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Original Article

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Exposure Group Development in Support of the NIEHS GuLF Study

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Abstract

In the GuLF Study, a study investigating possible adverse health effects associated with work on the oil spill response and clean-up (OSRC) following the *Deepwater Horizon* disaster in the Gulf of Mexico, we used a job-exposure matrix (JEM) approach to estimate exposures. The JEM linked interview responses of study participants to measurement data through exposure groups (EGs). Here we describe a systematic process used to develop transparent and precise EGs that allowed characterization of exposure levels among the large number of OSRC activities performed across the Gulf of Mexico over time and space. EGs were identified by exposure determinants available to us in our measurement database, from a substantial body of other spill-related information, and from responses provided by study participants in a detailed interview. These determinants included: job/

activity/task, vessel and type of vessel, weathering of the released oil, area of the Gulf of Mexico, Gulf coast state, and time period. Over 3000 EGs were developed for inhalation exposure and applied to each of 6 JEMs of oil-related substances (total hydrocarbons, benzene, toluene, ethylbenzene, total xylene, and n-hexane). Subsets of those EGs were used for characterization of exposures to dispersants, particulate matter, and oil mist. The EGs allowed assignment to study participants of exposure estimates developed from measurement data or from estimation models through linkage in the JEM for the investigation of exposure-response relationships.

Keywords: deepwater horizon; exposure assessment; exposure groups; oil weathering

Introduction

The GuLF Long-Term Follow Up Study (The GuLF Study: A Prospective Study of Persons Involved in the Deepwater Horizon Oil Spill Response and Clean-Up (Kwok *et al.*, 2017)), conducted by the National Institute of Environmental Health Sciences, is investigating possible adverse health effects in workers from *Deepwater Horizon (DWH)* exposures encountered during the oil spill response and clean-up (OSRC) effort following the sinking of the *DWH* and subsequent oil release. The exposure assessment was a crucial component of the study for investigating exposure-response relationships.

Traditionally, job-exposure matrices (JEMs) have been used to link exposure estimates developed from measurements taken in various industries, facilities, departments, or jobs classifications to groups of study participants of occupational epidemiologic studies, because rarely are sufficient measurement data available on all participants. The exposure group (EG) is the key to making that link. In our case, however, there was only a single non-traditional industry (oil spill response and clean-up), no production facility or department, and limited information on job titles. The development of JEMs and EGs was necessary because, despite the large number of measurements available (~143 000), insufficient measurements were available to fully characterize exposures of each of the approximately 32 000 study participants across a geographically dispersed area (Stewart, Groth *et al.*, 2021).

Factors affecting exposures, or at least surrogates for exposure, described as determinants, were used to define EGs. We used the work of Viet *et al.*, 2008 to frame our evaluation of: individuals (the work force); tasks (through work practices); and the location and major events (the workplace). We first identified *potential determinants* and the theory or basis for developing EGs in general. We then identified those potential determinants deemed appropriate to the exposure situations in our study, referring to them as *study determinants,* and provide the theory or basis for these study determinants in the development of the EGs.

An overview of the entire exposure assessment component of the study is found in Stewart, Groth *et al.*, (2021). The resultant exposure statistics derived from the monitoring data for these EGs for the oil-based chemicals of interest (total hydrocarbons (THC), benzene, toluene, ethylbenzene, total xylene (o-, m-, p- isomers) and n-hexane (BTEX-H)) are described in Huynh *et al.*, (2021a,b,c), Groth *et al.,* (2017, 2018), Groth, Banerjee *et al.*, 2021 and Groth, Huynh *et al.*, 2021, Ramachandran *et al.*, (2021) and Stenzel, Groth *et al.*, (2021). Estimates of other exposures are found in Arnold *et al.*, (2021) and Stenzel, Arnold *et al.*, (2021) (dispersant aerosols and vapors, respectively), Pratt *et al.*, (2021) ($PM_{2.5}$), and Stewart, Groth *et al.*, (2021), (oil mist). Dermal exposure estimation is described in Gorman Ng *et al.*, 2021 and Stewart, Gorman Ng *et al.*, 2021.

Here we first present a brief summary of the *DWH* OSRC effort and the personal air measurements taken during the effort. We present potential determinants and then describe the application of these to study exposure determinants that served to define our EGs.

Background

Response and clean-up

When the *DWH* oil rig explosion occurred in the Gulf of Mexico on 20 April 2010, nearby vessels immediately started search and rescue missions and attempted to extinguish the fire. When the oil rig sank on 22 April 2010, the riser pipe that connected the top of the wellhead and rig ruptured, releasing oil, which continued to be released into the Gulf for the ensuing 87 days, resulting in an estimated release of 4.9 million barrels of oil (779 million L) (Lehr *et al.*, 2010).

We considered the entire *DWH* effort as two components, response and clean-up. Response indicates the effort that occurred primarily within 5 nautical miles (nmi;

9 km) of the wellhead to stop the oil spill. Within about two weeks of the explosion, two oil drilling rigs had arrived on the scene: the *Discoverer Enterprise* (*Enterprise*) to stop the oil release (and later to collect and separate the released oil and flare the remaining gas) and the *Development Driller III* (*DDIII*) to drill a relief well to seal the base of the well in the rock formation above the well's reservoir. Two additional rigs arrived shortly afterwards to supplement the first 2 rigs' work. The oil release was stopped on 15 July 2010. The relief well intersected the original well casing at about 18 000 ft (5.5 km) below the water surface on 16 September 2010, and on 19 September 2010 it was confirmed that the well was sealed. The four rigs were supported by 14 vessels piloting remotely operated vehicles (ROVs), (referred to as ROV vessels) and by a large number of marine vessels (MVs).

The second component, clean-up, began within a month after the explosion. Water clean-up activities included searching for oil and oiled wildlife, skimming the water to collect surface oil, burning surface oil, deploying boom to contain the oil, decontaminating (deconning) the outside of oiled vessels to prevent oil from contaminating the waters around the ports and docks, and collecting water and other samples for research purposes (National Oceanic and Atmospheric Administration, 2011). Clean-up activities on land included patrolling beaches for oil, tar, and contaminated wildlife; cleaning beaches, jetties, and other manmade structures and marshes of oil; deconning ships, boats and equipment, such as boom; wildlife rehabilitation; and the disposal of hazardous waste. A large administrative support staff included office workers, security, cooks, housekeepers, material handlers, fuelers, and pilots.

Measurement data

The primary exposures of interest to the GuLF Study were total hydrocarbons (THC), measured as total petroleum hydrocarbons, and 5 volatile oil-related chemicals included in the THC mixture, i.e. benzene, toluene, ethylbenzene, total xylene (BTEX), and n-hexane (H) (Stewart, Gorman Ng *et al.*, 2021). In support of the OSRC effort, the Responsible Party (RP) of the spill (as designated by the US government) hired industrial hygiene/safety contractors, who collected personal passive dosimetry air samples for a range of OSRC activities at different locations between 22 April 2010 and 30 June 2011, the GuLF Study exposure assessment period. A database of almost exclusively oil-related air measurements (THC, BTEX-H, and other oil chemicals) was provided to us by the RP with accompanying descriptive fields (Supplementary Table S1).

Approximately 93% of all the measurements were censored (i.e. below the limits of detection, LOD). As reported in Stenzel, Groth *et al.*, 2021, the RP laboratories reported the measurements' LODs at the lowest calibration standards rather than at the analytical methods' LODs. All ~145 000 measurement results were recalculated to reflect the analytical methods' LODs, which resulted in the level of censoring for all measurements being reduced to 60.5% and, specifically for THC, from 83.1 to 11.2%.

Even with this substantial reduction in censoring, the literature was somewhat inconclusive on which statistical methods were capable of providing unbiased and precise estimates at the high degree of censoring observed in this dataset. Huynh *et al.*, (2014), evaluated the performance of various statistical methods i.e. the maximum likelihood (ML) estimation, the β-substitution, and the Kaplan–Meier (K-M) methods. Each method was challenged with computer-generated exposure datasets drawn from lognormal and mixed lognormal distributions with sample sizes (*N*) varying from 5 to 100, geometric standard deviations (GSDs) ranging from 2 to 5, and censoring levels ranging from 10 to 90% with single and multiple limits of detection (LODs), reflecting the characteristics of our EGs. Using relative bias and relative root mean squared error (rMSE) as the evaluation metrics, the β-substitution method generally performed as well or better than the ML and K-M methods in most simulated lognormal and mixed lognormal distribution conditions. Huynh *et al.*, (2016) then compared the relative performances of the β-substitution and Bayesian methods and found Bayesian's performance comparable to the performance of the β-substitution method with the added benefit of being able to calculate credible intervals (similar to confidence intervals) of the various metrics. We selected as study criteria an average relative bias of <15% and a relative imprecision of <65% (from the rMSE), which could be achieved for data sets with N≥5 and censoring of <80%. We, therefore, used Bayesian methods to calculate summary statistics of the arithmetic mean (AM), geometric mean (GM), GSD and 95th percentile, and each of their 95th percent credible intervals for each appropriate EG (Huynh *et al.*, 2021a,b,c, Ramachandran *et al.*, 2021).

Other personal air measurement data, primarily of oil-related chemicals, were available from governmental agencies (OSHA, NIOSH, US Coast Guard), but were more limited in scope due to the relatively smaller number of activities covered; the limited number of measurements per activity, location, and time period; and in some cases, the shorter measurement durations. These measurement results were reviewed and were found to be consistent with the measurements collected by the RP, but we did not use them because of these limitations. There were almost no air measurements for exposures that were not generated from the crude oil (i.e. the other exposures of interest: $PM_{2.5}$, dispersants, and oil mist) and there were no dermal measurements.

Methods

GuLF study questionnaire

Typically, in occupational epidemiology studies of industrial cohorts, work histories from the employer or trade union are available to investigators. Such information was not readily available to us because there were hundreds of employers contracted by, or subcontracted to, the RP. These employers were located across the waters and coastal states of the Gulf of Mexico and were not disclosed by the RP.

We, therefore, relied on a systematic interview of the study participants to provide us the details of their work on the OSRC effort. Due to the time constraints of getting into the field quickly (the enrollment interviews started 5 months after the start of the exposure assessment), we had limited time to develop the occupational component of the interview. (In this paper the term interview pertains to the study enrollment questionnaires. Telephone interviews were administered between March 2011 and May 2013 to all study participants (N = 32 608) to collect information on OSRC work, demographic data, health, and other data (Kwok *et al*., 2017)). It was critical that the interview included questions that allowed us to link the study participants to the measurement data. We, therefore, reviewed the available personal measurement data collected by the RP at the time of the response and clean-up to identify over 100 jobs, activities, or tasks performed over the study period, asking over 400 questions on the occupational part alone.

In the interview, we first asked whether the participant worked on a rig vessel; on another ship or boat; or on land (any combination was acceptable). Workers on the rig vessels were expected to have had some of the highest exposures in the study as they were working at the wellhead where the fresh oil was being released. For this reason, we asked the rig workers yes/no questions about the rig(s) on which they worked, and shortly after being in the field, we added an open-ended question on the participant's job title. Supplementary Table S2 identifies the questions in the questionnaire and how they were linked to the EGs.

The measurement database identified fewer job titles than expected for the remaining water and land workers. Many titles, for example, were entered as "deck hand" (on water) or "responder" (on water or land). For this reason, if the participant indicated a ship or boat, we asked a series of yes/no questions about the specific activity of the ship/boat as described above (**Background,** Response and Clean-up) and open-ended questions for other activities and the name of the vessel. If the participant worked on land, we asked about their activities there (**Background,** Response and Clean-up) in both closed and open-ended questions. Open-ended questions were included to obtain information that we might have missed. We also asked about specific tasks. For example, on vessels that likely had a wide distribution of exposures among its workers (generally the larger vessels), such that there were likely to be a small number of people who had direct or closer contact with the oil than the other workers such as crew members, we asked the participant whether s/he personally performed the vessel activity (e.g., for vessels handling oily boom, "Did you personally handle oily boom?") Also, for the activity of decontamination, we asked about deconning vessels, other equipment, boom or workers. We used screening questions to reduce interview time if the participant was not involved in a particular function or activity. A positive response to one of the rig jobs or to a water/land activity/task question was followed by questions on the dates of each job/activity/task. The questionnaire may be found at https://gulfstudy.nih.gov/en/fr_researchers/fr_studyquestionnaires.html.

Site visits

The study hygienists made four trips to the Gulf, with each trip approximately a week in duration. The first three trips were focused on beach and marsh cleanup effort and decontamination of vessels, equipment, and boom conducted at various ports and docks (the only activities on water or on land still being performed at that time). On the fourth trip, we visited the four rig vessels, met with the captain and crew, and viewed the physical layouts.

Exposure groups

The goal of the effort described here was to develop a set of EGs that were systematically, transparently, and precisely developed for linkage of our study participants' work histories to air measurement exposure estimates to the level of detail provided in the measurement documentation. We used a JEM with EGs to make this link. The effort was transparent in that the exposure groups were based on explicitly described qualitative or quantitative (depending on the determinant) sets of determinants of exposure considered in a systematic manner. They were precise in that the EGs were as concise as the available measurement data and work histories allowed.

(The use of the word precise here does not imply statistical precision.) As a general concept, we wanted to use the same EGs for all agents assessed in the study, with each EG linked to sufficient measurements to develop stable estimates as indicated by our defined level of bias and imprecision (Huynh *et al.*, 2016).

The development of an EG was considered when it was thought that multiple individuals worked under similar exposure conditions, performed comparable tasks at a comparable frequency and duration, and were exposed to the same inventory of agents. Members of the EG were expected to have had a similar exposure distribution for each stressor because of being characterized with similar determinants of exposure.

Basic characterization: determinants of exposure for THC and BTEX-H

After reviewing the literature, we identified potential determinants and discussed their scientific basis for consideration by agent, workplace, work practices, and work force (Table 1) (Viet *et al.*, 2008; Jahn. *et al*, 2015; Lasczcz-Davis *et al.*, 2021).

We then identified in Table 2, specific study determinants that corresponded to the potential determinants from Table 1. We used the term, *determinant value*, as the options comprising the determinant (e.g., near-shore is a determinant value of location). For a determinant to contribute to the definition of one of our study EGs, the determinant information had to be available or could be derived from the measurement database and could be derived, or at least inferred, from the study participants' responses to the questionnaire. In addition, the determinant needed to have an underlying (even if general) scientific reason for its effect on exposure levels. Finally, our goal was to have each determinant reflect the same situation for all stressors present, i.e. THC, BTEX-H, $PM_{2.5}$, dispersant aerosols, dispersant vapors, and oil mist, to develop as much as possible a single set of EGs.

Because the measurement database was the primary source of information for the identification and evaluation of determinants and their values, and because it essentially comprised only oil-related measurements, the EGs were developed initially within the context of the oil-related chemicals. These oil-related EGs were then evaluated for their appropriateness for the other exposures of interest.

The measurement database did not, however, provide direct information for some of the determinants evaluated, either because the accompanying information (Supplementary Table S1) was ambiguous or was missing in the database. We, therefore, used primarily two sources of information. More than 4600 written industrial hygiene field notes, referred to as time history reports (THRs), were available for the samples collected on the large vessels operating in the deep waters of the Gulf. These reports usually identified the individual's job activities performed throughout the day, the occurrence of any upset or unusual conditions, and other documentation. The combination of the information in the THR and in the measurement database helped clarify terminology used in the OSRC effort and, by reviewing multiple samples collected by the same technician, we better understood the meaning of comments in the measurement database. The second source was hundreds of photographs covering the spectrum of OSRC activities across the Gulf and over time.

It was not necessary that each type of determinant identified with an EG be mutually exclusive of other determinants, but rather that each determinant characterization be used in concert with other determinants to provide a structured and comprehensive approach to assure that all the major determinants that likely affected exposures were considered.

Although there was day-to-day variability associated with these characterizations, if at any point in time, the overall definition of the EG was no longer valid, i.e. a determinant value changed, a new EG group was formed. For example, in our study, different EGs were developed for the period before and after the oil release was stopped. Even though the response workers continued working the same activity in the same area in both time periods, we formed a new EG because the distribution of the workers' exposures to vapors from the crude oil likely changed (below, Agent of Interest, *Composition and Vapor Pressure: Weathering*).

Agent of interest

The determinants in Table 1 evaluated in the GuLF Study related to "Agent of interest" were the pathway into the body, the presence of pure chemicals or mixtures, the composition of the mixture, and vapor pressure. Temperature and surface area were not used in the development of EGs but were used in the estimation of exposures. Quantity was not used in either (Table 2).

Pathway into the body

The pathway of interest to this paper is inhalation. Dermal exposure was also of interest but is discussed in other papers (Gorman Ng *et al.*, 2021, Stewart, Gorman Ng *et al.*, 2021, Table 2).

Pure chemical or mixture

Mixture. In this study, the volatile hydrocarbon components of the fresh crude oil released comprised, by

Table 1. Potential determinants considered when developing exposure groups.

Type of determinants	General determinants	Discussion
Agent	Pathway into body	An agent may be inhaled, absorbed through the skin, remain on the skin or ingested. Each pathway depends on the physical state of the agent and the opportunity for contact and affects which determinants are most important.
	Pure chemical or mixture	Chemicals may be in the pure state or contained in a mixture. The vapor pressure of a chemical in a mixture is less than the chemical's corresponding vapor pressure in the pure state and thus can result in lower exposure than would be observed when handling the chemical in the pure state.
	Composition of the mixture	The composition of a mixture generating a vapor may be static or it may be changing. If the relative composition is changing slowly enough over a designated time period, it may be possible to consider the composition as relatively constant, i.e. in a pseudo equilibrium state. In a mixture, when the more volatile components evaporate over time, the impact changes the mixture composition. Because the overall mass of the mixture decreases (due to the elimination of the volatile components), the composition (i.e. % by weight) of the less volatile components in the mixture may increase with time. Once the volatile components have evaporated to a significant degree, the change in composition of the mixture may be very slow. Depending on the component, a change in composition can result in either an increase (for the more volatile components) or decrease (for the less volatile components) in exposure.
	Vapor pressure of agent	An agent's vapor pressure controls how much vapor of the chemical is generated and in turn, how much vapor is available to be inhaled by the worker. If the liquid/vapor concentration is in equilibrium, the vapor concentration is referred to as the saturated vapor concentration (SVC). In most actual exposure scenarios, the concentration of vapor in air that workers encounter is usually a small percentage (<<1%) of the SVC, with the actual percentage of the SVC dependent on a number of factors such as the

Table 1. Continued

Type of determinants	General determinants	Discussion
		effectiveness of ventilation (general and mechanical), position of the workers with respect to the source of emission, wind speed, etc. While the agent's vapor pressure controls the maximum concentration of vapor in the air above the liquid, the evaporation rate (mass/unit time) is affected by additional factors including: the agent's molecular weight, the size (surface area) of the pool of liquid, length and width of the pool and the velocity of the air moving over the pool. An increase or decrease in vapor pressure can increase or decrease exposure, respectively.
	Temperature of liquid generating the vapor	The vapor pressure of the chemical is affected by the temperature of the parent liquid generating the vapor (not by the ambient temperature of the air). An increase or decrease in temperature can increase or decrease exposure, respectively.
	Surface area	The surface area is the area of the liquid exposed to the air, and the greater the surface area the greater the amount of the agent that can be volatilized. The surface area may be due to either the liquid being in a pool on a surface or being in a container with an opening. Where the liquid is in a container, the potential exposure is dependent on the size of container's opening rather than the quantity of liquid in the container. The term container is being used in a very general way. It could be a vessel, process equipment, storage tank, pail, bottle, tote or transfer line, and the opening could be a deliberate opening (i.e. without a cap) or inadvertent opening (a pipe leak). If an operator is adding an agent to a process, the opportunity for exposure to the vapor is proportional to the number of times the agent is added.

Table 1. Continued

Type of determinants	General determinants	Discussion
	Quantity	The quantity of an agent may be important if it increases or decreases the surface area available for evaporation; however, an increase in quantity may not affect the exposure level if the surface area does not change. The same surface area can have a large or small quantity depending on the configuration of the liquid's container, i.e. a tall, wide container can have the same surface area as a short, thin container if the opening of the 2 containers is the same. In this case, quantity is not important (as long as some liquid is present).
Workplace	Emission points • Number Characteristics • Size • Emission rate • Mechanism of release	Emission points relate to positions where vapor is introduced into the workplace. There may multiple emission points in a workplace and increasing the emission points can increase exposure and vice versa. In an enclosed configuration, there is a zone of exposure in the worker's immediate breathing area and a zone containing the remainder of the work area, such as a room. There will be an exchange of air between the zones, but the vapor near the emission point in an enclosed area is not diluted as quickly as would be expected in an open area with even light winds. Each point can have a differently sized surface area and a different emission rate of the vapor (the speed at which the emission is released into the atmosphere) that contribute to the exposure (a greater size of the source or a greater rate can result in increased exposure and vice versa). The type of release mechanism can affect the speed at which the agent evaporates (spraying results in faster evaporation, and therefore exposure, than no spraying), as can the direction of the release (a release with more energy results in a narrower plume than a release with less energy, which can increase or decrease exposure depending on the worker's location in relation to the plume).

Table 1. Continued

Type of determinants	General determinants	Discussion
	Ventilation or engineering controls Types • General or natural dilution • Capture • Containment Characteristics • Height/location of vents • Efficiency • Location relative to the source	Ventilation provides a mechanism to remove or prevent vapor concentrations from entering the worker's breathing zone and/or the workplace. General dilution occurs with the presence of ceiling or room fans. Natural dilution ventilation indoors may be due to open windows or doors. Both types of ventilation are generally ineffective at consistently and efficiently reducing vapor concentrations in the worker's breathing zone if the worker is located near an emission point. Capture refers to collecting the vapor at the emission point (e.g., a duct with slot hood). With a capture configuration, the source of emission is outside of the duct, but the net flow of air into the duct is at a rate sufficient to capture molecules being emitted from the source. Depending on the configuration of the capture device, the efficiency of capture ventilation can vary significantly. Containment means that vapor is emitted to an area that is isolated from the worker (e.g., a closed process). There also is a variation of containment where capture ventilation is used within the contained area to further enhance efficiency (e.g., a duct with a slot hood located inside a contained area such as a lab hood). The height or location of a vent can facilitate movement of contaminated air to a different area. These characteristics may decrease exposure (by moving the air away from workers) or increase exposure (with improper design, such that the contaminated air is vented into an area with workers). Mechanical ventilation may be ineffective if improperly designed or maintained.

Table 1. Continued

Type of determinants	General determinants	Discussion
		Ventilation may have no effect on exposure if the ventilation is poorly located, such as being too far from the emission point to be effective. Random air speed (non-directional) indoors is on the order of 4 m/min (0.15 mph), and directional air speed due to air changes per hour (ACH) indoors is also very low. For example, consider an average size room (width, length and height of 4 m by 4 m by 3 m, respectively) with 6 ACH, which is considered good general ventilation. Although air flow patterns are very complicated, if very simple conditions are assumed where air is entering through a vent on one side of a room and exiting through a vent on the other side of the room, the directional air speed is equivalent to about 0.4 m/min or 0.02 mph. That is, indoor air speeds are low compared to even virtually still winds outdoors (see Wind, below).
	Wind • Speed • Direction	Air velocity increases the evaporation rate. A wind over the liquid can effectively carry vapor away from the workplace, reducing exposure, but it can raise exposures if so much air movement is present that it overwhelms the mechanical ventilation efficiency or if the movement contaminates areas downwind where the agent of interest would normally not be present.The intensity of an exposure is usually significantly higher indoors or in protected areas where the wind, if present, is relatively low. Wind can be directional or non-directional. Non-directional movement of air molecules from one position to another can dilute air near an emission point and raise air concentrations further from the emission point. Directional winds can increase the air concentration within the plume and lower it outside the plume, if clean. If contaminated, the opposite can occur. Evenly virtually still winds outdoors are 25 to 50 m/min (1 to 2 mph).

Table 1. Continued

Type of determinants	General determinants	Discussion
	Pressure differences in an area	The net pressure on the system can affect exposure. Contaminants flow from areas of higher pressure to lower pressure. Differences in pressure can occur during the filling or emptying of a container. For example, if a worker is monitoring the filing of a tank neat the opening to the tank, the displaced air from the tank (i.e. the flow of air out of the vessel) can increase exposure to the worker beyond that expected from diffusion. If a worker is monitoring a tank that is being drained from the bottom (i.e. air is flowing from outside of the tank into the tank), the expected exposure may be less than that observed with diffusion. The use of positive pressure in an area to prevent air contamination from entering into an area, such as in a "clean" room, is another example of how differential pressure can affect exposure.
Work Practices of activities/tasks	Location of the worker (relative to emission points, ventilation, and wind)	Distance from the emission point refers to the distance of the worker from the emission point. The distance influences how concentrated the vapor is when it reaches the worker due to interference by general, natural, or mechanical ventilation. Generally, the greater the distance, the lower the concentration and vice versa, as can be shown using a Gaussian Plume Model. For example, consider conditions of low wind <27 m/min (< 1mph) and a small surface area between 26 and 232 cm^2 (0.03 to 0.25 ft^2). If exposure at 0.3 m (~1 ft) from a source is 100 ppm, at roughly 0.75 m (~2.5 ft or arm's length), the exposure drops to 18 ppm. At ~1.5 m (about 5 ft), the exposure drops to 5 ppm and at 3 m (about 10 ft), the exposure would be only 1.5 ppm. A worker's exposure may be higher if the worker is located between an emission point and the exhaust point of the ventilation; alternatively, the exposure may be lower if the worker is outside the emission to ventilation plane. If a wind plume is moving clean air, a worker in the plume can have a lower exposure than if outside the plume; conversely, if the wind is moving contaminated air, exposures will be lower outside the plume than in the plume.

Table 1. Continued

Type of determinants	General determinants	Discussion
	Duration and frequency of an activity/task	Exposure can be affected by the task duration and the number of times (frequency) that the task is performed daily, weekly, etc. The longer the duration or the more frequent the exposed activity/task is performed, the higher the (cumulative) exposure and vice versa.
	Isolation	Isolation prevents workers from entering an area contaminated with the vapor, reducing or eliminating exposure.
	Other agents present	Specific activities/tasks can result in exposure to the agents of interest such as cleaning chemicals, fuels, etc. resulting in additional exposures beyond that attributed to the source.
Workforce	Personal protective equipment (PPE)	PPE can decrease exposure, but improper use of the equipment can result in an increase in exposure. Also, a false sense of protection when the PPE is not properly worn can result in behaviors that can increase exposure. It is important to know how long the PPE is worn and how frequent the PPE is replaced or decontaminated.
	Cleaning/ decontamination	Especially with dermal exposures, the decontamination or cleaning of the body part impacts exposure, i.e. the frequency hands are washed or a shower is taken. Additionally, the frequency that clothing is changed or PPE is decontaminated can impact dermal, inhalation and in some cases, ingestion of the agent. Contaminated clothing can result in continued exposure to an agent even after the task involving the agent is completed.
	Frequency and duration of tasks performed	The exposure frequency and duration can impact the effect on the body in addition to the exposure level. For example, the body may very efficiently eliminate or detoxify an exposure that occurs once a wk for a duration of 4 hr but if the exposure of the same intensity is encountered virtually every day, for the entire day, the capacity of the body to safely rid itself of the agent may be compromised.

Table 1. Continued

Type of determinants	General determinants	Discussion
	Shift	The activities performed, and their frequency and duration, may vary from shift to shift for a job title. For example, process samples may be collected during the night shift so they are available for analysis in the laboratory, which may be staffed only during the day. Activities like drumming product may occur during all shifts worked, but other activities such loading tank trucks may occur only during the day shift. Maintenance may be done 24 hrs/day, but the night shift may have different exposures due to performance of different maintenance activities or due to the shutdown of day production lines.
	Job rotation	Job rotation may affect exposure several ways. First, if a given job title works only one shift (days, evenings or nights), workers with the same job title within the same department may have very different exposures as described above in "Workforce/Shift", depending on the shift. Second, it is common practice for a job title within a department, e.g. "operator", to have multiple job assignments. For example, a process area may involve four job assignments: control room operation, raw materials addition, production, and product packaging, each being performed by workers with the job title of "operator". In this example, although the job title is the same for all 4 assignments, the workers may have very different exposures because of the exposure differences of the assignments. It is not unusual, however, for an "operator" to perform all 4 of these assignments. If the rotation through these assignments is the same for all workers, all workers would have a comparable exposure. Alternatively, some workers may have different skill levels or levels of training. As a result, some workers may rotate through all 4 assignments while others may rotate through only 2 or 3 of the assignments. In contrast, in some cases,

Table 1. Continued

Type of determinants	General determinants	Discussion
		different job titles, e.g., "senior operator" and "operator", may be assigned to workers even though the job assignments are identical, with the former title being a reward for more experience or longer tenure with the employer. Third, the rotation schedule for job assignments across the shifts (days, evenings or nights) may vary. For example, it the operation is continuous, four shifts (A, B, C & D (~40 hours each)) are required to cover the 168 hours in a week. Rotation among shifts or among job assignments may occur weekly, monthly or over a longer period of time, such as every 3 months. This rotation can impact the potential for an adverse heath outcome due to a lower recovery time, depending on the disease mechanism. Under the same workplace conditions, however, such varying rotations generally would have little impact on exposures. In contrast, in custom industries, such as machine shops or the pharmaceutical industry that run campaigns of varying duration for different products, different exposure levels to different agents could occur, because the job rotation is not synchronous with the campaign duration.

weight, approximately 17% of the overall crude oil (Reddy *et al.*, 2012). The vapor concentration of the volatile components was reported as total hydrocarbons (THC), measured as total petroleum hydrocarbons (TPH). The TPH measurement included at least 75 different volatile hydrocarbons with pure boiling points in the range of 36 to 216°C, with corresponding pure vapor pressures in the approximate range of 500 to 0.1 mm of Hg. The THC measurement included the BTEX-H chemicals of interest in our study.

Composition and vapor pressure

Weathering

The composition in the oil was dynamic due to weathering. Weathering is the natural process of change that oil undergoes as it travels in or on water. More information is provided in the SM, document 1 on weathering and how it impacted our THC and BTEX-H estimates.

The vapor concentration of any specific chemical in THC is dependent on the concentration of all 75 chemicals in THC due to the lowering in the vapor pressure that a pure chemical undergoes in the presence of other chemicals (Stenzel and Arnold, (2015). As crude oil evaporates, the more volatile components of the oil selectively evaporate more quickly than the less volatile components, resulting in changes in the composition of the oil. The evaporation rate is not linear. It takes only ~10 minutes to evaporate the initial 10% of the volatiles, several hours to evaporate the next 10% (a total of 20% of the volatiles), a couple of days to evaporate the next 10%, and finally 2–3 weeks to reach 40% evaporation (Supplementary Table S6).

Weathering also increased as the distance from the wellhead increased, primarily due to the dissolution of the compounds in the water and evaporation on the water surface as an oil slick. Thus, weathering resulted in changes in the oil composition over the time and location of the OSRC effort.

The degree of weathering, however, is not apparent by visual inspection, and so study participants would not likely have known the degree of weathering of the oil and tar with which they had come into contact had undergone. We, therefore, used two proxies of weathering: location (area of the Gulf or US state) and time as determinants.

The area determinant represented broad areas of the Gulf of Mexico in relation to the source of the fresh oil, i.e. the wellhead, by the following values: the hot zone (within ~1 nautical mile (nmi, 1.8 km) of the wellhead); source (within ~5 nmi (~9 km) of the wellhead excluding the hot zone) (these were combined into a single area, "could see the wellhead"); offshore (the area outside the source area to within ~3 nmi (~5.5 km) of the shoreline; and near-shore (<~3 nmi to the shore).

For land, we used the coastal states of the Gulf (Louisiana (LA), Mississippi (MS), Alabama (AL) and Florida (FL) and "All states" as determinant values, with the expectation that the further from the wellhead, the more highly weathered the oil, which likely resulted in lower exposures. Although the GuLF Study also included workers from Texas (TX), the amount of oil reaching the TX coast was negligible, and no beach or marsh clean-up activities took place in or near TX (Deep Water, 2011)).

As time passed, the degree of weathering increased (Supplementary Table S6). Therefore, we identified time as a determinant and developed time periods as determinant values, which reflected changes in weathering and resulted in step changes in exposures.

Workplace

The potential determinants in Table 1 evaluated for study determinants in Table 2 pertaining to the workplace were emission points and pressure differences in an area. Ventilation or engineering controls were not considered major determinants since few controls were identified and most operations occurred outside. Weather conditions i.e. wind speed was not considered because it was likely a component of time period. Other agents in the general work environment, such as engine exhaust, likely impacted the measurement results of several of the agents of interest (e.g., THC, benzene), but such sources were not considered as determinant values because they were expected to be incorporated into the job/activity/task and vessel determinant values (see below, *Emission Points: Job/activity/task, vessel or vessel type, and outside events*).

Emission points: job/activity/task, vessel or vessel type, and outside events

Although the study hygienists were unable to visit most of the worksites during operation, we had many published sources of information that described the workplace. We, therefore, had a general idea from our document reviews of the sources of exposure, their sizes, and the mechanisms of release (Table 2).

First, the workers on the 4 rigs located at the wellhead were expected to have had some of the highest exposures in the study due to the proximity of the fresh oil (Huynh *et al.*, 2021a). In addition, the rigs were characterized by a relatively large population per vessel (by the standards of our study, i.e. 140–200 individuals on the vessel on any specific day). We had collected activity information on various rig jobs during our site visit and so were able to identify emission points for the various jobs. Although

Table 2. Major potential determinants contributing to the study determinants.

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
Agents: THC, BTEX-H, dispersant aerosols and vapors, $PM_{2.5}$, oil mist	Pathway into body Pure chemical or mixture Composition (weathering)	Both inhalation and dermal exposures were of interest. All agents of interest are mixtures. See Supplemental Materials (SM) for a discussion of the weathering process due to evaporation and solubility. Supplementary Table S4 in the document presents each of the BTEX-H chemicals' solubility in water; Supplementary Table S5 presents the impact of weathering on the composition of the crude oil and the make-up of the THC concentration. Finally, Supplementary Table S6 presents the amount of time it takes to reach a level of weathering, expressed in percent. Weathering therefore affected THC and BTEX-H, but it did not affect the other agents of interest (dispersant vapors, $PM_{2.5}$or oil mist). The degree of weathering is expressed in percent (see Supplementary Table S5). The MC252 crude oil released during the *DWH* event contained 16.84% volatiles (by wt.). This 16.84 % included 1.68 wt % BTEX chemicals and about 1.4% n-hexane, i.e. for a combined ~20% of the volatiles. The SVC above the liquid crude oil expressed as a THC concentration (i.e. percent by volume) contained 5.58% BTEX vapor and 25.72% n-hexane vapor. That is, if the THC was measured to be 100 ppm, the combined BTEX concentration would be 5.6 ppm and the n-hexane 25.7 ppm. By the time the weathering reached 20% (2 to 3 hours, Supplementary Table S6), the BTEX chemicals increased to comprise 8.02% of the THC concentration and the n-hexane contribution was reduced to 21.05%. Weathering reached about 40% weathering within 2 to 3 weeks after the oil release, with the THC concentration comprising about 12.86% BTEX vapor and the n-hexane vapor concentration reduced to about 4.33%.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
		The change in weathering was used to identify areas in the Gulf, state, and time periods. In addition, the jobs/activities/tasks were associated with different degrees of weathered oil. For example, workers patrolling the shoreline were exposed to oil that was more weathered than the oil experienced by workers on vessels offshore. Composition was used in the priors in the Bayesian analyses to estimate exposures for the various exposure groups, but the actual priors were established empirically based on overarching correlations between THC and the BTEX-H concentrations observed in the measurement database. Composition was also used in the estimation of dermal exposure levels.
	Vapor pressure (VP)	The VPs of the pure BTEX-H chemicals at 25°C are 94.8, 24.8, 9.6, 7.72, 153 mm of Hg, respectively. With crude oil weathering of 0%, 20% and 40%, the benzene VPs are 0.864, 0.530 and 0.121 mm of Hg, respectively. The corresponding toluene VPs are 0.620, 0.595 and 0.0.470 mm of Hg. The corresponding ethylbenzene VPs are 0.027, 0.028 and 0.028 mm of Hg, and xylene's VPs are 0.157, 0.168 and 0.173 mm of Hg. N-hexane VPs are 7.690, 3.469 and 0.267 mm of Hg. The corresponding THC VPs are 29.900, 16.482 and 6.162 mm of Hg. Vapor pressure was not used in the development of EGS but was used in the estimation of dermal exposure levels.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
	Temperature	The temperature refers to the temperature of the oil and not ambient temperature. Every approximately 10°C (18°F) increase in the liquid crude oil temperature results in an approximate doubling of vapor pressure. As a point of reference the average water temperature at Grand Island, LA in April is about 70°F (21°C) and in July the water temperature is typically about 85°F (29°C). This means with everything else constant, the vapor generated from the fresh crude oil in April was about ½ the concentration that was generated from fresh oil in mid-July when the well was mechanically capped. Temperature was reflected in the determinant of time period.
	Surface area	The emission rate from a source is dependent on several factors including the surface area of the pool of the agent. The configuration of the pool (length versus width) is important but in general, the greater surface area, the greater the emission rate.Surface area applies to both oil in a pool on the water surface or in a plume under the water surface. It also covers the surface area of a transfer line during a connect/disconnect. The surface area of the oil on the water varied. In addition, the connect/disconnecting of dispersant-containing equipment and dispersant spills could have differently sized pools. The size of the oil pool was used in the modelling of dispersant vapor exposure levels.
Workplace: Job/activity/task	Emission points	The characteristics of the emission points (i.e. number of emission points, overall size of the emissions, etc.) varied across jobs on the rigs and across the activities and tasks of the workers on the vessels and on land. For some jobs/activities the exposure was attributed to both being in an area where the ambient air was contaminated and working with the oil related agent of interest (e.g., benzene) or the agent itself (such as 2-butoxyethanol), while for other jobs/activities exposure was attributed to being in the area where the agent(s) was present, but no direct contact occurred.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
		For example, workers in many rig jobs had direct contact with oil-contaminated equipment, while other rig workers received their only exposure from the ambient air outside on the rig deck. Job title was used as a determinant value for rig vessel EGs, but not on any other EG because such information was not available in the monitoring data. Information was available on what activities different vessels performed and we used vessel activity as a determinant (see Workplace: vessel/vessel type below). On some vessels, some jobs personally and directly performed an oil-related activity (such as handling oily boom) and thus were closer to the emission source, whereas other jobs on the same vessel did not perform any oil-related activity and thus were further from the emission source. These personally performed activities resulted in additional determinant values. Various tasks provided other determinant values. They were generally thought to be less than full-shift work, such as the connect/disconnect of transfer lines containing oil. The differentiation of job/activity/task was only for evaluation purposes and did not affect exposure levels *per se*. Finally, mechanisms of release were distinguished among decontaminating activities (i.e. pressure spraying, or cleaning with cloth and other absorbent materials) for THC, BTEX-H, and oil mist.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
	Ventilation	Most activities and tasks were performed outdoors, with the primary type of ventilation being natural dilution. Some of the rig vessels had inside areas not associated with living quarters such as engine rooms, storage areas, mud rooms, etc. where air changes were controlled by heating/ventilation/air conditioning equipment. Entry into a tank, by regulation, is considered a confined space, with mechanical ventilation required. The presence or lack of ventilation was incorporated by the job/activity/task determinant and not used as a distinct determinant. Ventilation was not considered for developing EGs but air changes per hour in likely work areas was considered for estimating exposure levels to dispersant vapor concentrations.
	Wind	The wind direction and speed varied over time. Wind was not considered for EGs but was incorporated in the estimation of exposure levels to dispersant vapors and $PM_{2.5}$ concentrations.
	Pressure differences in an area	The inside areas of the rig vessels, i.e. the living quarters and offices were under positive pressure. Jobs located inside the rigs were grouped and distinguished from jobs located outside.
Work Practices of activities/tasks	Location of the worker (relative to the emission points, ventilation and wind)	Activities performed by workers on vessels and on land were at different distances from the wellhead. Distance across the Gulf waters was particularly important for the $PM_{2.5}$ EGs. Distance was not used in the development of EGs for dispersant vapors but was used in the estimation of dispersant vapor concentrations.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
	Duration and frequency of an activity/task	Duration and frequency affect total exposure (i.e. cumulative exposure). The number of *in situ* burns per day, the number of days burns occurred and the number of days that oil and gas were flared were considered in the $PM_{2.5}$ exposure estimation process. Additionally, the number of days dispersant was applied aerially or by vessel was considered in developing the dispersant exposure estimates. The number of days was considered in the estimation of cumulative exposure. These metrics were used as a determinant in the calculation of cumulative exposure, but not in the development of EGs.
	Other Agents	Collected oil and oily water, cleaning or other support chemicals, and contaminated equipment contain varying concentrations of the agents being studied, but at levels different from those levels observed in the weathered crude oil. In some cases, especially in the cases of fuels and dispersants, these agents were transferred from land to vessels and planes and from vessels to other vessels. Workers connected and disconnected transfer lines with different chemicals, as they also pumped and performed maintenance on pumping equipment containing different chemicals. We distinguished between working with oil- and dispersant-containing equipment, but did not consider other agents for other EGs.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
Workplace: Vessel name, vessel type and (vessel) activity	Emission points	The 2 rigs that stopped the oil release were performing different activities with different equipment from all other vessels. Two other rigs were drilling new wells. Other vessels in the same area were piloting the remotely operated vehicles (ROVs). Several large and smaller vessels were located throughout the Gulf waters had different functions or performed different activities (e.g., transport, scouting, skimming, burning, and boom handling). The rig, the ROV, fire burner control and research vessels were identified by name. Workers who identified such vessel-related activity in open-ended questions but provided no vessel name, was assigned the determinant value of "All ROVs" or "All RVs" (this situation did not occur for the rig or fire burner control vessels). Other vessels performing a single activity were expected to have had different emission characteristics, but due to the large number of vessels and the lack of information on the vessel names and their characteristics from the study participants, we identified these by vessel type (barge, draft/air/jon boat) or activity (transport, scouting, etc.). Activity was a determinant for EGs where the workers on the vessel were expected to have the same distribution of exposures (vs. vessels where some participants had closer contact with the agent (Workplace: job/activity/task above)).
	Composition	The rig vessels and ROV vessels stayed in the immediate area of the well where the vapor concentrations of the oil constituents were the highest and thus was the least weathered. Also, these vessels had the highest PM2.5 levels associated with the flaring of oil and gas by two of the rig vessels. Vessels, such as skimmers, were in direct contact with the oil but it had been weathered, resulting in lower oil constituent concentrations than those experienced on the rig vessels. Weathering would be incorporated into time (see Dates (time periods) below). Weathering was used in the estimation of dermal exposure.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
	Distance from the source	The rig vessels were very large, with the main deck being about 30 m above the water surface, while the ROV vessels had decks about 10 m above the water surface and other vessels such as fishing and scouting vessels had decks about 3 m above the water surface. Air/jon/draft boats were <1 m above the water surface. In addition, the rig and ROV vessels worked within 5 nmi of the wellhead; whereas fishing and scouting vessels worked throughout the Gulf and air/jon/draft boats worked near shore. Distance from the source likely was incorporated into vessel name, type of activity and so was not used as a separate determinant.
Area/State	Distance from the source	Generally, the oil had undergone greater weathering the further the distance from the leaking well. Some oil remained in underwater plumes that surfaced beyond the immediate area of the wellhead. In these cases, although some weathering occurred due to dissolution, significant weathering may not have occurred until the oil surfaced. Similarly, PM2.5 levels decreased inversely to the distance from vessels burning oil *in situ* and the rigs flaring oil/gas. We divided the Gulf of Mexico into 3 areas: a combined hot zone and source ("could see the wellhead"), offshore and near shore (see text for definition). In addition, the 4 Gulf states in the study were distinguished for their distance from the wellhead: LA, MS, AL, and FL. We identified a forth area (hot zone alone) for $PM_{2.5}$.
	Duration and frequency	The duration and frequency of activities and tasks likely varied by Gulf state (and likely at even finer resolution than state). Because we had no information on such differences, we did not adjust for them for water workers. These determinants are reflected in the use of state as a determinant for land workers.

Table 2. Continued

Study determinant	Determinant considered	Discussion with examples used for GuLF Study EGs or exposure estimation*
	Emission points	For the most part, emission points were contained within the concept of activities, locations and/or time periods and so were not considered separately. The characteristics of emission points on the beaches (primarily pools of weathered oil and tar balls) were different from those at ports and docks (primarily oil-contaminated boom and other equipment). Activities occurring at the beaches and at the ports and docks were identified as different determinant values.
Dates (Time Periods)	Degree of weathering	The degree of weathering was the lowest before 15 July 2010 due to the continuous flow of fresh oil. Dispersant was applied by plane and vessel before this date, while after 15 May 2010, dispersant was also injected below the water surface, resulting in more weathered oil reaching the surface. Once the flow of oil was stopped (15 July 2010), the degree of weathering increased with increasing time. Time periods (TPs) were developed reflecting the degree of weathering in the oil and changes in events.
	Vessel name, vessel type, activity	The vessels deployed and the activities they performed changed over time. Almost all vessels were decommissioned by 31 December 2010, while land operations continued (albeit it at a reduced rate). The time periods developed reflected different functions and these broad decommissioning dates.
	Job/activity/task	The jobs/activities/tasks performed changed by time period. Marsh clean-up did not start until after August, 2010. Boom operations were generally over by 31 December 2010. The time periods developed reflected these various changes.

the work being done by many of the rig workers on the *Enterprise* and the *Helix Q4000 (Q4000)* during the response was atypical of the normal offshore drilling process, many of the crew workers had standard oil rig job titles. As the sources differed among the jobs, we used these standard titles for individual crew jobs (e.g., motormen, mechanics, and cooks) and drilling jobs (e.g., roustabouts, roughnecks, and floorhands). Other jobs were brought on board for the spill mitigation, including cementers, burner fire control workers, and field technicians. We retained all these rig job titles as determinant values.

Other than some of the response vessels (below, Work practices, *Location of the worker and duration and frequency*), we had incomplete information on where most vessels were located and what they did. Moreover, only about one-fifth of the participants provided the name of their vessel. For most water workers, as a substitute for job title, we had asked in the interview a series of closed-ended questions about vessel activity (for example, a vessel that handled oily boom or one that burned oil, in **Background**, Response and Clean-up above). We used these vessel activities as workplace determinant values for EGs comprising these remaining workers. We had also asked participants if they personally performed the vessel activity (e.g., handled oily boom). Thus, we identified as determinant values each of the major vessel activities and for some vessel activities, "personal" work on the water. On land, we used worker activities as the basis of our EGs (**Background**, Response and Clean-up above). Because the emission points varied by activity and task, we used each activity/task as a distinct determinant value.

For some activities, we were able to identify emission points in greater detail. Thus, for the decontamination activity, we identified deconning of vessels, other equipment, boom, and personnel, each as a determinant value. Finally, we reviewed all open-ended responses to activity questions and added other activities as appropriate.

Time also influenced emission points, as different events occurred over time. Seven time periods were developed over the approximate 14 months of the study to reflect changes in events (and thus in emission points) and changes in weathering (above, Agent of interest, *Composition and Vapor Pressure: Weathering)*. Table 3 summarizes the seven time periods used in the study to reflect the key events that occurred in each time period and therefore step changes in exposure levels.

Pressure differences

The living and office quarters on the rig vessels were under a pressurized system, such that contaminated air would be constrained from entering these areas. Administrative employees who spent most of their time in these living or office areas were assigned to a single EG to reflect their inside exposures.

Work practices

The potential determinants of location of the worker, duration, and frequency of an activity/task, were used as study determinants (Table 2). Isolation was not used as there were no instances where workers were isolated. We also did not consider the use of other agents by the study participants other than distinguishing between oil- and dispersant-containing equipment. Some agents, like diesel exhaust, would have contributed to the TPH measurement and could not be distinguished from the oil-related agents' contribution. There were also other non-oil-related agents. For these, although we collected some safety data sheets (SDSs) related to various products used in the OSRC effort, we do not know if we have a complete record. Also, it was not clear which of these products were associated with a particular job/activity/task, location, and time period. Also, some products had components that could have contributed to the THC measurement result, but in general, the THC components of the products were low (<10%), except for d-limonene, which could have approached 100% of the cleaning material.

Location of the worker and duration and frequency

As mentioned above, the hot zone and source, where the 4 rig vessels and the vessels supporting the response effort were deployed, were expected to be the areas where the workers with the highest exposures were located. The *Enterprise* was tasked with stopping the oil release and collecting oil and gas and flaring the gas. The *Q4000* supported the *Enterprise* and flared gas and oil. Relief wells were drilled by the *Development Driller II (DDII)* and *DDIII*. The *DDII*, however, started several weeks after the *DDIII* had started, so although exposures were expected to have been similar over time, for any given time period, worker exposures on the *DDIII* may have been different from those on the *DDII*. For this reason, we identified the 4 rigs as determinant values.

We had not asked any questions in the interview on other response vessels in wellhead area, and so we assigned workers to these other vessels based on the open-ended question asked of the vessel name. If a specific ROV was identified, the vessel name was considered a determinant value. We also developed an "All ROVs" category for study participants who indicated in their open-ended responses that they performed ROV-associated activities.

Table 3. Description of study time periods.

Time period	Dates	Major activities
1a	22 April to 14 May 2010	Oil was being released at the wellhead near the floor of the Gulf. Efforts to stop the release by containment were unsuccessful. Drilling started on a relief well. Aerial application of dispersant COREXIT™ 9527A (9527A) and 9500A (9500A) to the water surface began across the Gulf. *In situ* burns started. Oil reached the LA and MS shore, and beach cleanup started.
1b	15 May to 15 July 2010	Drilling began on a second relief well. Only 9500A dispersant continued to be applied by plane. 9500A dispersant was injected at the wellhead to break up the oil and applied by ship to the surface of the water near the wellhead to reduce THC air concentrations. *In situ* burning continued. Offshore skimming of oil and flaring by the rig vessels started. Beach cleanup continued, but now included AL and FL, and onshore and offshore decontamination of vessels and equipment started. On 15 July, the well was mechanically capped with a functional BOP and the oil flow stopped, but the well cap and well casing were still under considerable pressure from the oil formation. Flaring of oil and gas ceased with the well capping on 15 July.
2	16 July to 10 August 2010	The well was “static killed” (relieved pressure on well casing by pumping drilling mud and other components into the well) on 10 August. *In situ* burning ended by 19 July. Offshore skimming ended in early August but nearshore skimming continued. Beach cleanup and decontamination of vessels and equipment continued. The cleaning of the jetties and other structures such as bridges began.

Table 3. Continued

Time period	Dates	Major activities
3	11 August to 30 September 2010	The first relief well intersected the original well ~18 000 feet below the Gulf floor on 16 September. Heavy mud and cement were delivered at the base of the well to close off the well. The well was permanently sealed on 19 September. Underwater equipment used in the response was removed or repositioned. Large-scale decontamination of the vessels started. Nearshore skimming continued on a limited basis. Beach cleanup continued but started to decline. Efforts to clean the marshes began during this time period but only affected LA and MS.
4	1 October to 31 December 2010	Decontamination of the vessels and equipment continued. By 31 December, essentially all vessels had been decontaminated and were considered out of service. Beach and marsh cleanup continued, along with the cleaning of rock jetties, by an increasingly smaller number of people. Nearshore skimming ended in October. The decontamination and repair of boom was completed by the end of this time period.
5	1 January to 31 March 2011	Beach cleanup continued by an increasingly smaller number of people.
6	1 April to 30 June 2011	Beach cleanup continued by an increasingly smaller number of people. Distinguished from time period 5 because of the warmer ambient air temperatures that resulted in higher THC exposure levels.

BOP, blowout preventer.

Similarly, specific names of the various research vessels (RVs) and "All RVs" were determinant values for study participants who worked on these vessels. There were several other large marine vessels in the hot zone and source, but information was incomplete on the names, locations, and dates of many of these vessels. Therefore, we used a question "Could you see the individual ships or rigs in the wellhead area?" to identify those vessels in the hot zone and source, which was represented by the determinant value "could see the wellhead". Two other locations, offshore and near-shore, were also identified as determinant location values (above, Agent of interest, *Composition and Vapor Pressure: Weathering)*.

Duration and frequency also contributed determinant values. For some activities, we had asked screening questions in the questionnaire to reduce the time burden of the interview to the study participant. The screening questions asked about multiple related activities, with sub-questions asking about each of those activities. A positive response to the sub-question likely resulted in a higher duration or frequency of an activity than for each of the other activities indicated in the screening question receiving a negative response. We also developed an EG "Worked on a boat or ship" to provide a non-specific activity (i.e. being on the water) to participants who said they worked on a boat or ship (other than a rig vessel) but did not report doing any of the water-related activities asked about in the questionnaire.

Work force

No determinants for work force were used. The RP developed personal protective equipment matrices for each major activity, but the local site industrial hygiene representative was to use his/her discretion to deviate from the matrices. Cleaning/decontamination practices, exposure frequency and duration, and shift or job rotation information were generally not available on an individual level and therefore were not used.

Agents other than THC and BTEX-H

To develop EGs for the other exposures of interest (dispersants, $PM_{2.5,}$ and oil mist), we first reviewed the previously described EGs. Exposures to dispersants were associated with few activities in the OSRC effort; thus, we were able to retain all the developed EGs (with most of them being considered unexposed) with the single modification of changing the agent "being handled or transferred" from oil to dispersant. For $PM_{2.5}$, we required only a single activity-based EG (*in situ* burning) and the area-based EGs (hot zone, could see the wellhead, offshore, near-shore) and state. For oil mist, all EGs were retained with no modification (with most being considered unexposed).

Study participants' exposure assignments

After identifying the possible EGs, each of the measurements was also assigned one or more EGs from which we calculated our summary statistics of AM, GM, GSD, and 95th percentile and their credible intervals. We then assigned each study participant the appropriate statistics through the EGs in the JEM.

Results

Supplementary Table S2 identifies the number of determinant values associated with each study determinant. We identified 38 possible job titles or job groups across the 4 rig vessels. Some appeared on all 4 rigs; others appeared on a subset of the rigs. We identified 14 ROV vessels (plus "All ROVs"), 3 fire burner control vessels, and 33 research vessels (plus "All RVs"). We identified 73 activities or tasks across 4 states, plus an "All states" value to cover workers from outside these 4 states. Three water areas were identified (could see wellhead, offshore, near-shore), and the latter 2, as well as land work, were associated with the 5 state possibilities (workers who could see the wellhead were outside of state waters). All of the above were considered for the 7 time periods. This resulted in a total of 3420 possible EGs for inhalation that were evaluated for exposure. Supplementary Tables S3a–e summarize the specific jobs/activities/tasks for the rig vessels; ROV vessels; RVs; fire control vessels; and for other vessels and land. The other vessels and land activities/tasks are presented in one table because some of the EGs were associated with water, some to land, and some to both. For example, decontamination of a vessel occurred near shore and at ports and docks; the appropriate measurement data were used for each area.

In Table 4, we present the number of study participants by broad type of activity, state, and time period. An individual could have performed more than one activity within a broad type, but was only counted once for the broad type. Individuals could have been counted in multiple broad types and time periods. The broad group "response" had the fewest number of study participants of the groups presented (513–2065 depending on the time period). The numbers of workers offshore and the numbers near shore were similar for each state and time period (over all states 569–8352 and 457–8892, respectively, depending on the time period). The number of participants on land was greater than that on water, with beaches and

Table 4. Number of study participants by broad groups of activity and gulf area.

	Number of study participants[1]						
Broad category	**TP1a**	**TP1b**	**TP2**	**TP3**	**Tp4**	**TP5**	**TP6**
Response	**513**	**2065**	**1245**	**1255**	**591**	.	.
Clean-up on water	**4635**	**17 244**	**13 777**	**13 652**	**7711**	**1403**	**771**
Offshore	**2395**	**8352**	**6730**	**6709**	**3952**	**569**	**314**
AL	452	1582	1202	1166	654	74	41
FL	276	1150	868	828	408	60	34
LA	838	2588	2244	2301	1509	227	135
MS	342	1237	961	955	587	107	61
Other	487	1795	1455	1459	794	101	43
Near shore	**2240**	**8892**	**7047**	**6943**	**3759**	**834**	**457**
AL	465	1769	1344	1262	616	123	72
FL	307	1301	1000	955	430	107	53
LA	765	2675	2333	2346	1489	324	184
MS	346	1357	993	981	545	150	81
Other	357	1790	1377	1399	679	130	67
Clean-up on land	**5082**	**27 124**	**22 128**	**22 897**	**14 855**	**6262**	**3220**
Beaches & marshes	**1052**	**9924**	**8289**	**8596**	**5655**	**2691**	**1479**
AL	130	2087	1725	1772	1182	672	398
FL	103	2846	2376	2367	1383	638	336
LA	428	1706	1491	1611	1188	511	276
MS	89	1528	1298	1329	944	478	267
Other	302	1757	1399	1517	958	392	202
Ports & docks	**1204**	**8830**	**7164**	**7801**	**5103**	**1883**	**664**
AL	240	1842	1483	1604	1072	490	202
FL	185	1958	1575	1636	955	275	101
LA	388	2030	1656	1813	1292	460	162
MS	159	1277	1078	1199	846	364	141
Other	232	1723	1372	1549	938	294	58
Other land	**2826**	**8370**	**6675**	**6500**	**4097**	**1688**	**1077**
AL	483	1259	997	969	646	271	179
FL	405	1392	1090	1054	616	268	183
LA	751	1775	1408	1405	1020	414	263
MS	286	910	711	695	456	180	112
Other	901	3034	2469	2377	1359	555	340

AL: Alabama; FL: Florida; LA: Louisiana; MS: Mississippi; Other: other US state, excluding AL, FL, LA, and MS. TP: Time period. See Table 1.
[1]Participants reported an average of 9 (median = 6) job/activities/tasks. In each broad category, a participant is counted once, regardless of the number of jobs/activities/tasks that fit the category; a participant; however, may be counted more than once if his/her jobs/activities/tasks fit more than one category.

marshes being the area generally with the largest number of participants (1052–9924). The pattern of workers for each of the 3 land areas by state and time period, however, was similar to those on the water. For all areas, TP1a was generally characterized by the smallest number of workers and TP1b, the largest. LA was the state with the highest number of workers within each category.

After assigning the EGs to the measurements, many jobs, activities, and tasks had at least 20 measurements (some, hundreds) but others had substantially fewer. Although over 55% of the EGs were linked to at least 20 measurements, almost 15% had fewer than 10 measurements. As a result, 71% of the estimates for the EGs (43–95% by analyte) met the Bayesian performance goal of <15% and <65% average relative bias and rMSE, respectively (Stenzel, Groth *et al.*, 2021). The percent of THC, toluene, and xylene AMs that met the study criteria was 95, 87, and 90%, respectively, whereas benzene, ethylbenzene and n-hexane had the lowest percent (43, 56, and 55%, respectively).

Discussion

The goal of systematically developing our exposure groups was to have transparent and precise groups to allow the same EGs to represent all exposures of interest and to link air measurement data to our study participants. While estimation of exposures is an important component of an exposure assessment, also important is the development of appropriate EGs that link the study participants to exposure levels, typically via a JEM. We describe here the development of EGs used in the JEM, based on determinants that were expected to have affected exposure levels, to increase our chances of identifying workers who had similar distributions of exposures.

Development of EGs can be a complex process because of the need to reconcile information on the study participants' activities with the measurement data documentation to allow the appropriate assignment of measurement metrics and to distinguish among different groups of workers. We were unable to take the typical approach in epidemiologic studies of basing our EGs on job title, department, or facility, because relatively few job titles were identified in the measurement database, there were no departments or facilities, and work history records were not available to us. We, therefore, started our development of EGs with the evaluation of several potential determinants (Table 1) associated with the agents of interest, and the workplace, work practices, and work force. Only a limited number of these determinants, however, were identified in the monitoring data.

We, therefore, collected information from study participants in terms likely used by those participants but that still allowed us to make the link to the measurement data. We identified as determinant values, job titles, and rig vessels for the rig workers because of differences in emission points and location in relation to the wellhead. We resorted to specific vessel names for determinant values for other specific types of vessels in the hot zone and source that had different emission points but could not include jobs because we had not collected that information from the study participants. Because of the remaining thousands of vessels for which we had little to no information on each vessel's specific activities, locations or dates, we used vessel activities as determinant values. Similarly, for land, we used activities to represent emission points and locations. Time was important as it reflected both oil weathering and the various events (reflecting differing emission points) that occurred over the study period. Probably the most important event was the oil release in the first two time periods in contrast to the oil being contained in the remaining 5 time periods. Two other important events were the use of dispersant and the burning of oil/gas in the first two time periods. The importance of the remaining time periods was primarily due to further weathering and the start and cessation of the various activities.

Oil weathering was a major contributor to THC and BTEX-H exposure levels over time and space. The weathering process is extremely complex, and it is difficult to accurately quantify the degree of weathering at any specific point in time and space without laboratory analyses of the crude oil. We had no measurements of weathering in the oil with which specific workers had come into contact. We, therefore, used the agents' chemical and physical properties (vapor pressure, molecular weight, and percent composition) to estimate the effect of weathering over time and space and identified determinant values that reflected weathering. Estimates were developed for distances from the wellhead (by our 3 areas of the Gulf and the 4 Gulf coastal states), and for time, by our 7 time periods.

Our EGs, then, were primarily unique combinations of job/activity/task, location (i.e. vessel, type of vessel, area of the Gulf and coastal state), and time period. Our goal was to systematically develop EGs as precisely as possible. The EGs were systematic in that we considered the same set of potential determinants for each EG and then related them to possible study determinants. Further, we reviewed the multiple data fields associated with each measurement result in the measurement database and the THRs and assigned all EGs that the measurement could be reflecting.

Our goal of precision was, however, constrained by our data. First, we had study participant-specific information only from an interview, and so were limited in the interview, both in terms of time (the occupational component took 20 min of up to a 1-hr interview) and in terms of information that could be asked of the participants. For example, participants involved in the various clean-up activities generally moved around and would not have been able to identify every location on every day. The second constraint was related to the size and censoring of the EGs' measurements we accepted (Stenzel, Groth *et al.*, 2021) to meet the bias and imprecision goals of the study. As a result, there likely were other determinants that we did not consider. For example, workers decontaminating vessels likely varied in work practices and chemicals used, which, had we had the information in the measurement database, may have allowed us to distinguish among these various workers with further precision. As a result, several of our EGs had higher GSDs than expected. The high GSDs may, in part, be because most activities were performed outdoors. It is also possible that we did not identify other important determinants and so the EGs contained workers with different exposure distributions. Fortunately, the simulation work of Huynh *et al.*, 2016 demonstrated that with the criteria of $N \geq 5$ and censoring <80%, our Bayesian method still achieved our performance goal even with mixed distributions. Furthermore, it appears that we identified at least some of the major determinants as evidenced by our findings of credible differences in the THC AMs for the broad types of workers and vessels (Huynh *et al.*, 2021a,b,c; Ramachandran *et al.*, 2021).

We also found that 71% of the estimates for the EGs (43-95% by analyte) met the Bayesian performance goal of <15% and <65% average relative bias and rMSE, respectively (Stenzel, Groth *et al.*, 2021). The percentage of estimates for which we used our Bayesian method despite not meeting our performance goals was 15%. The methods used to address the remaining 14% of the EGs where the data were completely censored are presented in Stenzel, Groth *et al.*, (2021). This result provides confidence that our exposure estimates accurately reflect the measurements they represent.

The number of study participants varied considerably across broad activity group, state, and time period, but generally was the lowest in TP1a and highest in TP1b, as expected. The response effort had the fewest number of people, while beaches and marshes generally had the highest number of workers.

Limitations of this work included our inability to observe workers performing the OSRC work, because by the time the study exposure assessment was initiated in November 2010, most of the OSRC work had already been completed and exposure measurements already collected. Additionally, most of the larger ships had already left the area, and fishermen and many land workers had been released from work by the RP. During four site visits to the Gulf we met with about 100 OSRC workers but these workers were involved in only a small subset of the activities, tasks and locations worked during the OSRC effort. It is not known if these workers were study participants. We had available, however, hundreds of spill-related reports and photographs.

Another limitation is that we had to develop the occupational component of the questionnaire shortly after starting the exposure assessment effort. Although we were able to add some questions as our understanding of the clean-up effort grew, we also were required to simplify the interview to address concerns about respondent frustration and attrition. The questionnaire had to ask questions that the study participants were able to answer while allowing us to link their responses to the measurement data, but the questionnaire had to be completed before we had developed our exposure assessment methodology. Also, we did not ask the participants in which areas they performed specific activities even though there were notable differences among the areas (Huynh *et al.*, 2021a,b,c). The questionnaire comprised over 400 questions on the occupational part alone; asking about the area where each activity was done was considered too burdensome to the study participants. We were able to consider the 3 Gulf areas (wellhead, offshore, nearshore) unrelated to any specific activity, however, which provided the area where some water-based participants were located. Furthermore, we had only limited time to research the OSRC conditions. We, therefore, primarily relied on the extensive air measurement database provided by the RP to identify study exposure determinants and used those determinants as the basis for the interview questions. This database may have missed important exposure scenarios, so we asked open-ended questions of the participants to collect information on activities not specifically queried. We later reviewed the responses and found a small number of activities compared to the overall number of activity/tasks performed, and these were generally the lower exposed activities (e.g., kitchen worker, security), which we added to our EG list. Open-ended questions, however, can result in respondents providing information on what they think of as important, which may not be important to exposure assessment. Alternatively, respondents may fail to report an important event because of forgetfulness or because they don't think of it as important. For this reason, we conducted an extensive research effort of hundreds of documents developed on the disaster, but we found no additional EGs that we had missed. We also were limited in our determinants by other constraints of the study. We did not expect participants to know the degree of weathering that had occurred in the oil or tar with which they had come into contact and so used chemical and physical properties to identify surrogates of the distance from the well, state, and time period.

The strengths of this effort include a systematic and detailed review of the documentation of every measurement, including the thousands of THRs and the many other records available to us. We chose to develop many specific EGs, rather than a few broad EGs, in part, due to the large number of measurements available and the complexity of the exposure situation and for coverage of all exposures of interest. Fewer EGs could have resulted in more precise exposure estimates at the cost of combining groups of workers who may have had statistically different exposure levels, as evidenced by our analyses of the broad groups of rigs, ROV vessels, RVs, other vessels, and land described in Huynh *et al.*, (2021a,b,c) and Ramachandran *et al.*, (2021), which would have increased error in the assignment of exposures. In addition, it is much easier to group multiple EGs in an epidemiologic analysis than to later go back and develop smaller EGs. Given the large number of participants, the large number of measurements, and the extensive health information collected that may lead to investigation of different exposure hypotheses in the epidemiologic analyses, we chose to provide flexibility in our EGs over statistical precision.

Conclusion

We used exposure determinants to develop exposure groups to link our study participants to the measurement data, primarily using participant-self-reported activities on the water and on land. We found oil weathering was likely to be a major determinant of THC and BTEX-H exposures, but as study participants were likely unable to identify the degree of weathering the oil with which the participants had contacted, we used the proxies of location in the Gulf and time period. Location covered 3 general areas of the Gulf of Mexico and 4 Gulf coastal states. Seven time periods incorporated oil weathering but also the various events that occurred over the study period that likely affected exposures. Over 3000 EGs were developed that were used for the THC and BTEX-H and a subset of these for $PM_{2.5}$, dispersant components and oil mists. The determinants identified at least some of the variability in the measurements as indicated by our findings of credible differences (statistical differences in a Bayesian context) among the AMs of EGs based on the various determinants for THC. The differences should increase the chances of finding associations in the exposure-response investigation of the epidemiologic analysis should they exist.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article will be shared on reasonable request, consistent with protections for the privacy of study participants and existing multi-party agreements. Requests should be made following instructions on the study website https://gulfstudy.nih.gov.

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