Lawrence Livermore National Laboratory

Products to Support Shelter-Evacuation Decision Making in the Event of a Nuclear Detonation

Michael B Dillon

March 2022

LLNL-TR-832479

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

AUSPICES AND DISCLAIMER

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

ACKNOWLEDGEMENTS

We are grateful for the support provided by US Department of Defense, Defense Threat Reduction Agency.

We also thank Michael Traynor of the US Department of Defense, Defense Threat Reduction Agency as well as Brooke Buddemeier and Joe Morris of the Lawrence Livermore National Laboratory.

Table of Contents

Introduction

Response strategies implemented in the first few hours to days after a nuclear detonation on the US homeland may save more than 100,000 lives. Effective planning and pre-event capability development can increase the response efficacy and so the number of lives saved.

During such an event, the US Department of Defense, Joint Task Force Civil Support (DoD JTF-CS) provides command and control for the DoD forces supporting civil authority response operations. Among other activities, JTF-CS expects to support FEMA as well as State and local agencies in shelter and evacuation response activities. JTF-CS currently uses a manual method to generate evacuation decision making products. This method compares the dose that would be (a) acquired remaining at a given location to that (b) acquired during evacuation along a small number of routes. In these products, evacuation may be warranted when the projected "remain" dose is greater than the "evacuate" dose. This method only provides a limited consideration of the protection buildings provide their occupants.

To inform the JTF-CS nuclear detonation response, the DoD Defense Threat Reduction Agency (DTRA) has tasked Lawrence Livermore National Laboratory (LLNL) to design a set of planning and response products to support shelter-evacuation activities. This report documents these products to facilitate DTRA and JTF-CS planning efforts. To provide context, we also provide appendices that summarize US planning guidance response zones, early (<72 h) response strategies, and other key topics.

Product Types

This section describes the nuclear detonation shelter-evacuation planning and response products. These products are intended to supplement, not replace, existing US nuclear detonation planning and response products.

These products rely on 2 US national response planning zones. In the Moderate Damage Zone (MDZ), substantial building damage will be present but sturdy buildings (reinforced concrete structures) will remain standing. In the Dangerous Radiation Zone (DRZ), outdoor radiation levels can be life-threatening. *Appendix A: Response Zone Overview* provides more detail.

Product Type 1: Regional Shelter Quality Assessment

Buildings vary widely in their ability to protect their occupants from hazards. Knowledge of the amount and location of adequate shelter, as well as which buildings lack adequate shelter, is critical to minimize life-threatening radiation exposures in the DRZ. Planners can use this information to target shelter improvements, including identifying neighborhood fallout shelters. Emergency managers can use this information while carrying out the early response actions.

The first product type is a map showing three regional shelter categories.

MOST BUILDINGS POSSESS ABUNDANT, ADEQUATE SHELTER
In the DRZ, outdoor radiation levels are hazardous, but most individuals will be adequately sheltered and so not face life-threatening radiation exposures. Shelter transit - in which poorly sheltered individuals move to adequate, nearby shelter - would be appropriate for the minority of individuals lacking adequate, initial shelter.

MANY BUILDINGS LACK ADEQUATE SHELTER, BUT SUFFICIENT ADEQUATE SHELTER IS NEARBY
In the DRZ, outdoor radiation levels are hazardous and most individuals will lack adequate initial shelter. A shelter transit strategy will provide most individuals adequate protection.

THERE IS NOT ENOUGH ADEQUATE SHELTER CAPACITY
In the DRZ, outdoor radiation levels are hazardous and there is not enough adequate shelter. Individuals in this region should be prioritized for evacuation.

Product Type 2: Evacuation Prioritization

Sheltering is implicitly a short-term strategy. Initial sheltering is followed by a staged, facilitated evacuation for individuals in hazardous areas. Ideally emergency manager recommendations for evacuation prioritization and timing will reflect the overall goal of minimizing the number of people in immediately life-threatening situations, particularly early in the response.

The second product type are maps showing evacuation regions, suggested evacuation routes, and associated start times. Optionally, subpopulations within a region could be targeted for early evacuation. For example, it may be feasible to evacuate people in poor quality shelters while allowing those in adequate shelters to remain. Region identification and associated evacuation times would be based on the following prioritization.

1. **Individuals in immediately life-threatening situations are the highest evacuation priority**.

   The default inclusion criteria varies by hazard.

   RADIATION: Individuals in the DRZ who lack adequate shelter nearby (within 15 min travel).

   THERMAL (BURNS): Individuals in locations that are likely to be burned in the near future.

   WEATHER EXPSOURE: Unsheltered individuals at risk for exposure during adverse weather. People in hot, closed-up buildings may also be at risk.

   MEDICAL INJURY: Individuals with life-threatening, but treatable injuries, including those caused by the nuclear detonation. Most of these people will be in the MDZ.

2. **When there is available evacuation capacity, adequately sheltered individuals in the DRZ not facing a life-threatening hazard are the next priority**.

   These individuals should be prioritized for evacuation on, or after, their optimal shelter time. After the fallout has deposited, radiation exposures can be minimized by starting the evacuation from the DRZ at the optimal time. This time depends on the radiation dose rate inside the shelter and the dose incurred during evacuation [1]. These individuals should only evacuate after (a) appropriate evacuation routes have been identified and cleared and (b) there is at least basic information on the fallout distribution and radiation dose rates.

$$\begin{matrix} \text{Optimal Time to Start Evacuation} \\ (\text{from the nuclear detonation}) \end{matrix} \approx 1.2\ x\ \frac{\text{Evacuation Radiation Dose}}{\text{Sheltered Radiation Dose Rate}}$$

3. **Uninjured individuals outside of the DRZ are a low priority for evacuation**, particularly if they access to even minimally protective shelter, e.g., single-family homes.

   This category may include people with radiation exposures above the US Environmental Protection Agency Protection Action Guidelines (EPA PAG), which are primarily designed to minimize long-term cancer risk.

Product Type 3: Population Maps

Early response actions focus on minimizing the number of people in immediately life-threatening situations. As such, it is helpful to understand how many people are located where as well as key demographic information.

Initial population maps can be generated pre-event. Note that population density naturally varies spatially (e.g., high-density urban cores vs. low-density rural areas) and temporally (e.g., workday vs. night). To the extent that they are credible, updated (real-time) population maps will be helpful as self- and officially sanctioned evacuation will modify the normal regional population distribution.

The third product type are maps showing the following population-based information.

TOTAL POPULATION

Knowledge of the population distribution allows response officials to better target response activities and timing, particularly when combined with hazard maps and response capacity estimates. Real-time population estimates allow emergency managers to actively monitor the evacuation route load.

HIGH RISK POPULATIONS

Understanding the distribution of people in life-threatening situations (high risk populations) allows for the more efficient use of scarce resources. This map helps prioritize regions for evacuations and other response activities. In addition, high-risk population distributions inform post-evacuation medical resource requirements, either at official sites or general home regions. The latter point is particularly important for self-evacuating populations as some injury types have delayed onset and so may present only after evacuation is complete. These delayed onset injuries may place an unexpected burden on outlying medical centers.

EVACUATION “READY” POPULATIONS

A population-based variant of the evacuation prioritization maps will include both the high-risk populations described above as well as lower priority individuals for which evacuation orders have been issued.

VULNERABLE AND SPECIAL POPULATIONS

Vulnerable populations are individuals at a higher risk for poor health even under normal conditions. This elevated risk is often due to social, economic, and limited political and environmental resources as well as existing illness or disability. As such, this population may be more at risk than the general population to the hazards posed by a nuclear detonation.

Knowledge of special population hotspots, such children at schools, facilitates shelter and evacuation prioritization as well as awareness of ancillary impacts. For example, many parents may travel to school areas to collect their children.

Input Requirements

The following information is needed to develop these products.

To facilitate a rapid development strategy, we specify here the minimum set of information for radiation hazards. Later use of additional information, such as fire danger zones, will extend this work to other hazards and considerations. For a broader discussion, see *Appendix C: Situational Awareness*.

HAZARDS

We require the outdoor radiation dose rate time series in the analysis area. We anticipate that this will be provided by dispersion model output. Alternately, the Dangerous Radiation Zone (DRZ) could be used, but the optimal evacuation time would not be available.

POPULATION

We require the location and number of people in the analysis area. We anticipate the use of the Oak Ridge National Laboratory LandScan™ US population which provides regional workday and nighttime population estimates. Optionally, the US Census provides demographic information potentially suitable for vulnerable population assessments.

INFRASTRUCTURE

We require the *distribution* of US fallout building protection in the analysis area. We anticipate the use of the Regional Shelter Analysis method [2]. This method combines the recently developed US building protection estimates [3] with the US Emergency Management Agency (FEMA) HAZUS building databases.

We require the community preferred evacuation routes, nighttime and rush-hour capacities, as well as evacuation centers. We anticipate that this information will come from the community itself.

References

[1] M. B. Dillon, “Determining optimal fallout shelter times following a nuclear detonation,” *Proc. R. Soc. Math. Phys. Eng. Sci.*, vol. 470, no. 2163, pp. 20130693–20130693, Jan. 2014, doi: 10.1098/rspa.2013.0693.

[2] M. B. Dillon, “Regional Shelter Analysis - External Gamma Radiation Exposure Methodology,” Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-788418, Aug. 2019. [Online]. Available: https://doi.org/10.2172/1825367

[3] M. B. Dillon and C. Schwefler, “US Fallout Shelter,” Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-832679, Mar. 2022.

[4] National Security Staff Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats, “Planning Guidance for Response to a Nuclear Detonation, 2nd Edition,” Executive Office of the President, Washington DC, Jun. 2010. [Online]. Available: https://remm.hhs.gov/PlanningGuidanceNuclearDetonation.pdf

[5] M. B. Dillon, R. G. Sextro, and W. W. Delp, “Protecting building occupants against the inhalation of outdoor-origin aerosols,” *Atmos. Environ.*, vol. 268, p. 118773, Jan. 2022, doi: 10.1016/j.atmosenv.2021.118773.

[6] M. B. Dillon and R. G. Sextro, “Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures,” Lawrence Livermore National Laboratory, Livermore, CA, LLNL-TR-771864, Apr. 2019. [Online]. Available: https://doi.org/10.2172/1569185

[7] M. K. Lindell, P. M. Murray-Tuite, M. K. Lindell, P. B. Wolshon, and E. J. Baker, *Large-scale evacuation: the analysis, modeling, and management of emergency relocation from hazardous areas*. New York: Routledge, Taylor & Francis Group, 2019.

[8] W. Luke, S. Divarco, P. Schulze, and R. Gougelet, “Guidelines for Mass Casualty Decontamination During an HAZMAT/Weapon of Mass Destruction Incident: Volumes I and II,” Edgewood Research, Development, and Engineering Center, Aberdeen Proving Ground, MD, ECBC-SP-036, Aug. 2013. [Online]. Available: https://asprtracie.hhs.gov/technical-resources/resource/1807/guidelines-for-mass-casualty-decontamination-during-a-hazmat-weapon-of-mass-destruction-incident-volumes-i-and-ii

[9] S. M. Cibulsky, M. A. Kirk, J. S. Ignacio, A. D. Leary, and M. D. Schwartz, “Patient Decontamination in a Mass Chemical Exposure Incident: National Planning Guidance for Communities,” US Department of Homeland Security and US Department of Health and Human Services, Washington DC, Dec. 2014. [Online]. Available: https://www.dhs.gov/publication/mass-decontamination-guidance

Appendix A: Response Zone Overview

US national guidance identifies five key response zones, each with distinct hazards, to help organize and prioritize response activities. These zones are discussed in the US *Planning Guidance for Response to a Nuclear Detonation* [4] and briefly summarized here. The location and size of each zone depends on scenario details including, but not limited to, the detonation yield and height.

Blast damage from the nuclear detonation decreases with distance from ground zero. **The three damage zones are defined by blast damage** and can be determined by visual observations.

SEVERE DAMAGE ZONE (SDZ)

Almost no building will remain standing. Debris will make the streets impassable in urban areas. Very few people are expected to survive. Those who do survive will primarily be located within large, underground structures, such as subway tunnels or underground parking garages. Due to the likely presence of hazardous outdoor radiation levels, any survivors should shelter (if safe to do so) for the first 72 hours.

The SDZ is not a priority for early response activities.

MODERATE DAMAGE ZONE (MDZ)

Substantial building damage will be present. Sturdy buildings (reinforced concrete structures) will be damaged but will remain standing. Most wood-frame homes will be destroyed. Other likely damage includes blown down utility lines and telephone/streetlight poles as well as overturned automobiles. Fires may start, from either blast damage or detonation heat, and subsequently spread due to readily available fuel such as broken gas lines and wood. It will initially be difficult to travel along roadways due the presence of debris and damaged vehicles. Street clearing may be required. Surviving individuals will benefit from prompt medical care.

The MDZ is a priority for early response activities.

LIGHT DAMAGE ZONE (MDZ)

Most buildings will remain standing, although windows will break with enough force to cause serious injuries. Most injuries will not be life-threatening. Fires started in the MDZ may spread to the LDZ (and beyond). Vehicle accidents may block access and evacuation routes.

The LDZ is a lower priority than the MDZ for early response activities, except where fire danger or dangerous levels of outdoor radiation exist, see the *Dangerous Radiation Zone* below.

Residual radiation may pose a life-threatening hazard for hours to days after the detonation. **Outdoor radiation levels determine the degree of hazard and defines the two radiation zones.** These zones vary with time, partially overlap the three blast damage zones, and may have an irregular shape, including hotspots, due to weather and terrain.

DANGEROUS RADIATION ZONE (DRZ)

Outdoor radiation levels, > 10 R / h, can be life-threatening if people are exposed to them for a long time. This zone can grow during the first few hours as radioactive airborne particles "fall out" of the mushroom cloud. Later, radioactive decay causes the zone to shrink in size. Adequate shelter (see *Appendix B: Early Response Strategy*) can reduce radiation exposures enough to prevent acute (short term) radiation injury.

The DRZ is a priority for early response activities, although any in-person responder activity should be avoided unless (a) undertaking critical, planned protective actions for large populations and (b) responders are fully informed of the risks.

HOT ZONE (HZ)

Outdoor radiation levels, 0.01 R / h to 10 R / h, will not result in immediately life-threatening injuries, but radiation exposures will increase long-term risks such as cancer. This zone will grow over the first day and then shrink.

The HZ is a lower priority than the DRZ for early response activities.

Appendix B: Early Response Strategy

The early (<72 h) response activities described here will take place within the context of limited resources and mobility.

Immediately after a nuclear detonation, the number of people requiring assistance will greatly exceed available response capacity. Early, on-scene emergency response activities will primarily be performed by local and State agencies, particularly if there was no warning (some remote Federal assistance, such as modeling and public messaging, will be available almost immediately). Furthermore, the regional capabilities and capacities may be limited even relative to normal, smaller-scale responses. As one example, an ambulance cannot simultaneously (a) transport severely injured patients to a hospital and (b) free up hospital beds for new patients by transporting current patients to outlying medical centers. In addition, mutual aid may provide less, and less timely, capability and capacity than normal due to widespread, multiple jurisdictional impacts (the resources may be needed in the local jurisdiction); limited regional transportation capacity (difficulty arriving due to accidents and evacuating populations); and communication issues (difficulty requesting and coordinating assistance).

Regional mobility will be greatly reduced relative to normal events. Many of the nuclear effects reduce transportation capabilities and capacities. Roadways will be blocked by debris and disabled vehicles. Large regions may be unsafe to traverse due to radiation, fire, or others hazards. Loss of power can disable traffic management systems, such as messaging signs and traffic lights. Unusual traffic patterns may arise, including parents attempting to reunite with their children and large-scale self-evacuation. Finally, mass evacuation events can place demands on the local transportation infrastructure that exceed their design capacity. We note that while entry to affected areas may be challenging, some responders will already be present in the affected areas, especially for a no-notice event. After ensuring their own safety, it would be helpful for embedded responders to perform life-saving activities and develop situational awareness to facilitate a coordinated and rapid response.

Given the resource and mobility limitations, **early response actions may need to focus on minimizing the number of people in immediately life-threatening situations.** Per the US guidance, priority should be given to immediate, rather than longer term, concerns when faced with competing hazards. As a practical example, people in the DRZ should leave a burning building. The risk of delayed health effects due to radiation exposure is lower than the risk of immediate death due to the fire. Only when there is sufficient situational awareness and available evacuation capacity should adequately sheltered individuals in the DRZ not facing a life-threatening hazard be evacuated, see *Mass Evacuation* below.

Initial Shelter (Get Inside, Stay Inside, Stay Tuned)

Per the US planning guidance, **sheltering is the best default action to take immediately before or following a nuclear explosion.**

In the first minute after the detonation, being outdoors may result in severe burns, lacerations, bone fractures, and/or radiation injuries. The risk of these injuries (and death) increases with proximity to ground zero. Within hours, lethal radiation levels may be present in areas 10s of miles from ground zero, even when fallout is not apparent.

Sheltering can protect people from the following hazards.

RADIATION
Increasing protection comes with increased distance and amount of dense materials (e.g., concrete, brick, or earth) between the individual and the radiation source (e.g., fallout). In general, the best protection is underground (e.g., basements, subway tunnels, underground parking garages) or in the center of a large, heavy building. Adequate protection, which reduces fallout radiation exposure by a factor of 10 or more, protects against acute radiation injury in DRZ locations where buildings are still standing.

We have recently assessed the shelter quality of US buildings [3]. Most people in non-residential US buildings can find adequate shelter within their building. US residences are less protective but are better than being outside. US single-family homes, particularly wood/steel frame houses, do not usually provide adequate protection above ground (basements provide adequate shelter). Thick-walled (not veneer) masonry buildings generally provide adequate protection. Cars and other vehicles are poor shelters.

BLAST
Given warning, going inside a sturdy structure, such as a reinforced concrete building, may protect individuals against blast effects. Lightly constructed buildings, such as wood-frame houses, are more easily destroyed - injuring or killing their occupants. The best protection is well away from windows and other buildings openings, which may break and cause injury. Depending on the distance from ground zero, the blast wave may take seconds to minutes to reach a building.

THERMAL (BURNS)
Given warning, going inside will shield individuals from the thermal pulse, which can cause serious burns. The best protection is well away from windows and other buildings openings.

DUST AND SMOKE

Being inside will reduce exposure to dust and smoke [5], [6]. For the best protection, close windows and doors to reduce the amount of outdoor air being drawn into the building. Make sure to maintain enough ventilation to ensure adequate indoor air quality.

WEATHER EXPOSURE

The natural environment may present a life-threatening hazard. Due to the wide-spread building and infrastructure damage, individuals in the MDZ (and to a lesser extent the LDZ) may be at risk of exposure if adverse weather condition(s) are present including extreme temperatures, snow, high winds, and/or heavy rain. People in hot, closed-up buildings may also be at risk.

Sheltering also reduces population movement, which reduces the strain on the transportation infrastructure. This allows responders to better access the scene as well as facilitate the rapid evacuation of individuals facing immediately life-threatening hazards.

Mitigate Immediately Life-Threatening Situations

After initially sheltering, emergency managers should consider three major response actions to mitigate life-threatening situations. These actions may be taken individually or in combination.

SHELTER TRANSIT

In the DRZ, poor quality shelters do not sufficiently protect against potentially life-threatening radiation injury. In regions with abundant adequate shelter, emergency response officials could issue supplemental orders for poorly sheltered individuals to move to adequate shelters when there are no other imminently life-threatening hazards (e.g., fire). The optimal time to stay in the first shelter does not depend on the local radiation levels [1]. When adequate shelters are nearby (within a 15 min travel time), people in less than adequate shelters should transit to them, preferably within the first hour or two after the detonation.

FIRE CONTROL/SUPPRESSION

Fires ignited by the nuclear detonation have the potential to immediately threaten sheltered populations. Fire control and suppression measures are particularly helpful if the current or future burn areas are densely populated and/or difficult to evacuate. In the DRZ, successful use of these measures will allow people to remain (adequately) sheltered for longer periods of time. Outside the DRZ, this allows evacuation capabilities to be more focused on people experiencing medical emergencies, including blast and thermal injuries.

EVACUATION

When life-threatening hazards cannot be mitigated (e.g., lack of adequate shelter in the DRZ, serious injury, impending fire, freezing conditions), emergency response officials should consider evacuation, see *Appendix D: Mass Evacuation*.

Appendix C: Situational Awareness

Information is needed to effectively manage the response to a nuclear detonation and develop these products. Since the aftermath of a nuclear detonation will be a fast-paced, chaotic environment; acquire this information prior to the detonation (to extent reasonable) and update it as credible event-specific information becomes available. During the event itself, expect that each information source will only provide a partial characterization. As such, plan to deconflict multiple information sources and continuously update the situational awareness.

The following information is needed to develop these products. Additional information, such as the status of messaging infrastructure, may be helpful for other planning activities or to implement the discussed response strategies.

HAZARDS

The zones described in the *Appendix A: Response Zone Overview* section provide important information for shelter-evacuation decisions. The blast response zones (SDZ, MDZ, and LDZ) may be determined through imagery and local reports. The radiation response zones (DRZ and HZ) may be determined through radiation monitoring data and modeling. Plume models estimate current and future hazard regions; however their initial accuracy will be limited. Model predictions will improve over time as measurement data become incorporated into the model analysis. Visual observations of the fallout cloud, its downwind drift, and deposited fallout particles is also helpful. Fallout particles may not be noticeable on rough or dirty surfaces, so their absence does not mean no radiation hazard exists. Note that rain may cause a DRZ or HZ hotspot well downwind.

Fires may be ignited from the thermal pulse and blast damage, particularly in the MDZ, and subsequently spread to the LDZ and beyond. Fires may warrant the early evacuation of potentially impacted areas. Look for signs of coalescence, in which smaller fires combine into a larger front, and firestorms, where fires develop their own weather pattern.

Medical emergencies, including those caused by the nuclear detonation, may be life-threatening. Most people with treatable, life-threatening injuries will be located in the MDZ, however seriously injured people may not be evenly distributed throughout the zone. For example, injuries will differ for occupants in single-family homes (many of which will collapse) and for those in sturdy buildings (which will remain standing).

The natural environment may also present a life-threatening hazard, particularly in areas with wide-spread building and infrastructure damage. Unsheltered individuals may be at risk of exposure if there is adverse weather such as extreme temperatures, snow, high winds, and/or heavy rain.

POPULATION

The location and number of people are some of the most important pieces of information needed to manage the event. Due to workday migration patterns, population estimates for various times of day as well as days of week are particularly informative. Knowledge of the distribution of people among different building types is also helpful as it facilitates identifying those in life-threatening situations. Note that population density varies with building type, with suburban tracts containing many low-density, single-family homes while some commercial tracts contain high density, sturdy structures. Finally, identify school, childcare, and other special and vulnerable populations.

INFRASTRUCTURE

Infrastructure plays a critical role in minimizing the loss of life after a nuclear detonation.

Regional Shelter Analysis: Shelter is a vital early response strategy. Particularly within the DRZ, knowledge of the amount and location of adequate shelter, as well as which buildings lack adequate shelter, is critical for minimizing life-threatening radiation exposures. This information can be generated prior to the event based on knowledge of US building protection, local building construction, and the Regional Shelter Analysis method [2].

Evacuation infrastructure: Evacuation will be necessary to save lives in significantly impacted areas, particularly the MDZ and DRZ. It may also be necessary for other regions. Knowledge of access (road location, capacity, and condition), local law enforcement (police, traffic) stations, and power availability (needed for facilitating traffic flow) is helpful.

Appendix D: Mass Evacuation

Evacuation is the process of people moving from a hazardous to a safe location.

A broad array of evacuation options will be needed to manage the hazards caused by a nuclear detonation. On a local scale, people will need to evacuate burning or structurally unsound buildings. While these evacuations are important, State and local agencies are likely already familiar with them. In contrast, these agencies may require assistance in rapidly evacuating large numbers of people over significant distances, particularly when given little to no notice. This section briefly discusses select mass evacuation considerations to provide context for the mass shelter-evacuation support products discussed in this report. This is not a comprehensive discussion and interested readers should consult prior studies of mass evacuation, such as *Lindell et al.* [7].

The ability, and time required, to evacuate a region depends on both evacuation capacity and demand. In an ideal situation, evacuation demand is kept below the available capacity and evacuating populations are prioritized, see the *Product Type 2: Evacuation Prioritization* above. Actions taken by the evacuating population, emergency managers, and responders can change both evacuation capacity and demand. While this complicates evacuation planning and management, it also provides opportunities to optimize the evacuation. These considerations are briefly discussed here.

DEMAND

Demand refers to how many people (or vehicles) per hour are evacuating.

Demand can be reduced by the following means:

Minimize the number of people in life-threatening situations

Individuals facing immediately life-threatening situations are the highest evacuation priority. Efforts that reduce this population also reduces evacuation demand. These efforts can include shelter transit (moving to better nearby shelter to protect against fallout radiation and adverse weather), firefighting, and in-situ medical support.

Reducing the number of evacuating vehicles

Minimizing the number of vehicles on the road reduces the demand placed on evacuation routes. Emergency managers can request that families only use a single vehicle while evacuating. Carpooling, either informally or coordinated at a safe, accessible location is another option. Similarly mass transit - such as buses, boats, and trains - can move larger number of individuals.

Load balancing

Regional evacuation can have more than one evacuation route. Emergency managers can reduce the demand on an overtaxed route by directing some individuals to less impacted routes.

Emergency managers will likely have only limited control over demand as some individuals will evacuate, even if they are not advised to do so. In the context of a nuclear detonation, self-evacuation is discouraged due to the risks involved and the increased load on transportation infrastructure (reducing available evacuation capacity and responder access). Self-evacuation may occur spontaneously or may be triggered by response guidance. The latter case, also called shadow evacuation, can result in self-evacuating populations up to a factor of 10x larger than the target population (well managed evacuations can have a 20% self-evacuation population) [7]. Examples of self-evacuating populations include individuals both in the targeted region (e.g., after emergency managers direct poorly sheltered individuals in the DRZ to evacuate, some adequately sheltered people also evacuate) and adjacent regions (e.g., some people in the LDZ may self-evacuate when the MDZ is evacuated). Guidance provided to those who choose to self-evacuate may reduce their exposures to hazards and reduce their impact on evacuation capacity.

CAPACITY

Evacuation capacity refers to how many people (or vehicles) per hour can travel the available evacuation route(s).

Nuclear detonation hazards can significantly decrease the evacuation route availability and capacity. Disabled vehicles and debris can block roads and railways. Power loss can disable traffic lights, messaging systems, and mass-transit systems (e.g., subways). Furthermore, pre-established evacuation routes may go through regions too hazardous to travel due to fallout radiation or fire.

When it is safe to do so, evacuation capacity can be increased by the following means:

Increase roadway capacity

Roadway capacity can be increased by (a) facilitating traffic flow, (b) reducing background (non-evacuation) traffic, and (c) increasing the number of evacuation route(s) available.

Traffic flow can be improved by performing roadway clearance activities (including removing disabled vehicles), managing choke points (e.g., actively directing traffic at key intersections), and targeted infrastructure restoration (e.g., restoring traffic signals and metering lights). Where traffic signals are functioning, the choice of signal timing can affect travel time and so capacity. The best choice depends on the local area, but common options are rush-hour and long-green timings to prevent gridlock by allowing enough cross-traffic movement.

Reducing background traffic frees up existing capacity for evacuation purposes. Mass sheltering will inherently provide some reduction; however, a nuclear detonation has the potential to cause unusual non-evacuation traffic, such as parents picking up their children.

Parallel routes may be appropriate for mass transit options (e.g., organized bus evacuation of mobility-impaired individuals) or for responder access. These routes could also be used to relieve congestion on main evacuation roadways, but this option requires the ability to communicate with evacuees.

Increase roadway capacity (con'd)

Freeways play an important role in mass evacuation since evacuees will often select routes that are most familiar to them. There are a series of measures that can improve freeway capacity, but implementation can be challenging and so is best done in coordination with the appropriate regional transportation authorities. Such measures include contraflow (where most or all lanes are dedicated to evacuating traffic), using paved highway shoulders, strategically closing on- and off- ramps outside the evacuation zones (to minimizing highway backups), and route segment closure (to limit traffic to routes with limited capacity).

Supplement with other evacuation options
Emergency managers could supplement roadway evacuation with less traditional options. Boats may be helpful in regions with ready access to waterways. Similarly, railways may also be an option if tracks can be cleared.

Reduce evacuation hazards
Hazard reduction (e.g., decontamination and shielding for radiation; firefighting for fire) can open up new evacuation routes. Note that reducing the radiation dose along an evacuation may decrease the recommended time to stay sheltered.

Appendix E: Decontamination

Field (gross, hasty) decontamination serves two purposes: to stop (or reduce) ongoing exposure to affected individuals and prevent (or reduce) responder and facility contamination. After a nuclear detonation, the **radioactive contamination of individuals is not expected to be an immediately life-threatening hazard**. However, decontamination can reduce overall radiation exposures and so should be performed where it can be reasonably accommodated.

Use the fastest decontamination approach that causes the least harm and does the most good for the majority of people.

> Ideally, outdoor individuals will initially decontaminate themselves by periodically brushing fallout off clothes, skin, and hair.
>
> Responder decontamination of contaminated individuals can be relatively slow and require resources that are also needed for life-saving activities. For example, a Ladder Pipe Decontamination system, a common mass decontamination system, diverts resources from fire-fighting activities (ladder trucks, fire-fighting personal, and water). Dry decontamination techniques may be more practical, including directing individuals to remove outer clothing layers, brush off deposited material, or (more comprehensively) disrobe and rub with an absorbent material (towel) from head to toe. Be aware that decontaminating numerous individuals may result in a radioactive hotspot and so responders may want to decontaminate individuals outside or well-away from populated rooms. While primarily intended for chemical hazards, planners, emergency managers, and responders may find the following references helpful: *Luke et al.* [8], *Cibulsky et al.* [9], and the Primary Response Incident Scene Management (PRISM) method at https://www.medicalcountermeasures.gov/barda/cbrn/prism/ .