Industry Recommended Response Worker Safety Considerations for Requesting Regulatory Concurrence for Subsea Dispersant Use

API BULLETIN 4719(b)
NOVEMBER 2022

American Petroleum Institute

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1 Introduction

1.1 Background and Benefits of Subsea Dispersant Injection (SSDI)

During the response to the 2010 *Macondo* (aka *Deepwater Horizon*) incident in the Gulf of Mexico that released an estimated 3.19 million barrels of crude oil into the environment (U.S. v. BP et al., 2015), subsea dispersant injection (SSDI) was utilized for the first time in an oil spill response. SSDI involves applying dispersant directly to oil discharging from a damaged well at the sea floor, which, in the case of the *Macondo* incident, was approximately 5,000 feet below the water's surface. The use of SSDI facilitated the implementation of source control measures by creating a zone where emergency responders could safely access the well from the sea surface (i.e., safe vertical access) and eventually install a capping stack that terminated the oil discharge.

The primary objective of SSDI is to protect emergency responders from unacceptable safety risks. SSDI greatly reduces the size of the discharging oil droplets, which, through a variety of physical and natural processes, reduces the quantity and concentration of oil reaching the water's surface. The dispersed oil that does reach the surface contains fewer volatile organic carbons (VOCs) that can volatilize into the air, thus reducing the inhalation and fire and explosion risks (i.e., the safety case) to response personnel. Because these safety case risks can preclude or significantly impede implementation of the source control measures to stop the subsea oil discharge, SSDI is an important tool that should be considered in any offshore subsea loss of well control (i.e., well blowout) incident.

In addition to mitigating human health and safety risks, SSDI decreases the volume of floating oil, thus reducing impacts to surface dwelling wildlife such as turtles, birds, and cetaceans, as well as shoreline ecosystems in the path of the migrating oil slicks. The smaller oil droplets in the water column and at the surface also enhance the natural biodegradation of the oil, which further reduces the human health and safety risk and ecological risk. A depiction of a source control operation involving SSDI is shown below in Figure 1, and a description of a typical SSDI system and a discussion of the primary benefits is provided in Annex A.

1.2 Problem Statement

During the *Macondo* response, an SSDI-specific, regulatory authorization process did not exist since SSDI had not been previously used or considered. Consequently, a somewhat ad hoc process based on authorization of surface dispersant use was followed involving the cognizant regional response team (RRT), federal on-scene coordinator (FOSC), and unified command (UC).

Due to the continued absence of regulatory guidance, many of industry's post-*Macondo* subsea well blowout exercises also followed a similar ad hoc authorization process that involved the RRT and focused on SSDI efficacy, ecological impact mitigation, and water column monitoring. Subsequently, the American Petroleum Institute (API) developed an SSDI authorization guideline (API 4719) that included a suggested application process and justification based primarily on reducing ecological impacts.

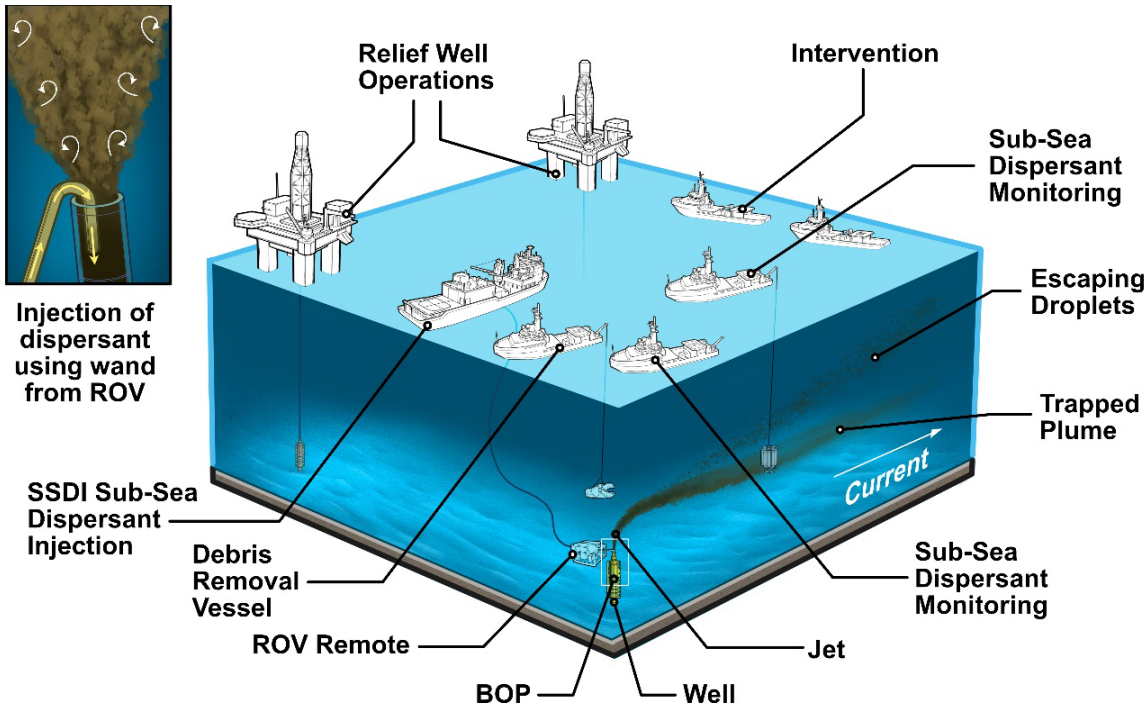

Figure 1—Well Control Operations With SSDI

A primary benefit of SSDI is, however, the reduction of surface VOCs and the associated responder safety case risks, which enables the safe deployment of well capping and containment equipment required to stop a subsea well blowout. During a recent industry subsea well blowout exercise, the SSDI authorization application submitted to the RRT only included the safety case justification, with no references to ecological impact mitigation. After some discussions, it was determined that the FOSC, not the RRT, has the sole responsibility of approving SSDI use for the purposes of mitigating safety case risks.

In the absence of published guidelines to address the safety case-related SSDI application process, API developed these guidelines.

1.3 Purposes and Use

The primary purpose of this document is to facilitate the collection and provision of appropriate information to the FOSC to enable a data- and science-based evaluation and decision on the use of SSDI to mitigate health and safety risks in response to a subsea well blowout incident.

Secondary purposes of this document include providing guidance on the:

— authorization process;

— collection of VOC data to evaluate the associated health and safety case risks and document the efficacy of SSDI in mitigating those risks; and

— using supporting evidence to validate SSDI's risk mitigation potential.

This document is intended to be used:

— as stand-alone guidance in requesting SSDI authorization based solely on mitigating health and safety risks; or

— in conjunction with API Bulletin 4719, *Industry Guidelines on Requesting Regulatory Concurrence for Subsea Dispersant Use*, which focuses on SSDI efficacy, water column monitoring, and ecological impact considerations.

It is also intended to supersede justifications for authorization based on ecological impact mitigation, as human health and safety is the highest priority in any oil spill response.

1.4 Focus Areas

The primary focus areas of this document include:

— responder health and safety hazards predominantly involving VOCs in the breathing zone; and

— the simultaneous operations (SIMOPS) zone, where the critical well control operations take place.

1.4.1 Health and Safety Hazards

VOCs can pose risks to responder health and safety, and, as such, are the primary hazard addressed in this document. Although uncommon in offshore oil reservoirs, H_2S gas is another key health hazard that can be toxic, even at low concentrations.

In general, the key hazards addressed in this document include:

— VOC exposure: Acute exposure to, or inhalation of, high concentrations can result in narcosis and possible unconsciousness; lower-level chronic exposures can lead to serious long-term health conditions, including eye irritation and damage.

— VOC fire and explosion: Concentrations below the lower explosive limit (%LEL) can be hazardous, with common safety action levels of 5 %–10 % LEL. An atmosphere below 10 % of the LEL may still be above the OSHA permissible exposure limit for that substance.

— Hydrogen sulfide (H_2S): Highly toxic and can be fatal at low concentrations.

— Benzene: One of the more toxic VOC components and a known human carcinogen.

Other oil spill health and safety related risks of concern are:

— PAHs: Toxic with low exposure limits but also low volatility so main exposure pathways are often oil ingestion or transdermal absorption.

— Crude oil**:** Dermal exposure can cause skin irritation, transdermal absorption of the oil's components, and skin cancer.

— Atmospheric $PM_{2.5}$ particles: Can be inhaled deep into the lungs and are toxic if inhaled, ingested, or from dermal exposures. $PM_{2.5}$ particles can be generated and form colloidal suspensions in air as the surfacing oil degasses or is physically dispersed by breaking waves.

— Low oxygen concentrations: VOCs and other hydrocarbon vapors can displace atmospheric oxygen, resulting in low oxygen concentrations that can be fatal.

1.4.2 SIMOPS Zone

The primary response option in controlling and stopping a subsea well blowout is the placement of containment devices and/or capping stacks over the damaged well head. Collectively, these activities are referred to as “source control” and require vertical access directly above the affected well, which must be maintained throughout the source control operations. Because these operations often involve multiple vessels operating in close proximity, a simultaneous operations (SIMOPS) zone is established wherein vessel movements must follow strict protocols to avoid collisions or allisions. The SIMOPS zone typically extends several hundred meters in all directions from the vertical access point and, being directly above the discharge source, it can contain substantial accumulations of floating oil.

Due to the SIMOPS zone involving a high density of response vessels and personnel with a significant source of VOCs, it typically presents the greatest health and safety risk, and, as such, is a primary focus area of this document.

2 SSDI Authorization Process

2.1 Overview

Following the occurrence of a subsea loss of well control incident where SSDI is applicable and feasible, the authorization process should begin immediately, as SSDI systems can be installed and become operational within approximately three to five days. It is important to note that current regulatory guidance for dispersant authorization does not include SSDI use, so the process described herein is based on information obtained during recent industry well control exercises involving the RRT, as well as the *Macondo* incident.

SSDI authorization can be based on the mitigation of health and safety risks and/or ecological impact risks with the associated applications submitted independently or packaged together. In either case, there must be close coordination during the preparation of the applications, as there will likely be considerable overlap between them.

Regarding the safety case authorization, the process will involve several steps leading to the submittal of an application and associated data/information for temporary SSDI authorization. If temporary authorization is granted, additional steps must be taken to validate the efficacy of SSDI in mitigating responder health and safety risks and obtaining authorization for continued SSDI use. The steps for both temporary and ongoing SSDI authorization and their typical sequence of occurrence are depicted in Figure 2.

2.2 Responsibilities

The responsible party (RP) incident management team (IMT) is accountable for conducting the various SSDI monitoring activities, analyzing the data, and preparing and submitting the authorization application, although the individual responsibilities can vary somewhat between IMTs. The roles and responsibilities of the regulatory organizations (FOSC and RRT) also vary slightly depending on if the authorization request is based on mitigating responder health and safety risks or ecological impacts.

2.2.1 Incident Management Team (IMT)

The IMT will prepare and submit the SSDI authorization applications, with the typical division of responsibilities as follows:

— safety case: safety officer (SOFR) function within the command staff;

— ecological impact: environmental unit or unit leader (EU or ENVL) within the planning section.

Prior to submittal for authorization, the applications must be reviewed and approved by the IMT unified command (UC), which includes the FOSC and the RP incident commander (IC).

Responsibility for the collection of data to be included in the authorization application(s), as well as to validate SSDI's efficacy in mitigating health and safety risks and ecological impact risks, also varies within the IMT depending on the purpose. The typical data collection and analysis responsibilities are as follows:

— SOFR: air monitoring (primarily VOCs, LEL, H_2S, and benzene), personnel exposures, and other health and safety related data;

— EU: SSDI efficacy, water column monitoring, ecological receptors/baseline evaluations, remote sensing/aerial imagery, etc.;

— source control branch/section: installation/operation of SSDI system; may monitor its efficacy instead of the EU, prepare operations plan.

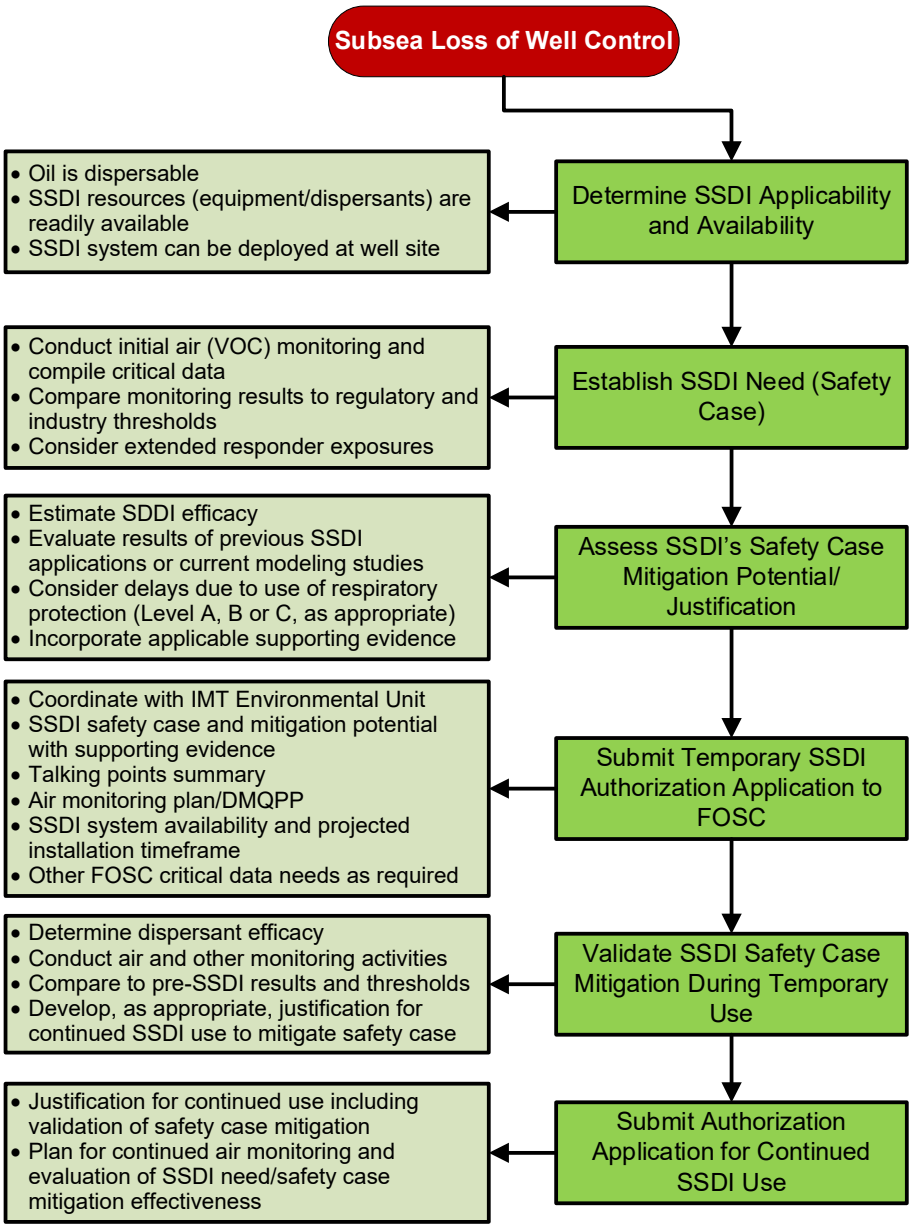

Figure 2—SSDI Authorization Flow Diagram

2.2.2 Regulatory Entities

Historically, all dispersant use applications were consistent with current regulatory guidance and submitted to the RRT for review and authorization even though the guidance does not consider SSDI use. However, during a recent industry exercise where the SSDI application was based only on safety case mitigation, the RRT determined the FOSC, and not the RRT, had sole responsibility for authorization in that situation.

Based on the above, the current regulatory responsibilities for SSDI authorization are:

— Safety case mitigation: The FOSC has unilateral responsibility but will likely seek consultation with other RRT members.

— Ecological impact mitigation: The RRT, which includes the FOSC, is responsible but also may consult with other organizations.

Since RP representatives may not be involved in FOSC consultations with the RRT, it is imperative that the FOSC be well informed on all aspects of safety case mitigation, using SSDI as early in the response as possible.

2.3 Temporary Authorization

Temporary authorization for using SSDI can often be obtained in the context of testing for proof of concept that SSDI will effectively disperse the oil and result in reduced surface oil and associated VOC concentrations. A proof-of-concept test/temporary use is anticipated to require three to five days of SSDI operations to ensure that steady state conditions are achieved. A variety of data should first be collected and evaluated, and a compelling justification should be developed around SSDI's safety case mitigation potential prior to submitting a temporary authorization application.

The key to expediting the SSDI safety case authorization process is to quickly provide the FOSC with a comprehensive application that generally includes:

— critical data;

— SSDI talking points;

— data evaluation;

— SSDI justification;

— supporting plans;

— signature page/cover sheet.

Each of the above items is explained in more detail in the following subsections.

2.3.1 Critical Data

The specific types of critical data and an example of a form that can be used to compile the data is provided in Table 1. Additional information on selected data types and their purposes is provided below.

— Incident information: The majority of the information in this section is self-explanatory, with the possible exception of the estimated volume, which is for oil releases that have been terminated,

whereas the estimated rate is for releases that are ongoing. Additionally, GOR refers to the gas-oil ratio of the oil, gas, and other reservoir fluids discharging from a compromised well.

— Air monitoring data and exposure thresholds: The information and associated formats identified in this section are only recommendations and can be modified as necessary based on the incident circumstances and the FOSC's specific data requirements. The data should be collected and recorded as described in Section 3.2.3 and the applicable exposure thresholds and action levels can be derived from Table 2 and Table 3.

— Response resources in the SIMOPS zone: This can be modified as necessary, but the intent is to provide the FOSC with information on the magnitude of the health and safety risks to personnel and assets operating within the SIMOPS zone.

— SSDI systems and dispersant availability: This information is intended to assure the FOSC that adequate SSDI resources are readily available and provide information on the timeline for their mobilization and installation.

— Aerial imagery: Ideally, this would be a time-series of aerial photographs that document the frequency and locations of significant surface oil accumulations within the SIMOPS zone that may pose safety case risks.

Table 1—Critical Data Sheet

Critical Data Sheet				
Incident Information				
Incident	Name:		Occurrence Date/Time:	
	NRC Report Number:			
Location	Block:	Well No.:	Lat/Long:	Water Depth:
Release	Depth:	Source (severed riser, BOP, wellhead, etc.):		
	Estimated Volume or Rate:		Estimation Method:	
Facility Type	Platform, Rig (TLP, SPAR, MODU, etc.):			
Oil Type	Name:		API Gravity:	GOR:
	Viscosity at Release (cPa):		Temp. (^{0}C):	Dispersible: Yes/No
On-Site Conditions	Wave Height (m):		Beaufort Scale:	Wind Direction:
	Wind Speed (kts):		Ceiling (m):	Visibility:
	Surface Current Direction:		Surface Current Speed (kts):	
	Five-Day Forecast:			
	Subsea Conditions Potentially Affecting Operations (currents, seeps, etc.):			
Brief Incident Description:				

Chronology of Key Response Actions:							
Key Contact Information							
FOSC	Name:				Sector:		
	Phone (mobile):				Phone (office):		
	Email:						
Responsible Party IC	Name:				Company:		
	Phone (mobile):				Phone (office):		
	Email:						
Air Monitoring Data and Exposure Thresholds							
Monitoring Locations	Attach aerial photo or spill trajectory map showing locations of monitoring stations, vessels, or transects relative to surface oil accumulations and response activities.						
Monitoring Data	Attach table or spreadsheet containing recent air monitoring data collected from the various locations indicating: location number, date/time, parameter(s) measured, instrument used, parameter concentration(s) (instantaneous or average over time).						
Data Analysis	Attach summary of data showing average/mean and peak concentrations at each location (station, vessel, transect).						
Exposure Thresholds	Attach table showing regulatory and industry thresholds or action levels for each of the parameters monitored similar to Table 2 and Table 3 in Section 2.3.2.						
Response Resources in SIMOPS Zone							
Vessel Name	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Total Vessels:
No. Personnel	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Total Personnel:
SSDI System and Dispersant Availability							
SSDI System	Company:				Shorebase Location:		
	Current Location:				Mobilization to Shorebase (hrs):		
	Est. Installation Time (hrs):				Est. Date/Time System Operational:		
Dispersant	Name:				Manufacturer:		
	Volume Available (gals):				Est. Application Rate (gals/day):		
	Stockpile Location:				Est. Date/Time Shorebase Arrival:		
Aerial Imagery							
Images	Attach copies of aerial images of SIMOPS zone showing surface oil concentrations.						

2.3.2 Data Evaluation

This step of the authorization process involves compiling the data and comparing it to relevant regulatory thresholds and industry action levels to determine the current level of health and safety risks to the responders.

The activities involved in collecting air monitoring-related data, primarily VOCs, are outlined in Section 3.2. To aid in the evaluation, the data should be:

— tabularized to facilitate comparisons between monitoring locations or transects, as well as to exposure thresholds or action levels; and

— plotted on a diagram, map, or aerial image to clearly show locations of different concentrations relative to surface oil accumulations.

The comparison of air monitoring readings to the associated risk metrics puts the data in perspective and determines if exceedances have occurred, to what degree, and where. If a more formal analysis is required, the European standard EN-689 provides a method for determining if monitoring results exceed a specific threshold.

It is important to note that there are no regulatory thresholds for total or accumulated VOCs. This has, in some cases, necessitated the use of thresholds for surrogate compounds such as total hydrocarbons as gasoline vapors. Depending on the characteristics of the oil, other surrogates, such as diesel or jet fuel, may also be appropriate. Additionally, thresholds for individual VOC constituents, such as benzene or semi-volatiles (total PAHs), can be appropriate due to their significant health risks. Relevant regulatory thresholds are provided in Table 2.

Table 2—Regulatory Hydrocarbon Exposure Thresholds

Parameter	LEL Vol%[1]	OSHA PEL (ppm)		NIOSH REL (ppm)			ACGIH TLV (ppm)	
		TWA[2]	STEL[3]	TWA[4]	STEL[5]	IDLH[6]	TWA[7]	STEL[8]
LEL		≥10%[10]				10%[11]		
Total HCs (as gasoline)		333 (12 hr)					33 (12 hr)	
PAHs							10	
Benzene	1.3	10		0.1	1	500	0.5	2.5
Toluene	1.2	200		100	150	500	20	
Ethyl Benzene	1.0	100	125	100	125	800	20	
Xylene	1.1	100	150	100	150	900	100	150
Hydrogen Sulfide	4.0	10	15	10[9]		100	1	5
Diesel No. 2	0.6						15	
Gasoline	1.2	300	500				300	500
Kerosene/Jet Fuel	0.7			14.4				

[1] LEL: lower explosive limit (percent by volume).
[2] OSHA PEL-TWA: The permissible concentration in air of a substance that shall not be exceeded in an 8-hour work shift (unless noted otherwise) or a 40-hour work week.
[3] OSHA PEL-STEL: The time-weighted average exposure that should not be exceeded for any 15-minute period.
[4] NIOSH REL-TWA: The recommended exposure level expressed as a time-weighted average concentration for up to a 10-hr work day during a 40-hr work week.
[5] NIOSH REL-STEL: The 15-minute TWA that should not be exceeded at any time during a work day.
[6] NIOSH IDLH: The "immediately dangerous to life and health" threshold represents the consequences of a 30-minute exposure.
[7] ACGIH TLV-TWA: The threshold limit value-TWA is the concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.
[8] ACGIH TLV-STEL: The maximum concentration to which workers may be exposed continuously for a short period of time.
[9] NIOSH TLV ceiling: The exposure limit that should not be exceeded for more than 10 minutes.
[10] Not an actual PEL, but OSHA considers it hazardous in confined spaces per Section 1915.12(b) (3) and in an OSHA/ NIOSH Hazard Alert for oil and gas workers dated February 2016.
[11] IDLH for petroleum distillates and other volatile liquids based on safety limit of 10 % LEL per NIOSH *Pocket Guide to Chemical Hazards*.

The absence of regulatory thresholds for VOCs prompted industry to establish conservative VOC action levels to minimize risks to responders (see Table 3). During the *Macondo* incident, the operator, in coordination with NIOSH, adopted a total VOC action level of 50 ppm, which, if exceeded, triggered VOC mitigation measures. These measures included the use of water sprays, surface dispersants, relocation to areas with less floating oil, and others. Many oil and gas industry companies and organizations have also adopted the 50 ppm VOC action level. A recent study provides recommended sequential VOC action levels and associated mitigation measures based on the general safety case risks of crude oil-related VOCs, as well as a 100 ppm action level based on their ocular irritant effects (CTEH, 2022).

Table 3—Industry Action Levels

Company/ Organization	Hazard	Action Level[1]	Recommended Actions	Notes
Clean Gulf Associates	VOC/ TPH	≥50 ppm	Evacuate the area	Monitor for benzene at ≥5 ppm VOC/TPH
BP *Macondo* Air Monitoring Plan for Source Control	VOCs	50 ppm	Consider use of water cannons for vapor suppression	Continuous >15 mins
		100 ppm	— Increase airflow with industrial fans — Wear half-face respirators — Relocate non-essential personnel to lower-hazard area of vessel — Re-orient vessel into the wind — Apply surface dispersant or vapor suppressing foam (if approved)	Continuous >15 mins
		1000 ppm	Move vessel to safe area	Continuous >15 mins
	LEL[2]	≥10%	— Reposition vessel if possible — Utilize fans/blowers — Use water cannons to physically disperse sheen in immediate area — Apply surface dispersant or vapor suppressing foam (if approved)	Continuous by 2 or more monitors for >15 mins
		≥40%	Move vessel to safe area	Instant by 2 monitors
Wild Well Control, Inc.	VOCs	50 ppm	— Start benzene monitoring — Limit exposure to 4 hr	
		100 ppm	— Evacuate and reassess — Upgrade to SCBA or supplied air	
	LEL[2]	≥10%	— Evacuate and reassess — Ensure O^2 levels are 19.5 %–23.5 %	
Anadarko Oil Spill Exercise	VOCs	50 ppm	Monitory for benzene and other volatiles	Sustained for 5 mins
	LEL[2]	2.5%[3]	Notify SOFR	Sustained 1-5 mins
		10%[3]	Exit area and notify SOFR	Sustained 1-5 mins
CTEH VOC Action Levels	VOCs	10 ppm	— Notify industrial hygienist — Increase vigilance around controlling exposures — Collect air sample for lab analysis	Sustained readings
		50 ppm	— Take early mitigative actions including positioning upwind — Apply surface dispersant or scavengers — Physically disperse/remove oil — Pre-plan for respiratory protection, risk communications, work habits, etc., to reduce exposures — Monitor for benzene exposure	Sustained readings
		100 ppm	— Wear air-purifying respirators — Implement SSDI to reduce exposure risk and PPE burden — Collect air sample for lab analysis — Increase air monitoring to establish safe work zones <100 ppm	Sustained readings
		100 ppm	Wear air-purifying respirators or move upwind or crosswind	Based on eye irritation

[1] Oil and gas industry action level (AL): Conservative action levels to ensure adequate protection of responders
[2] Oil and gas industry % LEL: The voluntary action levels adopted by industry for use in oil spills wherein, if exceeded, additional protection measures must be implemented or the area evacuated.
[3] Corrected LEL levels

2.3.3 Talking Points

When submitting the temporary SSDI authorization application to the FOSC, it will be beneficial to also discuss and/or submit a list of key talking points (see Table 4) highlighting the safety case-related and other benefits of SSDI. These talking points may also be useful to the FOSC when consulting with other RRT members.

Table 4—SSDI Talking Points

No.	SSDI Talking Point
1	VOCs emanating from surfacing oil are the primary safety concern for responders onboard well control vessels that must maintain position immediately above the flowing well (vertical access) a) Prior to SSDI use during *Macondo*, VOC concentrations near the well created potential safety and health risks that significantly reduced the efficiency of well control operations (Zhao et al., 2021) 1) Required personnel to move below decks or wear more protective PPE 2) Required some vessels to stop operations and relocate to safer area b) After SSDI was implemented during *Macondo*, VOC concentrations decreased to safe levels c) Standard hydrocarbon inhalation health thresholds (8 hr TWA) may not adequately protect offshore responders, who commonly work 12-hr shifts continuously for two weeks or more d) Response vessels are not always equipped with VOC filtration systems for interior living spaces, thus increasing VOC exposure risks or forcing vessels to relocate to areas with lower VOC levels
	Use of respiratory protection measures can significantly increase the required number of vessels and workers, slow source control operations, and may be discouraged by regulators: a) OSHA and NIOSH disapproved of respirator use during the *Macondo* response b) OSHA medical monitoring is required prior to use; many vessel crews not in a monitoring program c) Medical limits on the number of work hours, wet bulb temperature, and other conditions in which workers can safely use respirators d) Altered work/rest ratios to mitigate heat stress and heatstroke concerns in hot weather e) Logistics of rotating shifts within an elevated VOC zone f) Appropriate respirators and cartridges may not be readily available in required quantities
2	Mechanical recovery (booms and skimmers) historically has only recovered a small percentage of total offshore spill volumes (Etkin and Nedwed, 2021), including the estimated 3 % to 5 % during the *Macondo* response (Federal Interagency Solutions Group, 2010) a) SIMOPS zone typically too congested to safely conduct mechanical recovery b) Other non-SSDI VOC mitigation measures are very localized and temporary at best
3	SSDI is the only response option currently available that can continuously and effectively reduce VOC concentrations and mitigate associated health and safety risks in the SIMOPS zone a) Operates 24/7 (day and night); enables uninterrupted well control operations b) Operates in weather conditions that other response options cannot c) Potential to effectively disperse oil at the source, thus enabling source control work to continue
4	SSDI basics: a) SSDI equipment and dispersant stockpiles maintained at strategic U.S. and global locations b) Injects dispersants directly into the concentrated jet of oil at the source that can potentially treat 100 % of the discharge prior to wide distribution in the environment c) Dispersants reduce the oil interfacial tension, which enables the energy in the discharging oil jet to immediately break the oil into substantially smaller droplets d) Smaller droplets are less buoyant; this reduces rise velocity and increases water column residence time 1) Allows more dissolution and biodegradation to occur prior to surfacing, which reduces surface VOCs 2) Increases lateral transport of oil droplets by subsurface currents, resulting in more oil surfacing outside the SIMOPS zone 3) Very small droplets become neutrally buoyant and never reach the surface, thus reducing the quantity of surface oil and associated VOCs and ecological impacts

5	Reduced surface oil volume lessens the environmental/ecological impacts a) Minimizes impacts to surface dwelling fauna such as turtles, birds, and marine mammals b) Reduces the quantity of oil impacting shorelines and associated habitats where it typically persists for extended periods of time c) Reduces the quantity of oil impacting nearshore areas, which are often nursery grounds (including the Gulf of Mexico) for many fish, shellfish, and other marine organisms
6	Monitoring systems can be rapidly deployed to validate SSDI efficacy in reducing oil droplet sizes, quantity of surface oil, surface VOC concentrations, and other parameters
7	Keys to SSDI effectiveness a) Implement as quickly as possible (continued use often based on efficacy validation) b) Inject dispersants at rates (DORs) that will reduce oil droplet sizes to the extent practical [injection rates during *Macondo* were too low most of the time (Zhao, et al., 2021)] c) Maintain consistent/continuous injection to extent possible (very sporadic during *Macondo*)

2.3.4 SSDI Justification

If the above data evaluation concludes the presence of a significant health and safety risk, and SSDI is considered a viable response option, a justification for the use of SSDI to mitigate those risks must be developed and included in the authorization application. The justification should focus on SSDI's potential to mitigate those risks, as well as the evaluation of alternative risk mitigation measures that the FOSC will likely require in the application.

Assessing SSDI's potential to mitigate VOC and other safety case-related risks typically involves, but is not limited to, the following:

— oil dispersibility;

— modeling results, if feasible;

— supporting evidence/case histories.

Dispersibility

Most crude oils found in deepwater areas are dispersible, although it largely depends on the oil's viscosity. Dispersants are generally more effective on low- to medium viscosity oils, although some higher-viscosity oils are dispersible. Testing of oil samples taken during drilling operations or from the discharge point can be done to quickly validate dispersibility.

Modeling

Computer-based models have been developed to simulate subsurface oil and gas releases and predict plume characteristics and behavior as the oil rises through the water column, as well as oil droplet size distributions and surface expressions for dispersed and undispersed oil. These models can also be coupled with air dispersion models to predict surface VOC concentrations for dispersed and undispersed oil. Time permitting, results of these models can be used to demonstrate the risk mitigation potential of SSDI.

Respiratory Protection

A common VOC exposure mitigation measure for responders is the use of respirators, including air purifying (Level C) or supplied air (Level A or Level B). These can be effective in protecting the health of humans operating within hazardous environments, but can also significantly impede or slow down source control operations due to:

— Medical monitoring: OSHA requires that all personnel undergo medical monitoring prior to and following respirator use.

— Work/rest rations: Shorter work periods and longer rest times are generally required when using respirators.

— Heat stress: Increases when using respirators, particularly in hot/humid conditions, thus necessitating shorter work periods and longer rehab times.

— Impaired vision: Peripheral vision is reduced while wearing respirator face masks.

— Shift rotation logistics: Becomes more difficult in elevated VOC environments and may require more workers in the rotation.

— Additional precautions: More frequent air monitoring/sampling, medical monitoring for exposures, and other precautions.

Additionally, respiratory protection is only applicable for source control vessels that are equipped with interior air filtration/VOC removal systems, which is not always the case. If not, workers will continue to be exposed to VOCs when inside the vessel.

Supporting Evidence

In the early stages of most subsea releases, modeling results for the incident will not be available, thus necessitating the reliance on supporting evidence from previous studies and case histories to justify the use of SSDI. Summaries of the relevant supporting evidence projects are provided in Annex B. These projects document SSDI-related reductions in VOCs during the *Macondo* incident, as well as in laboratory tests, research efforts, and deepwater well blowout modeling projects. The various graphics, tables, and conclusions from each of these projects in Annex B and potentially others should be used to demonstrate SSDI's VOC mitigation potential.

Alternative VOC Mitigation Measures

Several non-SSDI, VOC-related risk mitigation measures were utilized during the *Macondo* response, with varying degrees of success. These measures were primarily used prior to SSDI becoming operational and during pauses in SSDI use to reduce VOC concentrations around vessels within the SIMOPS zone and should be considered for use in future oil spills. These measures included:

— Water sprays: Sprays from vessel fire-fighting equipment can temporarily knock down VOC vapors and reduce concentrations.

— Activated charcoal filtration: In some cases, activated carbon filters can be installed over the vessel HVAC air intakes.

— Higher levels of personal protective equipment (PPE): Air-purifying or supplied-air respirators can be very effective in reducing VOC exposure.

— Administrative controls: Limiting outside work periods on the vessels will reduce the duration of VOC exposure.

— Vessel surface application of dispersants: Dispersing surface oil into the upper water column can significantly reduce VOC concentrations and exposures.

Water sprays were the measure most commonly used during the *Macondo* response and were relatively effective in reducing VOC concentrations, but only in the immediate vicinity of the water sprays.

2.3.5 Supporting Plans

In most cases, the FOSC will require that one or more SSDI support plans be included as part of the authorization application submittal. These plans enable the FOSC to better understand the planned SSDI operations, as well as air monitoring and other activities intended to protect responder health and safety and validate the efficacy of SSDI in mitigating the safety case risks. Brief descriptions of the SSDI supporting plans that may be required for authorization are provided below.

Air Monitoring and Risk Mitigation Validation Plan

It is likely the FOSC will require an air monitoring plan to be submitted that describes the air-monitoring team and resources, planned air-monitoring activities (including data collection and management), and how the air-monitoring, aerial imagery, and/or other data will be used to validate SSDI's effectiveness in mitigating the safety case risks.

Dispersant Monitoring Quality Assurance Project Plan (DMQAPP)

A DMQAPP now is required under 40 CFR 300 Subpart J and primarily involves detailed descriptions of water column monitoring and quality assurance activities associated with determining the efficacy of SSDI and identifying potential ecological impacts. The monitoring activities covered by the DMQAPP are largely aligned with those described in *Environmental Monitoring for Atypical Dispersant Operations* [National Response Team (NRT), 2013]. Although water column monitoring is the primary focus, the plan is a regulatory requirement so it will likely be required even if the authorization is based solely on safety case risk mitigation. In this case, the above information on air monitoring and risk mitigation validation should be incorporated into the DMQAPP.

SSDI Operations

This plan should primarily include a detailed description of the SSDI system and how it will be configured, deployed and operated, including the means of dispersant injection and planned injection rates (dispersant-oil ratios or DORs). It should also describe the means of determining system efficacy, which generally involves the monitoring of oil droplet size distributions before and during dispersant injection. Additionally, a description of the dispersant supply chain should be included to assure the FOSC that an adequate and continuous supply of dispersants can be maintained.

SSDI Site Safety Plan

This may be a stand-alone document or an addendum to the overall incident site safety plan, but should describe the measures to be taken to ensure the safety of all personnel involved in the deployment, operation, and monitoring of the SSDI system. It should also include those personnel involved in the air-monitoring operations associated with SSDI operations.

2.3.6 Application Submittal

The information, data, forms, etc. identified in Section 2.3 should be compiled into a temporary SSDI authorization application and submitted to the FOSC. In some cases, only the critical data sheet and talking points may be required to initiate the review process. A checklist identifying the activities and questions often associated with a safety case-based SSDI authorization application is provided in Table 5. An example of a signature page/cover sheet that can be used when submitting the application is provided in Figure 3.

2.4 Ongoing Authorization

Following a successful SSDI test, a subsequent authorization for the continued use of SSDI will likely be required and should generally follow the same process discussed in Section 2.3 for temporary authorization. In this case, however, an even more data-driven justification will likely be required. As was the case for the *Macondo* incident, periodic or even daily reauthorizations may be required to enable regulators to use new data to reevaluate health and safety risk mitigation, as well as ecological, socioeconomic, and cultural tradeoffs prior to re-authorization. A decision guide for ongoing authorization is provided in Figure 4.

Table 5—SSDI Authorization Application Checklist

Status	Application Component
	Signature page for FOSC authorization and UC approval (Figure 3)
	Incident and key contact information (critical data sheet—Table 1)
	Attachments to the critical data sheet (Table 1) including: — tabulated air monitoring data — aerial image/map showing air-monitoring locations/transects — monitoring data analysis showing peak and average concentrations — relevant regulatory thresholds and industry action levels (Table 2 and Table 3)
	Identification of vessels operating in SIMOPS zone and number of personnel onboard each vessel to assess the magnitude of safety case risk (critical data sheet—Table 1)
	Discussion of the SSDI system and dispersant supply availability and a timeline for system mobilization, deployment, and initial operation (critical data sheet—Table 1)
	Aerial imagery showing locations of surface oil accumulations relative to well control vessels located within SIMOPS zone (critical data sheet—Table 1)
	Comparison of monitoring data to regulatory thresholds and industry action levels to establish level of risk (Section 2.3.2)
	List of SSDI talking points (Table 4)
	SSDI justification (Section 2.3.4) describing how SSDI can mitigate safety case risks and including discussions on: — oil dispersibility — dispersed oil plume and VOC dispersion modeling (if available) — supporting evidence — non-SSDI VOC mitigation measure evaluations

	— Supporting plans (Section 2.3.5) that may be required by the FOSC for inclusion in the application and potentially including:
	  — air-monitoring and risk mitigation validation plan
	  — dispersant monitoring quality assurance project plan (DMQAPP)
	  — SSDI operations plan
	  — SSDI site safety plan

2.4.1 Statistical Data Analysis

Once air-monitoring data has been collected before, during, and potentially after the initial SSDI test or subsequent use, a comparison must be conducted to evaluate its efficacy in mitigating risks to responder health and safety. If the collected data sets are of high quality (i.e., consistent, relevant, and of sufficient duration) and show an obvious reduction in VOCs in response to SSDI use, an in-depth statistical analysis may not be required. Conversely, if less obvious differences between the data sets exist, a formal analysis may be required to determine the degree of SSDI's VOC reduction effectiveness. If the reduction is so small that only a complex statistical analysis can confirm it, SSDI may not be a viable risk mitigation option.

A straightforward statistical analysis approach would be to calculate the means, medians, 75th, 95th, 99th, and 99.9th percentiles, as well as the number of measurements above specified thresholds for the pre-, during-, and post-SSDI data sets and compare the results. If SSDI is effective in reducing VOCs, the pre-SSDI results will be significantly higher than the during-SSDI results and the post- and pre- results will be similar.

To: FOSC
From: Incident commander and safety officer
Date:

[Responsible Party] is requesting formal approval for subsea dispersant injection (SSDI) as the primary means for mitigating significant health and safety risks to spill response personnel working in the SIMOPS zone. SSDI will be a key component of the overall response actions for the **[Insert Name of the Event or Exercise]**. We are respectfully submitting the following documents to support the FOSC's considerations (including seeking RRT concurrence) during this decision process:

1) signature page (this page) for authorization by the FOSC and approvals by other members of the UC.
2) critical data sheet, including:
   a) incident and key contact information;
   b) monitoring data attachments, including:
      — air monitoring data;
      — Aerial image/map showing monitoring locations/transects;
      — data analysis showing peak and average concentrations;
      — relevant regulatory thresholds and industry action levels;
   c) identification of vessels in SIMOPS zone and number of personnel onboard;
   d) discussion of SSDI system and dispersant availability, as well as timeline until operational;
   e) aerial imagery showing locations of surface oil relative to well control vessels;
3) comparison of monitoring data to regulatory thresholds and industry action levels;
4) SSDI justification (evaluation of risk mitigation potential);
5) supporting plans:
   a) air monitoring and risk mitigation validation plan;
   b) SSDI operational plan;
   c) others as required by FOSC.

Should you have any questions on this information, please contact the incident commander or safety officer.

Role in Unified Command	Signature	Agency	Date
Federal on-scene coordinator (FOSC)		USCG	
Unified Command Members (as appropriate)			
Responsible party incident commander (IC)		[INSERT]	
State on-scene coordinator (SOSC)		[INSERT]	
(Insert other state SOSCs as necessary)		[INSERT]	
(Tribal on-scene coordinator, as necessary)		[INSERT]	
(Additional signatures, as necessary)		[INSERT]	

Figure 3—Example SSDI Application Cover Page

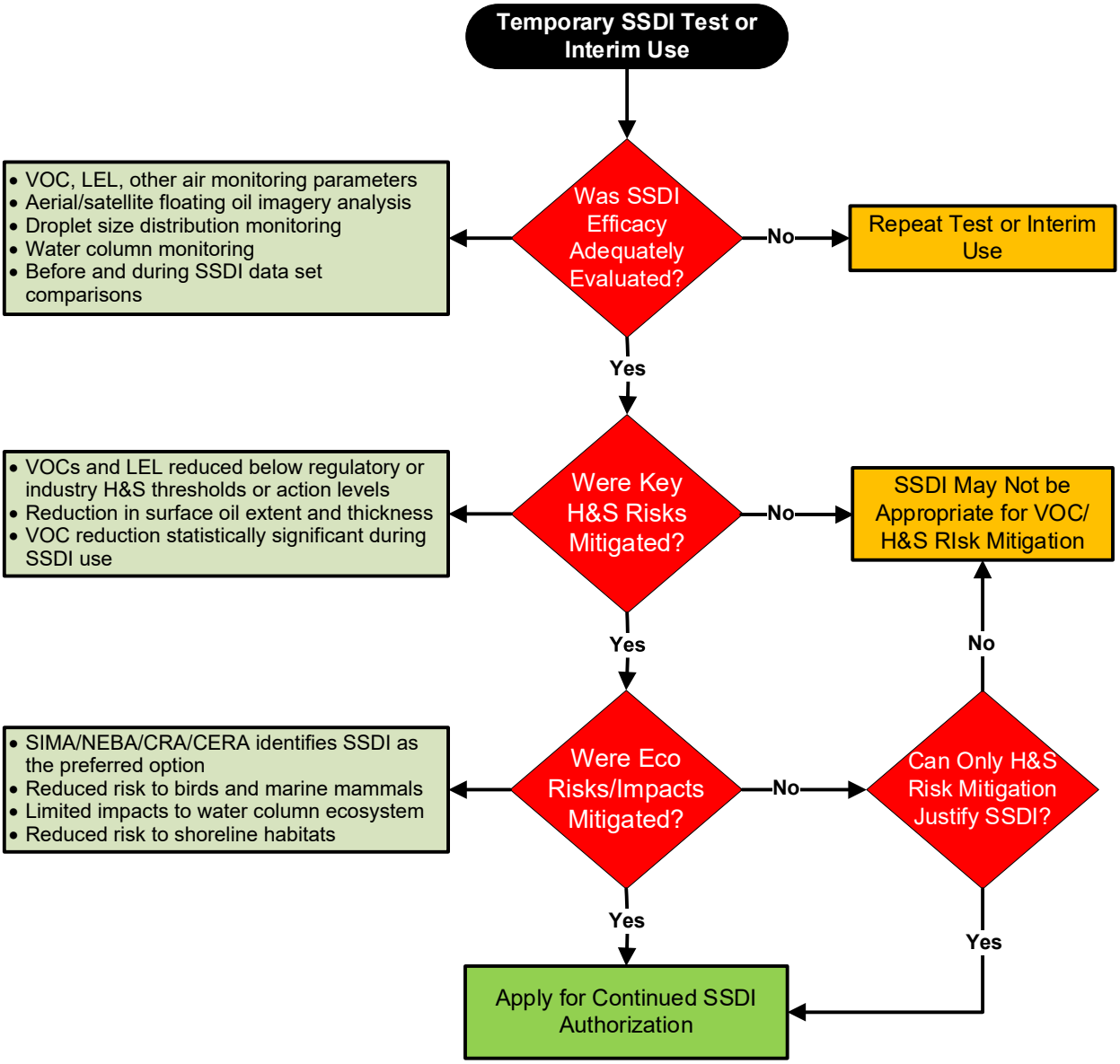

Figure 4—Ongoing SSDI Decision Guide

In the event that this approach does not produce a clear distinction between the data sets, a more sophisticated statistical analysis using the one-sided Kolmogorov-Smirnov test could be applied. This test compares the distribution functions (i.e., shapes of the distribution curves) for each data set, which is more sensitive than other statistical analyses. It should be noted that monitoring activities should target areas with significant floating oil accumulations, as numerous non-detect VOC readings can greatly affect the analyses.

2.4.2 Ongoing Authorization Justification and Application

Assuming the SSDI test, or subsequent use periods, demonstrate SSDI's efficacy in mitigating health and safety risks and ecological impacts, a subsequent justification will need to be prepared and an application for authorization submitted. The same checklist used for the initial authorization application (Table 5) can be used for subsequent applications. The data and other information that will be useful in developing a justification for subsequent SSDI authorizations will likely include:

— air and other monitoring data sets obtained before, during, and after the initial test or subsequent SSDI use to highlight the differences in VOC concentrations during those periods;

— results of data analyses, if necessary, illustrating a statistical difference in the different monitoring data sets;

— comparison of before, during, and after data to health and safety thresholds to show the degree of risk mitigation during the previous period;

— comparison of the changes in surface oil (see Section B.5) to corresponding variations in VOC concentrations to further assess SSDI effectiveness;

— results of any incident-specific surface VOC modeling;

— analytical results (VOC constituents) of corresponding water samples that may have been taken at air monitoring stations; and

— monitoring and sampling locations and associated data plotted on diagrams, maps, or aerial imagery that also display the locations of surface oil.

Due to the assumed availability of a comprehensive empirical data set, it is unlikely the supporting evidence recommended for justifying a temporary authorization will be required for subsequent justifications.

In addition to the above data collected for responder health and safety concerns, a variety of additional data is commonly collected by others that could be useful in analyzing VOC data and developing a justification for SSDI authorization. Examples and their relevance to VOC data analysis include:

— SSDI injection rate (GPM and DOR): Changes can be correlated to subsequent differences in quantities of surfacing oil and resulting VOC concentrations.

— Dispersed oil droplet size distributions: Monitored primarily to determine SSDI efficacy, droplet size changes can also be correlated to changes in surfacing oil and associated VOC concentrations.

— Discharge plume trajectories: Subsurface currents can significantly alter rising oil plume trajectories, resulting in the oil surfacing away from the well area, which could explain decreases in VOC concentrations above the well.

— Aerial/satellite imagery and remote sensing: Frequent images of the same areas along with remote sensor measurements of floating oil thickness are used to assess changes in surface oil that can be correlated to variations in VOC concentrations.

— Dissolved oxygen: As the dispersed oil droplets rise through the water column, they undergo aerobic biodegradation, which reduces their VOC content. A drop in dissolved oxygen generally indicates biodegradation is occurring, but a substantial drop could inhibit further aerobic biodegradation and the corresponding reduction in VOC content.

A weight of evidence approach should be taken when developing justifications for ongoing SSDI authorizations. A compilation of applicable data types and analyses mentioned in this section, along with any other relevant data and analyses, should be used to clearly demonstrate the degree in which SSDI has mitigated, and will continue to mitigate, risks to responder health and safety. This is particularly true with respect to source control operations.

3 Monitoring and Assessment

3.1 Introduction

Under optimal conditions, SSDI systems can be deployed and become operational in as few as three days following a deepwater loss-of-well-control incident. Consequently, the collection of air-monitoring and related data must begin as soon as possible. The purpose of this section is to provide general guidance on the preparation for and collection of VOC and other related data needed to facilitate obtaining authorization prior to the SSDI system becoming operational, as well as ongoing authorizations. A summary of common monitoring and assessment activities is provided in Table 6.

Table 6—SSDI Monitoring and Assessment Activities

Status[1]	Activity
Air Monitoring Preparation (Section 3.2.1)	
	Mobilize available air monitoring resources (equipment and personnel)
	Establish air monitoring/sampling team within the IMT (generally under the SOFR)
	Identify air-monitoring/sampling platforms (vessels, aircraft, etc.)
	Develop air-monitoring/sampling plan per critical data needs and available resources
	Develop air-monitoring-specific site safety plan (can be appended to incident action plan)
	Coordinate planned activities with the IMT EU, OPS, etc.
Initial Monitoring Activities, Locations, and Data Management (Sections 3.2.3, 3.2.4, and 3.2.5)	
	Conduct all field activities in accordance with the monitoring and safety plans
	Identify ideal monitoring locations/transects, but modify in the field as necessary
	Document all monitoring activities and results
	Develop data transfer and management protocols, including QA/QC requirements and distribution to end users, and document in the monitoring plan
	Communicate monitoring/analytical results to the SOFR per established protocols
	Utilize iterative process to update monitoring plan as appropriate
Ongoing Monitoring (Section 3.3)	
	Expand monitoring program to collect and effectively manage all data required to protect responder health and safety and continued SSDI authorizations
	Utilize iterative process to update monitoring program and plan as new data is collected, additional resources become available, or field conditions change
	Develop, if necessary, a comprehensive database and data management protocols to replace those utilized during the initial monitoring activities

3.2 Initial Air Monitoring

3.2.1 Preparation

Following a subsea well control incident, numerous activities will occur quickly and simultaneously, including the mobilization of substantial response resources. Implementation of an initial air monitoring program can be problematic as the IMT, communication channels, logistical arrangements, etc. are still being organized and resources are often limited. Consequently, data collection activities must be prioritized based on the available monitoring and sampling equipment, trained personnel, and platforms

(vessel, aircraft, drones). Ideally, at least one vessel and potentially an aircraft should be dedicated for air-monitoring activities.

The key preparation activities for establishing an initial air-monitoring program are listed below, along with brief explanations for each:

— Mobilize available resources: Expedite identification and mobilization of available equipment and personnel as this is time-critical.

— Establish air-monitoring team: Identify clear roles and responsibilities to effectively conduct and manage planned activities and determine where the team resides within the IMT (typically part of the SOFR function).

— Acquire monitoring platform(s): Identify available platforms such as vessels, aircraft, etc. and retain the best option(s). Should be dedicated to monitoring but may need to be a shared resource.

— Develop air-monitoring plan: Base the plan on prioritized data needs and available resources (i.e., what can realistically be accomplished) and include data management protocols, procedures, and qualified analytical laboratories.

— Develop site safety plan: Address safety issues for all planned monitoring activities and append to the incident safety plan, or create stand-alone plan.

3.2.2 Monitoring Considerations

It is important to note that a variety of factors can affect the monitoring results, as well as the analysis of the data, including:

— Wind speed: Measured VOC concentrations should be corrected or normalized (see Section C.5) for the dilution effects of the wind (higher speeds = lower concentrations).

— Instrument calibration: VOC monitoring data accuracy can be dependent on instrument calibration frequency and type of calibration gas used as different correction factors apply for different gases (see Section D.5).

— Instrument correction factors: Monitoring instruments may not measure VOCs directly, thus requiring the application of correction factors that vary depending on the instrument and calibration gas used (see Section D.3.1).

— Humidity and temperature: High humidity and temperatures can result in lower VOC readings, particularly when using photo ionization sensors.

— Trained monitoring technicians: Must be adequately trained to effectively operate monitoring equipment.

— Oil characteristics: A detailed hydrocarbon analysis of the crude oil will determine VOC and H_2S content, this analysis can be used to qualitatively estimate surface VOC and H_2S concentrations.

Other considerations that could affect monitoring results and data analysis include using monitoring instruments to collect real-time air quality data versus collecting air samples and submitting to a laboratory for analysis. An example is Summa canister air samples taken using a transect methodology and analyzed by a laboratory. This may provide low detection limits and resulting high quality data, but require at least a 24-hour turnaround time for the analyses. Additionally, data validation measures must

be reviewed prior to the use of aerial platforms to verify the accuracy and precision of samples taken using this method.

All monitoring activities should be coordinated with any other monitoring and sampling activities being conducted by the IMT's EU, operations section (OPS), and/or source control branch/section to better ensure the safety of monitoring personnel, maximize synergies, and avoid duplication. Monitoring should continue throughout the response.

Other associated data that should be collected will likely include:

— GPS coordinates of each monitoring location/station/transect;

— wind speed and direction at each location/station/transect;

— surface water current speed and direction;

— vessel/aircraft speed if conducting continuous monitoring;

— monitoring height above water surface;

— weather conditions such as humidity, temperature, presence of rain, etc.

Wind and weather conditions can affect VOC concentration measurements, and GPS coordinates will be used to overlay the monitoring stations on a map or aerial image that also shows surface oil locations, the leak location, and wind and current directions and speeds. More information on monitoring strategy/activities and equipment is provided in Annex C and Annex D, respectively.

Other air-monitoring information that should be collected to evaluate effects on instrument readings include:

— Proximity to surface oil accumulations: Distance to the accumulations and if they are upwind, downwind, or cross-wind of the monitoring site.

— Proximity to other VOC sources: Distance to and type of VOC source (vessel or deck equipment engine exhaust, on-deck recovered oil storage tanks, etc.) and if located upwind, downwind, or cross-wind of the monitoring site.

Other VOC sources on vessels should be considered carefully as they are frequently present and may result in incorrect readings.

3.2.3 Monitoring Activities

Due to their time-critical nature, monitoring activities should commence as soon as adequate resources have arrived onsite, suitable monitoring platforms have been acquired, and the appropriate health and safety measures are in place. This section provides basic information on conducting monitoring activities; additional information on monitoring activities and strategies is provided in Annex C.

A prioritized list of data needs, general types of monitoring equipment, and common platforms used to collect those data are shown in Table 7. This information can be used in the identification of the appropriate monitoring equipment and development of an initial monitoring plan. Basic information on VOC monitoring can also be found in Section 4.1 of API Technical Report 1152, *Industry Recommended Subsea Dispersant Monitoring Plan* (API, 2020) and Section 5.0 of *Environmental Monitoring for Atypical Dispersant Operations* (NRT, 2013).

Vessel-based air monitoring is often the primary means of gathering data during an oil spill response. Dedicated monitoring vessels will enable the optimization of data collection locations or transects, whereas if response vessels are utilized, locations will be dictated by wherever response activities are being conducted. Aerial platforms have few restrictions and can cover a large area during each sortie. The flight/monitoring paths will likely follow a grid pattern over the spill area.

Initial monitoring from vessels should always start upwind of the floating oil and work toward the oil to adequately assess the hazards and risks posed by the oil/VOCs prior encountering the oil. Go/no-go thresholds should be established beforehand and documented in the monitoring program-specific health and safety plan. Under no circumstances should attempts be made to collect data (other than remotely) if those thresholds are exceeded or anyone in the team feels unsafe.

Table 7—Air Monitoring Data Collection Guidelines

Priority	Parameter	Equipment Type	Common Platform(s)	Frequency (Instant/TWA)
High	VOCs	PID with multigas meter/GC PID and Summa canister sampling	Vessel, aircraft	Instant and 15-minute averages reported once per hour
High	% LEL	Combustible gas meter	Vessel	Continuous with 15-minute averages reported once per hour
High	Hydrogen sulfide	Multigas or H_2S meter	Vessel, aircraft	Continuous if present
Medium	Benzene	Passive VOC badge dosimeters and/or charcoal tube with pump	Vessel	One per 8 hours per individual and task sampling
		Sorbent/colorimetric tubes or PID w/ benzene scrubbing tube	Vessel	Hourly—simultaneous timing with a PID sampling event

Monitoring activities will typically involve using one or more devices to measure VOC, benzene, and H_2S concentrations, as well as other parameters along defined transects and/or at a several locations within the SIMOPS zone or general spill area. Monitoring from response vessels generally involves collecting data at the same location over long periods of time.

General guidelines for conducting monitoring activities are provided below; Annex C contains supplemental information on air-monitoring strategies and activities:

— Monitoring transects: Continuous monitoring with documentation of peak and average concentrations along each transect.

— Monitoring stations or response vessels: Multiple readings taken over a set time period to identify peak and average concentrations at each location.

— Monitoring instruments: Should be programmed for continuous data collection, as well as average and peak concentrations every 15 minutes.

— Vessel speed: Must be recorded for continuous monitoring to facilitate calculation of a VOC mass balance.

— Instrument locations: Monitoring instruments should be positioned, where practical, at the same deck height as the smallest response vessel to ensure adequate protection of all response personnel.

All monitoring activities, as well as documentation of the associated results (i.e., measurements, readings, oil observations, aerial imagery, analytical results, meteorological parameters, etc.) should be conducted in accordance with the monitoring and site safety plans. They should also be conducted in a consistent and systematic manner to facilitate direct comparisons of data from different locations and times, as well as performing statistical analyses. It is particularly critical if monitoring data from both the response and dedicated monitoring vessels will be utilized. In this case, it is important to record when response vessels enter and exit areas with surface oil accumulations.

If air, water, or other samples are taken, they should be stored per EPA guidelines until delivered to an approved laboratory following standard chain-of-custody protocols as described in the monitoring plan.

3.2.4 Locations

Monitoring locations may vary depending on the type of platform being used, but due to the criticality of maintaining vertical access to the damaged well, they should focus on the source control portion of the SIMOPS zone. Additionally, this area typically contains the most surface oil and highest density of response activities.

Monitoring transects or stations should be established within the SIMOPS zone to enable multiple monitoring events at the same locations and enhance consistency of the data. Monitoring transects should be oriented perpendicular to the wind direction and extend beyond either side of the target areas to ensure adequate coverage.

Absent directives or recommendations from the IMT, the general initial locations or transects targeted for VOC and other air monitoring include:

— upwind, downwind, and cross-wind around the perimeter of the main surface oil accumulations, in addition to the area above the well (if they are different);

— at the perimeter and 0.1 and 0.5 distance (logarithmic values) from perimeter to directly above the well beginning at perimeter and moving towards the well;

— directly above the well; and

— freshest and/or thickest oil, as it will often be associated with the highest VOC concentrations.

Response vessels equipped with X-band radar and infrared (IR) camera systems can be used to locate areas with thicker floating oil to aid in the assessment of worst-case VOC concentrations.

Monitoring locations and strategies should be site/situational specific, somewhat fluid, and modified in the field if necessary due to changes in environmental conditions, surface oil accumulation movements, SIMOPS considerations, and others. Since the surface oil accumulations/slicks move with the winds and surface currents, and may surface away from the source control area during SSDI use, those oil accumulations should be prioritized if minimal oil is present in the source control area.

3.2.5 Data Transfer and Management

All data collected in the field should be communicated back to the SOFR function as soon as practical and follow data management protocols that should be outlined in the monitoring plan. The data management protocols should specify the:

— data owner;

— laboratory data validation packages;

— laboratory calibration standards that provide lowest practical detection limits for compounds of interest;

— targeted frequency and means by which data is transmitted to the SOFR each day;

— responsibilities for data compilation and management;

— required level of QA/QC review prior to distribution within the IMT; and

— process for distributing the data (how, when, and who the end users are).

3.3 Ongoing Risk Mitigation Monitoring

The initial air-monitoring activities described in Section 3.2 should continue seamlessly from inception through temporary SSDI use and beyond to ensure adequate data is collected both to protect responder health and safety and validate SSDI's mitigation of safety case risks. Monitoring specific to validating risk mitigation should be initiated prior to temporary SSDI use and continue for at least 24 hours afterwards to determine if VOCs and surface oil return to pre-SSDI use levels.

In addition to mitigating safety case risks, SSDI should be considered successful if the oil consistently surfaces and remains away from the source control operations, thus maintaining vertical access to the well while eliminating the need for temporary VOC mitigation measures in that area. This is true even if SSDI does not significantly reduce VOC concentrations in the area where the oil does surface.

3.3.1 Air Monitoring

Assuming temporary authorization is granted and SSDI is used to disperse the oil subsurface, an ongoing air-monitoring program will be required for continued SSDI authorization and use. This will both ensure the health and safety of response personnel and continue to validate SSDI's efficacy.

Assuming additional resources have been mobilized to the site, an ongoing air-monitoring program may be more robust than what was described in Section 3.2.3 and implemented in the first few days of the incident. While incident circumstances, environmental conditions, and UC/IMT data needs will often dictate how and where data is collected, the additional ongoing monitoring activities may include:

— conducting continuous or frequent air monitoring on multiple monitoring and response vessels working within the floating oil;

— having response personnel wear exposure badges or carry personal sampling pumps with adsorbent tubes to assess time-weighted exposures;

— conducting biomonitoring (urine testing) to determine individual exposures to more toxic compounds such as benzene;

— establishing additional transects or monitoring stations;

— collecting data from each transect or station at preset intervals over an extended time period to assess spatial and temporal variability;

— using dedicated monitoring vessels to optimize VOC data collection and correlate VOC concentrations to quantities of floating oil;

— employing aircraft with air-monitoring/remote sensing devices to collect data over larger areas or where it is unsafe for personnel to operate; and

— developing a comprehensive database to compile, store, and easily access all air-monitoring data collected during the response.

3.3.2 SSDI Efficacy Monitoring

SSDI operations, including the well flow rates and DORs utilized, as well as any changes over time, should be monitored and documented along with the associated droplet size distributions. These activities will typically be conducted by the IMT source control branch/section but should be coordinated with the SOFR's air-monitoring activities. This data is essential in understanding any changes in VOC concentrations and other monitoring results on the surface. If VOC concentrations do not decrease significantly following SSDI use, the well discharge may be under-dosed and the DOR should be increased even if droplet size distributions suggest effective dispersion. Conversely, if SSDI results in a significant VOC reduction, the DOR can be decreased incrementally to evaluate the effects on VOC concentrations on the surface. The ultimate goal is to use the lowest DOR that will effectively disperse the oil subsea and significantly reduce VOCs on the surface.

3.3.3 Surface Oil Monitoring

Since VOCs are generated almost solely from the volatilization of surface oil, it is essential to track changes in its extent and volume to better understand, as well as predict, variations in VOC concentrations, particularly with respect to SSDI operations. Common surface oil monitoring methods include:

— Aerial/satellite imagery: Images of the SIMOPS zone can be used to assess SSDI effectiveness by documenting any reductions in the areal extent of surface oil and the associated generation of VOCs.

— Multispectral and infrared cameras: Mounted on aerial platforms and coupled with specialized computer software, this technology can determine changes in surface oil thickness (see Section B.5) and extent (i.e., oil volume).

The images and thickness measurements should be taken at least daily at the same locations to enable valid reference comparisons. In addition, corresponding wind and surface current speed and direction data, as well as wave heights, should be collected to aid in interpreting changes in surface oil between images and measurements. These analyses can then be used to validate or discount the effects of SSDI on changes in surface oil coverage.

3.3.4 Monitoring Equipment

Equipment identified in Section 3.2.3 for initial monitoring activities is based primarily on what is typically available on short notice, and can be used effectively by response personnel with limited training. Risk mitigation and general ongoing monitoring will, however, generally involve more sophisticated and complex equipment that may require specially trained personnel to operate. Table D.1 in Annex D provides examples of monitoring equipment, along with selected capabilities and other information, that could be used in an ongoing monitoring program.

4 Supplemental Information and References

4.1 Supplemental Information

In addition to the documents referenced in previous sections and listed in Section 4.2, other sources of information that may be useful in assessing the health and safety risks from a subsea well blowout incident are listed below:

— API *Dispersant Fact Sheets 1–10*

http://www.oilspillprevention.org/oil-spill-research-and-development-cente

— API *Evaluation of Models for Subsea Dispersant Injection*, 2017

http://www.oilspillprevention.org/oil-spill-research-and-development-cente

— API Recommended Practice 98, *Personal Protective Equipment Selection for Oil Spill Responders*

http://www.oilspillprevention.org/-/media/Oil-Spill-Prevention/spillprevention/r-and-d/spill-response-planning/98-e1-pa.pdf

— IPIECA *Oil spill monitoring and sampling, good practice guideline*, 2020

https://www.ipieca.org/resources/good-practice/oil-spill-monitoring-and-sampling/

— IPIECA *Oil spill responder health & safety*, 2016

https://www.ipieca.org/resources/good-practice/oil-spill-responder-health-safety/

— IPIECA *Dispersants: subsea application, good practice guideline*, 2016

https://www.ipieca.org/resources/good-practice/dispersants-subsea-application/

— Environmental Protection Agency *Quality Assurance Sampling for British Petroleum Oil Spill*, 2010

https://archive.epa.gov/emergency/bpspill/web/pdf/bp-oil-spill-sampling-plan.pdf

4.2 References

API Bulletin 4719, *Industry Guidelines on Requesting Regulatory Concurrence for Subsea Dispersant Use*

http://www.oilspillprevention.org/-/media/Oil-Spill-Prevention/spillprevention/r-and-d/dispersants/industry-guidelines-on-requesting-regula.pdf

API Technical Report 1152, *Industry Recommended Subsea Dispersant Monitoring Plan*

http://www.oilspillprevention.org/oil-spill-research-and-development-cente

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Annex A

Subsea Dispersant Injection (SSDI)

A.1 Introduction

SSDI involves injecting or applying dispersants into the flow of oil, natural gas, water, and other reservoir fluids at the point of discharge from a damaged well. During the *Macondo* incident, dispersant was applied to the oil discharging from the malfunctioning well blowout preventer (BOP) situated just above the sea floor. In other cases, it may be possible to inject the dispersant into the BOP or other well component just upstream of the discharge point.

The placement of a well containment device and/or capping stack over the damaged well head (i.e., source control) is the primary means of controlling and terminating the discharge. These devices are extremely heavy (up to 100 tons), which requires deployment vessels to be located directly above the affected well; this is known as vertical access. Therefore, it is critical to maintain continuous vertical access during source control operations to minimize the time required to install the well containment device. The general area where source control activities are conducted is commonly referred to as the simultaneous operations (SIMOPS) zone.

During the *Macondo* incident, the volatilization of the surfacing oil, particularly in the SIMOPS zone, resulted in elevated VOC concentrations and their related health and safety risks (primarily inhalation-related health effects, eye irritation, and potential explosion hazards).

Prior to the use of SSDI and during pauses in its use, high VOC levels on the decks of the response vessels within the SIMOPS zone were temporarily mitigated by several means depending on the concentrations that generally included:

— $\geq$50 ppm: Standby vessels used water cannons/sprays to break up and mechanically disperse surface oil sheens or thin oil slicks adjacent to the response vessel, or industrial fans were positioned in the work areas to increase air flow and dilute VOC concentrations.

— $\geq$100 ppm: In addition to all measures approved for use at 50 ppm, standby vessels applied, if approved, dispersants to the surface oil.

These water and dispersant sprays were effective in reducing VOC concentrations, but only in the immediate vicinity of where the sprays were applied. In cases where these measures could not adequately reduce VOC concentrations, response vessels had to transit to an area upwind of the oil until VOC concentrations decreased to levels that did not require respiratory protection per the UC-approved safety policies.

Once operational, SSDI use in the *Macondo* response facilitated continuous vertical access and the placement of containment devices and a capping stack that shut in the well. While SSDI system installation and support vessels do not generally require direct vertical access, they need to be in close proximity as dictated by ROV tethering limitations and, as such, are subject to the same VOC concerns as the other response vessels.

A.2 SSDI Systems

The deepwater SSDI systems that have been developed post-*Macondo* are typically designed for rapid deployment and becoming operational within as little as three days. They are still relatively complex and consist of several components that often require multiple support vessels on the surface. Many of the key

components are readily available from offshore well containment companies, while some ancillary components may still need to be sourced by the RP. Some of these organizations also provide water column-monitoring equipment packages.

The main components of an SSDI system are described below and shown in Figure A.1:

— Coiled tubing vessel: Contains large spools of tubing or drill pipe that, once deployed, are used in conjunction with a special pump to transfer the dispersants from the surface to the sea floor.

— Dispersant supply vessel: Provides the quantity of dispersants needed to sustain a constant flow to the sea floor via the coiled tubing vessel.

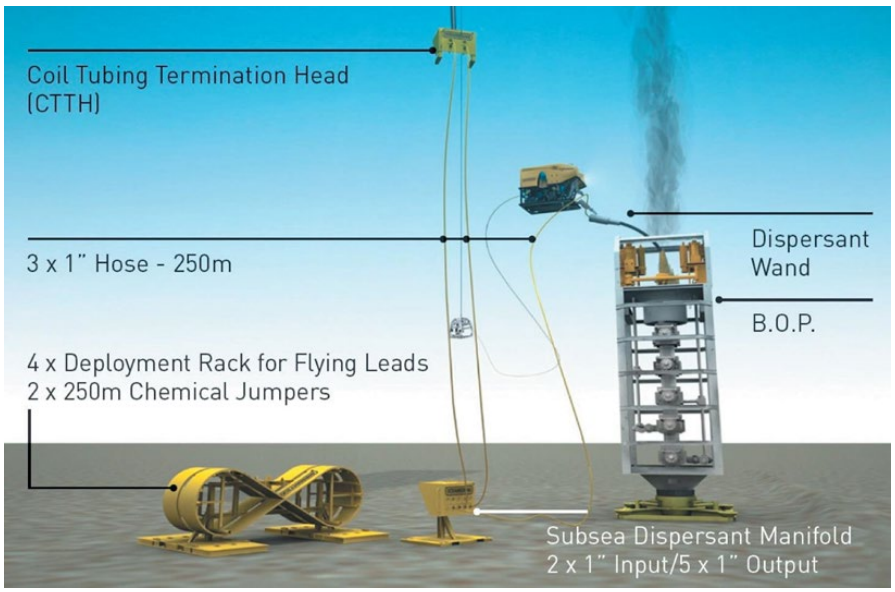
— Coiled tubing termination head (CTTH): Weighted device connected to the lower end of the coiled tubing and used as a connection point between the tubing and flexible dispersant transfer hoses called “flying leads” or “chemical jumpers.”

— Dispersant manifold: Situated on the sea floor and connected to the CTTH, it is used to distribute dispersants, via flying leads, to one or more injection devices.

— Dispersant wand: A hooked or straight pipe connected to the dispersant manifold via a flying lead and used to inject/apply dispersants into the oil as it discharges from the well.

— Flying lead deployment rack (FLDR): Situated on the sea floor, it temporarily holds the flying leads used to connect the dispersant manifold to the CTTH and dispersant wand(s).

— Remotely operated vehicles (ROVs): Subsea robots controlled by a surface vessel and used to connect flying leads between the various devices, as well as to hold the dispersant application wand adjacent to the discharging oil plume.



Source: Oil Spill Response Limited

Figure A.1—Subsea Dispersant System Components

A.3 SSDI Benefits

Historically, dispersants have been applied via aircraft or vessel to offshore surface oil spills or oil that has risen to the surface from subsea well blowouts. In the case of subsea spills, particularly in deep water, SSDI is a more effective means of application due to the following factors affecting surface dispersant application:

— Oil weathering: Volatilization and potential emulsification at the surface both increase surface oil viscosity, thus reducing dispersant effectiveness.

— Slick fragmentation: Difficult-to-uniformly-treat floating oil patches of various sizes, shapes, and spatial distributions.

— Daylight hours only: Must be able to see the oil to treat it and visually determine dispersant effectiveness.

— Wind and waves: Conditions are generally limited to < 30 mph (14 m/s) winds and < 9 ft (3 m) waves for aerial application, but is often less for vessels.

Additional benefits of applying dispersant subsea include:

— Increased efficiency and effectiveness: Although applying dispersants directly to the source is assumed to lose 20 % of the dispersants to the surrounding water, the remaining 80 % treats the oil with 100 % efficiency and may approach 100 % effectiveness (NASEM, 2020).

— Lower dispersant volumes: Increased treatment efficiency reduces the volume required to effectively treat the oil by up to five times relative to surface application (NASEM, 2020).

— Unaffected by high wind and wave conditions: Since dispersants are applied subsea, the operation is not affected by surface wind and wave conditions other than if the support vessel's safe operating limits are exceeded.

— 24-hour operations: SSDI operations are not dependent on daylight, so they can be performed 24 hours a day, seven days a week.

Similar to soaps and detergents, dispersants are comprised largely of surfactants that reduce the interfacial tension between the oil and water. This causes the oil droplets to break into substantially smaller droplets with diameters as small as a human hair or a period on this page (i.e., < 100μm). The smaller droplets, in turn, dramatically increase the oil's total surface area, which serves to:

— Increase biodegradation: Enhances the ability of naturally occurring marine bacteria to attach to the droplets, which then consume/degrade the oil.

— Increase dissolution: The more water-soluble components in the droplets can readily dissolve into the surrounding water as they rise through the water column.

— Reduce buoyancy and longer rise times: Very small droplets become neutrally buoyant and never rise to the surface, whereas slightly larger droplets rise more slowly in the water column, thus enabling more biodegradation and dissolution to occur before reaching the surface.

— Thinner oil slicks: Slowly rising droplets undergo more lateral transport by subsurface currents and will surface over a larger area, creating thinner slicks.

— Lower surface VOCs: Lighter oil components consist largely of VOCs and will readily degrade and dissolve during their rise through the water column, resulting in fewer VOCs being released at the surface.

While SSDI has been shown to mitigate many surface VOC- and oil-related environmental impacts, there has been some concern regarding VOCs derived from the natural gas component of subsea well discharges. Subsequent research projects have addressed this concern, including a project that evaluated the interaction between dispersants and natural gas bubbles in subsea well discharges and found that the gas bubbles did not significantly affect dispersant efficacy, but that the dispersant did significantly reduce the size of the bubbles, thus reducing buoyancy and rise time (P.J. Brandvick, 2017). Additionally, a deepwater well blowout modeling project (Pesch et al., 2020) and studies conducted during the *Macondo* incident (Kessler et al., 2011, Ryerson et al., 2011) concluded that natural gas bubbles readily dissolve as they rise through the water column, with few reaching the surface.

To emphasize the benefits of SSDI, the following discussion and figures highlight the differences between source control operations with and without SSDI.

A.3.1 Without SSDI

Oil discharging from the compromised well (i.e., the jet) will consist primarily of large droplets that are very buoyant and will quickly rise to the surface. Because of their buoyancy and rise velocity, the droplets are only minimally affected by subsurface currents that are typically present in offshore areas. Once the droplets reach the surface, they generally create a continuous layer of oil or slick above the well.

VOCs and other volatile hydrocarbons will evaporate from the oil into the air above the slick, creating an unsafe zone. That zone will be surrounded by a transition zone, wherein it may or may not be safe to conduct source control operations depending on the VOC concentrations. The transition zone is, in turn, surrounded by a safe zone with VOC concentrations being well below human health risk levels.

Without some form of VOC mitigation, it may not be possible to maintain vertical access to the well and conduct source control operations within the unsafe zone. As shown in Figure A.2, response vessels may be able to operate in the transition zone, but depending on the size of the oil slick and concentration of the associated VOCs, they may be too far away from the well to safely install an SSDI system.

A.3.2 With SSDI

As shown in Figure A.3, dispersants are injected into the damaged well head, causing the oil to break into very small droplets within the discharge jet. The smaller oil droplets are less buoyant, so they will rise much slower than the undispersed oil droplets discussed above and, consequently, will be transported laterally by subsurface currents. Oil droplets less than 75–100 microns in diameter are neutrally buoyant and will remain below the trap height in the water column (i.e., trapped plume). The larger, escaping droplets will continue rising through the water column.

Due to the lateral transport by subsurface currents, the escaping dispersed oil droplets will typically reach the water's surface at a significant distance from the well. They also tend to surface over a larger area, resulting in a thinner oil slick, and will, as discussed in Section A.2, contain fewer VOCs. The net result is a smaller unsafe zone that has lower VOC concentrations and is located farther from the well. Consequently, the dispersed oil reaching the surface will typically not affect vertical access to the well or impede source control operations.

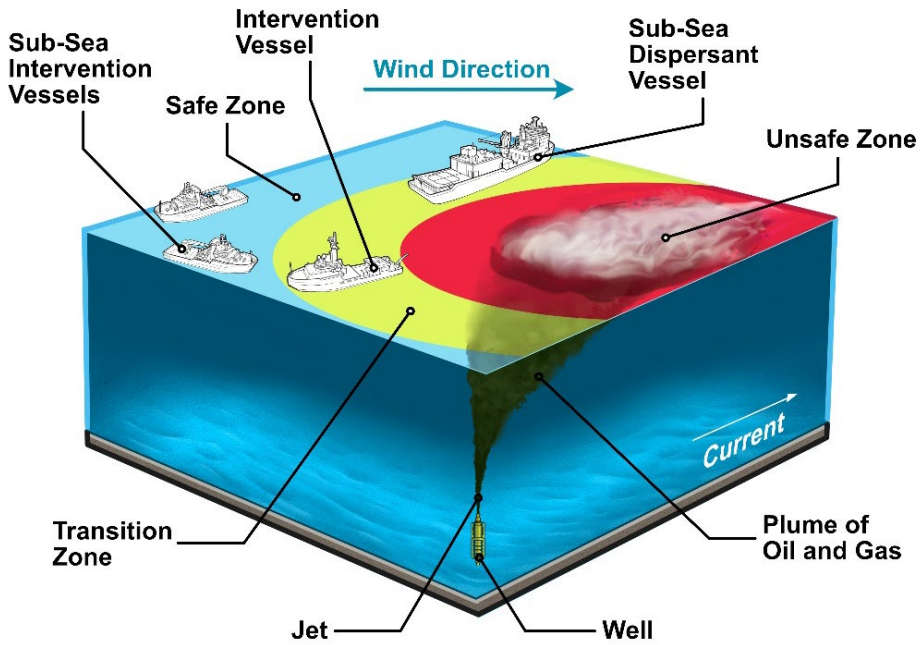


Figure A.2—Without Subsea Dispersant Injection (SSDI)

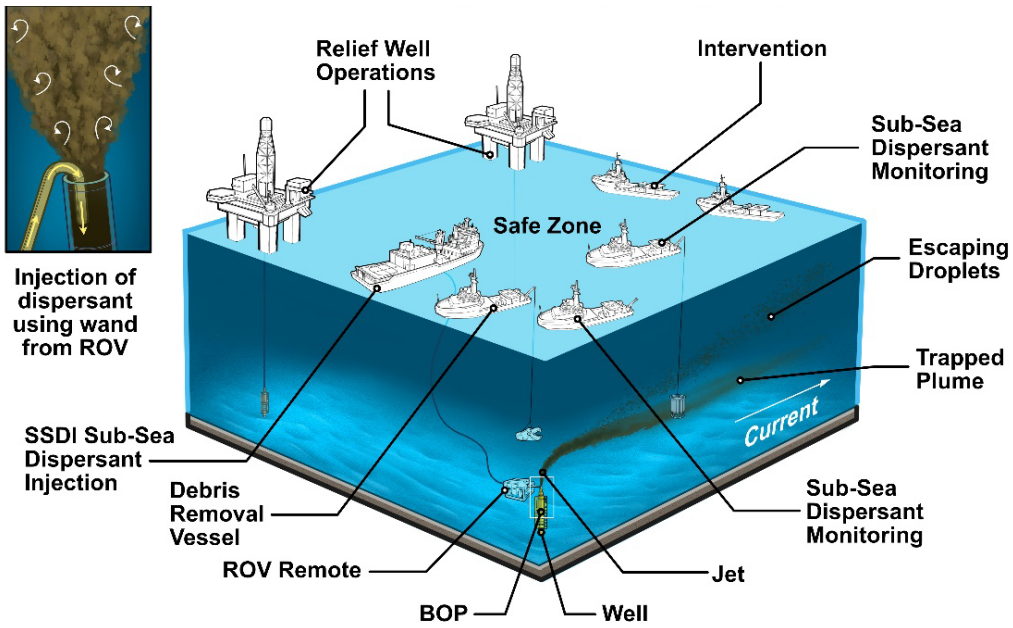


Figure A.3—With Subsea Dispersant Injection (SSDI)

Annex B

Supporting Evidence

B.1 Introduction

Several studies and projects have recently been completed on the effectiveness of SSDI in reducing the VOC concentrations in the air above the water's surface. Demonstrating this reduction in VOCs and the corresponding mitigation of responder health and safety risks is often critical in obtaining regulatory authorization for SSDI and in maintaining vertical access to the affected well.

Obtaining regulatory authorization for SSDI can be problematic, particularly in the early days of an incident where empirical data on VOC concentrations and other health and safety hazards are limited. However, the integration of available data with the results of recent studies can produce a compelling justification for SSDI use. Consequently, each of the relevant studies and their conclusions are summarized below. Links to the published study or research paper are also provided where available.

B.2 Correlation of *Macondo* VOC data and SSDI Use

A detailed analysis was conducted on the VOC data collected during the response to the *Macondo* incident, correlating it to SSDI use. The data set represents a total of 91,566 VOC concentration measurements taken on 20 different response vessels situated within the designated SIMOPS zone that housed up to 1,000 workers at any one time. The SIMOPS zone consisted of a 2.5-mile radius area located directly above the damaged well. The data points were obtained from the NODC Scribe[1] database and collected using MultiRAE monitoring devices. Each data point represents the highest 15-minute average VOC concentration measured each hour from each instrument.

Two data groups were analyzed representing different collection periods, including:

— 16 days prior to the initiation of regular SSDI operations on May 16; and

— 37 days between May 16 and June 21.

It is important to note that two SSDI tests were conducted prior to May 16 and, for various reasons, subsea dispersants were not always continuously or consistently injected after May 16, although SSDI was operational the majority of the second time period.

The key results of the analysis include:

— VOC levels on the vessels were clearly diminished ($p < 0.001$) during SSDI use.

— Peak VOC levels of > 50 ppm (immediate worker health concern) were reduced by a factor of ~ 6 to 19 when dispersants were injected at the intended rate.

Other pertinent results from the study are summarized below.

As shown in Table B.1, a basic analysis of the VOC data indicates a significant reduction in median, mean, and 95 % non-exceedance (NX) VOC concentrations during regular SSDI operations after May 16.

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[1] The National Oceanic and Atmospheric Association (NOAA) National Oceanic Data Center (NODC) SCRIBE database contains 14 data sets on water, sediment, oil, tar, dispersant, air, and other environmental samples taken during the *Macondo* incident.

Additionally, incidents of very high VOC concentrations decreased significantly during SSDI operations, dropping from approximately four times a day prior to May 16 to approximately 0.3 times a day after May 16.

Table B.1—Results of Basic VOC Data Analysis

Parameter	Prior to SSDI (4/28–5/15)	During SSDI (5/16–7/15)
Median VOC Concentration	0.16 ppm	0.02 ppm
Mean VOC Concentration	10.3 ppm	3.1 ppm
95 % NX* VOC Concentration	38.2 ppm	13.5 ppm
VOC Concentrations > 500 ppm	55 of 13,363 (0.45 %)	10 of 81,743 (0.01 %)
* 95 % NX (non-exceedance): 95 % of measurements are below this value.		

The results of a more detailed analysis of pre- and post-SSDI VOC data, as well as the effect of dispersant injection rates (gpm or DOR), the Top Kill well control attempt, and the flaring of recovered oil and gas on the Discoverer Enterprise vessel is provided in Figure B.1. The figure is from the pending manuscript and contains three graphs that display the results of different data analyses for the period between May 1, 2010, and June 20, 2010. The pertinent aspects of each graph are summarized below.

Graph A

This graph represents a compilation of all VOC detector data showing a large number of high concentrations prior to SSDI and significantly fewer after continuous SSDI operations began (May 15/Day 0), particularly during the Top Kill operation, which temporarily reduced the oil and gas flow rate from the damaged well. Note the y-axis scale change at 200 ppm and 1000 ppm. The graph also shows an increase in elevated VOC concentrations after the Discoverer Enterprise began processing and burning oil and gas that was captured at the well head. The increase in VOC is likely related to the flaring of excess recovered gas and oil.

Graph B

This is a compilation of VOC data from personal samplers worn by selected responders for the same periods noted above. This graph also indicates a decrease in high VOC concentrations after SSDI operations began (Day 0), but is followed by an increase after oil/gas processing begins (Day 19), although all readings are below BP's 50 ppm action level established in conjunction with NIOSH.

Graph C

This graph shows the daily average (through May) and hourly (starting in June) subsea dispersant injection rate(s). It includes the two tests conducted in early May prior to obtaining authorization for continuous use on May 15. The 10 gpm injection rate (1:108 DOR) was considered desirable and resulted in effective dispersion and mitigation of surface VOCs, whereas lower injection rates were thought to be suboptimal. As shown in the graph, consistent injection rates of around 10 gpm generally resulted in the greatest reductions in VOC concentrations.

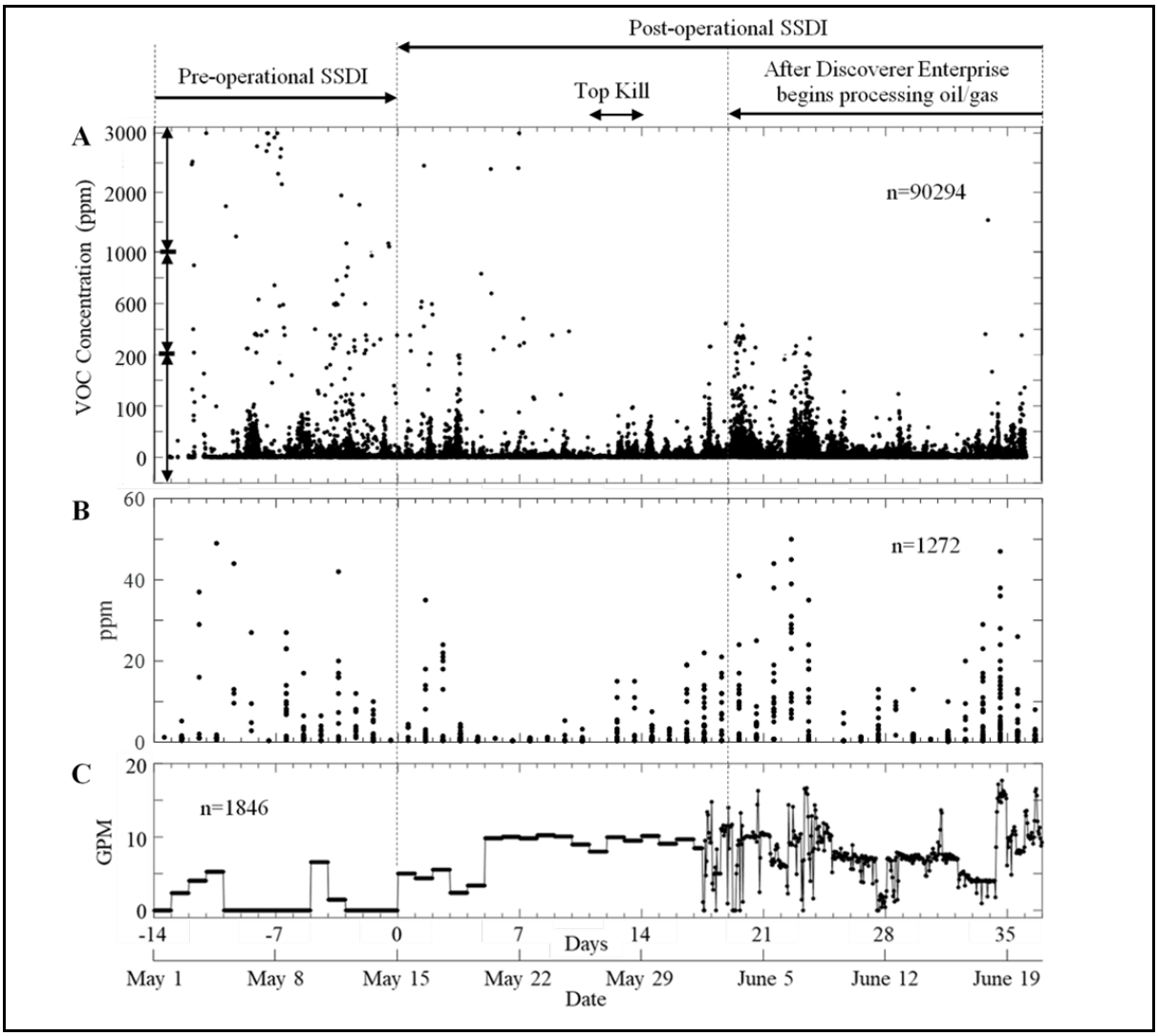


Figure B.1—Detailed Analysis of VOC Data and Dispersant Injection Rates

Another way to evaluate the potential benefits of SSDI is to consider the cumulative potential exposure above the 50 ppm action level. The study calculated the VOC measurements exceeding 50 ppm each hour and normalized to the number of detectors in the SIMOPS zone for that hour to generate a VOC-hours metric. VOC-hours, cumulative VOC-hours in particular, is thought to be a better indicator of the overall level of VOC exposure to responders (i.e., health risks) than individual measurements.

Figure B.2 includes three different graphs of VOC-hours data relative to dispersant injection rates to demonstrate the benefits of SSDI in reducing VOC exposures, particularly at higher injection rates. Graph A indicates an injection rate of > 10 gpm reduced VOC-hours 16-fold over no SSDI for all data collected and 29-fold in Graph B for data collected before gas and oil flaring began.

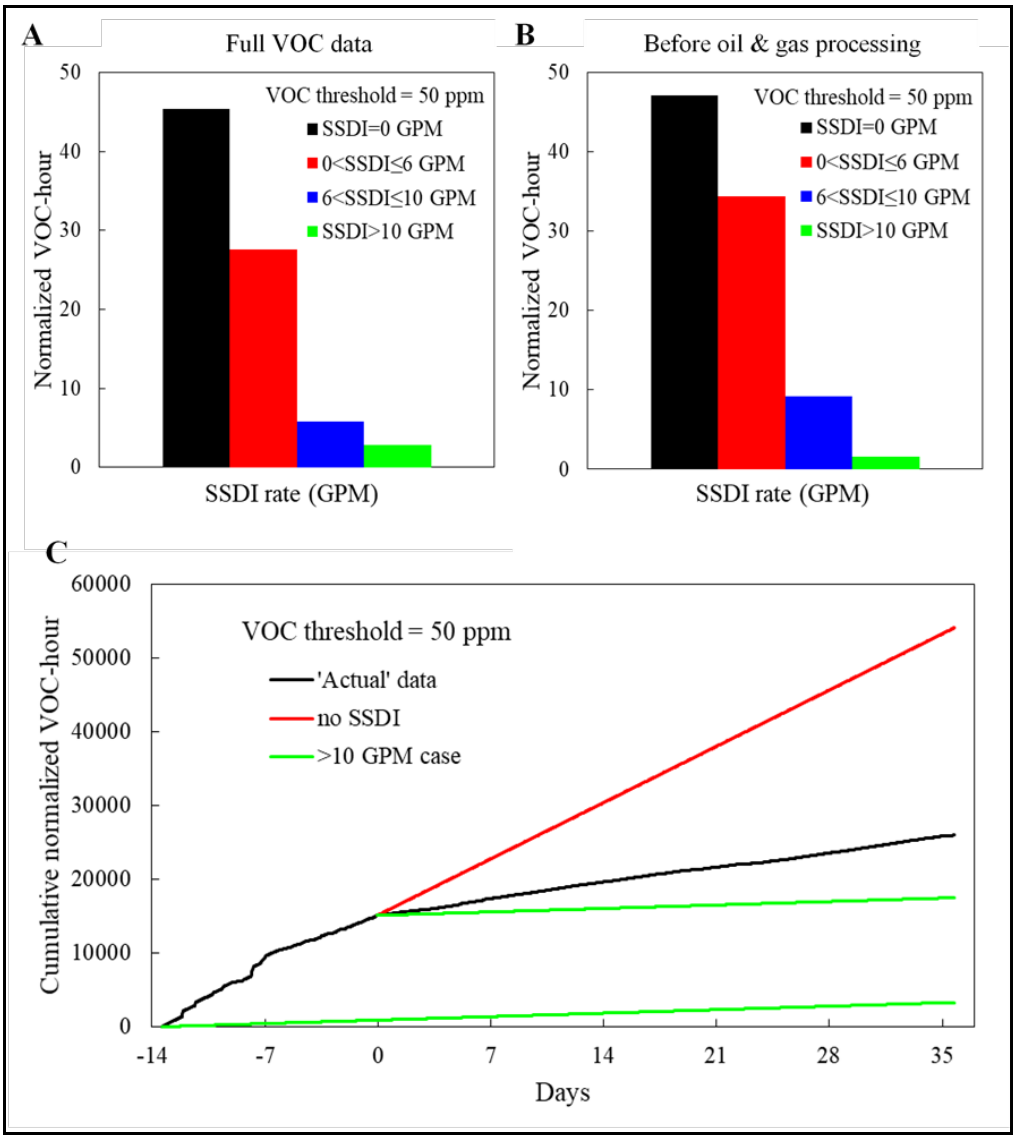


Figure B.2—VOC Accumulation as a Function of SSDI Dosage

Graph C of Figure B.2 displays the cumulative VOC-hours over 50 ppm for different scenarios, including the following "What If" data analyses:

— Black line: Actual data showing the accumulations of VOC-hours for the period from 14 days before SSDI operations began through 35 days after.

— Red line: Shows the projected accumulations of VOC-hours if SSDI had not been utilized.

— Green lines: Shows the projected accumulations of VOC-hours if the dispersant injection rate was > 10 gpm starting the first day SSDI operations began (Day 0) and if it had started 14 days before (Day -14) before.

Based on this analysis, it is estimated that a 94 % reduction in VOC-hours above 50 ppm compared to a scenario with no SSDI would have occurred if SSDI was continuously implemented at 10 gpm starting on May 1.

In summary, the results of this study show the following:

— SSDI significantly reduced mean and median VOC concentrations, as well as incidents of exposures to high VOC concentrations (>500 ppm).

— The flaring of oil and gas directly recovered from the well by the Discoverer Enterprise vessel beginning in June increased VOC concentrations on the surface.

— An SSDI injection rate of ≥ 10 gpm (1:108 DOR) was very effective in reducing VOC rates, even during oil and gas flaring.

— A > 10 gpm injection rate also significantly reduced total cumulative VOC-hours over the 50 ppm action level, which is thought to be a better health risk indicator than individual VOC measurements.

A peer-reviewed manuscript describing the above analyses and the results has been published in the *Marine Pollution Bulletin* and can be accessed at https://www.sciencedirect.com/science/article/abs/pii/S0025326X21010687.

B.3 VOC Modeling

API retained the RPS Group to model oil transport and fate, air emissions, and atmospheric dispersion of VOCs from a hypothetical deepwater (approximately 4,500 feet) well blowout in the De Soto Canyon area of the Gulf of Mexico. The crude oil type used in the model was similar to the characteristics of the light, sweet *Macondo* oil (API 35, 0.85 specific gravity). Separate modeling was conducted for two response options: 1) no intervention, and 2) use of SSDI at the source over three, week-long periods representing different atmospheric mixing conditions. The VOC concentrations were modeled for a height of 10 m above the water surface, which represents the approximate deck height (worker breathing zone) of most offshore response vessels.

As compared to the no-intervention case, SSDI dispersed the discharged oil over a larger water volume at depth and enhanced VOC dissolution and biodegradation. This reduced both the total mass of VOCs released to the atmosphere and the concentrations of VOCs in the worker breathing zone within a 2 km radius from the release site. Atmospheric conditions also influenced VOC concentrations, although to a lesser degree than SSDI.

The results of the modeling effort are displayed graphically in Figure B.3 for weak, typical, and strong wind conditions for both the no-intervention (untreated) and SSDI scenarios. The x-axis indicates the hours of simulation, and the y-axis shows the predicted VOC concentrations over the simulation period. As shown, the use of SSDI resulted in a substantial decrease in breathing zone VOCs for all three wind conditions.

The paper describing the modeling effort in detail can be found at:

https://www.sciencedirect.com/science/article/abs/pii/S0025326X18306404

B.4 EPA Dispersant Effectiveness

The Environmental Protection Agency (EPA), in conjunction with the Bureau of Safety and Environmental Enforcement (BSEE), published a report in 2016 that described a series of projects conducted to evaluate dispersant and SSDI effectiveness, as well as oil fluorescence. The SSDI evaluation included oil droplet size distribution measurements during a series of high-velocity subsurface releases of physically and chemically dispersed oil in a flow-through wave or flume tank, as well as numerical plume dispersion modeling.

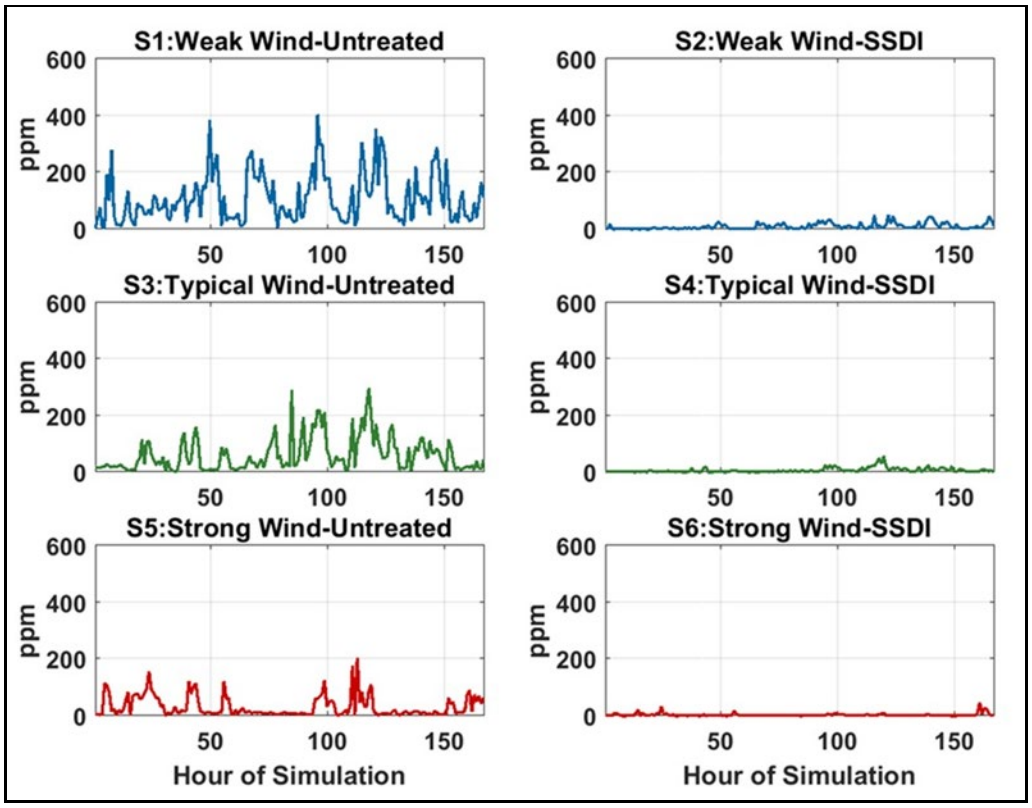


Figure B.3—VOC Modeling Results for Non-Dispersed (Untreated) and Dispersed Oil (SSDI) Scenarios for Three Wind Conditions

VOC measurements were also taken just above the water's surface during the tests to evaluate the effectiveness of SSDI in reducing VOC concentrations from the perspective of worker safety.

The tests were conducted using two dispersants as well as four oils [gas condensate (condensate), Alaskan North Slope (ANS) crude, South Louisiana Crude (SLC), and an intermediate fuel oil (IFO 120)]. Droplet size distributions were measured using a LISST device, and VOC measurements were taken using a handheld photo-ionization detector (PID) based meter. Water column samples were also taken during each test and analyzed for benzene, toluene, ethyl benzene, and xylene (BTEX). A statistical analysis using ANOVA, followed by a confidence interval test, were conducted to confirm differences in the test results were significant.

The general conclusions with respect to the VOC measurements were that the addition of dispersants, particularly at a DOR of 1:20, resulted in a significant reduction in surface VOCs as compared to the tests using non-dispersed oil. Examples of these results, as documented in the report, are the average peak VOC concentrations shown in Table B.2 and the VOC results for the tests involving ANS at various DORs under cold-water conditions displayed in Figure B.4.

Lower VOC concentrations measured in the dispersed oil tests were typically associated with higher BTEX concentrations in the water samples, whereas the opposite was true for the non-dispersed-oil tests. This finding supports other research that found that smaller oil droplets resulting from SSDI enhanced the dissolution of the lighter oil components as the droplets rose through the water column. The study conclusions do caution that the results "merely represent VOCs that make it to the air-sea interface from a very shallow wave tank" and cannot simulate the dissolution of VOCs into the water column in a deepwater incident. The report (EPA/600/R-16/152, September 2016) describing this study and the results can be accessed at www.epa.gov/research.

Table B.2—Test Results of Average Peak VOC Concentrations

Oil Type	Avg. Peak VOC Concentration (ppm), n = 3				ANOVA
	No Dispersant	DOR 1:200	DOR 1:100	DOR 1:20	p-value, α = 0.05
ANS (Dispersant A)	23.07	13.27	12.43	0.13	0.023
ANS (Dispersant B)	23.07	16.56	7.17	2.9	0.024
IFO 120	1.0	0.9	7.37	0.17	0.133
Condensate	121.23	—	—	19.73	0.152
SLC	28.53	27.5	16.75	1.53	0.001

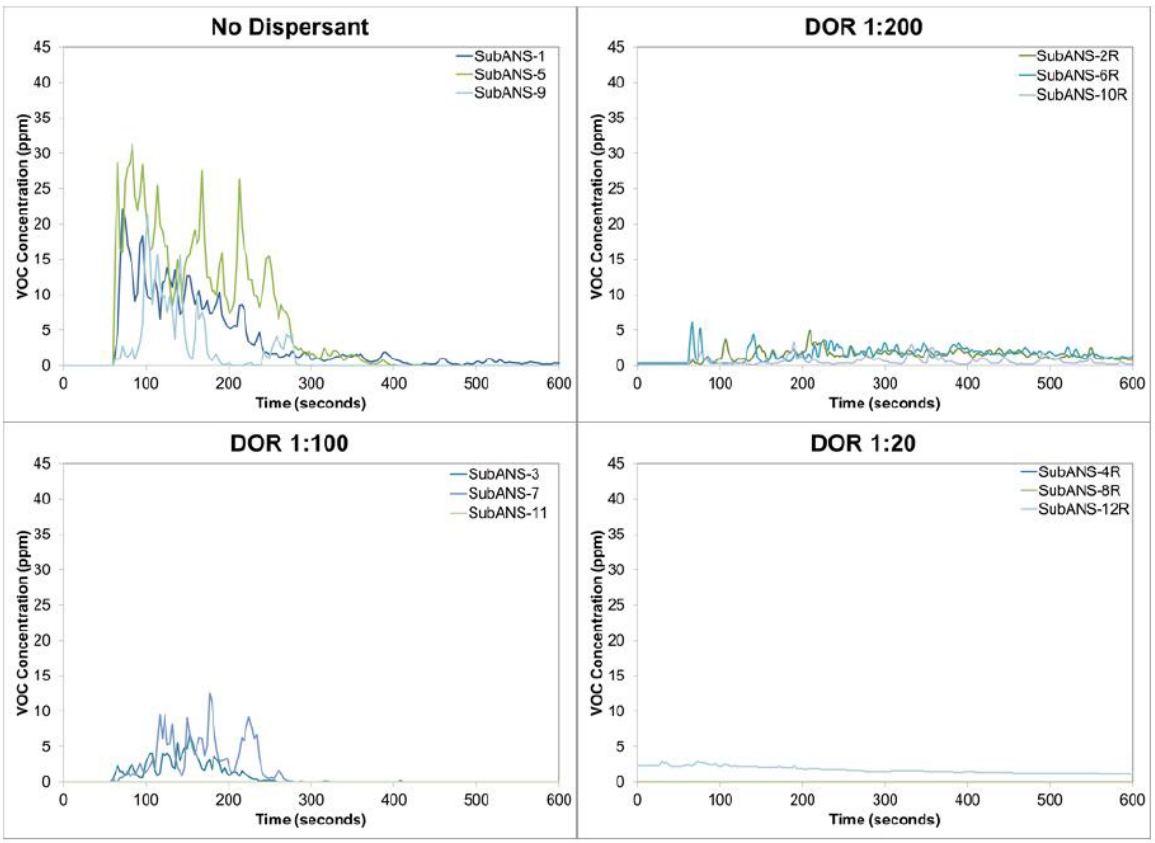


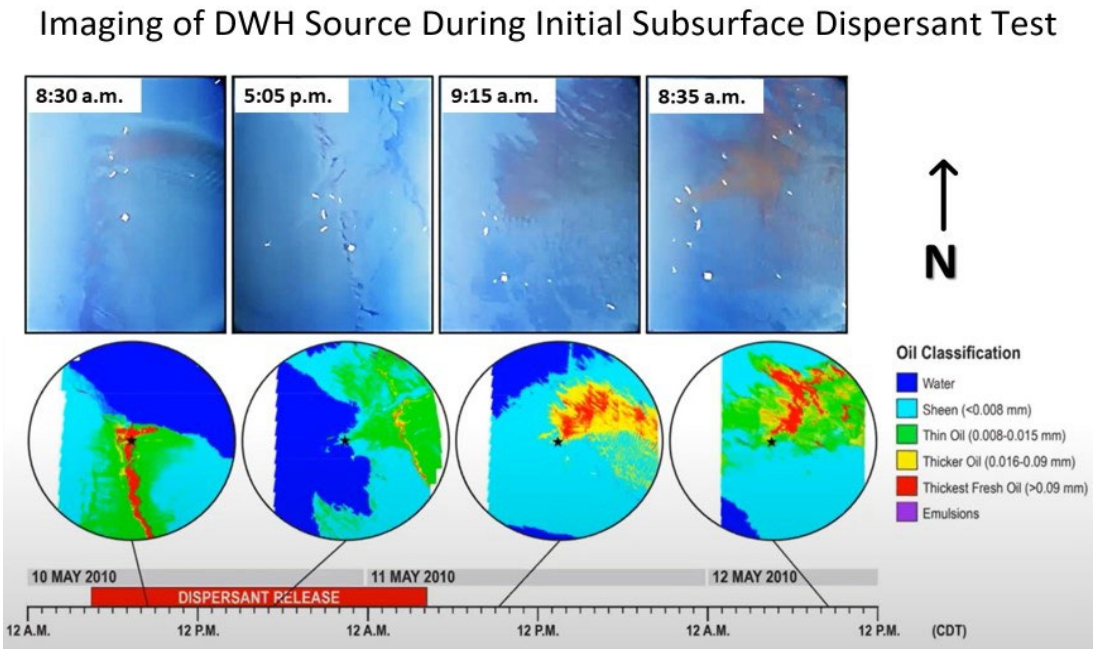
Figure B.4—VOC Results for Cold-water Tests Involving ANS Crude and Various Dispersant Oil Ratios (DORs)

B.5 *Macondo* Aerial Image Analyses

API sponsored a comprehensive analysis of aerial imagery, coupled with oil thickness measurements taken during the *Macondo* incident, to assess the effectiveness of SSDI in reducing the volume and thickness of surface oil. Since VOCs are generated from the natural volatilization of surface oil, a reduction in oil volume and thickness often correlates to a reduction in VOCs.

The oil extent and thickness measurements were determined by combining multispectral visible and thermal (infrared) aerial images and analyzing them with specialized software. The image dates and times were then correlated to changes in SSDI injection rates, which accounted for the delay of approximately four to five hours between those changes occurring subsea and when the corresponding oil reached the surface.

An example of the analysis conducted on a number of aerial images is shown in Figure B.5. The figure contains four aerial images of the water's surface above the damaged *Macondo* well (SIMOPS zone), along with their slick thickness measurements using multispectral remote sensing. The images represent the surface oil conditions that existed before, during, and after the initial SSDI test conducted May 10–12, 2010.



Source: ExxonMobil Dispersant and Herder Workshop—Week 3, Human Health and Worker Safety

Figure B.5—Examples of Detailed Aerial Imagery Analyses

The analysis of each of the above images is as follows:

— May 10, 8:30 a.m.: After SSDI began but before the treated oil reached the surface; shows a band of thick, fresh oil extending to the south from the well location (shown as a black star).

— May 10, 5:05 p.m.: Approximately 9.5 hours after SSDI began; shows primarily thin oil above the well with what appears to be remnants of the previous band of thicker oil that had migrated to the east.

— May 11, 9:15 a.m.: Approximately 5.5 hours after the SSDI test was terminated; shows a large area of thicker oil forming to the northeast and east of the well.

— May 12, 8:35 a.m.: Just over 28 hours after the SSDI test was terminated; shows significantly greater thick oil (and thin oil) to the north of the well.

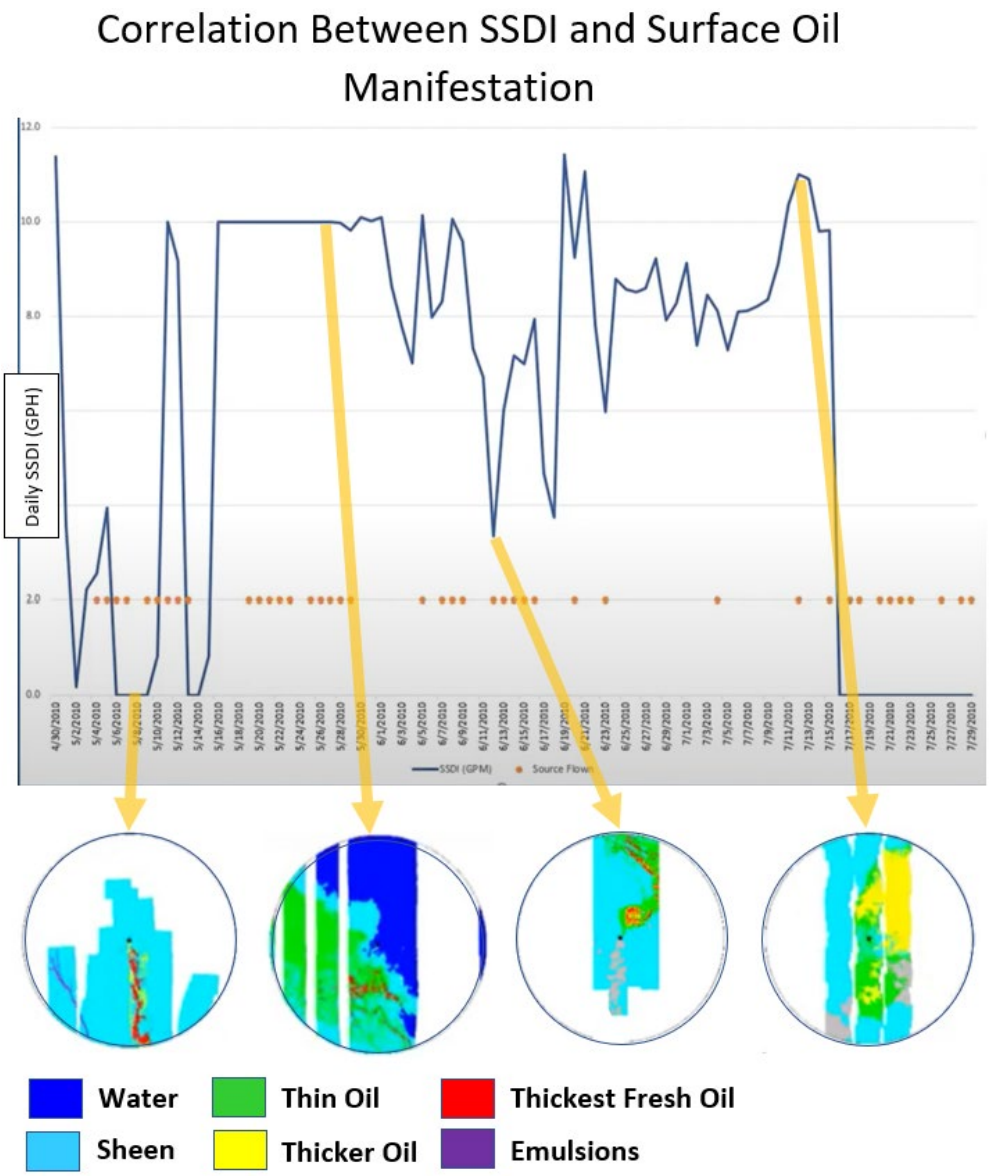
Selected examples of surface oil thicknesses and their relationship to SSDI use and injection rates, or DORs, is provided in Figure B.6 and indicate the following:

— First example: Shows a band of thick oil similar to the first image in Figure B.5 and is associated with a two-day period when no SSDI was conducted.

— Second example: Shows primarily thin oil during a multiple-day period when the injection rate was relatively high.

— Third example: Shows some areas of thicker oil and a fair amount of thinner oil during a low injection rate period.

— Fourth example: Shows a fair amount of both thick and thin oil shortly after the injection rate was increased to a high level.



Source: ExxonMobil Dispersant and Herder Workshop—Week 3, Human Health and Worker Safety

Figure B.6—Examples of Surface Oil Relative to SSDI Injection Rates

A manuscript summarizing this project and the results is expected to be published in late 2022.

In addition to the above, ExxonMobil conducted a more simplistic analysis of selected aerial images of surface oil relative to SSDI operations. Figure B.7 includes five images of the surface oil in the vicinity of the *Macondo* well location (circled in yellow) before, during, and after the May 10–11, 2010, initial SSDI test. The wind direction and speeds, where available, are also included on each image to show they had little influence on the amount of surface oil in the source control area.

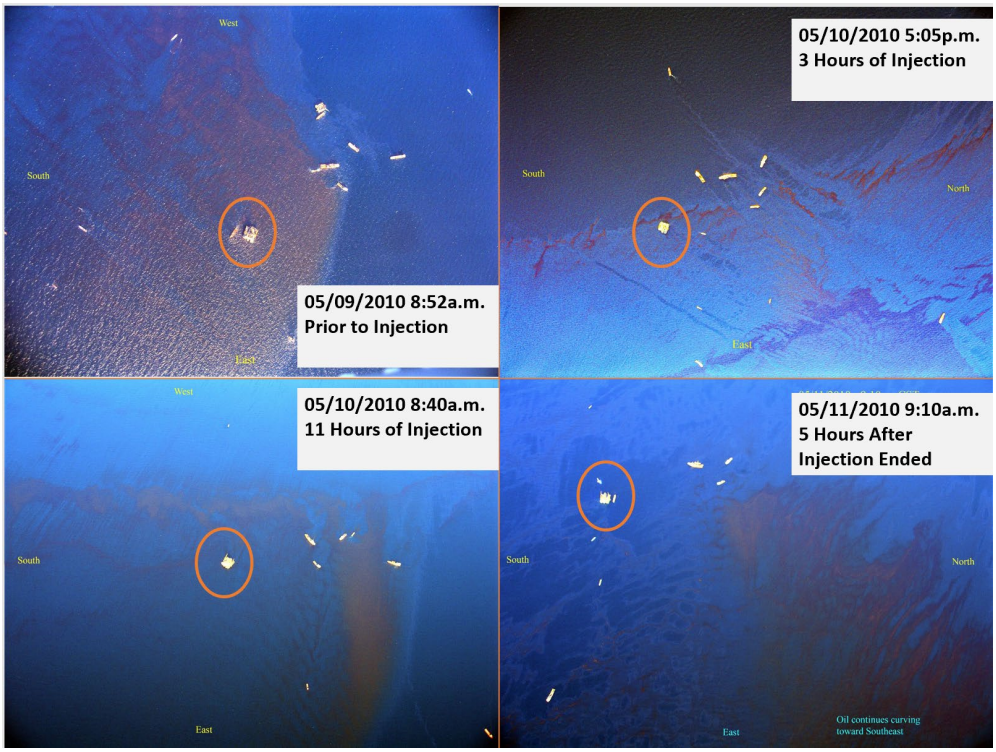


Figure B.7—ExxonMobil Analysis of Aerial Images Relative to SSDI

B.6 Comparative Risk Assessment

API sponsored a modeling study and the development of a comparative risk analysis (CRA) tool for a deepwater well blowout incident. The modeling effort predicted exposures to various receptors, and the CRA tool was used to systematically evaluate potential environmental trade-offs and consequences associated with key oil spill response options. Those response options include:

— No intervention: Natural attenuation.

— Mechanical removal (M): Removal of floating oil using skimming devices.

— In-situ burning (B): Containing and burning floating oil.

— Surface dispersant application (SD): Chemically dispersing floating oil.

— Subsea dispersant injection (SSDI): Chemically dispersing the oil at the source.

The project included establishing a technical advisory committee (TAC) consisting of subject-matter experts from the oil and gas industry, academia, federal and state regulatory agencies, and oil spill

removal organizations (OSROs). The TAC provided input to both the design and implementation of the CRA tool development.

The scenario used for the project involved a well blowout in the Gulf of Mexico at a depth of 4,500 feet and a discharge rate of 45,000 barrels per day of light crude oil (API 34.2) that continued for 21 days. Different wind and current conditions were modeled to determine their effect on the surface oil distribution modeling results. The CRA tool development involved dividing the potentially impacted marine environment (sediments, water column, water surface, shorelines, etc.) into environmental compartments (ECs), then identifying the valued ecosystem components (VECs) that typically inhabit each EC. The models predicted oil and dissolved hydrocarbon exposures to the various VECs in each of the ECs including the distribution of oil on the water's surface and shorelines. This enabled the use of the CRA tool to quantitatively evaluate the environmental trade-offs and consequences for the various response options.

The modeling results were reported for individual or groups of response options, including:

— no intervention;

— mechanical removal (M);

— mechanical removal, in-situ burning; and surface dispersants (MBSD); and

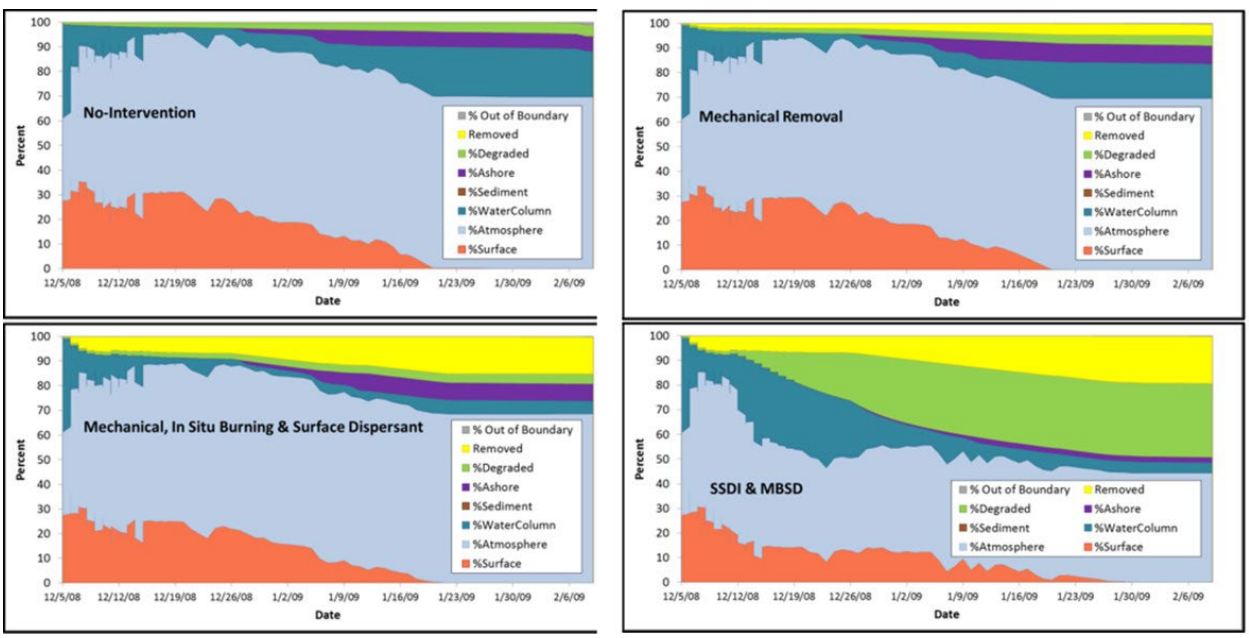
— MBSD and SSDI (combined surface and subsurface response options).

The combination of MBSD and SSDI requires comparing those results to the one for MBSD only to determine the influence of SSDI on the various performance metrics.

The results of the modeling for three of the above response option groups are shown in Table B.3. A more generalized depiction of the modeling results for the scenario involving the worst-case shoreline impact is provided in Figure B.8. These results indicate that the percentage of released oil reaching the surface as well as evaporating into the atmosphere remains relatively constant for the no-intervention and various surface response options, but decreases significantly with the addition of SSDI. Conversely, the percentage of oil removed through natural degradation increased significantly with the addition of SSDI. Furthermore, the application of the CRA tool indicated that SSDI was the most effective option in producing a net reduction in impacts to the various VECs.

Table B.3—Modeling Results for CRA Exposure Metrics

Exposure Metric	No Intervention	MBSD	MBSD and SSDI
Maximum surface oil mass (MT)	32,682 (0.14)	27,389 (0.10)	17,218 (0.13)
Maximum surface oil and mousse volume (m^3)	78,612 (0.14)	65,715 (0.10)	41,362 (0.13)
Maximum area covered by floating oil (km^2)	2150 (0.12)	1889 (0.12)	1438 (0.12)
Area swept by floating oil > 10 um (km^2-days)	112,913 (0.19)	92,593 (0.19)	72,546 (0.21)
Oil and mousse volume on shore (m^3)	2928 (2.31)	1896 (2.43)	2190 (1.77)
Shoreline length oiled by > 10 µm (km)	129 (1.53)	92 (1.75)	124 (1.44)
Mass evaporated (MT)	90,411 (0.0036	89,146 (0.0056	57,729 (0.0094)
Maximum mass in water column (MT)	29,196 (0.21)	16,050 (0.25)	32,316 (0.10)
Mass degraded (MT)	5185 (0.14)	4866 (0.13)	38,898 (0.02)



Source: *Evaluation of Oil Fate and Exposure from a Deep Water Blowout* (French-McCay, D., 2017)

Figure B.8—Mass Balance Over Time for Various Response Options

Copies of the associated papers for this project can be accessed at:

— Modeling effort: https://www.sciencedirect.com/science/article/abs/pii/S0025326X18303606

— CRA tool/risk assessment: https://www.sciencedirect.com/science/article/abs/pii/S0025326X18303485

— Project Overview—2017 International Oil Spill Conference Proceedings: https://meridian.allenpress.com/iosc/article/2017/1/362/198057/Evaluation-of-Oil-Fate-and-Exposure-from-a-Deep

B.7 Other Research

Other research conducted post-*Macondo* evaluated the behavior and fate of the smaller oil droplets created by SSDI. Key conclusions of those studies are summarized below:

— Neutrally buoyant droplets: Oil droplet sizes of ≤ 70–100 µm are common following SSDI application, wherein 70 µm droplets are thought to be neutrally buoyant and will not reach the surface (Lunel, T., 1995).

— Dissolution of water-soluble components: Due to a larger surface area-to-volume ratio of the dispersed droplets (P.J. Brandvick et al., 2017b), their water-soluble components (typically the lighter oil fractions) will dissolve more rapidly into the surrounding water, resulting in less VOCs being generated once the remaining buoyant droplets reach the surface.

— Lower rise velocity: Lighter oil fractions tend to more readily dissolve and biodegrade, thereby increasing droplet density and resulting in decreased rise velocity (Passow et al., 2012).

— Increased biodegradation: Lower rise velocities result in the droplets remaining in the water column longer, thus undergoing more biodegradation before reaching the surface and generating less VOCs (Hazen et al, 2010).

— Reduced surface oil thickness: Lateral subsurface currents have a greater effect on slowly rising droplets causing them to surface over a larger area, thus creating thinner surface slicks. These are less likely to form emulsions and more likely to be naturally dispersed into the upper water column by wind and wave action (P.J. Brandvick et al. 2017b), thereby producing fewer VOCs.

The combination of the above processes can result in a significant decrease in surface oil volumes along with a reduction in the soluble and semi-soluble hydrocarbon [i.e., VOCs, polycyclic aromatic hydrocarbons (PAH), and soluble alkanes] content of the surface oil. These factors not only reduce potential VOC inhalation and dermal exposure risks to responders, but to wildlife, as well (French-McCay et al., 2018).

Annex C

Air-monitoring Strategies and Activities

C.1 Introduction

When conducting air monitoring for health and safety risk evaluations, as well as the efficacy of SSDI use, it is imperative that high-quality and relevant data be collected and not just large quantities of data. Therefore, the purpose of this annex is to provide some guidance on developing an air-monitoring strategy and conducting the monitoring activities to collect the appropriate data.

The primary objective of a monitoring strategy is to ensure that the data is collected in a consistent and appropriate manner and in locations such that subsequent data analyses will produce statistically valid and defensible results. To that end, the strategy must target the areas and activities that will provide the highest-quality and relevant monitoring data.

For the purposes of this document, the target monitoring areas generally include the source control operations and areas with the greatest accumulations of surface oil within the SIMOPS zone. These target areas, at least in the early stages of a subsea well control incident, are often one and the same since source control operations are situated directly above the well, which is generally where the majority of the oil surfaces.

The targeting of source control and other high-activity areas is done mainly to protect the health and safety of the majority of responders, whereas there are multiple reasons for targeting surface oil accumulations, including:

— Represent worst case conditions.

— Result in risk mitigation measures that are more protective of responder health and safety (since the mitigation measures are based on worst-case conditions).

— Facilitate valid comparisons of before, during, and after SSDI data sets (generally produces mostly positive air-monitoring readings) .

— Account for potential surface oil movements in and out of high-activity areas.

C.2 Oil Behavior

There are many factors that affect where oil surfaces during a subsea well control incident, including but not limited to water depth, oil droplet size distributions, subsurface currents, and well control activities. Due to this complexity, the location of oil when it reaches the surface may change frequently. Droplet sizes of undispersed oil are much larger than dispersed oil and, as such, have higher rise velocities and are less affected by subsurface currents and other lateral distribution forces. Consequently, undispersed oil will often surface within the SIMOPS zone in the area above the damaged well. The smaller dispersed oil droplets have lower rise velocities and are more readily influenced by subsurface currents and distribution forces, so they may surface over a larger area and potentially away from the source control area. SSDI is not always 100 percent effective, and dispersed oil will also contain a percentage of medium- to large-size droplets so some oil may continue to surface above the well.

Once oil reaches the surface, its behavior or drift pattern is largely controlled by surface currents and wind, which, in turn, directly affects atmospheric VOC concentrations. Surface oil accumulations will often drift in and out of the source control/high response activity area(s), which is often unpredictable and can complicate surface VOC mitigation measures and pose a greater risk to response personnel. In the

absence of wind or surface currents, surface oil can remain in the high-activity areas, which, along with continually surfacing fresh oil, can result in prolonged exposure to elevated VOC concentrations.

C.3 Monitoring Strategy

The constantly changing behavior of oil surfacing and slick drift requires a consistent data collection strategy in order to make sound engineering judgments about reductions in VOCs due to SSDI operations. There are multiple ways a consistent data collection strategy can be accomplished. One method would be to utilize a grid of fixed monitoring locations where data would be collected at appropriate intervals. However, due to the variable location of surfacing oil and potential surface oil movements, a fixed grid may inconsistently sample VOCs present in an area due to their limited spatial coverage. Therefore, a relatively expansive, yet dense, array of monitoring locations may be needed in order to generate statistically valid data sets. It is also possible to completely miss VOC plumes altogether if a narrow oil slick surfaces between grid nodes. This suggests that many measurements collected using a fixed grid may not be relevant.

An alternative approach that is more likely to produce quality data is to conduct the air monitoring from vessels that move through the target areas along specific paths or transects. The trade-off is that data isn't collected multiple times at various fixed points to facilitate direct comparisons, but instead is collected continuously along a path allowing a synoptic view of VOC concentrations entering and exiting a specified area. An additional benefit is the ability to perform a mass balance analysis for each full transect. They can then be used to calculate total VOCs emitted or accumulations over time within a specific area.

As discussed in Section 3.3.4, the first phase of initial monitoring should ensure that it is safe to operate within the floating oil accumulations. If so, monitoring transect locations should then be designed to optimize data collection. The specific strategy will likely be influenced by safety considerations, environmental conditions, UC/IMT data needs, and other factors, but a general recommendation is described in the following paragraphs.

During the initial monitoring (pre-SSDI), aerial or satellite images should be used to identify location(s) with the greatest oil accumulation to target for monitoring. All transects should, where possible, follow a path perpendicular to the wind as transiting upwind or downwind could bias the measurements low or high, respectively. Additionally, they should extend somewhat beyond either side of the target areas to ensure adequate coverage.

The initial transect should cross through the middle of the main surface oil accumulation, after which the vessel would turn and follow a second, parallel transect approximately 200 meters upwind of the first transect. The third transect would similarly be located approximately 200 meters downwind of the first transect. This process can be continued until the entire surface oil accumulation is covered or it can be duplicated for another nearby significant surface oil accumulation.

If the surface oil accumulations are located away from the source control/high response activity areas within the SIMOPS zone, similar monitoring transects should be located, if safe to do so, a few hundred meters upwind and downwind of those areas. Air monitoring will also be conducted on the response vessels themselves and will serve to provide VOC data within the on-deck work areas. This data should be compiled as a separate data set.

Following the initiation of SSDI operations and after accounting for the rise time of the dispersed oil, monitoring should be conducted in the same manner and along the same transects as described above for pre-SSDI operations. In the event that SSDI results in the oil surfacing in a different area, it would be appropriate to monitor along at least a few of the original transects for direct comparison purposes before relocating to the new oil accumulation areas and running new transects in the same manner as before. Should time and resources allow, the same monitoring strategy should be used for post-SSDI time periods.

C.4 Monitoring Activities

The dedicated monitoring vessels, as well as the response vessels, should be equipped with multiple monitoring instruments. In most cases, the instruments will consist of multigas meters equipped with PIDs and other sensors to provide real-time monitoring for LEL and concentrations of VOCs and other gases. During the DWH incident, many response vessels were equipped with compound-specific VOC monitor meters for periodic benzene monitoring and more frequent measurements if VOCs exceeded 50 ppm. Otherwise, the vessels utilized multi-gas monitors and/or multi-sensor/multi-threat detectors to monitor for LEL, VOCs, H_2S, O_2, and CO.

Many monitoring instruments can be utilized to take instantaneous measurements every hour or so or can be programmed for continuous data collection. They have the capabilities to store the data internally and automatically transmit it to a local computer for compilation. They can also be programmed to conduct continuous monitoring and record average concentrations every 15 minutes, both of which are useful when evaluating the data. When conducting continuous monitoring, it is important to record the vessel's speed to enable calculation of VOC mass balances.

Monitoring instrument locations are largely dependent on their purpose. On response vessels, instruments are typically located in common work areas and inside crew quarters to protect responder health and safety. Additional monitors may be placed near the upwind edge of the vessel or other locations to provide early warnings of rising LEL, VOCs, or other hazards. For vessels conducting continuous monitoring along transects, the instruments should be placed on the upwind side and away from any non-floating oil sources of VOCs such as vessel or onboard equipment engine exhaust, fuel, or recovered oil storage tanks, etc. Additionally, the instruments or sensor intakes should be positioned, where practical, at the same deck height as the smallest response vessel to ensure that the health and safety of all response personnel is adequately protected. Copies of the vessel diagrams should be used to identify monitoring and sampling locations.

C.5 Monitoring Data Correction Factors

VOC concentrations and other air-monitoring data collected in the field often require the application of correction factors to ensure readings are representative of actual concentrations and that all data is directly comparable both spatially and temporally. The primary correction factors discussed below are related to:

— wind speed;

— monitoring instrument characteristics.

Other factors that may affect instrument measurements include wind direction, ambient temperatures, rain, and humidity, as they can affect the monitoring equipment readings.

Wind dilutes the VOCs and other airborne contaminants, resulting in significantly lower concentration readings than would be measured in calm conditions. In the absence of quantitative formulas for normalizing VOC measurements due to wind, a generalized correction factor can be used. Since the volume of air moving through a given location is proportional to the wind speed, it follows that measured VOC concentrations should be reduced by 50 % with each 100 % increase in wind speed. This relationship was used to develop the correction factors in Table C.1.

Table C.1—Generalized Wind Speed Correction Factors

Wind Speed Range (mph)	Midpoint Speed (mph)	VOC Correction Factor
0–5	2.5	1.0
5–10	7.5	0.33
10–15	12.5	0.20
15–20	17.5	0.14
20–25	22.5	0.11

Source: Personal communication (French-McCay, 2020)

A correction factor must also be applied to readings obtained from most hydrocarbon gas monitoring equipment utilizing photoionization detectors (PIDs) since they are calibrated for a specific compound. Similarly, LEL meters indirectly measure the percent LEL in the air, so correction factors may also be required depending on the target compound. The correction factors for VOCs and selected petroleum products using PID gas monitors equipped with a 10.6 eV lamp, as well as the LEL meter correction factor for crude oils, are provided in Table C.2. Additional information on and other examples of PID correction factors are provided in Section D.3.1.

Table C.2—Selected Petroleum Vapor PID and LEL Correction Factors

Instrument	Analyte	Correction Factor
PID	Total volatile organic compounds (VOCs)	1.3[1]
PID	Gasoline (No. 2; 92 octane)	1.0[1]
PID	Diesel fuel (automotive)	0.7[1]
LEL	Crude oil	2.5[2]

[1] CTEH study, 2021.
[2] CTEH rough estimate based on common crude oil volatiles.

Annex D

Monitoring Equipment

D.1 Introduction

The purpose of this annex is to provide additional information on the types, numbers, selected characteristics, and maintenance of the equipment typically required for the air-monitoring component of a large oil spill response. The primary objective is to have the appropriate monitoring equipment to provide initial data on the physical and chemical characteristics of the air at the water's surface to ensure adequate protection of response personnel health and safety. A secondary objective is to monitor the efficacy of health and safety risk mitigation measures, such as SSDI, as well as surface dispersant applications or mechanical recovery. Suggestions for monitoring equipment are made based on the typical needs in a large spill response and ease of use.

D.2 General Equipment Type, Characteristics, and Quantity Information

The types of monitoring equipment used in a spill response will vary depending on the incident circumstances (large or small spill), oil characteristics (sweet, sour, or highly degraded crude) and environmental conditions (high winds, rain, etc.). Certain equipment has a direct health and safety contribution; this includes monitoring for LEL, H_2S, and O_2 due to their potential for being immediate dangers to life and health. As such, it is essential that these and other monitoring devices provide direct, real-time measurements. They are generally not as accurate as the collection and subsequent laboratory analysis of air or sorbent tube samples, but do not involve delays of 24 hours or more for the analyses. The analytical results are, however, important, as they can validate monitoring device measurements and provide concentrations of individual VOCs contained in the sample.

When selecting specific air-monitoring equipment for deployment, there are certain basic and desirable characteristics that should be considered. These generally include:

— Be readily available.

— Do not require in-depth training or expertise to use.

— Be capable of real-time measurements in the ppb, low ppm. or % LEL ranges.

— Have straightforward maintenance and calibration requirements.

— Come equipped with data logging and wireless communications capabilities.

— Provide accurate and reliable data, within specific limits.

— Utilize removable, rechargeable batteries and have the appropriate spare batteries and charging systems to avoid interruptions in monitoring.

— Be suitably ATEX rated for potentially flammable/explosive atmospheres.

In any spill response, it is desirable to maintain redundancy for each type of monitoring equipment that will be used. This is based primarily on an accounting for equipment failures (two is one and one is none), charging cycles, and the availability of a second device as an initial QA/QC check, if needed.

D.3 Air-monitoring Equipment

The more specific types of air-monitoring equipment and sampling equipment that are typically used in a spill response include:

— photoionization detectors (PIDs);

— combustible gas sensors that detect vapors as percent LEL or ppm ranges;

— multigas monitors;

— colorimetric detector tubes;

— passive diffusion badge dosimeters;

— sorbent tube sampling systems (active or passive diffusion);

— air sampling systems (e.g., gas sampling bags and air pumps, gas sampling canisters).

Alternatives include:

— flame ionization detectors (FIDs);

— portable GC/MS Instruments;

— portable infrared analyzers.

The order of the above list is based on the practical use in early-stage monitoring activities. The most important instruments are the PID and combustible gas LEL instruments, which are discussed in more detail below. Brief descriptions of the other equipment types are also provided to aid in determining their applicability to a given oil spill incident. These instrument examples do not represent a product endorsement.

Examples of common oil spill-related air-monitoring equipment are provided in Table D.1.

D.3.1 PID

PIDs are very portable and easy to use, which is ideal for oil spill-related air monitoring. They use an internal pump to draw air into the unit and past an ultraviolet (UV) light source/lamp that breaks down VOCs in the air into positive and negative ions. The PID sensor then measures the charge of the ionized gas, with the charge being a function of the concentration of total VOCs in the air. They generally cannot measure individual VOC components unless equipped with compound-specific separation tubes. Although PIDs are typically the primary sensor in multigas meters, the meters may contain other sensors, as well.

PIDs can be equipped with ultraviolet lamps with different energy ratings that affect the ability to measure certain compounds and their detection limits. The primary lamp energy ratings include:

— 10.6 eV;

— 11.7 eV.

The 10.6 eV lamp is the most common and can detect a broad range of VOC compounds, including BTEX and other volatile hydrocarbons found in crude oils. The 11.7 eV lamp can detect a few additional hydrocarbons (acetylene, methanol, formaldehyde, and others), but has a lower practical life expectancy. The lower-energy lamps (e.g., 8.4 eV and 9.8 eV) do, however, offer the best selectivity and are better suited for measuring aromatic vapors such as benzene. Some PIDs (e.g., compound-specific VOC monitor) can operate in a benzene specific mode utilizing a 9.8 eV lamp and scrubbing tube to remove other compounds.

It is important to note that PID readings do not necessarily provide true quantification of airborne contaminates. As mentioned in Section 3.4.2, PIDs typically display the concentration of the instrument calibration gas, commonly isobutylene, that equates to the level of ionization detected by the meter for the gas being monitored. The concentration readings can also vary depending on the energy rating of the instrument's ionization lamp. Therefore, a correction factor often must be applied to the instrument reading depending on the compounds being monitored, lamp energy rating, and the chemical gas used for instrument calibration.

Table D.1—Monitoring Equipment Examples

Name	Type	Parameter(s)	Detection Range	Notes
UltraRAE 3000	Multi-gas PID	VOCs	0.05–10,000 ppm	Data logging and wireless communications
		Benzene	50 ppb–200 ppm	Benzene-specific mode with scrubbing tube
AreaRAE Pro	Multi-gas PID	VOCs	10 ppb–2000 ppm	Monitors up to seven threats, can add Met station sensor, data logging, wireless comms, GPS, etc.
		LEL	0–100%	
		H_2S	0.1–100 ppm	
		O_2	0–30%	
Aeroqual AQM 65 BTEX	Multi-gas PID	Benzene, toluene, ethylbenzene, xylene	0.1–50 ppb	Can be configured to measure VOCs, H_2S, CO, $PM_{1,\ 2.5,\ 10}$ and other compounds
Ion-science Cub/TAC	PID	VOCs, benzene (TAC model)	0.1–5000 ppm	Small size enables use as a personal monitor Data-logging capability
RKI GX-2009	Multi-gas PID	LEL	0–100%	
		O_2	0–40%	
		CO	0–500 ppm	
		H_2S	0–100 ppm	
MSA Sirius	PID	VOCs	0–2000 ppm	
Photovac 2020	PID	VOCs	0.5–2000 ppm	
Thermo 580B OVM	PID	VOCs	0–2000 ppm	With 10 eV lamp
Summa canister	Whole air sampler	VOCs, hydrocarbon constituents	Laboratory dependent	Used to collect air samples for subsequent laboratory analysis
TVA1000B Foxboro	FID/PID	VOCs	1.0–50000 ppm (FID) 0.5–2000 (PID)	Allows use as PID for intrinsically safe operation
PhotoVac Micro	FID	VOCs	0.5–2000 ppm 10–50000 ppm	Intrinsically safe
Dräger X PID 9000/9500	GC/PID	Wide range of VOCs	0.01-1000 ppm	Good sensitivity, lab-quality measurements
ToxiRAE PRO Personal	Combustible Gas	LEL	0–100% LEL	Onboard gas library
ToxiRAE Toxic Gas Monitor	Meter	H_2S	0–100 ppm 0–1000 ppm	High and low range
Jerome 860 H_2S Monitor	Meter	H_2S	0–200 ppm Spikes to 1000 ppm	
MIRAN Sapphire Foxboro	IR	Various gases and vapors	Compound-specific, typically 1–1000 ppm	Instrument is bulky

Most monitoring devices have a library of correction factors for various gases wherein the applicable factor for the target gas can be pre-selected; it is then automatically applied to the instrument reading to display the corrected concentration. However, very few instrument manufacturers have developed correction factors for VOCs. Consequently, a study was recently completed to determine the most appropriate correction factor for total VOCs (CTEH, 2021).

The results of the CTEH study are shown in Table D.2, which indicates that for PIDs equipped with a 10.6 eV lamp and calibrated with isobutylene, the appropriate correction factor for VOCs from crude oil spills is 1.3. Using this correction factor, a PID reading for VOCs of 77 would equate to an actual concentration of 100 ppm. PID correction factors for additional VOCs as well as selected physical properties are provided in Table D.3.

Table D.2—CTEH Study VOC and Petroleum Vapor PID Correction Factors

Analyte	Correction Factor (10.6 eV)
Total volatile organic compounds (VOCs)	1.3
Gasoline (No. 2; 92 octane)	1.0
Gasoline (No. 1; automotive)	0.9
Diesel fuel (automotive)	0.7
Diesel fuel	0.9
Mineral spirits	0.7
Jet fuel/kerosene	0.6 – 1.0
VM&P naptha	0.97

Table D.3—Example VOCs, Key Physical/Chemical Parameters, and Correction Factors

Chemical	Physical Properties			Correction Factor—RAE Systems PID Isobutylene Standard - 10.6 eV Lamp
	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	LEL (% by Vol.)	
Methane	22.7	Gas at STP	5.0	NA; methane not detected
Butane	61	Gas at STP	1.8	67; note at extreme range of detection
Propane	47	Gas at STP	2.0	NA; propane not detected
Benzene	1790	75.1	1.2	0.53
Toluene	520	22	1.2	0.5
Ethlybenzene	150	7.15	1.0	0.52
Xylene	106	6.16	1.1	m-0.44 o-0.46 p-0.39
Naphalene	31	0.05	NA	0.42
H_2S	1363	Gas at STP	4.0	3.3
CO_2	1450	Gas at STP	NA	NA; carbon dioxide not detected

D.3.2 LEL

Most combustible gas meter LEL sensors detect gas concentrations by first catalytically oxidizing the gas drawn into the device by an internal or external pump. The oxidation process generates heat that is proportional to the amount of gas in the air being measured. The measured heat is translated by the sensor to an LEL reading. The oxidation process in modern LEL meters takes place on an internal catalyst, making

the instrument intrinsically safe. Recent advances include the use of infrared detection systems rather than catalytic heat generation.

The LEL device reading is based on the gas used for calibration (typically methane). As for the PID instruments discussed above, a correction factor may need to be applied to the meter readings depending on the hydrocarbon(s) being measured. Many of the current combustible gas meters contain libraries of compounds and associated correction factors. Once the target gas/compound is selected, the device can automatically apply it to the sensor output, resulting in an accurate LEL reading.

D.3.3 Other Monitoring Equipment

Brief descriptions of the other monitoring equipment identified in Section D.3 are provided below to better inform the identification and selection of the most appropriate monitoring equipment for a given incident.

Multi-gas Monitors

These devices contain multiple sensors to monitor a variety of parameters. For some, the sensors are interchangeable and can be customized to monitor the parameters of highest concern. For oil spill response, they often include sensors for monitoring VOCs (PID), LEL, H_2S, CO, and O_2, and can preclude the need to bring separate monitoring devices for each parameter. Most current monitors come with internal data loggers and wireless capabilities to easily download the data to a laptop for compilation and transfer to the IMT. They often have multiple audio and visual alarms to alert personnel if a threshold is exceeded for any of the parameters.

Colorimetric Detector Tubes

These devices consist of graduated glass tubes filled with a chemical reagent that is specific to a target chemical vapor/gas such as benzene and other VOC constituents. A hand or electrical pump is used to draw air/gas into the tube, which then reacts with the reagent producing a color change. The point where the color change stops is read off the tube's graduated markings to reveal the concentration of the target chemical.

Detector tube accuracy is considered to be +/-25 % of the reading, which is less than ideal but allows for rapid determinations of field conditions, particularly for individual VOCs such as benzene, toluene, and other chemicals that do not pose an immediate health and safety threat. A common criterion for the formal use of colorimetric detector tubes is when VOC concentrations (determined using a PID) exceed 10 ppm.

Passive Diffusion Badge Dosimeters

These are small, badge-like devices that typically clip to a responder's garment or to a fixed object to measure average concentrations of, or exposures to, certain airborne contaminants over time. The badges often consist of a charcoal adsorbent pad that retains organic chemical vapors present in the air. The badges are then analyzed in a laboratory for concentrations of various chemicals adsorbed by the badge. The results are used to calculated time-weighted exposures with an accuracy of +/-25 %. While not applicable to obtaining real-time data, they are an inexpensive and simple means of determining exposure levels. They can also provide hydrocarbon speciation data that can be used as part of the overall risk management and evaluation program. However, passive sampling methods should not be used for short-term task sampling.

Carbon Adsorption Tube Sampling Systems

These devices generally consist of small tubes containing activated carbon or other adsorbent material connected to a personal or larger air sampling pump. The sampling system (pump and adsorbent tube) can be attached to a fixed object or worn by individual responders to determine exposure levels for a given period of time. The pump draws air/contaminants through the adsorbent tube at a fixed rate, wherein any airborne chemicals adhere to the material in the tube. Passive diffusion sorbent tubes can also be used that do not require a pump but that can be deployed at a fixed location over a period of time. At the end of the shift or other time period, the adsorbent tubes are sealed and sent to a laboratory for analysis.

The resulting chemical concentrations and the total volume of air drawn through the tube during the sampling period are used to calculate total or time-weighted average exposures to VOCs and/or individual chemicals. Because vapor concentrations vary considerably with changes in wind speed or proximity to floating oil or other vapor sources, obtaining time-weighted averages is often the best means of evaluating human exposures and associated health and safety risks. These devices also offer greater flexibility over badges with regard to time intervals between sampling events.

Air Sampling Systems

Air sampling systems often consist of a pump and a gas sampling bag or other flexible container or a gas sampling canister. The sampling pumps are often similar to those described above for use with sorbent tubes, except they are used to pump air into the sample bag until full. The Summa type canisters are typically stainless steel with the contents evacuated by the manufacturer. A valve allows the air sample to enter the vacuum canister at the required rate and then to seal the canister once it is full. The full sample bags or canisters are then sent to a laboratory for analysis.

Laboratory analysis of these whole air samples often provides the most accurate VOC and other airborne contaminant concentrations. Although they do not provide data on a real-time basis, they can be used to validate other monitoring data obtained at the same time and location. Unlike the canisters, the bags and pump are inexpensive and take up little space, but are not appropriate for ppb level VOC measurements. The bags also have shorter sample hold times than canisters (three days vs. up to 30 days).

Flame Ionization Detectors (FIDs)

An FID operates by using an internal pump to pull air into a chamber where any organic compounds are combusted by a hydrogen flame. The combustion forms ions that are measured by a sensor and are proportional to the concentration of organic compounds. Similar to PIDs, they report total VOC concentrations and cannot analyze individual compounds. They can, however, detect a larger range of compounds than PIDs, including the lower molecular weight alkanes (e.g., methane), which is similar to an LEL meter. The FID requires a compressed hydrogen source (complicating the ease of use) and may not be intrinsically safe in explosive environments. Therefore, they are not recommended for these types of monitoring programs.

Portable GC/MS Instruments

Field instruments for GC/MS analyses can provide rapid information on VOC and individual component concentrations that are otherwise only available from laboratory analyses. However, the equipment is often expensive and large, and requires a significant level of expertise to operate. They are also not well suited for use on non-stationary platforms such as vessels working offshore. Some newer instruments, such as the GC-PID, are, however, more portable and potentially serve as a substitute for GC/MS devices.

D.4 Equipment Recommendations and Considerations

The air-monitoring equipment generally required for responding to a subsea well control incident depends primarily on the incident circumstances and a number of monitoring teams. General information on the recommended types and numbers of monitoring equipment for each team, as well their primary uses and considerations, are provided in Table D.4.

D.5 Maintenance and Calibration

Most instruments require some level of maintenance and calibration. Provisions should be made for calibration tools such as air flow meters for the air sampling pumps and monitoring equipment with internal pumps. The appropriate calibration gases should be available for the PID, multi-gas, LEL, and other monitors, and in sufficient quantities to enable at least daily calibrations and “bump testing.” Sampling pump tubing should be changed after each use if located before the sample collection, and sensors on the various monitoring equipment should be cleaned daily where applicable. Adequate charging capabilities should be available for

equipment with both fixed internal and removable battery systems, along with spare removable batteries for each device.

Table D.4—Monitoring Equipment Recommendations

Equipment Type	Minimum Number	Primary Use/Considerations
Vessel	1	Physically support monitoring team and activities (adequate deck and cabin work space and bunks) with sufficient maneuverability to access desired monitoring locations.
PID/Multi-gas monitor	3	Monitor at different locations on the vessel. Includes a spare unit and adequate calibration gases and tools.
PID w/benzene monitoring	2	Monitor in proximity of workers to assess benzene concentrations/exposures. Includes a spare unit and adequate calibration gases and tools.
LEL meter	3	Monitor at different locations on vessel plus one LEL meter with alarm mounted shipboard and proximal to work area(s). Not required if multi-gas monitors with LEL sensors are used.
Diffusion badge dosimeter	1/member day	Monitor 8–12 hr benzene and total VOC exposures for each team member.
Colorimetric sample tubes	4/day	Benzene-specific tubes with two corresponding pumps for measuring breathing zone concentrations each day. Other tubes may include CO_2, H_2S, natural gas (methane), oil mist, toluene, xylene, and water vapor.
Hydrogen sulfide meter	1/member/day w/10 % redundancy	Continuously monitor H_2S concentrations for each active team member unless determined not to be a health risk. Mount additional meter(s) with audible and visual alarms to the vessel in the work area(s). Not necessary if multi-gas monitors with H_2S sensors are being used.
Adsorption tubes	5 tubes/day & 3 pumps	Attached to a fixed object near the primary work area(s) or to monitoring personnel, and run during each shift to enable time-weighted average exposure determinations .
GPS devices	3	Vessel has an integral GPS capability but needs two additional hand-held units (one primary/one backup) for tracking vessel movements and taking waypoints and time stamps at each monitoring location. If any monitoring devices are equipped with a GPS, that should be utilized, as well, and bear consideration in its selection.
Weather station	2	Portable devices (1 primary/1 backup) used to monitor: — wind velocity and direction; — temperature; — humidity; — barometric pressure; — other conditions, such as rainfall.

American
Petroleum
Institute

200 Massachusetts Avenue, NW
Suite 1100
Washington, DC 20001-5571
USA

202-682-8000

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