Homeland Defense & Security Information Analysis Center

DEPARTMENT OF DEFENSE CONSIDERATIONS FOR DISASTER RESPONSE

State of the Art Report

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STATE OF THE ART REPORT:
Department of Defense Considerations for Disaster Response

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2018

Contract Number: FA8075-13-D-0001

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Acronyms

AI .... Artificial Intelligence
AIDR .... Artificial Intelligence for Digital Response
ANG .... U.S. Air National Guard
APR .... Air-purifying respirator
APRS .... Automatic Packet Reporting System
AR .... Augmented Reality
AUDREY .... Assistant for Understanding Data through Reasoning, Extraction and Synthesis
CBP .... Customs & Border Protection
CBRN .... Chemical, Biological, Radiological, and Nuclear
CDC .... Centers for Disease Control and Prevention
CEX .... Emergency Management Office
CIMS .... Crisis Incident Mangement System
DARPA .... Defense Advanced Research Projects Agency
DHS .... Department of Homeland Security
DoD .... Department of Defense
DOE .... Department of Energy
DOMOPS .... Domestic Operations
DOT .... Department of Transportation
DRC .... DARPA Robotics Challenge
EOC .... Emergency Operation Center
EPA .... Environmental Protection Agency
ERHMS .... Emergency Responder Health Monitoring and Surveillance
FAA .... Federal Aviation Administration
FEMA .... Federal Emergency Management Agency
GIS .... Geographic Information System
GPS .... Global Positioning System
HDIAC .... Homeland Defense and Security Information Analysis Center
IAFF .... International Association of Fire Fighters
IC .... Incident Commander
ICMS .... Incident & Crisis Management System
ICS .... Incident Command System
IEEE .... Institute of Electrical and Electronics Engineers
IND .... Improvised Nuclear Device
IoT .... Internet of Things
ISA .... Integrated Sensor Architecture
ISO .... International Organization for Standardization
LiDAR .... Light Detection and Ranging
LMR .... Land Mobile Radio
LORELEI .... Low Resource Languages for Emergent Incidents
NFPA .... National Fire Protection Association
NIMS .... National Incident Management System
NIOSH .... National Institute for Occupational Safety and Health
NLP .... Natural Language Processing
NOAA .... National Oceanic and Atmospheric Administration
NRC .... Nuclear Regulatory Commission
NRF .... National Response Framework
NVESD .... Night Vision Electronic Sensors Directorate
OR .... Operations Research

PAPR .... Powered air-purifying respirators
PAST..Public Affairs Science and Technology
PCD ....Pueblo Chemical Depot
PPE...Personal Protective Equipment
Rad/Nuc .... Radiation/Nuclear
RDD .... Radiological Dispersal Device
RF .... Radio Frequency
ROSS... Radiological Operations Support Specialist
RUL..Remaining Useful Life
SAR.. Search and Rescue
SCBA .... Self-contained breathing apparatus
SCM ....Supply Chain Management
SCUBA..Self-contained underwater breathing apparatus
SLAM ....Simultaneous Localization and Mapping
SMS ....Short Message Service
SOAR..State of the Art Report
UAS.. Unmanned aerial systems
UAVs...Unmanned Aerial Vehicles
UGV ....Unmanned Ground Vehicles
USAR ....Urban Search and Rescue
USARIEM…….United States Army Research Institute of Environmental Medicine
USCG... U.S. Coast Guard
VOST ....Virtual Operations Support Teams
VR .... Virtual Reality
WMD..Weapons of Mass Destruction

Executive Summary

The Homeland Defense & Security Information Analysis Center (HDIAC) develops annual State of the Art Reports (SOARs) on scientific and technical topics that are highly relevant to the Department of Defense (DoD). This SOAR focuses on technologies and methods relevant to disaster response, in part because 2017 saw an unprecedentedly high number of major hurricanes make landfall in the United States. The concept and practice of disaster response aligns with at least five of HDIAC's focus areas:

- Critical Infrastructure Protection
- Chemical, Biological, Radiological, and Nuclear (CBRN) Defense
- Cultural Studies
- Homeland Defense and Security
- Medical

Because disaster response is a broad and diverse field, this report addresses six areas in which scientific and technical (S&T) research and development (R&D) are most likely to intersect with improving disaster response practices relevant to DoD and defending the homeland. These areas are communications management, data management, responder protection, search and rescue (SAR) technologies, supply chain management, and radiation emergencies.

This report also highlights six areas of technology likely to have an outsized effect on the current state and future practice of disaster response. These are blockchain technology and software, autonomous systems or drones, networked devices known as the Internet of Things (IoT), artificial intelligence (AI) (sometimes known as or associated with machine learning), robotics, and the use of social media in response activities. Use of these technologies has already contributed to the safety of first responders and enhanced situational awareness in response situations.

1

Introduction

Gregory Nichols, HDIAC

2017 was an unprecedented year regarding disasters (see Figure 1). Sixteen weather events caused damage exceeding $1 billion for each [1]. These billion-dollar disasters included three major hurricanes classified as a Category 3 or higher on the Saffir-Simpson Hurricane Wind Scale [2], breaking a record for three Category 4 or higher landfalls in one year [3]. Hurricane Maria's cost is estimated at approximately $92 billion [3].

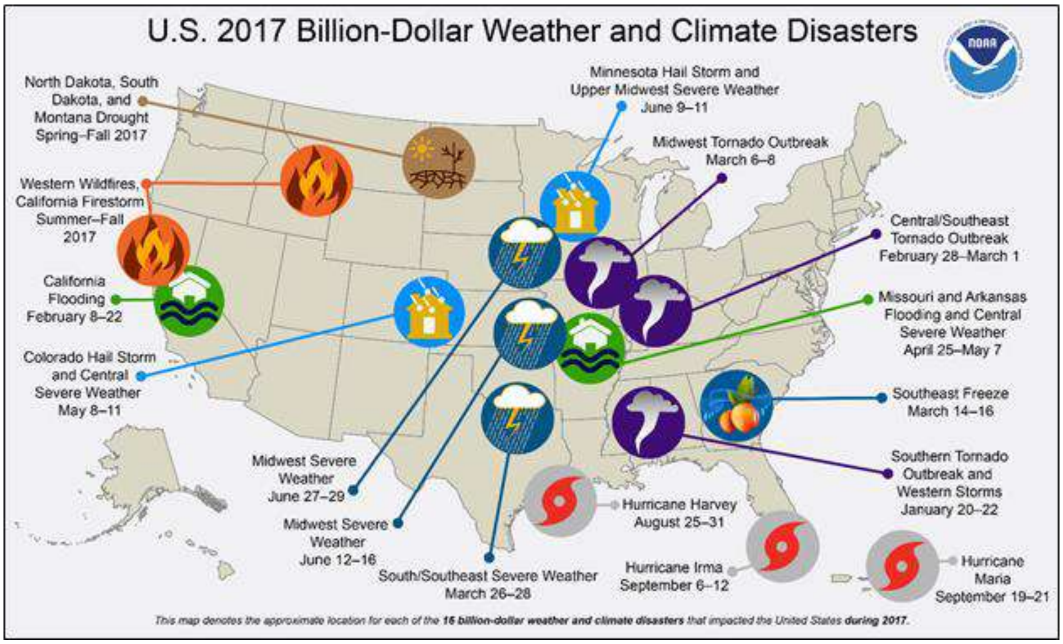

Figure 1. Overview of 2017 billion-dollar weather-related disasters [1].

The International Federation of the Red Cross and Red Crescent Societies defines a *disaster* as "a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources [4]."

In the U.S., the National Response Framework (NRF), overseen by the Department of Homeland Security (DHS), provides guidance on emergency and disaster response efforts [5]. The NRF establishes five preparedness mission areas, including *Response*, which is defined as "the capabilities necessary to save lives, protect property and the environment, and meet basic human needs after an incident has occurred [5]." The most recent *National Security Strategy* document highlights disaster response as critical to homeland defense. It emphasizes that the U.S. must "take steps to respond quickly to meet the needs of the American people in the event of natural disaster or attack on our homeland" as well as "provide our expertise and capabilities to those in need" during disaster events abroad [6].

Since 2011, DoD has provided assistance for several significant disasters, including the Tohoku earthquake and tsunami in Japan; the Ebola outbreak in West Africa; and Hurricane Maria in Puerto Rico. All three involved the mobilization of military resources and exemplified the wide range of circumstances in which DoD may be called upon to help.

The 9.0 magnitude earthquake and the resulting tsunami in Japan in March 2011 [7] resulted in significant damage to the Fukushima Daiichi nuclear power plant [8]. The DoD responded to this event by deploying 24,000 military personnel, 189 aircraft, and 24 ships under Operation Tomodachi [7, 8]. The catastrophic meltdown of nuclear reactor cores caused radiation to be dispersed in the area, leading to an additional hazard with which the military had to contend (see Figure 2).

Figure 2. Sailors scrub the flight deck aboard the aircraft carrier* USS Ronald Reagan (CVN 76) *following a countermeasure wash down to decontaminate the flight deck while the ship was operating off the coast of Japan [25].

The DoD disaster response teams routinely have to overcome severe obstacles in unique environments. For example, during the highly infectious Ebola epidemic in 2014 [9], DoD personnel directed resources toward constructing facilities for patient treatment because little of the infrastructure necessary was available to combat the epidemic [10]. After Hurricane Maria in Puerto Rico in 2017, the DoD had to coordinate and execute the import of nearly all critical supplies from the U.S. mainland to provide food, water, and medical care to residents, as well as to participate in the reconstruction [11].

The role of DoD and the uniformed services in disaster response may include the following responsibilities and actions:

- Search and rescue (SAR)
- Emergency medical care
- Emergency transport of people
- Distribution of essential commodities
- Decontamination
- Restoration of electrical power
- Bridge repair
- Epidemiological work and disease control
- Security [12]

Because disaster response is such a broad and diverse field, this report addresses six areas in which scientific and technical (S&T) research and development (R&D) are most likely to intersect with improving disaster response practices relevant to DoD and homeland defense. These areas are: Communications Management, Data Management, Responder Protection, SAR Technologies, Supply Chain Management, and Radiation Emergencies.

This report reflects the confluence of concepts related to DoD, disaster response, and S&T (see Figure 3). More importantly, the key driver of this report is to identify relevant principles where S&T developments for use in disaster response do, or could, apply to DoD operations in disaster management.

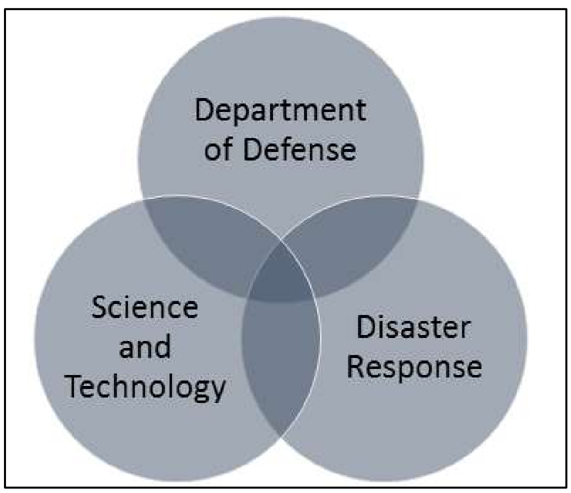

Figure 3. Confluence of key topics of discussion and their overlap for state-of-the-art on disaster response.

Technology plays an important role in disaster response. In fact, after reflecting on a decade of the impact of disasters, in early 2018 the World Economic Forum listed four advantages granted by technology deployment when responding to disasters:

- Technology can go where people cannot and where rescue efforts put the lives of responders at risk;
- Technology breaks down barriers to enable connectivity when we need it most;
- Mobile solutions, social media, and digital communities provide a new way for organizations and their beneficiaries to communicate; and
- Big data analytics creates a new era of intelligence for disaster response [13].

This report also highlights six areas of technology likely to have an outsized effect on the current state and future practice of disaster response: blockchain technology and software, autonomous systems or drones, IoT (networked devices), AI (sometimes known as or associated with machine learning), robotics, and the use of social media in response activities. Use of these technologies has already contributed to the safety of first responders and enhanced situational awareness in response situations.

At the time of writing, blockchain technology has received little discussion to date in relation to disaster response; however, since it may be applied in other areas (such as the financial sector) to protect privacy, experts speculate it may also be applied to disaster response when personally identifiable information is collected. Other technology areas, like social media and robotics, have demonstrated increased value in disaster response in recent years. The enormous amount of users engaged on social media generates data that can be used to enhance disaster response efforts. A prime example of this is Facebook's Safety Check [14], which allows users in an affected area to notify friends and family of their safety status.

In robotics, recent efforts by the Defense Advanced Research Projects Agency (DARPA) have sought to develop robots optimized for disaster response activities in a humanoid form, like the Atlas (see Figure 4) [15]. Much smaller drones—even micro-sized—are also proving valuable in disaster response activities and planning. DARPA has advanced the design of micro- and milli-sized robotics platforms, launching a new program in 2018 called the Short-Range Independent Microrobotic Platforms, which will produce devices capable of accessing environments that are either too small or hazardous for Atlas-sized robots to access [16].

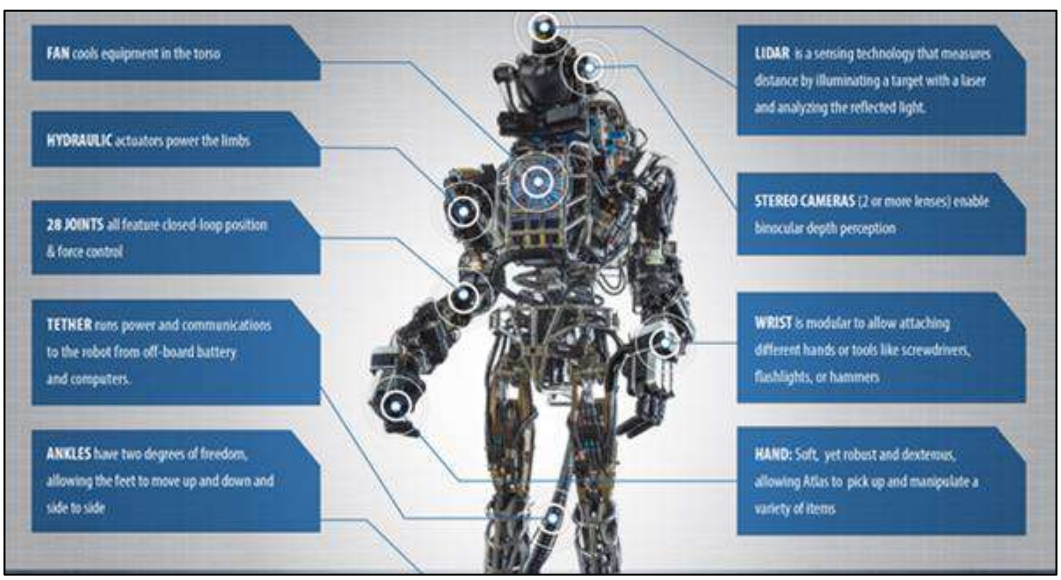

Figure 4. Overview of functions of the Atlas disaster response robot [15].

The remaining technology areas (autonomous systems/drones, IoT, and AI or machine learning) are still finding their way into disaster response. Drones (sometimes referred to as unmanned aerial vehicles [UAVs] or systems) have been used for surveillance and mapping in emergency response [17], but their use is expanding to encompass supply delivery missions [18]. Recent work at the National Institute of Standards and Technology has expanded the limits of what supplies non-airframe-sized drones can hoist and deliver, demonstrating a 35-pound drone capable of lifting 20 pounds of equipment into the air and hovering in place for a minimum of two hours [19].

The phrase *Internet of Things* refers to sensors and devices linked via wireless internet connections [20]. Since these devices can collect information in real time and be placed virtually anywhere, they are useful in monitoring how a disaster unfolds and tracking response efforts [21, 22]. Machine learning is a branch of AI focused on advanced pattern recognition. Applications in disaster response using machine learning to identify and categorize social media posts in order to provide a more comprehensive picture of where to deploy resources [23] are demonstrated by platforms such as AI for Digital Response [24].

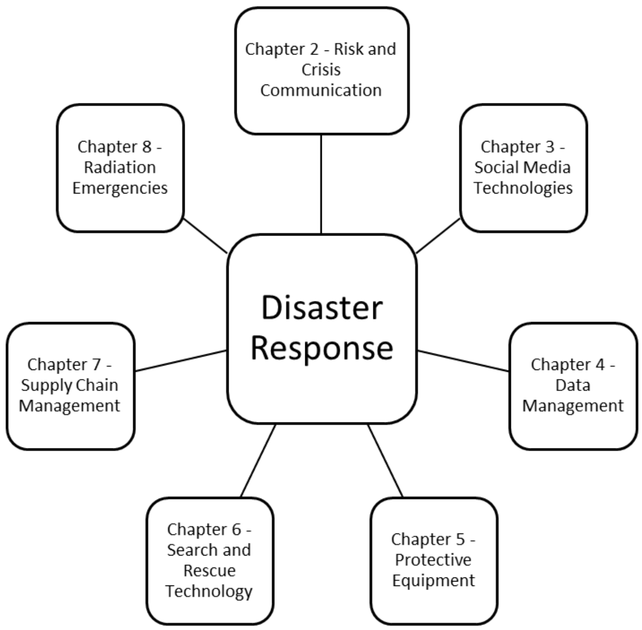

Figure 5. Relationship between aspects of disaster response and organization this report.

This report is divided into sections that mimic the flow of a typical response (see Figure 5). The report begins with an important discussion on communications management, and includes sections on risk and crisis communications. It follows with a detailed account on the use of social media for information dissemination and collection. The focus then shifts to technologies used for data management and explores the complexities of modern disaster response where millions of data points are being captured every minute. Next, responder protection is discussed and highlights materials, technologies, and standards being implemented to improve safety. Then, a review of the intricacies of managing SAR operations in a variety of environments is provided and includes a discussion on related technologies (such as communications and situational awareness). Later, supply chain management is reviewed and novel technologies for improving logistics in disaster response are evaluated. Finally, the report ends with an overview of radiation emergencies and emerging trends regarding technology implementation to handle these unique situations.

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Risk and Crisis Communication*:*
Achieving Communication Success During an Emergency Event

Ron Edmond, Independent Consultant

Risk and Crisis Communication Overview

Given the current low-trust, high-concern communication environment both nationally and globally (e.g., misleading social media posts sponsored by state actors and other organizations), knowledge and integration of risk and crisis communication principles and techniques can enhance an agency's communication and increase its credibility with stakeholders. The DoD faces many situations where the effective use of risk and crisis communication principles and techniques are pivotal.

The goal of risk and crisis communication is to keep the public informed about the status of an event may adversely affect the public. An effective risk communication plan maintains or restores the public's confidence in a given organization's ability to manage low-trust, high-concern issues. The greatest strength of crisis communication is its purpose: keeping all stakeholders informed.

Risk communication has two congruent functions: (a) to calm stakeholder's fears and anxieties and satisfy their need for empowerment by providing them with relevant safety information, and (b) to pique stakeholders' interest to listen and take appropriate actions to protect themselves and their families.

In a presentation developed for the American Nuclear Society, *Obtaining Communication Success during an Emergency*, Edmond describes the importance of risk and crisis communication processes:

> Risk and crisis communication is critical during an emergency event. A well-executed crisis communication plan provides organizations an opportunity to either calm people so they can internalize the message or excite people so they can implement protective action recommendations.... A poorly-executed crisis communication plan can have the opposite effect. [It] impacts the ability of the public to respond appropriately to messages designed to protect their health and safety [1].

Communicating risk and crisis information to stakeholders is critical in protecting the health and safety of the public. Vincent Covello, founder and director of the Center for Risk Communication, defines *risk communication* as any purposeful exchange of information about risk or risk perceptions; any public or private communication informing stakeholders about the existence, nature, form, severity, or acceptability of risk; or communication denoting the probability of losing something of value, such as health, safety, self-esteem, wealth, natural resources, or community [2].

Risk and Crisis Communication Principles

Crisis communication seeks to create an environment based on trust and credibility; produce an informed audience that is involved, interested, reasonable, thoughtful, solution-oriented, and collaborative; and build confidence in an agency's professionalism, commitment, and expertise. The foundation of risk communication is centered on four theories (see Table 1) espoused by Covello: (a) risk perception, (b) mental noise, (c) negative dominance, and (d) trust determination. These theories represent the communication challenges that must be addressed to build trust and credibility among all stakeholders [2].

Risk Perception Theory

Risk perception is influenced by cultural norms, individual perceptions, and past experiences. Risk perception can be influenced, either positively or negatively, by factors such as "…perceptions of trust and credibility; perceptions of knowledge and expertise; perceptions of openness and honesty; and perceptions of concern and care [3]."

Regardless of the communication medium they favor, stakeholders analyze, synthesize, and apply their perceptions of a given risk based on their understanding of its likelihood and potential impact. Effective implementation of risk and crisis communication principles related to risk perception can reduce frustration and outrage, enabling DoD to respond appropriately by identifying key audiences and stakeholders, anticipating questions and answers, and preparing accurate and well-crafted messages [2].

Mental Noise Theory

Covello's research addresses the impact of the concept of "mental noise" (defined as difficulty hearing, understanding, and remembering information) on stakeholders [2]. Understanding mental noise theory provides insight into how stakeholders understand and remember information delivered during a stressful environment or scenario. According to Covello's study, mental noise provides 50 to 75 percent of the message content, negatively influences message interpretation, and overrides verbal communication. Methods for overcoming the effects of mental noise include simplifying, limiting, and repeating critical messages; determining and prioritizing message placement; and using visual aids to convey important information.

Negative Dominance Theory

Typically, information evolving from a crisis is dominated by negative verbal communication and/or accompanied by negative nonverbal images such as photos and videos. Today's viral social media environment enhances instantaneous dissemination and access of negative verbal and nonverbal communication to stakeholders. During a crisis, social media contributes to increased message scrutiny, ensures messages are remembered longer, and provides limitless message accessibility—thereby potentially increasing emotional responses from stakeholders. Stakeholders will generally focus more on the negative than on the positive, and it is important to recognize that stakeholders' emotional responses may be based on their personal experiences during a previous crisis (i.e., a previous negative experience) with the response organization, the stakeholders' personal belief system, or community norms.

Trust Determination Theory

Alleviating low-trust, high\-concern environments requires integrating four factors into the communication environment: (a) empathy and caring, (b) competence and expertise, (c) honesty and openness, and (d) commitment and dedication [2]. Appropriate use of these principles reduces psychological barriers and enhances the communication process, resulting in added message buy-in.

Risk Communication Summary		
Theory	**Effect**	**Solution**
Risk perception	Frustration and outrage	Recognize and respond to risk communication factors
Mental noise	Blocks communication	Use clear, concise messages and active listening
Negative dominance	Distorts communication	Develop positive messages
Trust determination	Enhances or detracts from the message	Show that you care

Table 1. Risk Communication Summary [2].

Planning and Development

Planning for a crisis or emergency begins once the risk level has been determined, and the content of all risk communications has been confirmed. An effective communication response strategy seeks to: (a) communicate critical information, first, and to (b) respond to stakeholder questions raised during the planning stage. Examples cited below provide a snapshot into DoD's crisis communication process and the planning required long before an incident occurs.

In 2017, DoD issued *DoD Instruction 6055.17, DoD Emergency Management (EM) Program*, which "[e]stablishes policy, assigns responsibilities, and provides procedures for conducting EM activities at DoD installations worldwide." It also "establishes the DoD Emergency Management Steering Group to provide guidance and recommend policy on EM matters." Section 5, "Crosscutting Preparedness Capabilities: Public Information and Warning," describes the department's notification protocols and clearly designates primary and secondary populations to notify in an emergency [4].

DoD and the Army together deployed the *Interactive Crisis Communication Platform to Asia-Pacific, Fortifying Commitment to the Safety and Security of Personnel and their Families Worldwide* in 2014, which strengthens the Army's "ability to quickly alert and account for the safety of nearly a million personnel and family members in the event of any crisis." This communication platform notifies over 100,000 personnel and their families stationed in the Asia-Pacific region using social media platforms for mass notification [5].

The Navy and Marine Corps also provide guidance and planning in *A Risk Communication Primer: Tools and Techniques*. This document provides a framework for disseminating information during a crisis by the Navy and Marine Corps Public Health Center [6].

Risk and crisis communication plans have a fourfold purpose. First, they convey information about response, recovery, and re-entry efforts. Second, they provide relevant stakeholder information for decision-making purposes. Third, well-executed risk and crisis communication lessens the potential to misallocate limited resources. Fourth, risk and crisis communication plans allow organizations to correct rumors and misinformation in real time, as well as coordinate with other response agencies.

Not surprisingly, risk and crisis communication plans differ markedly from traditional communication plans. It is imperative that organizations develop realistic, specific, and most importantly—readily implementable—communication plans. The crisis communication mantra of the Centers for Disease Control and Prevention is to “be first, be right, be credible [7].” Successful implementation involves producing reliable and valid communication, which in turn strengthens organization credibility.

Developing Trust and Credibility

Risk and crisis communication principles are keys in establishing perceptions of trust and credibility. Covello and Allen determined four essential factors, and their associated weight of importance, for building trust within the stakeholder population (see Figure 1):

1. *Caring/Empathy* focuses communicating with stakeholder from their perspective rather than from the organizational perspective. In other words, communicate from the human perspective rather than corporate perspective;
2. *Honesty/Openness* entails speaking in an age-appropriate language, usually 10- to 12-year-old level for technical information, and speaking truthfully about the issue;
3. *Competence/Expertise* reassures stakeholders the organization is qualified to manage the situation; and
4. *Commitment/Dedication* demonstrates to stakeholders the organization’s responsiveness and obligation to resolve the issue to the best of their ability [8].

When developing risk or crisis communication strategies, planners should consider nonverbal communication approaches which complement the message, such as graphics, photographs, PowerPoint presentations, body language, camera positioning for video feeds, clothing, display models, etc. Additionally, research indicates that nonverbal communication can increase information retention by as much as 25 percent. However, information retention requires both the sender and the receiver to engage in active listening to maximize the effectiveness of the message.

Figure 1. Risk Communication Summary [24].

Minimizing Communication Issues during a Crisis

During a crisis, a key challenge is to reduce the number of issues, maximize communication opportunities, and limit communication difficulties that can impact operational success. When an organization sends mixed messages from multiple experts, the public is unsure which is most credible. As a result, the tendency is to reject the messages and seek others that reinforce existing beliefs. Contradictory messages affect stakeholders' ability to internalize and act upon risk or crisis information. Stakeholder rejection of risk and crisis messaging has the potential to impede their taking actions necessary to protect health and safety.

The late or tardy release of actionable information is another obstacle that must be addressed. The rise in popularity and use of social media applications (such as Twitter or Facebook) makes it imperative that organizations provide appropriate information to the public at a rate higher than that followed in the past, with conventional media like television or radio alone.

During an emergency, stakeholders have a responsibility to take affirmative measures to protect themselves. As witnessed during the 2017 hurricane season along the Gulf Coast, devastation can be so widespread that local, state, and federal governments lack the resources to meet the overwhelming needs of affected stakeholders. Hurricanes Maria and Irma caused especially extensive damage, which required an immense response by DoD. The Defense Logistics Agency moved over 124,000 gallons of diesel fuel into theater, while other DoD assets deployed ships, operated rescue flights, conducted damage assessments, and provided medical evacuations and logistics support [9].

DoD's Civil Authorities Information Support Element assisted with communication and outreach support in the U.S. Virgin Islands [10, 11]. During Hurricane Maria, DoD executed a massive communications effort before, during, and after landfall [12]. Another example of DoD's communication response efforts can be found in an article titled "DoD Officials Provide Update on Hurricane Relief Efforts [13]." The article discusses how the DoD response to Maria transitioned from a marine- to a land-based one. Articles such as these are important in keeping stakeholders informed about on-going response efforts.

Research conducted by the Center for Risk Communication confirms that countering rumors and myths perpetuated during a disaster is critical to preventing the institutionalization of misinformation [2]. Failure to counter inaccurate rumors information during an emergency can force response personnel to expend resources on rumor-chasing, detracting from the core risk communication effort.

NRF and Risk and Crisis Communication

The NRF dictates how DoD and other federal agencies engage in or support response efforts to national disasters or emergencies [14]. The NRF recognizes the need to coordinate efforts during an emergency, noting in part:

> It is essential that immediately following the onset of an incident, the State or tribal government, in collaboration with local officials, ensures that: communication lines with the press are open, questions receive prompt responses, and false rumors are refuted before they spread. Information about where to receive help is communicated directly to victims and victims' families. Note, this applies distributing information through social media platforms as well. Because of the speed of at which information travels through various social media platforms, it is imperative that the aforementioned requirements are followed, even more strenuously [14].

An effective risk communication plan is a useful tool for assisting responders in emergency preparedness. It addresses the development and delivery of appropriate messages, selects the appropriate spokespersons, and determines the appropriate communication medium, such as press conferences and releases, social media, the internet, or advocacy groups [15].

Risk Communication Lifecycle

DoD's strategic communication process involves (a) disseminating timely, accurate, and coordinated information, (b) delivering DoD messages, and (c) ensuring stakeholder involvement. In terms of risk communication lifecycle management, DoD establishes protocols, directives, and instructions to manage communication processes both domestically and internationally. They include, but are not limited to, the following:

- *Commander's Handbook for Strategic Communication and Communication Strategy* [16]
- *Campaign Planning Handbook* [17]
- *DoD Instruction 5405.03 Development, Submission, and Approval of Proposed Public Affairs Guidance* [18]

- *DoD Directive 5122.05* [19]
- *Principles of Strategic Communication* [20]
- *Military Strategic Communication in Coalition Operations: A Practitioner's Handbook* [21]

Developing a crisis communication plan helps communication professionals foresee, react to, and plan for challenges during an emergency. Edmond's study reveals the importance of planning not only for the four phases of emergency management—preparedness, mitigation, response and recovery—but for crisis communication across all areas [22]. Regardless of incident type, the communication lifecycle determines what resources are needed, the level of effort necessary to deploy them, and the staffing needed to implement a risk and crisis communication plan [23].

Conclusion

DoD's role in risk and crisis communication on the local, state, or territorial level is to supplement and enhance existing communication processes for stakeholders. The goal of developing and implementing an effective communication plan is to protect the health and safety of the public, maximize resources, reduce rumors, establish and gain support from other agencies involved, and conduct response and recovery efforts as effectively and succinctly as possible.

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3

Social Media Technologies for Disaster Response

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Introduction

Social media are forms of electronic communication (such as websites for social networking and microblogging) through which users create online communities to share information and other content [1]. This type of media has had an increasingly significant effect on disaster response over the past decade. Social media no\w shapes how crises are communicated, how responses are coordinated, and how stakeholders perceive the risks a given disaster poses.

When used properly, social media can be an invaluable resource for disaster response [2]. Social media technologies and platforms can enhance an agency's information network efforts, minimizing the loss of life and damage to property [3]. Responding agencies can use social networks as notification systems, emergency information gathering and situational awareness tools, and as information repositories. This chapter explores state-of-the-art technologies (and techniques) for leveraging social media for disaster response, illustrated by several lessons-learned case studies. Social media strategies are also discussed, where they relate to DoD crisis communication and disaster response.

The Evolution of Social Media and Disaster Response

The public receives a major percentage of its news directly from internet-based media outlets, "unmediated" through traditional media sources. As a result, social media now ranks as the fourth most popular medium for accessing disaster information [4]. According to a recent study conducted by the Pew Research Center, Facebook is the most widely used social media platform in the United States, with 68 percent of adults using the service. Rival networks such as Snapchat and Instagram are less popular overall, but have been more successful at attracting younger users [5].

Facebook had been in service for less than a year when Hurricanes Katrina and Rita struck the U.S. Gulf Coast in 2005, and social media played little to no role in the response to both storms. (Twitter and Instagram did not yet exist.) However, two years later, social media platforms had matured enough to play an important role in the response to the mass shooting at Virginia Polytechnic Institute and State University in April 2007. Social media networks became the standard method for contacting friends and family in the midst of a major emergency event. Additionally, reporters began using sites like Facebook (and even Craigslist) to quickly locate students on and around campus [6].

This trend continued unabated after 2007. Two years after the Virginia Tech shooting, the "miracle" landing of U.S. Airways Flight 1549 on the Hudson River illustrated how one person with a cell phone camera and Twitter account could tell the world the story long before traditional media outlets have a chance to dispatch a reporter to the scene. During 2012, when Hurricane Sandy struck the eastern seaboard, over 3.2 million tweets with the hashtag *#sandy* were sent within the first 24 hours of the storm's impact, and users sent over 11 million tweets in the first week [7]. At the height of the storm, users of the image-sharing service Instagram posted 10 pictures of the devastation every second [7].

In March 2018, the U.S. Army Pueblo Chemical Depot (PCD) experienced a warehouse fire that affected three PCD buildings— heavily damaging two buildings and partially damaging another [8]. PCD and its partnering agencies already had an established presence on Facebook and Twitter. During the response, PCD issued updates and posted news releases to its Facebook page and successfully leveraged partnering agencies' Facebook and Twitter accounts to coordinate and release consistent messaging. Overall, PCD and partnering agencies coordinated consistent, timely, and accurate information to the public and the media via both social media platforms.

State-of-the-Art Social Media Technologies, Methodologies, and Strategies in Disaster Response

The integration and institutionalization of social media into an agency's operational workflow greatly increases its ability to adapt as technology advances and internet trends change. According to the DHS report *Operationalizing Social Media for Preparedness, Response, and Recovery,* to effectively integrate social media, an organization must pursue or develop the following: planning and strategy development; operational and procedural documentation; legal, security, privacy, and other related policies; education, training, hiring, and exercises; evaluation and assessment; standards development; private sector collaboration and technology development; and funding strategies [9].

The DoD Chief Information Officer hosts an online "Social Media Hub" in order to assist the service branches and wider DoD community in using social media effectively and responsibly [10]. From this website, users can access education and training, terms of service agreements, and DoD policies related to social media and other internet-based capabilities. These resources are also component-specific for the Army, Navy, Air Force, and Marine Corps. In 2009, DoD became one of the first U.S. government entities to implement a social media policy as a way of providing the public with a transparent view of its overall mission and strategy [11]. Additionally, the Army published a *Social Media Handbook* in 2010 [12]. The Army has since updated the handbook to reflect changes in social media platforms and usage.

Social media can be best leveraged during time-critical response efforts if agencies have already established a high level of trust with stakeholders and users. However, many response agencies that have embraced social media as tools for disaster response do not use them as effectively as they could.

In 2017, the Public Affairs Science and Technology (PAST) Fusion Cell at Argonne National Laboratory monitored the evacuation messaging used in more than 43 counties, parishes, and municipalities in Texas and Louisiana during the onset of Hurricane Harvey. Between August 24 and September 1, more than two dozen counties and parishes issued voluntary or mandatory evacuation notices via Facebook and/or Twitter, whereas 28 did not use either social media platform [13]. While about two dozen jurisdictions in the study maintained an active and dual-track social media presence during the Harvey response, the majority were active on only one platform, with most electing to use Facebook.

Of the jurisdictions that used both platforms, few did so effectively, with most opting to post the same messages on both platforms (or simply link between the two). Only one jurisdiction monitored in the study demonstrated a strategy designed to maximize the value of each platform [13]. Facebook users typically skew older, and prefer messages with a high visual quotient. The Twitter demographic is younger, preferring more concise messages [5]. As a best practice, agencies should recognize that Facebook and Twitter (and other platforms) have different and sometimes highly specific messaging needs.

With the proliferation of social media, we can now watch disasters unfold before our eyes via smartphones and computers. During the 2013 fertilizer explosion in the city of West, Texas, photos and both live and recorded videos were shared throughout the event. In fact, many people in the affected community gathered news on the event from Twitter [14]. While social media is an excellent medium for communities to gather life-saving disaster information and experience the impact of a disaster in a shared manner, there is also concern that rumors, misinformation (unintentionally false information), and disinformation (intentionally false information) flourish in this medium.

According to a 2018 DHS Science and Technology Directorate report, *Countering False Information on Social Media in Disasters and Emergencies*, most social media information is posted in good faith. Consumers of information can be led to believe in "alternative, fake reality and suspicious behavior" by posts that have been manipulated to contain modes of false information, including manufactured uncertainty, exploitation of emotions, hijacking conversations, and financial scams. [15]. Social media provides the capability to go directly to an event, but it also runs the risk of promoting misinformation and disinformation.

However, if response agencies do not take the initiative to develop a foundation of trust and authenticity with the public before a disaster, the public may look to unofficial sources during a disaster. Likewise, if misinformation on social media is not corrected in a timely manner, rumors and disinformation will run rampant. The scientific adage that nature abhors a vacuum also pertains to the flow of information during a disaster—even if that information is inaccurate or misleading. For example, during the catastrophic explosion of a fertilizer plant in West, Texas in 2013, a photo widely shared on Facebook and Twitter was later proved to be from a 2008 oil refinery explosion in Big Spring, Texas [16].

During Hurricane Harvey, several responding agencies effectively re-asserted themselves as the source for official emergency information via social media. Residents, in turn, expressed gratitude for the clarification [13]. Additionally, the Federal Emergency Management Agency (FEMA) created a rumor control webpage to counter misinformation related to the storm and the response. The webpage was solely dedicated to listing incorrect pieces of information alongside the verified, correct information. FEMA began this practice during Hurricane Sandy and has done so for subsequent events.

Responding agencies should anticipate that stakeholders will turn to alternative methods of communication during disasters, particularly when emergency service call centers are overloaded or inoperable. In some jurisdictions, social media is now accepted as an officially approved medium for emergency information dissemination. During Hurricane Harvey, 911 emergency call centers in Houston were overloaded with high call volume. Residents began posting to Facebook and Twitter, asking for assistance—despite agencies' protestations that citizens should not use social media to request assistance or rescue [17, 18]. Establishing national guidelines for social media use in disasters should be considered, in addition to a national protocol for social media use in geolocation and SAR situations.

In terms of situational awareness and social media monitoring, Virtual Operations Support Teams (VOSTs) are an invaluable tool for providing surge support during disaster response. VOSTs are trained, trusted agents that lend virtual support to local jurisdictions overwhelmed by the volume of information generated during a disaster. VOST members follow National Incident Management System procedures to support social media monitoring and situational awareness data gathering in support of an affected jurisdiction [19].

Some guidance exists regarding how first responders should seek to correct misinformation, rumors, and disinformation online during a disaster. According to DHS, agencies should:

- Improve the quality of communication through the double-verification of information;
- Remove ambiguity and uncertainty caused by misinformation, rumors, and false information;
- Reduce alert fatigue and the risk of "cry wolf" scenarios;
- Seek ground truth as opposed to assumption;
- Be swift with releasing accurate information or acknowledging the situation to help the agency work with a network of truth amplifiers and establish credibility early on; and
- Determine relevance of various social media information [15].

According to the DHS Science and Technology Directorate's 2013 publication, *Using Social Media for Enhanced Situational Awareness and Decision Support*, equipping responders with the tools and strategies needed to successfully monitor and validate social media is one of the most important aspects of disaster response for operations and informed decision making [20]. One available humanitarian and crisis response tool is Artificial Intelligence for Digital Response (AIDR). Using a list of keywords, hashtags, and/or a geographical region of interest, AIDR uses a process to tag and classify tweets [21]. From this data, a crisis map and live dashboard provide users with key metrics to make more informed disaster response decisions (see Figure 1).

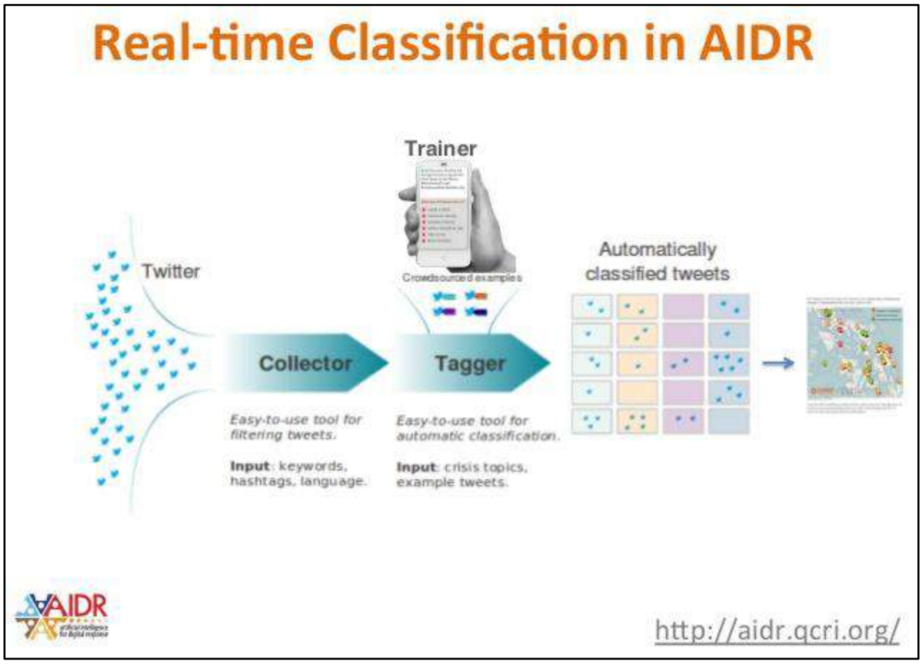

Figure 1. AIDR Real-Time Classification Process [21].

Integrating machine learning with social media has also proven effective for providing responders with information in real time during disasters. For example, researchers analyzed the series of devastating floods that struck Colorado in September 2013 and found that a combination of remote sensing and data from Twitter and Flickr could identify flooded areas (see Figure 2) [22]. While satellite imagery for a location may not be available in a timely manner, social media can provide mission-critical information to fill in the gaps. Ultimately, the research team found that satellite imagery on its own was not always reliable, and that social media could be combined with remote sensing imagery to help identify the extent of the flooding [22].

Social media data can also help identify someone's location or reassure loved ones that family members are safe. Facebook's Crisis Response tool offers a mapping capability to geolocate Facebook users in disaster-affected areas and activates a Safety Check feature which allows users to indicate they are safe [24]. Facebook disaster maps provide information about where populations are located, how they are moving, and where they are "checking in" safe during a disaster. Drones can aid in social-media-assisted disaster response, providing situational awareness and assisting recovery teams. During Hurricane Matthew in 2016, drone footage and a Twitter exchange led to the rescue of a man and his dog trapped on their roof by rising flood waters [17].

Social media-mapped and interactive crisis response maps provide responders and affected communities with a great deal of data for operational decision making and situational awareness. For example, during Hurricane Harvey, some affected jurisdictions frequently provided links to interactive maps showing evacuation zones [13]. By clicking on the link, residents could enter their address and determine whether they were living in an area subject to an evacuation order. Many jurisdictions in Colorado and California use this method for communicating wildfire boundaries and illustrating evacuation areas.

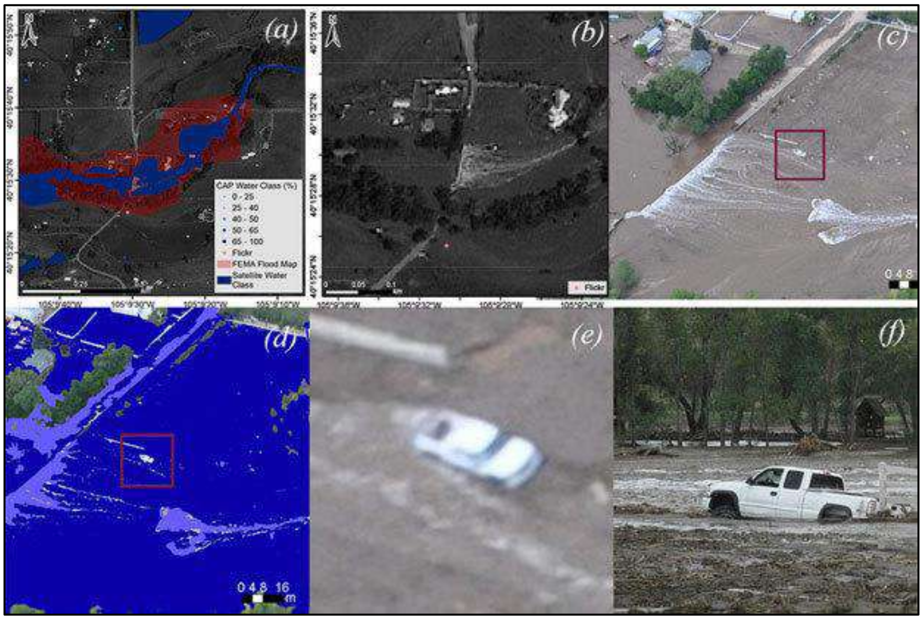

Figure 2. Water pixel classification in aerial images from study [23].

Emerging Trends

New technologies are constantly in flux, creating challenges and opportunities for how emergency professionals manage disaster response. While Facebook is clearly the leading social platform, data shows that Snapchat is gaining currency with younger users, and habits developed at younger ages are more likely to overflow into older cohorts over time [5]. During Harvey, Snapchat's "Snap Map" and "Stories" functions were used by the public and first responders to track the storm's impact. These geolocated newsfeeds offered insights into the impacted communities with close to 300,000 video/photo submissions in the 86 hours prior to the storm striking Texas [25].

New technologies built around decentralized networks, such as blockchain, AI, and internet-connected sensors, are also changing the way we manage disaster response. Blockchain, which is a decentralized network of computing "nodes," could give agencies a way to store, share, and secure data much faster [26]. One example is a public health crisis, such as a pandemic. In such a scenario, blockchain could be used to securely share data about patients, track outbreaks, and automate data entry in an emergency situation. DoD is already implementing blockchain technology in some areas [27].

Another area of technology that may assist disaster response is the Internet of Things (IoT), or the network-controlled management of certain types of electronic devices. Several Army programs were early adopters of IoT technology for situational awareness and mission command systems. In 2016, the office of the DoD Chief Information Officer published *DoD Policy Recommendations for the*

Internet of Things, which describes the potential benefits of IoT technologies for battlefield situational awareness [28]. While IoT is being implemented for defense programs, IoT applications could be useful for large-scale automated systems management in disaster response [21].

Conclusion

Disaster response agencies can leverage social media technology and their usage patterns to support efficient, consistent, and timely information management before, during, and after an emergency. However, disaster response will continue to change as technology quickly evolves, amplifying the need to ensure well-trained staff are available to manage and coordinate emergency communications to reach audiences with the critical information they need to protect themselves and others during disasters.

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4

Drowning in Data: Mitigating Data Overload in Disaster Response

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Introduction

The disaster response community in the United States has recognized that data is the common denominator across all phases of disaster operations. The provision of timely, reliable, and accurate data is critical for effective communication and coordination among the organizations involved [1]. The dynamic nature of technological development has led to new and improved capabilities to collect and accurately assess large bodies of data. Physical sensors are being fielded using emerging materials to detect and identify environmental changes minute-to-minute, whereas previous sensors measured on a daily or even weekly basis. Social media has allowed every individual with a mobile phone or connected device to act as a sensor, and the Internet of Things (IoT) has the potential to turn even the most innocuous objects in our homes and businesses into useful sensors, directly reporting disruption through their activities or a lack thereof.

This tsunami of data has the potential to improve and facilitate disaster response in transformative ways. However, it also has the potential to overwhelm even the most experienced incident response team. The rapid influx of data can bog down communications networks and interfere with responders' ability to identify actionable information, resulting in delayed decision making [1]. Noted scientist and father of sociobiology E.O. Wilson observed in 1999 that "we are drowning in information while starving for wisdom. The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely [2]."

Successful disaster response requires precisely that ability, affecting synthesis through three discrete but interconnected processes:

1. Optimizing the use of sensors to collect the right data, in the right format, at the right time;
2. Applying tools, techniques, and technologies to make sense of those data; and
3. Packaging the newly created information in such a way to directly and quickly communicate complex and dynamic concepts to decision makers who have varying levels of expertise and direct understanding of what they are experiencing based on the interpretation of data.

This chapter discusses some of the challenges associated with data overload; the concept of data literacy within the context of disaster response; and some of the tools and techniques capable of enabling a data-driven disaster response that avoids information overload.

Introducing the Challenge

There are five primary types of data most commonly applied in disaster response activities: traditional sensors, data exhaust, online or social media activity, crowdsourcing, and public/government data [3]. Each data category has the potential to provide value to disaster responders and managers.

Data from Sensors

One of the critical elements of managing data from traditional sensor technologies is maintaining an awareness of what data they can provide. The integration of “citizen-as-sensor” initiatives into disaster response operations has resulted in an immense pool of potential data sources that can move into and around a disaster scene. Identifying what sensors are in the area of disruption, when they depart that area, and if and when new sensors come online can be an overwhelming challenge. One approach for maximizing understanding of what sensors are available, what data they can provide, and how to access data is the use of a self-managing interoperable sensor architecture.

Such an architecture would establish a network, sharing the location, status, and data feeds of a set of sensors to provide decision makers with real-time situational awareness. Mobile sensors would “check-in” and “check-out” of the network as they move through an area. An interoperable sensor architecture would also allow for greater automation in sensor management. For example, in a chemical release scenario, a change in wind direction could be detected by an integrated sensor network, causing it to highlight data from sensors located outside of the initial exclusion zone, tracking shifts in the chemical plume’s path and speed.

This approach toward sensor management is being operationalized by the U.S. Army Night Vision Electronic Sensors Directorate (NVESD) as it rolls out the Integrated Sensor Architecture (ISA) to support shared situational awareness across all operation types. The value of this shared awareness in support of domestic and international disaster response and humanitarian operations is clear, but implementation within those contexts has yet to move beyond a conceptual phase.

ISA is designed to enable the rapid integration of systems, sensors, and services onto a standard data-sharing network. Once fully implemented, ISA will help to establish a common operating picture where sensors sign in and out as they become available or go offline, informing a human operator precisely what is available and providing limited tasking and redirection capability where appropriate. In its current iteration, ISA provides documentation, compliance tools, data generators, a reference implementation, and an API for software integration.

The shared data model and discovery aspects provide for a one-time integration of an asset into an ISA network and a universal layer that complex data processing services can be built on. This enables data processing at the point of collection, which in turn enhances collaboration and management of resources. ISA is currently being fielded by Army PM Terrestrial Sensors, Army PM Electronic Warfare & Cyber, PM Distributed Common Ground System–Army, the Joint Program Executive Office for Chemical and Biological Defense, and other DoD entities [4].

A team from the University of Bradford (U.K.) has proposed the application of semantic tools and technologies to create a semi-autonomous data processing framework; it would enhance manageability of the massive amounts of data that are generated in disaster response operations [5]. The framework is designed to enable disparate contacts to collaborate and share data across multiple systems or organizations. It applies semantic logic to provide a platform-independent data collection, exchange, and collaboration network, one scalable to the requirements of a scenario. The Bradford team is providing a three-component system within an extendable, resource-oriented architecture:

1. Abstract and resource-based sensor model, enabling the application of multiple layers of inspection to present data with a clear and logical hierarchy;
2. Resource-based access control, moving away from more traditional role-based access to provide more flexibility and allow distributed access to data of any granularity while maintaining scalability;
3. Service-oriented and semantic interaction model, enabling cross-organizational collaboration in a standardized, unified manner without imposing strict schemas, which could degrade system usability. This enables the capability to semi-autonomously profile and annotate sensors and data sources from external networks as well as integrate data that has already been published to the web but lacks the necessary semantic metadata to be used effectively.

These three components combine to enable disaster responders to better deal with the non-linear nature of the demand for (and availability of) data in a chaotic and unpredictable environment, as well as the broad array of actors, stakeholders, and consumers who may be both contributing to the available data and depending on the critical decisions that are being influenced by the associated information.

Data Exhaust

Data exhaust is the “background noise” of modern life generated by electronic devices and activities. Data acquired in real time from Emergency Medical Services Computer Aided Dispatch systems are already being used to identify potential threats from communicable diseases including influenza, Zika, Ebola, Middle East respiratory syndrome coronavirus, and enterovirus D68 [6]. These data are collected for operational systems management but also provide broader value in asking, “what else can we do with it?” Recognizing an increase in certain types of calls for help before the hospital emergency departments and other first receivers start seeing patients can provide critical time to recognize demand before the system is overwhelmed and an emergency becomes a disaster or a catastrophe.

During Hurricane Irma, disaster managers in Miami used data from Internet-connected weather stations to monitor micro-environmental wind speed conditions, allowing them to make decisions regarding responder safety [7]. The detailed data facilitated individual block assessments, as well as jurisdiction-wide actions based on extrapolated data. Rescue operations were then able to begin as soon as the wind speed dropped below the safety threshold.

Such datasets are often proprietary, generated and owned by individual service providers (e.g., Google, WeatherBug, American Express). There can be significant challenges to gaining access due to commercial interests, as well as concerns of privacy. This suggests the need to identify useful data sources from data exhaust proactively and address the challenges to obtain the information before an incident or event occurs.

Data from Online Activity and Social Media

Data-mineable internet activity includes the use of social networking sites, blogs, social media engines (Twitter, Gab.ai, Mastodon, Raftr, Snapchat), and search engines. A study completed by the American Red Cross in 2010 determined that the general public expects disaster response managers to use online and social media sources to guide their efforts [8]. Indeed, 35 percent of survey respondents expect first responders to react to a Facebook post, and 28 percent expect a response based on a tweet. “A tweet from someone stranded in their house as floodwaters grow is this generation’s emergency flare gun [9].”

There are numerous systems at present that aim to group social media content based on subject, source, and geotemporal point of origin in order to categorize them for operational use. The most notable systems use human operators to qualify certain data points [10]. Some automated solutions rely on Natural Language Processing (NLP) to automate the sorting and analysis of text-based data generated during a disaster. These evaluation methods consist of three phases: (a) detecting an incident through language analysis, (b) classifying the incident type, and (c) geolocating it [10]. Depending on several factors, including language complexity and translation, NLP methods can process data in hours to near-real-time and provide responders with detailed maps of activity “hotspots.”

These systems are challenged by the reality that online text content is “dirty,” meaning that it typically written with non-standard grammar and punctuation, drawing in part from vernaculars and internet slang. The situation is further complicated by the use of hyper-localized slang and colloquialisms. One of the most interesting systems being developed to address these challenges is a system referred to as a “Twitter Dashboard for Disaster Response” from the Qatar Computing Research Institute [11]. This system is designed to automatically extract and classify information applicable to a topic to accelerate the creation of an operational overview of a disaster.

Another complex and emerging NLP technology for disaster response is the Low Resource Languages for Emergent Incidents (LORELEI) program under development by DARPA. The LORELEI program processes information from public news and social media sources in so-called “low resource” language locations, where there is a lack of automated language tools available and traditional transcription into English is not possible or timely. Information about topics, entities, events, and sentiment are processed within hours or days of an incident [12]. “The global diversity of languages makes it virtually impossible to ensure that U.S. personnel will be able to understand the situation on the ground when they go into new environments,” explained Boyan Onyshkevych, DARPA program manager, in 2015 [13]. “Through LORELEI, we envision a system that could quickly pick out key information—things such as names, events, sentiment, and relationships—from public news and social media sources in any language, based on the system's understanding of other languages. The goal is to provide immediate, evolving situational awareness that helps decision makers assess and respond as intelligently as possible to dynamic, difficult situations [13]."

While LORELEI is still being developed for field use, a possible use case was explored by DARPA to monitor sentiments in Africa toward the U.S. and foreign aid personnel during the Ebola crisis. LORELEI could identify geographic hotspots of harmful sentimentality. In turn, responders could avoid such an area or send a more welcomed aid group to establish a field hospital. In another use case, 60,000 text messages sent in Haitian Creole were received by an aid group following the devastating 2010 earthquake. The messages included urgent needs for food, water, shelter, and rescue. Overwhelmed by the message volume, the aid group elicited help from the Haitian diaspora in the United States to translate the messages and compile them in spreadsheet software. This was an arduous task, which the LORELEI program was explicitly created to automate [14].

Crowdsourced Data

In addition to data mining of public internet activity, disaster response can also be aided through the active solicitation of individuals on specific topics or events—known as crowdsourcing. This approach has the dual value of significantly enhancing the processing capacity of the response system, while also engaging the online community and empowering its members as responders. As George Chamales writes,

> Crowdsourcing technology brings together a distributed workforce of individuals in order to collect resources, process information, or create new content. The implementation of a crowdsourcing system can vary widely, from complex online websites that coordinate a million simultaneous workers to low-tech, ad hoc approaches that use a shared spreadsheet [15].

As an example, data exhaust from mobile devices can provide specific information (e.g., location, traffic flow, environmental conditions), while using the crowd as a network of sensors. Crowdsourcing can provide real-time information on conditions. There are several technologies currently available that are specially developed for this purpose, available across online and mobile platforms (see Table 1). Online and cloud-based applications typically focus on single, location-specific scenarios and are designed for disaster responders or managers to collect and organize data from online and social media sources. Core functionalities include monitoring social media platforms for targeted metadata, data filtering and tagging, compiling and organizing volunteers and donations, and aggregating data into an easily usable formats such as maps, and tables or charts.

Mobile applications are designed to enable citizen-sensor activities, providing clean interfaces to facilitate the distribution of vital data from the public. For the most part, these applications are developed and distributed by concerned organizations and are voluntarily installed. For example, a mobile phone application, MyShake, was developed at the University of California, Berkeley, to utilize the accelerometers prevalent in today's smartphones to expand current seismic networks [16]. The data from individual phones help scientists to better study earthquakes and it can also be used to alert individuals of imminent shaking.

Online / Cloud Platforms			
Ushahidi	Crowdmap	Swiftriver	Eden (Sahana)
Crowdcrafting	OpenIR	Recovers	PADDDtracker
Vizie	Crisis Tracker	Souktel	GeoChat
InaSAFE	GeoFeedia	Tomnod	KoBoToolbox
Mobile Applications			
Geopictures	Fulcrum	Pushpin	OSMtracker
OSMand	Vespucci	UN-Asign	Jointly
Stormplns	EmergencyAUS	FEMA app	KoBoToolbox
Zello	RescueME	MyShake	Life360

Table 1. Examples of crowdsourcing platforms and mobile applications that can be used to facilitate disaster response [18].

While crowdsourced data can provide significant value in support of disaster response operations, they also present unique challenges. The varied quality of the data and frequently dynamic levels of trust translate into increased processing demand to ensure that decisions are made using the most appropriate data available. This is complicated by a strong desire not to alienate the public by making participation onerous [17].

Public/Government Data

A significant amount of public-related data that can aid disaster response is collected continuously by various government and non-governmental organizations. Census data; public health statistics; assessors' data on buildings, type and location of infrastructure; and climatological data can support disaster response operations by providing context and "painting a picture" of a community. While these data are not always publicly available, there is a trend toward the implementation of open data standards to support transparency and innovation in enhancing the effectiveness and efficiency of government [3].

Much of public data are static historical archives, while social media and online data are dynamic and ever-changing. This difference, however, does not diminish the fact that public data contribute significantly to disaster response. However, it can also contribute to information overload if users are not familiar with the available dataset and how to efficiently process and query it.

Processing and Data Management

The overabundance of sensors and data sources available to support disaster response activities has resulted in the need to sift through overwhelming volumes of data to identify which data are best suited to support decision making [18, 19]. This processing requirement includes:

- integration of data from heterogeneous sources;
- a search of the data store and identification of pertinent data;
- extraction of that pertinent data; and
- identification of patterns and trends in the data [20].

While research has shown that coordination processes during disaster response are re-invented after every disaster, more or less, there is no reason to re-invent data processing and management in the same manner [21].

Machine Learning

Machine learning, a subset of the branch of computer science known as AI, comes in either supervised or unsupervised forms. Supervised learning is a process for "teaching" the algorithms by providing training datasets that consist of labeled input. For example, providing the computer a set of pictures of various cats, all with the attached label "cat." The supervised learning algorithm analyzes this training data and produces a new function it has inferred from the data. This algorithm has now become able to identify a cat in a novel image. Unsupervised learning is the process of establishing a function to find innate structure from unlabeled data. The algorithm classifies the data into similar categories to identify hidden trends.

Researchers at the California Polytechnic State University, San Luis Obispo are using machine learning to identify types of post-earthquake structural damage from images [22]. Following an earthquake, structural damage is expected, but certain types of damage can signal imminent collapse—notably shear failures. When images of damage are gathered across a large geographic area through social media or crowdsourcing, responders can more quickly identify those buildings in need of rapid evaluation by officials.

Crowd Computing

Crowd computing is a method of utilizing many cognitive providers to solve a large and complex problem in need of human feedback. Individuals become networked, and each assumes responsibility to analyze a small piece of a much larger problem. For example, following the disappearance in 2014 of Malaysia Airlines Flight 370, DigitalGlobe's Tomnod team launched a search portal for anyone to comb over satellite imagery looking for clues. On the first day of the site's launch, 500,000 people logged on to help [23].

Because each disaster is different, crowd processing offers a flexible and rapid solution and is especially useful for disasters that garner much publicity, thereby a lot of "virtual" responders. Following the 2010 Haiti earthquake, for example, damage assessment of individual buildings was crowd computed by an army of concerned structural engineers and earthquake and building professionals by comparing before and after satellite imagery to identify skewed roof lines and debris piles [24].

Visual Analytics/Neo-Geography

During a disaster, much of the data utilized in the incident response process do not originate from sensors in real time, but instead is acquired long before an event happens. Physical and environmental data collected, processed, and analyzed before an event provide (a) crucial orientation and situational awareness to decision makers, (b) a contextual backdrop for the digestion of real-time data collected during an event, and (c) the basis for pre-disaster modeling and exercise scenarios.

The digital processing and aggregation of imagery is a specialized and emerging field, termed "imaging science," which combines color science, physics, engineering, and computer science. Image processing techniques extract relevant information from a sensor or camera and process those data into usable forms digestible in either a mapping format or aggregated for other analyses. For example, hyperspectral sensors capture spectral signatures within a scene that indicate material or chemical composition.

For example, the occurrence of a gas leak in hilly terrain could result in inadvertent casualties if responders fail to see hidden hazards [25]. If a simple circular evacuation zone is implemented around the leak without taking into account the downhill flow of gas, the fumes will concentrate in low-lying areas that the responders did not suspect were vulnerable. A three-dimensional virtual reality map can quickly provide a broader perspective of a disaster arena and alert decision makers of additional communities potentially at risk. This simulated visual platform can provide responders with an enhanced view of the situation and, in turn, facilitate their awareness of secondary hazards (like overhead power lines with the potential to arc and ignite).

While LiDAR (Light Detection and Ranging) imagery has been in use for decades, recent improvements in its function now allow for the extraction of geometric characteristics of individual buildings, which facilitate a detailed examination of the built environment for disaster mitigation [26]. LiDAR imagery taken of an urban area, for example, can be processed in such a manner that buildings can be isolated from the ground and vegetation. Geometric characteristics of each building can be aggregated and selected for analysis (see Figure 1).

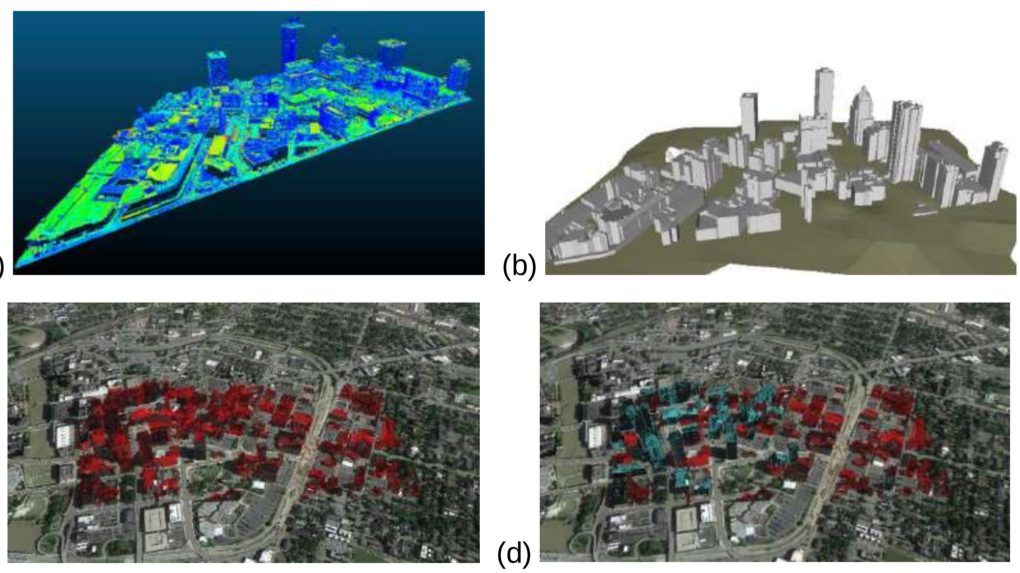
(a)


Figure 1. Demonstration of image processing capabilities to extract individual building characteristics from point cloud data such as LiDAR: (a) data points from aerial LiDAR survey of downtown Rochester, NY, (b) resulting watertight building models, (c) rendering in Google Earth, and (d) ability to select individual buildings based on their geometric characteristics such as elevation. (Courtesy A. Lang)

This ability allows scientists and planners to examine, in detail, building characteristics over a large urban area. When these data are coupled with additional descriptive information, such as material type or building age, engineers can begin to anticipate the vulnerability of these structures to hazards. For example, planners can use building sizes and locations to estimate population densities. Improvements in data science and AI are enhancing these capabilities. Researchers are now working to utilize machine learning to identify architectural characteristics that indicate structural vulnerability.

Other specialized algorithms exist that are well suited for rapidly processing LiDAR imagery to automate damage detection in ways that can be readily used by responders. The Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology has recently developed methods to automatically detect the flood depth of roadways from LiDAR detectors [27], locate and estimate roadway debris volume [28], and identify severely damaged structures [29]. These techniques may impact disaster response capabilities and are currently being considered for commercial development.

Using maps to create a geographic context for a crisis is the foundation for building common operating pictures. With maps, first responders efficiently and quickly know what is happening (e.g., a flood), who is impacted (a neighborhood of retirees), how many are impacted (100 residents), and where it is happening (Fifth and Main Streets). By knowing the precise location of the disaster's ill effects, it becomes easier to deploy resources. Unfortunately, with users providing GPS-tied crowdsourced social media posts, ever-increasing amounts of traditional sensor data, and the plethora of static and live Geographic Information System (GIS) data layers, the crisis manager's map becomes increasingly complex. This tendency, combined with significant amounts of data of unconfirmed veracity can lead to information overload. Also, if the information is located on different platforms, it becomes harder to gather actionable intelligence.

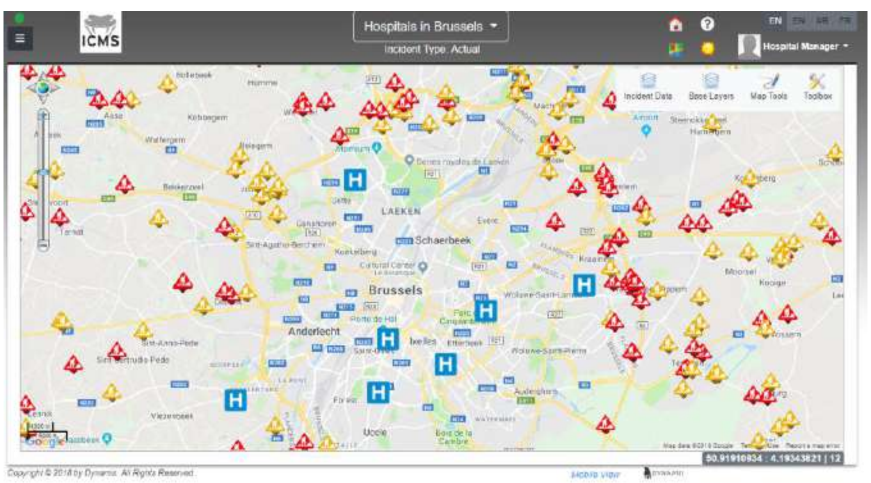


Figure 2. ICMS Visualization of Open Source Critical Infrastructure Data (Courtesy Dynamis, Inc.).

Multiple organizations have attempted to build a single solution that can integrate all information, thus providing a one-stop shop for visual data analysis. The federal public service office in Belgium has implemented a nationwide crisis management program named Incident & Crisis Management System (ICMS) (see Figure 2). This solution brings together thousands of facilities, hundreds of different data types and sources, and dozens of static and dynamic GIS layers to efficiently visualize data about crisis events [30]. Using ICMS, responders can activate GIS base layers showing flood zones, live weather, and the location of critical and vulnerable facilities potentially at risk. Sensors, such as weather gauges, hazmat chemical detectors, and vehicle movements help feed live data into the system.

Another organization with unique needs for capturing and managing multiple datasets is the U.S. Air National Guard (ANG) Emergency Management Office (CEX). ANG bases are unique in that each base is technically a state-level resource, but must meet the same readiness levels of the Air Force in times of federal deployment. In turn, each base level CEX office has a Domestic Operations (DOMOPS) requirement that they can efficiently manage a significant amount of information from multiple fielded sensor systems including chemical, radiological, drone-mounted, and counter-drone fielded sensor systems. Using the COBRA™ Crisis Incident Mangement System (CIMS) solution, ANG CEX customized a DOMOPS tool that allows users to aggregate data from multiple information sources, including user inputs, sensors, unit tracking, live data feeds, GIS layers, and critical facility information onto map imagery (see Figures 3 and 4).

Figure 3. ANG DOMOPS Tool - Ability to Survive and Operate Status Board (Courtesy Dynamis, Inc.)

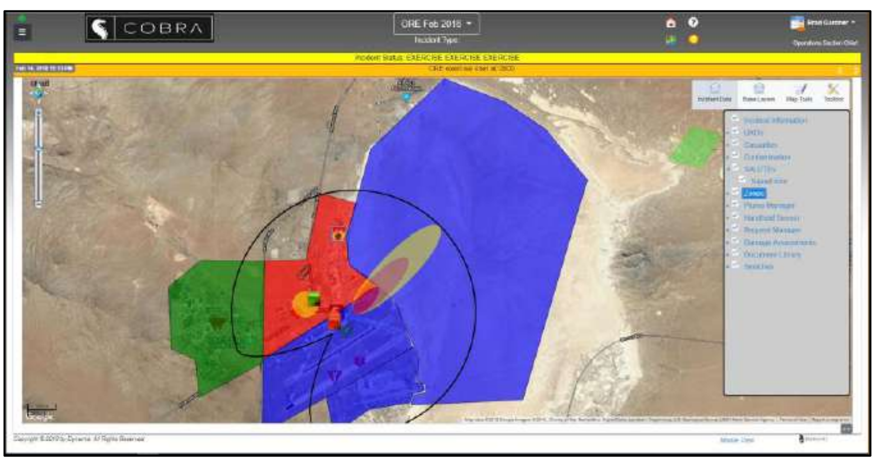


Figure 4. ANG DOMOPS Tool - GIS-based Common Operating Picture (Courtesy Dynamis, Inc.)

This platform provided a single decision support toolset with a near-real-time image of the ground truth. The COBRA™ toolset has been used to support ANG responses for multiple local incidents on individual bases as well as large-scale deployments, including the response to the Texas Gulf Coast following Hurricane Harvey in 2017. After action reviews of these incidents have consistently reflected that the ANG COBRA™ toolset has been effective in mitigating data overload and enhancing operational command and control capability and capacity [30].

There are many CIMS solutions on the market with different strengths and weaknesses. In general, corporations that expend time and resources building a solution seldom share information. This siloing of information can result in critical information being missed or left uncaptured if another response partner is using a different system.

Recognizing the importance of breaking down these information silos and combining different datasets into a single location, DHS and DoD worked together to develop an open source data sharing solution called XchangeCore [31]. Through a collaborative approach, both agencies built the XchangeCore platform to bring "web service data orchestration [of] associated and related content from many sources, in many formats, both non-geospatial and geospatial, that goes back-and-forth through XchangeCore in a two-way standards-based exchange among authorized applications [31]." By bringing together multiple sources of data into a single open source platform, DHS and DoD brought together multiple datasets, structured that data in a way to lower the potential for data overload, reduced data loss, and increased overall understanding of the crisis.

Conclusion

The disaster response community faces the daunting challenge of developing systems and procedures capable of ingesting and process massive amounts of data and swiftly extracting actionable information from them. The key to mitigating data overload during incidents is to create and maintain a culture of data literacy within the disaster response community.

Improved software and advanced computational techniques are helping to realize this goal. New techniques facilitate the rapid identification of which data types are needed; their collection and processing; and its presentation into formats that are timely and easy to consume by response leadership. Multiple efforts are underway within DoD and elsewhere to address this challenge. From the NVESD ISA and DARPA's LORELEI language processing capability to the University of Bradford's Semantically-Enriched and Semi-Autonomous Collaboration Framework for the Web of Things, tools and techniques are continuously being developed to manage the tsunami of data that makes disaster response so challenging.

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5

The Evolution of Protective Equipment for Disaster Response

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Introduction

This chapter focuses on the evolution of protective clothing for firefighting, special operations, and hazardous materials/CBRN threats. In addition, it covers heat stress management and respiratory protection.

Throughout this chapter there are references made to applicable voluntary consensus standards. Beginning in 1995, there was a push by the federal government to avoid duplication of efforts in standards development; allow the national economy to operate in a more unified fashion; and to enhance quality and safety by allowing Government personnel to use products and components designed for the commercial marketplace. The following documents support the use of voluntary consensus standards in the DoD operating environment:

- Public Law 104-113, the National Technology Transfer and Advancement Act of 1995 [1];
- Public Law 108-237, Standards Development Organization Advancement Act of 2004 [2];
- Office of Management and Budget's Circular Number A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities [3];
- DoDM 4120.24, Department of Defense Instruction: Defense Standardization Program [4]; and,
- SD-9, DoD Guidance on Participating in the Development and Use of Non-Government Standards [5].

During his tenure as the Assistant to the Secretary of Defense (Nuclear, Chemical, and Biological Defense Programs) from 2001 through 2006, Dale Klein released several guidance memos to the defense CBRN community regarding the implementation of national consensus-based standards, specifically those from the National Fire Protection Association (NFPA) and the National Institute for Occupational Safety and Health (NIOSH) [6, 7].

Fire-Fighting Protective Clothing

With the rise of new material and product requirements, gloves have been developed from ordinary insulated leather work gloves to multi-layered glove products that mimic some of the characteristics of garments, but with design intended for achieving balance between thermal protection, moisture protection, and hand function. While earlier firefighter footwear used high-temperature rubber coated boots, the latest trend has been toward lighter-weight, breathable, and more form-fitting leather footwear that uses similarly breathable moisture barrier layers coupled with internal thermal linings.

Firefighter helmets have probably shown somewhat less progression because the leather helmet design has become relatively iconic within the fire service. While new high-temperature-resistant thermoplastic materials are used in the majority of firefighter helmets, many helmet designs retain the same rib-based construction that was fundamental to the design of leather helmets. Nevertheless, the promotion of lighter-weight materials coupled with features such as ear covers and face/eye protection, has elevated levels of head and neck protection. Helmets are now supplemented with protective hoods, which are a relatively new addition to the overall protective ensemble.

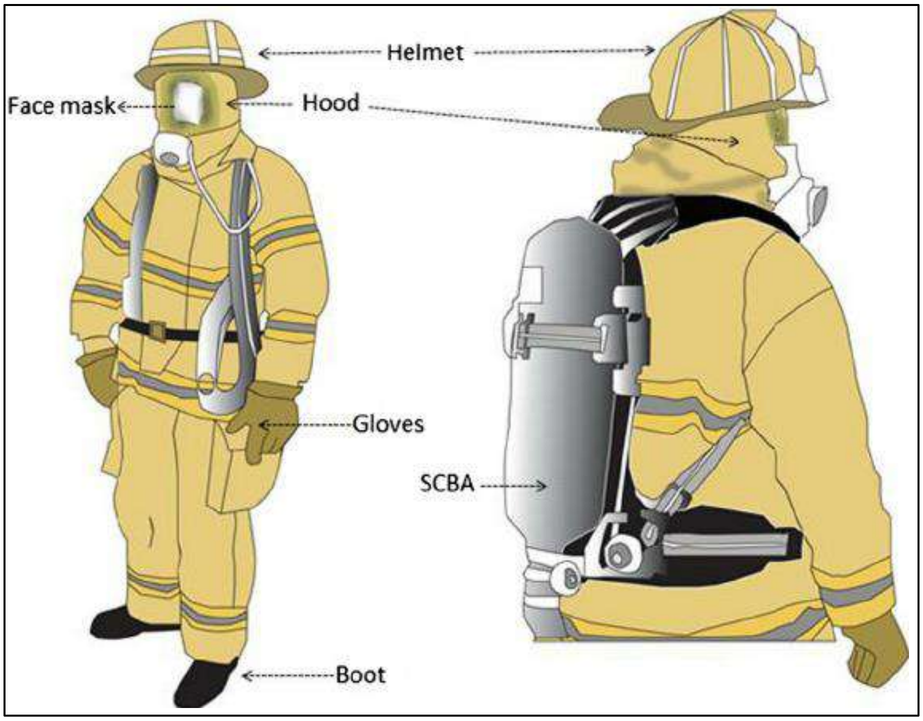

Figure 1. Configuration of modern turnout gear for firefighters (Courtesy Cornell University, Fiber Science and Apparel Design Department, College of Human Ecology)

Current Products

Modern turnout gear (see Figure 1) is designed using three protective layers: a thermal barrier; a moisture barrier; and an outer shell. The thermal barrier is generally made of aramid-based non-woven or batting materials that are then quilted to a flame-resistant facecloth for support. The quilted design creates more dead air space without adding weight. The makeup of the thermal liner is critical to the comfort and safety of firefighters, as it has the greatest impact on thermal protection and a significant role in affecting heat stress. The moisture barrier, often constructed from bicomponent polytetrafluorethylene and polyurethane film laminated to an aramid fabric, provides resistance from water, chemicals, and viral agents. While this layer of the clothing composite primarily functions as a barrier, it substantially affects the ability of clothing to release both evaporative and conductive heat, as well as contributing to the overall clothing system installation. The outer shell, generally made from an aramid and polybenzimidazole blend, provides primary physical protection for the individual wearer and for the underlying layers. All clothing layers are required to be flame and heat-resistant. Therefore, the specific layers and components used in current products are those that meet the respective performance characteristics. In addition, turnout clothing utilizes multiple features, such as high visibility trim, reinforcement layers for physical protection, and supplemental layers for additional insulation at critical areas such as the shoulders, where compression is likely to take place.

The turnout clothing industry includes a large number of manufacturers which use many of the same outer shell, moisture barrier, and thermal barrier layers, as well as supplemental materials and hardware in the construction of their clothing. The majority of clothing is manufactured as coats and pants designed to be worn as a set, with appropriate areas of overlap and interface with other ensemble elements. Manufacturers distinguish their products by the implementation of different design features that affect fit and function, though most of these designs share common attributes particularly as it relates to closures, reinforcement areas, and placement of high-visibility trim as dictated by the NFPA 1971 standard.

The NFPA 1971 standard has also affected the evolution of available products for the remainder of the protective ensemble. Helmets are classified as either having a traditional (leather-like) or modern design, where the latter uses a more efficient smooth helmet shell. All helmets include a suspension system that allows for positioning and adjustment of the helmet on the firefighter’s head. Helmets must be provided with either a set of flame-resistant goggles or a face shield for eye protection in the event that the firefighter is not wearing their self-contained breathing apparatus (SCBA) facepiece. Some newer helmet designs incorporate retractable face shields.

Multiple types of gloves are used in structural firefighting from a range of different manufacturers. The large majority of these gloves use an outer shell of a durable, heat-resistant leather combined with either one or two underlying layers for moisture and thermal protection. Some glove products have transitioned to outer fabric layers (particularly on the back of the glove) that must be supplemented with an additional insulation material. Depending on the glove material littering and design, ensuing gloves have varying impact on firefighter hand function.

Firefighter footwear includes both rubber and leather styles. The latest trend in footwear products is toward lighter weight, increased flexibility, better ankle support, and improved slip resistance (or traction). All footwear must be at least 12 inches in height as measured from the footwear interior. A variety of manufacturer designs also have introduced fabrics into a portion of the footwear exterior. Most footwear styles are of a slip-on design but others use gussets and other waterproof closure systems.

Whereas firefighter protective hoods have generally been two-layer flame resistant knit, sock-like products with a hood opening to accommodate the SCBA facepiece visor, a new generation of hoods has been recently introduced into the marketplace. These new hoods incorporate a particulate-blocking layer that is intended to limit the amount of soot particulates reaching the firefighter’s face. The advent of these new hoods has been in recognition of specific concerns firefighters now face with continuing exposure to fireground contaminants [8, 9].

Challenges with Current Products

Balancing Thermal Protection and Heat Stress

Over the past decade, firefighter turnout gear has seen a great increase in its thermal protection capabilities (by increasing insulation) and in the reduction of many steam burns (through the inclusion of moisture barriers). Unfortunately, the increase in thermal protection comes with an increase in the thermal burden to the wearer that can create physiological stress and limit firefighter time on scene. McQuerry et al. studied the component layers of turnout gear individually and in combination, and demonstrated that the inclusion of the moisture barrier provided the most resistance to heat loss and, therefore, played a large role in overall thermal burden [10]. For this reason, thermal protection is balanced with total heat loss. However, new information is emerging that the measurement of total heat loss may not provide a complete picture for predicting the impact of clothing on the wearer under different environmental conditions. The fire service industry is now studying evaporative resistance as either a replacement or as a supplemental measurement for understanding the physiological impact of material choices on firefighter heat stress [11]. In addition, the use of multiple reinforcements as well as pockets, and other supplemental layers warrants further study for efficiently designing turnout clothing to lessen stress on the firefighter.

Minimizing Firefighter Exposure to Products of Combustion

There are many combustion byproducts observed in structure fires, but the major ones include:

- Carbon monoxide [12–16]
- Nitrogen dioxide [12–14, 16–18]
- Sulfur dioxide [14, 18–23]
- Hydrogen cyanide [12–15, 18, 24–30]
- Hydrogen chloride [12, 15, 19, 31, 32]
- Hydrogen fluoride [15, 21, 33]
- Hydrogen bromide [19, 31, 32, 34–36]
- Phosphoric acid [21, 37–40]
- Nitric acid [15]
- Sulfuric acid [15, 18]
- Volatile organic compounds (VOCs) [13–15, 18, 41–44]
- Aldehydes [13–15, 18, 43]
- Polycyclic aromatic hydrocarbons (PAHs) [14, 15, 41, 42, 44–49]
- Phthalate diesters [48, 49]

According to the International Association of Firefighters (IAFF), 55 percent of line-of-duty firefighter deaths since 2002 were caused by occupational cancer [50]. Studies such as those described above have definitively shown the deposition of carcinogens onto firefighter gear and their skin, and the need for gross decontamination, showering, and laundering of gear. However, in a 2017 study, Harrison et al. surveyed 485 firefighters from four departments about their post-fire decontamination behaviors and found that while the firefighters had positive attitudes regarding post-fire decontamination, showering after a fire was the only decontamination process occurring regularly [51]. Cleansing wipe use, gear laundering, and other behaviors occurred less frequently mainly due to department resources (time and equipment) or wet gear concerns [51].

The routes of entry of airborne contaminants generated in a fire into the body include inhalation, ingestion, dermal, and injection. The most significant route of entry is through inhalation [52]. The contaminants (gases and particulates) can deposit or pass into the body through the lungs causing both acute and chronic adverse health effects. Despite the importance of this entry route, its significance within the firefighting environment should be considered in the context of firefighters' use of SCBA and their tactical methods.

Airborne contaminants (gases and particulates) generally will not be ingested because of good hygiene practices and the use of SCBA. However, the importance of the skin as an entry route is less certain. For example, it has been known for approximately 200 years that certain illnesses are likely associated with dermal absorption of occupational or environmental contaminants, but this association is not clear for all exposures. [53]. It is well established that polycyclic aromatic hydrocarbons, aromatic hydrocarbons, and acid gases will be absorbed directly from the vapor phase and penetrate the skin. The penetration rate is dependent on many factors and the dose is also affected by the body's ability to de-toxify and excrete the contaminant. There is increasing evidence reported highlighting the importance of the skin as an entry route in the context of firefighting [41, 47, 54, 55]. Given the extensive use of SCBA within the firefighting environment, the importance of the skin as an entry route has likely been underestimated.

Future Directions

New Materials to Increase Thermal Performance While Maintaining Breathability
There are several approaches being evaluated in this arena. One approach to increase thermal performance without reducing breathability is to maximize air insulation between layers. Another is to incorporate new, lighter materials which may provide a reduction in thermal liner thickness while maintaining similar thermal protective performance [56].

Ensemble Designs to Minimize Exposure to Products of Combustion
Manufacturers are designing the next generation of turnout gear with a specific goal to reduce the smoke and soot penetration through the ensemble interfaces. This approach to reducing the level of chronic exposures on the fireground could potentially result in a parallel reduction in cancer rates. Several approaches, including the use of smoke-impermeable fabrics at interface regions and inclusion of a removable bib onto the turnout gear pants are being considered [57].

Ensemble Cleaning
If frequent cleaning is to become the norm, then implications arise as to the impact on both the gear and the departments that choose to provide this level of cleaning. For years, many departments have struggled to outfit their members with two sets of gear. The push for two sets has been based on the argument that as one set becomes soiled or contaminated, an extra set is needed to prevent taking the unit out of service.

This two-set approach has been instrumental both in ramping up the ability to clean gear more frequently and in having cleaner gear available for fire department members.Yet, for some departments, a two-set approach may not be the solution or even possible within their available resources. This can occur because two sets are insufficient for a relatively busy station, or this simply creates a financial burden that a department cannot overcome.

In addition to the availability of clean gear, other questions have arisen regarding the ability to clean gear. Generally, the focus has been on garments, and to a lesser extent, more recently on hoods. This is because these items can be cared for much like regular apparel. Helmets, gloves, and footwear are generally more frequently ignored. Typically, these items cannot be machine-washed and sometimes are never cleaned after a fire incident. Yet, it is well recognized that these items become just as dirty, if not more so than the full garments. Thus, the ability to clean these items effectively remains a significant variable as the trend for frequent cleaning is increased.

Ensemble Durability for Increased Laundering

Even when it is possible to implement more frequent cleaning, there is still the issue of how cleaning can affect the long-term protective performance of the clothing and equipment. Regular cleaning can break down clothing over time. In the case of turnout clothing, only rudimentary controls are built into NFPA 1971 for making this assessment.

For most performance requirements within NFPA 1971 as a prelude to testing, only five cycles of laundering are applied for garments. For one property in particular—moisture barrier effectiveness—that number is increased to only 10 washing and drying cycles. Thus, if the expectation is that clothing is cleaned after every working fire, then some gear can be subjected to up to 25 cycles a year

Many manufacturers currently indicate that clothing generally has a service life, ranging from five to seven years for a moderately busy department. While it is recognized that many components are indeed quite rugged and durable, there remains some uncertainty as to whether frequent cleaning will cause some degradation of clothing and equipment performance. However, it is important to note that the flame resistance of the turnout gear is due to the base fibers used in the material, therefore, degradation in flame resistance is not expected.

Ensemble Issuance

The current system of PPE design, materials, cleaning, and decontamination may not be the best solution for managing firefighter exposure to contaminants. To address this problem more holistically, it may be necessary to think completely outside the box with respect to existing practices. Turnout clothing availability may be better served by clothing that is maintained by the department and issued as needed—meaning that gear is no longer specific to the individual, but to the organization. This approach creates significant problems such as ensuring appropriately sized ensemble elements for each firefighter, but it does provide a basis for ensuring that clean items are provided for each incident to the firefighter. Such practices are already being employed for protective hoods, a much simpler item of protective clothing.

What is clear from these issues is that conventional approaches probably will not provide long-term solutions and therefore other forms of technology, perhaps borrowed from other industries and adapted for the fire service, or altogether unique designs and techniques, should be considered to address the minimization of continued firefighter exposure to carcinogenic and other hazardous contaminants.

Special Operations Protective Clothing

Emergency responders in urban SAR (USAR) have to be prepared for potential exposure to a number of hazards (see Figure 2). Each response is different and the available protective clothing and equipment must provide adequate protection against each hazard. The unique nature and combination of these hazards warrant specialized clothing and equipment to protect emergency responders in the various missions they undertake. These requirements are generally different from those needed for related emergency response missions, such as structural firefighting, hazardous materials response, and emergency medical services.

Figure 2. This training exercise demonstrates the typical USAR protection worn during operations. (Photo courtesy of the authors)

Consequently, separate types of protective clothing and equipment have been established for special operations areas. While some elements of performance from each conventional response area are similar to those needed in USAR, USAR activities generally involve lower levels of the different hazards for longer potential exposure period and thus dictate specific requirements. Historically, practices for protecting emergency responders in special operations have varied dramatically throughout the country. In the past, depending on the type of mission, emergency responders from two different organizations would use completely different protective clothing in responding to similar incidents. Therefore, USAR protection strategies varied, as did the required missions to which rescuers respond. With little guidance previously being available, most emergency responder-based clothing and equipment purchases were based on experience but were unable to anticipate all possible situations or hazards.

Special operations evolved in the late 1980s when municipal and regional fire and police departments recognized special needs for more efficiently dealing with certain types of events. This recognition also took place at a national level through FEMA, which set up regional USAR teams. The specialized groups within the individual departments or regional teams created capabilities for addressing the following types of emergencies:

- Building/structural collapse
- Vehicle/person extraction
- Confined space entry
- Trench/cave-in rescue
- Search operations (air, water, terrestrial)
- High angle rescue
- Swift or still water rescue
- Contaminated water diving

The principal types of hazards associated with these events are generally physical in nature, but responders could also encounter flame and heat, such as incidental flash fire, exposure to chemicals and biological pathogens, and extremes of weather. The key separating elements for these types of missions as compared to more conventional emergency response were the longer length of mission time expected for the first responder were at lower protection levels.

Relative to the protection needs of their response, three different types of ensembles are categorized with the first area addressing extended physical protection needs and collectively referred to as technical rescue and separate areas for both swift/still/ice water rescue and contaminated water diving. For technical rescue, ensembles were defined as garments, helmets, gloves, and footwear for extended wearing operations. Potentially rugged physical environments demanded durable and physical hazard resistant clothing, which could be comfortably worn for long periods. For many of these operations, the potential also existed for exposure to incidental flame, or flash fire dictating the need for flame resistance, and in some cases included exposure to chemicals and blood-borne pathogens where a disaster scene may have caused the rupture and distribution of hazardous chemicals or during events where victims or bodies must be removed from the emergency scene. In many cases, emergency responders also need to be relatively visible to ensure their identification and prevent accidents at high-activity emergency sites. These clothing systems currently differ from turnout clothing by being substantially lighter and more functionally-oriented.

Swift water rescue and related emergency water operations defined a different type of ensemble that generally included garments that keep the wearer dry, warm, and protected against physical hazards such as debris and exposure hazards such as contaminated water. Ensemble elements such as helmets, gloves, and footwear all have to be devised for the difficult environment of rapidly moving water. Thus, helmets include perforations to prevent individuals being affected by current, special boots or fins are used to enable swimming or traversing uncertain bottom surfaces, and tethers are used for securing individuals. The ensembles are complemented with a personal flotation device, and other accessories to enable rescue activities.

Contaminated water diving, protective ensembles have similar features, but are designed for appropriate buoyancy and ensuring that individual responders are fully covered by their protective clothing and equipment to prevent any exposure to contaminated water. These systems must further integrate with self-contained underwater breathing apparatus (SCUBA). In some cases, ensembles have been developed to integrate with a surface supplied air system.

Current Products

Current products used in the technical rescue community are designed according to the following priorities: physical hazard protection from rough surfaces, jagged edges, pointed objects, and falling/flying debris; on-site visibility; clothing comfort, form, fit, and mobility; and, respiratory particulate protection. In addition, limited protection was necessary for: flame and heat; chemical flash-fire; and, electrical exposure. If chemical and biological detection is deemed necessary, products are cross-certified to the Hazmat/CBRN standards. In comparison to the turnout gear described previously, the special operations protective ensembles are meant to be lighter with less thermal insulation, more physically rugged, and intended for longer wearing times with a higher level of breathability. In addition, the current NFPA 1951 standard differentiates between utility technical rescue protective ensembles (exposure to physical and thermal hazards) and rescue and recovery protective ensembles (exposure to physical, thermal, liquid, and body fluid-borne pathogens).

Utility technical rescue garments tend to be rugged single-layer flame-resistant textile products using the form of coverall, many which are not certified to the NFPA 1951 standard. Some of these are similar to military battle dress uniforms. These products are supplemented by technical rescue helmets, gloves, and footwear. Several products are positioned against the NFPA 1951 standard for helmets and footwear; however, most special operations team personnel opt for heavy leather work gloves and wear examination gloves underneath their work gloves when liquid protection is needed. Extrication gloves that include a large number of reinforcements are also used by special operations teams for hand protection. Rescue and recovery garments comprise two basic design approaches: a single layer or two layers consisting of an outer shell and liquid barrier. Oftentimes, these are very similar to turnout gear but with limited thermal protection with the absence of the thermal barrier. These garments are combined with the same helmets, gloves, and footwear that are used for utility technical rescue operations.

Given their relative newness, there are no certified products to either the NFPA 1952 or 1953 standard on water rescue and contaminated water diving ensembles. Special operations teams requiring these capabilities use a combination of professional and sports equipment for these applications. For swift water rescue, conventional wet or dry suits are used with either kayak helmets or specialty professional products that have been represented for this application. Foot protection normally consists of neoprene water booties, sneakers, a nonslip boot, or swim fins. Dry suits are preferred where contamination may be suspected. Swim fins may greatly increase the speed of the rescuer in the water but their use takes training and frequent use to be an advantage. U.S. Coast Guard (USCG) Type III personal flotation devices (PFDs) are typically used; these PFDs have a sewn-in chest harness with a quick release buckle for the tether. Chest harnesses should have an attachment point on the back near the shoulder blades to tether a rescuer to rope as well as a one-hand release.

For contaminated water diving, a number of diving suit products have been positioned in the marketplace specific to contaminated water operations. These suits are fabricated from hybrid rugged rubber materials with demonstrated chemical resistance against a variety of products under use conditions and include high end closures and interface devices for attachment of diving gloves and booties with swimming fins. Most contaminated water diving suits share features with U.S. Navy products, which have gone through extensive validation testing. These suits are mated to a diving helmet and SCUBA system through a neck dam. However, many public safety diving systems use standard SCUBA worn over hoods and rely on the face-seal and hood mask seal for minimizing contaminated water contact with the wearer. These systems often require buoyancy controls and bail out systems.

Challenges with Current Products

Unfortunately, with some exceptions, there is a lack of selection for gear designed specifically for SAR missions, as there are currently no full ensembles certified to existing standards. For technical rescue operations, most products currently in use are adaptations from the products certified to NFPA 1971 or NFPA 2112, *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire* [58], though there are several garment and footwear products that have been certified with other standards such as for emergency medical applications. Some of the problems with industry acceptance of the standards are that many requirements remain overly rigorous, particularly when associated with barrier testing of materials and products. Several current products that have been deemed acceptable either cannot be certified, or the costs for certification are prohibitive when weighed against the volume of products sold for this specialty area. Therefore, changes in the standards may induce more certified products, but the changes needed to be coupled with realistic expectations of performance.

Specific to the area of technical rescue, the fire service has wrestled with the concept of garment convertibility where structural garments can be reduced in a consistent way that does not compromise their use for high-end hazards but still allows the garment to be used for events such as vehicle extrication (see Figure 3), which require less thermal insulation. While this concept is not new, departments believe that since a large proportion of their responses are non-fire, there is utility in garment conversion or having their second garment be a technical rescue garment. The principal criticism of this approach is that technical rescue garment configurations will incorrectly be used in structural fire environments given their better mobility and greater comfort; however, these types of issues can be addressed through proper emergency scene management.

Future Directions

There are no radically new material and clothing design technologies on the horizon that would change the market or use of technical rescue protective clothing and equipment. It is likely that the use of technical rescue gear will remain limited to the true USAR missions for which it was originally intended. With shrinking budgets and the diminishment of federally-funded PPE, technical rescue gear will remain a specialized product instead of a lower tier of protection for the fire service. It is expected that innovative solutions will be sought for the ability to convert structural garments to technical rescue garments. Departments facing restricted budgets for PPE in increased focused on addressing hazards for contamination gear with products of combustion may undertake more creative solutions for the type of gear used in different missions to allow for better customization of the ensemble for the respective hazards.

Figure 3. Example of protection worn during extrication. (Photo courtesy of the authors)

Hazardous Materials/CBRN Protective Clothing

Current Products

Most chemical protective ensembles were designed for industrial applications and later adapted for emergency response use. It has only been the more recent ensembles designed to meet NFPA 1994 specifications that have been designed specifically for a disaster response scenario. Unfortunately, PPE is often purchased in small lots by a widely distributed network of independent procurement activities, especially in the U.S. This is due to the vast number of emergency response organizations, most of which are managed at the local level. The broad user profiles and the infrequent use of products leads to a slow research and development process by companies, as the procurement rate does not allow manufacturers to amortize the development costs in a timely manner. In addition, there are significant mission and cultural differences within the emergency response community, which has resulted in uneven adoption of existing standards and, in many cases, uneven adoption of the legal requirements set forth by OSHA.

Table 1 shows the products currently certified against the applicable chemical protective clothing standards. For NFPA 1992 and NFPA 1994, the 2012 and 2018 editions are both shown as the 2018 standard was recently released, therefore many products are in the process of gaining certification at the time the table was developed. At any point in time, a user is able to visit the websites of the Safety Equipment Institute and Underwriter's Laboratory to find lists of products certified against the NFPA standards by each of the certification programs. The products certified against NFPA 1991 and NFPA 1992 are very similar in design, while the ensembles certified against NFPA 1994 are predominantly more form-fitting and, in many cases, are not fully encapsulated.

<table>
<tr><th>Standard</th><th colspan="4">Certified Products</th></tr>
<tr><td>NFPA 1991 (2016 ed.)</td><td colspan="4">• Dupont RF600 (Reflector)
• Kappler Frontline 500
• Saint Gobain ONESUIT Flash 2
• Saint Gobain ONESUIT Pro 2
• Trellechem EVO
• Trellechem VPS Flash</td></tr>
<tr><td>NFPA 1992 (2018 ed.)</td><td colspan="4">• Blauer RC3
• Lion MT-94 Ruggedized
• Microchem by AlphaTec 68-4000</td></tr>
<tr><td>NFPA 1992 (2012 ed.)</td><td colspan="4">• Ansell 8017, 8057, 66-680, 66-683 (coats)
• Ansell 8018, 8058, 66-682 (overalls)
• Ansell 8016, 8056, 66-687 (coveralls)
• Dupont X3198T, C3199T, TP198T, TP199T
• Kappler ANC3E, Z3H426, Z3H427, Z3H428, Z3H432, Z3H437, Z3H576, Z3H577, Z3H579
• Saint Gobain ONESUIT Shield</td></tr>
<tr><td>NFPA 1994 (2012 ed.)</td><td>Class 1
Not Applicable</td><td>Class 2
• Blauer Multi-Threat
• Drager CPS 5900
• Kappler Zytron 500
• LION MT-94
• Saint Gobain ONESUIT Shield</td><td>Class 3
• Blauer XRT
• LION ERS</td><td>Class 4
• Blauer BRN-94</td></tr>
<tr><td rowspan="2">NFPA 1994 (2018 ed.)</td><td rowspan="2">Class 1</td><td>Class 2
• Trellechem ACT</td><td>Class 3
• No certifications awarded</td><td>Class 4
• No certifications awarded</td></tr>
<tr><td>Class 2R
• Lion MT-94 Ruggedized</td><td>Class 3R
• Blauer RC3</td><td>Class 4R
• No certifications awarded</td></tr>
</table>

Table 1. Products currently certified against the applicable chemical protective clothing standards (as of May 29, 2018).

Challenges with Current Products

Current Level A/NFPA 1991 Products are Design-limited

During a recent survey of the hazardous materials response community (398 respondents), the main concerns of the operators related to the Level A/NFPA 1991 ensembles were in priority order, physical hazard resistance, clarity of vision, fine hand function, field of vision, general mobility, liquid penetration, speaking communications, comfort, flame/heat resistance, and overall durability [59].

Limited Visibility

The greatest safety issue that remains today with all current Level A/NFPA 1991 ensembles is limited field and clarity of vision [59]. While several manufacturers have begun to address system “fogging” of the face piece, very few overarching design changes have been made to address the field of vision or the clarity.

Operational Utility of Gloves

Gloves have been designed to meet the level of protection necessary, but very little thought has gone into the design of gloves to meet the operational needs of the user. One issue frequently brought up by the operational community is the lack of comfort and fine hand function with the current gloves used in hazardous materials response [59].

Current Level A/NFPA 1991 Products are Over-Protective

In the responder survey mentioned above, the operational community perceived that the NFPA 1991 standard requirements were set at the correct levels of protection and felt that they should at a minimum have flame and heat resistance, and in many cases, flash fire protection. However, in the same survey, the responders stated that they very rarely or never came across small fires, flames, or chemical flash fires. In addition, the hazards that were most frequently seen included liquid exposures, gas/vapor exposures, liquefied gas leaks, and physical hazards. Unfortunately, in the desire to provide enhanced protection, manufacturers have had to forego design considerations that could greatly enhance comfort, mobility, and operational tactility.

Service Life Issues

The issue of longevity for chemical protective ensembles has been highly debated. Ensembles can be engineered using rugged materials to withstand repeated use and physical wear and tear so that acceptable levels of protection are provided. However, once an ensemble becomes contaminated, then the question arises whether the ensemble can be adequately decontaminated to permit further use. This topic has been the subject of extensive research that is captured in several sources [60-66].

While performance criteria have been factored into the NFPA standards to address ensemble and material ruggedness, the representation of the ensemble’s service life has been left to the discretion of the manufacturer with the exception of NFPA 1994. NFPA 1994 specifically states within its scope that “the standard shall establish requirements for protective ensembles and ensemble elements for a single exposure at incidents involving CBRN terrorism agents.” The committee developed this statement to require that CBRN protective ensembles be disposed of following any CBRN terrorism agent exposure; however, it recognized that ensembles could be repeatedly used if such exposure did not occur.

Storage Life Issues

Another related area of concern is the longevity of chemical protective suits when stored, but not used. All three standards require that the manufacturer report the “storage life” of their ensemble as part of the technical data package that is provided with the clothing. The committee set this requirement with the anticipation that some ensembles could be stored for an extensive period but could also deteriorate over time. Each NFPA standard establishes the following definition:

> Storage life—The life expectancy of the CBRN protective ensemble and ensemble elements from the date of manufacture when it is only stored and

inspected and has undergone proper care and maintenance in accordance with manufacturer's instructions, but not used, donned, doffed, or repaired [67].

The storage life is established by the manufacturer and must be reported in the user information provided in the ensemble. No specific criteria are provided for how the manufacturer establishes the storage life for its products.

Future Directions

Over the past ten years, great strides have been made in the chemical protective clothing marketplace. However, there are still many gaps to be filled.

Form-fitting Gloves

Most gloves currently in use in the CBRN environment are not breathable and have poor moisture management, resulting in significant discomfort for the wearer. In addition, the gloves are made with a thick butyl rubber with little focus on usability. AirBoss Defense, with funding from DoD, is developing a new glove providing greater tactility, durability, dexterity, breathability, and comfort when compared to the traditional gloves [68]. The glove has been designed to exceed the requirements set forth in NFPA 1994, Class 3.

Balancing Protection with Comfort

The most significant driver for current material technology is the various tests that are applied in qualifying product materials and components. Early philosophies towards the evaluation of protective clothing materials have involved relatively severe challenge conditions that minimize choices of products that can provide greater levels of comfort and function. The development of NFPA 1994 and its ensuing revisions has led to the classification of ensemble levels, unlike what had previously existed through the use of NFPA 1991/NFPA 1992 alone.

The recognition that many exposures will be incidental coupled with material technology that can achieve high levels of evaporative heat loss is leading to products that can be worn more comfortably and functionally under a range of conditions. Separating biological and radiological particle hazards from chemical hazards (as one part of the hazardous material PPE strategy) is another means for allowing first responders to have optimal levels of protection.

Non-Encapsulating Vapor-Protective Ensemble Designs

Over the past three decades, there has been considerable focus on the quality of totally encapsulating chemical protective suits representing Level A performance, which is further defined by compliance with NFPA 1991. Nevertheless, the use of Level A ensembles represents only a fraction of the overall use of PPE for hazardous materials response. Moreover, many of the exposure levels used in qualifying these ensembles is well in excess of the maximum exposure conditions responders face in actual incidents. Emergency responders increasingly desire more tactically-oriented ensembles for which encapsulating suits cannot deliver the requisite functional performance. To this end, there are different government-sponsored projects that are focused on providing new ensembles that use relatively high, but credible, levels of chemical resistance and overall integrity tests for defining ensembles that can provide Level A performance. The acceptance of these products will likely change the spectrum of hazardous materials PPE.

Managing Heat Stress

Each of the types of protective clothing described previously in this chapter plays a role in the overall heat stress of the operator. The core temperature of the operator should be maintained at 37 degrees Celsius +/- 1 degree Celsius for continued normal body function [69]. The human body naturally maintains this equilibrium by balancing the rate of heat exchange between the body and the environment. Parameters affecting the total heat load on an individual are:

- Conduction, or the direct transfer of heat between and object and the operator;
- Convection, or the heat exchange between the operator's skin and the ambient air immediately surrounding the skin;
- Radiation, or the heat exchange between the operator's skin and the radiant temperature of the surroundings; and
- Evaporation, or the heat loss from the operator's body due to the evaporation of sweat from the skin surface.

When looking at the above parameters, it becomes obvious that the protective clothing will play a significant role in the amount of heat stress as it will affect all four parameters. Oftentimes, operators reach an uncompensable environment which could result in heat stress. The heat stress will manifest itself in progressively more serious ways, including heat rashes, heat syncope (fainting), heat cramps, heat exhaustion, and heat stroke.

The addition of protective clothing creates a microenvironment around the operator that becomes the driving force behind the heat stress. The operator can make educated decisions regarding selection of PPE with heat stress in mind, but choosing breathable materials where possible, reducing the total weight of the garment, and reducing the number of layers of material. In addition, engineering controls such as pre-cooling or operational/post-cooling can be implemented where feasible.

Current Products

Pre-Cooling
Products used for pre-cooling of operators prior to the donning of protective clothing include cooling vests, arm immersion, water-perfused suits, heliox, and ice slushy. In a study performed by Maley et al., it was determined that the ice slushy was the only method of pre-cooling that reduced the core temperature, while all others reduced the skin temperature [70]. For those reducing the skin temperature, the ice vest provided the most marked difference and demonstrated that time periods of pre-cooling greater than 20 minutes were not necessary.

Operational Cooling
Products used for operational cooling, or post-operational cooling, include ice phase change, non-ice phase change, liquid cooled, water immersion, evaporative, or hybrid systems. A recent market survey by Stewart et al. found 46

different products on the market for cooling from 15 different manufacturers with use cases in industry, sports, law enforcement, military, medical, hazardous materials, firefighting, and everyday use. The team has developed a database as a means of distributing technical and scientific data on system functionality [71].

Physiological Status Monitoring

Most commercially available physiological status monitors capture the operators' blood pressure, heart rate, respiratory rate, and skin temperature. The data is used for a variety of purposes including developing a baseline for the individual operator, monitoring status remotely, and in some cases, as indicators of overexertion. The most common physiological status monitors used in the emergency response community today are products from Hidalgo and Zephyr.

Challenges with Current Products

One of the most obvious problems with the current products on the market is that the technical data provided to the operational community is inconsistent. This is mainly due to the fact that no standards exist in the cooling field outside of test methods. In 2016, NIOSH released *Criteria for a Recommended Standard for Occupational Exposure to Heat and Hot Environments* [69].

Many of the cooling technologies that are available focus on cooling the skin which can be counterproductive for the operator. With the exception of those within the lower wrist, hands, and feet, blood vessels in other areas of the body will vasoconstrict with reduced temperatures. This narrowing of the blood vessels decreases blood flow to the skin's surface and minimizes the body's natural ability to cool itself using evaporative sweating. In addition, the extra weight of the cooling device can add physiological work to the operator, thereby increasing heart rate.

There are two different factors that are generally used as indicators of physiological stress in emergency operations—elevated core temperature and elevated heart rate. For operations involving chemical protective clothing, elevated core temperature is the first indication of heat stress due to the uncompensable environment created by impermeable materials including materials with multiple layers and air gaps. For operations involving significant weight of equipment, as often seen in bomb suits and firefighting, elevated heart rate may be the earliest indicator of physiological stress. The U.S. Army Research Institute of Environmental Medicine (USARIEM) ECTemp™ algorithm has shown promise in estimating core temperature from heart rate, especially for those cases where impermeable materials are not in use [72]. As estimations do vary +/- 0.3 degrees Celsius from real measures, it is highly recommended that baseline information on operators is maintained to ensure application and operational safety.

Future Directions

Significant strides have been made in the past five years on understanding and managing heat stress, but this field still has significant room for growth.

Product Standard Development

Using the materials set forth by NIOSH in 2016, a standard setting organization, such as NFPA might develop a product standard to set the minimum technical requirements for cooling products, especially when used in combination with other protective equipment. The work performed by Ian Stewarts's team at the

Queensland University of Technology, which resulted in the development of the Cooling Database website will provide a first step in categorizing equipment by capability [71].

Non-Invasive Measures of Core Temperature

The deep body, or core, temperature of an individual is the measurement that drives the deleterious effects of heat stress. Unfortunately, the gold standard methods for measuring core temperature are the rectal thermometer and the esophageal thermometer, both of which are not operationally relevant to the disaster response community. There also are ingestible core body temperature sensors that can wirelessly transmit data as it travels through the digestive tract, but these must be administered several hours prior to an event to ensure that they are in the proper position for measurements and tend to have error rates similar to those observed with the ECTemp™ algorithm. This is often not possible for disaster response operations. Therefore, for operations where the driving factor his work rate related, such as work in bomb suits, firefighting gear, as well as SAR, the ECTemp™ algorithm should be utilized. For operations where uncompensable environments are due to chemical protective clothing, a non-invasive measure of core temperature should be developed or further studies on the ECTemp™ applicability to this environment should be performed. The research team from USARIEM published a technical report in 2016 detailing the past accomplishments and future defense needs in the field of physiological status monitoring [73]. In parallel, Pacific Northwest National Laboratory published a report on the use of physiological status monitoring in the first responder community [74].

Effects of Chronic Heat Exposure

All of the studies on heat stress have been performed on short exposures, generally in the minutes to hours timeframe. Little is known about the long-term effects of repeated exposures to high heat environments such as those in firefighting and within the microclimates of chemical protective clothing.

Heat Stress and Toxicology

It is widely accepted that increases in sweat and skin blood flow increase the dermal absorption of some toxicants [75, 76]. This becomes increasingly important when dealing with the disaster response arena, especially firefighting, as it is known that many of the toxicants are dermal threats.

Hydration Status Monitoring

Many methods, each with their own drawbacks, have been used over the years for monitoring the hydration status of an individual. Unfortunately, the ability to measure hydration status in a complex fluid matrix with many interconnected fluid compartments, is unlikely to have high accuracy when using only one technique. In a laboratory, measurements of plasma osmolality (concentration) and total body weight (estimating volume) are excellent indicators of hydration status. In the operational environment, the volume and concentration of available fluids are constantly fluctuating, and the use of non-invasive techniques such as total body weight (estimating volume) and urine color (estimating concentration) are more relevant [77]. Work has also been done correlating salivary osmolality as an indicator of hydration status, but the measure was very dependent upon the individual and their baselines, therefore not as applicable broadly [77, 78]. In parallel, Eccrine Systems, Inc. is working on a non-invasive, electronic sweat sensor capable of transmitting real-time data on human sweat [79]. There remains a need for the development of real time, non-invasive measures of fluid volume and concentration.

Heat Stress Calculators and Estimating Work-Rest Cycles
There are a variety of heat stress calculator tools available today. An excellent tool for estimating heat potential for heat stress, not involving impermeable protective clothing, is available online from the Queensland Government. The Georgia Tech Research Institute, in partnership with Queensland University of Technology, North Carolina State University, and the Netherlands Organisation for Applied Scientific Research, developed a heat stress calculator specific to disaster response PPE using machine learning functions across data from multiple human trials in various chemical protective clothing, turnout gear, and bomb suits [80]. The calculator is available as a tool within the Emergency Response Decision Support System. More work needs to be done to develop capabilities that are specific to the PPE worn and the work performed. The calculators should be used for mission planning versus operational tools.

Physiological Monitoring and Work-Rest Cycles
Physiological monitoring devices have gained popularity over the past 10 years in emergency operations. Guidance documents need to be developed to ensure that the data is used properly to develop individualized work-rest cycles based upon the physiological status of the operator. Once sufficient data is available for operators in disaster response scenarios, guidance can be provided to minimize the number of heat casualties seen in emergency operations.

Respiratory Protection

Many of the applications for disaster response involve different types of respiratory hazards:

- Structural fires often result in high levels of smoke (particles) and toxic gases;
- Wildland, forest, and other outdoor fires also create smoke and gases, but exposure is usually at lower levels because fire responders often do not get as close to the source of the fire;
- Building collapses or other disasters release chemical vapors and large concentrations of suspended particles;
- Hazardous materials emergencies often involve the release of chemical gases and vapors;
- Rescue or emergency medical operations may result in exposure to tuberculosis and other airborne pathogenic diseases; and
- Terrorism incidents may result in exposure to chemical warfare agents, toxic industrial chemicals, and biological pathogens or toxins.

Respirators protect the wearer from inhalation of harmful dusts (particles), chemicals, and other respirable substances. Respirators provide protection to the wearer by:

- Removing contaminants from the air (air-purifying); or
- Supplying an independent source of respirable air (atmosphere-supplying).

The first type of respirators includes chemical or particulate air-purifying respirators (APR) and powered air-purifying respirators (PAPR). Examples of atmosphere-supplying respirators include supplied-air respirators and self-contained breathing apparatus (SCBA).

Current Products

Currently certified NFPA 1981 products are listed in Table 2.

Standard	Products
NPFA 1981 (2013 ed.)	• Avon Protection Systems Deltair (300027, 300028, 300029, and 300030) • Draeger Safety UK PSSS5000/PSS7000 Series and PSS7000H series • Honeywell Safety Products (Sperian Respiratory) Titan • Interspiro, Inc. Spiromatic S8 • MSA Safety FireHawk M7 XT Air Mask and G1 SCBA • Scott Health & Safety, Inc. Air Pak 2013 CBRN, Air Pak X3 CBRN, and NxG7 CBRN
NFPA 1986 (2017 ed.)	No certifications awarded as of 29 May 2018; therefore, responders continue to use NFPA 1981 certified products.

Table 2. Certified NFPA 1981 products (adapted from www.seinet.org). Products certified to the NIOSH standards can be found on the NIOSH Certified Equipment List.

Challenges with Current Products

SCBA development has traditionally focused on the delivery of air, versus operational performance. More recently, the trend has been to increase performance with technology enhancements such as communications clarity, integrated sensing systems, data collection and display, and others. In addition, SCBA systems have been hardened for use in specific environments, but little change has been made in the system profile.

Breathing Rates

It is important to note that the NIOSH CBRN filter certifications for air purifying respirator canisters are tested at a constant breathing rate of 85 liters per minute. For disaster response operations, this respiratory flow rate is very low when compared to the International Organization for Standardization (ISO) metabolic rates and respiratory flow rates referenced within ISO/TS 16976-1:2015 [81]. However, studies by Hofacre and Richardson, using cyclic breathing rates with peaks at approximately 400 L/min, demonstrated that the products currently certified to the NIOSH CBRN standards are protective, even at the higher, cyclic respiratory flow rates [82].

Mask Interoperability

Most current products use either a positive-pressure mask for SCBA operations or a negative-pressure mask for APR operations. Unfortunately, this requires many operators to have multiple masks to maintain and creates an additional burden for fit testing.

Fire-Hardened Designs

Currently certified SCBA products on the market are hardened for both CBRN environments and structural firefighting needs. The high temperature needs of the firefighting community in addition to reserve air requirements and personal alert safety system devices drive up the cost and complexity of SCBA products. While these enhanced capabilities are necessary when using an SCBA in firefighting operations, they are not critical when responding to the other disaster response scenarios. This led to the development of the NFPA 1986 standard where the operational community on the technical committee included operators from defense, hazardous materials, law enforcement tactical teams, and bomb squads.

Future Directions

Combination Unit Respirators
A Combination Unit Respirator incorporates two or more types of respiratory detection devices within one unit, for example a combination APR/SCBA, and allows the user to switch between modes of operation without doffing the respirator. One of the driving forces behind the lag in product development in comparison to the user-identified need for combination unit systems is the lack of guidance on performance requirements, switching mechanism design, and risk compensation. For example, the guidance on when respiratory protection is required, and to what level the protection is necessary, are very straightforward in terms of APR versus PAPR versus SCBA, but the line becomes blurred when a combination unit is employed. Currently, the system is certified to its lowest level of protection offered.

Manual and Automated Switching Mechanisms
When a combination unit respirator is employed, the operator must know how to safely and effectively switch modes of operation. There are currently several manual switching mechanisms that includes a physical toggle switch, filter covers, and others. There are automated switching mechanisms under development that detect changes in inhalation profile and research is also being performed on switching mechanisms actuated by a chemical detector. As you can imagine, this is a very difficult task as the number of chemical threats of interest is very broad.

Low-Profile SCBA Cylinder Design
Over the last 10 years, there has been a push to redesign the concept of air cylinders. IAFF paved the way with their first attempt to develop a “flat pack” during the 2008 timeframe. The prototype system, developed in partnership with MSA, was able to reduce the profile, but did not significantly reduce the weight. This product did not become commercially available. Currently, Avon Protection is working in coordination with DoD to develop a confined-space SCBA with reduced profile and weight [83]. The product is intended to meet NFPA 1986 certification.

Conclusions

Hazard and risk assessments should be performed at all operational scenes. This information should drive the response considerations, especially as it relates to the implementation of engineering controls. PPE is the last line of defense to minimize exposure of hazards to the operator, but this must be balanced with operational effectiveness and thermal burden. The implementation of an effective PPE program, in concert with the hazard and risk assessment process, will maximize operator safety in the disaster response arena.

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6

State of Search and Rescue Technology

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Introduction

The landscape of Search and Rescue (SAR) technologies is diverse and expanding. Research on machine learning, a subcategory of artificial intelligence, is gaining traction in both general and specialized applications. Reductions in cost, increased standardization, and the rowing accessibility of SAR training technologies has resulted in a lower barrier to entry for SAR agencies to apply them to their training regimens.

The military and homeland defense-related implications of the research and development opportunities discussed below include an increase in the physical resiliency of animal partners; increases in mental, physical, and output capabilities of personnel; reductions in overhead expenses; improvements in the efficacy of training exercises; and the minimization of unnecessary human-operated data processing and analysis efforts.

Communications

Radio platforms can use one or more frequency bands, and employ from consumer to professional grade technologies. Accordingly, costs range widely based on system requirements and capabilities. Depending on the organization affiliated with (or sponsoring) a given SAR agency, an array of radio communications platforms can be deployed, including amateur radio, local and state public safety networks, portable tactical systems, and satellite communications. Due to increasing demand for space in the radio frequency (RF) spectrum, organizations like DoD must compete for spectrum space that is rapidly shrinking and often interference-filled. DARPA introduced the Spectrum Collaboration Challenge in 2016 [1] to foster the development of an RF spectrum that autonomously coordinates in real time between radio networks to avoid interference and maximize the use of available RF spectrum space.

Through a public-private partnership, telecommunications provider AT&T is working with the First Responder Network Authority (FirstNet) to build a nationwide broadband network for first responders [2]. As state governors across the nation opt in, priority access to voice and data on the AT&T network is being granted to primary users of FirstNet [2]. If a SAR agency is organized under a public safety entity, they may be eligible to utilize the feature-rich services provided by the network [2]. It is important to note that FirstNet is not designed to replace voice communications provided by land mobile radio (LMR) systems, but to enhance the capabilities of data transfer and voice connection via the AT&T cellular network [2].

A subset of radio communication tools, mesh networks connect different types of devices (cellphones, routers, mesh extenders, etc.) as nodes in radio signal networks. Each node boosts the radio signal further, extending coverage outside of regular mobile phone tower range. The networks promote voice call, SMS, file sharing, and geolocation/navigation abilities. Mesh networks may provide communication capability in non-existent or unstable service areas.

With all mesh networks, the network becomes stronger the more users (nodes) are in the network [3]. An American mesh network company, goTenna, describes this phenomenon as "people-powered connectivity [3].” An Australian project, the Serval Project [4], is an Android application that promotes mesh networking as a "powerful backup mobile communication system" [4] that is intended to provide resilient communications during a crisis, and communication capabilities to communities cut off from services. A European company, Gotoky, has iOS and Android-compatible mesh network devices and mobile applications [5]. Gotoky has proposed an emergency location beacon that is activated via the Gotoky device, even when the corresponding mobile phone is out of battery power [5]. FireChat is a smartphone application that allows users to send even in the absence of internet access or a cellular network [6]. It was originally developed during a pilot program for emergency response in the Philippines [7].

Mesh networks have been an increasingly useful technology for DoD. Recently, the Defense Innovation Unit Experimental released a call for solutions that would include “high-speed resilient ad hoc/mesh networks for austere environments [8].” In addition, the Wireless Network Defense program, funded by DARPA, seeks to better control wireless networks, including “the class of emerging wireless mesh networks [9].” Mesh networks are ideal for use in disaster settings and military operations, given that they build off other devices and do not rely on indigenous wireless towers.

Mesh networks may provide alternative means for SAR teams to communicate within the team, with the command center, and/or with survivors. Emergencies can lead to gridlock on cellular networks [10], as survivors reach out for help or call loved ones, and emergency responders work to coordinate their efforts. Mesh networks may not be overwhelmed as traditional signal networks, as mesh networks grow stronger with more users linking to the network instead of reducing network speeds.

Mesh networks may also provide SAR teams with GIS location and mapping solutions to poor cellular service. OpenStreetMap [11] is a community-driven, open source mapping platform for users to crowdsource aerial images, GPS devices, and other technology to verify that the OpenStreetMap is up to date with current conditions [11]. A mesh network could provide SAR teams with further GIS and cartography crowdsourcing ability when paired with tools like OpenStreetMap.

Crowdsourcing

Crowdsourcing involves large groups of people voluntarily inputting data into a public database or web platform (one example is the large-scale crowdsourced image search operation initiated by DigitalGlobe/Tomnod in 2014 to aid in locating missing Malaysian Airlines Flight 370) [12]. Social media platforms have been building applications and products with user feedback, via crowdsourcing, as the foundation of their information collection processes. In some GPS mobile applications, users can input road hazards, disabled vehicles, and traffic feedback that in turn is displayed for all users to see. The application's information is updated in real time, and users tend to be more engaged with the tool as they have direct influence on the quality of the product they receive.

Facebook's Crisis Response and Safety Check [13] services are a new mode of disseminating real-time information during disaster events. Users can "check-in" as a disaster progresses, or afterwards; this self-reporting service allows loved ones to know at a glance if the user is safe or as of yet unaccounted for [13]. This program and others like it may allow authorities to quickly scrub big data and highlight highly impacted areas, or injured persons, based on the geolocated reports populated by users. An often-overlooked benefit of social media check-ins is that traditional communication lines may be freed up for SAR/emergency personnel. Instead of trying to call or receive calls from multiple family members, friends, and colleagues, survivors can post a quick check-in that notifies their personal social media network of their status. Reducing SMS and especially telephone call loads on cellular networks frees the channels for more urgent needs.

Other popular crowdsourcing services include Crisis Mappers Net, and Ushahidi. The International Network of Crisis Mappers (Crisis Mappers Net) is an international community that leverages mobile and web-based applications to gather, process, and provide crowdsourced event data, aerial and satellite imagery, and modeling to create effective "early warnings for rapid response to complex humanitarian emergencies [14]." Ushahidi is a non-profit technology company that works to collect reports from victims and document ongoing updates within an event zone, to generate real-time information and visualization tools [15]. (In 2015, the Crowdmap application name was rebranded to match its developer, Ushahidi [16].)

The defense community is beginning to embrace crowdsourcing, due to its ability to save time while minimizing response resources. The use of social media as a crowdsourcing tool to enhance situational awareness was a focus of an annual exercise, the Joint Interagency Field Experiment, held in 2014 by the Naval Postgraduate School [17].

Unmanned Aerial and Ground Systems

In recent years, the proliferation of unmanned aerial systems (UAS or UAVs; commonly referred to as "drones") has introduced a new means of locating missing persons. UAV use for SAR teams remains in its relatively early stages, while personal, professional, and government use is more mature. UAVs have long been equipped with remote cameras, but the addition of thermal imaging and other sensing technologies to a UAV imaging suite has grown more common in the market.

The Federal Aviation Administration (FAA) governs UAV regulations, fly zones, and initiatives within the United States [18]. The Association for Unmanned Vehicle Systems International has co-hosted symposiums on UAVs each year since 2016.

Domestic security concerns maintain a priority for the FAA with regard to drone use.

Medical and mission equipment cargo drops, thermal imagery search capabilities, and providing otherwise inaccessible perspectives to SAR teams are just a few examples of how UAVs can support SAR efforts. Zipline International Incorporated is an automated logistics firm partnering with the Rwandan government to deliver essential medical supplies by UAV [19]. Matternet Incorporated continues to explore similar projects in Haiti, Bhutan, and Papua New Guinea [19]. Receiving test results in a timely manner is critical, especially for patients located far from permanent medical facilities; UAVs may be the key to expediting shipments of samples to and from laboratories for testing [20]. Rugged terrain, bad roads, seasonal flooding, congested traffic, and other obstacles that currently delay medical supply shipments may be avoided through the expansion of UAV usage in medical supply chain logistics.

Much like medical supplies, mission supplies may be delivered to SAR teams via UAV. On the commercial front, Amazon PrimeAir has petitioned the FAA for regulatory approval to initiate UAV package transportation and delivery operations [21]. The delay in SAR teams looking toward UAV supply support in the field is due to the same barriers that PrimeAir currently faces: the FAA's approach to opening up national airspace to UAVs has been a deliberate process. Under Part 107 of FAA regulations, the UAVs used in Texas, Florida, and Puerto Rico were authorized under a special exemption to survey wreckage, bridges, rail lines, damaged cell towers, and spot oil and gas leaks. According to the FAA's standard small UAS operation rules (Part 107), UAVs must fly below 400 feet while staying within the operator's visual line of sight [18, 22]. Populated areas must also be avoided [18].

In October 2017, the U.S. Department of Transportation established the UAS Integration Pilot Program to provide "an opportunity for state, local, and tribal governments to partner with private sector entities, such as UAS operators or manufacturers, to accelerate safe UAS integration [23]."

The ability of UAS to enhance situational awareness in post-disaster urban environments was successfully demonstrated at Camp Roberts, California [24]. Researchers developed an algorithm designed to maximize UAV search area based on the number, range, and required paths of available UAVs. The test successfully ended in the development of a mission-planning tool using data collected from multiple drones. Figure 1 shows the optimal path given for a specified area using one UAV.

The use of unmanned ground vehicles (UGV) has become more prevalent in military and police applications. UGVs can cover a variety of terrain types without risking the life of a rescuer; increase the search distance capability of a SAR mission; and may be capable of delivering emergency medical supplies to stranded or trapped survivors (while human counterparts work to reach the scene). Oshkosh Defense's TerraMax, and QinetiQ North America and Milrem Robotics' Titan are examples of UGVs available for the military market [25, 26]. While capable of clearing hidden improvised explosive devices (IEDs) or delivering explosive payloads to locations, these UGVs may also be used to transport casualties, assist with evacuations, or widen search ranges for military SAR operations.

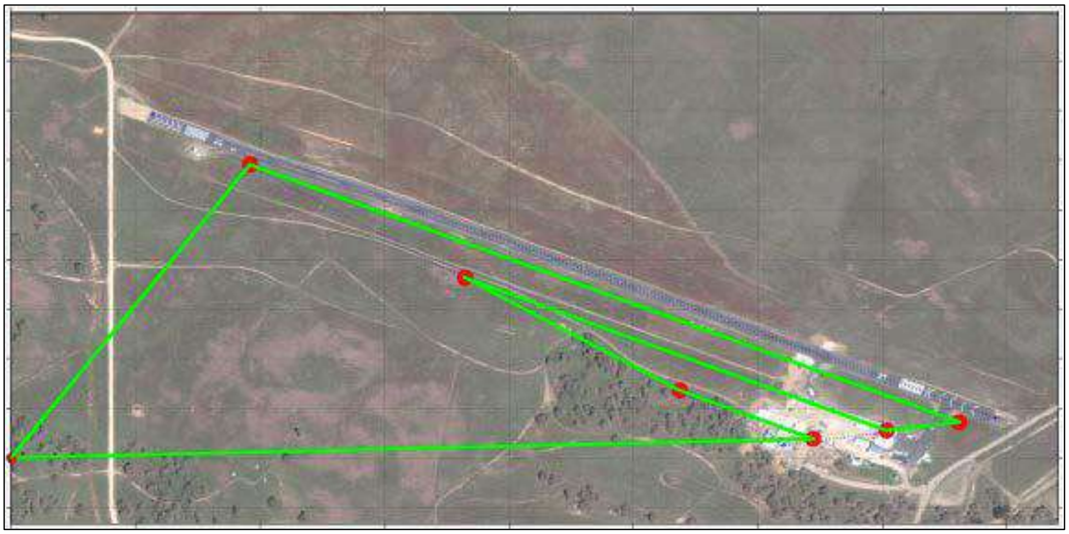

Figure 1. Search pattern for the area of operations at Camp Roberts [24].

UGV research and development continues to expand, including live-streaming video from the UGV to SAR team smartphones [27]. UGVs are not as limited as UAVs are by high winds, rain or snow, or dense forest canopies. Unlike UAVs, small UGVs may be designed to search through narrow earthquake or tornado rubble, as demonstrated by a 2016 research project that explored use of semi-autonomous serially-connected multi-crawler robots for SAR purposes [28]. In this project, a snake-like robot was created to search for survivors under rubble—where UAVs cannot reach, and human searchers may not reach survivors in time.

AI and Machine Learning

Design, payload, air temperature, wind, and other atmospheric conditions can negatively impact the battery life of UAVs. Considering that time is a critical factor in any SAR mission, limited fly time restricts the practicality of UAV support for SAR teams. Battery failure can lead to damage to or total loss of UAV equipment and its acquired data. If UAV operators are provided with real-time estimations of remaining battery life, such outcomes may be avoided. Research into machine learning is exploring such Remaining Useful Life (RUL) enhancements for UAV technology and sophisticated heads-up display and dashboard complements will allow for future growth in this area [29].

Recent research on non-linear battery reduction factors and predictions of the RUL of batteries has begun to take shape by exploring four machine learning prediction methods: Least Absolute Shrinkage and Selection, Multi-Layer Perceptron, Least Squares Support Vector machines for Regression, and Gradient Boosted Trees. Further development of nonlinear approximators should be continued to improve the capabilities of UAV fly time (and other technologies built on similar platforms) in both civilian and military applications [29].

UAVs are not ideal for deep forest/heavy foliage environments, or high-wind SAR scenarios. However, UGVs are currently limited, too, by impassable terrain and extreme slopes. This is where machine learning or AI research can assist. In 2016, researchers explored the adaptation and improvement of robotic visual perception of forest trails. Forest trails are much more difficult than paved roads for unmanned vehicles to navigate, as trail surface appearance changes quickly, and the shape, width, depth, and boundaries of the trail are not restrained (or bounded). Using a forward-facing, color camera and a deep learning neural network, researchers created a deep-learning algorithm for unmanned robotic navigation. Completely void of human interaction, micro UAVs were able to navigate a previously (to the robot) unseen trail at an 85 percent success rate [30].

If UAVs and UGVs can learn to navigate trails autonomously without direct human operation, search efforts can be expanded without incurring a significant increase in personnel burden. Simultaneous efforts between robots and SAR field teams can be conducted to cover more ground, which may reduce the time delay between discovery, rescue, and medical response. Machine learning may further explore autonomous path navigation for robotics by teaching the robots to report back to operators any hazards that SAR teams may face when following the same direction [30].

DoD may take special interest in the implications of machine learning for military SAR missions. Civilian interests in reducing response time, expanding simultaneous search capabilities, reducing of SAR personnel risk, and the ease of downloading updates to UAV/UGV systems could outweigh existing personnel training/exercise costs. Additionally, DoD teams may benefit from enhanced UAV/UGV autonomous navigation while addressing missing personnel. By enabling SAR technology to think for itself and learn from deployments (past and present), SAR team members are more available for more complex tasks.

Robotics

Research and development teams around the world continue to build and test algorithms used to guide autonomous and multi-path robotic operations. This technology will allow search team leaders to use predictive data to more effectively prioritize operations. Partnering with the Robotics and Automation Society of the Institute of Electrical and Electronics Engineers (IEEE), the RoboCup Federation is a global organization focused on promoting robotics and AI research [31, 32]. The Rescue Robot League, part of the RoboCup Federation, hosts annual competitions to challenge international teams and their robotic SAR capabilities [33]. Competition arenas resemble urban disaster environments, such as after an earthquake or tsunami [33]. Adaptive robotic equipment can include video, infrared, or 3D cameras, laser scanners, and other tools; these are combined with robotic programming and the latest algorithms [33]. Robotic algorithms, adaptive programming, and system designs are put to the test to explore and showcase practical robotic applications in SAR environments [34].

The reliable and quick detection of emergency survivors in unstructured environments is crucial to the value and progression of autonomous robots in Urban Search and Rescue (USAR) efforts [35]. These robots must simultaneously conduct operations around mapping, object recognition, terrain adjustments, exploration, and telecommunication with the USAR human team, all while deployed [35]. The 2016 RoboCup China Open Robot Rescue League champions incorporated multi-sensor information and an exploration planer to create an autonomous USAR robot. Stabilizers for 2D LiDAR Ranging sensors, laser-based 2D Simultaneous Localization and Mapping (SLAM) sensors, front-based grid processing, and other data was combined into the search algorithm for the teams' robot. The autonomous robot successfully found five out of eight "survivors" in the competition [35].

DARPA hosted the 2015 DARPA Robotics Challenge (DRC) finals [36]. Teams had to develop human-supervised ground robots capable of using standard tools and equipment to navigate rubble, stairs, and doors, in a manner similar to how SAR team members would [36]. The South Korean team, Korea Advanced Institute of Science and Technology's "DRC-HUBO" robot prevailed on the basis of its speed, adaptability, and ability to balance [37]. The requirements posed by the DARPA challenge were the following: driving a four-wheeler/off-road vehicle, egressing said vehicle, opening doors via door knobs, turning valves on pipes, grasping power tools and cutting a circle into drywall, pulling a plug and putting it into another socket, navigating through or over rubble, and climbing stairs [37].

VR and Augmented Reality

A virtual reality (VR) environment fully encompasses the operator's sight, sound, movement, and sometimes voice and speech capabilities. Often likened to an immersive video game, VR training and exercise opportunities are poised to become much more common in the decade to come. VR missions can simulate SAR operations, providing year-round experience for SAR teams. Users may improve personal decision making, teamwork, and communication with multiple team members logged in to the same event and have the opportunity for repetitive practice without additional costs to the hosting agency [38].

VR movement mechanics can trigger VR motion sickness in some users [39]. Such motion sickness occurs when the mind struggles to process how the body is moving visually (in the VR visor or display), but not physically (the user is standing still in reality). For these users, virtual walking triggers real nausea, dizziness, or vomiting; however, being in a virtual vehicle (such as a truck) does not trigger the same effects. This may be due to their minds connecting virtual movement with a virtual transportation device, as their minds see the vehicle as moving their body. Game companies and graphics development teams are exploring methods to reduce VR motion sickness [39].

Augmented Reality (AR) is best described as layering a virtual plane of holographic or digital vision over an operator's actual visual field. Mobile gaming companies are utilizing AR to design and sell monster-catching, wizard-playing, and scavenger-hunting games that blend virtual elements with real terrain. AR is one of the most promising fields of development that could improve SAR unit effectiveness in the field, allowing team member access to shared real-time data and other multimedia.

For the further development of SAR training and exercise, both synthetic and real-world obstacles could be incorporated into wearable technologies. For training, an outdoor course could be created using physical obstacles, combined with an AR overlay of hazards, tracks, and mission objectives. SAR teams could practice different techniques, skills, and team coordination while testing hands-on applications. The AR scenario would allow for multiple teams to be on the same field without an overlap of objectives or environmental signals. In an urban setting, the AR exercise could notify users that certain roads are blocked by rubble on the screen, or that power lines are down when the device is within a geolocation for activation of that in-play event.

Providing the mental stimulation, social coordination, and physical movement of such exercises without the physical setup of roadblocks or damaged power lines could allow a more cost-effective alternative to full-scale exercises, and improved realism or verisimilitude in training exercises. Especially for DoD, that may provide multiple batches of training provided to various teams across geographic locations, the ability to remote log in to the same exercise will strengthen unit training and collaborative exercise value.

Wearable Technology

Numerous wearable SAR technologies already exist within the public domain—GPS watches, biometric reading wristbands like those provided by Fitbit [40] and Garmin [41], camera and live-stream video via GoPro [42] and other action cameras, as well as mobile phones carry active SAR support for civilians and military personnel alike.

As discussed above, wearable technology can both guide and provide haptic, audio, health, or visual feedback to the SAR responder and aid in situational awareness, geolocation/navigation, and other critical tasks. Extreme conditions, such as avalanche rescue and other SAR work in extreme conditions, may be less risky if responders are actively aware of their core body temperature, heart rate, perspiration, and other personal biometrics. Command centers may be better informed of when to change out teams or pause missions to maintain personnel safety.

Less considered but vital to SAR mission advancement is the evolution of canine and equine wearable technology. GPS, still-photo camera, video communication, and heart rate monitoring applications are examples of development needs within this field. Having an objective view into real-time data could reduce injury and risk to canine units. GPS and visual recording of surroundings or events may also assist handlers in locating separated canines and guide SAR teams toward mission objectives.

Equine SAR teams train horses to provide SAR mission support over long distances, trails, and in remote areas. Capable of carrying heavy gear, continuing at quick paces for long distances, and providing a raised point of view for the rider, horses are crucial in some regions to achieving success in narrow windows of rescue time. Heartrate monitors, GPS and mileage tracking, and blood pressure monitoring may increase the partner-care toward horses unable or unwilling to express concerning health limits. Also, in the event of separation, tracking sensors could also reunite partners faster and inform team members of potential issues that lead to separation.

Conclusion

Understanding the skills, scope, and practice-based implications of SAR technologies provide clear value to DoD, its partners, and government leadership. It is important for operations personnel to apply the tools available to enhance their mission areas and for program- and policy-level administrators to understand the evolving technological landscape.

The current approach for technological adoption favors attention and interest to individual technology solutions themselves, rather than a focus on mission scope and identified needs/gaps. DoD and other operations-focused groups must evolve this thinking to consider technology solutions that meet specific and current needs, but also provide sustainability for future operations and integration with other systems.

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7

Supply Chain Management in Disaster Response

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Introduction

Supply Chain Management (SCM) has become a critical focus in disaster response over the past decades. This article presents a comprehensive review of the state-of-the-art of the research focused on SCM in disaster response.

SCM is defined slightly differently in different areas. In military use, SCM is defined as a cross-functional approach to procuring, producing, and delivering products and services to customers [1]. In disaster response and humanitarian applications, SCM refers to the process of planning, implementing, and controlling efficient and cost-effective flow and storage of goods and materials from the point of origin to the point of consumption [2]. SCM is sometimes referred to as logistics. A comprehensive review of the definition of SCM, especially the risk and the vulnerability of the system, is presented by Heckmann et al. [3].

SCM in disaster response is different from routine SCM, for three reasons: the uncertainty of the system, supply good types, and the structure of the system. First, the largest difference is the uncertainty of the system. For disaster response SCM, uncertainty comes from both the supply and demand ends, as well as the affected transportation network and infrastructure [4]. Conversely, routine SCM can be treated as an approximately deterministic system. The sources are managed by a standard procedure with minimal dislocation [5].

Second, the supply good types differ between the two, as do their unique transportation requirements. In disaster response SCM, two types of supplies are typically needed [6, 7], and each type has its own demand, storage, and transportation requirements. In some circumstances, individuals who are affected or wounded can also be considered as a special type of good. This property makes the system a multi-commodity transportation network, a characteristic not common to routine supply chain management.

Third, a routine SCM comes from business activities that follow a product's chain of production, transportation, and sales [8]. However, disaster response activities are usually provided and managed by government agencies. The SCM structure in disaster response is usually determined by government orders.

Theoretical Research

This section provides a review of theoretical research in disaster response SCM. It summarizes various mathematical models and solutions algorithms developed to deal with or are applicable to disaster response SCM. SCM is a complex system with many different subjects and planning stages and objectives. The complete supply chain includes the following:

- Logistics network design
- Inventory deployment and management
- Distribution management
- Fleet management
- Production Planning
- Demand planning, and forecasting
- Procurement/purchasing: managing supplier databases, sending bid requests tracking information, order and shipment status
- Warehouse control system and transportation management that improves customer service performance
- Information sharing: order entry, requisition, and bill of materials [9]

The essential research subjects of SCM in disaster response can be categorized as the facility location problem, the goods transportation problem, and the inventory management problem.

Facility Location Problem

The facility location problem involves finding the best facility locations to satisfy a goal. The facility represents various facilities needed in disaster response—including shelters for affected people, warehouses to store goods, or vehicle depots. Mathematically, the facility location problem can be formulated as a P-Median problem, center problem, or covering problem [10–12].

The P-median problem finds *p* facilities such that transportation costs from customers to these facilities are minimized [10, 13]. The center problem minimizes the distance from any customer to the nearest facility (under a limited number of facilities or a limited budget for locating the facilities) to avoid an artificial definition of coverage. The covering problem can be divided into a "set covering" problem, and a "maximum covering" problem. The set covering problem aims to minimize the facility location cost while ensuring that every node in the network is served by at least one facility within the maximum service range (also known as critical coverage). The maximum covering problem, on the other hand, finds the facility location that maximizes coverage area under a limited budget.

Among these facility location problems, the set covering problem is the only one potentially infeasible due to budget limitations. The facility location problems are flexible, given model assumptions. Rawls and Turnquist [13] chose the best locations for the facilities and assigned customers to these facilities with the objective of minimizing facility fixed cost and customer transportation cost. More realistic constraints are imposed when solving the problem, such as the capacities of the facilities [10].

Apart from the models discussed above, formulation of the facility location problems can be very flexible, using different assumptions and objectives. Amiri [14] solved the facility location problem while optimizing the capacities of the plants and the warehouses. The problem was solved using an iterative Lagrangian-based heuristic. Duran et al. [15] optimized the facility location budget allocation while minimizing the mean response time. Yi and Özdamar [11] minimized the weighted sum of unsatisfied demand and the weighted sum of wounded personnel waiting time at the demand nodes and emergency units. Haghi et al. [16] designed the humanitarian logistics system with the objective of minimizing total cost (facility, transportation, shortage, and inventory holding costs) and sum of the maximum shortages in demand points. Balcik and Beamon [12] developed a variance maximum covering problem with consideration of stochastic demand. They optimized the number and locations of the distribution centers and the number of supplies at each center with the objective of minimizing the total expected demand covered by the established distribution centers under a given hypothetical earthquake scenario. A variance of the facility location problem is the vehicle allocation problem, wherein the decision is how to allocate a number of vehicles among facilities or depots. Liu et al. [17] solved the vehicle allocation problem as the maximum covering problem by maximizing the coverage of the demand site.

Goods Transportation Problem

The goods transportation (or logistics) problem aims to find the best transportation plan to transfer disaster response materiel (goods) from supply nodes to demand nodes with a detailed vehicle routing and scheduling plan. This problem can be divided into three types:

Multi-commodity Transportation Problem

The first decision is to determine how many units of each good type need to be transported. This problem is usually formulated as a multi-commodity transportation problem [18, 19]. Tzeng et al. [19] also include transshipment nodes in the problem. Rawls and Turnquist [13] used three types of resources: water, food, and medicine. Zhou et al. [20] minimized total unsatisfied demand and the risk of choosing damaged roads, which increases the robustness of the transportation plan. This problem can determine not only the goods transportation plan but also the transfer of wounded people to emergency units [11].

Usually, the entire planning horizon is discretized into several time intervals. There are two ways to solve this problem. One way is to consider all the time intervals in a time-space network [10, 20]. Due to the complexity of this system, many papers do it dynamically—solve one time interval problem, with the solution treated as the input for the next time interval. The length of the interval is generally treated as a fixed parameter in the literature. Haghani and Afshar [10] used 30 minutes as the interval at the federal level and five minutes at the state level.

Vehicle Routing and Scheduling Problem

The vehicle routing and scheduling problem optimizes the routing and schedule of each vehicle as well as the load/unload/driver assignment to implement a transportation plan. Haghani and Oh [21] provided a multi-commodity, multi-modal vehicle routing and scheduling model with time windows, which found the best delivery routes and schedule to minimize the costs of vehicular flow, commodity flow, supply/demand carry-overs, and transfers over all time horizons. Two heuristic algorithms were proposed, the first based on Lagrangian relaxation and the second based on an iterative fix-and-run strategy. Balcik et al. [7] and Haghani and Afshar [10] solved the problem while minimizing unsatisfied demand.

The same vehicle routing and scheduling techniques can be used for rescue team scheduling [22], helicopter route and schedule design [23, 24], and ambulance routing [22]. Talarico et al. [25] proposed a probability-based dynamic model that found the optimal resource schedule that minimized the total number of fatalities over all rescue periods. This rescue plan is critical for response troops to perform the rescue operation immediately after the disaster [26]. Simulated Annealing and Tabu Search were compared to hill-climbing procedures. Barbarosoğlu et al. [23] developed a two-layer framework to schedule helicopter activities. The operational decisions are the routing of helicopters, load/unload, delivery, transshipment and rescue plans of each helicopter, and the refueling schedule of each helicopter with the goal of minimizing the maximum tour duration. The rescue also requires close cooperation and communication among different agencies. During the response to Hurricane Katrina, for example, five helicopters from different agencies showed up to rescue the same person [27].

Dynamic Traffic Assignment Problem

The dynamic traffic assignment problem finds the most likely traffic assignment in a network. Traffic assignment has an impact on the travel cost estimation in the multi-commodity transportation problem as well as in the vehicle routing and scheduling problem. Chiu and Zheng [28] proposed an integrated mobilization destination, traffic assignment and departure time model, which minimizes the total system prioritized travel time of all mobilization groups over the planning horizon. Chiu et al. [29] incorporated the Joint Evacuation Destination/Route-Flow-Departure problem of a mass evacuation into a system-optimal dynamic model. The objective of such an evacuation is to select a set of destinations, evacuation routes, and evacuation schedules to minimize the evacuation time or the network clearance time (the time until the last vehicle leaves the affected area). Ben-Tal et al. [30] incorporated a linear programming version of the Cell Transmission Model and Affinely Adjustable Robust Counterpart.

Inventory Management Problem

The inventory management problem mainly refers to inventory replenishment needs over the entire planning horizon. The replenishment decision highly depends on the prediction of demand and inventory. This is more important in disaster response SCM than routine SCM because of the uncertainty of the emergency disaster response system.

Inventory Planning/Prediction

In most published research, the inventory is considered jointly with the facility location problem. The customer demand is assumed, and the problem is to find optimal facility locations and inventory levels at each facility [31]. Changing circumstances are highly stochastic (e.g., due to the uncertainty of customer demand). Aviv [32] used Kalman filtering to combine prediction and observations to achieve better inventory level predictions. This combined methodology proposed a new cost-assessment method, which considered not only the individual forecasting performance of the members of the supply chain (like most of the literature), but also their correlation. Efendigil et al. [8] used neural networks and neuro-fuzzy models to predict uncertain customer demand. Sheu [6] also proposed a probability-based model to predict the demand for earthquake relief.

Inventory Replenishment

Inventory replenishment requires deciding how many goods are needed to replenish throughout the planning horizon, and when. Beamon and Kotleba [33] developed a probability-based stochastic inventory control model that determines the optimal reorder quantity and level based on reordering, holding and backorder costs. The model was tested on onset data collected in Lockichoggio, Kenya, by interviewing warehouse managers and reviewing warehouse stock-keeping cards during humanitarian relief operations in the Sudan over September 2004.

Problem Integration

Although the above discusses many different sub-problems separately, they are highly interrelated. Many attempts have been made to solve the integrated problem such that the best overall plan can be obtained. Many studies combined the multi-commodity transportation problem and the vehicle routing and scheduling problem into a two-stage process. Each vehicle is first treated as the flow in the multi-commodity transportation problem and then considered as an individual vehicle in the vehicle routing and scheduling problem [11].

Özdamar et al. [34] proposed a hybrid multi-commodity network flow and vehicle routing problem. The model optimized the mixed pickup and delivery schedules for vehicles within the considered planning time horizon as well as the optimal quantities and types of loads picked up and delivered on these routes. The objective is to minimize the sum of unsatisfied demand for all commodities throughout the planning horizon. The models were solved using the Lagrangian relaxation technique. Najafi et al. [35] solved the integrated facility location and inventory determination as well as transportation problem with the goal of minimizing the cost and response risks, where the risks were expressed as the mean distance between the customers and the facilities.

Caunhye et al. [36] solved the joint facility location and vehicle routing problem in a two-stage manner, in which the locations of the warehouses and their inventory level were determined in the first stage, and the transshipment and delivery quantity and vehicle routing were solved in the second stage. Tofighi et al. [37] proposed a two-stage method where the first stage determined the facility location and the inventory level and the second stage determined the distribution polity based on different possible disaster scenarios.

Rodríguez-Espíndola et al. [38] combined the problem of selecting the location of the facilities and the transportation of the affected people and the goods. The objective was to minimize the total cost of the facilities and the transportation cost of people and foods as well as to minimize the maximum unfulfillment over all shelters in response. Although much of the literature considered the uncertainty as essential in disaster, Rodríguez-Espíndola et al. [38] claimed that uncertainty is negligible in the preparedness stage.

Technologies and Methodology

In this section, we review the main methodologies used in disaster response SCM research. These include mathematical programming, simulation, probability theory and statistic, fuzzy programming, and social science.

Mathematical Programming

Mathematical programming is the most widely used method for solving disaster response problems. Mathematical programming methods are applied to solve different types of disaster response problems with both deterministic and stochastic components.

Operations research (OR) models are also applicable in dealing with uncertainty components by the use of rolling horizons. Short-term predictions are assumed to be reliable [12]. The important issue in implementing rolling horizons is how to re-plan the problem. Time-space networks are used to connect the solution from the previous horizon to the next planning horizon. Özdamar et al. [34] updated the input parameters for the next planning horizon at the end of the previous horizon. This method is also applied in the research conducted by [7, 11, 14, 21, 23, 39].

Stochastic programming can handle the uncertainty easier with the trade-off of computing complexity. OR models dealing with stochastic problems are also applied in the following areas. Salmeron and Apte [40] provided a two-stage optimization model for prepositioning assets for a natural disaster. Bozorgi-Amiri [4] developed a multi-objective robust stochastic programming approach for logistics in the relief phase of disaster response, considering both the demands and supplies where the cost of procurement and transportation are taken as stochastic parameters.

Another multi-objective optimization model based on goal programming was developed for solving emergency logistics problems in multi-supplier, multi-affected, multi-relief and multi-vehicle area considering demand, supply, and available paths as uncertain [41]. Garrido et al. [42] focused on a specific example of a flood emergency. It developed a model to optimize inventory levels in emergency supplements using a spatial-temporal stochastic process to represent the flood occurrence. Models considering uncertainties in demand and resources for both pre- and post-disaster times are also developed by researchers [16].

For reducing the uncertainty of demand for humanitarian relief supply chains, Ben-Tal et al. [30] generated a robust logistics model to optimize dynamic traffic assignment problems. A case study in robust supply chain network design problem was provided in Baghalian et al. [43]. Scavo et al. [27] stressed that a network model is better when it is attempting to look for a single agency to control homeland security and disaster response.

Simulation

In using simulation methods in the pre-disaster phase, it is necessary to assess in advance the risk of supply chain disruption. Schmitt and Singh constructed a simulation model to evaluate the potential for disruption in supply and studied its influence on customer service quantitatively [44]. In this model, the Monte Carlo simulation method was used to develop the disruption risk data for the locations and their joints as the inputs. The disruption risk of different locations was quantified. The discrete-event simulation technique was adopted in modeling the mutual effects of the flow of material and network. The results show that the risk level is dynamic in the system and hard to capture, which requires changeable handlings in the network.

For the post-disaster phase, Zou et al. [45] proposed a simulation-based tool to study the emergency evacuation system during hurricanes. This tool was developed for Ocean City, Maryland, with the function of performing planning and simulating real-time traffic conditions under different management plans. There are five principal modules in this system: input, database, optimization, simulation, and output modules. These allow users to integrate evacuation demand, geometric information and other control parameters to generate potential traffic conditions to inform decision-making. Jain and McLean introduced the Integrated Emergency Response Framework that can utilize different kinds of modeling and simulation tools [46]. The tools are different based on their application, disaster event, the most considered issues, scope and abstraction criterion, and the specific applied modeling method.

Probability Theory and Statistics

Probability theory and statistics are applied across the different stages of SCM. Aviv [32] and Beamon and Kotleba [33] both developed probability-based models for inventory management. A dynamic relief-demand management model was presented by Sheu [6] for emergency logistics operations. Efendigil et al. [8] proposed a probability-based demand forecasting model deploying artificial neural networks and an adaptive-network-based fuzzy inference system. This research provided a forecasting methodology regarding the uncertain customer demands in a multi-level supply chain structure via neural techniques.

For emergency resource scheduling, Chi et al. [47] constructed a non-linear timeliness evaluation function for one affected point, several supply facilities, and one kind of resource into a timeliness function. This function is monotonically increasing with respect to the resource quantity and monotonically decreasing with respect to the resource arriving time.

Fuzzy Programming

Sheu [6] used fuzzy clustering to classify affected areas into groups dynamically, as fuzzy clustering is applicable in both data compression and data categorization areas. This facilitates changing the allocation and distribution of the relief demand and further helps to identify the urgency of the relief demand based on groups. Tzeng et al. [19] constructed an optimal planning model for designing relief delivery systems using fuzzy programming. The model is designed with fuzzy multi-objective programming for offering assistance to decision-makers to deal with the emergency relief distribution.

Social Science

Disaster logistics has also been studied from a social science perspective. Several humanitarian logistics problems have been outlined by social science theorists. Van Wassenhove [48] took a close look at the concept of the humanitarian logistics. This research contends that both humanitarian and private societies in emergency relief operations should be employed to enhance the disaster SCM.

Tomasini and Van Wassenhove [49] define a successful humanitarian operation as one that mitigates the emergency needs of an affected populace with a reasonable vulnerability release by paying with the least time and good resources. To have a successful and effective response, this paper emphasized good preparedness and effective coordination. Good preparedness requires five key elements: human resources, knowledge management, process management, resources, and community. Effective coordination has three forms, including coordination by command, by consensus and by default such as desk officers and civil-military operation centers. Tomasini and Van Wassenhove [49] provided a guideline and a framework for considering humanitarian response operations with two main contributions. One is to investigate the various vulnerability factors that may impede long-range influence of any effort; the other is to state the mutual effect between vulnerability factors which may either increase disaster rapidity or make the disaster a more complex one.

Applications

Disaster Data Analysis

Disaster data analysis can be classified into real-world data and artificial data. Real-world data includes those collected during an earthquake, flood, or humanitarian disaster. Among current researchers, examples of earthquake disasters attract the most publicity and research attention.

Real-world Data Analysis

Researchers use real-world case studies to illustrate their proposed models. Based on the disaster from the 1993 Erzincan earthquake in Turkey, a mixed integer programming model was constructed to schedule helicopter activities in disaster response [23]. Two layers were used. The top tactical decisions were the disposition of the helicopter fleet, pilot assignments and the number of tours performed by each helicopter. The objective was to minimize the cost of selecting different helicopters and pilots from the bases. The base or the operational decisions were routing of helicopters, the load/unload, delivery, transshipment and rescue plans of each helicopter in each tour, and the refueling schedule of each helicopter. The objective was to minimize maximum tour duration. A hierarchical multi-criteria approach was proposed to solve the models.

Testing on real-world data announced by the Ministry of Internal Affairs for the Izmit earthquake in Turkey that took place in August 1999, a model that solved the hybrid multi-commodity network flow problem and the vehicle routing problem was constructed by Özdamar [34]. Another two-stage stochastic programming model was built by Barbarosoğlu and Arda [18] in response to earthquakes, which was tested on the real data from August 1999, Marmara earthquake in Turkey. Each realization was solved to optimality. The models were solved using GAMS/OSL20 and SLP-IOR.21. The models were initially coded in GAMS and solved as a single large-scale linear program.

Besides mathematical programming, statistical methods were also applied to study the use of real-world data in disaster logistics management. To investigate the management of dynamic relief-demand in emergency logistics when the disasters are large scale, Sheu [6] used the case of the Chichi earthquake, which occurred in September 1999 in the center of Taiwan, with a large affected area. By processing procedures of the data acquisition, model testing, and scenario design and analysis, Sheu [6] approximated time-sensitive relief demands with indeterminate information and reassigned relief demands dynamically within the affected areas labeled with identified relief-demand urgency degrees.

Artificial Data Analysis

One example of data analysis using artificial data is the mathematical optimization model developed by Fiedrich et al. [22] for optimizing the problem of technical response resources allocation after a strong earthquake. It showed that fatalities might result from secondary disasters, duration of the rescue operation, lack of rescue attempts, delayed transport, duration of transport, and lack of transport. Simulated Annealing and Tabu Search were compared to hill-climbing procedures.

Chiu and Zheng [29] proposed a simultaneous mobilization destination, traffic assignment, and departure time model, which can minimize the total system-prioritized travel time of all mobilization groups over the planning horizon. The model was tested on artificial data. Another model simulated no-notice mass evacuation based on a dynamic traffic flow model. The problem was focused on building a Joint Evacuation Destination–Route-Flow-Departure problem of a no-notice mass evacuation into a system optimal dynamic traffic assignment model [50]. Such an evacuation operation's task is to choose a group of destinations, evacuation paths, and evacuation timelines to reduce the time of evacuation or network clearance, which may be represented as the last vehicle leaving the influenced zone.

The key evaluation criteria contain three parts. The first is to choose available safe destinations, such as areas not inside the danger zone or the designated sheltering sites inside the danger zone. The second is to determine the evacuation path and the traffic volume that best fit each assigned path. The third is to decide the optimal departure schedule for people evacuating through the whole network with the least overall clearance time. The test network was constructed by Ziliaskopoulos [50].

Future Research

Summary

Future research directions can be considered from four perspectives: emerging technologies and methodologies; future disaster relief issues that might concern government organizations; upcoming challenges in future responses; and cooperation and communication of agencies (federal, state, local, military, nonmilitary, government, nongovernment, etc.).

Models can be built or simulated based on more scenarios in future studies. For instance, social media data has proved valuable in disaster response logistic planning by the evaluation framework built by Kirac and Milburn [51]. However, the only scenario that was included in its case study was for earthquake events. So the results may not be applicable to other kinds of disasters, such as hurricanes, or disasters of any type in a developing country. Afshar and Haghani [52] also recommend developing a variety of potential disaster scenarios for better analysis. When more scenarios are developed, the problems at hand will become much larger in scale, especially those containing a concurrent increase not only in the scenario number, but also in the commodity and the potential number of locations. It is necessary to expand the application of meta-heuristics from deterministic optimization programming to stochastic optimization programming [4].

The robust optimization approach is also a useful method that can be applied to various uncertainty sources, such as capacity uncertainty or cost uncertainty. Another point that can be noticed is that other transportation modes, especially aircraft and helicopters, are adopted more frequently in both domestic and oversea disaster relief activities. Most existing research has focused on highway transportation modes. Research can be focused more on multimodal response to disasters and management of the fleet. Clearly, managing disaster response in real time in multiple locations, using multiple supply points and multiple modes, is a very challenging task. Developing efficient models and algorithms that can assist responders to make the best and most efficient decisions to save lives and minimize property damage is a very fruitful avenue for future research.

The following problems may need to be considered regarding disaster relief issues government organizations might be concerned with. To evaluate a model developed to support logistics operations in catastrophic disasters, the following functions are recommended for government agencies to put to consideration: (a) information technology system requirements, (b) staffing needs, and c) coordination with emergency management partners [53]. For disaster relief, it may be useful to look at the "humanitarian space," which is described as the realm of operations where three important concepts are exhibited: humanity, neutrality, and impartiality. Humanity means that the human suffering should be relieved no matter where it happens; neutrality indicates that no political agendas or affiliations should serve as barriers to provide assistance; and impartiality indicates the absence of any discrimination in providing assistance [54]. With regard to the military, both DHS and DoD should make plans and preparations for crucial rules when a catastrophe happens. For DoD, war efforts overseas reduced the volume of equipment available in the homeland and reduced supplies available during Hurricane Katrina. This reality may happen in future disasters [55] and therefor government agencies must be cognizant of this issue.

Five issues need attention due to upcoming challenges in future disaster response actions. These issues are: responding to urban disasters, responding to disasters in developed countries, responding to disasters in conflict zones, responding to events when natural disaster and technological accidents overlap, and responding to events that seriously reduce the authority of local governments [56]. The first issue means that urban areas tend to bear a higher risk than countryside areas, due to high population densities. As violent incidents may happen when distributing disaster relief items in disaster situations, it is necessary for the government to protect relief goods for better delivery to affected communities.

The second issue is that developed countries are especially vulnerable to disasters. This is because rich countries may sustain higher economic cost. Examples can be seen from the Japan earthquake, tsunami, and nuclear accident, with losses totaling in excess of $300 billion. The third issue is that situations get worse when natural disasters happen in an area experiencing armed or violent conflict. It will become more difficult for humanitarian organizations to enter or even approach such influenced neighborhoods. The fourth challenge is that of planning ahead for the dangers posed by any combination of natural hazards, simmering conflict, and industrial and technological accidents.

The last problem concerns difficulties in the relationships between local governments and international aid organizations. International military and humanitarian actors should seek to ensure that local and national authorities' capacity and authority are not undermined. This means that international aid organizations need to assist local governments to relieve the harmful effects of a disaster event, rather than simply bypassing them during aid actions. Taking history as a lesson, it is a recognized fact that the military is the primary disaster relief assistance agency in domestic situations [57]. This is a role well-suited and well-earned for the military in this century.

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8

Responding to Radiation/Nuclear Emergencies

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Introduction

The term *nuclear* has become synonymous with the most extreme possible outcome, available only as a last resort, as in the phrase *nuclear option*. The emergency response community is well-versed in natural disaster scenarios. However, radiation/nuclear (Rad/Nuc) emergencies present challenges in the extreme. They can begin with little advanced warning, as with the formation of an F5 tornado, and they can inflict damage more widespread and lasting than a Category 5 hurricane. In terms of management, they are governed by regulations that are unfamiliar to most responders, and require the use of specialized and expensive equipment and training. Fear and a general lack of familiarity about the fundamentals of radiation hazards add complexity and uncertainty to response decisions, causing responders to delay essential lifesaving activities and/or not adequately manage their own safety.

An act of nuclear terrorism, such as the detonation of an improvised nuclear device (IND), would cause widespread devastation. The immediate blast zone from a 10-kiloton nuclear bomb would destroy an area up to 2 miles in diameter and cause a very high number of fatalities. Surrounding areas would sustain less severe damage, but would be contaminated with deadly radioactive fallout exposure for the following 24 hours. A plume of radioactive material would spread over a large area. An electromagnetic pulse could disrupt communications and electric power generation and transmission far beyond the blast zone [2].

Although a nuclear attack (such as an IND detonation) presents the most extreme type of Rad/Nuc emergency, there are others, such as nuclear power plant and U.S. Department of Energy (DOE) site incidents, that can present responders with many of the same challenges. For most Americans, the occurrence of a Rad/Nuc emergency has long been but a faint possibility, remote in both time and place. We have developed a sense that these events happen only far away, in places with exotic names such as Chernobyl or Fukushima, or are consigned to history, seen only in 1950s Cold War-era civil defense instructional films.

Recently, we have been reminded that the need for a homeland defense from these threats still exists. In early 2018, the *Bulletin of the Atomic Scientists* described the world security situation to be as "dangerous as it has been since World War II [3]." The *Bulletin* continued: "North Korea's nuclear weapons program made remarkable progress in 2017, increasing risks to North Korea itself, other countries in the region, and the United States [3, 4]."

Background

The U.S. currently follows the National Response Framework (NRF) for emergency response guidance. The NRF can draw resources from the DoD, DHS, DOE, the Environmental Protection Agency (EPA), the Coast Guard (USCG), Department of Justice, Department of Agriculture, and the Nuclear Regulatory Commission (NRC). The NRF pertains to all types of emergencies; however, this article focuses on the unique challenges of Rad/Nuc emergencies and discusses some of the supplemental procedures, technologies, and competencies available to improve response outcomes. For Rad/Nuc responses, DoD has the following assets available within its CBRN Response Enterprise [2]:

- Command and Control CBRN Response Elements
- Defense CBRN Response Force
- National Guard Teams
- Medical Radio-Biology Advisory Teams
- CBRN Military Advisory Teams

History

Fortunately, the U.S. has not had any major Rad/Nuc emergencies occur in the homeland from which to draw lessons learned. The federal response to emergencies has been refined and improved over the last 30 years, tested on natural disasters (e.g., hurricanes and floods), anthropogenic disasters (e.g., oil spills), and terrorist attacks. However, the system has never been tested under an actual Rad/Nuc event. However, many drills have been conducted with federal, state, and local agencies to examine the initial (early) phases of such an event.

Emergency Recognition

One of the challenges facing emergency responders is the ability to quickly recognize the presence of radioactive material and modify their actions to address their attendant Rad/Nuc aspects. Since radiation cannot be detected by human senses, it is imperative that the accompanying signals are identified, and the emergency is appropriately categorized as either radiological or nuclear in scope.

Nuclear Emergency

A nuclear (Nuc) emergency involves only those events that begin with a nuclear weapon detonation. These weapons require a fair amount of sophistication to create, and would likely—but not certainly—be the product of a state-sponsored weapons program. An IND is a cruder nuclear bomb assembled by terrorists that would lack a delivery vehicle, and has diminished effectiveness and blast yields.

In the case of a nuclear emergency, it will be obvious what happened and easy to recognize that a radiation hazard exists. The detonation begins with a bright flash of light, followed by a shock and overpressure wave that brings extreme high winds, and an electromagnetic pulse (or high-voltage surge) that damages electronic equipment and disrupts communications. In addition, within the first minute after detonation, the blast will generate heat extreme enough to cause a firestorm. A mushroom cloud will form above the detonation site (ground zero), created when debris is carried upward from the blast and spread by winds until it becomes radioactive fallout [2, 5].

Radiological Emergency

A radiological (Rad) emergency includes all incidents with radioactive material that do not begin with a nuclear detonation. They could be caused by a terrorist's theft of radioactive material to construct a radiological dispersal device (RDD), or caused by the release of radiological material from a technological disaster alone, or a technological disaster triggered by a natural disaster (such as a tsunami). The 2011 Fukushima Daiichi accident is an example of the latter, and so far, no terrorist has exploded an RDD. A radiological emergency will most likely be detected via the radiation detectors routinely worn by emergency responders, or installed at facilities that handle radioactive materials. The primary concern with a radiological emergency is widespread contamination and problems caused by a panicking general public [2].

Authorities

Table 1 delineates authorities with jurisdiction during Rad/Nuc emergencies [2].

Incident Type, Facilities, or Materials Involved	**Primary Authority for Federal Response**
Nuclear Facilities that are: a) Owned or operated by the DoD b) Owned or operated by the DOE c) Licensed by the NRC or an NRC Agreement State d) Not licensed, owned, or operated by a federal agency, an NRC Agreement State or currently or formerly licensed facilities for which the owner/operator is not financially viable or is otherwise unable to respond	 a) DoD b) DOE c) NRC d) EPA
Nuclear Weapons and Components that are: e) In the custody of the DoD f) In the custody of the DOE	 e) DoD f) DOE
Radioactive Materials Being Transported: g) By or for the DoD h) By or for the DOE i) Containing NRC or NRC Agreement State licensed materials j) Within the coastal zone for materials that are not licensed or owned by a federal agency or an NRC Agreement State k) All others	 g) DoD h) DOE i) NRC j) USCG k) EPA
Disused and Unwanted Sealed Sources with no Disposition Pathway l) Off-Site Source Recovery	 l) DOE
Unknown or Unlicensed Materials, and Domestic Response to Foreign Materials and International Incidents: m) Outside of certain areas of the coastal zone n) Certain areas outside of the coastal zone o) Imported contaminated consumer products that are distributed before detection p) Inadvertently imported radioactive materials q) All others	 m) USCG n) EPA o) EPA p) CBP q) EPA
U.S. Assistance to Foreign Governments for Incidents with International Impacts r) U.S. Government assistance to foreign government response and recovery efforts	 r) DOS/ USAID
All deliberate attacks involving nuclear/radiological facilities or materials (e.g., RDDs, INDs)	DHS
Note: DHS/FEMA may be called upon to lead or provide supplemental operational coordination support for the primary authority during complex incidents.	

Table 1. Authorities for Interagency Coordination [2].

Emergency Response

Zoned Response

Nuclear emergencies involve more severe, widespread damage, and although there are no clear boundaries, it is extremely useful to divide the theatre of emergency operations into zones as depicted in Figure 1.

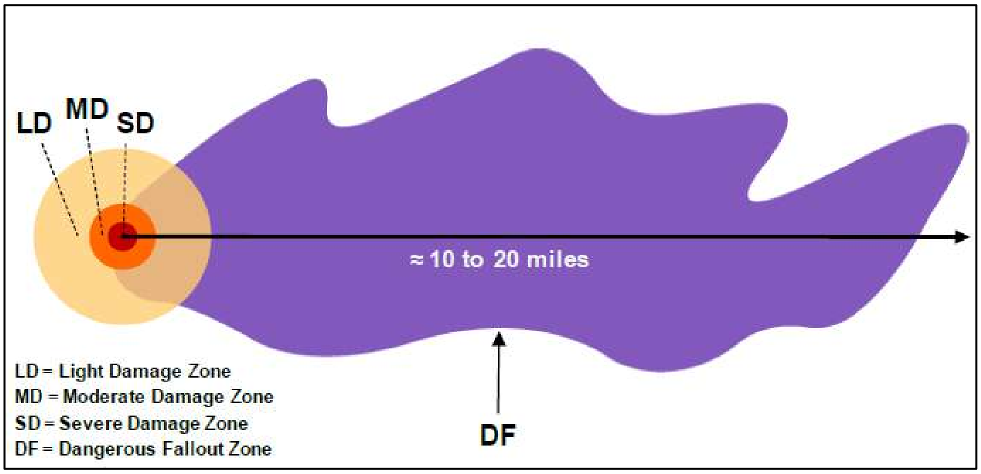

Figure 1. Damage and Fallout Zones [5].

The Light Damage zone is characterized by broken windows and few serious injuries; the Moderate Damage zone by significant building damage, rubble, downed utility lines and poles, overturned cars, fires, and serious injuries; and the Severe Damage zone by destroyed infrastructure and high radiation levels resulting in unlikely survival of victims. Emergency responders should not enter the Severe Damage zone during the first 72 hours after detonation [2].

The other important zone classification that responders should be aware of is the Dangerous Fallout zone (DF). The actual location of fallout is dependent on atmospheric conditions and wind direction. Fallout particles within the DF should be readily visible to responders on surfaces, appearing similar to grains of sand. The DF zone may extend 20 miles downwind from the detonation site for a 10-kiloton explosion. Dangerous radiation levels associated with fallout will dissipate quickly. For this reason, emergency responders should not enter the DF zone during the first 24 hours until these fatal radiation levels have subsided [2].

Responder Protection

Even during a Rad/Nuc emergency, employers, including federal agencies, must still comply with applicable requirements for protecting worker safety and health, including Occupational Safety and Health Administration and NRC dose limits for workers [2]. This means that all responders must receive 40-hour Hazardous Waste Operations and Emergency Response training before attending to a Rad/Nuc emergency.

In addition, DHS has adopted NFPA Standard 472, *Standard of Competence for Responders to Hazardous Materials-Weapons of Mass Destruction Incidents*. This standard dictates the required competencies for all Rad/Nuc emergency responders and stipulates that “Allied Professionals” must direct these responders.

An Allied Professional is a technical specialist or subject matter expert who possesses the knowledge, skills, and technical competence to aid in the selection, implementation, and evaluation of tasks at hazardous materials/weapons of mass destruction (WMD) incidents. Examples of those qualified to be Allied Professionals include Certified Safety Professionals, Certified Health Physicists, and Certified Industrial Hygienists.

Emergency Responder Health Monitoring and Surveillance System

Lessons learned during the response to the terrorist attacks of September 11, 2001, and other disasters, highlight the deficient way in which emergency response exposures were documented and tracked. During a disaster, responders can include thousands of spontaneous volunteers who are focused on the health of others, and with little regard for their own well-being. As a result, there can be many unnecessary exposures and needless suffering from the after-effects of a poorly coordinated response. For this reason, the Emergency Responder Health Monitoring and Surveillance (ERHMS) system was developed by the National Institute of Occupational Safety and Health (NIOSH). Introduced in July 2017, it provides response organizations with comprehensive personnel monitoring capabilities (see Figure 2).

Rad/Nuc responders are required to be certified to perform duty-specific tasks, which may have federal, state, or locally-mandated training requirements. Prior to a disaster, the ERHMS software can be used to track vital personal data and help ensure that responders have the required credentials, training, and medical screenings. During the disaster, monitoring information, such as radiation exposure, can be imported and tracked (here, from dosimetry data). All of this information can be shared in real time with members of the command staff at remote locations to control entries to hazardous areas.

The design of the ERHMS is based on the Incident Command System (ICS). Therefore, unlike methods currently in use, which amount to a hodge-podge of documents, spreadsheets, and databases, the ERHMS ensures the Incident Commander (IC) has ready access to needed resources. Planning and executing an incident response optimizes the health and safety of responders and volunteer workers before, during, and after their response.

The ERHMS provides real-time data and recommendations on issues that arise among responders. For example, it provides the IC with:

- A complete roster of responders including spontaneous volunteers;
- A summary of data regarding responder readiness (health status, training level, certifications, credentials, and receipt of on-site training), with a focus on the ability to safely and effectively deploy;
- A summary of occupational health and safety issues that have occurred, and recommendations for controlling exposures and hazards;
- Identification of responders or responder groups who have experienced hazardous exposures, with recommendations for tracking their health after the event; and
- Out-processing assessments upon completion of response duties [6].

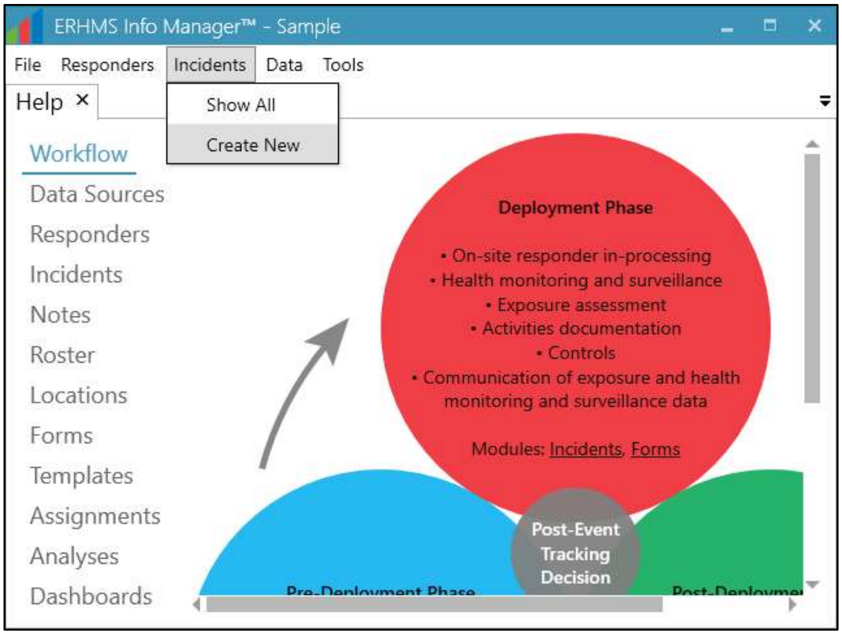

Figure 2. Screenshot of the NIOSH ERHMS Software Interface [6].

Planning Guide for Protecting Responders following a Nuclear Detonation

The National Security Council's Domestic Readiness Group created this guide in 2016 to provide planners, safety officers, and supervisors with recommendations to protect responders from the initial effects of a nuclear emergency. The group of authors for this guide represent the Departments of Energy, Labor, Homeland Security, Health & Human Services, and Defense. Contributing authors also represent the U.S. Army Nuclear & Countering WMD Agency, the FBI, and the EPA. The guide specifies the use of the ICS, stipulating that "no single agency, jurisdiction, region, or even state will have all of the capabilities needed," and that a Unified Command structure is required. It also functions as a primer, providing the reader with the basics of Rad/Nuc response. An important distinction for nuclear emergencies is the need to wait, and not rush into ground zero. In addition, responders need to be prepared for all hazard types, since the IND will release any chemical and biological materials present in the blast area, and destroy infrastructure, presenting further physical hazards [5].

Planning Guidance for Response to a Nuclear Detonation

This report was developed by a federal interagency committee, including representatives from DoD, to provide response recommendations to save lives in the event of an urban nuclear detonation. The guidance provides response activities for an environment with a severely compromised infrastructure during the first few days (i.e., 24–72 hours post-detonation) when it is likely that federal resources will still be en route to the incident. The report provides an excellent description of the effects and impacts in an urban environment, with details regarding what responders should expect. Other notable topics include:

- Responder health and safety strategies
- USAR guidance
- Shelter and evacuation guidance
- Medical care (scarce resource) considerations

Decision Making

Radiological Operations Support Specialist

Since 9/11, DHS has analyzed our country's ability to respond to major disasters. One of the more critical gaps identified in our emergency preparedness is the need for Rad/Nuc subject matter experts that can integrate with the NRF and Incident Command structure. The Radiological Operations Support Specialist (ROSS), a National Incident Management (NIMS) position, was created to fill this gap and provide actionable guidance for ICs to address the significant complexities of Rad/Nuc emergencies. The first ROSS class was certified in September 2016, and a second in September 2017. At the time of writing, approximately 50 officials are ROSS-certified.

The ROSS became a necessary position within NIMS because Rad/Nuc hazards are not well understood by first responders, forcing DHS's Science and Technology Directorate to develop a solution in the form of the ROSS Program. The ROSS supports Rad/Nuc emergency response by integrating with the ICS. It can operate anywhere from the hot zone to the Emergency Operation Center (EOC).

In the field, the ROSS makes recommendations, interprets models, and analyzes data for the IC. In the EOC, the ROSS brings specialized skills and understanding in plume modeling, radiological data assessment, and a comprehensive understanding of Rad/Nuc emergencies. A ROSS uses technical tools such as RadResponder to help collect, collate, and communicate critical technical data to federal partners and key state and local decision makers. In addition, the ROSS is an essential member of a Rad/Nuc response that can help communities use and integrate federal response assets. An emergency response IC should be prepared to respond to the complexities of Rad/Nuc incident. Because the learning curve for an IC to learn health physics is steep, an IC with a ROSS by their side is better equipped for success [7].

FirstNet

For nearly a century, state and local agencies across the nation have used Land LMRs as their primary wireless communication devices for emergency services [8]. These LMR operate on more than 10,000 separate and incompatible radio networks without data capabilities. The First Responder Network Authority was created in 2012 by the U.S. Department of Commerce. Its mission is to build, deploy, and operate a nationwide broadband network (FirstNet) for first responders. By January 2018, it was approved for use in all 50 states and began deployment.

The ability to share information affects the success, safety, and speed of Rad/Nuc responders; FirstNet enables a more efficient response with better information, in turn allowing for better results. For example, technologies such as RadResponder and DARPA SIGMA are powerful tools that can provide an invaluable description of the hazard landscape. However, these technologies rely on the wireless transmission of data, from hundreds or thousands of responders competing with civilians for bandwidth. FirstNet gives Rad/Nuc responders a fast, reliable, and secure way to seamlessly share data and communicate with each other. Using FirstNet, responders can instantly exchange information, photos, and video. In addition, FirstNet provides instant, comprehensive information that enhances situational awareness and reduces duplication of efforts [9].

RadResponder

RadResponder is software developed for the management of radiological data and is a product of FEMA, the National Nuclear Security Administration, and EPA. Its flexible architecture enables organizations to rapidly and securely record, share and aggregate large quantities of data while managing their equipment, personnel, interagency partnerships, and multijurisdictional event space (see Figure 3).

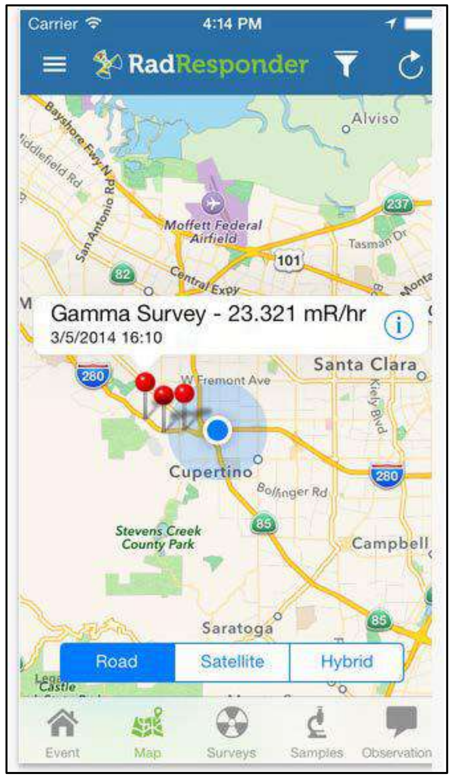

Figure 3. Screenshot with Examples of Radiation Measurement Data [12].

RadResponder is provided free of charge to all federal, state, local, tribal, and territorial response organizations, and can be accessed on smartphones, tablets, and via the internet. This allows it to easily deploy at all levels of government during a Rad/Nuc emergency response.

Conclusion

In December 2017, the Deputy Secretary of Homeland Security provided the following assessment: “We face a persistent and ever-evolving threat from WMDs. Whether the threat comes from rogue states or terrorist groups, our adversaries are interested in creating terror and destruction using chemical, biological, radiological and nuclear weapons [10].”

Important innovations are on the horizon over the next 3–5 years with regards to Rad/Nuc emergency response. For example, the DARPA SIGMA project promises to equip responders with passive CBRN detectors that continuously upload ambient condition data to a remote location. Launched in 2014, SIGMA has successfully demonstrated an operationally effective, continuous radiation-monitoring network of wearable, vehicle-mounted, and stationary radiation detectors that provide coverage across a large city or region. SIGMA capabilities are currently transitioning to operational use by various law enforcement and counterterror entities [11].

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9

Conclusion

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Disaster response is typically handled by state and local governments, but there are times when the DoD is called upon to assist and lead such efforts. DoD must be prepared to act using the best available technologies, methods, techniques, and science. A complete understanding of what is available to DoD must be gathered from both inside and outside the Defense community. The findings of this report center on six key areas of disaster response:

- Communications Management
- Data Management
- Responder Protection
- SAR Technologies
- SCM
- Radiation Emergencies

Many of the technologies described above can be grouped into six categories of technological development, which promote four key outcomes in modern disaster response (see Figure 1).

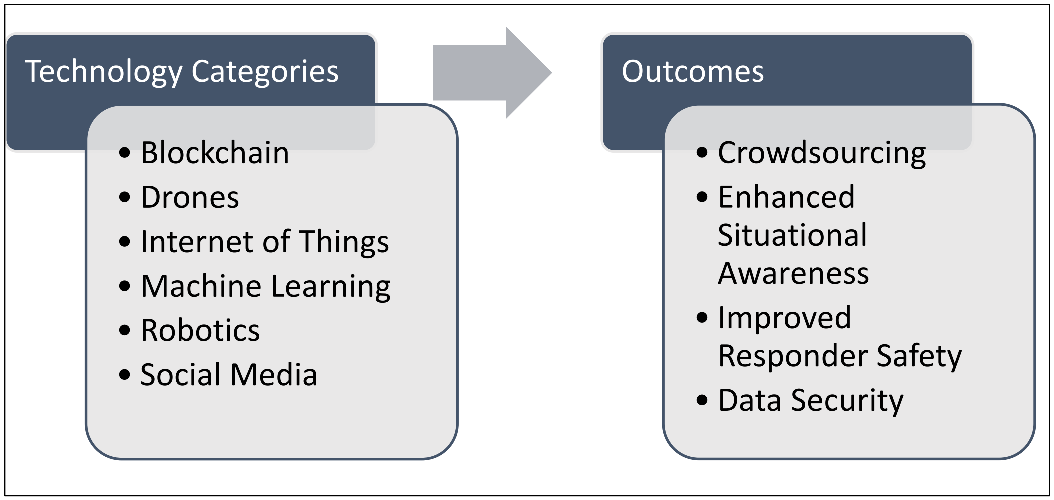

Figure 1. Outcomes associated with emerging technology categories.

Five technical trends in disaster response are likely to grow in importance over the next three to five years: continued advancement of the technologies discussed in this report; implementation of “next wave” technology; technological convergence; overlap of functions; and a rising emphasis on the primacy of first responders.

Many of the technology categories mentioned in this report have been around for decades (see Figure 2, dark blue circles), but only recently have they found their way into disaster response. Likewise, another set of emerging technologies (see Figure 2, light blue circles) are slowly creeping into disaster response and will likely emerge as the next “hot” categories within the near future. For example, additive manufacturing (3D printing) is revolutionizing industrial production, and is rapidly being incorporated into disaster response and recovery [1, 2].

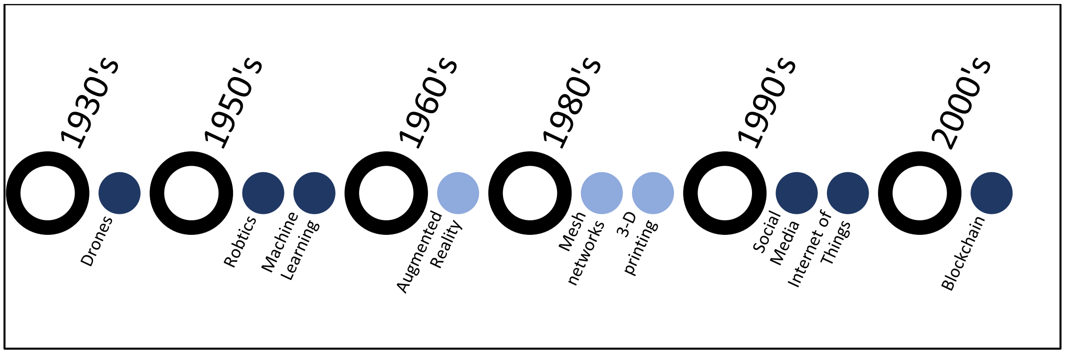

Figure 2. Timeline of technology development discussed in this report.

Convergence is the notion that multiple technologies can combine to create even more powerful tools [3]. The interface of social media, AI, IoT, drones, and robotics will enhance the abilities of situational awareness, communications, data management, and responder safety. Tools such as FireChat [4] combine social media functions, and double as an integral part of mesh networks, allowing first responders to communicate offline. The Assistant for Understanding Data through Reasoning, Extraction and Synthesis (AUDREY), developed by DHS and the NASA Jet Propulsion Laboratory, uses AI and IoT to seamlessly manage communications among responders [5, 6].

The Next Generation First Responder Apex Program [8], managed by DHS, is on the forefront of developing novel technologies for responders. In addition, DHS released Project Responder 5 in 2017, which highlights 37 capability needs identified by the first responder community [9]. These needs, coupled with the rapid pace of innovation and technology development, will drive the incorporation and implementation of new technologies into the hands of first responders.

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