

The **World Trade Center** **Aftermath** *and Its* **Effects** *on* **Health: Understanding** *and Learning* *through* **HUMAN-EXPOSURE** **Science**

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Survivors of
the 9/11 WTC
collapse were
blanketed
by dust and
smoke.

The principles of human-exposure science are important for identifying and mitigating environmental-health problems. They permit the acquisition of knowledge to understand the environmental-health consequences of single and multiroute contacts with toxicants. Although a relatively young field, human-exposure science “is the study of human contact with chemical, physical, or biological agents occurring in their environments, and advances knowledge of the mechanisms and dynamics of events either causing or preventing adverse human health outcomes” (1). As such, it should be central to the mitigation of exposures during and after catastrophic events such as the attack on the World Trade Center (WTC).

Historically, a variety of conventional approaches have been used for measuring the “quality” of the environment. For example, air and water analyses have been used as surrogates for exposure when environmental risk-management decisions are made. Such efforts have been successful in understanding potential exposure to chemical, physical, or biological agents in situations when the agent is emitted by numerous sources or when there is an overwhelming contribution from a specific source or source types.

The greatest difficulties associated with such strategies are defining the exposures that result from emissions by small, specific sources; intermittent sources; and/or acute toxic events. Typical attempts to examine these events have used “least-case” or “worst-case” exposure-characterization scenarios during the development of management decisions. Unfortunately, such scenarios usually lack a realistic scientific foundation for providing a practical solution, and they do not appropriately address the individual’s or community’s concerns.



Although still in its infancy, human-exposure science is a key to understanding environmental and health consequences of disastrous events such as the 9/11 terrorist attacks.

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From 1970 through September 11, 2001 (9/11), the focus of environmental protection in the U.S. moved from primarily regulating short-term pollution to estimating the lifetime cumulative exposures and reducing long-term health effects. The approach has been used for many toxicants found in air, water, and food. A recent draft document by the U.S. EPA describes how to look more closely at the different layers of cumulative exposure to and risk of environmental contaminants, but it still focuses primarily on long-term health outcomes (2). Unfortunately, the major exposure and health issues associated with the 9/11 WTC terrorist attack resulted from acute or subacute exposures that did not fit neatly into this working model of environmental health. In addition, the alkalinity of the cement and glass-fiber mixture led to health effects that were higher than expected (3).

environment and to a biologically relevant duration of contact (4). Thus, characterization of exposure goes beyond the simple application of exposure multiplied by time. A critical value of concern is time, the duration of exposure relevant to the concentration present for each route of contact and to the health effects (5).

In the case of the attack on the WTC, duration of contact and health issues were complex. They still need more global understanding if the U.S. intends to establish a credible path forward for addressing exposures from such events in the future. Negative acute health outcomes have already been documented for responders, and concerns have been raised about their long-term health outcomes. These findings have prevented WTC-exposed populations from achieving closure, thereby prolonging the recovery (3). If the nation is to minimize the potential for this

happening in a future disaster, it must evaluate past inadequacies; establish credible, realistic exposure-response evaluations for the future; and develop effective prevention strategies, including when and where avoidance or respirator use is mandatory for the local community as well as responders.

In this article, we discuss the issues associated with application of the conventional environmental measurements to the WTC aftermath as surrogates for exposure, how the divergent exposure periods cascaded into unusual adverse health observations, and the degree of follow-through on the lessons learned from the WTC episode.

Exposures caused by the events of 9/11

The exposures that occurred post-collapse must be placed into a temporal perspective. In contrast with typical environmental source emissions, the time course of exposure for the emissions from within and around the 16-acre site of the WTC collapse (Ground Zero) had five distinct categories. Each category had different spatial and temporal scales, levels and types of gases and particles emitted, and exposure groups and activities (3, 6, 7). These have been described previously, and a synopsis of the 5 categories is found in Table 1 (3, 6, 7).

The most intense period of exposure was during the collapse and the next 12 h (Category 1; 3, 6, 7). At that time, as seen in many pictures and video clips, southern Manhattan was enveloped by unprecedented concentrations of dusts, smoke, and gases. This yielded a very intense period of particle and gas

TABLE 1

Sequence of environmental and occupational exposures

Category	Time period for categories of exposure	Predominant sources of pollution	Pollutants and pollutant classes	Primary exposure groups
1	First 12 h post-collapse (9/11)	Collapse of Twin Towers Burning jet fuel Building fires Resuspended dust and smoke	Combustion products Evaporating gases Gaseous, fine, and supercoarse particles	WTC workers Local employees Local residents Commuters Rescue workers Fire and police Federal law enforcement Press
2	Days 1.5–2	Burning jet fuel Building fires Resuspended dust and smoke	Combustion products Evaporating gases Gaseous, fine, coarse, and supercoarse particles	Rescue workers Fire and police Federal law enforcement Local residents Press
3	Days 3–13	Smoldering fires Resuspended dust and smoke	Combustion products Gaseous, fine, and coarse particles	Recovery workers Construction workers Local residents Fire and police
4	Day 14 through Dec 29, 2001	Smoldering fires Debris removal by trucks and equipment	Combustion products	Recovery workers Construction workers Local residents Fire and police
5	Indoors: 9/11 through ?	Resuspended dust and smoke	Supercoarse particles Some fine and coarse particles	Cleanup workers Local residents Employees Building visitors

Specific applications of human-exposure science must link results effectively with potential health outcomes. This was articulated in the 1991 National Research Council (NRC) report *Human Exposure Assessment for Airborne Pollutants*, which tied contact with an agent to the concentrations found in the en-

exposure to residents, commuters, and rescue personnel in southern Manhattan, which is graphically illustrated for immediate survivors in the photo on page 6876. Dust and smoke were deposited on the ground and surfaces both outside and inside offices, businesses, and residential buildings. High levels of smoke and resuspended material continued 10–12 h post-collapse, and the dust and smoke associated with the collapse covered most of lower Manhattan and sections of Brooklyn.

The event progressed to a 2-day period of exposure (Category 2), during which the previously deposited large and small particles were resuspended around southern Manhattan, and gases and fine particles were emitted from intense fires at Ground Zero. Rescue personnel inhaled these emissions. This exposure was complicated by brief plume impacts at various locations within and outside of southern Manhattan.

It rained 4 days after 9/11, washing much of the resuspendable material from outdoor surfaces in downtown Manhattan. The fires weakened, and on September 17, fires burned at 16 specific locations at Ground Zero. From September 15 until the second rain, on September 25, parts of the area still had occasional instances of resuspended dust and smoldering fires but yielded much less intense exposures (Category 3).

From September 26 until the fires burned out in late December (Category 4), smoke plumes that emitted fine particles and gases were noticeable on some days, and debris removal continued to resuspend particles at Ground Zero. However, outside of Ground Zero, where most air sampling was occurring, the air was returning to typical New York City (NYC) levels (3).

One difficult problem remained: the dust that had settled within offices, businesses, and residential buildings (Category 5) was a source of considerable concern to the local community. Ongoing cleanups and demolitions continue to fuel concerns about recontamination that may lead to persistent WTC indoor dust and chronic health outcomes. Despite considerable debate, no agreement has been reached on how to effectively determine whether WTC dust persists indoors or whether it is at levels that have the potential to cause new health conditions or exacerbate preexisting ones.

The settled dust generated during the WTC collapse was characterized in detail, but the overall message associated with exposures and health outcomes has not been thoroughly understood by the scientific community. Further, the U.S. population has not been informed about how to respond in the future to a WTC-type event. For instance, 5 yr after the attack, many people still do not know that the complex mixture of dust and smoke initially sus-

pended in the air remains somewhat of a scientific mystery, because its composition and the concentrations and exposures caused by the gaseous species will remain unknown (7). The gases were not measured in Manhattan during the initial hours post-attack; the measuring devices were just not available. Thus, nobody knows how the gases intermingled with the dust and other combustion products to cause exposures to a complex mixture among rescue workers, firefighters, and others within and around Ground Zero for the next 24–48 h and intermittently thereafter when confined-space air pockets were explored.

This major information gap could not be filled by the asbestos measurements made during the first 48 h post-collapse (8). Numerous investigators and agencies—for example, the U.S. Geological Survey (USGS) and the Agen-

cy for Toxic Substances and Disease Registry (ATSDR)—collected settled dust samples, which provided information on particle size and composition outdoors and indoors but not on the gases contributing to human exposure during the Category 1 and 2 periods (9–13).

EPA began planning its response immediately after the collapse. However, because the situation was a complicated crime scene, war zone, and rescue operation, the long-term sampling only started on September 21. A wealth of ambient gaseous and fine-particle air-quality data was collected by EPA from September 21 through December 20, 2001, (Categories 3 and 4) and beyond. Other groups, including universities supported by the National Institute of Environmental Health Sciences, collected ambient air data primarily during that time. A few volatile organic compound measurements were made by EPA Hazmat teams and Occupational Safety and Health Administration (OSHA) personnel between September 13 and 25 (Category 3; 14–16). The question still remains: how can such significant and important gaps in data be prevented in the future during a sudden attack or other disaster? Even before such data acquisition and analysis are complete, however, realistic, rather than politically driven, policies and procedures must be in place to protect workers, volunteers, and residents—by exposure avoidance or by respiratory protection in the affected area(s).

Eventually, conditions reverted to smoldering fires and recovery-vehicle emissions, and measurements were available for gases and fine particles (Category 4). The good news that was lost during post-9/11 reporting was the speed with which the ambient air reverted to typical NYC urban levels during October and November 2001 (3). However, many recovery workers, volunteers, and residents deemed this information irrelevant, because they were understandably more concerned with exposures in their work and living spaces.

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Composition of settled dust

Details on the composition of material measured in the air within and around Ground Zero have been evaluated according to the date that different types of samples were collected post-9/11. One important observation was that the nature of the materials measured outdoors changed over time (3, 6, 7). The initial post-collapse period included both dust (initial and settled) and combustion products (gases and particles) (13–15). The environmental science community has been slow to understand that the acute health effects were attributable to a complex mixture of gases and particles and that the particles in greatest abundance (mass) in the dust were the unregulated supercoarse ($>10\text{-}\mu\text{m}$ -diam) particles, not the fine ($<2.5\text{-}\mu\text{m}$ -diam) or coarse ($2.5\text{--}10\text{-}\mu\text{m}$ -diam) particles that are typically measured.

TABLE 2

Contribution of various particle-size ranges to WTC settled dust in indoor and outdoor samples (9, 11)

Particle diameter (μm)	Indoors (%)	Outdoors (%)
<2.5	0.40–0.80	0.88–1.33
2.5–10	0.20–2.30	0.30–0.40
10–53	20.1–78.5	34.6–46.6
>53	19.1–79.1	52.2–63.6

Table 2 shows that the settled dust did contain the fine and coarse particles that are part of the U.S. regulatory paradigm. However, these mass fractions were dwarfed by the other ~98% of the material that was in the dust: the supercoarse particles. This should not have been a surprise, because WTC dust (coated with chemicals of potential concern) was a complex mixture generated initially by building collapse/pulverization, incomplete combustion, and subsequently resuspension. This observation is important, because $10\text{--}50\text{-}\mu\text{m}$ -diam particles are deposited in the nasal passages and will penetrate farther into the upper and lower respiratory system when the exposure is intense (17, 18).

Unfortunately, the supercoarse particles are not measured by outdoor monitors, and the amount of supercoarse particles that were aerosolized on 9/11 cannot be quantified by laboratory resuspension or aerosolization of sedimented dust mixtures collected days later. The lack of air measurements for even a portion of the supercoarse particle fraction during the various stages post-9/11 is confusing, because the material burning and/or resuspended within Ground Zero was a complex mixture, the fires were uncontrolled, and the mass of these materials was significant. Samples collected during the Category 3 exposure period by OSHA, and by Geyh et al. in October from recovery truckers (Category 4) within Ground Zero, found peak total particle levels of $>15,000$ and $300\text{ }\mu\text{g}/\text{m}^3$, respectively (8, 19). However, these data were never totally considered in the

post-9/11 advisories. In 39 firefighters with significant WTC exposure, Fireman et al. found significant amounts of both fine and supercoarse particles in induced sputum (mid- and lower-airway sampling), with a size distribution and composition similar to WTC dust (20).

Although it is now understood that specific types of personal and stationary monitors (e.g., portable, chemical-specific, or material-specific) need to be made available and placed in strategic locations, a solution for measuring supercoarse particles still needs to be provided by EPA, OSHA, or the U.S. Department of Homeland Security (DHS) (21). And, 5 yr later, short-term acute exposure standards do not exist and clearly defined monitoring plans for WTC-type emissions (e.g., cement and fibrous dusts) have not been presented.

Indoors, the main issue was the presence and persistence of the settled dust and smoke, the amounts of which initially varied because of geographic factors (distance and elevation from Ground Zero), wind and weather conditions, and penetration (open windows and vents; architectural damage; and heating, ventilating, and air conditioning systems [HVACs]). Over time, the levels varied with the effectiveness of the indoor cleanups performed by residents, organizations, and EPA (22–25). These concepts need to be examined in preparedness exercises and in the education of the scientific community and the general public. Presently, no national protocol exists for systematically establishing the hazardous extent of indoor/outdoor contamination (walk-through/sample/analyses) after an event. In addition, no protocol exists for assessing cleanup effectiveness. EPA developed cleanup methods over a relatively short period of time, and indoor cleanups were performed (24, 25). However, the lessons learned from the cleanups need to be systematically evaluated, and protocols need to be refined, where necessary, to address future events that contaminate indoor settings. Another issue is how to define a contaminant-safe home. Clearly, the task was daunting, and EPA applied best-available practices, but the agency was limited by weak databases available for deriving air and dust clearance values for homes and other buildings (24).

Indoors, the persistence of the settled dust depended upon the quality and completeness of the indoor cleanups. However, credibility issues remained because HVACs received little attention, and those areas cleaned by different organizations were subject to varying levels of quality assurance (24). Because of claims that the volunteer cleanup was inadequate, a technical advisory board was formed in 2004 to help EPA define a sampling program for the continued presence of WTC dust. Initial plans to focus solely on asbestos-fiber measurements as a surrogate for persistent WTC dust were abandoned when the advisory board determined that the amount of asbestos was too low compared with the background to enable an accurate examination of the geographic area in question to be made. Deliberations centered on the geographic area of concern, chemicals of potential concern, and health outcomes related to WTC dust. These efforts were severely hampered by in-

complete data on current indoor dust exposure and the spatial extent of the dust indoors immediately after 9/11. To date, consensus has not been reached on a systematic plan for indoor sampling, cleanup, and quality-assurance testing, but such plans are needed for disaster preparedness.

Patterns of exposure

Analysis of the patterns of population exposure that occurred during and after the WTC event is still needed. The lack of a clear characterization of the patterns of contact with gaseous and particle species and the patterns of dust deposited after the attack made it difficult to understand the variability in human exposure, with and without respirator use, to substances released during each exposure-category period. Such an understanding is essential for developing a new level of preparedness for terrorist attacks or accidents. Data have come from various health studies: the Fire Department of NYC (FDNY) Bureau of Health Services (BHS) WTC medical monitoring and treatment program for FDNY rescue workers; the Mount Sinai Medical Center monitoring and treatment program for non-FDNY responders, workers, and volunteers; studies of pregnant women conducted by the Mount Sinai Medical Center and Columbia Presbyterian Hospital; and the NYC Department of Health and Mental Hygiene WTC Health Registry (26–28). Each focused on a particular period of post-9/11 exposure and attempted to characterize the contact in space and time in combination with human-health effects. For FDNY workers, the time of their arrival at Ground Zero was coupled with the duration of their rescue activities to estimate exposures (26). In the WTC Health Registry study, an individual's location during the first few hours after the event was used to determine his or her level of acute exposure (28).

Data compiled on pregnant women during the first 30 days post-collapse were coupled with the exposures that occurred during that period at various locations at or away from Ground Zero (27). The results from a model of the plume intensity and direction were used to develop an exposure index (27). These data could be evaluated and coupled with prospective preparedness analyses based on the material distributed throughout southern Manhattan (Categories 1–3). This type of estimate could be used prospectively to assess how long people would be in harm's way and what activities should be implemented in the future to reduce exposure and disease incidence for similar toxicants.

Health effects

Before 9/11, risk assessments that could be easily applied to the WTC attack were primarily for long-term

health effects and typical environmental agents (23, 29). EPA's risk assessment for 9/11 acknowledged the lack of health-based outcome information on acute exposures to the airborne materials during the first few days post-9/11 (Categories 1 and 2).

The major health consequences of WTC exposure have been aerodigestive and mental-health-related illnesses. The WTC aerodigestive inflammatory syndrome consists of "WTC cough", irritant asthma or reactive airways dysfunction syndrome (RADS), rhinosinusitis or reactive upper-airways dysfunction syndrome (RUDS), and gastroesophageal reflux disorder (GERD). Mental-health disorders have primarily consisted of posttraumatic stress disorder (PTSD), anxiety, and depression (30).

Currently, the National Institute for Occupational Safety and Health funds two WTC medical screening/monitoring and treatment programs—the FDNY BHS program and the Mount Sinai Center for Occupational and Environmental Medicine program. Each monitors ~14,000 rescue and recovery workers, and each has reported similar findings. The FDNY BHS WTC medical monitoring and treatment program found that during the first week post-exposure, 99% of 12,000 FDNY fire and rescue workers reported at least one new respiratory symptom. Six months later, 38% still reported a severe cough and 25% reported persistent and severe nasal/sinus congestion. Of those with persistent respiratory symptoms, 85% reported new or increased GERD.

Biomonitoring of blood and urine specimens from WTC-exposed FDNY rescue workers revealed elevated levels of combustion byproducts that were of statistical but not clinical significance (31). Biomonitoring should be considered a priority in future types of events. Large, supercoarse particles consistent with WTC dust were obtained from bronchoscopic lavage (20, 32) and induced sputum of FDNY rescue workers. In the first 6 months, 332 firefighters

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required extensive medical leave for "WTC cough" (26). Five years later, >3000 FDNY firefighters have been treated for respiratory disease and >600 (~5% of the exposed workforce) have qualified for permanent respiratory disability benefits (3–5× the pre-9/11 rate).

The FDNY BHS WTC medical monitoring and treatment program compared post-9/11 and pre-9/11 data and demonstrated clinically and statistically significant pulmonary function declines above those expected for normal aging (33). More than 25% of those tested who sustained high exposure during Category 1 or 2 exposure periods had demonstrable airway hyperactivity (26, 34) that persisted for at least 2 yr, consistent with asthma or RADS (35). Respiratory symptoms, pulmonary function decline, and airway hyperactivity correlated with

exposure intensity in a dose-dependent fashion (26, 34). Chest imaging and related studies have also demonstrated rare but increased incidences of unusual lung diseases, such as eosinophilic pneumonia (32) and sarcoidosis. In the future, researchers and agencies must determine how to evaluate and mitigate acute exposures to supercoarse alkaline and glass-fiber particles as well as cogaseous and fine-particle species.

Mount Sinai has found similar results in its cohort to those originally reported in the FDNY cohort. Mount Sinai found that nearly three-quarters of its cohort reported new or worsened upper respiratory problems while working at Ground Zero, with half presenting upper and/or lower respiratory symptoms persisting up to the time of their examinations, at least 1 yr later (30). In addition, more than half had persistent psychological symptoms, with risks for PTSD 4× the rate in the general male population (30). Recently, Mount Sinai reported its findings in 8000 non-FDNY WTC rescue workers and volunteers (36). Seven out of 10 reported new or worsening respiratory symptoms persisting several years after 9/11. Pulmonary functions demonstrated greater reductions than expected in either normal or cigarette-smoking populations. These findings corroborate its initial publication in the *Morbidity and Mortality Weekly Report* and the studies already published by FDNY and the WTC Health Registry (36).

The WTC Health Registry includes >70,000 workers and residents and has recently reported similar findings with increased symptom reports of aerodigestive and mental health illness in nearly 8500 survivors of the collapse (28). A population-based survey among residents of lower Manhattan (some of whom are in the WTC Health Registry) has found higher rates of respiratory symptoms in previously healthy persons, worsened asthma control in previously asthmatic individuals, and lower peak flow rates, in conjunction with worsened asthma control, in pediatric asthma patients. However, the spirometry results were not different between controls and the affected individuals (37).

Implications

Although the lack of data precludes quantitative exposure characterizations for most people, unprotected firefighters and rescue workers were exposed to significant quantities of gaseous (uncharacterized) particles and particles of various sizes during at least the first 48 h post-9/11 (Categories 1 and 2). Further, model simulation results on the WTC

plume should be fully used in preparedness exercises to fill gaps in exposure characterization (38). But, how can the U.S. also use all WTC results to prospectively characterize the hazardous situations and activities that can occur in the future? For this, the country needs to understand the post-collapse exposure scenarios more clearly, and then develop criteria and protocols for evaluating the potential magnitude and extent of exposure for people in harm's way. Initial applications can be provided in multiagency preparedness exercises and develop-

ment of new exposure tools to assess the severity of the situation for high concentrations of a variety of materials.

To date, most preparedness exercises deal with emergency-response activities and medical and law-enforcement response to biological and chemical events. Frequently, however, they do not simulate realistic human activities that can occur during an event or determine how such activities may lead to acute or chronic exposures and health effects. In addition, they do not provide guidance on how to systematically define and measure the horizontal, vertical, and actual extent of contaminants after an event. Even DHS's Top Official (TOPOFF) exercises did not have realistic expectations for typical human-activity patterns during a terrorist event. Thus, pro-

spective human-exposure-science simulations need to be planned and completed to fill this void (39). The Urban Dispersion Study experiments in NYC, which were conducted to examine the meteorology, concentrations, and exposures after a simulated release, were a start, but they were discontinued by DHS before all field studies were completed (40).

A detailed evaluation of the measured and modeled (computer and physical) environmental and occupational WTC exposures can provide information to reconstruct the intensity of exposures that occurred among the various segments of the population. A report on the above could educate us all. Unfortunately, to date, the general evaluations of the WTC collapse have focused primarily on problems identified in an EPA Office of Inspector General (OIG) report (22). This should not be the legacy of the WTC event left for use by the environmental-health community.

The aftermath of the WTC attack also showed that a series of very rapid decisions need to be made about what can and should be monitored to assess acute exposures and whom is at highest risk. The WTC experience provides data to create monitoring plans appropriate for both the environment and ex-



Unprotected firefighters and rescue workers were exposed to significant amounts of uncharacterized particles following the WTC collapse.

posed populations (responders, workers, volunteers, and residents). As stated previously, this critical issue has received little public attention and must be addressed in preparedness activities to define who will be in harm's way, and where and why. Table 1 shows examples of such populations during 9/11.

Given the health effects, one issue that should have been obvious after 9/11 was the need for a rapid characterization of the total (alkaline) dust. Because exposure and environmental-health scientists were still thinking in the "pre-9/11 world" on the day of the event, most of the initial measurements were made for asbestos. This was reasonable considering the frame of mind, but asbestos was not the most immediate problem. In the future, "unrestrained" thinking should be applied when addressing catastrophic events. For example, an agent that results in acute exposures and health effects should be examined first, not an agent that takes many years to manifest its health effects.

The measurements made on the settled dust indicated that exposure and environmental-health scientists should be concerned about the composition of the initial dust that was settling out "on" and "overwhelming the lungs of" individuals in lower Manhattan during the first few hours post-event (9, 11–13). These results eventually sharpened researchers' focus on the potential for the acute health outcomes among individuals in harm's way during Category 1 and 2 rescue efforts (3, 6, 7). Acute exposure concerns were redirected to effects caused by high pH, mass, and the presence of cement and glass fibers, although the gases associated with the fires were still unknown (9). Overall, the health focus was first the acute exposures and then both short- and long-term health effects. However, the general environmental-health community is drifting back to business as usual, and we remain concerned that, over time, WTC-related exposures, health concerns, and developing new standards in response to this disaster will no longer be a top priority.

Efforts must be made to standardize and optimize approaches for avoidance, reentry, respirator use, and exposure reduction, and to establish clearance standards for materials that could be encountered indoors after an accident or a deliberate release (21). The supercoarse particles encountered during 9/11 could be encountered again, but so could other materials, including nonvolatile and semivolatile chemicals, biological agents, and radiation deposited indoors. However, exposure scientists should recognize that the issue of indoor contamination must be considered after an event, and not just from the perspective of air measurements. Unfortunately, the environmental managers have not yet taken heed of the events of 9/11 and used the EPA efforts to start developing a consistent suite of environmental testing and cleanup guidelines for indoor dust contamination to deal with multiple types of interventions.

The opportunity to characterize the gaseous component after the WTC collapse was lost during the first few hours. The magnitude of the fire and its composition most likely changed in char-

acter over this short time. The initial exposures to the complex mixture that irritated the lungs of rescue workers and firefighters would have been high. The question remains: where does the U.S. stand in the development of protocols for real-time, portable personal samplers to reduce this gap in exposure information?

In the months after 9/11, dust that settled either indoors or outdoors became the concern. However, the only health-based clearance values available for settled dust were for lead, dioxin, and PAHs, and these were only minor constituents of the deposited dust. The highly alkaline cement and vitreous fibers that composed the vast majority of the mass had no health-based clearance values. Such guidelines need to be established for indoor and outdoor surfaces for multiple substances.

The NRC Subcommittee on Acute Exposure Guideline Levels (AEGs), Committee on Toxicology, has developed AEGs based on a list of extremely hazardous substances. The 4 volumes that have been released include level 1, 2, and 3 AEGs, which cover acute community exposures of 10 min to 8 h for ~30 chemicals (41). Guidelines should also be developed for alkaline dusts, or WTC-type dusts, especially the supercoarse particles.

Future recommendations

Disaster planning should be based on lessons learned from WTC-related human-exposure science about the differences and similarities between the nature and intensity of exposure during rescue, recovery, and cleanup operations; acute versus chronic exposures; first responders and other rescue and recovery workers; workers, volunteers, and residents; adults and children; and those with and without preexisting disease or comorbidity. For example, first responders are typically better trained, have personal protective equipment (PPE), and are less likely to have preexisting disease. Understanding the potential environmental contaminants and the human subjects involved can guide disaster managers in determining avoidance criteria, PPE selection, training, safety messages, work and volunteer assignments, and post-exposure healthcare. Understanding differences in exposure categories, PPE use, preexisting conditions, and the surviving post-disaster healthcare infrastructure in the community can allow us to shape a responsive, exposure-based healthcare monitoring and treatment program.

We need to develop exposure-science measurement tools (personal and biological markers), models, and strategies for event preparedness (42–45). A set of "on-the-ground" protocols is necessary for quickly assessing the hazards and extent of contamination indoors and outdoors (42–44). Specific types of personal and stationary monitors must be made available for placement in strategic locations. A solution for measuring supercoarse particles still needs to be provided by EPA, OSHA, or DHS (21). Disaster preparedness requires that we develop an effective, universal disaster plan, with disaster-specific components, for outdoor and indoor sampling and cleanup with appropriate quality assurance.

Until clear evidence exists that the environment is safe, on-site disaster managers should be prepared to immediately implement acute human-exposure characterization and avoidance strategies (e.g., stay in place vs evacuation). Exposure avoidance advisories and PPE advisories for emergency responders and the general public, during or immediately after a terrorist attack, should be publicly posted. In addition, many questions remain. What type of respiratory protection (dust mask, N-95 respirator, P-100 respirator, self-contained breathing apparatus, etc.), if any, is required? Where can they be obtained, and how can they be provided immediately? Preparedness would require predisaster stocking of PPE and training of first responders and additional deployment strategies for secondary and tertiary response.

How can respirators be redesigned to (a) avoid fit-testing or make it easier and (b) improve compliance by addressing comfort and communication issues? Can N-95 respirators be reused and, if so, for how long? Replacement P-100 cartridges and self-contained breathing apparatus air bottles should be universal to all manufacturers. Knowledge derived from WTC and other experiences should provide the scientifically sound underpinnings of such advisories. The U.S. should determine the ways in which population exposure issues can be effectively included in the national response plan.

Exercises must include simulations of the types of contacts and exposures caused by large-scale accidents or terrorist events, which require extremely rapid response. Rapid-response, personal exposure-measurement tools; exposure-avoidance strategies; and flexible, reusable respirators with built-in communication capabilities are needed to reduce the number of potential victims in such circumstances. For future disaster preparedness, DHS must provide the public with its modified and improved toolbox for intervention and cleanup. This should include the types of preparedness strategies that account for the potential magnitude of human exposures; definitions of the routes of exposure and agents of concern; and, more importantly, the types of avoidance or prevention strategies that can reduce typical or important human contacts during an event.

A disaster registry should be an automatic response to any serious disaster, and it should serve not only as a research tool but primarily as a record of exposure history from which future health-care notifications can be made directly to those most exposed. During prolonged rescue and recovery efforts, disaster site boundaries should be established and responders only allowed to enter with proper clearance, including adequate PPE and training. Every responder entering and leaving the site should be automatically entered into the registry via an electronic registration database (e.g., badge scanners), thereby allowing for proper classification of exposures and the ability to perform future health-care monitoring and treatment without costly expenditures in trying, after the fact, to identify and locate those in need.

Education and public-health strategies must be

developed that make the public active participants in understanding the impacts and health effects of catastrophic environmental exposures. Least- and worst-case scenarios have the potential for undermining the responsible organizations' credibility, and worst-case scenarios, if false, only serve to dangerously aggravate the psychology of exposure-related fear. The public message and response to an environmental disaster must be a responsibly balanced, public-health priority based on human-exposure science.

Traditional activities in environmental science, environmental health science, and exposure science are important, but the events of 9/11 still need to be placed within the appropriate context for the future, so that all facets of society will not have to relearn these hard lessons. If the U.S. is to minimize the potential for having inadequate tools and procedures in a future disaster, past inadequacies must be evaluated; credible, realistic exposure-response evaluations established; effective prevention strategies developed, including when and where avoidance or respirator use is mandatory for the local community as well as responders; and health-care monitoring and treatment provided to those exposed.

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References

- (1) Barr, D. Expanding the Role of Exposure Science in Environmental Health. *J. Expo. Sci. Environ. Epidemiol.* **2006**, 6, in press; www.nature.com/jes/index.html.
- (2) *Considerations for Developing Alternative Health Assessment Approaches for Addressing Multiple Chemicals, Exposure and Effects*; Report EPA/600/R-06/13A; U.S. EPA, National Center for Environmental Assessment: Cincinnati, OH, March 2006.
- (3) Landrigan, P. J.; et al. Health and Environmental Consequences of the World Trade Center. *Environ. Health Perspect.* **2004**, 112, 731-739.
- (4) NRC Committee on Advances in Assessing Human Exposure to Airborne Pollutants. *Human Exposure Assessment for Airborne Pollutants: Advances and Opportunities*; National Academies Press: Washington, DC, 1991.
- (5) Liroy, P. J. Exposure Analysis and the Biological Response to a Contaminant: A Melding Necessary for the Environmental Health Sciences. *J. Expo. Sci. Environ. Epidemiol.* **1992**, 2 (Suppl. 1), 19-24.
- (6) Liroy, P. J.; Weisel, C. P.; Georgopoulos, P. G. An Overview of the Environmental Conditions and Human Exposures That Occurred Post 9-11. In *Urban Aerosols and Their Impacts: Lessons Learned from the World Trade Cen-*

- ter Tragedy; Gaffney, J. S., Marley, N. A., Eds.; ACS Symposium Series 919; Oxford University Press: U.K., 2005; pp 2–22.
- (7) Liou, P. J.; Georgopoulos, P. G. The Anatomy of the Exposures That Occurred around the World Trade Center Site: 9-11 and Beyond. In *Living in a Chemical World: Framing the Future in Light of the Past*; Mehlman, M., et al., Eds.; New York Academy of Sciences: New York, 2006; pp 54–79.
 - (8) Ambient (Outdoor) Monitoring, www.epa.gov/wtc/monitoring; OSHA Sampling Results Summary as of 10/08/2002, www.osha.gov/nyc-disaster/summary.html.
 - (9) Liou, P. J.; et al. Characterization of the Dust/Smoke Aerosol That Settled East of the World Trade Center (WTC) in Lower Manhattan after the Collapse of the WTC September 11, 2001. *Environ. Health Perspect.* **2002**, *110*, 703–714.
 - (10) NYC Department of Health and Mental Hygiene and ATSDR. *Final Report of the Public Health Investigation to Assess Potential Exposures to Airborne and Settled Surface Dust in Residential Areas of Lower Manhattan*; ATSDR, U.S. Department of Health and Human Services: Atlanta, GA; Sept 2002.
 - (11) Yiin, L. M.; et al. Comparisons of the Dust/Smoke Particulate That Settled Inside the Surrounding Buildings and Outside on the Streets of Southern New York City after the Collapse of the World Trade Center, September 11, 2001. *J. Air Waste Manage. Assoc.* **2004**, *54*, 515–528.
 - (12) Oktay, S. D.; et al. WTC Geochemical Fingerprint Recorded in New York Harbor Sediments. *EOS Trans. AGU* **2003**, *84*, 21–24.
 - (13) Meeker, G. P.; et al. *Determination of a Diagnostic Signature for World Trade Center Dust Using Scanning Electron Microscopy Point Counting Techniques*; Report 2005-1031; USGS: Denver, CO, 2005.
 - (14) EPA Response to September 11, www.epa.gov/wtc.
 - (15) Vette, A.; et al. Air Pollution Measurements in the Vicinity of the World Trade Center: Summary of Measurements Conducted by EPA-ORD. *Environ. Manage.* **2004**, Feb, 23–26.
 - (16) Cahill, T. A.; et al. Analysis of Aerosols from the World Trade Center Collapse Site, New York, October 2 to 30, 2001. *Aerosol Sci. Technol.* **2004**, *38*, 165–183.
 - (17) Brennenman, K. A.; et al. Olfactory Transport of Inhaled ⁵⁴Manganese Chloride to the Brain in Male CD Rats. *Toxicol. Sci.* **2000**, *84* (Suppl.), 54 (abstract #397).
 - (18) Dorman, D. C.; Struve, M. F.; Wong, B. A. Brain Manganese Concentrations in Rats Following Manganese Tetroxide Inhalation Are Unaffected by Dietary Manganese Intake. *Neurotoxicology* **2002**, *23*, 185–195.
 - (19) Geyh, A. S.; et al. Assessing Truck Driver Exposure at the World Trade Center Disaster Site: Personal and Area Monitoring for Particulate Matter and Volatile Organic Compounds During October 2001 and April 2002. *J. Occup. Environ. Hyg.* **2005**, *2*, 179–193.
 - (20) Fireman, E. M.; et al. Induced Sputum Assessment in New York City Firefighters Exposed to World Trade Center Dust. *Environ. Health Perspect.* **2004**, *112*, 1564–1569; www.ehponline.org/members/2004/7233/7233.html.
 - (21) Liou, P. J.; Gochfeld, M. Lessons Learned on Environmental, Occupational, and Residential Exposures from the Attack on the World Trade Center. *Am. J. Ind. Med.* **2002**, *42*, 560–565.
 - (22) *Evaluation Report: EPA's Response to the World Trade Center Collapse: Challenges, Successes, and Areas for Improvement*; Report 2003-P-00012; U.S. EPA OIG: Washington, DC, Aug 2003; www.epa.gov/oig/reports/2003/WTC_report_20030821.pdf.
 - (23) National Center for Environmental Assessment. *Exposure and Human Health Evaluation of Airborne Pollution from the World Trade Center Disaster*; Report EPA/600/P-2/002A, U.S. EPA, Office of Research and Development: Washington, DC, 2002.
 - (24) *World Trade Center Indoor Environmental Assessment: Selecting Contaminants of Potential Concern and Setting Health-Based Benchmarks*; U.S. EPA, Region 2: New York, May 2003; www.epa.gov/wtc/copc_study.htm.
 - (25) *World Trade Center Background Study Report, Interim Final*; U.S. EPA, Region 2: New York, April 2003; www.epa.gov/wtc/background_study.htm.
 - (26) Prezant, D. J.; et al. Cough and Bronchial Responsiveness in Firefighters at the World Trade Center Site. *N. Engl. J. Med.* **2002**, *347*, 806–815.
 - (27) Wolff, M. S.; et al. Exposures among Pregnant Women Near the World Trade Center Site on 11 September 2001. *Environ. Health Perspect.* **2005**, *113*, 739–748.
 - (28) Brackbill, R. M.; et al. Surveillance for World Trade Center Disaster Health Effects Among Survivors of Collapsed and Damaged Buildings. *MMWR CDC Surveill. Summ.* **2006**, *55*, 1–18.
 - (29) Lorber, M.; et al. Assessment of Inhalation Exposures and Potential Health Risks That Resulted from the Collapse of the World Trade Center Towers. *Environ. Manage.* **2004**, Feb, 27–29.
 - (30) Centers for Disease Control and Prevention. Physical Health Status of World Trade Center Rescue and Recovery Workers and Volunteers, New York City, July 2002 to August 2004. *MMWR CDC Surveill. Summ.* **2004**, *53*, 807–812.
 - (31) Edelman, P.; et al. Biomonitoring of Chemical Exposure among New York City Firefighters Responding to the World Trade Center Fire and Collapse. *Environ. Health Perspect.* **2003**, *111*, 1906–1911.
 - (32) Rom, W. N.; et al. Acute Eosinophilic Pneumonia in a New York City Firefighter Exposed to World Trade Center Dust. *Am. J. Respir. Crit. Care Med.* **2002**, *166*, 797–800.
 - (33) Feldman, D. M.; et al. Initial Symptoms, Respiratory Function and Respirator Use in New York City Firefighters Responding to the World Trade Center (WTC) Disaster. *Chest* **2004**, *125*, 1256–1264.
 - (34) Banauch, G. I.; et al. Persistent Bronchial Hyperreactivity in New York City Firefighters and Rescue Workers Following Collapse of World Trade Center. *Am. J. Respir. Crit. Care Med.* **2003**, *168*, 54–62.
 - (35) Banauch, G. I.; et al. Bronchial Hyperreactivity and Other Inhalation Lung Injuries in Rescue/Recovery Workers after the World Trade Center Collapse. *Crit. Care Med.* **2005**, *33*, S102–S106.
 - (36) Herbert R.; et al. The World Trade Center Disaster and the Health of Workers: Five-Year Assessment of a Unique Medical Screening Program. *Environ. Health Perspect.* **2006**, doi 10.1289/ehp.9592.
 - (37) Reibman, J.; et al. The World Trade Center Residents' Respiratory Health Study: New Onset Respiratory Symptoms and Pulmonary Function. *Environ. Health Perspect.* **2005**, *113*, 406–411.
 - (38) Stenchikov, G.; et al. Multiscale Plume Transport from the Collapse of the World Trade Center on September 11, 2001. *Env. Fluid Mech.* **2006**, <http://dx.doi.org/10.1007/s10652-006-9001-8>.
 - (39) DHS National Response Plan, www.dhs.gov/dhspublic/interapp/editorial/editorial_0588.xml.
 - (40) Watson, T. B.; et al. *Brookhaven National Laboratory Report: The New York City Urban Dispersion Program March 2005 Field Study: Tracer Methods and Results*; Brookhaven Science Associates, LLC: Brookhaven, NY, Oct 2005; pp 1–40.
 - (41) NRC. *Acute Exposure Guideline Levels for Selected Airborne Chemicals*; Vols 1–4; National Academies Press: Washington, DC, 2001–2004.
 - (42) Tang, K. M.; et al. Evaluation of Vacuum and Wet-Wipe Methods for Removal of World Trade Center Dust from Indoor Environments. *J. Air Waste Manage. Assoc.* **2004**, *54*, 1293–1298.
 - (43) Tang, K. M.; et al. Characterization of Background Concentrations in Upper Manhattan, New York Apartments for Select Contaminants Identified in World Trade Center Dust. *Environ. Sci. Technol.* **2004**, *38*, 6482–6490.
 - (44) Kalton, G.; Ferraro, D.; Rizzo, L. *Sample Design Options for the Survey of Apartments Participating in the World Trade Center Residential Cleanup Program*; Westat: Rockville, MD, 2004, pp 1–10; www.epa.gov/wtc/panel/pdfs/WTCsampleDesign3_19.pdf.
 - (45) Centers for Disease Control and Prevention. Use of Respiratory Protection among Responders at the World Trade Center Site, New York City, September 2001. *MMWR CDC Surveill. Summ.* **2002**, *51*, 6–8.