Non-mechanical Response Gap Estimate for Two Operating Areas of Prince William Sound

Report to
Prince William Sound Regional Citizens' Advisory Council

April 15, 2008

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Executive Summary

Technological, planning, and environmental monitoring improvements over the past two decades have greatly enhanced the ability to respond to an oil spill in Prince William Sound. The "response gap" is the window between the upper limits of the response system (in terms of environmental conditions) and the conditions at which Hinchinbrook Entrance is closed to laden tankers.

Nuka Research and Planning Group, LLC (Nuka Research) developed a methodology to estimate the response gap by comparing response limits for dispersant and in-situ burning tactics to environmental conditions data from 2000-2005.

Nuka Research then used a Response Gap Index to estimate how often a specific response tactic would be effective in a particular operating area. When one environmental factor would preclude a response completely, or two environmental factors would compromise a response, then a response is judged not possible for that time period. This study indicates that:

- Dispersant application in the Central Sound is *not* possible 75% of the time year-round, mostly because of darkness and conditions too calm for dispersant mixing.
- Dispersant application at Hinchinbrook Entrance is *not* possible 80% of the time year-round, mostly because of darkness, conditions too rough for application, or too calm for mixing.
- In-situ burning in the Central Sound is *not* possible 25% of the time in summer and 70% of the time in winter, mostly because of darkness and sea state.
- In-situ burning at Hinchinbrook Entrance is *not* possible 86% of the time in winter and 35% of the time in summer, mostly because of darkness and sea state.

Nuka Research then compared the results of these response gap estimates with the results of the *mechanical* response gap estimate for the same two operating areas of Prince William Sound, concluding:

- When all technologies are considered together, some type of response can be mounted in Central Prince William Sound 90% of the time and 70% of the time at Hinchinbrook Entrance.
- Mechanical Response is a more robust response technology than either dispersants or in-situ burning in both operating areas. Mechanical response is the response method *least* likely to be precluded by environmental conditions in both the Central Sound and Hinchinbrook Entrance areas.
- Overall, response in either area is more likely to be precluded by environmental factors in winter than in summer.

Numerous factors challenged this analysis, including the lack of clearly established operating limits for both dispersants and in-situ burning. Also, factors additional to the environmental observations used in this analysis impact the effective application of both response methods. Other factors include the type of oil, type of dispersant or ignition method, oil viscosity and weathering, dispersant dosage and droplet size, ice, and precipitation. Because of these other factors, the results of this study should not be used to determine when or when not to implement the dispersant or in-situ burning tactics.

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Introduction

Technological, planning, and environmental monitoring improvements over the past two decades have greatly enhanced the ability to respond to an oil spill in Prince William Sound. However, tankers may still be transiting the Sound when weather conditions would preclude a response. Realistic planning requires a good understanding of how often this may be the case. The "response gap" is the window between the upper limits of the response system (in terms of environmental conditions) and the conditions at which Hinchinbrook Entrance is closed to laden tankers.

Prince William Sound Regional Citizens' Advisory Council (PWSRCAC) contracted Nuka Research and Planning Group, LLC (Nuka Research) to analyze the response gap that may exist for non-mechanical response tactics (dispersants and in-situ burning) at two locations in Prince William Sound (PWS). This analysis and report follow a February 2007 report by Nuka Research: "Response Gap Estimates for Two Operating Areas in Prince William Sound." This first report considered only the open-water mechanical response tactic.

Purpose of the Report

Nuka Research developed a methodology to estimate the response gap by comparing response limits in terms of four environmental factors[1] to environmental conditions data from 2000-2005. The same methodology and dataset used to estimate the *mechanical* response gap in the February 2007 study were used again to estimate the *non-mechanical* response gap for PWS. Dispersants and in-situ burning are the two non-mechanical response tactics in the PWS Tanker Oil Discharge Prevention and Contingency Plan (C-plan).

This report shows the results of the hindcast analysis for both mechanical and non-mechanical response. It is not intended to imply anything about the compliance of the C-plan or any other document with state or federal laws or regulations. It also should not be used to make decisions about when non-mechanical response methods should be used, as there are multiple factors

1 The environmental factors considered were: wind, sea state (wave height and period), temperature, and visibility.

impacting their effectiveness that are not addressed here, including: the type of oil, type of dispersant or ignition method, oil viscosity and weathering, dispersant dosage and droplet size, ice, and precipitation.

GOALS AND CHALLENGES

The study goal was to determine the percentage of time that a response would not be possible for: a) aerial dispersant operations and b) in-situ burning operations. The following challenged this as well as the mechanical response gap study:

- There are multiple, diverse operating areas in PWS and the environmental conditions may vary widely at any given time, both across and within operating areas.
- The response limits are affected by a number of environmental factors that interact with each other.
- Environmental factor data is not available for all operating areas.

Background

Legal and Regulatory Framework

This section describes the legal and regulatory framework for response gap issues as they relate to non-mechanical response.

STATE REQUIREMENTS

The possibility of a response gap has been established in State of Alaska laws and regulations since the early 1990s, but applies only to mechanical response. Still it may be useful to understand what percentage of time a non-mechanical response tactic can be counted as effective.

Anyone operating a tank vessel must have a contingency plan approved by the Alaska Department of Environmental Conservation (ADEC).[2] One requirement of these plans is to describe the realistic maximum response operating limitations (RMROL) that might be encountered during a response. This description must include an analysis of the frequency and duration of the limitations, expressed as a percentage of time, for the following environmental factors:

- Weather, including wind, visibility, precipitation, and temperature;
- Sea states, tides, and currents;
- Presence of ice and debris;
- Hours of daylight; and
- Other known environmental conditions that might influence the efficiency of the response equipment or the overall effectiveness of the response.[3]

2 Alaska Statute 46.04.030(c)
3 Alaska regulation: 18 AAC 75.425(e)(3)(D)

According to these requirements, the PWS Tanker C-plan specifies the limits to non-mechanical response shown in Table 1.

Table 1. PWS Tanker C-plan RMROL for non-mechanical response

Environmental Factor	Conditions that Could Preclude a Response: Dispersants	Conditions that Could Preclude a Response: In-situ Burning
Wind	Winds > 27 knots across the track of the aircraft applying the dispersants.	Winds > 20 knots make it difficult to ignite or maintain a burn.
Sea State	Not mentioned.	Limited in much the same way as mechanical response, because of the need to contain oil. Seas > 10 ft with strong tides and currents.
Air Temperature	No appreciable impact.	No appreciable impact.
Visibility	Visibility may preclude application by aircraft. Flight operations limitations are based on visual flight rules for rotary and fixed-wing aircraft: a 500-ft ceiling and 1 mi visibility if in sight of land, or 500-ft ceiling and 3 mi of visibility over open water and land is not in sight.	Poor visibility that precludes seeing oil, vessels towing boom, burning, potential dangers, and aircraft operations. Depending on other factors, visibility limitation may be < 0.5 nm for vessels tracking oil.

FEDERAL REQUIREMENTS

In 2002 the US Coast Guard issued a proposed rulemaking to require vessels federal contingency plans to show a dispersant capability (*Federal Register*, Vol. 67, No. 198 issued October 11, 2002). The Coast Guard has not yet finalized these regulations, however. There are no federal regulations related to non-mechanical response operating limits.

Methods

This methodology assumed that past weather patterns and associated environmental factors are predictive of those in the future, and that the limitations on dispersants and in-situ burning would remain consistent. Nuka Research used a "hindcast" to estimate the probable distribution of environmental factors and the Response Gap Index over time by assembling a large dataset of environmental factors for 2000-2005.

Nuka Research developed the following methodology for this response gap analysis. Steps 1-4 below were based entirely on the mechanical response gap study (Nuka Research 2007). Steps 5-8 were specific to the non-mechanical response strategies and therefore unique to this report.

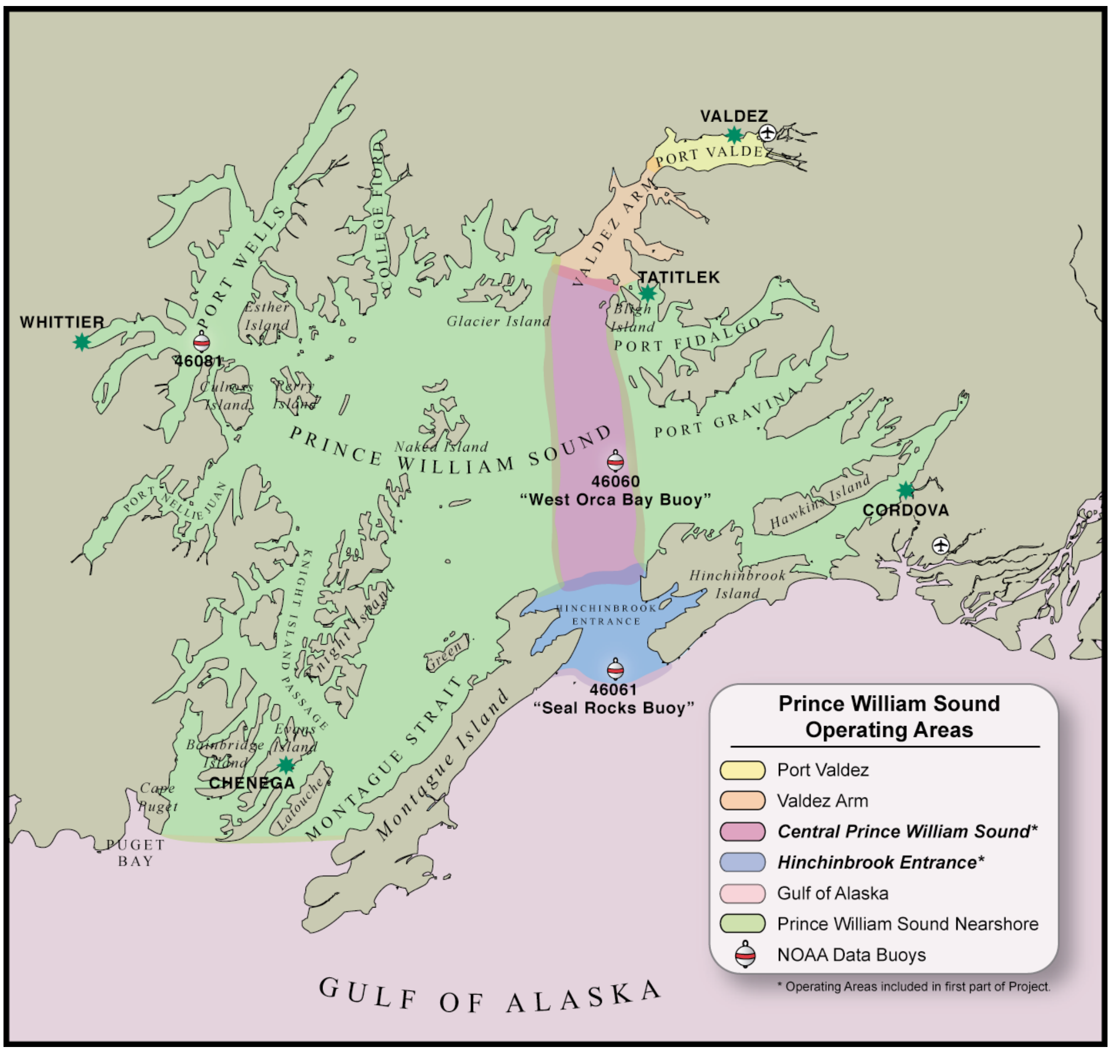
1. Select operating environments.
2. Identify environmental factors.
3. Assemble dataset.

4. Characterize dataset.
5. Review operational limits.
6. Establish operational limits.
7. Calculate a Response Gap Index.
8. Summarize the Response Gap Index.

Operating Areas

As with the mechanical response gap study, this analysis was challenged by the fact that PWS has diverse operating areas and conditions that are difficult to generalize even within the same area. Weather conditions are markedly different between winter and summer,[4] and can vary widely by micro-climate. The study focused on the Central Sound and Hinchinbrook Entrance, the same two operating areas used in the mechanical response gap analysis. They are the only areas for which sufficient environmental data are readily available for analysis.

Figure 1. PWS operating areas and NOAA buoys



4 For the purposes of this study, winter is October-March and summer is April-September.

Environmental Factors and Dataset

ENVIRONMENTAL FACTORS

Datasets for the two operating areas were built from civil twilight tables and NOAA's National Data Buoy Center buoy observations. West Orca Bay Buoy (#46060), commonly referred to as the Mid-Sound Buoy, was used for the Central Prince William Sound. Data from the Seal Rocks Buoy (#46061) was used for Hinchinbrook Entrance. These buoys provided data on the following environmental factors: wind speed, wave height and wave period (sea state), and temperature.

There was no actual observations of visibility data describing fog, precipitation, other such factors available, so the visibility limits were considered only in terms of darkness, based on the civil twilight tables.

Table 2 shows the data sources used for each environmental factor.

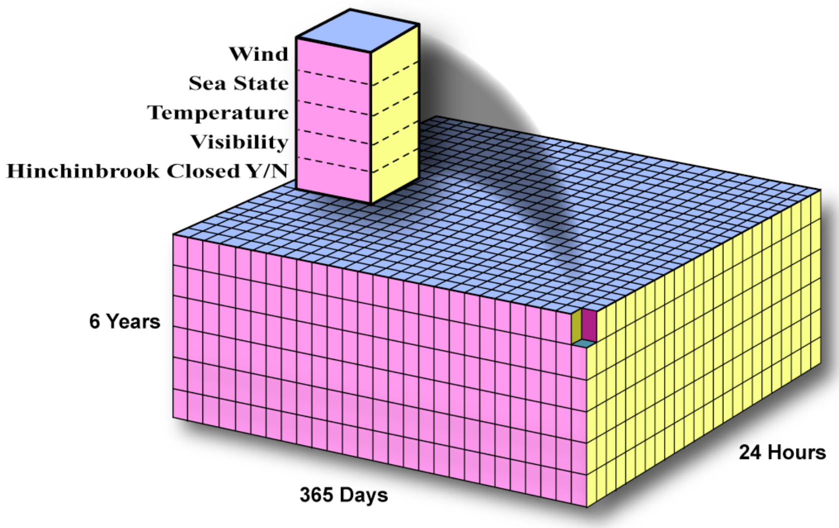
Table 2. Data used for each environmental factor

Environmental Factor (units)	Data Source	Comments
Wind (knots)	Buoys 46060 and 46061	None.
Sea State (wave height in feet and wave period in seconds)	Buoys 46060 and 46061	Because the short-period waves are more detrimental to response operations than long-period waves, a wave steepness parameter was calculated to distinguish between swell and wind driven waves. The wave steepness parameter (WSTP) is calculated as **WSTP = WVHT / (*g* X DPD^2)**, where: WVHT=Significant wave height, calculated as the average of the highest one-third of all of the wave heights during the sampling period, g=the acceleration due to gravity (32.174 ft/s^2), and DPD=Dominant wave period is the wave period with maximum wave energy.
Temperature (°F)	Buoys 46060 and 46061	None.
Visibility	Civil twilight tables	Reliable observations of visibility during daylight hours were difficult to obtain, so the only visibility restriction considered for this phase of the study was due to darkness. Using only daylight/darkness visibility restrictions resulted in a conservative estimate of the response gap.
Hinchinbrook Status	Each hourly set of observations in the matrix included another bit of data. A flag was set to indicate if Hinchinbrook Entrance was opened or closed at the time of the observation. This information was calculated from data obtained at the Seal Rocks Buoy; if WSPD equaled or exceeded 45 knots or if WVHT equaled or exceeded 15 feet, then Hinchinbrook Entrance was deemed closed. Observations for times when Hinchinbrook Entrance was closed were not considered when determining the response limits.	

THE DATASET MATRIX

Figure 2 depicts the normal size of the matrix for each dataset, consisting of hourly observations over 6 years. Each cell of the matrix contains observations for four environmental factors (when available): wind, sea state, air temperature, and visibility.

Figure 2. The dataset matrix



Omitting data gaps (see discussion of Missing Data Observations, below), a dataset was generated with about 42,000 concurrent observations for the Central Sound and Hinchinbrook Entrance for 2000-2005. Civil twilight data for Valdez were added.

MISSING DATA OBSERVATIONS

The objective was to enable a meaningful statistical analysis by assembling 6 years worth of recent data, for a total of 6 years x 365 days x 24 hourly observations. Data were assembled for both operating areas for the years 2000-2005.

The number of hourly observations available ranged from about 4,300-8,700 per year for Buoy #46060 (Central Sound), for a total of about 46,000 valid observations over the 6-year period. For Buoy #46061 (Hinchinbrook Entrance), the number of hourly observations available ranged from about 6,700-17,500 (in 2005, an observation was made every hour and 30 minutes past the hour), for a total of about 57,000 valid observations over the 6-year period. For more details, including graphics showing the completeness of data by month for each location, please refer to the mechanical response gap study (Nuka Research 2007).

CHARACTERIZING THE DATASET

The mechanical response gap study (Nuka Research 2007) also provides extensive description of the dataset, including histograms and cumulative-distribution plots of significant wave height, wind speed, wind direction, gusts, and air temperature from the NOAA buoys; joint-probability-distribution plots of wave height and modal wave period for summer, winter, and annually; and daylight curves based on civil twilight data.

Establishing Response Limits

At the start of the non-mechanical response gap analysis, Nuka Research reviewed published literature on response limits to dispersant application and in-situ burning. This review included scientific articles, both peer-reviewed and otherwise, operational guidance documents, and the PWS Tanker C-plans from the past several years.[5]

The literature review focused on the environmental factors to be used in the response gap analysis, and did not consider other factors such as water temperature, salinity, precipitation, or visibility other than darkness vs. daylight. Extensive literature (based primarily on laboratory-scale testing) on the relationship between oil weathering and dispersant or in-situ burn effectiveness was also omitted.

After considering the results of this literature review, the PWSRCAC Oil Spill Prevention and Response Committee, Scientific Advisory Committee, and Dispersants Project Team requested slight modifications then approved the limits described in this document.

Establishing Limits for Dispersants

Dispersant effectiveness is impacted by the environmental factors selected for consideration in this study, as well as several other critical factors omitted due to a lack of data.

Studies of the relationship between chemical dispersant use and the relevant environmental factors focused primarily on the need for wave energy, which is related to the interconnected factors of wind and sea state. Effective dispersion requires an accurate application of the chemical and sufficient mixing (wave) energy. On the other hand, if wave energy is high enough, then the chemical application will provide no added benefit over natural dispersion. There are thus both maximum and minimum wind and sea state limits for dispersant use.

These generalizations are complicated by the fact that dispersant applied to calm water may be effective if the sea state increases, though for how long after a application this may be the case is unknown (NRC 2005). It is also possible that naturally-dispersed oil may resurface when conditions calm (NRC 1989).

5 Only the most recent version is cited: there has been no change in the response limits cited in the c-plans.

Both aircraft and vessels can be used to apply dispersants. In order to function correctly, responders must be able to operate these platforms safely, access and visualize the spill area, and target the spilled oil with the sprayed dispersant. This analysis focused on aircraft as the dispersant platform because this method would be used for very large spills.

Many statements in the literature about environmental factors and response limits for dispersants were too vague for the purposes of identifying specific response limits for a gap analysis. Such statements have been omitted, except those from the Tanker C-plan.

While the data available on response limitation due to environmental factors considered in this stud was relatively thin, there is a much greater body of literature on the other factors—not included in this study—that are critical to the efficacy of dispersant application. These factors include:

- Type of oil,
- Type of dispersant,
- Oil viscosity and weathering,
- Dispersant dosage,
- Slick thickness,
- Presence of ice, and
- Dispersant droplet size.

Furthermore:

- For aircraft application, ceiling is a key limiting factor omitted from this gap analysis due to lack of data.
- Flying conditions must be suitable to transport dispersant supplies from Anchorage or Valdez, but this analysis considered only conditions at the hypothetical spill site (Central Sound or Hinchinbrook Entrance). The fixed-wing aircraft listed in the 2007 SERVS Technical Manual is based in Anchorage.
- Environmental conditions could hamper or preclude accurate monitoring operations, but limits of monitoring operations were not considered in this study.
- Both dispersants stockpiled by the PWS shippers must be stored at or above -30ºF (EPA 2007).

OVERVIEW OF LIMITS IN THE LITERATURE

Table 3 summarizes the ways in which the selected environmental factors can impact dispersant application and efficacy, as described in the literature. The limits cited in the Tanker C-plan are shown in **bold.**

Table 3. Impact of select environmental factors on dispersant use reported in literature.

Factors	Limits Related to Platform & Application	Limits Related to Dispersion of Oil
WIND (knots)	*Aircraft:* Maximum 25 knots, according to ARPEL guidelines (2007), but no basis given. Maximum 30-35 knots (ExxonMobil 2000 in Fingas 2004). Maximum 25 knots or the dispersant will not hit the slick (NRC 2005). **Maximum 27 knots** (2007 Tanker C-plan). *Vessel:* Maximum 7-21 knots (ExxonMobil 2000 in Fingas 2004). Maximum 29 knots for spray boom, based on workers' observations that dispersant application was "relatively unaffected" up to this speed (Lichtenthaler and Daling 1983 in Fingas 2004).	*Minimum* 4-6 knots, or Beaufort 2 (Allen 1988*). *Minimum* 5-23 knots (Scholz et al. 1999 in Fingas 2004). Maximum 22-27 knots (Beaufort 6), or natural dispersion will be equally effective (Allen 1988). Maximum 25 knots, per EPA Region 6 guidelines (Fingas 2004).
SEA STATE (feet)	*Aircraft:* Maximum 17-23 ft (ExxonMobil 2000 in Fingas 2004). *Vessel:* Maximum 1-9 ft (ExxonMobil 2000 in Fingas 2004).	*Minimum* 0.3-6.5 ft (Scholz et al. 1999 in Fingas 2004). *Minimum:* 0.5 ft (Allen 1988). Maximum 10 ft (Beaufort 6), or natural dispersant will be equally effective (Allen 1988).
AIR TEMP. (ºF)	**No appreciable impact** (2007 Tanker C-plan). **Subzero temperatures may require equipment modifications** (2007 SERVS Technical Manual). Temperatures of 32ºF or lower may cause re-freezing in the application device or dosage problems (Lethinen 1981 in Lindgren et al. 2001).	Some laboratory studies show that as *water* temperature is lowered, dispersant effectiveness is reduced, but no clear limits are reached. In general, the research has not been designed to establish limits, but to show effectiveness under a range of potential high latitude conditions (Daling 1988; Daling et al. 1995; Brandvik et al. 1991 in Fingas 2004; SL Ross and MAR, Inc. 2006; White et al. 2002). Farmwald and Nelson (1982) found no clear correlation between air temperature and dispersibility in wave tank tests of Prudhoe Bay crude. While there may be real operational constraints posed by air temperature, the literature is inconclusive. **Both dispersants stockpiled by the PWS shippers must be** *stored* **at -30ºF or above (EPA 2007).**

* Allen provides one of the more comprehensive overviews of the impact of environmental factors on different response mechanisms, which appear to be based on his (at the time) 20 years of experience, not experiments or trials.

Factors	Limits Related to Platform & Application	Limits Related to Dispersion of Oil
VISIBILITY (nautical miles)	*Aircraft:* **May preclude air operations. Cannot apply dispersants at night** (2007 Tanker C-plan). 2.2 nm required for helicopter, as with burning (Buist 2003). 0.9 nm required for fixed-wing aircraft. Dispersant application at night is unreliable: it is hard to track oil for accurate application** (Salt 2001). 14 CFR 91.155 requires fixed-wing aircraft operating under visual flight rules in daylight to have 1 stature mile visibility and remain clear of clouds in uncontrolled air space. At night, the limits increase to 3 stature miles visibility, and 500 ft below and 2000 ft horizontally away from clouds.	Not applicable.

** Infrared may be effective in early hours of darkness, but oil will gradually take on ambient temperature of seawater and be undetectable (Salt 2001).

LIMITS USED FOR DISPERSANTS

As with mechanical response, specifying environmental conditions which would preclude a non-mechanical response is largely subjective. Based on the results of the literature review, Nuka Research proposed dispersant response limits for use in this study. At the request of PWS RCAC, these limits were modified, but are still within the bounds reported in the literature.

It is important to note that much of the information on non-mechanical response comes from laboratory or small-scale tests; however, it appears that the better-established limits relate to the application platform, rather than the technology. The dispersant limits designated for this study are based on application by aircraft, rather than vessel.

Response limits for the purpose of the response gap analysis for dispersant use are presented in Table 4.

Table 4. Response limits for dispersants used in this study.

Environmental Factor	Green Response Not Impaired	Yellow Response Impaired	Red Response Not Possible/Effective
Wind (knots)	≥ 10 to < 22	≥ 6 to < 10 or ≥ 22 to < 28	≥ 28 or ≥ 0 to < 6
Sea State (feet)	≥ 2 to < 10	≥ 1 to < 2	≥10 ≥0 to < 1
Temperature (ºF)	No practical limits		
Visibility (nautical miles)	> 2 (daylight)	≥ 1 to ≤ 2	< 1 (civil twilight darkness)

Establishing Limits for In-situ Burning

As with dispersant use, the in-situ burning tactic effectiveness is impacted by numerous factors, including the environmental factors selected for the response analysis. Other important factors include:

- Oil weathering,
- Precipitation,
- Presence of ice, and
- Oil thickness.

In particular, slick thickness and oil weathering are considered to be the critical factors in determining the effectiveness of in-situ burning, and have been the focus of the literature to date. While sea state could be an indicator of how quickly spilled oil will weather, this could not be extrapolated from the data available. Oil spills usually require containment to create a thick enough slick to burn, subjecting in-situ burning to many of the same constraints as mechanical open-water recovery in terms of wind, waves, or ice impacting the containment boom.

One report shows a link between the relative impact of sea state depending on the degree of emulsification of the oil. In wave tank tests at Prudhoe Bay, "increasing wave steepness (or wave energy) appeared to reduce both burn rates and burn efficiencies of the unemulsified oil slicks. For emulsified slicks, increasing wave steepness did not appear to appreciably affect the oil burning rates, but did reduce the oil removal efficiencies" (Buist et al. 1997). Wave energy and steepness were not use for this analysis.

The success of an in-situ burn relies on tracking the slick, accessing it for ignition (from an aircraft or vessel), successful ignition, and a sustained burn that achieves the desired result. Conditions therefore need to be amenable throughout the course of the burn and subsequent residue collection, if required (Buist et al. 2003).

OVERVIEW OF LIMITS IN THE LITERATURE

Table 5 summarizes the ways in which the selected environmental factors can impact in-situ burning, as described in the literature.

Table 5. Impact of select environmental factors on in-situ burning.

Factors	Containment	Ignition Platform	Ignition and Burning
WIND (knots)	Conditions are "unfavorable" at 20 knots and marginal from 10-20 knots (Buist et al. 2003). 15-18 knots for boom failure (Tedeschi 1999 in Fingas 2004).	No literature to cite.	Maximum 20 knots or it is difficult to ignite oil and sustain a burn, due in part to the wind-driven waves created (Buist et al. 2003). Maximum 11-16 knots (Allen 1988 in Fingas 2004). Maximum 16-21 knots (no waves*) for pools of oil or 19-23 knots for large slicks (Buist 2003, Buist 1999). 17-21 knots (Allen and Ferek 1993). Less than 20 knots (In-Situ Burning Guidelines for Alaska 2001** and ACS 2007). **Maximum 20 knots to ignite or maintain burn** (2007 Tanker C-plan, ASTM 2003). Maximum 40 knots (Fingas 2004).
SEA STATE (feet)	3 ft (Fingas and Punt 2000). 3.2 ft (ASTM 2003). "Unfavorable" at 5 ft seas. Marginal from 3-5 ft, or if very long-period swells, then 6 ft (Buist et al. 2003). **Maximum 10 ft waves with strong tides/ currents** (2007 Tanker C-plan).	No effect on aircraft application. For vessel application, must be safe to operate the vessel in use.	2-3 ft (Florida DEP 1999 and ACS 2007). 3 ft if choppy, 5.7 ft if swells (In-Situ Burning Guidelines for Alaska 2001). 3-6.5 ft significant wave height or less, assuming containment is achieved and maintained (Buist 2003, Buist 1999) 4 ft (Allen 1988). 4.1-8.2 ft (Allen and Ferek 1993).
AIR TEMP. (ºF)	2007 Tanker C-plan says **"no appreciable impact."**	No literature to cite.	Successful *in situ* burns have been conducted at ambient temperatures from 30.2º - 59º, with little or no loss of efficiency (NRT 1997). This does not define a limit, however.
VISIBILITY (nautical miles)	**Not in darkness if unable to tow, contain, ignite, and monitor burn. C-plan does not specifically restrict burning to daylight hours, though says Unified Command may do so** (2007 Tanker C-plan).	Helicopter: 2.2 nm visibility required per Visual Flight Rules (Buist 2003, Buist 1999).	In general, burning should be done in daylight only, not in heavy rain or if rain is forecasted during the burn (Buist et al. 2003).

* Though Buist (2003) states that the limited knowledge available about the impact of wind on ignition and burning indicates a maximum wind speed of 16-21 knots for pools of oil "in the absence of wind," the Beaufort Scale shows that winds in this range would be associated with 1.6-8.2 ft waves.

** The guidelines for in-situ burning were revised as of April 2007, but remain in draft form awaiting approval from the Regional Response Team. However, no changes were made to the wind and wave parameters (Iwamoto 2007).

LIMITS USED FOR IN-SITU BURNING

As with mechanical response, specifying environmental conditions which would preclude a non-mechanical response is largely subjective. Based on the results of our literature review, we used the following in-situ burning response limits in this study.

It is important to note that much of the information on non-mechanical response comes from laboratory or small-scale tests; however, it appears that the better-established limits relate to containment where knowledge is much more extensive from mechanical response experience.

Response limits for the purpose of the response gap analysis are presented for in-situ burning in Table 6.

Table 6. Response limits for in-situ burning used in this study.

Environmental Factor	Green Response Not Impaired	Yellow Response Impaired	Red Response Not Possible/Effective
Wind (knots)	< 15	≥15 to <20	≥ 20
Sea State (feet)	< 3	≥ 3 to < 6	≥ 6
Temperature (ºF)	≥ 26 at any wind speed, or otherwise as not included in yellow or red conditions	>16 to < 26 and wind speed ≥ 12 knots	≤ 16 and wind speed ≥ 5 knots
Visibility (nautical miles)	≥ 0.5 (daylight)		< 0.5 (civil twilight darkness)

MECHANICAL RESPONSE LIMITS

The report *Response Gap Estimates for Operating Areas in Prince William Sound* (Nuka Research 2007) explains the basis for the limits used for mechanical recovery by the open-water response system used in PWS. The limits themselves are shown here for reference when comparing the estimated mechanical response gap with the estimated response gaps for dispersants and in-situ burning.

Table 7. Limits used for mechanical response gap analysis (based on the open-water recovery system).

Environmental Factor	Green Response Not Impaired	Yellow Response Impaired	Red Response Not Possible/Effective
Wind (knots)	0 to < 21	21 to < 30	≥ 30
Sea State (feet)	≤ 3 when wave steepness parameter is greater than or equal to 0.0025, otherwise ≤ 4	> 3 to < 6 when wave steepness parameter is greater than or equal to 0.0025, otherwise > 4 to < 8	≥ 6 when wave steepness parameter is greater than or equal to 0.0025, otherwise ≥ 8
Temperature (ºF)	≥ 26 at any wind speed, or otherwise as not included in yellow or red conditions	>16 to < 26 and wind speed ≥ 12 knots	≤ 16 and wind speed ≥ 5 knots
Visibility (nautical miles)	≥ .5 (day light)	.5 to .25 (civil twilight darkness)	< .25 (not used for 2006 analysis)

The PWS Tanker C-plan uses the following upper limits for mechanical response:

- Wind: >30 to 40 knots
- Sea state: 10 ft waves, with strong tides and currents
- Air temperature: < 15, with winds ≥ 24 knots
- Visibility: 0.125- 0.5 nm for booming and skimming vessels, depending on other factors

Review of Limits by Factor

For comparative purposes, the following three tables show the response limits used for dispersants, in-situ burning, and mechanical response, by environmental factor.

Table 8. Comparison of limits by environmental factor: red (response not possible/effective).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	≥ 30	≥ 28 or ≥ 0 to < 6	≥ 20
Sea State (feet)	≥ 6 when wave steepness parameter is ≥ 0.0025, otherwise ≥ 8	≥10 ≥0 to < 1	≥ 6
Temperature (ºF)	≤ 16 and wind speed ≥ 5 knots		≤ 16 and wind speed ≥ 5 knots
Visibility (nautical miles)	< 0.25 (not used in analysis, though)	< 1 (civil twilight darkness)	< 0.5 (civil twilight darkness)

Table 9. Comparison of limits by environmental factor: yellow (response impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	21 to < 30	≥ 6 to < 10 or ≥ 22 to < 28	≥15 to <20
Sea State (feet)	>3 to < 6, when wave steepness parameter is ≥ 0.0025, otherwise >4 to < 8	≥ 1 to < 2	≥ 3 to < 6
Temperature (ºF)	> 16 to < 26 and wind speed ≥ 12 knots		>16 to < 26 and wind speed ≥ 12 knots
Visibility (nautical miles)	0.5 to 0.25 (civil twilight darkness)	≥ 1 to ≤ 2	

Table 10. Comparison of limits by environmental factor: green (response not impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	< 21	≥ 10 to < 22	< 15
Sea State (feet)	≤ 3 when wave steepness parameter is greater ≥ 0.0025, otherwise ≤ 4	≥ 2 to < 10	< 3
Temperature (ºF)	≥ 26 at any wind speed, or otherwise as not included in yellow or red conditions	No practical limits	≥ 26 at any wind speed, or otherwise as not included in yellow or red conditions
Visibility (nautical miles)	≥ 0.5 (day light)	> 2 (daylight)	≥ 0.5 (daylight)

Response Capability Degradation

The degradation of response capabilities does not occur at a single point, nor is it necessarily linear in nature. The degradation curve is probably different for each environmental factor. This further complicates the task of setting discrete operational limits, which is why the Green (response not impaired), Yellow (response impaired) and Red (response not possible/effective) are used in setting the limits.

Response Gap Index

INTERACTIONS BETWEEN ENVIRONMENTAL FACTORS

Interactions between environmental factors have a big effect on response operating limits. For example, low temperatures and strong winds cause freezing spray that can impede or prevent on-water response operations much sooner than either temperature or wind alone. Likewise, waves of a certain height are much more limiting in the presence of a strong wind, or when visibility is diminished. We accounted for these interactions by with a simple set of rules to develop a Response Gap Index.

CALCULATING THE RESPONSE GAP INDEX

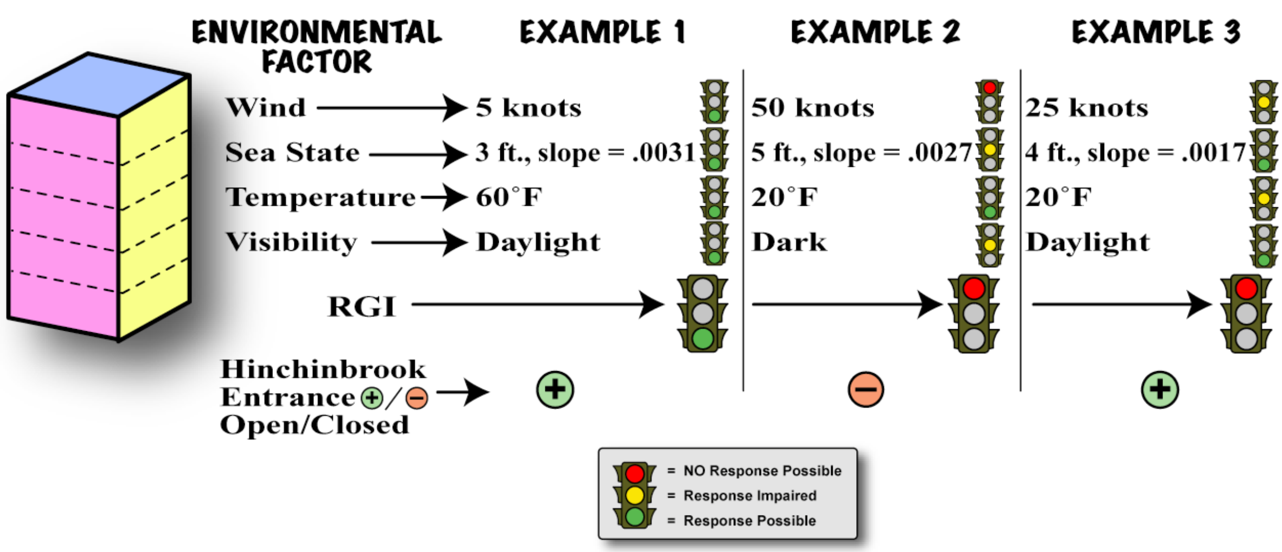
A Response Gap Index (RGI) was computed for each observational period based on a rule that considers the interaction of the environmental factors. RGI was recorded as either green or red. Since an RGI was only computed for observational periods when Hinchinbrook Entrance is *open*, the tabulation and analysis of the red RGI results in a reasonable estimate of the response gap.

The RGI was calculated as follows:

1. If *any* environmental factor is ruled red, then RGI=RED.
2. If *all* environmental factors are ruled green, then RGI=GREEN.
3. If only one environmental factor is ruled yellow and the remainder are green, then RGI=GREEN.
4. If two ore more factors are ruled Yellow, then RGI=RED.

Figure 3 shows how the RGI calculation process works.

Figure 3. An example of how an RGI rule might be applied.



Dispersant Results

Central Sound

This section presents the results of applying the dispersant operating limits to the dataset used for the Central Sound when Hinchinbrook Entrance was computed to be open.[6]

Table 11 shows how often, as a percentage of time, dispersant application and/or effectiveness would be possible/effective (green), impaired (yellow), or not possible/effective (red).

When each factor was considered independently, response was precluded about one-third of the year by wind and visibility, and one-fifth of the time by sea state. For the 34% of the observations calculated as red due to wind, 94.7% were calculated as such because of *low* wind speed (≥ 0 to ≤ 6 knots). Only 5.3% of these red observations were because of high wind speed (≥ 28 knots). Almost all (99.8%) of the observations calculated as red for sea state were because the sea state was too *low* (≥ 0 to ≤ 1 feet).

Table 11. Results of applying dispersant response limits to Central Sound data (when Hinchinbrook Entrance was open).

Environmental Factor	Green	Yellow	Red
Wind (knots)	35.5%	30.5%	34.0%
Sea State (feet)	42.4%	36.7%	21.0%
Temperature (ºF)	100%	0.0%	0.0%
Visibility (nautical miles)	62.5%	0.0%	37.5%

Table 12 shows the results of applying the RGI rule to Central Sound data for dispersants. Considering the environmental factors together, we estimate that dispersant application would be impossible or ineffective 74.9% of the time in the Central Sound. When looking at the seasons separately, this is the case slightly more often in summer (76.1%) than in winter (73.3%). The most significant factors limiting dispersants operations were darkness and winds/waves too calm for dispersant effectiveness.

Table 12. Results of applying the RGI rule to Central Sound data for dispersants.

Environmental Factor	Green	Red
Entire Year	25.1%	74.9%
Summer (April-September)	23.9%	76.1%
Winter (October-March)	26.7%	73.3%

6 An analysis of wind and wave data at Hinchinbrook Entrance revealed that closure conditions were reached at Hinchinbrook Entrance only 1.7% of the time during 2000-2005 (inclusive).

Hinchinbrook Entrance

This section shows the results of applying the dispersant operations limits to the dataset for Hinchinbrook Entrance.

Table 13 shows that wind was the primary environmental factor inhibiting or precluding a dispersant response at Hinchinbrook Entrance. For the 27.7% of observations calculated as red for wind, 83% were due to low wind speed (≥ 0 to < 6 knots) and 17% due to high wind speed (≥ 28 knots).

Sea state was calculated as red just 7% of them time, almost all of these (98%) due to high sea state (≥ 10 feet).

Table 13. Results of applying dispersant response limits to Hinchinbrook Entrance data (when Hinchinbrook Entrance was open).

Environmental Factor	Green	Yellow	Red
Wind (knots)	41.2%	31.0%	27.7%
Sea State (feet)	81.0%	12.0%	7.0%
Temperature (ºF)	100%	0.0%	0.0%
Visibility (nautical miles)	62.5%	0.0%	37.5%

Considering the environmental factors together, we estimate that a dispersant response would be impossible or ineffective 61.6% of the year at Hinchinbrook Entrance; slightly more often in winter (70.3%) than in summer (54.7%). This is shown in Table 14. The most significant factors limiting dispersant application/ effectiveness were darkness and winds too calm for dispersant effectiveness.

Table 14. Results of applying the RGI rule to Hinchinbrook Entrance data for dispersants.

Environmental Factor	Green	Red
Entire Year	38.4%	61.6%
Summer (April-September)	43.5%	54.7%
Winter (October-March)	29.7%	70.3%

Both Operating Areas

Table 15 presents the results of considering the RGI for both operating areas simultaneously. For any given observation, if the RGI for either area was computed as red, then the aggregate RGI was assessed as red. According to this table, a dispersant response would be impossible or ineffective in either or both the Central Sound and Hinchinbrook Entrance approximately 80% of the time during the year.

Table 15. Aggregate RGI for the Central Sound and Hinchinbrook Entrance (dispersants).

Environmental Factor	Green	Red
Entire Year	19.9%	80.1%
Summer (April-September)	19.6%	80.4%
Winter (October-March)	20.2%	79.8%

In-situ Burning Results

Central Sound

This section presents the results of applying the in-situ burning operating limits to the dataset used for the Central Sound when Hinchinbrook Entrance was computed to be open. When the environmental factors were considered separately, visibility was the dominant limiting factor: it was estimated to make a response impossible or ineffective 37.5% of the time. Wind would likely preclude an in-situ burning response in the Central Sound only 10.6% of the time, and sea state only 2.4% of the time.

Table 16. Results of applying in-situ burning response limits to Central Sound data (when Hinchinbrook Entrance was open).

Environmental Factor	Green	Yellow	Red
Wind (knots)	76.8%	12.6%	10.6%
Sea State (feet)	79.2%	18.4%	2.4%
Temperature (ºF)	99.7%	0.3%	0.0%
Visibility (nautical miles)	62.5%	0.0%	37.5%

Considering the combined effects of the environmental factors by applying the RGI rule, an in-situ burning response would be impossible or ineffective an estimated 45.0% of the time for the year, or 24.8% in the summer and 70.0% in the winter (largely due to visibility).

Table 17. Results of applying the RGI rule to Central Sound data for in-situ burning.

Environmental Factor	Green	Red
Entire Year	55.0%	45.0%
Summer (April-September)	75.2%	24.8%
Winter (October-March)	30.0%	70.0%

Hinchinbrook Entrance

Table 18 shows the results of applying in-situ burning response limits to the data for Hinchinbrook Entrance. This table shows visibility as the primary factor that would make an in-situ burn impossible or ineffective at Hinchinbrook Entrance, at 37.5%, with sea state (28.0%) and wind (18.8%) following.

Table 18. Results of applying in-situ burning response limits to Hinchinbrook Entrance data (when Hinchinbrook Entrance was open).

Environmental Factor	Green	Yellow	Red
Wind (knots)	66.1%	15.1%	18.8%
Sea State (feet)	33.0%	39.0%	28.0%
Temperature (ºF)	99.5%	0.05%	0.0%
Visibility (nautical miles)	62.5%	0.0%	37.5%

Considering environmental factors together, Table 19 shows that an in-situ burning response would be impossible or ineffective at Hinchinbrook Entrance an estimated 57.9% of the time, with a wide seasonal variation between summer (35.3%) and winter (85.9%).

Table 19. Results of applying the RGI rule to Hinchinbrook Entrance data for in-situ burning.

Environmental Factor	Green	Red
Entire Year	42.1%	57.9%
Summer (April-September)	64.7%	35.3%
Winter (October-March)	14.1%	85.9%

Both Operating Areas

The aggregate RGI for in-situ burning—combining both operating areas—shows that overall an in-situ burn will be impossible or ineffective in either or both the Central Sound and Hinchinbrook Entrance 58.5% of the year, or 36.0% of the summer and 86.4% of the winter.

Table 20. Aggregate RGI for the Central Sound and Hinchinbrook Entrance (in-situ burning).

Environmental Factor	Green	Red
Entire Year	41.5%	58.5%
Summer (April-September)	64.0%	36.0%
Winter (October-March)	13.6%	86.4%

Combined Results: Mechanical and Non-mechanical

This section compares the results of the mechanical and non-mechanical response gap studies for the Central Sound, Hinchinbrook Entrance, and both operating areas combined. The detailed results of the mechanical response analysis are shown in the February 2007 report of that study.

Central Sound

Table 21. Comparison of estimated response gap in the Central Sound by environmental factor: red (response not possible/effective).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	1.0%	34.0%	10.6%
Sea State (feet)	1.6%	21.0%	2.4%
Temperature (ºF)	0.0%	0.0%	0.0%
Visibility (nautical miles)	0.0%	37.5%	37.5%

Table 22. Comparison of estimated response gap in the Central Sound by environmental factor: yellow (response impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	7.8%	30.5%	12.6%
Sea State (feet)	13.7%	36.7%	18.4%
Temperature (ºF)	0.3%	0.0%	0.3%
Visibility (nautical miles)	37.5%	0.0%	0.0%

Table 23. Comparison of estimated response gap in the Central Sound by environmental factor: green (response not impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	91.9%	35.5%	76.8%
Sea State (feet)	84.7%	42.2%	79.2%
Temperature (ºF)	99.7%	100.0%	99.7%
Visibility (nautical miles)	62.5%	62.5%	62.5%

Considering the environmental factors together, Table 24 (below) shows that some kind of response would likely be effective 90.3% of the time during the year. Table 23 (above) indicates that this would more probably be a mechanical or in-situ burning response rather than the application of dispersants.

Table 24. RGI for each technology and all technologies combined for the Central Sound.

Season		Mechanical	Dispersants	In-situ Burning	All Technologies
Entire Year	Green	87.4%	25.1%	55.0%	90.3%
	Red	12.6%	74.9%	45.0%	9.7%
Summer	Green	95.8%	23.9%	75.2%	97.7%
	Red	4.2%	76.1%	24.8%	2.3%
Winter	Green	76.9%	26.7%	30.0%	81.2%
	Red	23.1%	73.3%	70.0%	18.8%

Hinchinbrook Entrance

Table 25. Comparison of estimated response gap at Hinchinbrook Entrance by environmental factor: red (response not possible/effective).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	2.9%	27.7%	18.8%
Sea State (feet)	19.2%	7.0%	28.0%
Temperature (ºF)	0.0%	0.0%	0.0%
Visibility (nautical miles)	0.0%	37.5%	37.5%

Table 26. Comparison of estimated response gap at Hinchinbrook Entrance by environmental factor: yellow (response impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	13.5%	31.0%	15.1%
Sea State (feet)	34.6%	12.0%	39.0%
Temperature (ºF)	0.5%	0.0%	0.5%
Visibility (nautical miles)	37.5%	0.0%	0.0%

Table 27. Comparison of estimated response gap at Hinchinbrook Entrance by environmental factor: green (response not impaired).

Environmental Factor	Mechanical	Dispersants	In-situ Burning
Wind (knots)	83.6%	41.2%	66.1%
Sea State (feet)	46.2%	81.0%	33.0%
Temperature (ºF)	99.5%	100.0%	99.5%
Visibility (nautical miles)	62.5%	62.5%	62.5%

Considering the environmental factors together, Table 28 shows that a response of some type at Hinchinbrook Entrance would likely be effective 69.9% of the year. There is a marked difference in the overall probability of being able to some kind of response: the estimated likelihood is 90.2% in summer and 44.8% in winter.

Table 28. RGI for each technology and all technologies combined for the Hinchinbrook Entrance.

Season		Mechanical	Dispersants	In-situ Burning	All Technologies
Entire Year	Green	62.6	38.4	42.1	69.9
	Red	37.7	61.6	57.9	30.1
Summer	Green	84.4	43.5	64.7	90.2
	Red	15.6	54.7	35.3	9.8
Winter	Green	35.4	29.7	14.1	44.8
	Red	65.4	70.3	85.9	55.2

Considering the open-water recovery system in PWS the options available for dispersants and in-situ burning, and the combined effects of the four environmental factors (through the RGI rule), Table 29 shows the overall estimated frequency during which a spill response of some type would be possible or impossible for the entire year, summer, and winter.

Table 29. Aggregate RGI for Central Sound and Hinchinbrook Entrance (mechanical and non-mechanical).

Environmental Factor	Green	Red
Entire Year	69.5%	30.5%
Summer (April-September)	89.9%	10.1%
Winter (October-March)	44.1%	55.9%

Discussion

This study sets out a methodology to analyze the strength and limitations of various response tactics in any operational area where environmental data has been collected for an extended period. Establishing the correct limitations for the method is challenging. For example, the data would indicate that calm conditions (winds <6 knots) in Central PWS are a major limiting factor for dispersant application. Calm conditions are ideal for dispersant application by aircraft, but the literature indicate that calm conditions will preclude mixing for the dispersant and oil, thus limiting effectiveness. It is not readily intuitive that Central PWS is often too calm for dispersant use. The sensitivity of the limits are also unknown, for example setting the red wind limit one knot higher or lower might significantly modify the results. Also, in reality, wave energy is the mechanism for mixing, so establishing wind limits based for dispersant mixing may produce misleading results.

The key to this method of analysis is to accurately quantify the limitations of each technology. This presents many opportunities for valuable data collection during drills and exercises, but protocols for efficacy observations should first be established.

Challenges

SIMILARITIES WITH MECHANICAL RESPONSE GAP STUDY

This study was challenged in many of the same ways as the mechanical response gap analysis:

- The “hindcast” methodology assumes that future conditions in PWS can be predicted by past conditions. However, some scientists predict that storms will increase, bringing more frequent high winds, high sea states, and low visibility (McCarthy et al. 2001).
- The use of NOAA buoys as the primary source of environmental data assumes they reflect the operating areas overall; however, we acknowledge that conditions can and do vary from the buoy location even in the same operating area.[7]

7 At Hinchinbrook Entrance, actual conditions in the narrows can vary significantly from the Seal Rocks Buoy’s location due to tidal currents and exposure to williwaw winds at Port Etches. In the Central Sound, the West Orca Bay Buoy is influenced by easterly winds from Orca Bay, while conditions elsewhere in that operating area can be quite different.

- The only component of visibility as an environmental factor that was considered for this and the mechanical response gap studies was daylight vs. darkness. However, fog and precipitation could pose a substantial challenge to response effectiveness.
- There is reason to believe that the NOAA buoys under-report wind and sea state data. This was discussed in the mechanical response gap study (Nuka Research 2007).
- Setting response limits requires using best professional judgment and the best available information to assign specific numbers to the inherently ambiguous, cumulative effects of many factors on a response.

CHALLENGES SPECIFIC TO NON-MECHANICAL RESPONSE GAP

- The extensive literature on dispersants and in-situ burning generally does not focus on operational aspects of non-mechanical response, but on the relative efficacies of different dispersant products under varying conditions, primarily in laboratory studies.
- As mentioned previously, most published studies on non-mechanical response operating limits are intended to show what *does* work (burning in waves, dispersants in cold, etc.), as opposed to identifying the point at which the response would become ineffective in terms of environmental factors. With increasing exploration and production in the Arctic region, recent studies have included the efficacy of non-mechanical response options in extreme cold and ice conditions. These include cold water tests of dispersant effectiveness on Alaskan crude oils conducted at the OHMSETT test tank in New Jersey (SL Ross and MAR, Inc. 2006) and other studies specific to ice conditions.[8]

Recommendations

Nuka Research makes the following recommendations, many of which echo recommendations made at the conclusion of the mechanical response gap analysis.

1. **Conduct field trials aimed at quantifying the operational limits of dispersants and in-situ burning tactics.**

   Better quantification of response limits would significantly improve response gap measurements. As discussed above, the operating limits for dispersant application and in-situ burning are not firmly established in the literature. We recommend that PWSRCAC advocate for field-scale tests designed to establish the operating limits applicable to the in-situ burning and dispersant application systems.

8 These studies are not considered here, as ice coverage is not one of the selected environmental factors. In general, the research is at a very early stage. They include two recent studies funded, in part, by the US Department of the Interior's Minerals Management Service: "Mid-Scale Tests to Determine the Limits to In-Situ Burning in Broken Ice" in 2004 and "Mid-Scale Test Tank Research on Using Oil Herding Surfactants to Thicken Oil Slicks in Broken Ice" in 2007.

2. Improve visibility data and repeat the response gap analyses.

Fitting the NOAA data buoys with visibility instrumentation, or agreeing to a method to capture reliable mariner observations to measure visibility, would improve the accuracy of the response gap measurements by incorporating visibility factors beyond daylight/darkness. Ceiling height is another important factor for operations depending on aircraft. Incorporating the presence or absence of fog or precipitation can only further increase the estimated amount of time a response of any kind will be precluded by poor visibility. We recommend PWSRCAC explore these options with NOAA. This would enhance both the non-mechanical and mechanical response gap analyses.

3. Conduct additional analyses on these data.

Additional analysis of the datasets may clarify the response gap. A sensitivity analysis shedding light on the effect of each variable on the response gap would explain more about how changing the response limits and/or closure limits would impact the response gap estimate. An analysis of the frequency and duration of series in the dataset where the RGI is deemed red would indicate how often oil is shipped when no response is possible. We recommend PWSRCAC further explore these data.

4. Explore ways to reduce the response gap by enhancing response capabilities.

Subsequent to the completion of field-scale tests to establish more accurate response operating limits for dispersants and in-situ burning (Recommendation #1), PWSRCAC should advocate for efforts to mitigate the shortcomings of each response tactic. Visibility was the primary obstacle to both mechanical and non-mechanical response, and thus presents a logical starting point. The proven ability to implement a response in darkness will have the most significant impact on the estimated response gap for mechanical recovery, but will also reduce the non-mechanical response gap estimates.

5. Develop data set for Valdez Arm and conduct a similar analysis.

A response gap analysis should be conducted for Valdez Arm because it is a critical portion of the PWS tanker route subject to challenging conditions varying greatly from the areas included in this analysis. An analysis of the response gap for Valdez Arm requires better data on environmental conditions that is currently available: the Potato Point Coastal-Marine Automated Network (C-MAN) provides data for wind and air temperature, but not sea state and visibility. Wind data could be modeled to predict sea state, but this would introduce a source of error into the analysis.

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