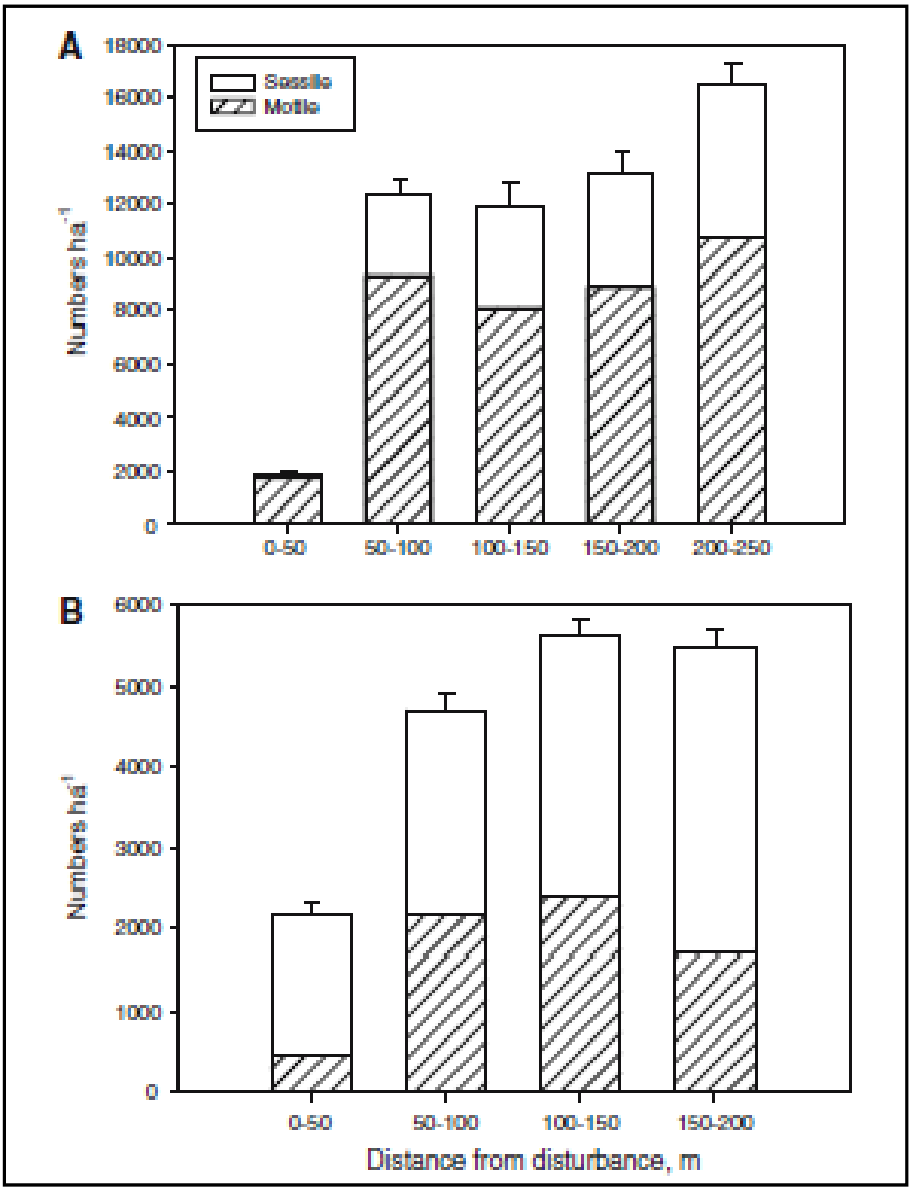
Although there had been less drilling at Schiehallion, visible cuttings accumulations on the sea floor extended up to 500 ft from the drill site in some directions. However, declines in megafaunal abundance were restricted to within 150 ft of the discharge as a Foinaven (Figure 8-3). Abundance of sedentary animals was depressed more than that of motile animals. Abundance was at normal levels at greater distances. As at Foinaven, species abundance and diversity increased to a maximum at 325 to 490 ft. The differences in distribution of drill cuttings and benthic impacts at Foinaven and Scheihallion probably were caused by differences in bottom current speeds and amounts of exposed rocky substrates at the two sites.

The decreases in species abundance, density, and diversity in the benthic megafaunal community near the three drill sites was caused primarily by physical smothering of the benthic infaunal community and burial of the sedentary epifauna. The composition of the sea floor changed with the deposition of fine-grained drill cuttings from a heterogeneous substrate with extensive exposed hard surfaces to a homogeneous soft substrate. Gills of filter-feeding benthic invertebrates probably were clogged with fine drilling particles. It is probable that the periodic high speed bottom currents in the area removed some of the fine particles, reexposing hard substrates, and restoring the heterogeneous substrate in the area.

Exxon Neftgas Ltd performed a multiyear water column and benthic monitoring program during development drilling in the Arkutun-Dagi area off the northeast coast of Sakhalin Island in the Russian far east (O'Reilly et al., 2000). Six wells were drilled in 118 to 137 ft of water between 1996 and 1998. All wells were drilling with a spud mud (similar to generic mud #6, Table 4-2) for the top hole sections and a sodium chloride/polymer mud (similar to generic mud #1) for deeper sections of the wells. The polymers in the latter drilling muds included PHPA and xanthan gum. The WBM and cuttings were discharged to the ocean. These drilling muds resemble those that Shell proposes to use to drill exploratory wells in the Chukchi and Beaufort Seas (Table 3-6).

Figure 8-3 shows the abundance of motile and sedentary benthic megafauna near drill sites in 1665 ft of water in the Foinaven field and in 1375 ft of water in the Schiehallion field in Faroe-Shetland Channel in the northern North Sea. From Jones et al. (2007).

Figure 8-3 Abundance of Motile and Sedentary Benthic Megafauna, Foinaven Field, Northern North Sea



The drilling muds and cuttings were fine-grained, with a predominant grain size in the 0.003 to 0.1 mm size range. Local sediments were coarser, classified as fine to medium sands, probably reflecting the high energy water current regime in the area. Total suspended solids (TSS) concentrations in the water column were highly variable, depending on season and weather conditions. TSS ranged from 0.3 to 23 mg/L under calm conditions to more than 40 mg/L during storms.

The drilling muds contained metals concentrations similar to those in U.S. drilling muds (Table 3-2), with one exception, and were in the range expected for uncontaminated marine sediments (Neff, 2002a). The concentration of mercury in a few samples of drilling mud used in 1998 was just over 1 ppm. This mercury was associated with the barite. Drilling muds used in 1996 and 1997 contained 0.006 to 0.062 ppm mercury. Total petroleum hydrocarbon (TPH) concentrations in the drilling muds ranged from <0.02 to 75 ppm, which is in the range of pre-drilling background concentrations in surface sediments in the area.

The water column productivity in the area was high with strong seasonal blooms of phytoplankton and zooplankton. There was no change in plankton community composition and biomass that could be attributed to drilling discharges in the three years of drilling. Water quality parameters, such as salinity, temperature, and chlorophyll *a* concentration were unaffected by the discharges. Although TSS concentration increased during drilling mud and cuttings discharges, concentrations never exceeded the range of natural TSS values.

The sediments in the drilling area support an abundant and diverse benthic community. However, benthic biomass and diversity is highly variable on both temporal and regional scales, as was observed for similar marine environments on the Norwegian continental shelf (Pearson and Mannvik, 1998) and the Gulf of Alaska (Eckert, 2009).

Video surveys of the sea floor did not detect any evidence of an accumulation of drilling muds and cuttings during drilling. There was no change between pre- and post-drilling surveys in sediment physical and chemical parameters, except at stations within 50 ft of the discharges. TPH, barium, and lead concentrations increased slightly (by less than 2-fold) in a few sediment samples near the drill sites. Mean sediment grain size also decreased slightly at a few locations near the discharges. However, there was no correlation between these changes and benthic community characteristics. A year after drilling, sediment grain size and TPH concentrations had returned to pre-drilling levels at all locations. A few sediment samples collected near the drill site still contained slightly elevated concentrations of a few metals.

Thus, drilling of six wells in a shallow cold-water marine environment and discharge of WBM and cuttings had no short-term or chronic effect on water column and benthic communities in the area.

Relatively little field monitoring of biological effects of exploratory drilling discharges of WBM and cuttings has been performed in coldwater development areas in Canada and Alaska. Environmental effects monitoring programs often are required for exploration and drilling in the Canadian Atlantic and Beaufort Sea regions (Cranford and Lee, 2005). However, monitoring has focused on long-term effects of OBM and SBM cuttings discharges and produced water discharges. There has been little monitoring of WBM discharges. Monitoring in Alaska has focused on determination of the fates of WBM discharges in Cook Inlet and the near-shore Beaufort Sea.

Benthic communities in the vicinity of a COST well in lower Cook Inlet were monitored before, during, and after drilling (Dames and Moore, Inc., 1978; Lees and Houghton, 1980; Houghton et al., 1981). The well was drilled in about 200 ft of water in a dynamic, high-energy environment. Mean tide height ranges from about 10 feet at the mouth to 30 ft at the head of the inlet, with

extreme spring tides reaching 40 ft. Mean current speeds range from 0.9 to 2.3 mph during different phases of the tidal cycle. Because of the dynamic mixing environment, drill cuttings and elevated barium concentrations were not detected in sediments near the drill rig. Some changes in benthic communities were detected near the rig during drilling. However, the investigators had difficulty relocating and resampling stations sampled during the pre-drilling survey. Because of the extreme patchiness and seasonal variability of the benthic fauna, probably due to differences in successional stages of benthic communities among areas sampled, caused by natural disburbance, it was not possible to demonstrate a statistically significant effect on the benthic community that could be attributed to drilling discharges.

Pink salmon fry, coonstripe shrimp, and hermit crabs were suspended in live boxes at 50, 100, and 200 ft below the surface 325 and 650 ft down-current and about 6600 ft upcurrent (reference) from the rig. There were no mortalities or sublethal effects in the three species in the live boxes that could be attributed to the drilling mud discharge plume.

NTS (1981) investigated the effects of above-ice and below-ice disposal of WBM and cuttings on the nearshore benthic community near the Reindeer Island COST well drilled near shore in Beaufort Sea in 1979. Experimental and reference sites were located in 16 to 26 ft of water. The maximum thickness of WBM and cuttings that accumulated on the sea floor immediately after both types of discharge ranged from 0.4 to 1.2 inches. Grain size and metals concentrations remained near background values, indicating that the mud and cuttings were swept out of the area rapidly. The abundance of some species of benthic invertebrates changed in the three to six months after the experimental discharges. Numbers of polychaete worms and harpacticoid copepods were lower at discharge than at reference sites. However, the grain size was different in sediments at the discharge and reference sites, probably accounting for most of the differences observed in benthic community structure.

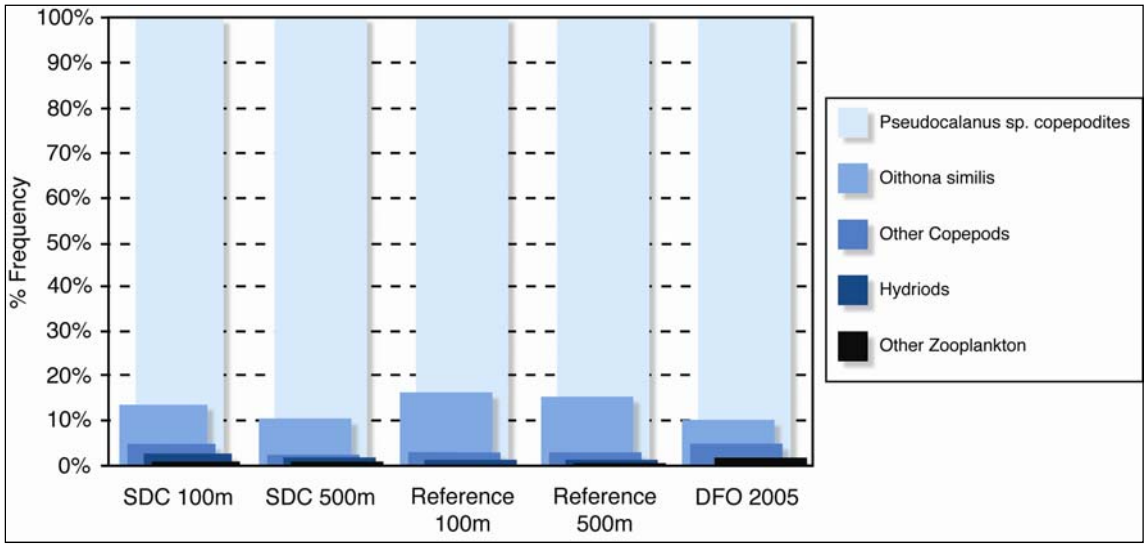
Amphipods and bivalve mollusks were placed in live boxes or trays on the bottom near the discharge site before the discharges and for up to 89 days after the discharges. The amphipods suffered few mortalities. More bivalves died or were missing from the tray deployed at the discharge site than in trays from reference sites. However, the discharge site tray had been disturbed, possibly contributing to the differences. Thus, the slight disturbance from drilling mud and cuttings discharges to the near-shore Beaufort Sea had no significant effect on the benthic community.

Devon Canada Corp. drilled an exploratory well in about 40 ft of water in the Canadian Beaufort Sea off the Mackenzie River delta in December 2005 through March 2006 (KAVIK-AXIS, 2007). Devon Canada Corp. performed a baseline survey before drilling and additional surveys during and after drilling. Zooplankton monitoring near the drilling platform was performed during drilling. Water column biological production is high off the Mackenzie River delta, with seasonal blooms of phytoplankton, followed by blooms of zooplankton. The zooplankton community at all sampling sites around the drilling platform during early February 2006 was dominated by copepods. Two species, copepodites (life stages between nauplii and adult) of *Pseudocalanus* sp. and *Oithona similis* accounted for at least 95% of the zooplankton at all sampling locations. There was a statistically significant lower abundance of zooplankton at a few sites within about 300 ft (100 m) of the SDC than in the reference area (Figure 8-4). The differences were small and due mainly to differences in the abundance of *Pseudocalanus*

copepodites. Zooplankton samples collected by Canadian Dept. of Fisheries and Oceans (DFO) in the area in 2005 were different from all 2006 samples. These differences probably were caused by the extreme patchiness of zooplankton under the ice in the winter or to the effect of the SDC on local water currents. Thus, drilling waste disposal had little or no effects on zooplankton communities in the Canadian Beaufort Sea.

Figure 8-4 shows the frequency of occurrence of zooplankton collected in the vicinity of the SDC during drilling in February 2006 and in the winter of 2005 (DFO 2005) before drilling at the Paktoa-60 drill site in the Canadian Beaufort Sea. From KAVIK-AXIS (2007).

Figure 8-4 Frequency of Zooplankton Occurrence Near SDC, Paktoa C-60 Drill Site, Canadian Beaufort Sea



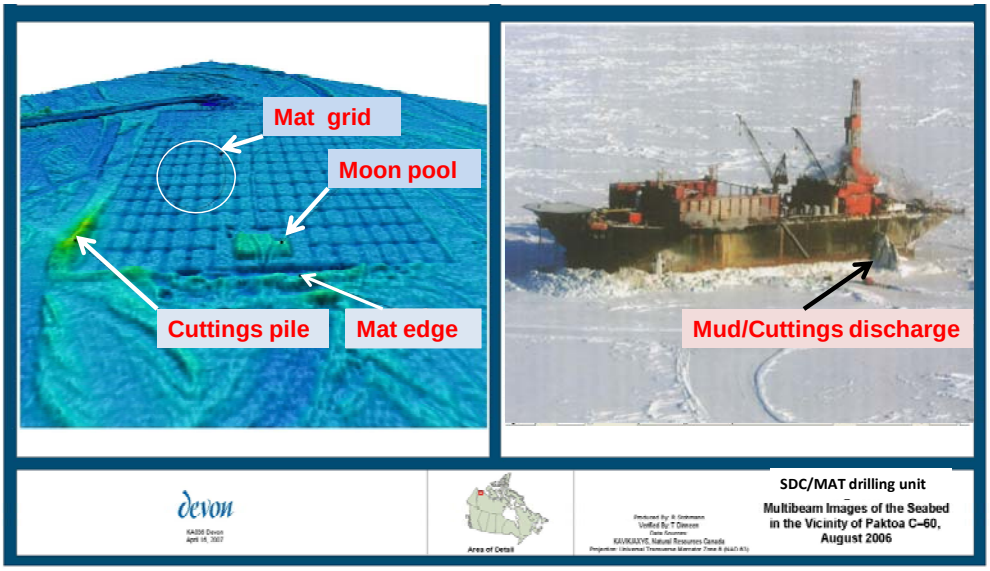
The post drilling monitoring program was conducted from August 25-28, 2006, five months after completion of drilling and included sampling and analysis of sediments and benthic amphipod crustaceans at an array of stations located in different directions at 330 and 1650 ft. around the drill site. There were slightly elevated concentrations of a few metals in sediments from a few stations near the SDC (Table 5-21). Hydrocarbon concentrations in all sediments were at background concentrations for this area. Concentrations of four metals and hydrocarbons were similar in amphipods collected near the former location of the SDC and at reference stations five months after drilling (Table 6-7). Iron and lead concentrations were highest in amphipods collected near the location of the former gray water discharge. KAVIK-AXIS (2007) concluded that there was no evidence of bioaccumulation of metals from drilling wastes by the amphipods.

Because the SDC sat on the sea floor during drilling, there was strong evidence after the drilling vessel completed drilling and was moved from the site of physical disturbance of the sea floor at the site (Figure 8-5). The impression of the SDC on the sea floor is quite clear, and the drill cuttings pile is evident. A resurvey a year later showed that this disturbance of the sea floor was still present but less prominent. There also was an ice scour mark deeper than the impressions left by the SDC running through the center of the area. This indicates that the disturbance from

the drilling platform and drill cuttings discharge are similar to natural physical disturbances of the sea floor in the area.

Figure 8-5 shows multibeam images taken in August 2006 of the sea floor in the vicinity of the Paktoa C-60 well completed in March 2006. The left frame is a broad view of the area were the SCD was located, showing the impression of the mat on the sea floor and the locations of the moon pool and cuttings discharge. The right frame is a picture of the SDC at the drill site, showing the location of the cuttings discharge. From KAVIK-AXIS (2007).

Figure 8-5 Seafloor Multibeam Sonar Images, Paktoa C-60 Well, August 2006, Canadian Beaufort Sea



8.2.3 Summary of Ecological Effects of WBM and Cuttings Discharges in Cold-Water Marine Environments

Modern WBM of the types proposed for exploratory drilling in the Beaufort and Chukchi Seas (Table 3-7) contain only non-toxic ingredients (Table 7-2). Many acute and chronic toxicity tests have been performed with cold-water species, including species from the Alaskan and Canadian Beaufort Sea and Norwegian Barents Sea, and currently used WBM additives and whole WBM. The studies show that cold-water species have a similar or slightly greater sensitivity compared to temperate water species to WBM and additives as species.

The results of the limited number of microcosm and field monitoring studies of effects of WBM and cuttings discharges on Beaufort Sea biological communities have been confirmed by the results of more comprehensive microcosm and ecological investigations near WBM and cuttings

discharge sites in the southern and northern North Sea, the Barents Sea, off Sakhalin Island in the Russian Far East, and in the Canadian Beaufort Sea off the Mackenzie River. All the studies show that WBM and cuttings discharges have no or minimal and very short-lived effects on zooplankton communities. Effects on benthic macrofaunal and megafaunal communities are minor and nearly always restricted to a zone within about 300 ft of the discharge. There is no evidence of ecologically significant bioaccumulation of metals or petroleum hydrocarbons by marine animals residing or deployed in cages near WBM and cuttings discharges in cold-water environments. There is no evidence that effects are caused by chemical toxicity of any WBM ingredients. The lack of bioaccumulation or toxicity of drilling waste components assures that effects of WBM cuttings piles are highly localized and will not be exported to the local food web.

Ecological effects of WBM and cuttings discharges are caused by physical disturbance of the water column and benthic environment. Elevated suspended particle concentrations associated with the discharges may clog the gills or digestive tract of zooplankton or benthic filter-feeding invertebrates. Accumulation of drilling wastes on the sea floor buries some of the immobile benthic fauna. Changes in sediment grain size and texture render the sediments unsuitable for settling and growth of some species, while rendering the substrate more suitable for other, usually opportunistic, species. If the WBM contains biodegradable organic additives, it may stimulate growth of microbial communities in the sediment and cuttings, often leading to depletion of oxygen in the sediments. Anaerobic, sulfate-reducing bacteria may further degrade the organic matter, producing hydrogen sulfide. This process, called organic enrichment, causes marked changes in the abundance, species composition, and diversity of the benthic community.

Organic enrichment is more pronounced in OBM and SBM cuttings piles where concentrations of biodegradable organic matter (mostly hydrocarbons) are higher than in WBM cuttings piles. Benthic communities in WBM cuttings piles recover much more quickly than those in OBM and SBM cuttings piles due to the more rapid return of sediment texture and oxygen concentration to pre-discharge conditions and the more rapid degradation of the organic matter in the WBM cuttings piles.

The physical disturbances to the water column and sediments from WBM and cuttings are similar in character and magnitude to the disturbances caused by natural processes, such as storms, river floods, and ice scour. Arctic planktonic and benthic communities are well adapted to seasonal disturbance and recover rapidly from the relatively brief and intermittent disturbances associated with exploratory drilling operations.

9.0 GLOSSARY OF ACRONYMS, ABBREVIATIONS, AND SPECIAL TERMS USED IN THE REVIEW

ADEC - Alaska Dept. of Environmental Conservation

ADNR - Alaska Dept. of Natural Resources

APD - Application for Permit to Drill. An APD must be submitted to MMS for exploratory or development drilling in offshore Federal/State blocks leased by MMS.

AOGCC - Alaska Oil and Gas Conservation Commission

ANIMIDA, cANIMIDA - Arctic Nearshore Impact Monitoring in the Development Area (1999 - 2002) and Continuation of Arctic Nearshore Impact Monitoring in the development Area (2004 - 2007). An environmental studies program sponsored by MMS to investigate the long-term environmental effects of offshore oil and gas development (the Northstar and Liberty prospects) in the Beaufort Sea.

APEO - Alkylphenol polyethoxylates A widely used type of detergent whose degradation products are toxic.

API - American Petroleum Institute

APN - Akvaplan-niva. A private Norwegian research institute

Arctic - Officially, all lands and seas lying above the Arctic Circle, 66°33' N latitude.

Arctic Archipelago (Arctic Islands) - A region in northern Canada above about 70°N latitude, including the Queen Elizabeth Islands and Sverdrup Basin

Arctic Council - The Arctic Council as a high level intergovernmental forum established in 1998 to provide a means for promoting cooperation, coordination, and interaction among the Arctic States, with the involvement of the Arctic indigenous communities and other Arctic inhabitants on common Arctic issues, in particular issues of sustainable development and environmental protection in the Arctic. Member States are Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, Russia, Sweden, the United States, and Arctic indigenous organizations.

Arctic Ocean - The ocean lying north of the Arctic Circle and bordering the North American (including Greenland) and Eurasian continents.

Arctic region - The Arctic Council defines the Arctic region as including marine and coastal areas where median summer temperatures do not exceed 10°C (50°F).

Atlantic Canada - Canadian provinces bordering the north Atlantic Ocean, including New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland/Labrador.

bbl - Barrels = 42 gallons or 159 liters, the standard unit of measure for petroleum. There also are 5620 ft^3 of natural gas per barrel.

BBO - Billion barrels of oil.

BBOE - Billion barrels of oil and oil-equivalent natural gas.

Barents Sea - Part of the Arctic Ocean off northern Norway and eastern Russia.

Barite - A natural mineral, composed of barium sulfate ($BaSO_4$) used as a weighting agent in drilling mud and in various industrial and medical processes.

BAT - Best available technology economically achievable (USEPA). Also best available technique in Norwegian regulations.

BCF - Bioconcentration factor, a measure of the tendency of a chemical to be accumulated from water into the tissues of a freshwater or marine organism: concentration in organism tissues/concentration in water.

Beaufort Sea - Part of the Arctic Ocean extending from Point Barrow, Alaska to Banks Island, Northwest Territories, Canada.

Bentonite clay - A natural clay (sodium montmorillonite). Bentonite clay is very abundant in natural marine sediments, representing between 15 and 55 % of the clay fraction (<2 µm grain size) of marine sediments throughout the world. It has many commercial uses, including use in drilling muds.

Bering Sea - A northward extension of the North Pacific Ocean, bordered by the Aleutian Islands in the south and the Bering Strait in the north, Alaska to the east and Russia to the west.

BMF - Biomagnification factor: the ratio of the concentration of a chemical in the whole tissues of the consumer to its concentration in the tissues of the prey. Concentrations of chemicals with a BMF >1 may increase in a food web with increasing trophic level.

BOD_{28} - Biological oxygen demand at 28 days. A measure of the biodegradation of organic chemicals in water or sediment by aquatic microorganisms.

BPXA - BP Exploration (Alaska), Inc.

BSStRPA - Beaufort Sea Strategic Regional Plan of Action. The Canadian plan for management of the environment and resources of the Canadian Beaufort Sea.

Cal EPA - California Environmental Protection Agency.

CAPP - Canadian Association of Petroleum Producers.

CMC - Carboxymethyl cellulose is made from a natural plant polymer, cellulose, and is widely used for a variety of commercial products, including water based drilling mud.

CEFAS - Centre for Environment, Fisheries & Aquaculture Science. The UK government organization with a primary role in managing offshore oil and gas operations in the UK sector of the North Sea.

CEPA - Canadian Environmental Protection Act.

CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act. The U.S. Superfund laws governing cleanup and restoration of hazardous waste sites.

CHARM - Chemical Hazards and Risk Management. A mathematical model developed by Syntef, Norway to predict the environmental fates of oil spills and ocean discharges.

CNLOPB - Canada-Newfoundland and Labrador Offshore Petroleum Board. The Canadian agency responsible for managing offshore oil and gas operations off Newfoundland.

CNSOPB - Canada-Nova Scotia Offshore Petroleum Board. The Canadian agency responsible for managing offshore oil and gas operations off Nova Scotia.

COST - Continental offshore stratigraphic test wells. Test wells usually drilled offshore in the U.S. by a group of oil companies and the government to provide preliminary information about the geologic structure of different layers below the earth surface to determine if there are geologic structures where fossil fuels could accumulate.

CPAI - CononoPhillips Alaska, Inc. is proposing to drill exploratory wells in the Chukchi Sea.

CWA - Federal Water Pollution Control Act, commonly known as the Clean Water Act.

DSL - Canadian Domestic Substances List. DSL is a list of substances approved for use in Canada.

EEM - Environmental Effects Monitoring. Programs in Canada and Northeast Europe designed to periodically monitor environmental effects of offshore industrial activities, particularly oil and gas operations.

Chukchi Sea - Part of the Arctic Ocean extending from Point Barrow, Alaska, and the Beaufort Sea in the east, Wrangel Island and the East Siberian Sea in the west, and the Bering Strait in the south.

Cook Inlet - A large inlet of the western Gulf of Alaska extending from north of Anchorage, Alaska, in the north to south of Anchor Point and bordered to the east by the Kenai Peninsula.

CSA - Continental Shelf Associates, Inc. An environmental consulting firm located in Florida.

CYP1A - Cytochrome P4501A, an enzyme system in most animals that degrades and detoxifies several organic contaminants and can be induced (activity increases) by exposure to these contaminants in food or water.

DNV Det norske Veritas - A Norwegian company that consults primarily on human health and environmental risk management.

DOCD - Development Operations Coordination Document (DOCD). The DOCD is a plan submitted by the offshore operator to MMS that contains environmental impact-related information, such as frequency of boat and aircraft arrivals, wastes generated and their disposal methods, air emissions, and the risk and significance of any impacts on the marine ecosystem during development and operation of an offshore facility.

DPP - Development and Production Plan. The DPP is a plan submitted by the offshore operator to MMS that contains information on practices to be implemented for developing and producing offshore oil and gas resources.

DREAM - The Dose related Risk and Effect Assessment Model (DREAM) is an environmental fates and ecological risk model developed by Sintef Norway to predict the fates and environmental effects of drilling mud, cuttings, and produced water discharges to the ocean.

DOE - U.S. Dept. of Energy

Drill cuttings - Clay to gravel-sized particles of crushed rock produced by the drill bit as it penetrates the earth.

EA/EIS - MMS is required under the National Environmental Policy Act (NEPA) to produce Environmental Assessments (EA) and Environmental Impact Statements (EIS) for offshore industrial activities. These documents describe the environment where the activity will occur, and the possible environmental effects of the proposed activity and alternative activities, and possible mitigating measures.

E&P - Oil and gas exploration and production.

EC - Environment Canada. The environmental protection agency of Canada. Also the European Community (EC), which was the predecessor of the European Union (EU).

ECOMAR - An environmental consulting firm in southern California.

Eh - The reduction/oxidation (redox) potential is a measure of the relative intensity of oxidation or reduction in solution. Eh is the equilibrium electrical potential, in millivolts (mV), of an oxidation-reduction reaction. Eh values greater than 0 indicate oxidizing conditions, those less than 0 indicate reducing (low oxygen) conditions.

EIF - Environmental Impact Factor. The EIF for each chemical ingredient of a complex discharge (produced water or drill cuttings) is calculated by the DREAM model and is the estimated volume of water or area of sediment containing the chemical at a concentration higher than the predicted no effect concentration (PNEC).

EEZ - The Exclusive Economic Zone, defined as all waters up to 200 nautical miles (230 statute miles) from the coastline of a country.

EG&G - EG&G Environmental Consultants, an environmental consulting firm in Massachusetts.

ELG - Effluent limitations guidelines. Guidelines in a NPDES permit on the types and quantities of different types of substances that can be discharged to navigable waters.

EPA - The US Environmental Protection Agency.

Epontic community - Communities of bacteria, plants, and small invertebrate animals that live on the underside of sea ices.

ERCO - Energy Resources Co. Inc., an environmental consulting company in Massachusetts.

ERMS - Environmental Risk Management System, a joint industry project of exploration and production companies active on the Norwegian continental shelf to develop ecological risk based tools (DREAM and the EIF) for managing discharges of produced water and drilling muds/cuttings to the ocean.

ERT (Scotland) Ltd. - A British environmental consulting company.

ESA - The Endangered Species Act. A law administered by the National Marine Fisheries Service (NMFS) or the U.S. Fish and Wildlife Service (USFWS), depending on the species, to protect endangered species of plants and animals.

Euphausiids - Planktonic marine crustaceans, sometimes called krill, that are favorite foods of several species of baleen whales in cold-water marine environments.

Federal waters - Defined by the Submerged Lands Act of 1953 as waters lying more than 3 nautical miles (3.45 statute miles) from the coastline, except in Texas and the west coast of Florida, where State jurisdiction extends to 9 nautical miles (10.35 statute miles) out to the border of the EEZ, 200 nautical miles (230 statute miles) from the coastline of the US.

GC/FID - Gas chromatography with quantification by flame ionization detection. An advanced analytical method for separating and measuring the concentrations of slightly volatile organic chemicals.

GC/MS - Gas chromatography with quantification by mass spectrometry. An advanced analytical method for separating and measuring the concentrations and chemical identities of slightly volatile organic chemicals.

Gel -The clay fraction of a water based drilling mud.

GESAMP - The IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. An international group of scientists from different United Nations agencies that collaborate in advising countries about marine contaminants.

GIS - Geographic information system. A computer-based system for managing geo-spatial data (maps showing distributions of environmental data).

Glutaraldehyde - A chemical disinfectant widely used to kill harmful bacteria and fungi. Glutaraldehyde sometimes is used inhibit bacterial growth and hydrogen sulfide production in water based drilling muds.

HOCNF - Harmonized Offshore Chemical Notification Format. A management system developed by OSPAR to provide uniform guidelines for use and disposal of chemicals offshore by countries bordering the northeast Atlantic Ocean.

HQ - The hazard quotient, and estimated concentration ratio of the measured or estimated concentration of a chemical in water to the no observed effect concentration. An HQ > 1 indicates that the chemical could be hazardous to freshwater/marine organisms.

HSE - Health, safety, and environment. Many companies group management of human health and safety with environmental protection into a single department.

ICES - International Council for Exploration of the Sea, an intergovernmental council with 19 member countries on both sides of the Atlantic Ocean concerned with marine and fisheries science.

KAVIK-AXYS, Inc. - An Inuvialuit-owned environmental consulting company.

Law of the Sea Treaty - The Law of the Sea Treaty was enacted by the UN in 1982. It gives countries exclusive economic rights to any natural resource that is present on or beneath the sea floor out to a distance of 200 nautical miles (230 mi or 371 km) from their shores. Countries that ratify the treaty can extend their claim up to 350 nautical miles (402 mi or 647 km) from shore for those areas that can be demonstrated to be an extension that country's continental shelf. The United States has not yet ratified the treaty.

LC_{50}/EC_{50} - The end-point of aquatic toxicity tests. LC_{50} is the median lethal concentration, the concentration at which 50 % of test organisms die after a specified exposure time. EC_{50} is the median sublethal effects concentration, the concentration at which 50 % of the test organisms exhibit a particular sublethal effect after a specified exposure time.

LSP - The layered solid phase is the fraction of drilling mud that settles to the bottom of a bioassay container and is a standard preparation for testing the toxicity of the settleable solids of drilling muds and cuttings.

Lignosulfonate - Lignosulfonate is an organic salt that is produced as a by-product of the sulfite pulping process for separation of cellulose pulp from wood during the manufacture of paper. It can be combined with a cation (sodium, iron, chromium, calcium) to prepare a drilling mud additive that is effective in preventing clumping (flocculation) of the clay in WBM.

Mackenzie River - The Mackenzie River is the longest river in Canada and the largest one discharging into the Arctic Ocean from North America. It is 1738 km (1080 miles) long and has an average discharge rate of 10,700 m^3/sec (380,000 ft^3/sec).

MAF - The mud aqueous fraction is the dissolved fraction of a 1:10 mixture of WBM and seawater that has been allowed to settle for 20 hours before being used as an aquatic bioassay test medium. It represents the dissolved and dispersed fine particulate fraction of the drilling mud.

MMPA - The Marine Mammal Protection Act - A law administered by the National Marine Fisheries Service (NMFS) or the US Fish and Wildlife Service (USFWS), depending on the species, to protect marine mammals and their critical habitats.

MDS - Multidimensional scaling, is a statistic method for evaluating complex data sets of, for example, sediment chemical or benthic ecology data, to help identify relationships among the measured parameters or locations.

Mesocosm - An artificial habitat used to study the effects of different disturbances on biological communities.

Microcosm - A smaller version of a mesocosm.

Mi SWACO - An international drilling services company.

MLC - The mudline cellar is a large hole, usually 20 ft or more in diameter, in the upper 40-50 ft of top-hole section of a well in Arctic waters. The MLC is intended to ensure that the top of the wellhead and blowout preventer are located well below the maximum ice keel-scour depth.

MMS - The US. Dept. of the Interior Minerals Management Service is the Federal bureau that administers the Outer Continental Shelf Lands Act (OCSLA) and its amendments. As directed by OCSLA, MMS guides and regulates many offshore oil and gas activities from initial leasing of Federal lands on the US outer continental shelf to emplacement of offshore development and production platforms, pipelines, and floating production, storage, and offloading facilities (FPSO), to final decommissioning and removal of platforms.

MSDS - A Material Safety Data Sheet is a form containing data regarding the properties of a particular chemical or commercial substance. In the U.S, the Occupational Safety and Health Administration (OSHA) requires that MSDS be available to employees for potentially harmful substances handled in the workplace under the Hazard Communication regulation.

NAS - The National Academy of Sciences is a private, nonprofit institution of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare.

NRC - The National Research Council is one of four institutions that form the National Academies (the National Academy of Sciences, the National Research Council, the National Academy of Engineering, and the National Institute of Medicine). The NRC provides elected leaders, policy makers, and the public with expert advice based on sound scientific evidence.

NPR - Naval Petroleum Reserve - A large area of the western North Slope of Alaska that the U.S. government set aside from oil and gas exploration in 1923 as a potential reserve for naval fuel needs in time of war.

NEBC - National Energy Board of Canada is an independent Canadian Federal agency established in 1959 to regulate international and interprovincial aspects of the oil, gas, and electric utility industries.

NEPA - The National Environmental Policy Act requires federal agencies to consider environmental impacts in their decision-making process by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. Federal agencies, including MMS prepare Environmental Assessments (EA) and Environmental Impact Statements (EIS) for proposed new development and construction activities on Federal lands and waters.

NME - Norwegian Ministry of the Environment.

NMFS - National Marine Fisheries Service is a branch of the National Oceanic and Atmospheric Administration responsible for management and research on marine fisheries resources of the U.S.

NMOE - Norwegian Ministry of Oil and Energy.

NORM - Naturally occurring radioactive materials are chemicals naturally present in soils, sediments, rocks and water that are slightly radioactive.

Norwegian Sea - As defined in the Management Plan for the Norwegian Sea area, the Norwegian Sea includes the areas of the Norwegian exclusive economic zone outside the baseline (~4.8 km from shore) from 62°N latitude northwestward to 80°N at Framstredet, northwest of Svalbard, including the area around Jan Mayen Island. The waters of the Lofoten and Vesterålen Islands also are geographically in the Norwegian Sea but are administered as part of the Barents Sea.

NOAA - The National Oceanic and Atmospheric Administration is in the U.S. Department of Commerce and is responsible for management and research relating to the atmosphere (meteorology) and oceans (fisheries science and oceanography).

NSDL - Non-Domestic Substance Lists are lists issued by the Canadian Centre for Occupational Safety and Health that summarize physical, chemical, and toxicological properties of imported chemicals and complex commercial mixtures or substances, similar to the MSDS.

North Sea - An eastern sea of the North Atlantic Ocean, extending from the Straits of Dover in the south to the southwest coast of Norway at about Bergen, westward through the Shetland Islands to northern Scotland. The North Sea is bordered to the west by the United Kingdom, to the east by France, Belgium, the Netherlands, Germany, Denmark, and Norway and to the north by the Norwegian Sea.

NOW - Nonhazardous oilfield waste. Chemicals and substances associated with oil and gas exploration, development, and production that are not considered hazardous to the environment.

NPDES - National Pollutant Discharge Elimination System permits are issued by EPA under the Clean Water Act for all discharges to navigable waters of the U.S.

NSPS - New source performance standards are guidelines issued by EPA in NPDES permits for the best available demonstrated control technologies to be incorporated into new offshore facilities or operations.

NTS - Northern Technical Services. An Alaskan environmental consulting company, now part of ENSR.

OBM - Oil based drilling muds in which the continuous phase usually is a diesel fuel or a refined mineral oil.

OCNS - The Offshore Chemical Notification Scheme is a hazard ranking system for chemicals and substances used offshore in the OSPAR region based on physical, chemical, and ecotoxicological properties of products. The OCNS was introduced by the Paris Commission (PARCOM), now OSPAR, based OCSG Offshore Chemical Selection Guidelines.

OCSLA - Outer Continental Shelf Lands Act. MMS administers The OCSLA that guides and regulates many offshore oil and gas activities from initial leasing of Federal lands on the US outer continental shelf to emplacement of offshore development and production platforms, pipelines, and floating production, storage, and offloading facilities (FPSO), to final decommissioning and removal of platforms.

ODCE - Ocean Discharge Criteria Evaluation. Before issuing a new NPDES permit, EPA issues an ODCE report that identifies pertinent information and concerns relative to the ODC and exploration/production activities in the area covered by the permit.

OECD - The Organization for Economic Cooperation and Development - An international organization helping governments tackle the economic, social and governance challenges of a globalised economy. The OECD Environmental Directorate develops standard protocols for environmental measurements.

OPF - Drilling muds in which the continuous phase is an organic chemical, usually a petroleum mixture or a synthetic hydrocarbon. The term OPF is used by OSPAR to include OBM and SBM.

OCS - The outer continental shelf. Coastal marine waters extending from the State/Federal boundary (3 nautical miles in most states) to the edge of the continental shelf, usually 200 m (656 ft) water depth.

OGP - International Association of Oil & Gas Producers.

OLF - Oljeindustriens Landsforening. The Norwegian Oil Industry Association.

OSPAR - The Convention for the Protection of the Marine Environment of the North-East Atlantic. The North-east Atlantic includes five regions: Region I - Arctic waters; Region II - Greater North Sea; Region III - Celtic Sea; Region IV - Bay of Biscay and Iberian coast; Region V - Wider eastern Atlantic. Member countries include: Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

PARCOM - The Paris Commission. One of the two forerunners of OSPAR.

PAME - The Protection of the Arctic Marine Environment (PAME) Working Group of the Arctic Council.

PEC/PNEC - The ratio of the predicted environmental concentration to the predicted no effect concentration. It is a quotient recommended by the European Commission (now the European Union: EU) Technical Guidance Document for estimating the hazard of chemicals in an ecological risk assessment. A PEC/PNEC ratio ≥ 1 indicates a potential environmental hazard.

PCPA - Pest Control Products Act. A Canadian regulation for registering different biocides and their intended uses and limitations.

PERF - Petroleum Environmental Research Forum is an oil industry organization that sponsors research on the effects of petroleum exploration, development, production, refining, and use.

Petroleum hydrocarbons - Organic chemicals in petroleum and petroleum products that are composed of just carbon and hydrogen.

PHPA - Partially hydrogenated polyacrylamide is a high molecular weight, water soluble polymer that is used in water treatment and as a viscosifier and fluid loss control agent in WBM.

PLONOR - The List of Substances/Preparations Used and Discharged Offshore that Are Considered to Pose Little or No Risk to the Environment. This list was developed and is continually updated by OSPAR and lists chemicals that are not hazardous to the marine environment if discharged to the ocean.

POC - Particulate organic carbon. Organic particles in the water column, derived primarily from decaying plankton organisms. The POC settles to the sea floor and is an important source of nutrition for bottom-dwelling marine animals.

PAH - Polycyclic aromatic hydrocarbon, are hydrocarbons composed of two or more fused 6-carbon rings (benzene). They are abundant in coal, petroleum, coal tar, creosote, and in the smoke from burning of organic matter (e.g., engine exhaust, wood fire smoke).

ppb - Parts per billion. A measure of volume or mass concentration, such as nanoliters/liter (nL/L), micrograms/liter (µg/L), micrograms/kg (µg/kg). The mass concentration can be expressed on a wet-weight or dry-weight basis.

ppm - Parts per million. A measure of volume or mass concentration, such as microliters/liter (µL/L, milligrams/liter (mg/L), milligrams/kg (mg/kg). The mass concentration can be expressed on a wet-weight or dry-weight basis.

PSAC - The Petroleum Services Association of Canada is a national trade association of the Canadian oilfield service, supply, & manufacturing sectors.

RCRA - The Resource Conservation and Recovery Act gives EPA the authority to control hazardous waste from the "cradle-to-grave." This includes the generation, transportation, treatment, storage, and disposal of hazardous and some non-hazardous wastes.

RPD - The Redox potential discontinuity is the depth in sediment or stratified water where the oxidation/reduction potential (Eh) is zero.

SAIC - Science Applications International Corp. An environmental consulting company.

Sakhalin Island - Russia's largest island, located in the western Pacific Ocean and Sea of Okhotsk at about 50°N latitude.

SBM - Synthetic based drilling mud is a drilling mud in which the continuous phase is a synthetic organic chemical, usually an olefin or ester. SBM were developed as an environmentally acceptable replacement for oil based drilling muds (OBM).

SDC - Steel drilling caisson is a type of exploratory drilling platform designed for offshore Arctic ice conditions.

SERPENT - Serpent Project (Scientific and Environmental ROV Partnership Using Existing Industrial Technology). An organization fostering use of remotely operated vehicles for marine research and monitoring.

SFT - Statens forurensningstilsyn (Norwegian Pollution Control Authority). SFT, recently renamed the Climate and Pollution Agency, is a directorate under the Norwegian Ministry of the Environment.

SGOMI - Shell Gulf of Mexico, Inc. is a Shell subsidiary that will be managing proposed exploratory drilling in the Chukchi Sea.

SLA - The Submerged Lands Act gives coastal states jurisdiction over submerged lands seaward of the coastline to a distance of 3 nautical miles (5.6 km) or 9 miles (16.7 km) for Texas and the west coast of Florida.

SOI - Shell Offshore, Inc. is a Shell subsidiary that will manage proposed exploratory drilling operations in the Beaufort Sea.

SPE - Society of Petroleum Engineers.

SPP - The suspended particulate phase is a drilling mud preparation used to test the aquatic toxicity of drilling muds. The SPP is prepared by allowing a 1:10 drilling mud/seawater mixture to settle briefly. The aqueous phase containing drilling mud particles is used for the bioassay. This is the test method required by EPA in the current NPDES permits for the Gulf of Mexico and Alaska.

TEH - Total extractable hydrocarbons is the low-solubility organic chemicals that can be extracted from a sediment sample with an organic solvent, usually hexane or methylene chloride.

Most of the material is saturated hydrocarbons of fossil or modern plant origin, and is often equated with total petroleum hydrocarbons.

THC - Total hydrocarbons is essentially the same as TEH and TPH.

TOC - Total organic carbon is an easily measured estimate of the concentration of organic matter in a water or sediment sample.

TPAH - Total polycyclic aromatic hydrocarbons. There are often hundreds of PAH in major source materials (e.g., petroleum, creosote, combustion soot, cigarette smoke) and in environmental samples contaminated with these materials. TPAH is the sum of a large number of PAH in the sample, usually ranging from the sum of the 16 EPA priority pollutant PAH to 40+ parent and alkylated PAH groups, sometimes measured in environmental monitoring programs.

TOM - Total organic matter is the same as total organic carbon (TOC).

TPH - Total petroleum hydrocarbons is the sum of all hydrocarbons in an organic extract of water, sediment, or biological tissues, usually measured gas chromatography/flame ionization detection (GC/FID) or infrared spectrometry (IR).

TCF - Trillion cubic feet is a measure of the volume of natural gas in a reservoir.

UKOOA - The United Kingdom Offshore Operators Association is the trade organization for the upstream (exploration & production) sector of the UK offshore oil industry.

USCG - U.S. Coast Guard

USGS - U.S. Geological Survey

UTRR - Undiscovered, technically discoverable reserves are oil and gas resources that have not yet been discovered but could be discovered with current technology.

WBM - Water based drilling muds are drilling muds in which the continuous phase is freshwater, seawater, or a saline brine. WBM are considered cause little or no harm to the environment if discharged.

Xanthan gum - Xanthan gum is a natural high molecular weight sugar polymer, produced by bacterial fermentation of glucose or sucrose.

Zooplankton - Zooplankton are freshwater or marine animals that remain suspended in and drift with the water currents. They include the eggs, early life stages, and adults of many taxa of protozoans, invertebrates, and fish. The most abundant zooplankton in Arctic seas often are small crustaceans, such as copepods and euphausiids, upon which many marine animals, including fish, birds, and baleen whales depend for food.

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