A Review of Oil Spill History and Management on the North Slope of Alaska

A
PROJECT REPORT

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ABSTRACT

Alaska has an abundance of natural resources including oil, natural gas and coal. It is critical to minimize the occurrence of oil spills to ensure protection of Alaska's people and the environment. The objective of this project is twofold. One is to provide a quantification of the number of spills on the North Slope (NS) as well as the number of contaminated sites that are generated, describe the regulatory requirements for the Arctic zone, and discuss cleanup methods. Second is to describe the ADEC regulations as they pertain to terrestrial oil spills. The region of study begins north of Alyeska's Pump Station 4 at the Dalton Highway milepost 270, TAPS 144, north to the Beaufort Sea, encompassing all oil related operations. This review excludes spills at villages (not related to oil field operations), and releases to the atmosphere (e.g., halon, propane). Additionally, spills at formally used defense sites (FUDS) and long range radar sites are also excluded from this study. Spills that result in long term monitoring and cleanup are managed as contaminated sites. The data reveals that the majority of contaminated sites have been cleaned up with no institutional controls in place. The number of spills on the North Slope is consistent with activity. The time during the peak oil is when there are a higher number of spills. Over time, as the oil production and activity decline, so do the number of spills with a few exceptions. The decline in oil production has limited activity and growth on the NS.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

Alaska's natural resources are a vital part of the state's economy. Alaska's land area exceeds 580,000 square miles that holds endless supplies of resources such as crude oil, natural gas and timber. However, the handling of oil and hazardous substances can pose a significant threat to Alaska's economy and environment.[1] Oil is used in nearly every facet of American life; providing energy to heat homes and places of work, fueling our vehicles, powering manufacturing processes and tools, as well as providing a source for numerous synthetic materials we take for granted. Prudent management of oil and hazardous substances and the enactment of environmental laws are essential to ensure protection.[1] State and Federal laws prohibit the discharge of oil or hazardous substances, require prompt reporting when a spill does occur, and mandate containment, control, removal, and proper disposal of all waste materials.[1] Under these laws the spiller or responsible party (RP) is liable for cleanup and the Alaska Department of Environmental Conservation (ADEC or Department) is the enforcer of these laws. Spills are generally defined as releases or discharges that may adversely impact, or threaten to impact human health, welfare or the environment. The ADEC's Prevention and Emergency Response Program (PERP) protects public health, safety and the environment by preventing and mitigating the effects of oil and hazardous substance releases and ensuring their cleanup. Spills that are unable to be adequately cleaned up, meeting regulatory definition, are transferred to ADEC's Contaminated Sites Program (CSP) for long term management and cleanup. If EPA has jurisdiction, a Federal On-Scene Coordinator (FOSC) will oversee the RP's cleanup. The FOSC may determine that the RP's response, and/or the ADEC response are inadequate. If so, the EPA can assert jurisdiction and direct the cleanup. The two complicated pieces are jurisdiction, and responsible party's willingness and/or ability to adequately respond. The two main sources of EPA jurisdiction are the National Contingency Plan (NCP), and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA).

The purpose of this manuscript is twofold. One is to provide a quantification of the number of spills on the North Slope (NS) as well as the number of contaminated sites that are generated, describe the regulatory requirements for the Arctic zone, and discuss cleanup methods. Second is to describe the ADEC regulations as they pertain to terrestrial oil spills.

2.0 Overview of the North Slope

2.1 Arctic Environment

Though the North Slope lies entirely above the Arctic Circle, portions of the region are in three different zones: the arctic, transitional, and continental climatic zones.[6] Two of these zones are divided by mountain ranges - the arctic and transitional zones. The weather in this region is the result of the interaction between global air movements, land topography, and major weather systems that move north-south and east-west across the Bering Sea.[6] This region is dominated by a persistent high-pressure system, and where the potential warming effect of the Arctic Ocean is largely prevented by ice cover, mean temperatures rise above freezing point for only 2-3 months a year.[8] As a result, water temperature fluctuates very slowly.

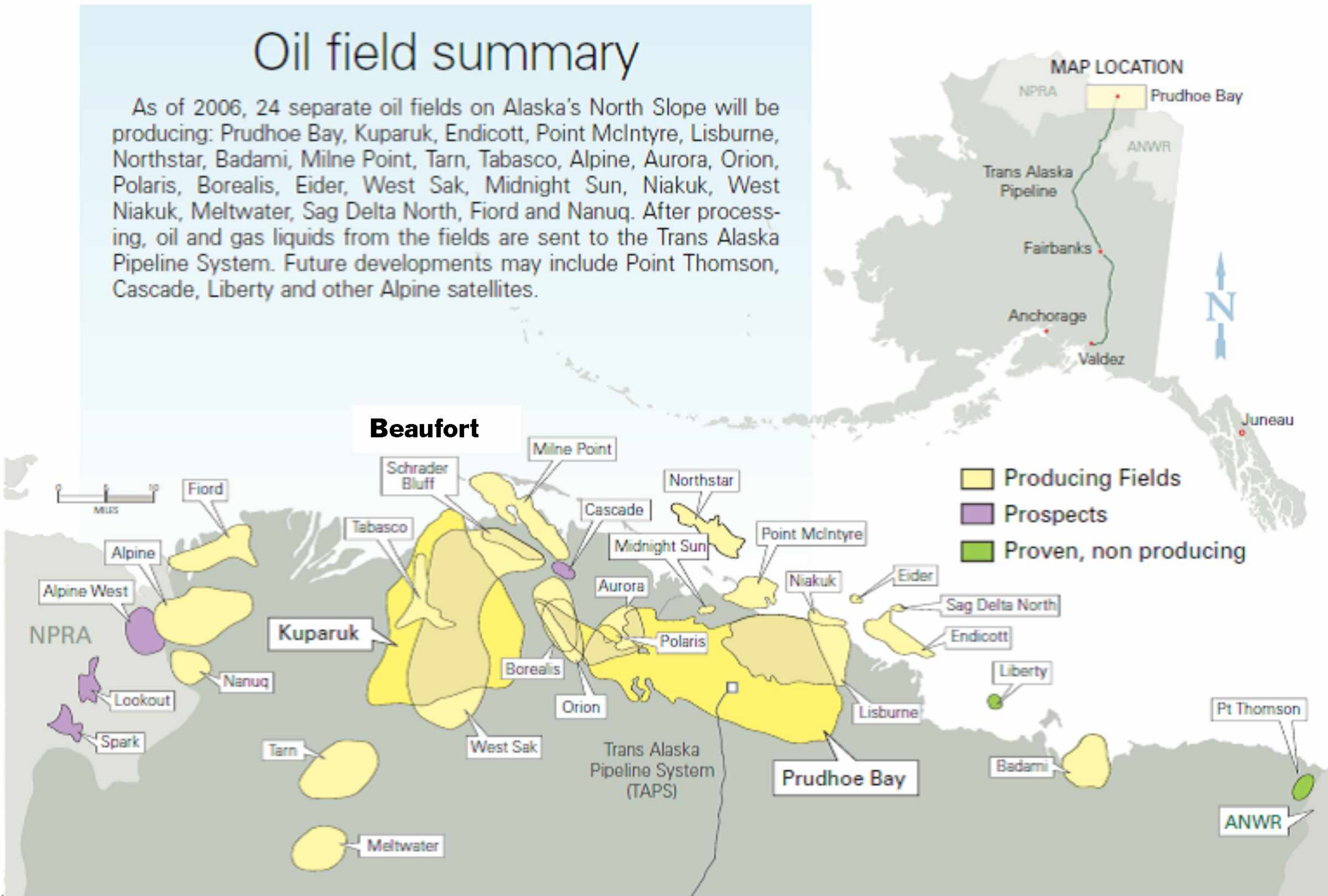

Figure 1. Map of the North Slope of Alaska[32]

The Beaufort Sea washes again the North Slope of Alaska (Figure 1). These waters remain ice-covered for eight of more months each year. The ice pack is the winter home for polar bears and numerous seals. During the summer, whales migrate through these waters. A total of 48 species of terrestrial mammals occur in the Arctic, a little over 1% of the world total.[8]

A major feature of Arctic lands, and one of considerable economic importance, is permafrost.[8] It underlies the entire region. Permafrost is defined on the basis of temperature. It is ground that stays below 0°C for two winters and the intervening summer.[29] On the Arctic Coastal plain, permafrost starts between 1 to 2 feet below the surface and has been found at depths of 2,000 feet.[6]

The Arctic and Subarctic are inhabited by indigenous peoples, some of which are based largely on subsistence economies and are dependent on renewable resources, in particular plants and animals. The largest community in the region (aside from the oil production facilities) is Barrow; seven other smaller villages dot the coast of the North Slope Borough.[6] There are no roadways to connect the villages; air travel provides the only year-round access. Oil and gas development and production on the arctic coastal plain has provided the primary source of wage employment and government funds.[6] Approximately 7,000 people live in the North Slope Borough (NSB) and the greatest impact the oil and gas industry has on them is through oil-related property tax revenues.[28] Local oil-related property taxes totaled $271 million in 2010, 98% of the NSB's total property tax revenue, which in turn generates a significant portion of local government jobs and spending throughout the borough.[28]

2.2 Alaska's Oil Industry

In 1968 the Atlantic Richfield Company (ARCO) and Exxon discovered and drilled what is known as the Prudhoe Bay State #1 well.[22] In the 1970's, the population of Alaska nearly doubled. People came to work in the oil fields, to build the Trans-Alaska Pipeline, and to provide services to the workers.[2] In 1974 the State of Alaska's Division of Geological & Geophysical Surveys estimate that the one Prudhoe Bay field held 10 billion barrels of recoverable oil and 26 trillion cubic feet of recoverable natural gas.[21] The Prudhoe Bay field is the largest field in North America and the 18th largest field ever discovered worldwide.[22]

The conception of the Trans-Alaska Pipeline in 1969 was almost concurrent with the National Environmental Policy Act (NEPA).[2] The Act establishes national environmental policy and goals for the protection, maintenance, and enhancement of the environment and it provides a process for implementing these goals within the federal agencies.[3] As a result, the environmental controls on the pipeline were the most rigorous of any project in Alaska.[2]

The nation's largest pipeline, the eight-hundred-mile pipeline from Prudhoe Bay to Valdez, was built in three years and two months, and employed a peak work force of 28,072 people.[7] ADEC was created in 1971 in part to provide oversight for the Trans-Alaska pipeline, and the federal government created similar environmental protection programs around the same time.[2] An oil spill contingency plan guided responses to the estimated 16,024 oil spills with a total aggregate amount of more than 771,000 gallons spilled during the construction of the pipeline.[4] Many of the spills and leaks during the 1970's and 1980's were a result of the growing industrialization and accompanying support services and infrastructure development stimulated by construction of the pipeline.[2]

Since that time an immense amount of oil activity has taken place on the NS of Alaska. Prudhoe Bay came on stream in June 20, 1977, rapidly increasing production until the field's maximum rate was reached in 1979 at 1.5 million barrels per day.[22] This rate was maintained until early 1989, and is currently declining by 10% per year.[22] Overall production on the NS has dropped as depicted in Figure 2.

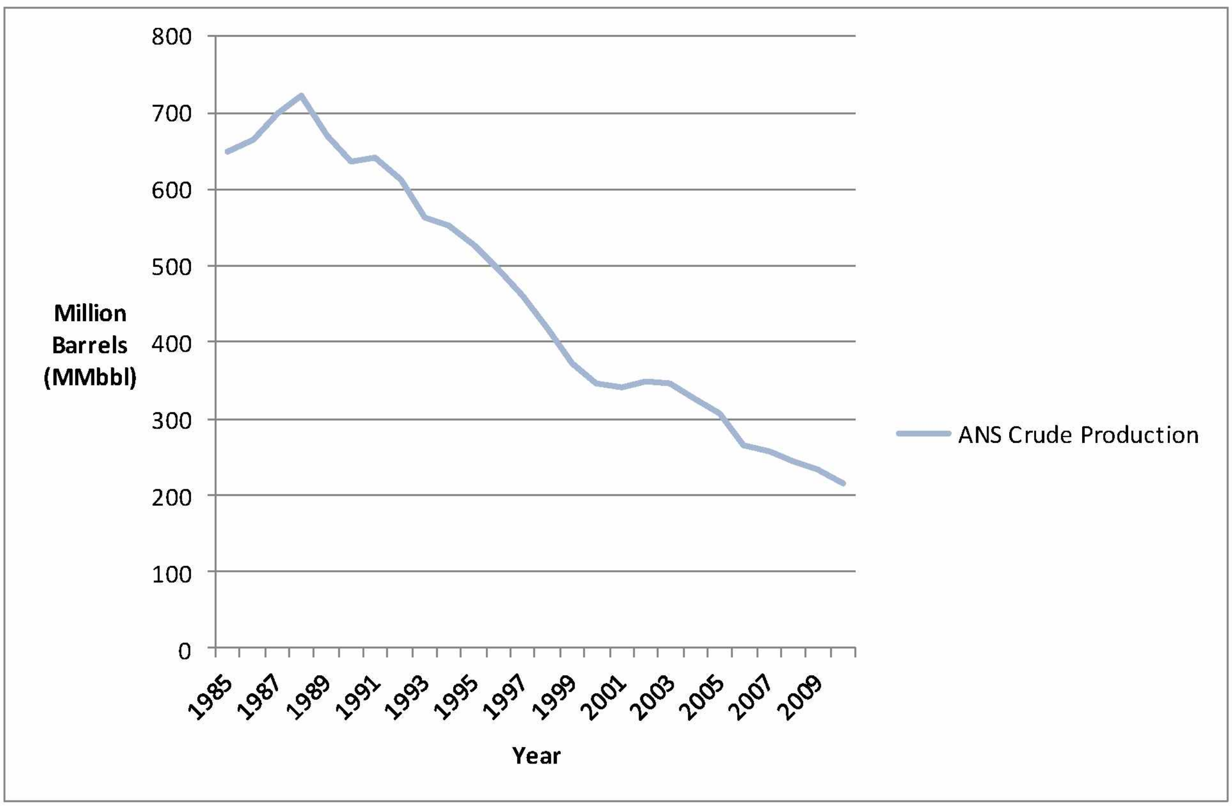

Figure 2. Alaska North Slope Crude Production[25]

The process of finding and producing oil on the North Slope has required the build-up of a considerable infrastructure, including thousands of well sites; hundreds of miles of pipelines, roads and airstrips; and numerous oil production facilities and living facilities. Most of this infrastructure is located on lands owned by the state of Alaska. However oil companies and the state are now seeking additional sources of oil on adjoining federal lands to compensate for declining oil production on state lands. Eventually, even with additional oil production from federal lands, production on the North Slope will decline to the point that operating the Trans-Alaska Pipeline will no longer be profitable. After that, the oil industry's considerable infrastructure, estimated to be as much as $53 billion, will no longer be needed.[5]

2.3 Exploration, Production and Development

In order to appreciate the potential impacts of oil and gas development upon the environment it is essential to understand the activities involved.[8] Oil activity can be dissected into three categories: exploration, development and production. Oil exploration includes surface investigations by geological field crews, seismic surveys, and exploratory drilling. The planning and permitting process for an onshore North Slope exploration well, can take up to several months. For a large project that includes multiple new pads, new developments, modification of or a new air permit, permitting is estimated between 6-30 months.[28] Once additional drilling confirms a commercial discovery, detailed engineering, economic, and environmental studies commence. During the development phase, a proposed project undergoes a thorough regulatory review which usually includes preparation of an environmental impact statement (EIS). Specific permits are required for most oil field activities including placement of fill, disposal of wastes, drilling activities, emissions from facilities, etc. The greatest level of activity occurs during the development phase as additional wells are drilled and camp and production facilities are constructed. The emphasis during the production phase shifts from construction to maintenance activities.

Increased federal and state surveillance of industrial activities on the North Slope in the 1980's documented many problems.[2] These included contaminated gravel pads and campsites, unreported spills, more than 400 disposal pits for drilling mud, plus a full spectrum of solid waste from drilling operations and camps. [2]

In the late 1970's, ADEC's attention was drawn to problems associated with the North Slope oil fields and the region's first major hazardous waste incident.[2] During the development of the Prudhoe Bay Field, the numerous oil field support contractors routinely stored and used hazardous substances. The North Slope Salvage Company reportedly dumped 15,000 drums of hazardous materials on a gravel pad and subsequent enforcement action by the Environmental Protection Agency (EPA) and ADEC ensued, requiring cleanup.[2]

3.0 ADEC

The ADEC was created in 1971 to "conserve, improve, and protect its natural resources and environment and control water, land, and air pollution, in order to enhance the health, safety and welfare of the people of the state and their overall economic and social well-being."[2] The Department was organized into five basic programs: air quality, solid waste, water quality, wastewater and sanitation. Oil and hazardous substance response efforts were initially handled on a case-by-case basis with no dedicated Spill Prevention and Response program (SPAR) staff.[2]

3.1 Program Development

As a result of the growing number of contaminated sites and the March 1989 tank vessel *Exxon Valdez* disaster, increased emphasis was placed on spill response and site cleanup.[2] The Contaminated Sites Section was formed in 1990 and ensures responsible parties clean up sites contaminated by past improper disposal of oil and hazardous substances.[1]

In July 1992, ADEC established the SPAR division in order to streamline and focus State responsibility and authority for developing and managing the state's programs for prevention and response to oil and hazardous substance releases.[2] Within the SPAR division, the Prevention and Emergency Response Program (PERP) was created on June 1, 1995.[2] PERP is responsible for all ADEC emergency response activities related to oil and hazardous substance releases statewide. The mission of the PERP is to respond to spills to ensure cleanup measures are implemented, as soon as possible, and institute a statewide spill prevention program.[1] PERP staff are the state's emergency responders to oil and hazardous substance spills.

When a spill occurs PERP uses 18 Alaska Administrative Code (AAC) 75.315's nine criteria for lowest practicable limits of contamination to determine clean up levels.

> “(c) For containment and cleanup under this section, the Department will determine the lowest practicable level of contamination based on (1) protection of human health, safety, and welfare, and of the environment; (2) the nature and toxicity of the hazardous substance, including amount and concentration; (3) hydrogeological and climatological factors; (4) the extent to which the hazardous substance has migrated, or is likely to migrate, from the area of original contamination if the hazardous substance remains onsite; (5) the natural dispersion, attenuation, or degradation of the contamination; (6) the extent to which residual soil contamination exceeds the cleanup levels in 18 AAC 75.340 and 18 AAC 75.341; (7) the extent to which groundwater contamination exceeds the groundwater cleanup levels in 18 AAC 75.345; (8) the current and future use of the groundwater under 18 AAC 75.350; and (9) the need for an interim removal action under 18 AAC 75.330.”[12]

If the State On Scene Coordinator (SOSC) determines that a site does not meet this criteria or that long term treatment is the best course for site remediation, then the RP will be required to use the Site Cleanup Rules found in 18 AAC 75.325. It is at this point usually, but not always, that a spill will be transferred to the CSP. It is at the SOSC’s discretion for transfer of a spill site from the PERP to the CSP. If the SOSC determines that a spill should be transferred to the CSP, then an internal Site Intake Form will be filled out and a State letter issued to the RP to inform them of the transfer.

3.2 Regulations

ADEC is the state agency which conducts, oversees, and approves activities associated with a discharge of oil or hazardous substances under the authority of Alaska Statute (AS) 46.03, AS 46.04, and AS 46.09 and the regulations promulgated therein.[9] State of Alaska regulations under 18 AAC 75, Article 3 establish soil and groundwater cleanup levels for sites contaminated by oil or hazardous substances.

3.2.1 North Slope Cleanup Levels

There are currently four methods to determine cleanup levels used by ADEC – Method One, Method Two, Method Three, and Method Four. Method One uses a matrix score sheet to determine cleanup levels for Gasoline Range Organics (GRO), Diesel Range Organics (DRO) and Residual Range Organics (RRO) in non-arctic zones. The matrix consists of 5 items of consideration: depth to groundwater, mean annual precipitation, soil type, potential receptors, and volume of contaminated soil. Each item has an associated value, and when all five values are added a category is assigned containing the appropriate site specific cleanup value/concentration. Method One also includes cleanup values for petroleum in the Arctic Zone. These values are not determined by a score. The matrix cleanup levels applied to the "man-made pads and roads" on the North Slope are: GRO @ 100 mg/kg, DRO @ 200 mg/kg and RRO @ 2,000 mg/kg.[9] The matrix score sheet also allows for a higher DRO cleanup level if the responsible party could prove the contamination was only caused by a diesel product.[9] The regulations differentiate between man-made roads and pads and off-pad areas of native tundra, with the cleanup level for DRO on gravel pad being lower that the cleanup level for DRO on native tundra as 12,500 mg/kg (ADEC Method Two, Table B2, Under 40 Inch Zone [Ingestion])[12].

PERP has never stopped using Method One primarily because it is the only soil cleanup method that can be used that offers clear and logical end points/items of consideration. These endpoints help ensure the project manager is protecting adjacent surface waters found around the NS pads. The downside to Method One is that nobody has been able to establish who wrote the original guidance or if the cleanup standards have any scientific justification.[10] It is believed that the Method One matrix and soil cleanup levels for petroleum hydrocarbons have been used by the Department for approximately 21 years.

3.2.2 Development of Risk-Based Method Two

The cleanup regulations were amended in 1999 and incorporated a risk-based approach into the cleanup process. The original matrix score process was retained in the regulations in addition to the new cleanup level based on the risk posed by the contaminant on human health and the environment.[9] The contaminants of concern were evaluated (and scored) based on their toxicity and the pathways through which they may reach receptors.[9]

The Department identified three exposure pathways for which soil cleanup levels were developed: ingestion of contaminated soil, inhalation of contaminants in air above contaminated soil, and contaminant migration to surface waters.[10] Other complete exposure pathways could be addressed site-specifically. By employing this method, the ADEC project manager could select the most conservative value that would be applicable to site specific conditions.

Concurrent with the development of Method Two was the inception of a guidance issued in 1999, stating that groundwater did not exist on North Slope.

> "In accordance with 18 AAC 75.341, the migration to groundwater pathway for sites in the Arctic zone is not considered due to the presence of continuous permafrost that acts as a barrier for contaminant migration to a groundwater zone of saturation that is a current or reasonably expected future source of drinking water. However, soil contaminant migration can occur via seasonal groundwater present beneath the surface of the soil above the permafrost layer (suprapermafrost groundwater). To the maximum extent practicable, migration of contamination in suprapermafrost groundwater must be eliminated. A demonstration must be made that the selected cleanup levels and cleanup remedy address off-site migration of contamination. Long term monitoring of suprapermafrost groundwater, if technically feasible, may be required to ensure migration of soil contamination has ceased."[11]

Groundwater, as defined in 18 AAC 75.990, is "water in the saturated zone, for purposes of evaluating whether the groundwater is a drinking water source under 18 AAC 75.350; or water beneath the surface of the soil, for purposes of evaluating whether the water will act as a transport medium for hazardous substance migration".[11]

"The Department recognizes that permafrost acts as a barrier for soil contaminant migration to a subpermafrost zone of saturation. However, suprapermafrost groundwater can seasonally exist above the permafrost layer as soil moisture or within a seasonal saturated zone. The Department acknowledges that due to the proximity to the surface of the soil, limited vertical extent and its transient nature, supapermafrost groundwater would not likely pose a risk to human health as a potential drinking water source. However, suprapermafrost groundwater can act as a transport medium for soil contaminants. Therefore, the Department requires that the proposed cleanup levels and cleanup technique(s) selected eliminate the transport of contaminants off-site to the maximum extent practicable."[11]

The elimination of groundwater as a protected receptor created a problem that was unique to Alaska's Arctic Zone. First, the "groundwater" found in the pads on the North Slope did not have a cleanup level. The "groundwater" could be saturated with a dissolved phase contaminant and the ADEC had no regulatory authority to require cleanup unless it can be demonstrated that the contaminated water in the ground will either (1) surface and damage an ecological receptor, or (2) commingle with surface water and break the regulation limitations enforced by the ADEC's Water Quality Program.[10]

In other areas of the state, the Method Two migration-to-groundwater is normally several orders of magnitude more conservative than the inhalation or ingestion levels.[12] Groundwater, as a receptor, is of greater concern in areas that receive mean annual precipitation of 40 or more inches per year. Therefore the migration-to-groundwater is typically the standard that an ADEC project manager would select as a cleanup level for a site. When a site was cleaned up to the migration-to-groundwater standard, that value was typically conservative enough such that an ADEC project manager rarely had to consider ecological receptors that may have required a more conservative cleanup value.

In the Arctic Zone, without the migration-to-groundwater pathway, a project manager using Method Two, Table B2 found in 18 AAC 75.341 would have to default to the ingestion and inhalation cleanup (health-based) levels. For GRO, the cleanup value is 1,400 mg/kg for each pathway and for DRO, the value for inhalation is 12,500 mg/kg and 10,250 mg/kg for ingestion.[12] In the regulations it states that if a petroleum hydrocarbon concentration is exceeded, it may form free phase product making it more susceptible to migration.[15] This concentration is based on the nature of the fuel product and the soil type. The maximum allowable ranges in the regulation for GRO and DRO were based on a soil type that might be indicative of the North Slope gravel pads.[15] Therefore the concentrations for North Slope pads whereby free phase product may form and migrate may be less than the maximum allowable concentrations.[15]

The distribution of light non-aqueous phase liquids (LNAPL) in the subsurface is a complex process and depends on the amount of the release, the type of LNAPL, capillary pressure, and the pore size distribution of the earth material.[16] LNAPL is less-dense-than-water non-aqueous phase liquids. They do not mix well with water; gasoline and fuel oil are common LNAPLs. As a LNAPL plume passes through the unsaturated zone, some LNAPL will remain behind in a residual state.[16] ADEC had used an American Petroleum Institute document titled "A Guide to the Assessment and Remediation of Underground Petroleum Releases" which documented the concentration of residual LNAPL in the unsaturated zone in coarse gravel may be 950 ppm for GRO and 2,200 ppm for DRO.[16] LNAPL can be present in the residual state due to the strong capillary forces between the soil particles. Therefore the mobility of the LNAPL is significantly reduced. The concentrations for GRO and DRO once served as guidance to the ADEC.

There was also the consideration of migration to surface water which would be calculated using a fate and transport model. There could be a concentration [of LNAPL] in a gravel pad, and if there was a concern that it might impact surface water, ADEC could calculate what concentration could remain there without violating the 18 AAC 70 water quality standards.[15]

Historic high residual concentrations of DRO in the North Slope gravel pads resulted in the eventual off-pad migration of DRO.[10] This fact makes potential ecological receptors and surface water quality regulations the predominant considerations when selecting a cleanup standard in the North Slope gravel pads and roads.

3.2.3 Current Methodology - Pathway Exposure Calculations

Current practice to determine Arctic Zone cleanup levels, applicable to the North Slope, is to use calculations found in the 2008 ADEC Cleanup Levels Guidance[33], specifically the petroleum fraction equations[23]. Some of the parameters come from EPA guidance, but the parameters used to develop the separate climate zones (e.g. the precipitation numbers) were developed at the

ADEC through a contract[27]. Guidelines to assess potential migration to groundwater have been mostly developed by EPA, although the ADEC uses their own dilution attenuation factors and fraction of organic carbon[27]. So generally, ADEC uses the EPA equations but tweaks the parameters for all compounds. ADEC's petroleum fraction equations are more detailed than EPA's equations since they traditionally have not looked at petroleum.

The groundwater cleanup level equation for non-carcinogenic contaminants is calculated according to equation 1.

$$\text{Cleanup Level (mg/L)} = \frac{THQ \times RfD_o \times BW \times AT \times 365\ d/yr}{IR \times EF \times ED \times A} \quad (1)$$

Parameter/Definition (units)	**Default**
THQ/target hazard quotient (unitless)	1
BW/body weight (kg)	70
AT/averaging time (yr)	30
RfD_o/oral reference dose (mg/kg-d)	Chemical specific (See Table 1)
EF/exposure frequency (d/yr)	350
ED/exposure duration (yr)	30
IR/ingestion rate (L/d)	2
A/absorption factor	1

For non-carcinogens, averaging time is equal to exposure duration.

The soil cleanup level equation for ingestion of non-carcinogenic contaminants in residual soil is calculated according to equation 2.

$$\text{Cleanup Level (mg/kg)} = \frac{THQ \times BW \times AT \times 365\ d/yr}{1/RfD_o x10^{-6}\ kg/mg \times EF \times ED \times IR} \qquad (2)$$

Parameter/Definition (units)	Default
THQ/target hazard quotient (unitless)	1
BW/body weight (kg)	15
AT/averaging time (yr)	6[a]
RfD_o/oral reference dose (mg/kg-d)	Chemical specific (See Table 1)
EF/exposure frequency (d/yr)	Arctic Zone – 200 d/yr Under 40" Precipitation Zone – 270 d/yr Over 40" Precipitation Zone – 330 d/yr
ED/exposure duration (yr)	6
IR/ingestion rate (L/d)	2

[a] For non-carcinogens, averaging time is equal to exposure duration. Cleanup levels are calculated for 6-year childhood exposure

The soil cleanup level equation for direct inhalation of non-carcinogenic contaminants in soil is calculated according to equation 3.

$$\text{Cleanup Level (mg/kg)} = \frac{THQ \times BW \times AT \times 365\ d/yr}{EF \times ED \times [\ (1/RfC) \times (1/VF)]} \qquad (3)$$

Parameter/Definition (units)	Default

THQ/target hazard quotient (unitless)	1
AT/averaging time (yr)	6[a]
EF/exposure frequency (d/yr)	Arctic Zone – 200 d/yr Under 40" Precipitation Zone – 270 d/yr Over 40" Precipitation Zone – 330 d/yr
ED/exposure duration (yr)	30
RfC/inhalation reference concentration (mg/m^{3})	Chemical Specific (See Table 1)
VF/soil-to-air volatilization factor (m^3/kg)	Chemical Specific (See Table 1)

The derivation of the volatilization factor is calculated according to equation 4.

$$VF\ (m^3/kg) = \frac{Q/C \times (3.14 \times D_A \times T)^{1/2} \times 10^{-4} m^2/cm^2}{(2 \times \rho_b \times D_A)} \qquad (4)$$

where

$$D_A = \frac{[(\theta_a^{10/3} D_i H' + \theta_w^{10/3} D_w)/n^2]}{\rho_b K_d + \theta_w + \theta_a H'}$$

Parameter/Definition (units)	Default
VF/volatilization factor (m^3/kg)	---
Q/C/inverse of the mean conc. at the center of a 0.5 acre square source (g/m^2-s per kg/m^3)	Arctic Zone – 100.13 Under 40" Precipitation Zone – 90.80 Over 40" Precipitation Zone – 82.72
T/exposure interval (s)	9.5×10^8 s
ρ_b/dry soil bulk density (kg/L)	1.5

ρ_s/soil particle density (kg/L)	2.65
n/total soil porosity (L_{pore}/L_{soil})	0.434 or ($1 - \rho_b/\rho_s$)
θ_w/water-filled soil porosity (L_{water}/L_{soil})	0.15 or $w\rho_b$
θ_a/air-filled soil porosity (L_{air}/L_{soil})	0.284 or $n - w\rho_b$
D_i/diffusivity in air (cm^2/s)	Chemical Specific (See Table 1)
H'/Henry's law constant (unitless)	Chemical Specific (See Table 1)
W/average soil moisture content $kg_{water}/kg_{soil\text{-}dry}$	0.1 (10%)
D_w/diffusivity in water (cm^2/s)	Chemical Specific (See Table 1)
K_d/soil-water partition coefficient (cm^3/g)	K_{oc} x f_{oc} (organics)
K_{oc}/organic carbon content of soil (g/g)	Chemical Specific (See Table 1)
f_{oc}/fraction organic carbon in soil (g/g)	0.01 (.01%)

The derivation of the soil saturation limit is calculated according to equation 5.

$$C_{sat}\ (mg/kg) = \frac{S}{\rho_b}\left(K_d\,\rho_b + \theta_w + H'\theta_a\right) \qquad (5)$$

Parameter/Definition (units)	Default
C_{sat}/soil saturation concentration (mg/kg)	---
S/solubility in water (mg/L-water)	Chemical Specific (See Table 1)
ρ_b/dry soil bulk density (kg/L)	1.5
ρ_s/soil particle density (kg/L)	2.65
n/total soil porosity (L_{pore}/L_{soil})	0.434 or ($1 - \rho_b/\rho_s$)

θ_w/water-filled soil porosity (L_{water}/L_{soil})	0.15 or $w\rho_b$
θ_a/air-filled soil porosity (L_{air}/L_{soil})	0.284 or $n - w\rho_b$
K_d/soil-water partition coefficient (cm^3/g)	K_{oc} x f_{oc} (organics)
K_{oc}/organic carbon content of soil (g/g)	Chemical Specific (See Table 1)
f_{oc}/fraction organic carbon in soil (g/g)	0.001 (0.1%)
w/average soil moisture content $kg_{water}/kg_{soil\text{-}dry}$	0.1 (10%)
H'/Henry's law constant (unitless)	Chemical Specific (See Table 1)

For organic contaminants, the soil-water partitioning is calculated according to equation 6 for migration to groundwater.

$$\text{Cleanup Level (mg/kg)} = C_w \{(K_{oc}\, f_{oc}) + ((\theta_w + \theta_a H')/\, \rho_b\,)\} \qquad (6)$$

Parameter/Definition (units)	Default
C_w/target soil leachate concentration (mg/L)	Groundwater Cleanup Level x (10 + DF), 10 is attenuation factor
K_{oc}/soil organic carbon/water partition coefficient (L/kg)	Chemical Specific (See Table 1)
F_{oc}/fraction organic carbon in soil (g/g)	0.001 (0.1%)
ρ_b/dry soil bulk density (kg/L)	1.5
ρ_s/soil particle density (kg/L)	2.65
n/total soil porosity (L_{pore}/L_{soil})	0.434 or $(1 - \rho_b/\, \rho_s)$

θ_w/water-filled soil porosity (L_{water}/L_{soil})	0.3 (30%) or $w\rho_b$
θ_a/air-filled soil porosity (L_{air}/L_{soil})	0.13 or n - $w\rho_b$
w/average soil moisture content $kg_{water}/kg_{soil\text{-}dry}$	0.2 (20%)
H'/Henry's law constant (unitless)	Chemical Specific (See Table 1)

Aliphatic and Aromatic fractions are combined to produce a total number using conservative percentages.[23]

Carbon Range	Percent Aliphatic*	Percent Aromatic*
GRO – C_6-C_{10}	70	50
DRO – C_{10}-C_{25}	80	40
RRO – C_{25}-C_{36}	90	30

* Because the fuel constituents vary considerably, the default composition of the percent aliphatic and percent aromatics was set at 120% of the total.

For example, the C10-C25 DRO cleanup levels in Table B2 were calculated by dividing the corresponding C10-C25 aliphatic level by 0.80 and also dividing the corresponding C10-C25 aromatic level by 0.40.[23] The lowest result of these two calculations became the method two C10-C25 DRO cleanup level.[23]

HENRY'S LAW CONSTANT, H' (unitless)

aromatics $\log_{10} H = [-0.23][EC] + 1.7$
aliphatics $\log_{10} H = [0.02][EC] + 1.6$

ORGANIC CARBON PARTITION COEFFICIENT, Koc (ml/g)

aromatics $\log_{10} Koc = [0.10][EC] + 2.3$
aliphatics $\log_{10} Koc = [0.45][EC] + 0.43$

Hydrocarbon Range	Equivalent Carbon Number (EC)	Oral Reference Dose (mg/kg/day)	Reference Concentration (mg/m^3)	H' (unitless)	K_{oc}	Diffusivity in Air	Diffusivity in Water
C_6-C_{10} Aliphatics	8	5	18.4	5.75 E+1	1.07 E+4	1 E-1	1 E-5
C_6-C_{10} Aromatics	8	0.2	0.4	7.24 E-1	1.26 E+3	1 E-1	1 E-5
C_{10}-C_{25} Aliphatics	14	0.1	1	7.59 E+1	5.37 E+6	1 E-1	1 E-5
C_{10}-C_{25} Aromatics	14	0.04	0.2	3.02 E-2	5.01 E+3	1 E-1	1 E-5
C_{25}-C_{36} Aliphatics	30.5	2	n/a				
C_{25}-C_{36} Aromatics	30.5	0.03	n/a	4.86 E-6	2.24 E+5	1 E-1	1 E-5

*Note that no values are recommended for the C_{25}-C_{36} aliphatic fraction, as these compounds are essentially immobile in the environment.

Table 1. Chemical Specific Parameters for Petroleum Hydrocarbon Fractions

The cleanup values calculated with these equations are designed to be protective of human health. This is considered by ADEC as the first threshold. In terms of sensitive ecological receptors, any petroleum contamination that migrates off pad must meet Alaska Water Quality criteria under 18 AAC 70. This is the second threshold (18 AAC 70(5)(A)(iii):

Total aqueous hydrocarbons (TAqH) in the water column may not exceed 15µg/l (see note 7). Total aromatic hydrocarbons (TAH) in the water column may not exceed 10µg/l (see note 7). There may be no concentrations of petroleum hydrocarbons, animal fats, or vegetable oils in shoreline or bottom sediments that cause deleterious effects to aquatic life. Surface waters and adjoining shorelines must be virtually free from floating oil, film, sheen, or discoloration.

Note 7. Samples to determine concentrations of total aromatic hydrocarbons (TAH) and total aqueous hydrocarbons (TAqH) must be collected in marine and fresh waters below the surface and away from any observable sheen; concentrations of TAqH must be determined and summed using a combination of: (A) EPA Method 602 (plus xylenes) or EPA Method 624 to quantify monoaromatic hydrocarbons and to measure TAH; and (B) EPA Method 610 or EPA Method 625 to quantify polynuclear aromatic hydrocarbons listed in EPA Method 610; use of an alternative method requires Department approval; the EPA methods referred to in this note may be found in Appendix A of 40 C.F.R. 136, Appendix A, as revised as of July 1, 2003 and adopted by reference.

These criteria are designed to be protective of ecological receptors in the water column. As a result of their stringency, this limits the concentrations permitted in the soil/sediments of the wetland environment.

The third threshold – if ADEC felt additional measures were needed to protect ecological receptors, the Department would likely require an ecological risk assessment. There is additional guidance for this level of effort. A RP also may propose to do a risk assessment. Still, all surface water must meet Alaska Water Quality Criteria, regardless.

The CSP takes a holistic approach to arctic zone contamination issues, for instance, in the Closure letters for Arctic Zone sites, the following language is used when describing cleanup levels:

"The cleanup levels for petroleum hydrocarbon-contaminated soil in the Arctic Zone are established in 18 AAC 75.341 Method One, Table A2 and 18 AAC 75.341 Method Two Tables B1 and B2.

A number of factors are considered by ADEC when evaluating site specific cleanup levels in the Arctic Zone including:[12]

- human health (ingestion/inhalation);
- ecological impacts (contamination impacting ecological species other than humans);
- groundwater and surface water quality;
- presence of free phase product; and
- any other factors that might cause a deleterious impact to the environment.

In the Arctic Zone, the migration to surface water pathway is evaluated as the primary migration pathway because the migration to groundwater pathway is not considered applicable due to the presence of continuous permafrost. Impacted surface water can adversely affect both human and ecological receptors, depending on the location of the contaminant source, its proximity to surface waters, and water usage in the impacted area. Therefore the migration to surface water pathway is evaluated as a possible risk to human health (drinking water source) and/or for compliance with Alaska Water Quality standards (18 AAC 70).

In addition, the migration to surface water is evaluated as a possible exposure pathway for ecological receptors because of the tundra wetland ecosystem that exists throughout the Arctic region. Potential future use of the property must also be taken into account when determining closure status."[23]

To reiterate, if contamination on a pad or in the tundra is causing a water quality violation, cleanup may be required regardless of the DRO concentrations in soil. Similarly, if DRO is detected, but there is no evidence of any impacts from contamination, ADEC may not require cleanup, as the native tundra is considered a sensitive environment. Removing native tundra material could lead to thermal instability that may cause thermo-karsting, or other adverse impacts.

The Method 3 Hydrocarbon Risk Calculator is designed for sites with petroleum contamination, with the intention and purpose of providing an improved tool for assessing human health risk from this type of contamination.[17] This method allows for flexibility in determining alternative cleanup levels for soil and groundwater; primarily utilized for non-arctic zones.

Method 4 determines cleanup levels based on a risk assessment. ADEC provides a Risk Assessment Procedures Manual as guidance when utilizing this method. It is not meant to replace national EPA guidelines on risk assessment, it is a supplemental document.

3.2.4 Laboratory Methods

The method to determine GRO, AK 101, is designed to measure the concentration of gasoline range organics in water and soil. This corresponds to a n-alkane range of C_6 - C_{10} and a boiling point range between approximately 60°C and 220°C.[14] This, and most other volatiles aliphatic/aromatic, fractionation methods are based on the EPA SW-846 Method 8015 & 8020 and related techniques employed throughout the petroleum industry.[14] Automotive and aviation gasolines, mineral spirits, stoddard solvents, and naphtha are common examples of petroleum products that are detected in a GRO analysis. A soil, water, or sludge sample must be appropriately diluted, extracted (if a soil) with methanol, and analyzed by gas chromatography. The gas chromatograph (GC) must be equipped with a dynamic headspace concentrator, e.g. a purge and trap device, and detection system capable of detecting both aromatic and aliphatic hydrocarbons, a Photoionization Detector (PID) and Flame Ionization Detector (FID) in series is recommended.[14]

The AK 102, DRO method, provides gas chromatography extraction for the detection of semi-volatile petroleum products. This corresponds to a n-alkane range from the beginning of C_{10} to the beginning of C_{25}, and a boiling point range of approximately 170° C to 400°C.[14] This carbon range includes: kerosene, several types of jet fuel, several types of motor fuels commonly referred to as diesel fuels, and several light heating oils. The extraction and detection method for DRO is similar to the GRO method.

Method AK 103 is designed to measure the concentration of RRO in soil. This corresponds to a n-alkane range from the beginning of C_{25} to the end of C_{36}, and compounds with boiling points from approximately 400° C to 500° C.[14] This range includes heavy heating oils, lubricating oils, and hydraulic fluids. This method is typically employed along with its diesel range organic counterpart in a combination analysis. Components greater than C_{36} are present in products such as asphalts, and mid-range boiling point products such as diesel and bunker C, are also detectable under the conditions of the method. Additionally, this method is based on a solvent extraction, gas chromatography (GC) procedure.

Petroleum concentrations in non-aqueous phase liquids (NAPL) source must be characterized in two ways. Total petroleum concentrations must be analyzed using the AK series methods (AK 101, 102, and 103 for GRO, DRO, and RRO, respectively). The character of the GRO, DRO, and RRO is assessed by subdividing the GRO, DRO and RRO into smaller aromatic and aliphatic equivalent carbon groups (for example C_8 – C_{10} aliphatics; C_{10} – C_{12} aromatics and C_{10} – C_{12} aliphatics, etc.) using EPH (for extractable aromatic and aliphatic petroleum hydrocarbons) and VPH (for volatile aromatic and aliphatic petroleum hydrocarbons) methods.[17]

4.0 North Slope Spills

Spills have been reported and recorded over the many years of operation of the North Slope oil fields and the TAPS. A focus of this paper is to present spill information over a 25 year period, from 1985 to 2010. The region of study begins north of Alyeska's Pump Station 4 at the Dalton Highway milepost 270, TAPS 144, north to the Beaufort Sea, encompassing all oil related operations. This review excludes spills at villages (not related to oil field operations), and releases to the atmosphere (e.g., halon, propane). Additionally, spills at formally used defense sites (FUDS) and long range radar sites are also excluded from this study.

Alaska state law requires all oil and hazardous substance releases to be reported to the ADEC. The Alaska Statute (AS) 46.03.755 and 18 AAC 75.300 outlines the spill notification requirements[12]:

- Immediately notify ADEC of any discharge or release of hazardous substances, to any media, as soon as the person has knowledge of the discharge; and
- Immediately notify ADEC of any discharge or release of oil to water, or any release (including a cumulative discharge or release) of oil in excess of 55 gallons solely to land outside an impermeable secondary containment area or structure; and
- Notify ADEC within 48 hours after discovery (including a cumulative discharge) of oil discharge solely to land in excess of 10 gallons, but 55 gallons or less, or in

excess of 55 gallons, if the discharge or release is the result of the escape or release of oil from its original storage tank, pipeline, or other immediate container into an impermeable secondary containment area or structure; and

- A person in charge of a facility or operation shall maintain, and provide to the Department, on a monthly basis, a written record of any discharge of oil from 1 to 10 gallons.

In early 2000, the primary operators on the North Slope asked the ADEC to consider alternative reporting requirements. The intent was to help remove questions that existed about the reporting of smaller non-oil spills to low sensitive environments (e.g. gravel pads). The agreement established applicable alternative reporting requirements for spills of low risk substances to low sensitivity receiving environments. Releases of substances that have been defined in the agreement either: do not represent an imminent and substantial danger as described in AS 46.09.900 (4) (A) (B) or, are to be reported periodically as defined below:[26]

- A discharge of any quantity to water or tundra (snow, ice roads and ice pads are to be treated as gravel pads) shall immediately notify the ADEC as soon as the person has knowledge of the discharge.
- Immediately notify the ADEC of a discharge to gravel pads in excess of 55 gallons. If the discharge is less than 55 gallons but greater than 10 gallons, then a person in charge of a facility or operation shall maintain, and provide to the Department on a monthly basis, a written record of the discharge including

a cumulative discharge. If the spill is less than 10 gallons, no reporting is required.

- In the event of a discharge to Impermeable Secondary Containment Areas in excess of 55 gallons, the notification must be made immediately to the ADEC. If 55 gallons or less was discharged, no reporting is required.

Below is the list of substances that are included in the agreement.[26]

1. Glycols used for, or intended to be used for, antifreeze protection or in heating systems, these include: propylene glycol, ethylene glycol, and tri-ethylene glycol.
2. Brines used for, or intended to be used for, well control, drilling mud formulations, well work-over operations or as completion fluids.
3. Drilling fluids that are complete in formulation.
4. Seawater or source water (to freshwater environment only).
5. Produced water (oil component must be reported under 18 AAC 75.300)
6. Methanol diluted with 30% or more water. A spill report is triggered by total volume released not the volume of methanol only.

These substances, by definition of the statute, would be considered hazardous substances and therefore would need to be reported as soon as the person has knowledge of the discharge. The amendment has allowed some ‘breathing room’ in the reporting of these low risk substances. The agreement only changes the reporting requirements for certain substances, it does not change the requirement that all spills will be immediately cleaned up, worksites routinely inspected for releases, and all equipment kept in working order.[26]

Other conditions of the agreement include:[26]

- If a release, that is defined by the agreement, occurs during drilling operations and the released material is under the drill rig, the cleanup may be delayed until drilling operations on that well have been completed.
- The low concentrations and volumes of scale inhibitors, corrosion inhibitors, or biocides that are contained in and being used for their intended purpose in brines, seawater, produced water, drilling fluids or crude oil do not trigger a spill reporting requirement. Rather the requirement to notify ADEC of the release shall consider the parent material without the inclusion of these substances. As with all spill reports, all materials released must be included in the report whether or not they would, on an individual basis trigger a reporting requirement to the state.

The agreement may also be modified by written concurrences of both parties.[26] The agreement does not have a termination date. However, ADEC may terminate it and the company may withdraw from it upon fourteen days notification to the other party.[26] To date, seven (7) companies have signed and are operating under this agreement.[26]

4.1 25 Year Spill History

The initial data set utilized for this study was an export from the ADEC SPILLS database[13]. This initial data set included all spills between July 1995 and December 2010, all spill substance types and all sources. Additionally ADEC provided another data set, with data for spills occurring between 1971 and 1995. This data set included over 10,000 spill cases of all substance types and sources that occurred prior to the establishment of the SPILLS database.

The ADEC SPILLS database was originally launched July 1, 1995 with the goal of electronically managing information about oil and hazardous substance releases on a statewide basis[31]. Oil and hazardous substance spill reports / notifications are received by the ADEC Area Response Teams from the responsible party or complainant by telephone or facsimile. The report is then entered into the database by ADEC staff. Spill records are loaded into a web application for browsing and editing by the individual spill upon user request.

In order to effectively manage the effort of compiling, validating and manipulating the spill data, the information was first sorted by year. The most time consuming effort was in the data validation process. The spill data was sorted by individual record. Sorting by unique spill number was not possible due to multiple duplications of spill numbers for an individual spill or a single spill with multiple products (i.e. produced water, having both crude oil and seawater typically) with multiple spill numbers. This was verified by examining the spill date and time, location, source, product and spill volume for the duplications.

Spill substances were then grouped for simplicity. Three groups were created: crude oil, petroleum products and hydrocarbons. The crude oil category is just for crude oil spills only. The petroleum product category assumed anything processed. Gasoline, diesel, grease, engine lube, and transmission oil spills are examples of what is grouped in the petroleum product category. The hydrocarbon spills encompass all spills from the crude oil category and the petroleum products category.

Figure 3 summarizes the spill data for crude oil, petroleum products, and all spill substances. Over the 25 year period, there was an average of 76 crude oil spills, 253 petroleum product spills, and 538 hydrocarbon spills associated with North Slope operations. Although statistics on the number of spills are presented, the environmental consequences of oil spills are likely to depend more on the volume than the number of oil spills.

	Crude Oil		Petroleum Products		All Spills	
Year	**Number**	**Volume (gal)**	**Number**	**Volume (gal)**	**Number**	**Volume (gal)**
1985	107	33,685	223	37,642	421	86,613
1986	101	15,022	179	28,087	376	1,545,071
1987	104	10,616	166	5,804	381	47,775
1988	127	15,973	350	13,519	729	120,900
1989	228	85,625	491	17,606	1,060	213,201
1990	190	28,469	473	14,213	1,065	126,255
1991	181	3,053	525	14,960	1,148	441,063
1992	39	579	203	4,183	330	23,352
1993	95	85,560	401	5,739	921	125,302
1994	84	21,763	305	25.712	743	97,928
1995	17	383	85	4,457	192	51,240
1996	60	9,832	181	7,323	388	48,810
1997	59	13,526	173	14,026	414	1,058,066
1998	63	6,003	152	2,914	383	107,478
1999	29	6,797	173	5,247	338	57,050
2000	56	34,074	196	12,537	348	106,819
2001	54	41,162	260	9,530	521	203,185
2002	40	2,954	220	4,506	495	69,226
2003	48	6,997	212	17,258	414	63,498
2004	50	2,583	190	4,648	415	61,099
2005	35	2,200	180	6,642	416	106,601
2006	41	226,147	205	4,731	505	805,502
2007	34	6,015	300	13,232	600	92,198
2008	52	5,601	268	7,555	551	261,507
2009	49	22,755	243	6,629	471	102,322
2010	30	1,731	212	6,931	375	27,173

Table 2. Number, Volume and Type of Spills Occurring from 1985 to 2010

Produced water is water that is associated with oil and gas formations. This water may be extracted from the reservoir or injected into it. Produced water may also be known as "brine" that commonly contains high mineral or salt concentrations.

The data, however, may include the crude component of the produced water. If the crude oil component was calculated and reported, it was included in this research. It is not possible to determine if it was only the crude fraction reported or a separate crude oil spill without going back to the original records, many of which don't exist.

Listed below is a brief synopsis of the significant releases of oil-related spills in the NS subarea. This information was collected from the ADEC spill database.[13]

Date	Incident	Amount (gal.)	Product	Cause
November 14, 1985	Prudhoe Bay Fuel Terminal	10,500	Gasoline	Valve left open
July 28, 1989	Central Processing Faciltiy, Milne Point	38,850	Crude oil/source water	Overfill of tank
December 10, 1990	Drilling Site L5	25,200	Crude oil	Explosion
April 17, 1996	Gathering Center 2, Prudhoe Bay	6,300	Crude oil	Corrosion
August 21, 2000	Gathering Center 2, Prudhoe Bay	30,030	Crude oil	Equipment failure
January 12, 2001	Gathering Center 1, D-Pad Flowline	38,000	Crude oil	Line Failure
November 17, 2003	Deadhorse	11,000	Diesel	Human Error
June 18, 2004	Flow Station 2	28,350	Crude oil/produced water	Equipment failure
March 2, 2006	Flowline between Gathering Center 1 and2	201,000	Crude oil	Line Failure
November 29, 2009	Lisburne Production Center	45,828	Oily material	Line Failure

Table 3. Significant Spill Events between 1985 and 2010.

As can be seen from Figure 3, the number of reported spills was higher in the early 1990's. This trend corresponds to the height of the crude oil production of the North Slope. Additionally, as previously discussed, the SPAR division had just been formed, possibly resulting in an increase in oversight of the North Slope oil activities. The petroleum products and crude oil spills also follow this trend. The graph also demonstrates that approximately half of all spills can be attributed to petroleum product releases. Therefore, half of all reported spills are associated with the oil production and not the direct process of crude extraction. The number of crude oil spills makes up only a fraction of the total reported spills on the North Slope.

There are three primary peaks, for all spills depicted in Figure 4. The spill volume peak in 1986 was attributed to a >1 million gallon drilling mud release. Drilling mud was exempted from this study. There are several types of drilling fluids used depending on the drilling conditions encountered. They may either be water-based or oil-based fluids; water-based may either use fresh water or salt water. Synthetic based materials are also frequently used as a high performance drilling fluid. Drilling muds typically have several additives such as corrosion inhibitors and surfactants. Drilling mud spills are usually accompanied by varying amounts of crude oil and saline water.[20]

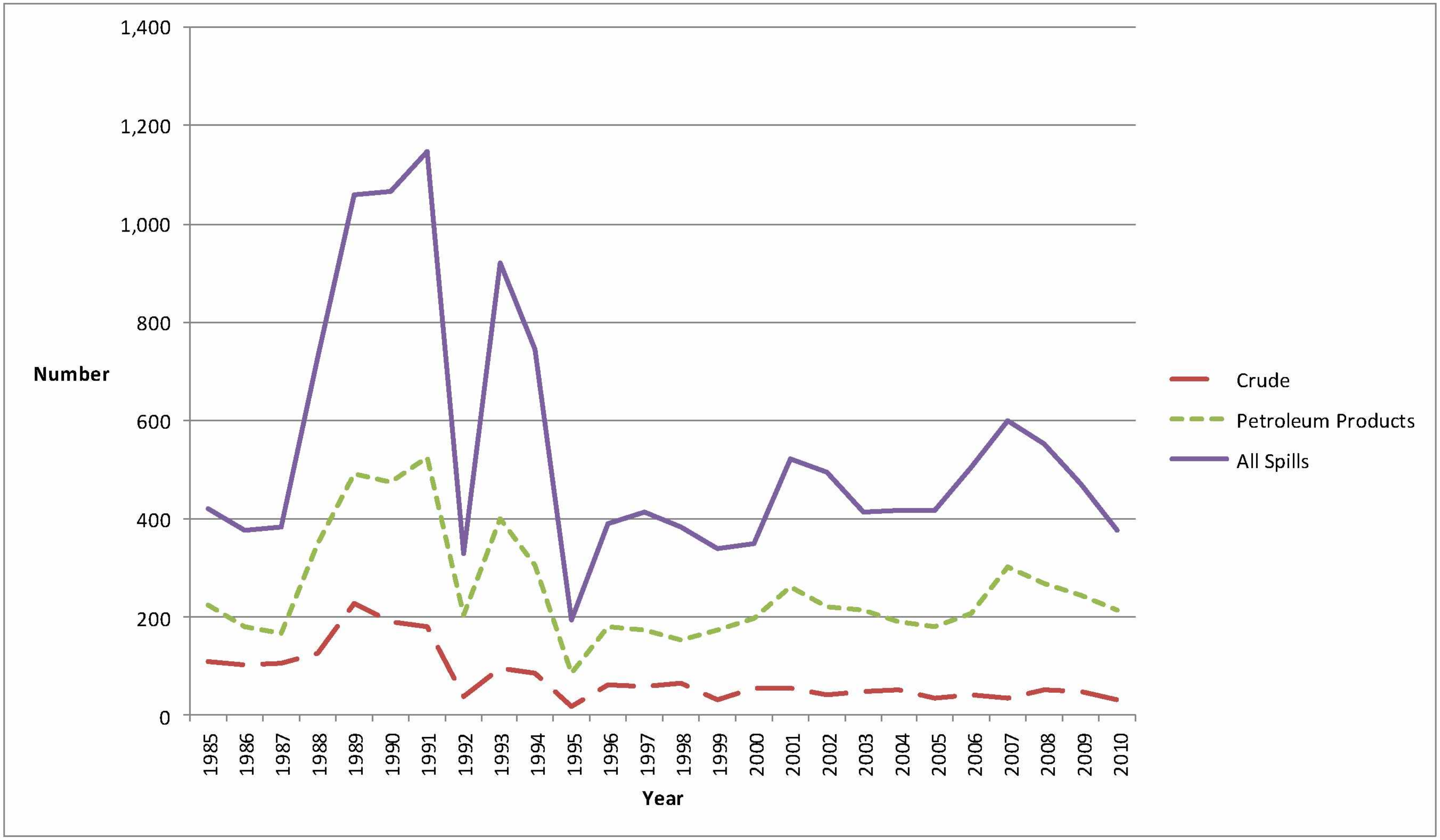

Figure 3. Number of Spills Over 25 Years of Alaska North Slope Crude Production.

The second peak in 1997 was a spill of just under 1 million gallons of seawater. Seawater is typically injected into the petroleum reservoir to maintain formation pressures and allow secondary oil recovery from production wells. Seawater spills are also reportable events to ADEC. The high levels of sodium and chlorine ions in saline spills increase the osmotic potential of soil water, making water uptake more difficult or impossible for non-salt tolerant tundra plants.[20]

The third peak in 2006 is primarily attributed to three spill events. The first contributing spill event was an almost quarter of million gallons of produced water. The second contributing spill was just shy of a third of a million gallons of drilling muds. Lastly, was the Gathering Center #2 (GC-2) Oil Transit Line Release. On March 2, 2006 a transit line between GC-2 and GC-1 developed a quarter inch hole in the pipeline due to internal corrosion.[13] Approximately 201,000 +/- gallons of crude oil spilled and covered almost 2 acres consisting of tundra and a frozen lake.[13]

The number of spills on the NS and the crude production can be seen in Figure 5. The trend is consistent with activity. The time during the peak oil is when we see the higher number of spills. Over time, as the oil production and activity decline, so do the number of spills with a few exceptions. The decline in oil production has limited activity and growth on the NS. However we may see more spills as the infrastructure ages.

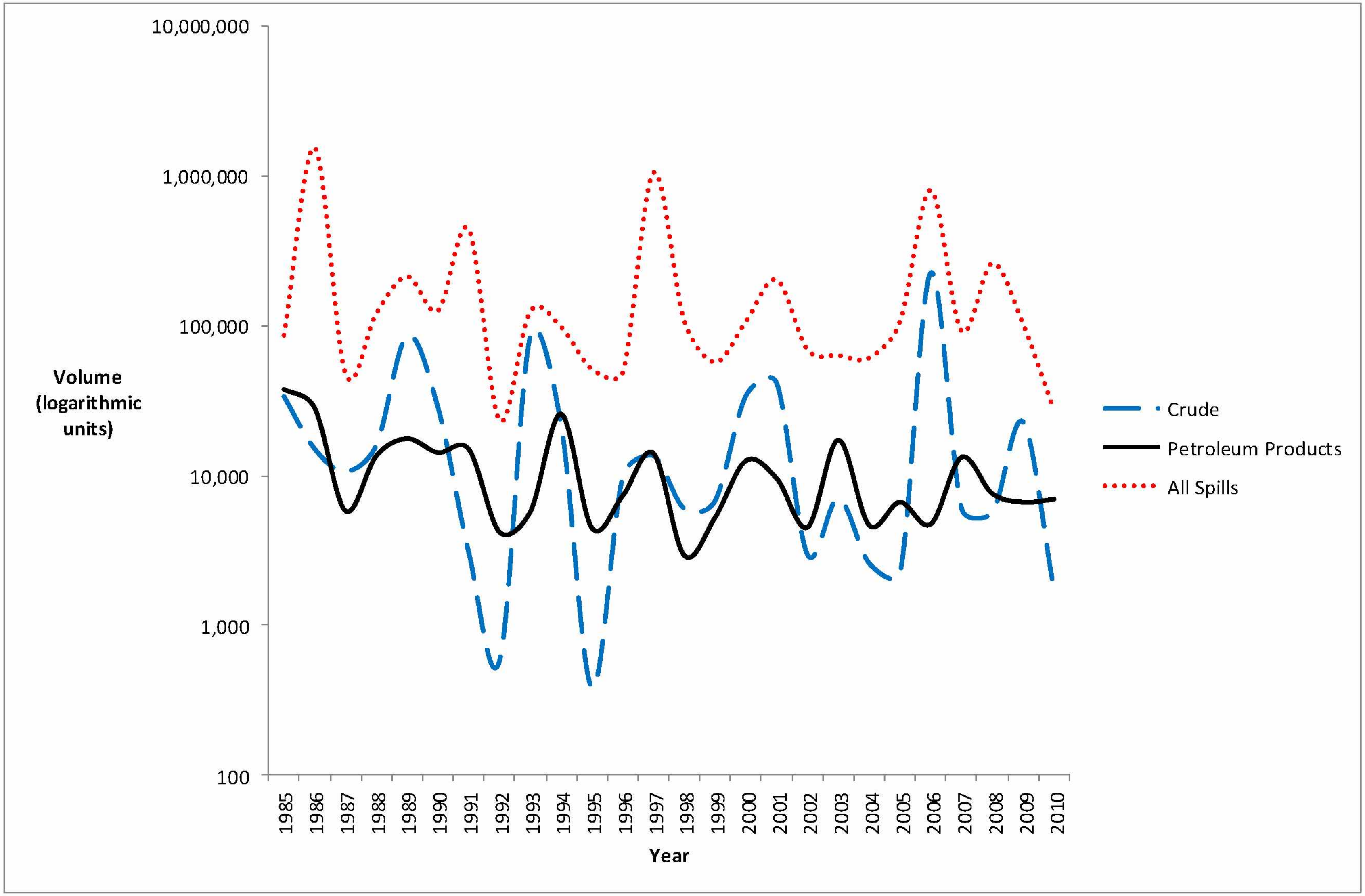

Figure 4. 25 Year Spill Volume Summary.

Figure 5. Number of Spills Over 25 Years of Alaska North Slope Crude Production

5.0 Contaminated Sites 25 Year Summary

Contamination can result from a variety of intended, accidental, or naturally occurring activities and events such as manufacturing, waste disposal, accidental spills, illegal dumping, and leaking underground storage tanks. Contaminated sites are categorized in a variety of ways, often based on the level and type of contamination and the regulations under which they are monitored and cleaned up. Many sites, particularly the largest and most severely contaminated, are tracked at the national level, but many others are tracked only at state or local levels.

Institutional controls are non-engineered instruments, such as administrative and legal controls, that help minimize the potential for human exposure to contamination and/or protect the integrity of whatever is at risk.[18] Institutional controls often are used in conjunction with, or as a supplement to, other measures (such as treatment or containment) to prevent or reduce exposure. They may exist after a site has been cleaned up to the extent possible, as determined by the ADEC.

ADEC rarely relies on natural attenuation as a remedial strategy. Natural attenuation generally describes a range of physical and biological processes which, unaided by deliberate human intervention, reduce the concentration, toxicity of mobility of contaminants. The advantages of natural attenuation include the reduced generation of wastes, possible reductions in the cross-media transfer of contaminants, and lower remediation costs. The disadvantages include slower cleanups, the creation of transformation products that may be more toxic than the original contaminants, more costly site characterization, a reliance on uncertain institutional controls to ensure long-term protection, and the chance that subsurface conditions will not support natural attenuation as long as necessary.

Table 4 summarizes the number of contaminated sites on the North Slope of Alaska over a 25-year period. The year listed is the known or estimated date of contamination. Sites listed as open are currently open versus only open at the end of their respective year.

As can be demonstrated from the table, about half of the number of cases has been cleaned up completely. Approximately one-quarter of the sites are still open and the other one-quarter of sites have been cleaned up with institutional controls in place.

Year	Number of Cases	Open	Cleanup Complete	Cleanup Complete – Institutional Controls
1985	2	1	0	1
1986	2	1	1	0
1987	2	1	1	0
1988	4	1	1	2
1989	19	3	10	6
1990	8	2	4	2
1991	15	2	8	5
1992	16	4	8	4
1993	9	3	3	3
1994	12	1	10	1
1995	5	1	4	0
1996	12	6	5	1
1997	12	1	7	4
1998	3	1	1	1
1999	5	0	2	3
2000	3	1	1	1
2001	9	2	7	0
2002	6	1	4	1
2003	8	2	6	0
2004	4	2	1	1
2005	3	0	1	2
2006	3	0	1	2
2007	8	3	3	2
2008	3	2	0	1
2009	16	2	12	2
2010	9	2	7	0
TOTAL	**198**	**45**	**108**	**45**

Table 4. Current Status of Contaminated Sites.

6.0 Cleanup Tactics Utilized on the North Slope

"Tundra" is a word to describe the treeless landscape found north of the boreal forest and above tree line in the mountains throughout Alaska.[19] Due to the soil staying or falling below the freezing point of water for two of more years, permafrost is formed. The presence of permafrost, in addition to the short growing season in Alaska allowing only shallow ground to thaw, tundra is the most predominant vegetation type to survive these conditions. There are four tundra types in Alaska, aquatic tundra, wet tundra, moist tundra and dry tundra; all four tundra types are found on the North Slope:

Tundra Type	Typical Topography	Soil Conditions	Vegetative Growth
AQUATIC TUNDRA	Ponds, lakes, or streams	Sediment under shallow water, organic accumulations	Aquatic sedges, grasses, and forbes
WET TUNDRA	Coastal or low areas	Soil saturated, standing water often present, thick root and organic layer	Primarily emergent aquatic grasses and sedges
MOIST TUNDRA	Foothills, gentle slopes	Well-drained to saturated soil. Dense root mat with some organics	Includes tussock tundra, grass meadows, low shrubs, and some forbes
DRY TUNDRA	Mountains, steep slopes, bluffs and riverbanks	Well-drained, exposed, rocky, or barren location with little root mat or organics	Sparse, often low-lying plants such as mat-forming heathers, cushions plants, lichens, and mosses

Table 5. Characteristics of Different Tundra Types

Although tundra can survive in the harshest of conditions, it is sensitive to disturbance. Surface disturbances can cause ice in the soil to melt resulting in subsidence, which affects drainage patterns and tundra type.[20]

In its third edition, the Tundra Treatment Guidelines provides a list of tactics that may be used to treat and monitor tundra impacted by spills of crude oil, petroleum products, seawater and other substances after the initial response of eliminating spill migration.

Treatment of spills to tundra is difficult for several reasons:[20]

- Short summer season available when most treatments can be implemented
- Cold temperatures that limit biological activity and biodegradation
- Physical damage that may be caused by surface activities
- Remote locations

To develop a cleanup strategy for the North Slope, consideration must be made in regard to site characterization, treatment goals, appropriate treatment tactics, and the implementation of the treatment tactics. Much information needs to be gathered about the treatment site such as spilled material, to what tundra type the spill occurred, spill effects to media (i.e. geology, hydrogeology, vegetation), and any human health or wildlife risks.

Objectives for spill site characterization are, to define site features that may influence oil fate and persistence, delineate areas affected by the spill, describe the variations in oil's physical character, concentration and mode of occurrence, and evaluate the variability of oil concentrations and oil penetration depth. The type of information to be assessed for site characterization should lead to a clear understanding of the spilled oil's source and fate.

The objectives of any tundra cleanup are to recover spilled material, minimize the potential for migration of contaminants into the surrounding tundra, minimize damage to the tundra from both the spilled material and the response actions, and minimize the time period for tundra recovery[20].

Because the goal of spill response is to minimize the overall impacts on natural and economic resources, some resources will be of greater concern than others; and response options offering different degrees of resources protection will be selected accordingly. Decisions regarding cleanup method(s) must balance two factors (see also Figure 6):

1. The potential environmental impacts with the natural recovery alternative, and
2. The potential environmental impacts with a response tactic or group of tactics.

The tactic or group of tactics that most reduces consequences effectively should be the preferred response tactic.

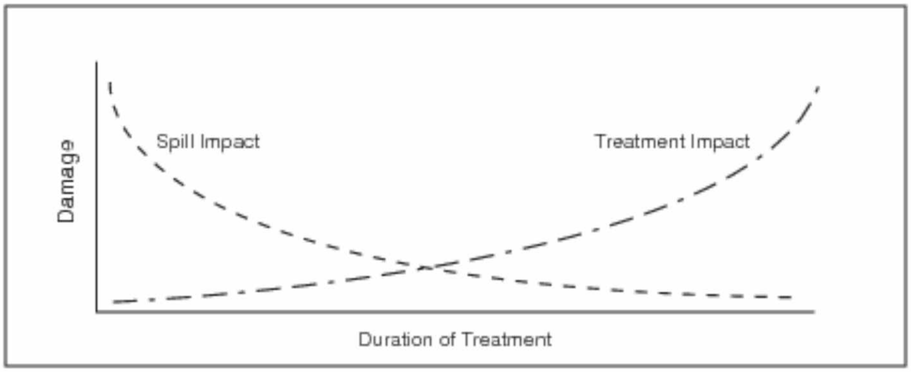

Figure 6. Spill Impact versus Treatment Tactic[20]

Potential impacts can be determined before considering the need for, or type of, response strategies. For example, evaluating a gasoline spill in an exposed seawall environment might lead to the conclusion that, due to evaporation and low habitat use, minimal environmental effects will occur and further evaluation is unwarranted. On the other hand, assessing a spill of a light-weight crude oil in a soft intertidal area would likely indicate a high potential for environmental effects; therefore sensitive environment response tactics would need to be evaluated.

There are four types of tactics outlined in the TTG and they are labeled according to their purpose: P (Planning), CR (Containment Recovery), TR (Tundra Rehabilitation) and AM (Assessment and Monitoring). For example, Tactic P-3: Understanding the Effects of Spills on the Tundra, provides a description of some of the potential spill substances and their expected effects on tundra vegetation and soil.[20] Some of the CR tactics include flooding, flushing, burning contaminated vegetation, mechanical removal – scraping, trimming and brushing, and excavation for offsite disposal. Tundra Rehabilitation Tactics incorporate irrigation, tilling, enhancing natural vegetation, transplanting, seeding and backfilling. The AM tactics take into account delineation of the spill area, field indicators, preventing damage from cleanup activities and testing soil and water for re-vegetation. Each tactic contains an objective, deployment depictions, resource sets required to implement the tactic and deployment considerations and limitations.

It is critical in spill responses that plans reflect the sequential step-by-step nature of tasks. A tundra treatment tactic strategy consists of a set of tactics implemented sequentially (Figure 9).[20] Using multiple methods simultaneously throughout an incident can produce a more effective response and minimize environmental impacts. Periodic review of the tactic strategy must be part of the spill response. Each response tactic has advantages, disadvantages and limitations in its effectiveness.

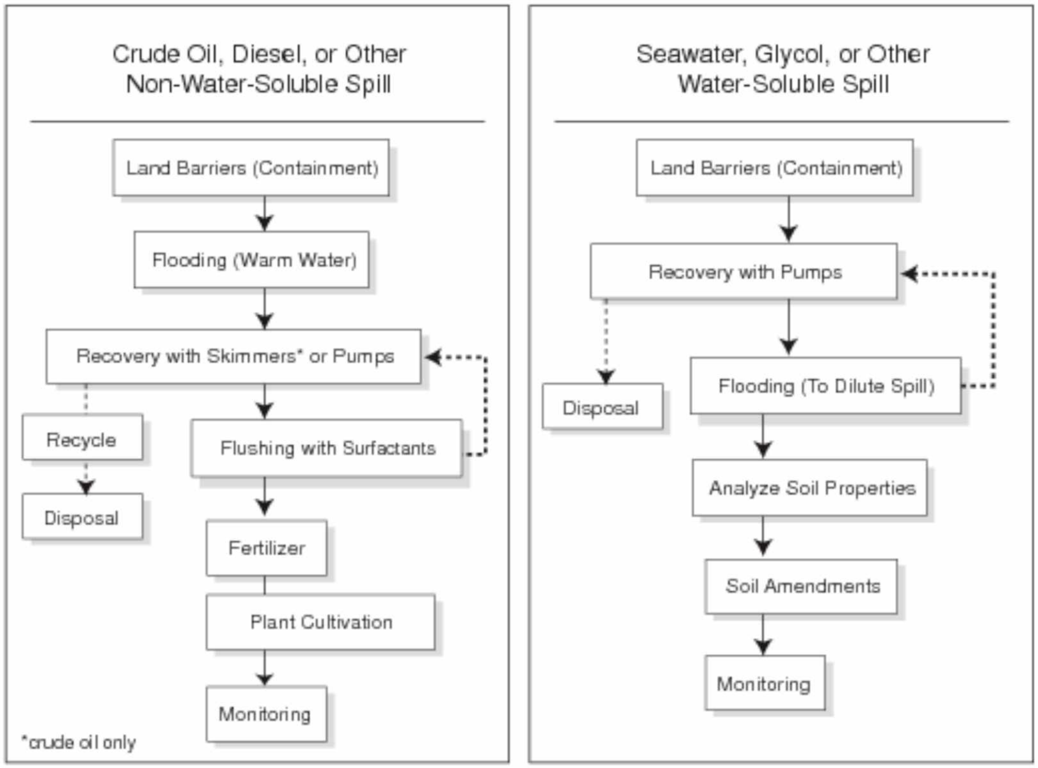

Figure 7. Sequential Tundra Treatment Tactic Strategies.

The production of the TTG resulted in a major shift for spill site closure actions from the ADEC. Closure is based on restoration rather than achieving a cleanup level.[24] The TTG defines conditions under which restoration and re-growth are most likely to occur following a spill event. Although the decision tree for cleanup actions still lists numerical standards, they are not necessarily used for site closure (Figure 4).[20] They are intended to be used as action levels during the response phase of following a spill. If contaminant levels exceed these values, it can be expected that moderate to severe tundra damage will occur.[24]

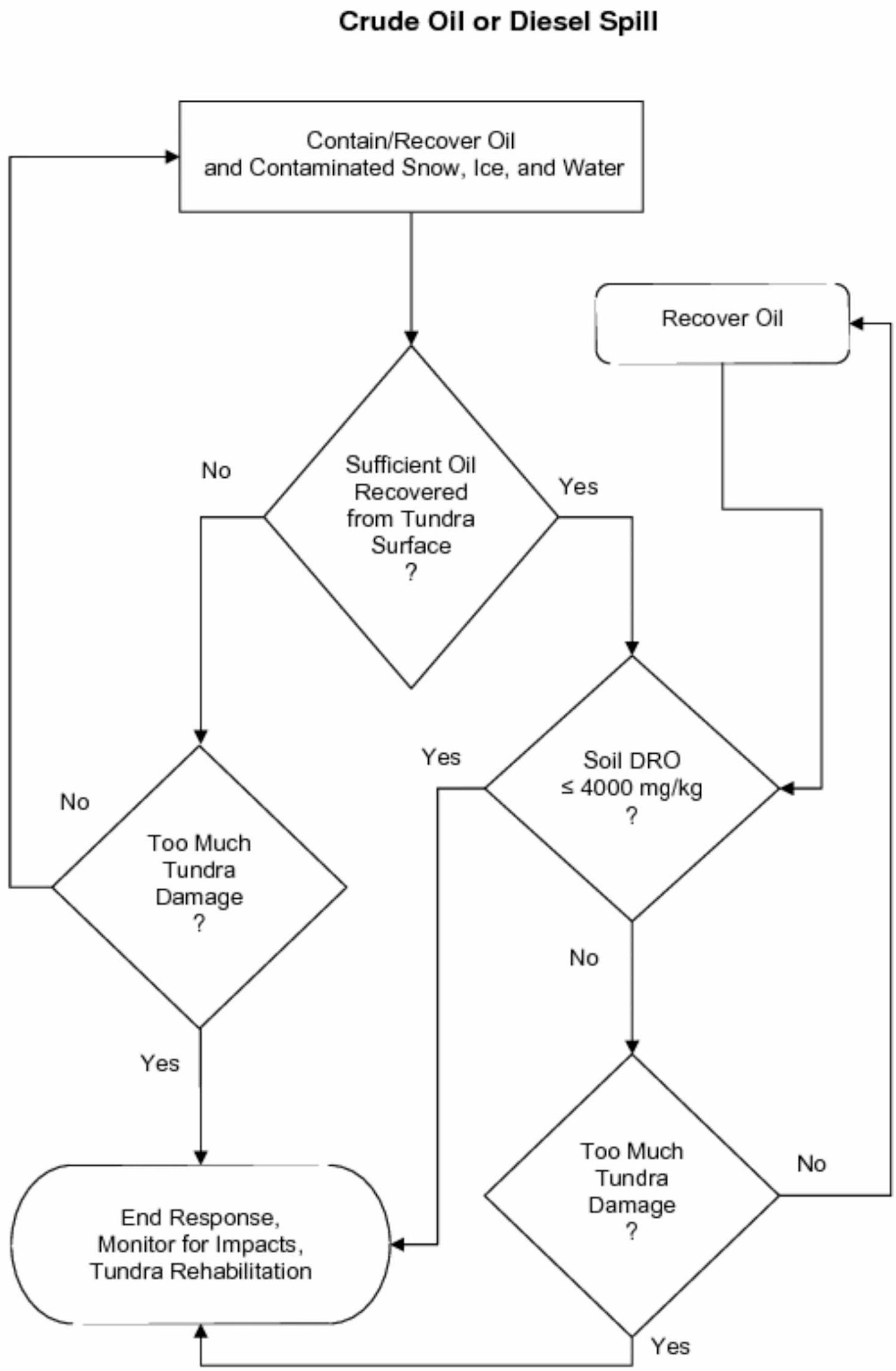

Figure 8. Generalized example of a decision tree to help develop a site-specific treatment strategy for crude oil and diesel spills.[24]

The TTG was first applied to an incident that occurred in April 2001, at the Kuparuk Oil Field Central Processing Facility, North Slope, Alaska. An estimated 92,400 gallons of produced water containing 554 gallons of crude oil spilled to the tundra. The release was due to external line corrosion. The technique used to remove the oil and salt water (produced water) consisted of more than one tactic as outlined in the TTG. A regimen of hot water flushing, thermo-remediation (burning) and detergent washing was implemented. As expected, it took multiple flushing events to loosen and remove the crude oil from the tundra vegetation. The areas of the spill site that did not containing floating crude took less effort to remove the produced water but the removal techniques remained the same. Conductivity (salt levels) and hydrocarbon testing was conducted in all areas of the spill site. Target levels for conductivity were <3 mmhos/cm, total petroleum hydrocarbons (TPH) <13,000 mg/kg and DRO <1,000 mg/kg. It was with the aid of the TTG that the spill site was cleaned up to a standard that allowed for optimal re-growth/regeneration of the tundra.[24]

The TTG is an excellent tool that contains site-specific response strategies to oil and hazardous substance spills to tundra. It was designed to be a dynamic and living document such that additional information from research and future spill events can easily be incorporated.

7.0 Summary

Alaska has an abundance of natural resources including oil, natural gas and coal. It is critical to minimize the occurrence of oil spills to ensure protection of Alaska's people and the environment. The goal of spill response is to minimize the overall impacts on natural and economic resources, with some resources being of greater concern than others.

Prudhoe Bay remains the largest oil field in North America, with four of the top 10 producing oil fields existing on the North Slope[28]. Aging infrastructure on the North Slope could cause oil spills and "warrants increased vigilance, corrective actions and oversight," according to an Alaska Risk Assessment conducted by ADEC[31]. However in looking at the spill data gathered over the period of 25 years, the number of crude oil and petroleum product spills has declined. The number of spills is consistent with North Slope activity. The reduction in the number of spills may also be due to a greater awareness of how to minimize the probability of spills as well as better oversight.

ADEC's Prevention and Emergency Response Program's mission is to protect public safety, public health and the environment by preventing and mitigating the effects of oil and hazardous substance releases and ensuring their cleanup through government planning and rapid response[2]. Soil cleanup levels can be determined by one of the following four methods:

- Method One provides original cleanup levels based on a decision matrix.
- Method Two provides pre-calculated risk-based cleanup levels.
- Method Three levels are calculated using site-specific information.

- Method Four levels are calculated on the basis of a risk assessment.

The majority of spills are cleaned up under Method One. When a spill cannot be cleaned up with the PERP, those sites are transferred to the CSP for long term monitoring and cleanup. The data reveals that the majority of contaminated sites have been cleaned up with no institutional controls in place.

Complexity of spill cleanup will vary with the receiving environment. The nature and severity of impacts from a spill vary with tundra type, due to differences in hydrology, soils and vegetation. Tundra types also differ in their sensitivity to the physical impacts that may result from a cleanup operation. ADEC uses the Tundra Treatment Guidelines as a tool for spill cleanup. The manual provides a list of tactics that may be used to treat and monitor tundra impacted by spills.

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