NIST Technical Note 1882

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ABSTRACT

NIST is developing a planning guide to define programs and strategies to increase community-based resilience in the face of a broad range of natural disasters and other extreme events. Many of these events will affect indoor environmental quality. either through the potential for increased airborne contaminant levels or due to challenges in providing acceptable indoor environments for building occupants during the event and afterwards in the recovery phase. However, the elements of indoor environmental resilience (IER) have not been identified and discussed in a systematic fashion, which needs to be done to determine the role of these factors in the context of community resilience. This report presents a review of existing information, standards, programs and other technical resources related to the events that are likely to impact IER in order to describe the scope and potential impacts of the problem, current activities that address these issues, important gaps requiring research and other technical analyses, and needs for standards and related guidance. The conclusions presented in this report include the following needs: passive building design approaches that can maintain safe and comfortable conditions during extended power outages; definition of short term acceptable ventilation and indoor air quality conditions for living and working in buildings temporarily during power outages; development of guidance to provide community-wide sheltering in response to heat waves, wildfire and other events; tools to help communities identify buildings that may be subject to poor IER conditions during disasters; thermal comfort and ventilation standards or guidelines that cover extreme conditions; and, guidance for homeowners and volunteers engaged in mold/wet building cleanup following large scale flooding events.

Keywords: disaster; indoor air quality; indoor environmental quality; thermal comfort; resilience; ventilation

1. INTRODUCTION

The NIST Community Disaster Resilience Planning Guide (NIST 2015) addresses resilience of buildings and infrastructure systems at the community scale and provides guidance on establishing long-term goals and plans for recovery following a disaster, with consideration of social needs. In addition to the development of the planning guide, the NIST community disaster resilience program is pursuing a number of other activities to support the overall program goals. This report describes one such activity, an effort to define the role of indoor environmental quality (IEQ) in the context of community resilience. This work is motivated by the fact that many of the natural and human-caused disasters being considered under the broader program will affect IEQ. These effects include both increased airborne contaminant concentrations associated with the disaster or its aftermath and challenges in providing acceptable indoor environmental conditions during an event or afterwards during recovery.

In order to examine resilience, particularly recovery of functionality in the context of the indoor environment, it is important to consider what the indoor built environment is expected to provide for occupants. One key objective is to maintain thermally comfortable conditions, which are a function of air temperature, relative humidity, air speed and radiant temperature in the space as well as human factors such as the occupants' level of physical activity, clothing and physiological ability to adapt to thermal conditions. In addition, the indoor environment should limit concentrations of airborne contaminants to safe and comfortable levels. Contaminants of interest include organic and inorganic gases, particulate matter, and bioaerosols. The indoor environment, primarily via the building enclosure, is also intended to isolate the building occupants from the exterior environment, specifically including precipitation, pests, noise and threats to the physical security of the occupants. Finally, the indoor environment is expected to provide various amenities such as light, power and food storage to support the intended activities for the space in question, including working, learning, or residing.

Additional concepts to consider in the context of indoor environmental resilience (IER) are the features of the indoor environment that impact occupant health, comfort and productivity, i.e., IEQ. The four primary factors of IEQ are indoor air quality (IAQ), thermal comfort, acoustics and illumination (ASHRAE 2011). IAQ refers to indoor levels of airborne contaminants as well as odors, without specific reference to the compounds causing those odors, and perceived indoor air quality, i.e., human perception of indoor air in terms of irritation and other non-specific symptoms (Fanger 2006). Thermal comfort describes building occupants' sense of the warmth or coolness and is a function of the parameters mentioned above. Acoustics refers to the levels and frequencies of sound and vibration in a space, while lighting concerns the levels and frequencies of visible electromagnetic radiation as well as variations among surfaces in the space.

The role of IEQ issues in the context of disasters has been identified in two prominent documents. The National Climate Assessment summarizes the impacts of climate change on the United States, now and in the future, and highlights several anticipated changes that are relevant to IEQ (Melillo et al. 2014). Under extreme weather, the increased frequency of heat waves, heavy downpours, floods and hurricanes are all noted. The discussion of human health mentions vulnerable people and communities, wildfire smoke, increased levels of pollen, and impacts on asthma and allergies. Finally, under infrastructure, disruptions in energy production and delivery are noted. The IEQ impacts of these topics, as they relate to disasters, are all reviewed later in this report. The Institute of Medicine (IOM) published a study on climate change and indoor environmental health in 2011, which contained several key findings: poor IEQ is creating health problems today, impairing the ability of occupants to work and learn; climate change may worsen existing IEQ problems and introduce new ones; and, there are opportunities to improve public health while mitigating or adapting to alterations in IEQ induced by climate change (IOM 2011). This report also noted several problematic indoor exposures including the following: indoor contaminants; dampness, moisture and flooding; infectious agents and pests; thermal stress; and, building ventilation, weatherization, and energy use. Several of these exposures are discussed later in this report.

Fisk (2015) reviewed the potential health consequences of climate changes that affect indoor environments including consideration of the IOM report, recent contributions of working groups to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Smith et al. 2014, IPCC 2013) and other resources. Fisk discusses the potential health impacts of increases in urban airborne ozone concentrations (not considered in this report), as well as increases in the frequency and severity of heat waves, flooding associated with severe storms and sea level rise, and wildfires, all of which are considered in this report.

This report identifies and discusses the elements of what is referred to here as indoor environmental resilience through a review of existing information, programs and other technical resources related to events that are likely to impact IER. It reviews such events, describing how those events may impact IER and what is known about their impacts. For each event, existing standards and guidelines are described, as well as other programs and activities to support planning and response strategies. In the discussion that follows, the community resilience perspective is employed in presenting each of the events.

2. SCOPE OF INDOOR ENVIRONMENTAL RESILENCE

The first step in this effort was to consider the types of extreme events that have the potential to impact IEQ and which may merit planning and responses in support of increased community resilience. Table 1 contains a list of the events considered in this discussion, along with the associated indoor environmental exposures of interest.

Type of event	Indoor environmental exposure
Heat waves	High indoor temperatures/heat stress High levels of outdoor pollution
Storms causing power failure	Lack of heating, cooling, and ventilation leading to heat/cold stress and elevated indoor contaminant levels Carbon monoxide exposure from portable generators
Floods and mold exposure	Microbial growth affecting occupants and remediation workers
Wildfires	Particulate and other contaminant exposure
Airborne releases of chemical, biological or radiological (CBR) agents	Exposure to agent

Table 1 Events relevant to indoor environmental resilience

Each of the events listed in Table 1 was analyzed in terms of what is known about the scenarios of interest and the associated impacts. This effort involved examining available information on these events and their indoor environmental impacts, technical gaps in understanding these impacts, existing standards, and how they are being addressed by various guidance documents.

An important aspect of the NIST Community Resilience Planning Guide is addressing recovery from disasters, which is usually divided into three phases: short term (days), intermediate (weeks to months), and long term (months to years). The impacts of the events considered in Table 1 are primarily in the short to intermediate phases, though the effects of floods and airborne CBR releases could extend into long term recovery phases.

Each of the following sections describes the event and its potential impacts, relevant standards that currently exist, and a summary of other guidance and activities that might support increased resilience. Following the discussion of each of the topics in Table 1, this document discusses two other issues that are relevant to IER but do not necessarily relate to a particular event in the same way as the topics in Table 1. These issues are pandemics and the role of healthcare facilities and indoor environmental conditions in safe rooms and shelter-in-place facilities. These discussions are followed by a review of existing standards and guidelines relevant to IER.

2.1 Heat Waves

Heat waves are prolonged periods of high outdoor temperatures, often accompanied by high outdoor humidity levels, typically lasting for two or more days. These events are typically associated with high-pressure atmospheric conditions that hold air in place over a limited geographic area, preventing cooling from rain and other mechanisms or replacement with air from other areas. The human health effects of excessive heat are well understood and include a range of health effects from mild, e.g. dehydration and cramps, to severe, e.g. heat exhaustion and heat stroke. The elderly, infants and children, overweight individuals, and people with chronic medical conditions are more susceptible to heat related health effects. There have been a number of heat waves in recent years, with several recent events captured in Table 2. In fact, during the period of 1979 to 2003, more people in the U.S. have died from extreme heat than from hurricanes, lightning, tornadoes, floods, and earthquakes combined (CDC 2012). As the climate warms, longer and more severe heat waves are predicted to result in significant increases in heat wave deaths in the U.S. over the next several decades (Wu et al. 2013).

Extreme Heat incident, year	Deaths
Philadelphia heat wave, 1993	118
Chicago heat wave, 1995	739
European heat wave, 2003	70 000
California heat wave, 2006	650
Russian heat wave, 2010	11 000 to 50 000

Table 2 Selected extreme heat events (CAT 2013)

There has been a lot of work done on heat stress in occupational settings, primarily to protect workers against adverse health effects through a combination of personal protection and limits on time in work settings with elevated temperatures (Charmichael et al. 2011). In terms of non-occupational exposures, there have also been many studies to understand the health risks associated with elevated temperatures in the general population (Basu and Samet 2002; Basu 2009). These epidemiologic studies have identified associations of elevated temperature with death and disease and identified vulnerable subgroups including children, infants, the elderly and those with pre-existing health conditions. CDC (Berko et al. 2014) recently published an analysis of deaths due to heat, cold and other weather events by income level of the affected U.S. county, level of urbanization, age, and race, but did not specify whether the exposure occurred indoors or outdoors. Table 3 summarizes some of the vulnerabilities to heat illnesses. Of particular note are the environmental factors, which relate to how building design, community programs and communication could potentially reduce the human health impacts of heat waves.

Fisk (2015) suggests that many and perhaps most heat wave deaths occur indoors, thus, buildings and community environments play a key role in these effects and their control. Individuals spend most of their time indoors, about 90 % (Klepeis et al. 2001), and as noted in the last column of Table 3, the health impacts are associated with several building features. Note that a lack of air conditioning may be a feature of the building itself or associated with an event that leads to a power outage. Other building and community features not noted in the table are increasing levels of insulation in buildings driven by energy efficiency goals, which can contribute to elevated indoor temperatures during heat waves when air conditioning is not available. There has been renewed attention to passive cooling designs as a means to both save energy and to deal with situations in which mechanical cooling is not available. Passive cooling approaches have been around for centuries, with increased levels of interest as building energy efficiency has become a more important design goal. Common passive cooling approaches include natural ventilation, use of building mass to dampen outdoor temperature extremes, and building orientation to reduce solar loads and shading, again to reduce solar heating. Concerns have been expressed that as buildings are designed to use less energy through the use of higher insulation levels, fewer operable windows and more reliance on mechanical ventilation, that these buildings will be harder to cool during power outages (CCC 2014). Fisk (2015) identified thermal insulation of attics, cool roofing materials, external shading, and energy efficient windows as mitigation measures for protection against heat waves regardless of climate change.

<table>
<tr><th>Pre-existing health conditions</th><th>Extremes of age</th><th>Environmental Factors</th></tr>
<tr><td rowspan="3">Obesity
Poor existing health
Pre-existing dehydration
Cardiovascular conditions
Respiratory conditions
Low fitness or physical disabilities
Uncontrolled diabetes
Medications affecting thermoregulation
Alcohol and/or drug abuse</td><td>Elderly (particularly > 65 y)
Children and infants</td><td rowspan="3">Residing in upper floors of buildings
South facing flats
Lack of adequate ventilation in home or air conditioning
Living alone
Socially isolated
Lack of acclimatization
Urban dwelling
Care home residents</td></tr>
<tr><td>Inability to adapt behaviorally</td></tr>
<tr><td>Alzheimer's
Confinement to bed
Disabilities</td></tr>
</table>

Table 3 Vulnerabilities to heat illness (Carmichael et al. 2011)

Standards and Guidance

Recommendations exist for mitigating heat stress in occupational settings. The American Conference on Government Industrial Hygienists (ACGIH 2014) addresses heat stress using the wet bulb globe temperature (WBGT), a metric that accounts for air and radiant temperatures, humidity, solar exposure and clothing level. The ACGIH provides workplace screening criteria for WBGT that depend on the level of activity and whether or not the worker is acclimatized to the conditions. For example, an unacclimatized individual engaged in light work is associated with a criteria value of WBGT of about 30 °C, assuming their time is evenly split between light work and rest. Note that these criteria are applicable to healthy workers and not to the susceptible populations listed in Table 3. While the Occupational Safety and Health Administration does not have a specific standard that covers working in hot environments, they do provide resources for employers and workers to reduce worker risk to heat related illnesses (OSHA 2014).

ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, specifies indoor environmental factors that will produce conditions that are acceptable to a majority of the occupants in a space (ASHRAE 2013a). The factors in this standard include primarily air temperature and humidity, but it also speaks to air speed, draft and temperature stratification. This standard, which is based on healthy adults, has historically been focused more on mechanically ventilated commercial buildings than on residential buildings, though recently it has considered naturally ventilated buildings. However, it still focuses on thermal comfort when buildings are being operated as designed and does not address extraordinary circumstances such as power outages and extreme outdoor weather events. Also, it addresses thermal comfort, and not physiological concerns such as heat stress. The most familiar information from Standard 55 is the so-called comfort chart, which shows the range of acceptable operative temperatures and relative humidity levels for a specific range of physical activity and clothing levels. Operative temperature is a measure that combines air temperature with radiant effects. The maximum operative temperature on that chart ranges from about 27 °C to 28 °C depending on humidity.

ISO Standard 7933 contains an analytical method for assessing heat stress experienced by an individual in a hot environment, including the prediction of sweat rate and internal core temperature under working conditions (ISO 2004). As noted in the standard, it only considers individuals "in good health and fit for the work they perform" and is intended for evaluating "working conditions." It is not applicable to the general population in non-work environments.

Local building regulations address minimum indoor temperatures during cold weather but not maximum temperatures. However, there are several sources of guidance that address heat waves, which could be incorporated into a more comprehensive community resilience approach. Many state and local governments, e.g., Wisconsin (Wisconsin Department of Health Services 2014), as well as the CDC (2012) and the American Red Cross (2014), have warning and prevention plans with guidance on how to prepare for and respond to extreme heat conditions. This guidance identifies risk factors for heat-related illness, including age, being overweight, taking medication that affects the body's ability to regulate temperature, and lack of air conditioning. Steps to prevent health problems are also highlighted, such as communication with susceptible individuals, use of fans, drawing shades and curtains, and drinking fluids. The potential for power outages during heat waves is noted, with suggestions of testing alternative power systems before such events and communicating with vulnerable individuals.

<u>Other relevant efforts</u>

In terms of building design, as noted above, passive design approaches that avoid overheating of buildings during heat waves and loss of air conditioning are being developed by CIBSE (2014) and others. These approaches are focused on window selection, solar shading, operable windows, flow-through ventilation, and natural ventilation design principles. In addition, weather data for building design is being projected into the future to enable consideration of warmer conditions as well as extreme heat events. The impacts of urban planning on heat islands is also being considered as a means to reduce localized heating through the use of green spaces, building spacing to allow air to flow through urban areas and shading strategies (Hong Kong Planning Department 2002, Rosenthal et al. 2008, San Francisco Department of Public Health 2013).

<u>Summary</u>

Heat waves are already known to be a serious health issue, with a good understanding of the health effects and the large numbers of people being impacted and with concerns noted for the potential increase in the frequency and severity of heat waves due to climate change. While the data on the health impacts of heat waves has not been parsed to determine the fraction of exposures that occur inside buildings, building factors have been identified that contribute to overheating. Guidance materials and programs exist describing how to prepare for and respond to heat waves, but standards and regulations are limited. Thermal comfort standards for example address building design and operation under normal conditions but do not address extreme conditions that might exist in a building without air conditioning where survivability is more of an issue than simply comfort. Also, local building regulations address minimum indoor temperatures during cold weather but not maximum temperatures. Building and community design guidance is being developed to reduce heat island effects in urban areas and to enhance the ability of buildings to be cooled passively, without relying on mechanical cooling. While this building design guidance is important and helpful, additional guidance and perhaps standards are needed to address the range of climates and different building types.

2.2 Storms causing power failure

Electric power outages are a common occurrence during many types of disasters and, given its importance to communities, issues relating to the electric infrastructure are addressed in detail in the NIST Community Resilience Planning Guide (CRPG). The CRPG includes a discussion of the importance of standby power for continuous operation of critical facilities and considerations for safe and reliable operation of onsite standby power, including proper ventilation of combustion products. Standby and emergency power issues are also addressed by codes such as the National Electric Code (NFPA 2014a) and Life Safety Code (NFPA 2015). The Planning Guide discussion focuses largely on larger, permanently installed systems, though it mentions that small mobile generators can be easily deployed but have shortcomings including the need for frequent refueling, risk of theft, potential lack of reliability due to infrequent use and poor maintenance, and safety hazards due to inexperienced operators. This section expands on the issue of IAQ-related safety hazards due to the use of portable generators and addresses other IAQ-related power outage issues, such as cold indoor environments due to loss of heating.

Klinger (et al. 2014) reviewed the potential health-related impacts of international power outages during the first three months of 2013, including loss of public health infrastructure, carbon monoxide (CO) poisoning, and food safety (see Figure 1 from that reference for a list of services lost during power failures). According to Klinger et al., storms, wind and snow accounted for the majority of power outages during that period, but many other types of events (such as flooding) were also responsible to a lesser extent. They concluded that research on the impacts of power outages is scarce and that the only area where quantification has been attempted is CO poisoning.

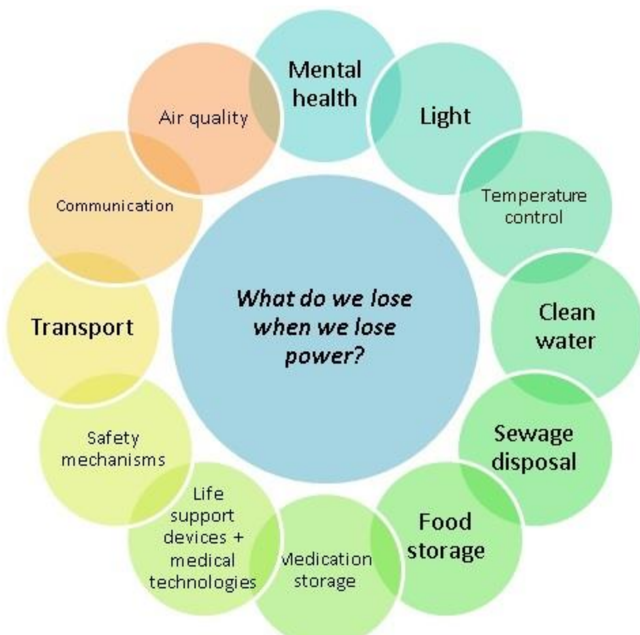

Figure 1 Services lost during power outages (from Klinger et al. 2014)

Recent scientific literature has documented the occurrence of CO-poisoning deaths and injuries due to improper use of portable electric generators following a wide range of disasters including windstorms (Goldman et al. 2014), coastal storms and flooding (Lane et al. 2013), earthquakes (Iseki et al. 2013), winter storms (Klinger et al. 2014) and blackouts (Anderson and Bell 2012). The aftermath of superstorm Sandy in October 2012 highlights the potential scope of this problem for a major event, as this storm resulted in loss of power to over 8.5 million people in 21 states, caused at least 263 CO poisonings, led to the need to move over 100 patients from New York area hospitals, and created other significant issues such as elderly occupants being trapped in high-rise residences (Manuel 2013).

Hnatov (2013) summarizes non-fire CO incidents associated with engine-driven generators and other engine-driven tools reported to the U.S. Consumer Product Safety Commission (CPSC) between 1999 and 2012. The CPSC databases contain records of 236 CO poisoning deaths involving generator use associated with power outages (in some cases in combination with another CO source) for the same 14-year period. The vast majority of these deaths occur when consumers use a generator in an enclosed space, though a small percentage occurs when the consumer uses the generator outdoors but near a building. The two most common causes of fatal CO incidents due to weather-related outages were ice/snow storms (77 incidents, 107 deaths) and hurricanes/tropical storms (49 incidents, 71 deaths). The U.S. Centers for Disease Control and Prevention (CDC) has reported that 34 % of non-fatal CO poisoning incidents after hurricanes in Florida in 2004, and 50 % during Hurricanes Katrina and Rita in 2005, involved generators operated outdoors but within 2.1 m of the home (CDC 2006).

Other IAQ-related issues stemming from disaster-related power outages include the inability to operate electric-powered building heating, ventilating and air-conditioning (HVAC) equipment, which could lead to uncomfortable or even unhealthy indoor environments. While blackouts during extreme heat events may be relatively rare in the U.S. (SFDPH 2013), power outages during hot weather that does not qualify as a heat wave may still result in increased mortality (Anderson and Bell 2012). Lack of power will significantly impact the ability of residents to remain in or return to their residences, as described by Kennedy et al. (2012). That paper describes a situation in which conditions in tall buildings in Brisbane became “unliveable” due to loss of air-conditioning during power outages during and after a major flood event in January 2011, with some remaining “uninhabitable” for several weeks after the event. Kennedy et al. list the livability issues facing residents: “basement inundation without water pumps; vertical access and mobility issues without elevators; poor ventilation and air quality issues as apartments became overheated and stifling without air-conditioning; loss of potable water for drinking, bathing and clothes washing without booster pumps; disruptions to communications phone and internet cabling; sanitary issues without flushing toilets; lack of security without electronic locking; and lack of fire safety including failure of fire sprinkler systems and alarms.”

Loss of power and utilities can also lead to unacceptably cold indoor temperatures. There were over 6600 cold related deaths (twice as many as heat related deaths) in the U.S. between 2006 and 2010, with age, sex, ethnicity, and income level cited as risk factors (Berko et al. 2014). However, the current literature review revealed little study of the building factors affecting cold related deaths, though Aylin et al. (2001) reported an association between the lack of central heating and mortality. Others have studied the factors involved in cold weather related morbidity rather than mortality (e.g., Rudge and Gilchrist 2007). However, no specific study of power/utility outage and its impacts on mortality or morbidity was found. Fisk (2015) indicates that studies have reached different conclusions on whether and how much climate change may reduce cold related deaths.

Standards and Guidance

ASHRAE Standards 62.1 and 62.2 specify required ventilation and other building and system parameters (e.g., particle filtration levels) to achieve acceptable IAQ in nonresidential and residential buildings, respectively (ASHRAE 2013b and 2013c). In general, these standards are written to address normal conditions when buildings are being operated as designed and do not address extraordinary circumstances such as outdoor contamination events, unusual indoor contaminant sources, and other than healthy occupants. They primarily rely on mechanical ventilation but do contain limited provisions to address natural ventilation. As discussed previously, ASHRAE Standard 55 addresses thermal comfort under normal operating conditions and, as such, does not contain specific requirements that would be applicable to extreme heat or cold during a power outage.

UL Standard 2200 Standard for Stationary Engine Generator Assemblies (UL 2012) covers construction and performance of portable generators. Other relevant standards include National Fire Protection Association Standards 110 Emergency and Standby Power Systems (NFPA 2013a) and 111 Stored Electrical Energy Emergency and Standby Power Systems (NFPA 2013b). The NFPA standards cover installation, maintenance, operation, and testing requirements for emergency and standby power systems and stored electrical energy systems providing an alternate source of electrical power in buildings and facilities in the event that the normal electrical power source fails.

The CDC has published a prevention guide for personal health and safety in extreme cold weather that is targeted primarily towards homeowners and addresses alternate methods of heating (e.g., kerosene space heaters) and monitoring body temperatures in addition to many other issues (CDC 2014a).

Practical guidance for other power outage issues is contained in the New Jersey Department of Health *Emergency Action Planning Guidance for Retail Food Establishments* (NJDPH 2009), which assists retail grocery and food service establishments in planning for and responding to emergencies that have the potential to create an imminent health hazard. That document includes the following guidance:

- "Consider your access to an electrical generator to be used in emergencies. Make certain that the generator has the capacity to operate critical equipment such as refrigeration and freezer units, pumps, safety lighting, hot water heaters, etc. Make certain that individuals are trained to operate the equipment safely. Be sure to consult with a licensed electrician. Advise the utility company that you are using a generator as a safety precaution for their employees.
- Dry ice should not be used in enclosed spaces (i.e. walk-in cooler) because of the potential build-up of carbon dioxide. If used, pack potentially hazardous food in dry ice using precautions, such as utilizing insulated gloves to handle and venting the area before entering.
- Prepare an "emergency menu" in advance including recipes for food items that do not require cooking since the ventilation system will no longer remove smoke, steam, grease laden air, etc."

FEMA P-1019 Emergency Power Systems for Critical Facilities: A Best Practices Approach to Improving Reliability, (FEMA. 2014) provides guidance on how to assess the risks and vulnerabilities to the electrical power system, identify performance goals for an emergency power system, and the importance of having realistic emergency management policies that address emergency power for critical facilities. The critical facilities addressed include hospitals and emergency medical treatment facilities; fire, rescue, ambulance and police stations; buildings designated as earthquake, hurricane, or other emergency shelters; and emergency preparedness and operations centers and other facilities required for emergency response command and control. This document is intended as an introduction to the fundamental principles of providing emergency power for critical facilities but not to be a comprehensive design manual. While the document is not aimed at buildings other than critical facilities, some of the information may be useful to consider for other buildings.

FEMA Standard P-361 Design and Construction Guidance for Community Safe Rooms (FEMA 2008) addresses the need for standby power in both residential and community safe rooms (or storm shelters). Other requirements for such spaces, such as ventilation, are discussed later in the section on Indoor Environments in Safe Rooms and Shelter-in-Place (SIP) Facilities. In terms of standby power, Section 8.10 of this document states:

> "Safe rooms designed for tornadoes and hurricanes will have different standby (emergency) power needs. These needs are based upon the length of time that people will stay in the safe rooms (i.e., shorter duration for tornadoes and longer duration for hurricanes). In addition to the essential requirements that should be provided in the design of the safe room, comfort and convenience should be addressed.
>
> For tornado safe rooms, the most critical use of standby power is for lighting. Emergency power may also be required in order to meet the ventilation recommendations described in Section 8.3. The user of the safe room should set this requirement for special needs facilities, but most tornado community safe rooms would not require additional emergency power. The ICC-500 (ICC 2008) standard for the design and construction of storm shelters requires standby power systems to be designed to provide the required output capacity for a minimum of 2 hours and to support the mechanical ventilation system, when applicable.
>
> For hurricane community safe rooms, standby or emergency power may be required for both lighting and ventilation by the local building code. This is particularly important for safe rooms in hospitals and other special needs facilities. Therefore, a standby generator is recommended. Any generator relied on for standby or emergency power should be protected with an enclosure designed to the same criteria as the safe room. The ICC-500 requires the standby electrical system to have sufficient capacity to power all the required (critical support) systems and circuits at the same time continuously for a minimum period of 24 hours."

The GSA Climate Change Action Plan (GSA 2014) outlines important actions that GSA has taken to better understand and address the risks and opportunities brought on by climate change. This includes partnering with customer agencies to determine Climate Protection Levels at the site and facility scale for mission-critical sites. Depending on the customer mission, GSA may need to provide buildings that maintain livable conditions in the event of extended power outages, interruptions in heating fuel, and shortages of water to ensure resilience and survivability.

Other relevant efforts

NIST has recently conducted a research effort to help understand the building and engineering issues involved in CO poisonings due to improper generator use and to help identify and evaluate potential solutions. Emmerich et al. (2013) reported measurements of CO emission rates from stock portable generators, which ranged from around 400 g/h at near ambient conditions to nearly 4000 g/h as the oxygen level reduced when the generators were tested in an enclosed chamber. Tests of two different low-emission prototype generators showed the potential for over 90 % reductions of CO emissions. Tests of the stock generators operated in the attached garage of a research house showed that CO levels could quickly reach life threatening levels depending on the house and generator configuration. Wang (et al. 2013) conducted a simulation study to examine the impact of distance on indoor CO exposure when operating a generator outside a house, which also considered the effects of generator location, exhaust temperature and discharge velocity, and weather conditions. It was found that in most cases, to reduce CO levels for the conditions modeled, it was more effective to direct the generator exhaust away from the house and position the generator at a distance of more than 4.6 m from the house.

NIST has developed a draft test method to measure generator emission rates in a chamber at reduced O_2 levels to support CPSC proposed rulemaking and the potential inclusion of a CO emission limit in UL Standard 2201 *Standard for Portable Engine-Generator Assemblies* (UL 2013). UL 2201 currently addresses the potential fire and electric hazards associated with portable generator use, but does not address CO poisoning. The NIST draft test method was developed based on NIST and CPSC testing experience in indoor environments ranging from a 10 m^3 chamber to a 90 m^3 garage (Emmerich and Persily 2014). However, to address the large number of units already existing, public health education efforts should be improved by emphasizing pre-disaster risk communication and tailoring interventions for racial, ethnic, and linguistic minorities (Iqbal et al. 2012). Many federal agencies and other organizations publish information on portable generator safety directed primarily towards consumers (CDC 2014b, CPSC, NFPA 2014b, USFA 2006).

Summary

Loss of power due to extreme weather events and other disasters have potentially significant IAQ and thermal comfort impacts due to loss of building HVAC system functioning. The relevant issues that have received attention include deaths and injuries due to CO entry into buildings from portable generators, and heat or cold related health impacts after loss of heating and cooling. Research and standards are needed to evaluate and define short term acceptable ventilation and IAQ conditions for living and working in buildings temporarily during power outages and to ensure the safe use of temporary power alternatives like portable electric generators.

2.3 Mold Exposure Associated with Flooding

The hazards associated with floods due to weather events, failures of levees and dams, and spring thaws are serious concerns given the damage they can inflict on buildings and people. Much of the discussion of these hazards is focused on the immediate risks to life from drowning as well as severe structural damage to buildings and other constructed facilities, and both planning and response strategies for these immediate risks are well established (FEMA 2014). The health risks, both short and long term, associated with the potential for occupant exposure to mold and other bioaerosols associated with prolonged wetting of building materials are also relevant in preparing for and responding to floods. Mold growth in buildings is generally associated with any event or circumstance that leads to prolonged wetting of organic materials within buildings, including roof and plumbing leaks, HVAC system design or performance problems that lead to poor control of indoor humidity levels, and building envelope designs that increase the likelihood of condensation within the envelope.

Concern about indoor exposure to mold has increased in recent years, much of which has been independent of flooding events. Some of this concern is evidenced in the popular press where numerous items about so-called "toxic mold" were published (CDC 2012 and 2014). While many of these stories do not contain technically complete descriptions of the issues and risk, valuable scientific research has been pursued on building moisture and occupant health. The Institute of Medicine published a report titled Damp Indoor Spaces and Health in 2004 (IOM 2004) that characterized the health problems associated with indoor dampness, recommended measures to prevent and remediate damp indoor environments based on existing knowledge, and identified additional research to answer the numerous remaining questions. This work was focused on the linkages between indoor dampness and a wide range of health effects including allergic responses, suppression of immune response, and respiratory symptoms and disorders. A more detailed presentation of the meta-analysis on which the IOM conclusions are based is contained in Fisk et al. (2007), which describes the association between health outcomes and damp buildings in detail. The World Health Organization has also published a comprehensive review of the associations of health problems with building moisture and biological agents, which in effect builds on the earlier report by the Institute of Medicine (WHO 2009). This document identifies flooding as one of many sources of indoor dampness.

Additional research has been performed on the health effects following specific flooding events, i.e., Hurricanes Katrina and Rita. One study found an increase in mold growth following the hurricanes but no increase in adverse health outcomes (Barbeau et al. 2010). The authors discussed several potential reasons for the lack of observed health effects, including a lack of reporting, people moving to alternate housing, and limited availability of healthcare leading to reduced reporting of health effects. Another study measured bioaerosols in three homes before, during and after interventions to address flood damage in the aftermath of Hurricane Katrina (Chew et al. 2006). The measured levels of mold and endotoxin were quite high, similar to those seen in agricultural environments. The authors recommended the development of safe remediation techniques for those involved in such cleanup activities.

Fisk (2015) indicates that water entry into buildings through both failures of the envelope and via flooding are expected to increase due to climate change impacts such as increased frequency, intensity and amount of heavy precipitation and rising sea levels. In the absence of steps to make buildings less susceptible, Fisk concludes that the evidence suggests that climate change will lead to significant increases in adverse health effects associated with building dampness and mold. He also identified the following mitigation measures for protection against severe storms and sea level rise: building envelope design and construction practices to reduce the potential for water entry; improved maintenance of building envelopes; elevating buildings above grade level in flood-prone locations; and, locating fewer buildings in flood plains.

Standards and Guidance

Several federal agencies, state and local governments, and other organizations have developed guidance on dealing with mold, mostly in terms of clean up, as well as repairing and replacing mold damaged materials (CARRI 2008, EPA 2007 and 2008, NYC 2008, OSHA 2006 and 2013, University of Minnesota 2010, University of Wisconsin). Some of this guidance is developed specifically for cleaning up after floods (EPA 2007, ARC and FEMA 1992). A standard on water damage and mold restoration was issued by the Institute for Inspection, Cleaning and Restoration Certification (IIRCRC 2006). This standard and the other guidance documents provide information on how to clean up mold-contaminated materials and to repair and replace materials after the cleanup. Most, though not all, of the guidance on mold cleanup is directed towards remediation professionals, rather than homeowners or community volunteers who might be engaged in such efforts following a large scale event. This focus is due to the potential for significant mold exposures and subsequent health effects from the mold during the cleanup if not using personal protective equipment, as well as from chemicals that might be used in the cleanup.

Other relevant efforts

While there has been much attention given to mold due to flooding and other causes, including the development of useful guidance on remediation and repair, no activities have been identified on planning for large scale flooding events and the massive remediation efforts that would likely be required to make a community safe and livable after the event is over. Similarly, guidance appears to be lacking on how to determine if a building is safe for occupancy after a flooding event with respect to the presence of mold. ASHRAE and the Indoor Environmental Standards Organization have recently issued a standard for public comment, i.e., BSR/IESO/ASHRAE Standard 3210, Standard Guide for the Assessment of Education Facilities for Moisture Affected Areas and Fungal Contamination. While this standard, as drafted, deals with assessment only, it could serve as a first step in the development of a broader set of standards on mold remediation. FEMA (2006) provides general guidance on mold remediation including use of containment strategies, personal protective equipment, and mold remediation methods (such as wet vacuuming, damp wiping, high efficiency particulate vacuuming, and discarding materials).

Summary

Mold growth and bioaerosol exposure due to floods has the potential for serious health outcomes, possibly affecting large numbers of buildings and building occupants. While some guidance exists on remediation of mold and repair of water damaged building materials, larger scale response efforts have not been addressed and are likely to constitute a significant challenge in terms of training sufficient numbers of remediation workers and protecting homeowners who might be inclined to do their own remediation work. If climate change does increase the frequency and severity of flooding, these concerns are going to become more of an issue. There has been limited development of standards in this area, with additional efforts needed in terms of remediation and defining criteria to clear buildings for reoccupancy.

2.4 Wildfires

It is well-established that smoke from wood and other plants contains significant quantities of health-damaging pollutants (e.g., polycyclic aromatic hydrocarbons, benzene, aldehydes, respirable particulate matter, carbon monoxide [CO], nitrogen oxides [NOx], and other free radicals), some of which are carcinogenic compounds (Naeher et al. 2007). Finlay et al. (2012) reviewed numerous studies on the health effects of wildfires and concluded that published evidence shows that human health can be severely affected by wildfires. They also described specific health effects (dominated by respiratory morbidity but including cardiovascular and ophthalmic problems) and vulnerable populations, and identified factors that may reduce public health risk from wildfires. Some of those studies have focused on the health impacts of firefighter exposure to smoke, but such exposure is outside the scope of this effort. In contrast, Fowler (2003) reviewed the literature and found the evidence for human health impacts from forest fire smoke to be somewhat equivocal.

In one study, Mott et al. (2002) assessed the health effects of exposure to smoke from a large wildfire in 1999 and evaluated whether participation in interventions to reduce smoke exposure prevented adverse lower respiratory tract health effects among residents of the Hoopa Valley National Indian Reservation in northwestern California. They found that an increased duration of the use of high-efficiency particulate air cleaners and the occupants' recollection of public service announcements were associated with reduced frequency of reporting adverse health effects of the lower respiratory tract, but no protective effects were observed for duration of mask use or evacuation.

Increased outdoor temperatures, heat waves, and number and severity of droughts due to climate change are expected to contribute to increased wildfires, including a significant increase in average acreage burned in the western U.S. (Spracklen et al. 2009). Increased wildfires in the U.S. may lead to greater exposure to airborne particles, much of which happens while people are indoors, and, therefore, potentially increased adverse health effects (Fisk 2015). Fisk also identified improvements in particle filtration as a mitigation measure for protection against particles from wildfires.

To address the need for evidence based guidance for public health decision making during wildfire smoke events, the British Columbia Centre for Disease Control (BCCDC) recently completed a series of systematic reviews, which has produced several documents addressing wildfire-related topics: Home and community clean air shelters (Barn 2014), Reducing time outdoors (Dix-Cooper 2014), Public health risk (Durán 2014), Filtration in institutional settings (Keefe 2014), Health surveillance (Morrison 2014), Use of evacuation (Stares 2014), Using masks to protect public health (Sbihi 2014), and Exposure measures for wildfire smoke surveillance (Yao 2014).

Conclusions reached from the BCCDC reviews on measures to mitigate the health effects include the following:

- Reviewed air sampling studies suggest that staying indoors can be effective at reducing wildfire smoke exposure (using particulate matter (PM) as an indicator) when a building has little air infiltration from outdoors, for shorter duration wildfires, when sources of indoor air pollution are minimal and if effective indoor air cleaners are used (Dix-Cooper 2014).

- Filtering half facepiece respirators (FHFR), such as N95 masks, provide effective protection against PM. FHFRs are cost effective and can be stockpiled for use at the population level during wildfire events (Sbihi 2014).
- Filtration is a potentially effective intervention to reduce PM2.5 (particulate matter with diameter of 2.5 μm or smaller) exposures among community members exposed to wildfire smoke. Filtration can be implemented by establishing home clean air shelters (HCAS) (using portable or in-duct filters) or community clean air shelters (CCAS) (using in-duct filters in larger public buildings). (Barn 2014)
- When determining the appropriateness of filtration in smoke-affected communities, several things should be considered, including the intensity of the smoke event, timing and preparation for and implementation of filtration, and availability of potential CCAS. (Barn 2014)
- The effectiveness of existing healthcare institutional filtration systems may be enhanced with the use of pre-filters or higher MERV rated filters, more frequent change-out of the filters, as well as portable air cleaning devices equipped with HEPA filters. (Keefe 2014)
- Those wildfire smoke response guidelines that do consider evacuation to reduce smoke exposure recommend it only for those who are vulnerable rather than for entire populations. Vulnerable individuals include both those who are particularly susceptible to health effects from smoke exposure and those requiring special assistance for evacuation. Evacuation decisions (who, how best, and when to evacuate) can be part of a blend of interventions for the general population and subpopulations with particular sensitivities and vulnerabilities. (Stares 2014)

Other considerations mentioned in the BCCDC reviews include:

- When recommending HCAS (Barn 2014):
  - Poor quality housing, as well as older housing, is expected to have higher infiltration rates, making such homes less effective as HCAS.
  - Availability of central air conditioning will encourage residents to remain indoors with windows closed.
  - More than one portable air cleaning unit may be required for large rooms or homes with high air change rates.
- When identifying potential community clean air shelters (CCAS) (Barn 2014):
  - Consider whether large air conditioned spaces are available and whether it is feasible to use these spaces over the short term (hours) and long term (days to weeks).
  - For communities where wildfire smoke is a frequent seasonal exposure, installation of high efficiency filters in community shelters before the fire season may be needed. For other communities, establishing an inventory of buildings with sufficient conventional in-duct filtration may be a more feasible approach.
  - Upgrades to buildings may be required to provide adequate electrical power, fan capacity, or structural support to handle the added airflow resistance of high efficiency in-duct filtration.
- When considering CCAS versus HCAS (Barn 2014)
  - The benefits of potentially more effective filtration obtained intermittently at CCAS should be weighed against less effective but more consistent filtering obtained in HCAS for extended periods of time.

    - Encouraging individuals to remain in CCAS may be a challenge if extended stays are required. If smoke events are expected to persist, HCAS might be a more viable option than encouraging prolonged stays at CCAS.
- Vulnerable populations, including children, the elderly, pregnant women, and those with pre-existing respiratory and cardiovascular disease, may be at higher risk of adverse health effects related to wildfire smoke, and therefore may benefit most from decreased exposures through filtration. Measures to best implement the use of filters among these groups should be considered (e.g., high efficiency in-duct filters could be installed in long-term care and retirement facilities and schools). Additionally, portable filters could be preferentially made available to homes with children or elderly occupants. (Barn 2014)
- Because of its episodic nature, smoke from wildfires can quickly overload filters and adversely impact an air cleaner's ability to function properly. (Keefe 2014)
- It is theoretically possible to set up clean air shelters in areas of institutions with positive pressure and higher filtration efficiency (e.g., operating rooms); however, it is not clear how the necessary alterations in the HVAC system may affect airflow and filtration in other areas of the hospital. Therefore each such alteration should be individually designed by a qualified professional to ensure that important HVAC functions, including infection control, are maintained. (Keefe 2014)
- In the absence of adequate in-duct filtration in an institution, the development of clean air shelters using portable HEPA filters is a reasonable approach. (Keefe 2014)

Other international, federal and state agencies, and private organizations have addressed the health threats posed by wildfire smoke in various publications (EPA 2003, CDC 2007, CDPH 2008, PEHSU 2011, WHO). These documents describe the hazards due to wildfire smoke, vulnerable populations, acute and chronic health impacts, and steps to mitigate the hazard.

Standards and guidance

While there are no standards on protecting building occupants from airborne contaminant exposure associated with wildland urban interface (WUI) fires, there are several guidance documents. In addition to describing the hazard and health impacts related to vegetation fires, the WHO/UNEP/WMO Health Guidelines for Vegetation Fire Events - Guideline Document (WHO/UNEP/WMO 1999) discusses mitigation measures in detail including remaining indoors, use of air cleaners, use of respirators (but not dust or surgical masks), outdoor precautionary measures, and evacuation to emergency shelters. Many of the recommendations are fairly general such as taking action to "reduce infiltration" and installing and maintaining "effective filters." While moving susceptible individuals to emergency shelters with effective particle filtrations is a protection strategy option, the emergency evacuation of whole populations to other geographical locations in response to smoke haze is not recommended as a mitigation measure. Similar guidance is available in documents published by the EPA (2003) and the CDC (2007).

The California Department of Health and others (CDPH 2008) provide similar guidance but also warn of the potential increased risk of heat stress for at-risk individuals when staying inside without air-conditioning, since fire season typically occurs during the hottest part of the year. Such individuals may be advised to seek shelter with others or go to a community Clean Air Shelter. General recommendations for identifying and setting up Clear Air Shelters are provided. The CDPH document also discusses reducing occupant activity and other sources of indoor air pollution, considering residential air cleaners (but not ozone generators), and possibly using humidifiers in arid climates.

The BCCDC recently published preliminary guidelines for British Columbia public health decision-making during wildfire smoke events based on recommendations from an international working group (Elliott 2014). This guidance describes wildfire smoke hazards and identifies health effects associated with wildfire smoke exposure and susceptible populations. It provides BC-specific guidance about tools for situational awareness, including smoke and health surveillance. It then summarizes the evidence for effectiveness of intervention measures to protect public health. A consideration raised in the guidance is that most current guidelines use PM concentration thresholds as the basis to recommend various public health intervention measures. However, it is not clear whether these thresholds are appropriate for wildfire smoke because they are derived from studies based on urban PM health effects not wildfire smoke. As with the other guidance, recommendations address public communications, staying indoors, wearing N95 respirators, using home clean air shelters, providing community clean air shelters, increasing air filtration in institutions and evacuation.

There are numerous programs and activities in place that address smoke from wildfires. These include documents published by the EPA (2003), the CDC (2007), and WHO (1999), as well as guidance from many states (e.g., CDPH 2008 and CDPHE 2006). This guidance addresses monitoring, public notification and education, and mitigating public exposure.

The International Wildland-Urban Interface Code (ICC 2012) and the NFPA Fire Code (NFPA 2015a) contain provisions addressing wildfire issues such as fire spread, accessibility, defensible space, and water supply for buildings constructed near wildland areas, but do not address the threat from exposure inside buildings associated with smoke from wildfires. The NFPA has proposed NFPA 1616, Standard for Mass Evacuation and Sheltering, whose purpose is to establish a common set of criteria for the process of organizing, planning, implementing, and evaluating programs for mass evacuation, sheltering, and reentry (NFPA 2015b). Wildland fires are among the many hazards to be considered in such programs, but there is not specific guidance related to addressing indoor exposure to smoke from such fires.

<u>Other relevant efforts</u>

The BCCDC review identified several knowledge gaps, which could support future guidance efforts, including the following:

- Evidence that staying indoors reduces smoke exposure would be strengthened by studies with improved personal exposure assessment and those that examine populations living in a wide range of housing types and geographical areas (Dix-Cooper 2014).
- The effectiveness of respirators as a public health intervention has not been fully evaluated (Sbihi 2014).
- Most studies of portable air cleaners report on “best case” scenarios and do not take into consideration variations in usage, indoor activities, or housing characteristics. (Barn 2014)
- Effectiveness of portable air cleaners over longer use periods (e.g., months) has not been well studied. (Barn 2014)
- There is a lack of research on the impact of in-duct filters in reducing infiltration of PM from wildfire smoke. (Barn 2014)

- There is a dearth of evidence on the effectiveness of filtration to reduce wildfire smoke exposures in healthcare institutional settings. (Keefe 2014)
- There is no literature specifically examining the issue of infiltration of wildfire smoke particles into healthcare institutional settings. (Keefe 2014)
- It is not clear how best to use existing filtration capacity within healthcare facilities' HVAC systems to create clean air shelters. (Keefe 2014)
- It is not clear how to use portable filtration to establish clean air shelters within healthcare facilities. (Keefe 2014)
- A blend of targeted mandatory and voluntary evacuation, clean air shelters and other measures may be used to reduce smoke exposures across a population. However, it is not clear how best to combine these measures to maximize benefits and minimize harm. (Stares 2014)

Summary

The health impacts of wildfire smoke entry on building occupants is well recognized and guidance addressing monitoring, public notification and education, and mitigating public exposure has been available from state, federal, and international agencies for more than a decade. However, this guidance could be more specific such as providing specific levels of filtration or air cleaning device ratings needed to provide significant reductions in particle concentrations. A recent systematic review of the evidence-based guidance for public health decision making during wildfire smoke events identified many important gaps in knowledge that could be addressed by future research. These gaps include studies of the effectiveness of portable air cleaner usage that consider real-world variations in usage and housing characteristics and development and evaluation of guidance on how to establish clean air shelters in healthcare facilities using either existing HVAC system filtration capacity or portable air cleaners.

2.5 Airborne releases of chemical, biological, or radiological agents

Exposures to airborne chemical, biological, and radiological (CBR) releases have been of interest for many years, with increased attention since the terrorist attacks of 2001. In the context of community resilience, outdoor CBR releases, whether intentional or not, are most relevant to indoor exposures. Unintentional releases include a range of events such as industrial plant accidents, releases associated with accidents involving the transportation of hazardous substances, and earthquakes and other disasters damaging chemical facilities, water treatment plants and other facilities. These types of releases have the potential for generating large airborne plumes of hazardous substances that can impact the occupants of buildings downwind from the release site. The release of a CBR agent in urban areas has been identified as a homeland security threat of particular concern (GAO 2008), and the Department of Homeland Security has pursued a number of strategies to plan for and respond to such releases (DHS 2009). In the event of such a release, hundreds, even thousands, of buildings and building occupants could be affected, leading to large economic costs and other disruptions (Judd, et al. 2009; Franco and Bouri 2010). The resilience issues related to outdoor CBR releases include approaches to warning building occupants and recommending either evacuation or sheltering in place, identification of buildings impacted by such releases, building decontamination, and clearing buildings for reoccupancy.

Standards and guidance

While there are no standards on protecting building occupants from outdoor CBR agent releases, there are several guidance documents. The National Institute of Occupational Safety and Health (NIOSH) issued two such guidance documents early in the 2000s. The first (NIOSH 2002) provides general guidance on protecting building environments from airborne CBR agents, including how to modify existing buildings, how to design new buildings that are more secure, and plans for building managers to prepare in advance for a potential CBR incident. While this was a relatively short document, it provided sound guidance. NIOSH followed a year later with another document specific to the roles of particle filtration and gaseous air cleaning in protecting buildings against potential CBR releases (NIOSH 2003).

Several years later, ASHRAE published Guideline 29, Guideline for the Risk Management of Public Health and Safety in Buildings (ASHRAE 2009). This document provides guidance beyond just CBR incidents on how to design, operate and maintain buildings using a general risk management approach. It contains specific guidance on building CBR protection related to building airtightness, HVAC systems, and air cleaning and filtration. It does not address building decontamination and reoccupancy or other such issues that fall under community resilience.

FEMA and other groups within DHS have also issued guidance on protecting buildings against potential CBR attacks. Of particular relevance are FEMA 430, Site and Urban Design for Security Guidance Against Potential Terrorist Attacks (FEMA 2007), and BIPS 06, Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings (DHS 2011). The former document contains information relevant to the design of building sites, including discussion of CBR issues and both protection and response strategies. The latter document contains more information specific to CBR threats including strategies to reducing building vulnerability using a range of engineering approaches and plans for responding to emergencies including training, decision-making and building restoration. These and other FEMA documents also address shelter-in-place approaches, but these approaches are discussed later in this report.

Other relevant efforts
There are several programs and activities in place to address CBR releases that have the potential to impact indoor environments.

The Chemical Stockpile Emergency Preparedness Program (CSEPP) is a partnership between FEMA and the U.S. Department of the Army that provides emergency preparedness assistance and resources to communities surrounding the Army's chemical warfare agent stockpiles. At this point, most of the Army stockpiles have been destroyed, but this program has generated a range of useful materials for planning and responding to incidents involving one of the remaining stockpiles that would also be potentially applicable to other chemical incidents. Available CSEPP resources include a shelter-in-place guide book on planning and implementing temporary SIP in response to airborne chemical hazards (Yantosik 2006) and detailed guidance on conducting exercises (U.S. Army/DHS 2012). CSEPP is currently developing a public affairs workbook on community education and emergency public information programs for government public affairs offices, and a guidance document for public alert and warning systems.

The National Institute for Chemical Studies (NICS, www.nicsinfo.org/SIPcenter.asp) is a non-profit organization that works mainly through federal, state, county and local government agencies as well as businesses on a broad range of projects related to chemical risks in communities. Examples of NICS projects include research, education, training, and consultation on various topics related to chemical accidents and releases. One of their more relevant efforts is the development of information on SIP as a strategy to reduce exposure during chemical releases (NICS 2001).

The U.S. EPA's Emergency Management website (http://www.epa.gov/emergencies/index.htm) describes a range of activities related to responding to various environmental emergencies, including responding to hazardous releases in coordination with federal, state, and local agencies. These activities fall under the National Response System (http://www2.epa.gov/emergency-response/national-response-system), which is set up to respond to environmental releases. While the material available under these and related programs cover the response processes, they do not focus on specific exposure scenarios such as those associated with the indoor environment. EPA's National Homeland Security Research Center (http://www.epa.gov/nhsrc/) is another part of the agency that performs research into ways to decontaminate buildings and public areas. This work includes determining whether an attack has happened, characterizing the extent of its impacts, controlling contamination, assessing and communicating risks, getting useful information to first responders, and safely disposing of cleanup materials.

Two studies at NIST provide useful information for reducing occupant exposure to potential CBR releases. The first was a study of retrofit options to increase building protection, which included detailed discussion of when these options are most applicable and their advantages and disadvantages (Persily et al. 2007). The options relevant to outdoor CBR releases included enhanced particle filtration, gaseous air cleaning, envelope airtightening, building pressurization, relocation of outdoor air intakes, SIP, and HVAC system responses. Another NIST effort was focused on the development of a systematic approach to identify which buildings are more or less likely to be contaminated by an outdoor CBR release and to what level (Persily 2011). This approach, in which the design and operational characteristics of specific buildings are used to estimate contamination levels, is referred to here as "building triage" and is intended to assist in allocating resources for sampling and decontamination, and for facilitating the clearance of buildings for reoccupancy. The referenced report constitutes a first step in the development of the triage approach, specifically an initial description of the concept, the development of an associated building classification system, and the definition of generic building models.

Summary

Outdoor CBR releases have been the focus of much discussion, research and guidance in recent years, with the focus being more on intentional attacks than on accidental releases. However, much of the guidance on protecting against and responding to intentional releases also applies to unintentional CBR release events. This guidance addresses how to make a building less vulnerable to outdoor releases through a range of engineering controls such as filtration and air cleaning and HVAC system controls using active sensing in some cases, but these strategies may be harder to justify economically in buildings other than high-profile facilities that may be more likely targets for intentional attack. There has also been important work in the area of building decontamination after a release but important questions remain such as identifying the most appropriate decontamination strategy in a given building for a given agent, how to deal with large numbers of buildings that might be affected, and finally how to determine when a building is clean enough for reoccupancy.

3. OTHER ISSUES

In addition to the events discussed above, this section discusses two additional topics that are relevant to IER. These include the role of healthcare facilities in responding to pandemics and indoor environmental conditions in safe rooms and shelter-in-place facilities.

3.1 Pandemic response

The fact that healthcare facilities play a key role in community-based disaster resilience is well recognized, and the need for these facilities to be operational following disasters is addressed in the NIST CRPG. However, the response to a pandemic infection is not specifically addressed. Nevertheless, it constitutes a need for preparation and response on both the individual building and community levels. This topic is reviewed briefly in this paper and is an important candidate for follow-up work.

The Centers for Medicare & Medicaid Services (CMMS) recently published a proposed rule that would establish national emergency preparedness requirements for Medicare- and Medicaid-participating providers and suppliers to ensure that they adequately plan for both natural and man-made disasters, and coordinate with federal, state, tribal, regional, and local emergency preparedness systems (CMMS 2013). Previously, the CDC published guidance on public health preparedness capabilities including surge management (CDC 2011). One hazard planning scenario in the CMMS proposed rule's scope is biological disease outbreak, including pandemic influenza. One key issue to be addressed is establishing the capacity to address a surge in patients seeking treatment. ASHRAE (2014) recommends that new health-care facilities incorporate infrastructure to quickly respond to a pandemic: such as HVAC systems that separate high-risk areas, physical space and HVAC system capacity to upgrade filtration; the ability to increase ventilation to 100 % outdoor air; the ability to humidify air; and, receptacles to enable air cleaning using upper-room ultra-violet germicidal irradiation (UVGI). Mead et al. (2012) evaluated expedient methods for surge airborne isolation space in existing healthcare facilities during response to a natural or manmade epidemic, noting that further research is needed to evaluate the options. A tool such as the NIST CONTAM model could be used for such a study, as has been done previously to evaluate airflow and infectious agent transport in healthcare facilities (Emmerich et al. 2013).

ASHRAE Standard 170-2013 Ventilation of Health Care Facilities contains ventilation system design requirements that provide environmental control for comfort, asepsis, and odor in health care facilities. It does not address emergency situations, such as accommodating pandemics in the community or functioning with emergency power. An infectious disease management manual published by the Minnesota Department of Health (MDH 2013) provides guidance on providing temporary negative pressure isolation space in healthcare facilities.

3.2 Indoor Environments in Safe Rooms and SIP Facilities

Safe rooms and shelter-in-place (SIP) facilities are discussed in the context of community resilience for providing temporary protection against the hazards associated with many different events. These discussions often focus on tornados and other severe weather events, as well as many of the indoor environmental events discussed in this report such as heat waves, loss of power, wildfires, and CBR releases. FEMA has published several guidance documents on safe rooms for sheltering from storms. The first document (FEMA 2008a) focuses on tornadoes and hurricanes and the design of such facilities in terms of location in a building, size, and structural issues. FEMA P-361 (2008b) addresses the need for ventilation in both residential and community safe rooms, making reference to the ventilation requirements in building codes The ventilation requirements contained in this FEMA document do refer to ICC 500, ICC/NSSA Standard for the Design and Construction of Storm Shelters (ICC 2008). If mechanical ventilation is provided, it should be connected to a standby power system and, for single-use safe rooms, 7.5 L/s per person is the recommended minimum ventilation rate in the FEMA document. The ICC standard refers to applicable building code provisions for mechanical ventilation rates, which as noted earlier in this report are developed for application under normal building occupancy. The FEMA and ICC documents both specify that hurricane safe rooms designed for occupancy by more than 50 people must use mechanical ventilation at a minimum rate determined in accordance with applicable building code provisions for the normal use of the space. These documents also contain ventilation opening areas per occupant for both residential and community tornado and hurricane shelters. Neither the FEMA nor the ICC documents consider air conditioning or heating as part of the design criteria for safe rooms due to the expected short duration of occupancy.

FEMA 453 addresses shelters and safe rooms for protection against terrorist attacks, including outdoor CBR agent releases (FEMA 2006). This document recommends a minimum ventilation rate of 7.5 L/s per person based on the International Mechanical Code (IMC). These documents also contain minimum floor areas per person depending on the age and position of the occupants (e.g., standing, seated or bedridden), and the duration of the sheltering event. In terms of temperature control, this document states that safe rooms do not require heating or cooling, but acknowledges that conditions can become intolerable without heating or cooling. The U.S. military has design guidelines for collective protection shelters against CBR agents, which contain target outdoor air ventilation requirements consistent with ASHRAE Standard 62-99 (U.S. Army Corps of Engineers 1999).

While these documents recognize the need for adequate ventilation, the issue remains as to how these spaces will be ventilated in the event of power failures and whether the design ventilation rates are sufficient if extended sheltering times are necessary, since these spaces are typically intended for short term sheltering only. The ventilation requirements contained in ASHRAE Standard 62.1 and 62.2, building codes and other such documents are intended for normal operation and usage and do not address extreme conditions of extended sheltering and overcrowding or occupants with pre-existing health conditions. Similarly, the control of temperature and humidity levels is not dealt with in these guidance documents and not under conditions of power outages, extended sheltering periods, and recognizing the needs of sensitive populations.

4. STANDARDS

In reviewing the events and issues related to IER, this effort also considered existing standards and guidance documents related to post-event conditions. As part of this review, standards development needs were identified.

As noted earlier, ASHRAE has several standards related to indoor environmental conditions in buildings. These include Standards 62.1 and 62.2, which cover ventilation and IAQ. The scope of Standard 62.1 includes commercial, institutional, and high-rise residential buildings, while Standard 62.2 covers low-rise residential. (Note that the scopes of both standards are in the process of being revised such that Standard 62.2 will include all residential occupancies.) Both of these standards focus primarily on design and construction of new buildings or significant renovations. While they can be useful in evaluating existing buildings, they do not address operation of existing buildings to any significant degree. They also do not address extraordinary circumstances such as power outages, extreme weather events or conditions, or unusual outdoor pollutant events (such as outdoor chemical releases). The required ventilation rates (and other requirements such as filtration) are defined to support occupant health and comfort under normal circumstances and were not developed to serve as minimums to provide a tolerable environment for shorter-term human occupancy during or after an extreme event. Nor do they specifically speak to susceptible populations, who might be more vulnerable to some of the extreme circumstances relevant to this discussion.

ASHRAE Standard 170, Ventilation of Health Care Facilities, is also focused on design and construction of new buildings or significant renovations and does not address operation of existing buildings to any significant degree. It does have requirements for ventilation under loss of electrical power for several critical space types, such as airborne isolation rooms. It also has heating and cooling requirements when the primary systems break down or are under maintenance. Other than that, it does not address extraordinary circumstances such as power outages, extreme outdoor weather events or conditions, or unusual outdoor pollutant events, nor does it speak to emergency situations such as accommodating pandemics in the community. The required ventilation rates are defined to support occupant health and comfort under normal circumstances, as well as to reduce hospital-acquired infections, but do not serve as absolute minimums that humans can tolerate.

ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy, specifies indoor environmental conditions (e.g., air temperature, relative humidity, and air speeds) that will be acceptable to a majority of the occupants within the space. This standard has historically been focused more on mechanically ventilated commercial buildings than on residential, though more recently it has addressed the issue of naturally ventilated buildings. But it is still about thermal comfort when buildings are being operated as designed and does not address extraordinary circumstances such as power outages and extreme outdoor weather events or conditions. Also, it is about comfort, not physiological concerns such as heat stress.

ASHRAE/IES/USGBC Standard 189.1, Standard for the Design of High-Performance Green Buildings (except low-rise residential), contains IEQ requirements consistent with its goal of supporting high-performance buildings. In terms of IEQ, it references the requirements of ASHRAE Standards 55, 62.1 and 170, with some additional requirements addressing ventilation monitoring, filtration and air cleaning, volatile organic compounds emissions from building materials, and other items. While it is aiming for a higher level of performance, Standard 189.1 does not address extreme conditions and other aspects of resilience.

ASHRAE has also published two guidelines of interest in the context of IER. The first, Guideline 10 Interactions Affecting the Achievement of Acceptable Indoor Environments, describes how different indoor environmental factors interact to determine occupancy acceptability of a space. While this document recognizes the complex interactions of these various factors, for example how air temperature impacts perception of chemical odors, it is focused on normal conditions, not extreme events or occupancy when heating, cooling, and ventilation may be severely limited. The other ASHRAE Guideline, Guideline 29 for Risk Management of Public Health and Safety in Buildings, has already been discussed in this report. As noted earlier, this document provides a very general framework on moving from threat assessment to risk categorization, then using the “decision makers” evaluation criteria to define interventions. It speaks to a broad range of threats including natural disasters, accidents, and intentional acts including both criminal and terrorism. It speaks to a broad range of issues and offers some general recommendations on each. These issues include building siting, utilities, the building envelope, HVAC, food service, fire protection, communications, etc. The treatment of each is rather uneven, with a lot of detail on air filtration, for example, and much less on many others. It has material on operation and maintenance of existing buildings as well as training of staff and occupants.

The U.S. Department of Housing and Urban Development (HUD) Manufactured Home Construction and Safety Standards (24 CFR Part 3280, 1994) contains a broad range of requirements related to the design and construction of manufactured homes. The HUD regulation contains ventilation requirements as well as heating and cooling system requirements, but it is focused on normal conditions of occupancy and not extreme events.

5. DISCUSSION AND FOLLOW-ON ACTIVITIES

This report has reviewed existing technical information related to disaster events that are likely to impact IER with a focus on post-event IAQ. The purpose of the review was to describe the scope and potential impacts of these events, current activities that are addressing these issues, important gaps requiring research and other technical analyses, and needs for standards and related guidance. The primary events reviewed in detail include heat waves, power outages, floods and mold exposure, wildfires, and airborne releases of chemical, biological or radiological agents. Other issues discussed include sheltering-in-place and responses to pandemic infection events. While the amount and detail of available technical information varies across these events, it is clear that these topics have received growing interest in recent years due to high profile events, such as heat waves, hurricanes and major storms, wildfires, and terrorist attacks, as well as government initiatives in response to these events. Despite the attention given to these areas, their impact on indoor environment resilient issues is not fully appreciated in many discussions.

This review has identified important knowledge gaps requiring research as well as the need for improved and more relevant standards and guidance. Additionally, much of the existing knowledge needs to be better integrated into a more comprehensive community resilience approach, such as the one being established in the NIST Community Resilience program, to maximize its impact.

The important research gaps identified include the following, organized by the type of event:

- Heat waves: Development and evaluation of passive design approaches and building retrofit measures to avoid overheating during heat waves. Such research needs to consider a variety of building types (i.e., single family and high-rise residential, institutional) and building occupants (i.e., beyond only healthy adults).
- Power outages: Definition of short term acceptable ventilation and IAQ conditions (beyond thermal comfort) for living and working in buildings temporarily during power outages which impact HVAC system function.
- Floods: Coupled thermal/airflow simulation tools to better predict conditions that will lead to the potential for mold growth.
- Wildfires: The BCCDC review of evidence based guidance for public health decision making during wildfire smoke events identified a number of research topics relating to the infiltration of smoke into buildings and the use of air cleaning to create clean air shelters in buildings.
- Airborne CBR releases: Building protection approaches based on design and system operation in new and existing buildings. Tools to identify buildings most likely to be impacted by outdoor releases. Determination of how clean is clean enough following decontamination. Tools to support deciding between evacuation and sheltering in place.
- Pandemic response in healthcare facilities: Evaluation and comparison of options to create surge airborne isolation space and temporary negative pressure isolation space and the impacts on overall building operation.
- Sheltering in place and safe rooms: Development of detailed coordinated guidance to deal with community-wide sheltering in response to events such as heat waves, CBR releases, wildfires, and power outages.
- Metrics and tools to help communities identify building classes that may be subject to poor IER conditions, and to support planning for improved performance.

Several topics for potential standards development were identified during this effort and are summarized below. Some are motivated by the fact that most published standards and guidance relevant to indoor environmental quality consider only normal operating conditions for buildings, e.g., ASHRAE Standards 55, 62.1 and 62.2, which cover thermal comfort and ventilation. A need exists to develop standards and guidance to address these requirements during or following a disaster, when indoor conditions may not be consistent with normal operation and occupancy. Specific standard and guidance needs identified in this effort include the following:

- A thermal "comfort" standard or guideline that covers conditions outside the current scope of Standard 55. Such a document should define conditions that are safe for both residential occupants (including other than healthy adults) and non-industrial occupants during heat waves and power outages.
- Ventilation standards or guidelines that cover extreme conditions, which are currently beyond the scopes of Standards 62.1 and 62.2. Such documents might include separate requirements for safe rooms and shelter-in-place facilities.
- Current efforts underway at CPSC and UL to address CO emission limits from portable generators should be continued.
- Guidance should be developed and provided for homeowners and volunteers engaged in mold/wet building cleanup following large scale flooding events.
- Specific guidance to support deciding between evacuation and sheltering-in-place in response to wildfires and CBR releases.
- Standards for portable air cleaner performance to reduce indoor particulate exposure during wildfires, and guidance on system selection.

As efforts to increase community disaster resilience continue, the indoor environmental impacts need to be considered and their proper role identified. This report provides the background to support these discussions.

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