HAZMAT Technician-level Emergency Response: A Mental Model Framework for Radiological Dispersal Device (RDD) Incidents

STRUCTURED ABSTRACT

Introduction

This research examines the cognitive frameworks utilized by HAZMAT technicians when responding to incidents involving Radiological Dispersal Devices (RDDs), which are conventional explosive devices with radioactive materials incorporated. The objective is to introduce the Expected Mental Model State (EMMS) as a comprehensive evaluation tool for assessing and enhancing the expertise and situational awareness of emergency responders dealing with radiation crises.

Methods

Through a series of expert focus group sessions using the well-established qualitative methodology of grounded theory, an Expected Mental Model State (EMMS) was developed. The methodology utilized an influence diagram architecture to conceptually capture and codify key areas relevant to effective emergency response.

Results

The research identifies fourteen EMMS key conceptual domains, further elaborated into 301 subtopics, providing a multi-dimensional structure for the proposed mental model framework. Three pivotal notions of mental model emerged within the EMMS framework: Knowledge Topology, Envisioning (Belief), and Response and Operability. These notions were found to align with previous theories of mental models and are vital for understanding how HAZMAT technicians conceptualize and respond to RDD incidents.

Discussion

The study emphasizes the critical role of mental models in enhancing preparedness and effective response strategies during radiation emergencies. The EMMS framework offers a versatile methodology that can be adapted across various kinds of emergency responders and high-risk situations, including the broader Chemical, Biological, Radiological, and Nuclear (CBRN) spectrum. Using this EMMS framework to develop an EMMS Diagnostic Matrix can provide a roadmap for identifying areas for the development of specialized training modules that have the potential to significantly elevate both the quality and efficacy of responder training and preparation.

BACKGROUND

First responders, including those from fire and HAZMAT organizations, are trained to handle a broad spectrum of incidents and hazards to safeguard themselves and their communities. These responders must rapidly assess situations, secure the scene, make informed decisions, and take action to protect people and infrastructure affected by hazards. While training and experience help refine these skills, radiation presents unique challenges in situational awareness for several reasons:

1. The invisible nature of radiation requires specialized detection and measurement.
2. The technical units and conversion factors involved complicate the risk assessment.
3. Radiation incidents are highly infrequent, limiting real-world repetitive practice opportunities.

The constraints described above may limit the extent to which emergency responders can develop proper mental models of radiation risk and incident response. Mental models are internal representations of an individual's understanding of systems or concepts, which can influence reasoning and situational awareness in real-world situations. Poor or limited mental models are likely to lead to suboptimal response actions, resulting in significant consequences for the safety of responders and the public. Although considerable research has been conducted on the influence of decision-making biases and situational awareness levels across various responder professions (e.g., Bayouth et al., 2013, 2019; Keren et al., 2013a,b; Klein, 1999), limited attention has been given specifically to mental models related to radiation incidents. Further, a literature review failed to identify works that address the relationship between responders' mental models of radiation and the quality of their response to hazardous radiation situations.

Decision-making biases and levels of situational awareness have been explored in the responder community across firefighter, emergency medical services, and law enforcement professions. Significant work (e.g., Bayouth et al., 2013, 2019; Keren et al., 2013a,b; Klein, 1999) has evaluated decision-making factors across firefighters. Much of the literature explored by Bayouth et al. (2013) outlines the importance of a responder’s ability to make decisions under stress. Hardison and Gray (2021) explored energy-based hazard recognition across firefighters and cited the importance of recognizing and mitigating safety hazards to reduce the likelihood of exposure and injury to the responder (Carter & Smith, 2006). Hardison and Gray found that firefighter experience may not be the sole indicator of a firefighter’s ability to recognize a hazard and that specific training may be necessary to improve hazard recognition across all experience levels (Hardison & Gray, 2020). Influences such as inherent biases or incomplete mental models may limit the extent to which experience improves a responder’s understanding, which justifies the need to further understand firefighters' perceptions and knowledge levels of hazards and the impacts of gaps in their mental model on the responder’s ability to make safety-related decisions. Leek et al. (2023) explored the effect of priming on the perceived manageability of a radiation-hazard environment and found that exposing industrial hygiene students to alarming words (the priming intervention) prior to engaging in a simulation scene with radiation hazards resulted in an increase in perceived manageability of the scene (Leek et al., 2023). This indicates that knowledge is influenced by belief.

MENTAL MODELS IN RADIATION PERCEPTION

Mental models are fluid cognitive depictions of understanding and interpretations of the world, which individuals form through lived experiences, learning, and instruction (Norman, 1983). As Norman states, mental models serve as blueprints enabling individuals to predict outcomes, achieve goals, and enhance their comprehension of the world, and a person possessing a strong mental model related to a particular topic can foresee potential risks or implications of their actions in an event. A responder’s own mental model evolves with the acquisition of new information or observations, particularly when the expected outcome diverges from the actual one. Even if the responder’s mental models are not scientifically precise, practical mental models can be sufficient for effective task performance (Norman, 1983).

While some research has focused on radiation-related mental models, there is substantial room for further exploration into detailed depictions and mapping of mental models specific to radiological incidents. A few scientists have focused mental model research on radiation-related topics and outlined a methodology by which notions of mental models can be elicited and assessed for gaps in relation to radiation perception. Morgan et al. (2002) detailed the process for eliciting expert and public mental models and comparing them to identify gaps in the public's understanding and misconceptions about radon risk in an effort to focus targeted communication strategies to address these gaps. The outlined mental model approach outlined four general steps: (1) establishing an expert mental model that outlined the expected concepts the public should understand about a risk based on experts' extensive experience, training, and immersion in the field of interest, (2) eliciting the existing mental model for the risk concepts from members of the public, (3) identifying gaps between these two mental models to identify areas where communications could be focused to target gaps or misunderstandings, and (4) the creation and evaluation of these communication messages on addressing these gaps (Morgan et al., 2002). Melo et al. (2020) further adapted this methodology to evaluate mental models' impact on radiation emergency response by first creating a cloud of concepts representing the expert mental model of overarching radiation concepts, then eliciting the mental model of Portuguese firefighters and military personnel, and finally identifying areas of similarity and differences between the responders and the public mental models. The results of this work highlighted general concepts where the experts' and responders' mental models did not align, specifically noting findings around the concept of contamination (Melo et al., 2020).

Expert mental models have been addressed in numerous studies (e.g., Hanisch et al., 2007; Klein, 2015; Lowe & Lorenzoni, 2007; Seel et al., 2009). Expert mental models, formed through extensive experience and training, enable the rapid analysis of complex situations and effective decision-making. They feature interconnected concepts, theories, principles, rules, and heuristics, providing a cognitive structure for information organization, pattern recognition, and outcome prediction. Expert mental models enable these experts to quickly identify relevant information, filter out irrelevant details, and focus on key factors influencing their decision-making process, allowing for adaptability as new information emerges. Furthermore, expert mental models often emerge through the expert's ability to think abstractly, connect different pieces of information, and effectively apply their knowledge to new and unfamiliar situations. Experts with proper level of a mental model can also recognize and understand the limitations and assumptions underlying their mental models, allowing them to adapt and refine their understanding as new information or evidence emerges.

In challenging or hazardous circumstances, mental models act as conceptual blueprints that responders use to interpret their surroundings and make informed decisions. These cognitive schemas are cultivated by integrating a visual conceptualization of an idea with its mechanistic explanation, based on the responder's comprehension of a specific device or system. As responders develop their individual mental models, however, they may be incomplete or be influenced by varying levels of confidence in radiation-related concepts. Understanding both the knowledge and the confidence levels or beliefs of responders in these concepts can offer a more comprehensive insight into how beliefs are formed and applied in practice (Griffin & Ohlsson, 2017). The development of an expected mental model framework based on expert understanding and beliefs of radiological incident response provides a framework for eliciting the individual responder's mental model. It is critical to explore the level of a responder's understanding of the concepts and where they may hold an underlying belief related to that concept that may prevent the creation of a complete mental model related to radiation incident response.

STRUCTURE OF THIS PAPER

In this paper, Section 1 introduces the grounded theory methodology used to formulate the Expected Mental Model State (EMMS), a framework for the ideal cognitive state of HAZMAT technicians dealing with the consequences of Radiological Dispersal Device (RDD) incidents, which are conventional explosive devices with radioactive material incorporated within. Section 2 investigates the EMMS elements, exploring the conceptual domains, subcategories, and mental model notions. This structure is illustrated through an influence diagram for clearer comprehension of the mapped concepts. Section 3 further elaborates on the nuances of mental models that emerged during the development and thematic analysis of the EMMS. Section 4 outlines the practical applications of the EMMS, demonstrating how it can be utilized to evaluate the preparedness of individual emergency responders or whole teams.

SECTION 1 - GROUNDED THEORY DEVELOPMENT OF THE EMMS

In grounded theory methodology, the gathering and interpretation of data happens concurrently, each shaping the other. Information is organized into distinct elements, such as notions, classifications, and subject matter. Moreover, as the aspects of these elements evolve, they, in turn, guide the ongoing data collection process. The basis of this research leverages a mixed methods methodology with an emphasis on constructivist grounded theory, as outlined by Charmaz (2014). Using the constructivist approach to the grounded theory methodology, it is recognized that the researchers will bring their own biases and perceptions to the data collection and analysis process. However, these biases are effectively moderated through objective procedures and acknowledged when necessary (Charmaz, 2014). Grounded theory methods are frequently used to elicit and evaluate mental models related to decision-making related to safety and hazardous occupational settings (Austin et al., 2020; Wong et al., 2020; Han et al., 2022).

From these foundational concepts related to grounded theory and the elicitation and evaluation of mental models, a methodology for developing the EMMS for HAZMAT technicians and RDD incident response was formulated. This began with the creation of an initial influence diagram template which incorporated an adapted version of the initial cloud of concepts from Melo et al. (2020), common radiation principles from current US references and guidance for radiological dispersal device incident response, and input from the first focus group session.

The focus group engagements employed a grounded theory methodology, allowing participants to collectively refine this initial template into a comprehensive map of radiation concepts related to RDD response. The first focus group discussion started with a broad scope that included various radiation and emergency response topics. Subsequent discussions narrowed this scope, concentrating on RDD incidents and the roles of HAZMAT technicians. The focus group discussions continued and led to the identification of conceptual domains, the organization of detailed subcategories, and the emergence of notions of the mental model through thematic analysis. This iterative process culminated in the creation of the final refined version of the EMMS, represented as a mapped influence diagram based on the use of maps to display qualitative results as a fundamental technique in grounded theory to assist in representing the strength of the relationships between data (Charmaz, 2014). The grounded theory process employed to develop the EMMS is outlined in Figure 1.

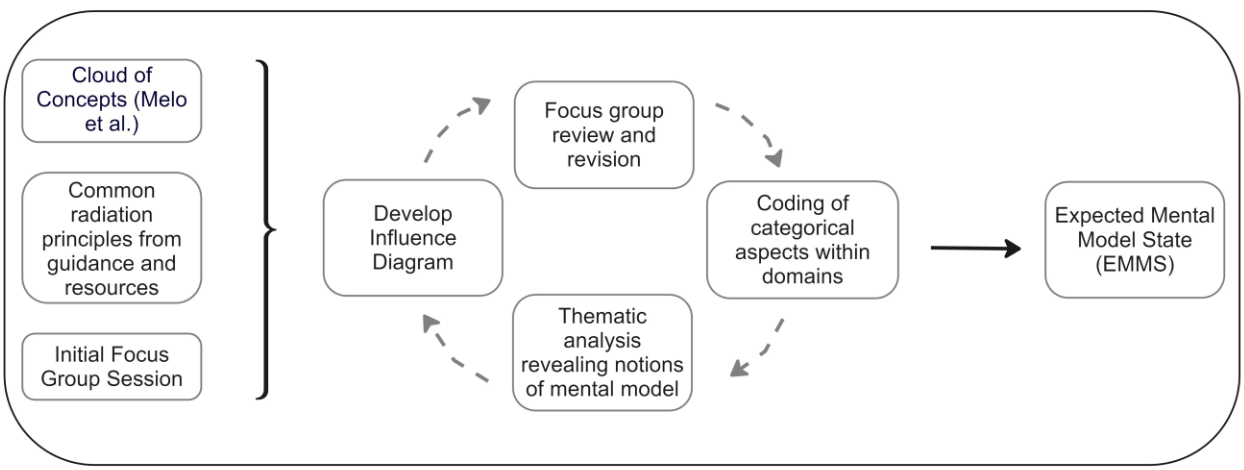

Figure 1. Grounded Theory process used to develop EMMS

As the focus group progressed, it became evident that while basic radiation principles apply across different incident types, the importance and application of these principles vary depending on the specific nature of the radiological incident. Limiting the scope to focus solely on RDD incidents facilitated more targeted and productive discussions. The discussions progressed to defining the conceptual domains and subcategories to create a robust and detailed EMMS. Limiting the scope of the EMMS also helped to align the core assumptions to RDD incidents parameters and ensure that the same generalized assumptions informed the responses from both experts and field responders during the EMMS elicitation process. The grounded theory facilitation cycle continued iteratively until no further significant refinement in the conceptual domains or categorical subtopics was identified by the focus group members, and no additional themes emerged through thematic analysis.

The expert focus group members convened to develop the EMMS possessed diverse and substantial qualifications, including doctoral degrees in fields related to toxicology and radiation protection, Certified Health Physicist certifications, NCRP council memberships, comprehensive radiation emergency response expertise, and played instrumental roles in developing national and international reference and guidance documents. All members either met or exceeded the criteria, or equivalent criteria, set for a Type 1 Radiological Operations Support Specialist according to FEMA's National Qualification System[1].

SECTION 2 - EXPECTED MENTAL MODEL STATE FOR HAZMAT TECHNICIAN RESPONDERS FOR AN RDD INCIDENT

The derived Expected Mental Model State for HAZMAT technicians established the following fourteen key conceptual principle domains: (1) radiation detection equipment, (2) radiation detection operations, (3) response zones, (4) worker protective considerations, (5) public protective considerations, (6) important reference documents, (7) responder confidence level/trust, (8) inherent radiation sentiment origins, (9) core understandings about RDD response, (10) radiation protection principles, (11) radiation dose, (12) radiation characteristics, (13) realistic RDD principles of dispersion of material, and (14)

[1] ROSS Qualifications in FEMA 509 Resource Typing Definition
https://www.fema.gov/sites/default/files/documents/fema_radiological_operations_support_specialist_03023.pdf

radiation units. Figure 1 presents a collapsed overview of the EMMS structure, reflecting the conceptual domains; from which 301 specific subtopics emanated. The full EMMS with expanded versions of each subdivision can be viewed here. [Insert link to digital media pdf - Digital Content_AngelaLeek_EMMS diagram]

The members of the focus group concurred on twelve domains reflected in the influence diagram that capture the key knowledge base or beliefs required for HAZMAT technicians in RDD incident responses. In addition, they highlighted other elements that may suggest the root influence of various components of the mental model, which were incorporated as two of the domains (Domains 7 and 8), as follows:

- **Domain 1** includes concepts specific to radiation detection equipment functionality categorized by probe types, sensitivity, efficiency, and identification capabilities. The key concept for this domain is an understanding that equipment may not be relevant in all incidents and may not measure and read accurately in all types of radiation fields.
- **Domain 2** is related to radiation detection operations and includes concepts related to the use of radiation detection equipment to detect various types of radiation, quantify the amount of radiation, and identify the types of radiation. The key concept for this domain is an understanding that radiation detection equipment must be turned on for an incident to promptly detect whether radiation is present.
- **Domain 3** reflects the concepts of response zones, which include hot zone, cold zone, dangerous radiation zone, beta deposition concentration zone, and alpha deposition concentration zone. The key concept for Domain 3 is an understanding that response zones may need to be adjusted from what is listed in procedures based on incident hazards and priorities.
- **Domain 4** outlines worker protective considerations, organized under the main categories of As Low as Reasonably Achievable (ALARA), which are optimized actions to keep exposures as low as possible, Personal Protective Equipment (PPE), and non-radiological or other hazards. The key

concept for this domain is an understanding that radiation risk is only one of the hazards that may be present during an RDD incident.

- **Domain 5** includes the concepts for public protective considerations, grouped into the categories of minimizing immediate dose, minimizing overall risk, weighing radiation risk in light of all risks present, and the concept of avoidable dose. The key concept noted for Domain 5 is an understanding that initial generic public protection actions may need to be implemented with sparse and incomplete field radiation measurements.
- **Domain 6** covers important reference documents and is categorized under the subtopics of the Department of Homeland Security (DHS) Radiological Dispersal Device (RDD) Response Guidance, National Council on Radiation Protection and Measurement (NCRP) guidance documents, the Environmental Protection Agency (EPA) Protective Action Guidance Manual, and the Emergency Response Guidance (ERG). Domain 6, covering important reference documents, does not have a designated 'key concept,' as it is a foundational resource.
- **Domain 7** lists aspects that may influence a responder's confidence level or trust in the other conceptual domains. These are noted as confidence in their Incident Commander's decision-making, in their established procedures, in their training, in themselves and their ability to apply their knowledge, and in the assumptions made in reference and guidance documents. There is no key concept for Domain 7 because these are potential indicators that may influence an incomplete understanding of the other conceptual domains.
- **Domain 8** is similar to Domain 7 in that it lists aspects that may provide insight into the origin of how responders developed their overall sentiment toward radiation and risk. These aspects include general risk aversion or tolerance, characters from comic book series with radiation themes, radiation therapy treatment experiences of themselves or family members, movies depicting radiation incidents, a sense of perceived control over exposure or risk from radiation,

and the perceived likelihood of a radiation incident actually occurring. Domain 8 does not have a key concept because it focuses on the potential root source of biases that may contribute to an incomplete understanding of the other conceptual domains.

- **Domain 9** captures core concepts that are generalizations or applications of factual knowledge critical to RDD response considerations. These are reflected in this separate conceptual domain since they represent a combination of the subtopics across multiple conceptual domains. The core concepts include nine generalized statements such as “Standard precautions for blood-borne pathogens are effective in protecting workers and contamination control” and “There will be areas where radiation readings are elevated but do not require any immediate public or worker protective actions.” There is no key concept for Domain 9 because it captures interrelated considerations from each of the other domains.
- **Domain 10** includes basic radiation protection principles with some refinement to those topics most relevant for RDD response considerations. The subtopics are categorized under time, distance, and shielding. The key concept for the domain is that time is the most significant factor in radiation protection during an RDD incident.
- **Domain 11** includes concepts related to dose, categorized under the subtopics of contamination, exposure, established decision dose levels, and dose terminology. The key concept for Domain 11 is an understanding that most personal radiation detectors or dosimetry devices measure external dose only.
- **Domain 12** includes general radiation characteristics with a focus on those characteristics important for the types of radiation most likely to be involved in an RDD incident. The subtopic categories include radiation emission, elemental/chemical properties, and radioactivity. This

domain does not include a key concept because the concepts within are largely factual knowledge.

- **Domain 13** represents concepts regarding general RDD principles related to the dispersion of radioactive materials. These are categorized under subtopics of explosive and non-explosive with a key concept of an understanding that any explosion incident could include radiation.
- **Domain 14** includes concepts related to radiation measurement units and is organized by the subtopics of roentgen, rad, rem, sievert, gray, prefixes, and count rate. The key concept is an understanding that roentgen, rad, and rem can generally be considered equivalent for initial field measurements during gamma-only radiation incident types.

Figure 2 presents the structure of the emerging EMMS and its 14 domains for technician-level HAZMAT responders in RDD Incident Response as built in XMind software[2]. The domains are color-coded as described below. Each domain is expandable into further subtopics. The number of the corresponding subtopics is indicated in the small circle beside each domain box, and when selected in XMind expands to show all subtopics, as shown in the full EMMS digital content link. [Insert link to digital media pdf -

[2] XMind is an online software application that allows the creation of mind maps or other visual diagrams. Xmind.app

Digital Content_AngelaLeek_EMMS diagram]

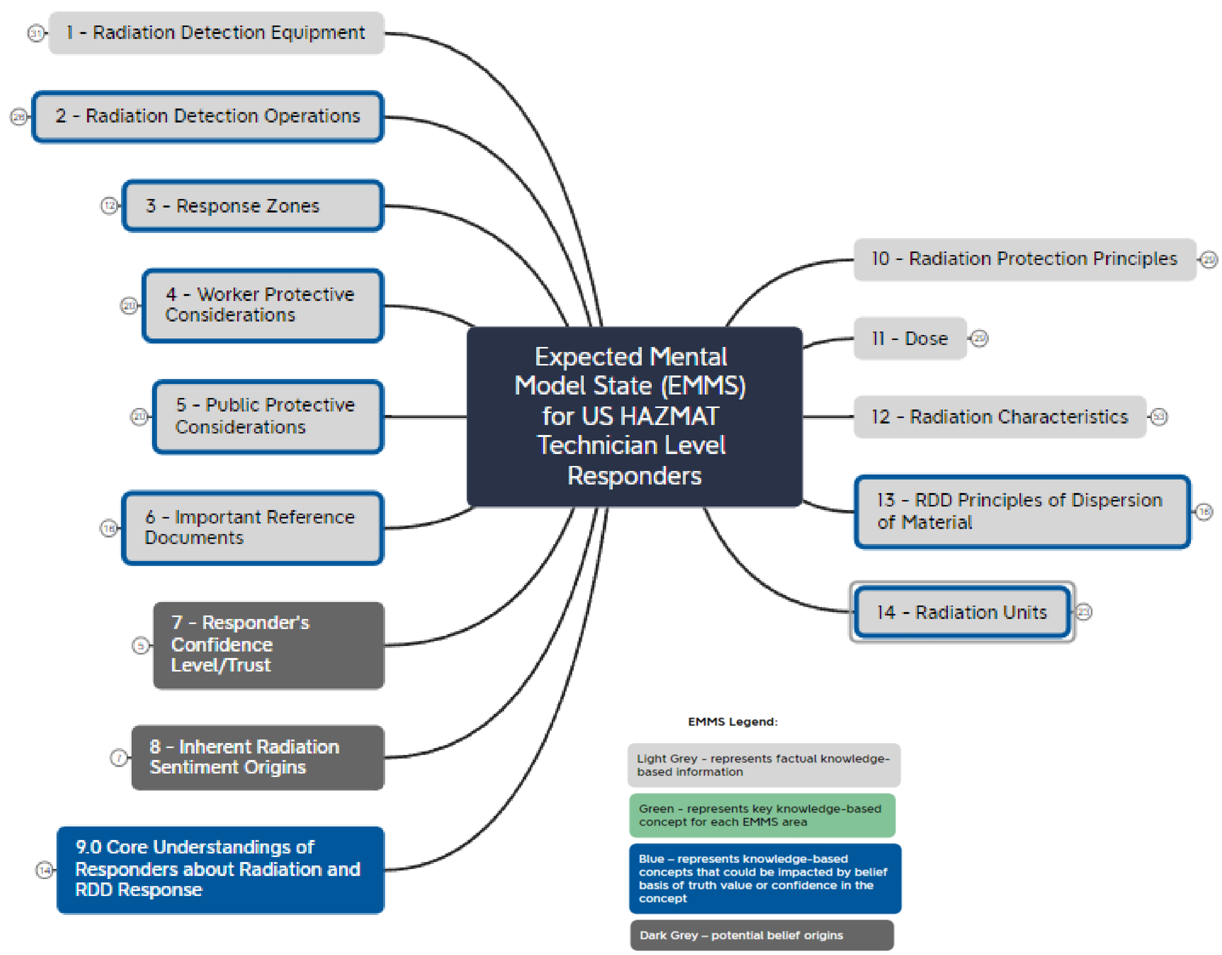

Figure 2. The Expected Mental Model State (EMMS) structure and its principle domains.

As the EMMS was developed, themes emerged across the fourteen conceptual domains and were designated colors throughout the influence diagram. These categories are defined as (1) fact-based knowledge denoted by light grey shading; (2) knowledge that could be affected by beliefs or perceptions denoted by blue shading; (3) the key concept of understanding for each conceptual domain denoted by green shading; and (4) potential root source of perceptions or beliefs denoted by dark grey shading. A legend describing the color designations is included in Figure 1 and in the link to the full EMMS framework in the digital content link. A conceptual domain is shaded light grey with a blue outline when some, but not all, subtopics include knowledge that could be affected by perception or belief within the branch. When all subtopics within the branch are potentially influenced by perception or belief, the conceptual domain is shaded entirely in blue. An example of this shading concept used to denote domains with multiple categorical themes within a branch of a primary category is shown in Figure 3.

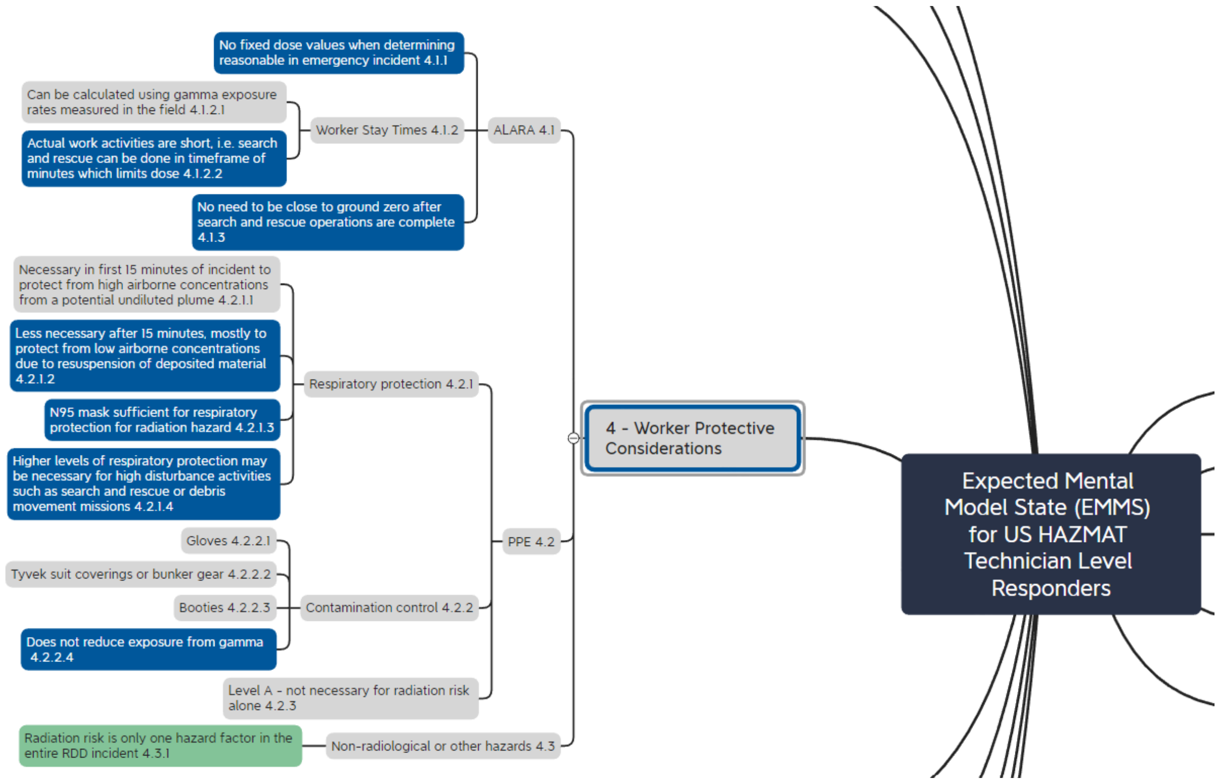

Figure 3. Expanded Worker Protective Actions Principle Domain of the Expected Mental Model State (EMMS).

SECTION 3 - NOTIONS OF MENTAL MODEL

A more detailed examination of the developed mental model state framework and its primary themes revealed three distinct categories representing the core concepts of the mental model framework. These were determined to be the three notions of mental model:

1. **Knowledge Topology Notion**: The Knowledge Topology notion of the mental model depicts the level to which the responder understands the factual concepts as represented in the light grey boxes as fact-based concepts.

2. **Envisioning (Belief) Notion**: The Envisioning notion reflects the level to which the responder believes certain technical or response concepts to be accurate or true. This could also be reflected in the responder's confidence in applying the concepts. This is represented by the blue knowledge concepts that could be influenced by perception or beliefs.
3. **Response and Operability Notion**: The Response and Operability Notion outlines the level to which the responder can pull together the concepts for application in an operational situation. This is represented by essential concepts within each domain coded in green and each of the core understandings in domain 9, which are color-coded in blue because they can also be influenced by perception or beliefs.

Table 1 presents a cross reference of conceptual domains to notions of mental model. Each domain is charted to indicate the notions reflected within. Note that two domains, the level of the responder's confidence level or trust (Domain 7) and inherent radiation sentiment (Domain 8), do not map to a mental model notion because they reflect potential origins for these notions of mental model.

EMMS CONCEPTUAL DOMAINS	KNOWLEDGE TOPOLOGY NOTION	ENVISIONING (BELIEF) NOTION	RESPONSE AND OPERABILITY NOTION
1 - Radiation Detection Equipment	X		X
2 - Radiation Detection Operations	X	X	X
3 - Response Zones	X	X	X
4 - Worker Protective Considerations	X	X	X
5 - Public Protective Considerations	X	X	X
6 - Important Reference Documents	X	X	
7 - Responder's Confidence Level/Trust			
8 - Inherent Radiation Sentiment Origins			
9 - Core Understandings of Responders about Radiation and RDD Response		X	
10 - Radiation Protection Principles	X		X
11 - Dose	X		X
12 - Radiation Characteristics	X		
13 - RDD Principles of Dispersion of Material	X	X	X
14 - Radiation Units	X	X	X

Table 1. Cross-reference of conceptual domains to notions of mental model in the EMMS.

Of particular interest, these notions align with three of the four mental model notions of physical mechanisms identified by de Kleer and Brown (2013). As outlined in the EMMS, these conceptual domains and the identified notions of the mental model reflect the interrelated nature of how knowledge and beliefs shape the mental model and provide insight into how these influences can alter how the individual responder's mental model may be developed. The EMMS domains and subtopics include a wide range of complex systems and concepts that can each be challenging to develop complete mental models. Effective RDD incident response, however, requires each concept to be considered part of an entire system of interdependent influences that inform and guide response actions. A specific example of the need for a complete mental model for interrelated domains is knowledge of radiation detection equipment (Domain 1) and the use of the equipment in operations (Domain 2). People tend to have a very limited understanding of the inner workings of technological equipment, even common technology such as a calculator, so a responder's mental model of these conceptual domains related to radiation detection equipment alone could be limited and influence the overall systematic mental model (Norman, 1983).

However, even with a complete understanding of each conceptual domain, a lack of confidence in their knowledge and understanding of the respective topic can impact the level to which the mental model is formed or called upon when needed. Individuals can add extra precautionary steps or refrain from certain actions when they develop a partial conceptual understanding, which may be exacerbated when individuals have familiarity with many similar systems (Norman, 1983). Chemical and radiological incident responses are examples of similar systems that HAZMAT technicians are expected to be familiar with. Each HAZMAT incident response is similar in nature but has unique critical differences that, when not adequately accounted for, may impact the effectiveness of the response and the safety of the responders and the public.

SECTION 4 - THE UTILITY OF EMMS TO EVALUATE AND IMPROVE MENTAL MODEL STATES

Mental models are essentially cognitive frameworks that responders construct to make sense of the world around them and guide them in decision-making throughout all hazardous situations. Individuals develop mental models by merging a visualized idea of a concept with its causal explanation, which is formed based on one's understanding of a machine or system. However, it is important to note that these mental models are dynamic rather than static constructs. The process of merging these concepts can either be fully carried out, resulting in a complete mental model, or it may be constrained by cognitive biases, leading to an incomplete depiction, or flawed mental model (deKleer and Brown, 2013).

The distinction between complete and incomplete mental models is crucial in emergency response settings. For instance, a responder may possess sufficient factual knowledge about a procedure or system, but if their underlying perception of, or confidence in, these facts is flawed, it could detrimentally affect their ability to integrate this knowledge into an effective causal model. These limitations could be influenced by a range of factors, such as prior experience, training, or even cognitive biases. Understanding where these constraints or flaws exist, and common influences that may result in incomplete mental model formation will help to identify specific areas where targeted training or reevaluation of existing training methods could enhance a responder's mental model state. This is where the Expected Mental Model State (EMMS) can influence future training development. Developed as a structured framework, the EMMS identifies key conceptual domains and associated notions crucial for effective response strategies. One of the most innovative applications of the EMMS framework presented herein is the ability to expand the conceptual domains and sub-categorical topics from this EMMS into a traceable matrix to create an EMMS Diagnostic Matrix. This EMMS Diagnostic Matrix can then serve as a tool to evaluate the responder’s actual level of mental model and can define the parameters for the survey questions or simulation observations designed to elicit each responder's mental model. By mapping survey questions or observations directly onto the EMMS framework, a rapid assessment can be conducted to pinpoint disparities between the established conceptual model and the mental models held by individual responders. By identifying these gaps, the EMMS Diagnostic matrix can shed light on patterns, interdependencies between different conceptual areas, and even potential root causes for any shortcomings in a responder's mental model state.

This EMMS Diagnostic Matrix can also serve as a dynamic tool. It can highlight recurring patterns and serve as a longitudinal tracking system, documenting changes in mental models and providing tangible evidence of the impact of training interventions across interconnected conceptual domains. Therefore, the EMMS and its derivative matrix offer a multi-faceted, adaptable method for improving the mental readiness of emergency responders, ensuring they are better equipped to handle complex and high-risk situations effectively.

LIMITATIONS

One limitation of this study lies in its focus on U.S.-based data and guidelines. As a result, the EMMS framework developed may not fully capture the nuanced variations that could emerge in different international contexts. While the elements of the framework related to the 'Knowledge Topology notion' are likely to hold true across different cultures, the more subjective 'Envisioning notion’ could be influenced by local practices or beliefs. Specifically, this subjectivity may be shaped by various cultural dimensions, such as the power distance index, uncertainty avoidance index, masculinity vs. femininity, long-term vs. short-term orientation, institutional collectivism, and indulgence vs. restraint, as theorized by Hofstede, to account for cross-cultural differences (Hofstede, 1980).

Another important consideration is that the development of the EMMS framework, developed via grounded theory, may be subject to the biases of the expert focus group members. This was mitigated by ensuring that the focus group comprised of experts in radiological emergency response who were engaged in the development of national-level policy and guidance for RDDs.

CONCLUSION

The creation of this Expected Mental Model State (EMMS) adapted for HAZMAT technicians dealing with RDD incidents is a cornerstone for future research and operational improvement. Using the EMMS to create an EMMS Diagnostic Matrix to facilitate the elicitation of responder mental models will provide a framework to systematically identify and quantify gaps between the EMMS and responder mental models, which can guide more effective development and delivery of training. Future investigations can explore the mental models of individual responders, scrutinize any discrepancies or gaps found in their conceptual understanding as compared to this EMMS, and assess the significance of such gaps. This foundational framework is comprehensive for evaluating multiple facets of a responder's cognitive preparedness.

Once gaps in the responder’s mental model are identified with one or more of the domains in the EMMS, they can be targeted with specially developed tools designed to complete the notion of mental model influenced by the incomplete conceptual domain. Tools such as virtual reality simulations with strategically designed after-action review applications, including segmented reports and interactive simulation playback, have improved performance in complex assessment environments (Keren et al., 2023). Focusing on what conceptual domains to develop these complex but effective simulation and after-action tools can ensure resources are spent in areas with the highest potential of improving or maintaining responder performance.

Considering the potential influence of biases in focus group members, future studies should adopt a similar approach by involving top subject matter experts for the specific topic of the mental model exploration and should ensure the focus group includes an appropriate representation to reflect the cultural dimensions of the specific target cohort for which the resulting expected mental model state (EMMS) will characterize.

The methodology behind the EMMS framework is designed to be versatile, allowing it to be adapted to various kinds of emergency responders and situations. This includes the broader Chemical, Biological, Radiological, and Nuclear (CBRN) spectrum and other occupational hazards. Utilizing this framework as a roadmap for crafting specialized training modules has the potential to significantly elevate both the quality and efficacy of responder preparation. As a result, responders will be better equipped to make sound decisions and communicate in a wide array of high-risk environments.

REFERENCES

Austin, L. C., Kovacs, D. C., Thorne, S., & Moody, J. R. K. (2020). Using grounded theory and mental modeling to understand influences on electricians' safety decisions: Toward an integrated theory of why electricians work energized. Safety Science, 130, 104826. https://doi.org/10.1016/j.ssci.2020.104826

Bayouth, S. T., Keren, N., Franke, W. D., & Godby, K. (2013). Examining firefighter decision making: How experience influences speed in process and choice, International Fire Service Journal of Leadership and Management, 7.

Bayouth S. T., & Keren, N. (2019). Fireground cue recognition: Effects on firefighter situational awareness when facing high-risk situations in virtual reality, International Fire Service Journal of Leadership and Management, 13, 35-44.

Carter, G., & Smith, S.D., (2006). Safety hazard identification on construction projects. J. Constr. Eng. Manage. 132 (2), 197–205.

Charmaz, K. (2014). Constructing grounded theory. SAGE Publications.

Chun Tie, Y., Birks, M., & Francis, K. (2019). Grounded Theory Research: A design framework for novice researchers. SAGE Open Medicine, 7, 205031211882292. https://doi.org/10.1177/2050312118822927

de Kleer, J., & Brown, J. S. (2013). Mental models of physical mechanisms and their acquisition. In Cognitive skills and their acquisition (pp. 285-309). Psychology Press

Duran, F., Woodhams, J., & Bishopp, D.. (2018). An Interview Study of the Experiences of Firefighters in Regard to Psychological Contract and Stressors. Employee Responsibilities and Rights Journal, 30(3), 203–226. https://doi.org/10.1007/s10672-018-9314-z

Endsley, M. R. (1988, May). Situation awareness global assessment technique (SAGAT). In Proceedings of the IEEE 1988 national aerospace and electronics conference (pp. 789-795). IEEE

Griffin, T. D., & Ohlsson, S. (2017). Beliefs versus knowledge: A necessary distinction for explaining, predicting, and assessing conceptual change. Proceedings of the Annual Meeting of the Cognitive Science Society. https://escholarship.org/uc/item/65q2p667

Han, Y., Li, X., Feng, Z., Jin, R., Kangwa, J., & Ebohon, O. J. (2022). Grounded Theory and Social Psychology Approach to Investigating the Formation of Construction Workers' Unsafe Behaviour. Computational Intelligence and Neuroscience, 2022, 3581563. https://doi.org/10.1155/2022/3581563

Hanisch, K. A., Kramer, A. F., & Hulin, C. L. (1991). Cognitive representations, control, and understanding of complex systems: a field study focusing on components of users' mental models and expert/novice differences. Ergonomics, 34(8), 1129-1145. https://doi.org/10.1080/00140139108964851

Hardison, D., & Gray, D. (2021). Improving firefighters hazard recognition with energy based hazard recognition training. Safety Science, 136, 105128. https://doi.org/10.1016/j.ssci.2020.105128

Hofstede, G. (1980). Culture and organizations. International studies of management & organization, 10 (4), 15-41

Iyama, K., Takano, Y., Takahashi, T., & Hasegawa, A. (2020). Factors associated with the intention to participate in activities during a nuclear disaster situation among firefighters. Journal of Radiation Research, 61(6), 871–875. https://doi.org/10.1093/jrr/rraa061

Keren, N., Bayouth, S. T., Godby, K. M., & Franke, W. D. (2013b). Examining the effect of stress and firefighters' experience level on time-to-decision in virtual reality, In Proceedings of the 2013 International meeting of the Human Factors and Ergonomics Society, San Diego, CA, September 30 - October 4, 2013.

Keren, N., Franke, W. D., Bayouth, S. T., Godby, K. M., & Harvey, M. E. (2013a). VirtuTrace: Training for Making Decisions under Stress in virtual environments. In Proceedings of the 2013 I/ITSEC - Concepts and Technologies, Empowering an Agile Force. Orlando, FL, December 2-5, 2013.

Keren, N., Lawson, A., Jacob, A., McAllister, A., Leek, A., Webster, A., Johnson, R., Boswell, C., Goode, G. (Accepted 2023, November). Me and my Report: A segmented After-Action Review embedded Report Application for Supporting Maintenance Training in VR. In Proceedings of the 2023 Interservice/Industry Training, Simulation and Education Conference (I/ITSEC) - HPAE 2: Tailored to Me: Immersive Technologies. Orlando, FL, November 27 – December 1, 2023.

Klein, G. (2015). A naturalistic decision making perspective on studying intuitive decision making. Journal of applied research in memory and cognition, 4(3), 164-168. https://doi.org/10.1016/j.jarmac.2015.07.001

Klein, G. (1999). Sources of power: how people make decisions, MIT Press, Cambridge: Massachusetts, USA.

Lanzilotti SS, Galanis D, & Leoni Netal. (2002). Hawaii medical professionals assessment. Hawaii Med J; 61:162–73.

Leek, A., Keren, N., Lawson, A., Webster, A. (Accepted 2023, November). Using Non-immersive VR Simulations in Conjunction with Priming to Enhance Conceptualizing Radiation and Risk. In Proceedings of the 2023 Interservice/Industry Training, Simulation and Education Conference (I/ITSEC) - ED 1: Evaluation and Application of Instructional Strategies. Orlando, FL, November 27 – December 1, 2023.

Lowe, T. D., & Lorenzoni, I. (2007). Danger is all around: Eliciting expert perceptions for managing climate change through a mental models approach. Global Environmental Change, 17(1), 131-146. https://doi.org/10.1016/j.gloenvcha.2006.05.001.

Melo, A. R., Silva, R. M., Palma-Oliveira, J. M., & Martins, D. R. (2020). Ionising radiation risk perception through mental models: Towards Radiological Emergency Preparedness. Journal of Radiological Protection, 40(4), 1179–1195. https://doi.org/10.1088/1361-6498/abbb26

Morgan, M. G., Fischhoff, B., Bostrom, A., & Atman, C. J. (2002). Risk communication: A mental models approach. Cambridge University Press.

Nagel, D. A., Burns, V. F., Tilley, C., & Aubin, D. (2015). When novice researchers adopt constructivist grounded theory: Navigating less travelled paradigmatic and methodological paths in Ph.D. dissertation work. International Journal of Doctoral Studies, 10, 365-383. Retrieved from http://ijds.org/Volume10/IJDSv10p365-383Nagel1901.pdf

Norman, D. (2013). The design of everyday things. Basic Books.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. Stevens (Eds.), Mental models (pp. 7–14). Hillsdale, NJ: Erlbaum.

Seel, N. M., Ifenthaler, D. I. R. K., & Pirnay-Dummer, P. A. B. L. O. (2009). Mental models and problem solving: Technological solutions for measurement and assessment of the development of expertise. In Model-based approaches to learning (pp. 17-40). Brill.

Smith, E. C., Burkle, F. M., Jr, & Archer, F. L. (2011). Fear, familiarity, and the perception of risk: a quantitative analysis of disaster-specific concerns of paramedics. Disaster medicine and public health preparedness, 5(1), 46–53. https://doi.org/10.1001/dmp.10-v4n2-hre10008

Wong, T. K. M., Man, S. S., & Chan, A. H. S. (2020). Critical factors for the use or non-use of personal protective equipment amongst construction workers. Safety Science, 126, 104663. https://doi.org/10.1016/j.ssci.2020.104663

Yamada, K., Yamaguchi, I., Urata, H., & Hayashida, N. (2020). Survey of awareness of radiation disasters among firefighters in a Japanese prefecture without nuclear power plants. PLOS ONE, 15(7). https://doi.org/10.1371/journal.pone.0236640