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Analysis of Sheltering and Evacuation Strategies for a National Capital Region Nuclear Detonation Scenario

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Abstract

Development of an effective strategy for shelter and evacuation is among the most important planning tasks in preparation for response to a low yield, nuclear detonation in an urban area. Extensive studies have been performed and guidance published that highlight the key principles for saving lives following such an event. However, region-specific data are important in the planning process as well. This study examines some of the unique regional factors that impact planning for a 10 kT detonation in the National Capital Region. The work utilizes a single scenario to examine regional impacts as well as the shelter-evacuate decision alternatives at one exemplary point. For most Washington, DC neighborhoods, the excellent assessed shelter quality available make shelter-in-place or selective transit to a nearby shelter a compelling post-detonation strategy.

Acknowledgements

The authors gratefully acknowledge the insights and support of Brooke Buddemeier, Michael Dillon, and Joshua Valentine of Lawrence Livermore National Laboratory in this study. The LLNL-generated plume data and regional shelter quality assessments provided key inputs underlying many of the primary conclusions of this study.

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Executive Summary

Execution of an appropriate sheltering and evacuation strategy following the detonation of a terrorist Improvised Nuclear Device (IND) in an urban area can save thousands of lives. These strategies can reduce the dose that many receive from the fallout radiation following the detonation, thereby minimizing the incidence of acute radiation sickness. Some of the best strategies can be implemented even in the confusion and disrupted communication environment that will likely follow such an event. However, prior planning and education of both response personnel and the affected population is necessary. Science-based information and federal guidance that supports planning for an urban IND event has become increasingly available in recent years. However, analyses that consider the key factors that are unique to specific urban areas are also important inputs to the planning process.

Evaluations of alternative shelter-evacuate strategies following a 10 kT detonation in the National Capital Region have been completed. A range of strategies that include shelter-in-place, shelter transit, uninformed evacuation, and informed evacuation are included. In addition, a strategy that employs major official evacuation routes is evaluated. The prior planning and post-detonation requirements differ for each strategy. Each strategy is evaluated based on the total number of people in the region who are exposed to fallout radiation doses that would result in injury or death due to high total radiation doses.

The following are the principal findings of the analyses:

- The recommendations of prior federal guidance were again confirmed in these analyses. These include shelter-in-place when adequate shelter (protection factor >10) is available, and early shelter transit or evacuation from inadequate shelter.
- Outside exposure should be avoided during the first few hours following the detonation when the radiation hazards in the high dose rate zones are the highest. The only exception is for those in very poor shelter who should take the fastest path to better shelter or out of the hazardous fallout region.
- The radiation protection capabilities of many structures in the Washington, DC are quite good. If all residents in the hazardous fallout region adopt a shelter-in-place strategy, the total number acute radiation casualties is estimated to be ~3000, as compared to ~130,000 casualties if all are outdoors and unsheltered. Some further reductions in casualties can be realized if those in the poorest shelters transit to better shelters soon after the detonation.

The modeling and visualization tools developed for the analysis of shelter-evacuate strategies can be useful in informing the planning and training efforts of responders preparing for nuclear events. A set of regional analyses, as well as the examination of specific exemplary points, highlight the issues and tradeoffs that should be considered in the shelter-evacuate planning process.

Analysis of Sheltering and Evacuation Strategies for a National Capital Region Nuclear Detonation Scenario

1. Introduction and Background

1.1. The Need for IND Response Planning

The prospect of the detonation of a low yield Improvised Nuclear Device (IND) in a U.S. urban area is a growing national security concern. While many U.S. government and international programs are seeking to prevent such an event, past studies have indicated that an informed response in the first 72 hours following the detonation could significantly reduce casualty levels.¹ Early sheltering and evacuation actions of populations within or near the hazardous fallout regions caused by the detonation are particularly important determinants of the level of casualties associated with such events. Both sheltering inside structures and evacuation away from the fallout hazard zone can reduce total radiation exposure. The best strategy for any individual depends critically upon the nature of the fallout plume, the quality of immediately available shelter, and the ability to execute effective evacuation away from the most hazardous zones.²

The effectiveness of various sheltering and evacuation strategies is impacted by several key characteristics of the region under attack. Urban regions within the U.S. have widely different predominant building construction types, resulting in different sheltering effectiveness to fallout radiation. Physical constraints to evacuation will also depend on the target region, and will affect the relative effectiveness of evacuation options. The detonation location and weather conditions are also very important determinants of the casualties associated with a specific event. Hence, it is important to examine regional data in the assessment of the likely impact of alternative sheltering and evacuation strategies.

The work documented in this report examines a 10 kT nuclear detonation scenario in Washington, DC. The primary objective of this study is to review the effectiveness of various shelter and evacuation response strategies in reducing the numbers of individuals that receive high radiation doses due to exposure within hazardous fallout regions. This work incorporates high resolution

¹ Background and top level insights drawn from work focused on a Los Angeles scenario are highlighted in: Broad, William J., “New Advice On The Unthinkable: How To Survive A Nuclear Bomb,” The New York Times, December 16, 2010; and Sternberg, Steven, “L.A. Dry Run Shows Urban Nuke Attack 'A Survivable Event'”, USA Today, December 16, 2010. A more technical summary of the opportunities for life saving responses can be found in Buddemeier, Brooke, “Reducing the Consequences of a Nuclear Detonation: Recent Research,” The Bridge – National Academy of Sciences, Volume 40, Number 2, Summer 2010, pp 28-37.

² Comprehensive and coordinated guidance generated by the federal government on IND response issues can be found in “Planning Guidance for Response to a Nuclear Detonation”. 2nd ed. Washington, DC: Homeland Security Council, Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats; May 6, 2010.

data of the shelter quality distribution in the National Capital Region (NCR). A single representative baseline scenario is employed to illustrate the key tradeoffs faced by response planners for such an event.

This report begins with a review of earlier studies in this area, followed by a short summary of the analysis approach and modeling tools. Subsequently, results that address both the regional population dose distributions due to fallout radiation exposure, as well as more focused analyses of a specific exemplary point, are reviewed. Several general strategies representing a range of shelter-evacuate decision alternatives are examined. Sensitivities to various aspects of the implementation (e.g., evacuation timing) are also included.

1.2. Earlier Studies

An extensive set of tools and results based on both experiments and analyses performed during the Cold War provides a scientific basis for understanding the major effects of nuclear detonations. These tools have been applied to terrorist scenarios to estimate both the immediate (or “prompt”) effects as well as the delayed effects due to the longer term exposure to fallout radiation. However, much of the early work focused on damage levels and phenomena, with less emphasis on prescriptive response planning. In recent years, a growing number of analysts and policy makers have begun to address the question of what local medical and first responders should do immediately following an event.³

Since 2007, scientific investigations regarding IND response issues have been supported first by the DHS Office of Health Affairs, and subsequently by the Federal Emergency Management Agency (FEMA). These analyses have been coordinated and dispersed via the Modeling and Analysis Coordination Working Group (MACWG) that has included National Laboratory and private sector participants addressing the key response questions with the support of various DHS and DoD offices. Products of the participants in this working group have supported both individual city planning efforts as well as the development of Federal IND response guidance.

The issues surrounding the shelter-evacuate decision following an IND detonation have been examined by Sandia National Laboratories over the course of the MACWG collaborations that have supported urban and federal planning efforts. Early published results addressed the impact of alternative sheltering policies for a Los Angeles detonation scenario.⁴ A variety of situational assessment and information communication assumptions underlie the postulated shelter-evacuate strategies. “Informed evacuation”, whereby evacuees from the fallout zone evacuate at the optimal time using accurate route information provides an upper bound on the effectiveness of an evacuation strategy. Several other strategies, including evacuation strategies that require less information, as well as shelter-in-place and shelter transit options, were identified and analyzed.

³ An early examination of nuclear response issues (including the DoD perspective) is contained in Brinkerhoff, John R. et al, “Managing the Consequences of a Clandestine Nuclear Attack,” Institute for Defense Analysis, Document D-3170, August 2005, Official Use Only.

⁴ Brandt, L.D. and A.S. Yoshimura, “Analysis of Sheltering and Evacuation Strategies for an Urban Nuclear Detonation Scenario,” Sandia National Laboratories, Report SAND2009-3299, June 2009 discusses the Los Angeles cases. A condensed summary of the core findings of this research is included in Brandt, L.D., “Mitigation of Nuclear Fallout Risks Through Sheltering and Evacuation”, a paper presented at the American Nuclear Society Special Session on Risk Management, Washington, DC, November 18, 2009.

Many of the key results that supported development of the Federal response guidance⁵ evolved from Los Angeles analyses.

This report is the second of a series of studies intended to examine the impact of unique, region-specific features of the major U.S. metropolitan areas on planning for IND response. The first study in this series examined shelter-evacuate issues for the Chicago region.⁶ The results documented here focus on a baseline 10kT National Capital Region scenario. This work also addresses the specific concerns of NCR planners, particularly regarding the use of current official evacuation routes as one possible basis for IND evacuation planning.

1.3. Goals of the National Capital Region (NCR) Analysis

The analyses documented in this report incorporate key data specific to the National Capital Region to provide tailored results in support of regional IND planning activities. In addition, the use of high resolution data on regional shelter quality enables more accurate assessment of overall impacts than are possible using postulated shelter quality assumptions. Specifically, the analyses documented here address the following two goals:

- **Evaluation of the effectiveness of shelter-evacuate strategy options:** Available computational tools and databases allow the estimation of regional casualties expected for various sheltering and evacuation policies. In addition, analysis of specific, exemplary points can highlight the decisions and uncertainties faced by individuals within the hazardous fallout region.
- **Consideration of NCR-specific data and strategies:** Available national response guidance provides a foundation for response planning. However, the data available from region-specific analyses can assist NCR planners in assessing the unique factors that will impact their planning. This includes the specific data on the road network and shelter quality that will impact response planning. In addition, regional planners may have specific requests (e.g., IND evacuations based on established official evacuation routes) that mandate consideration of modified shelter-evacuate strategies.

⁵ See “Planning Guidance for Response to a Nuclear Detonation,” Chapter 3.

⁶ Brandt, L. D. and A. S. Yoshimura, “Analysis of Sheltering and Evacuation Strategies for a Chicago Nuclear Detonation Scenario”, Sandia National Laboratories, SAND2011-6720, September 2011.

2. Technical Approach

2.1. Analytical Framework and Key Assumptions

The two principal elements that have been developed within the analytical framework of this study are:

- **Regional assessment of strategy effectiveness:** The overall regional assessment calculates a distribution of integrated doses received by individuals in the fallout region. The regional assessment requires assignment of a shelter-evacuate strategy to all individuals in the region. This strategy specifies the sheltering characteristics and movement within the hazardous fallout region for every individual who is initially inside the hazardous fallout area. The regional strategy first subdivides the fallout area into zones, and then assigns shelter and evacuation tactics to each zone.
- **Exemplary point analysis of strategy sensitivities:** The exemplary point analyses permit high resolution specification of the shelter quality and evacuation route pursued by individuals at or near single points of interest. These exemplary calculations highlight the factors facing individuals at unique points within the urban area as they consider available information and decide on their actions in the hours following the detonation.

The focus of the analysis is on actions within the first 72 hours that might reduce the population exposure to acute doses of fallout radiation. During this time window, the most severe impacts of fallout radiation will occur. Furthermore, many believe that local responders will be the principal, on-scene participants during this period, prior to the arrival of significant national personnel and equipment.

The metric for evaluation of alternative strategies is the reduction of the expected number of casualties due to acute radiation sickness. These casualties consist of both injuries and death, and are derived from the total integrated dose using probit models with ID50 of 150 rem for casualties, and LD50 of 300 rem for fatalities. Only radiation casualties due to fallout exposures outside of the prompt moderate damage areas are included in the evaluation to avoid excessive double counting of prompt health impacts. Use of acute as compared to latent health effects seems consistent with the expected emphasis on life saving measures immediately following the event.

The analyses here make several important assumptions. These include:

- **Sufficient information for strategy implementation:** The various shelter-evacuate strategies evaluated here require very different levels of information about the fallout hazard area. Some (e.g., shelter-in-place) can be executed with little information. Others (e.g., informed evacuation) presume complete knowledge of the hazardous fallout area. While it is unrealistic to assume such excellent situational assessment and communication in the early minutes following a detonation, these analysis cases remain important to provide upper bounds on the effectiveness of early evacuation options.
- **Full compliance:** It is assumed that all individuals comply with the shelter-evacuation policy under consideration. This supports the normative goals of this analysis in

specifying the preferred behavior. In a real incident, compliance may be much smaller, depending in part on the level of prior education addressing best response actions.

- **Non-vehicular transit:** The most significant sheltering and evacuation actions that impact acute radiation sickness incidence will occur relatively near the moderate damage area of the detonation. Significant debris and other obstructions are likely in this area. Even in the absence of such impediments, traffic issues could cause gridlock. For these reasons, all analyses here presume evacuation or shelter transit on foot, with a speed of three km/hr generally assumed.

2.2. Modeling Shelter-Evacuate Strategy Effectiveness

The primary analysis tool utilized in this study is the NUclear EVacuation Analysis Code (NUEVAC), which was developed to calculate integrated doses resulting from exposure to fallout radiation during shelter and evacuation.⁷ The calculations draw on high resolution scenarios developed for DHS by the Interagency Modeling and Atmospheric Assessment Center (IMAAC) at Lawrence Livermore National Laboratory (LLNL). The baseline scenario used in this analysis is a 10 kT detonation in downtown Washington, DC. The data files from IMAAC specify the fallout dose rate and integrated doses for exposed personnel at selected times following the detonation. These data are specified on a grid centered on the detonation point. High resolution data (100 meter grid points) are included for a 10 km square area. Lower resolution data (500 meter grid points) are included for a 400 km square area. The data included in the scenarios reflect only groundshine sources and not radioactive particulate inhalation. The doses resulting from inhalation have been estimated to be much smaller than those from surface deposition, particularly in the high dose rate regions that are the focus of these studies.⁸ Note that the NUEVAC model does not modify the fallout plume predictions provided through IMAAC. It does, however, provide temporal and spatial interpolation of the data to support the integration of total dose received by sheltering or evacuating personnel.

The NUEVAC software can calculate the population dose distributions for a wide range of prospective shelter-evacuate plans. Several features of the model are illustrated using the simplified example in Figure 1. One set of possible evacuation zones and several evacuation path options are illustrated for a standard Gaussian plume extending downwind beyond the prompt effects region. In this example, six evacuation zones are defined by circular arcs and lines extending outward from the detonation point. The options for movement from any cell within a zone (indicated by the green squares in Figure 1) include:

- Shelter (No movement; protection factor specified)
- Radial movement away from detonation point at specified velocity
- Movement to specified point at specified velocity

⁷ Brandt, L.D. and A.S. Yoshimura, "NUclear Evacuation Analysis Code (NUEVAC): A Tool for Evaluation of Sheltering and Evacuation Responses Following Urban Nuclear Detonations", Sandia National Laboratories, SAND2009-7507, November 2009.

⁸ Raine, Dudley et al, "The Relative Importance of Internal Dose: An Analysis of the Detonation of a Low Yield Improvised Nuclear Device in an Urban Setting", Applied Research Associates, Report ARA-TR-09-SEASSP-17176-010, 9 Jan 2009, For Official Use Only.

- Movement in specified direction at specified velocity
- Movement to a designated line (shortest path)

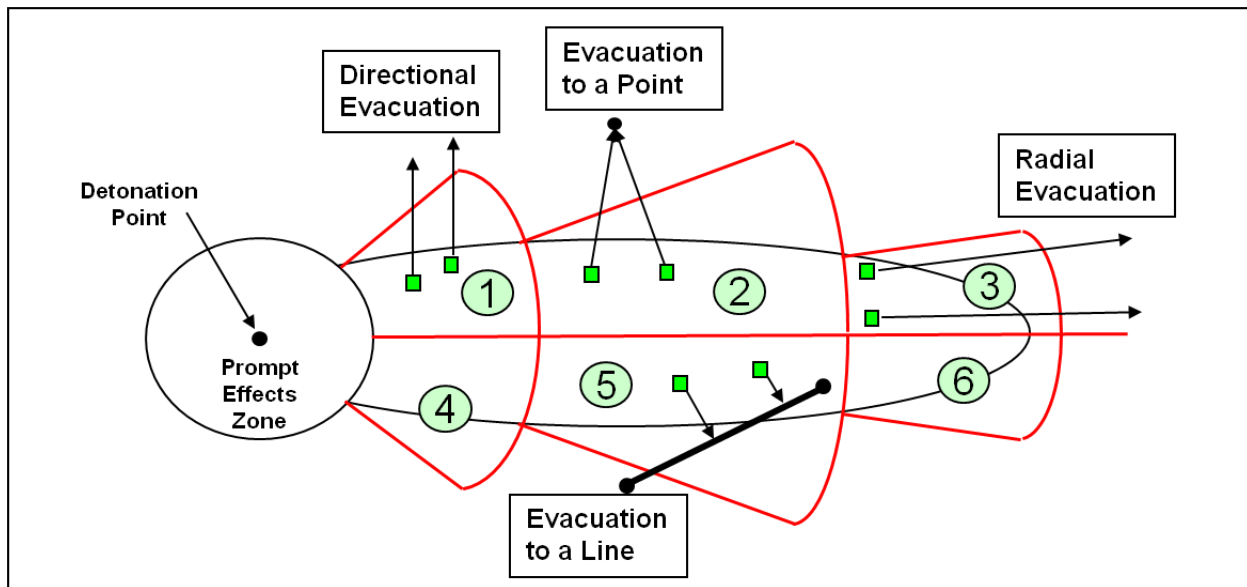


Figure 1. Exemplary evacuation regions and movement options for a typical Gaussian plume

The radial and directional movements can be designated for a specified time interval and distance. Piecewise linking of the movement commands can create a complex evacuation path for members of each evacuation zone. Using this approach, the effects of obstructions, irregular evacuation routes, and choke points can be included in the evacuation plan. Individuals outside of all designated evacuation zones are assumed to shelter-in-place at a prescribed, default shelter protection factor.

The dose rate at any time for any point within the fallout area is calculated by a software routine that fits the high resolution IMAAC data with the power law fallout decay model. This is illustrated in Figure 2. The fitting curve utilizes the standard $t^{-1.2}$ decay assumption for fallout radiation. The fitting algorithm calculates an arrival time for the front of the fallout cloud. Deposition at a point is assumed to occur rapidly following the arrival of the cloud, resulting in a step increase in the dose rate to its maximum value. This abrupt rise is only an approximate representation of the deposition phase of the fallout, but provides for accurate integrated dose calculations at later times (i.e., > 0.5 hours after detonation in high dose rate regions) after the fallout cloud has passed. In addition to modeling temporal decay of the radiation field, NUEVAC also utilizes the spatial variations in dose rates along an evacuation path as provided in the high resolution input data (i.e., 100 meters x 100 meters near the detonation point), supplied in the IMAAC databases.⁹

⁹ More detailed discussion of NUEVAC can be found in “Nuclear Evacuation Analysis Code (NUEVAC): A Tool for Evaluation of Sheltering and Evacuation Responses Following Urban Nuclear Detonations”. However, the current version of NUEVAC incorporates several upgrades (e.g., Svalin-based calculations) not reviewed in that report.

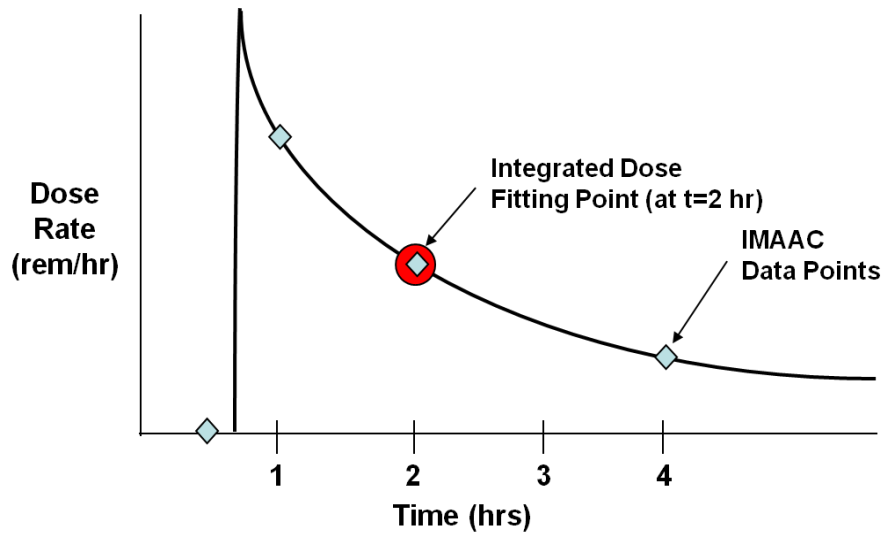


Figure 2. Temporal fitting protocol for IMAAC dose rate data

Evacuation regions within NUEVAC can also be described by arbitrary polygons, permitting broad flexibility in the design of sheltering or evacuation plans. The use of these polygonal regions can accommodate physical barriers to evacuation, neighborhood planning regions, or other planning constraints. An example of evacuation zoning that matches the neighborhood structure in the region most impacted by the NCR scenario is shown in Figure 3.



Figure 3. Illustrative NCR neighborhood zones for evacuation planning

2.3. Regional Shelter Quality

The ability of shelters to attenuate external fallout radiation can vary over a wide range. The quality of shelter is prescribed by a “protection factor” that is equal to the ratio of outside dose rate divided by inside dose rate. In this report, protection factor will be designated by the abbreviation “PF”. Similar to other cities in the eastern half of the U.S., the radiation protection capabilities of buildings in many areas of the NCR are generally quite good. This is due to the large number of multi-story stone, brick, or concrete buildings, many of which have basements. These buildings will usually provide adequate protection (i.e., $PF > 10$). However, there will be cases in which individuals find themselves in less protective structures or in vehicles. For these cases, the analyses here provide sensitivity results down to $PF = 2$. The $PF = 2$ case is a lower bound that applies to some wood frame residential sheltering without basements and is considered inadequate shelter from the response planning perspective. Note that multi-story office buildings and other large facilities such as hospitals can offer options for shelter factors much greater than ten.¹⁰

Recent research within the IND response R&D community has resulted in development of regional shelter quality databases that enable more realistic strategy effectiveness calculations for specific urban areas. These databases (termed “Svalin” data in this report) estimate the distribution of radiation shelter protection factors for each census tract in major U.S. urban areas. The estimates are derived from the building type and structural information contained in the FEMA HAZUS database, combined with radiation transport modeling to determine the attenuation of external sources. The Svalin data for the NCR have been incorporated into the sheltering calculations performed by NUEVAC. Sheltering effectiveness results that incorporate the Svalin data are discussed later in this report.

¹⁰ For more discussion of shelter protection factors of various structures see references in footnotes 1 and 2.

3. NCR Baseline Scenario – Regional Results

3.1. NCR Baseline Scenario and Evacuation Options

Analysis of the regional evacuation options for the NCR was based on a 10 kT detonation assumed to occur in downtown Washington on February 14, 2009. At the time of the detonation, lower winds are generally from the south, causing the central area of the plume, with the highest concentration of radioactive particles, to extend north from the detonation point. However, higher level wind shear is present, resulting in a large plume side lobe, having a lower deposition level, extending to the east. The plume shape at one hour following the detonation is shown in Figure 4.

The analysis of the NCR scenario considers the following shelter-evacuate protocols:

1. **Shelter-in-Place Followed by Early, Informed Evacuation (IE):** Individuals immediately shelter-in-place to minimize exposure to falling radioactive particulate, then evacuate when better situational assessment indicates the hazard zones and safest evacuation directions. Determinants of the optimal initial shelter interval and regrets associated with ill-timed evacuations are key issues addressed primarily in later exemplary point studies.
2. **Extended Shelter-in-Place (S-i-P):** One frequently recommended strategy¹¹ is to shelter-in-place for an extended period (1 to 3 days) following the detonation to allow deposited radioactive material to decay to a safer level, hence reducing the dangers of leaving the region.
3. **Shelter-in-Place with Early Transit to Better Shelter (S-t-S):** Individuals immediately shelter-in-place to avoid direct contamination during fallout deposition, but soon after the detonation transit to more effective, nearby shelters (e.g., subway stations, building basements).
4. **Shelter-dependent Transit or Evacuation (S-d-T):** This is a mixed strategy that assumes that individuals initially in adequate shelters do not move, while those in inadequate shelters transition to better shelter or evacuate the hazardous fallout zone. The regional shelter distribution (Svalin) database is used to calculate the effectiveness of this strategy.
5. **Radial (Uninformed) Evacuation Away from Detonation Location (UE):** Radial evacuation has been used as a surrogate for uninformed evacuation away from the detonation area.
6. **Route-Based Evacuation (RBE):** A new strategy added for the NCR analyses is the use of current official evacuation routes as the basis for evacuation zoning and departure from the area. Details concerning this strategy are reviewed later in this report.

The informed evacuation plan for the NCR scenario is illustrated in Figure 4. The arrows in the figure depict the evacuation direction for arbitrarily selected points in each zone. Occupants of

¹¹ See, for example, Carter, A., May, M., and Perry, W. *The Day After: Action Following a Nuclear Blast in a U.S. City*, *The Washington Quarterly* 30:4, pp. 19-32, Autumn 2007. Similar extended shelter strategies are derived for certain scenarios in Florig, H.K. and B. Fischhoff, "Individuals' Decisions Affecting Radiation Exposure After a Nuclear Explosion," *Health Physics* 92(5): pp. 475-483; 2007.

the zone west of the centerline of the highest intensity plume travel westward away from the highest dose rate zones, then northwest to leave the area. Those between the two plumes travel generally northeast. Those to the south of the less intense easterly plume travel directly south as the shortest path away from the fallout zone. The evacuation paths for these calculations do not attempt to match a specific road network. To compensate for inefficiencies caused by potentially circuitous routing in some areas, a relatively slow average evacuation speed is assumed (nominally 3 km/hr for walking evacuation). The small dot along the evacuation paths in Figure 4 illustrates the position of the evacuee after 30 minutes of travel at the assumed 3 km/hr evacuation speed.

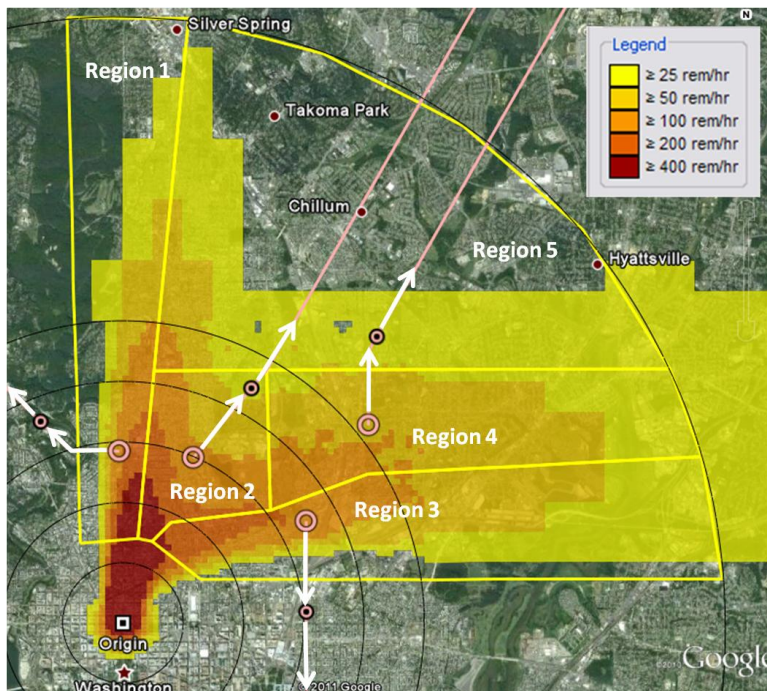


Figure 4. Informed evacuation routes for the NCR baseline 10 kT scenario

3.2. Regional Results – Sensitivities to Shelter Quality

The casualty levels (numbers of injuries and deaths) caused by the baseline NCR scenario for various sheltering and evacuation strategies are shown in Figure 5. These calculations assume that the entire population of the region utilizes shelter at the prescribed shelter factor, and pursues the evacuation strategies indicated. The top bar of the histogram shows that the worst strategy (by far) is the no-shelter (outdoor exposure) case. This action would result in approximately 130 thousand casualties. If only poor shelter ($PF = 2$) is available, shelter in place (S-i-P) is not a good choice. Where information on the plume location is available, early informed evacuation (IE) away from poor shelter and out of the region will reduce casualties. Even radial/uninformed evacuation (UE) will reduce casualties below those resulting from remaining in poor shelter. If the entire population had adequate shelter ($PF = 10$), the total casualty level for S-i-P is reduced to ~8,100. Informed evacuation three hours after the detonation will reduce the casualty level to only ~5,100. Note that casualties are increased if

informed evacuees leave too early (i.e., at 1 hour after detonation) from adequate shelter and transit the radiation field before the highest dose rates have decayed.

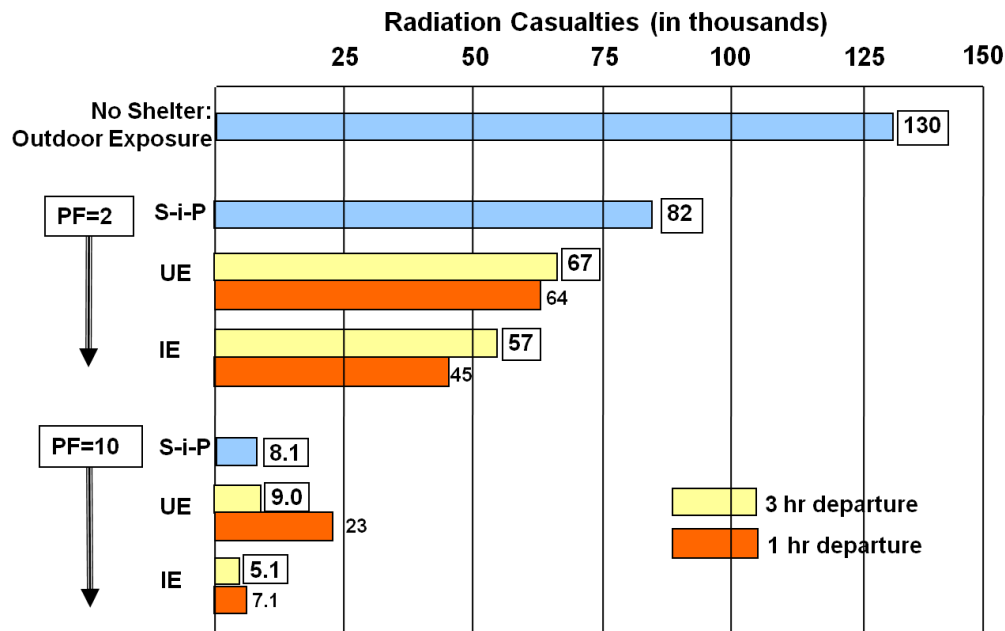


Figure 5. Casualty numbers for alternative shelter-evacuate strategies

3.3. Regional Results for Route-Based Evacuation Strategies

Rather than prescribing arbitrary directions for evacuation routes, populations might use existing official evacuation routes prescribed for other emergencies. In the case of the NCR, a network of arterial streets has been designated for these situations. A reasonable approach to evacuation might be the use of these arterials to define evacuation zones following an IND detonation. Figure 6 shows the set of zones that were established to evaluate the performance of this evacuation concept. The zones were defined within the hazardous fallout region on the basis of proximity to an evacuation route. Note that these zones and routes will not always correspond to the official evacuation path for specific addresses as prescribed by the DC Homeland Security and Emergency Management Agency (e.g., see <http://dcatlas.dcgis.dc.gov/evac/>). However, they represent a reasonable approximation of the routes that residents might follow as they seek the nearest evacuation route to move away from the detonation.



Figure 6. NCR Zoning and Routes for the Route-Based Evacuation (RBE) Strategy

The casualty levels for the Route-Based Evacuation (RBE) strategy are compared to those for Informed Evacuation in Figure 7. The RBE strategy results in considerably higher casualties than the informed evacuation strategy particularly when evacuees depart from adequate ($PF \sim 10$) shelter. From poor shelter ($PF \sim 2$) the results are more ambiguous. Waiting in $PF = 2$ shelters until 3 hours after the detonation for information to inform evacuation would slightly reduce (from 63,000 to 57,000) the number of casualties as compared to RBE at 1 hour. However, this presumes that situation assessment, determination of optimal evacuation paths, and communication to evacuees can occur within three hours. This is a very optimistic assumption. Using more realistic assumptions, RBE from poor shelters at one hour after detonation is likely to be preferred over waiting in anticipation of better evacuation route information. Again, it must be noted that the numbers in Figure 7 are based on the assumption that all shelters in the fallout region have the indicated shelter factor. This is clearly not the case, as will be discussed later in this report. However, this construct serves to illustrate the relative impact of the alternative strategies across the region. Furthermore, as will be shown in the later examination of an exemplary point, use of official emergency evacuation routes can sometimes lead to much worse outcomes than other evacuation choices. Figure 7 highlights the point made earlier, that early departure (e.g., at 1 hour after detonation) from adequate shelter (i.e., $PF > 10$) is worse than staying put while the peak outside radiation dose rate decays.

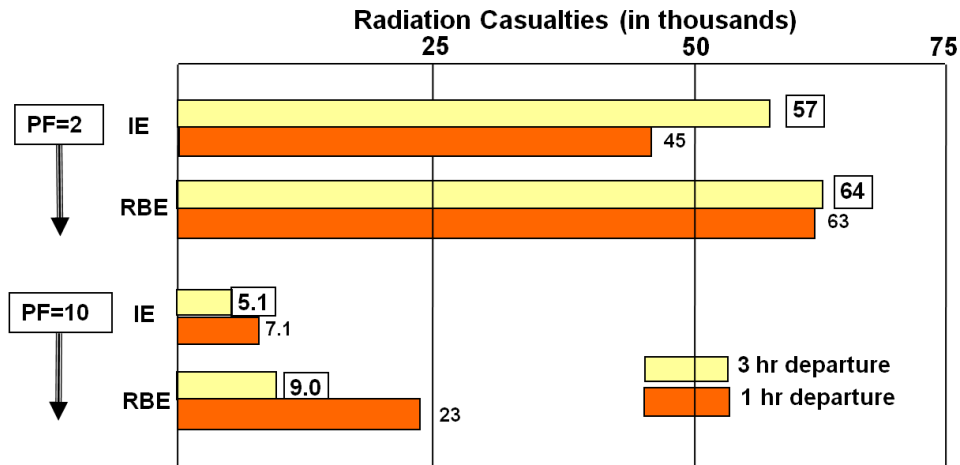


Figure 7. Comparison of Route-Based Evacuation with Informed Evacuation

3.4. Regional Results for Shelter Transit Strategies

For those who find themselves in poor (PF = 2) or inadequate (PF = 4) shelter, transit to better shelter can reduce the number of casualties from the shelter-in-place levels shown in Figure 5 above. Within NUEVAC, shelter-to-shelter (S-t-S) transit is modeled by a short period of outside (PF = 0) exposure following an initial occupancy of the poor shelter, before final occupancy of the adequate shelter. Figure 8 shows the reduction in radiation casualties (as compared to shelter-in-place) from inadequate or poor shelters resulting from shelter transit or route-based evacuation. (Note that a higher number in Figure 8 represents a good outcome – a REDUCTION in injuries and fatalities.) The greatest improvements occur when transiting or evacuating from the worst shelters (PF = 2). Individuals will usually be better off waiting a least an hour after detonation before attempting shelter transit or evacuation. Only those in the poorest shelter (PF ~ 2 or less) with access to nearby adequate shelter should contemplate very early (i.e., < 1 hour) departures.

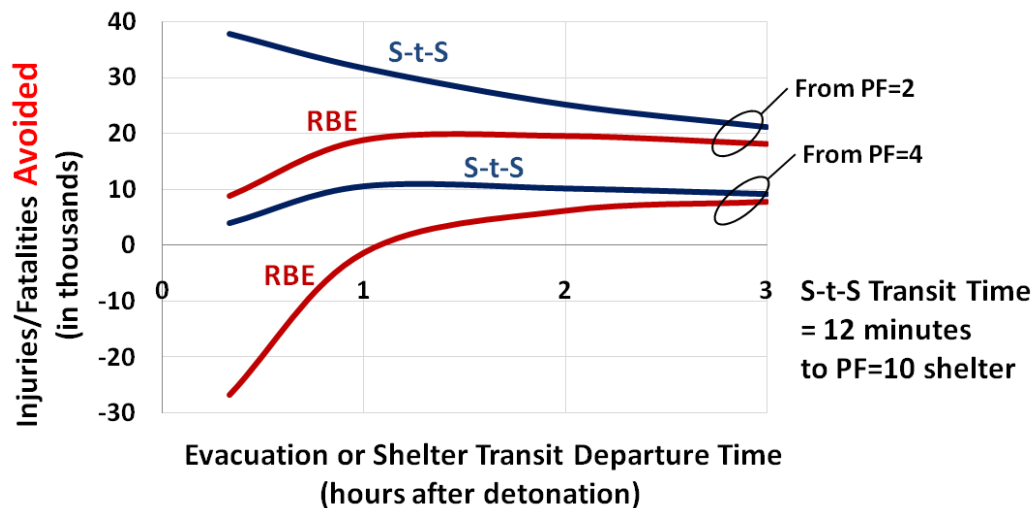


Figure 8. Evacuation time sensitivities from inadequate shelters

When comparing two evacuation strategies, it is often useful to understand the geographical areas in which differences in casualty incidence occur. This information can be displayed in a differential incidence diagram, which shows the change in the probability of becoming a casualty when an alternative shelter-evacuate strategy is implemented. An example is shown in Figure 9. The green shaded areas show the reduction in casualty incidence when occupants of poor shelter (PF = 2) transit to adequate shelter (PF = 10) one hour after detonation. Transit time is assumed to be 12 minutes.

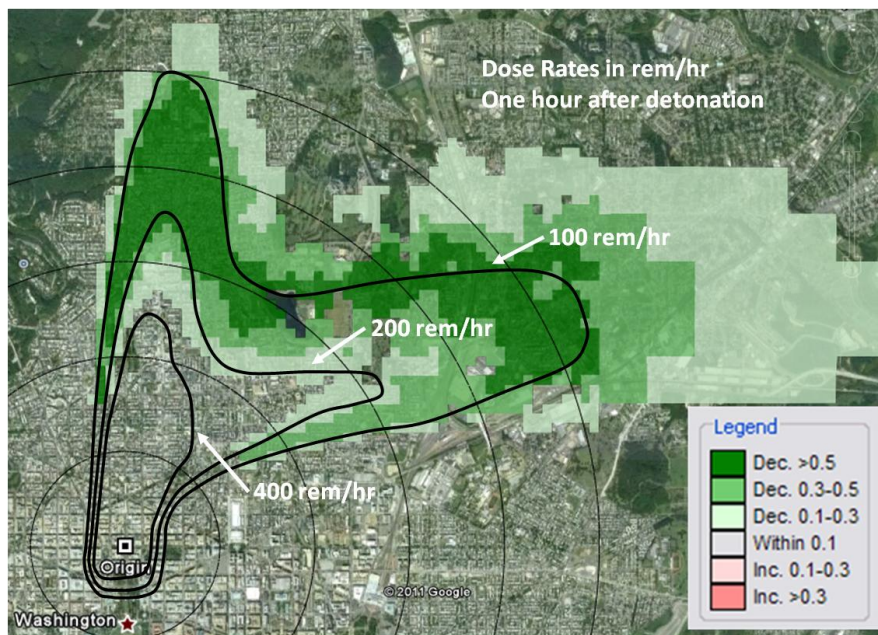


Figure 9. Reduction in casualty incidence due to shelter transit from PF=2 to PF=10

The greatest reduction due to transit from poor to adequate shelter occurs near the edge of the region where the dose rate one hour after detonation is about 100 rem/hr. In higher dose rate regions, the high exposure during transit negates the subsequent benefit of better shelter. The use of this and similar incidence maps can assist planners in understanding the relative spatial impacts of their sheltering and evacuation recommendations.

3.5. Regional Results Using NCR Svalin Data

The use of the Svalin data permits a more realistic calculation of total regional casualties than can be achieved by presuming a nominal regional protection factor, as was done in the last section. The Svalin data seeks to estimate the protection factor of all buildings within an urban area based on analyses that use FEMA HAZUS data. Figure 10 shows two depictions of the Svalin data for the portions of the NCR that are included within the most hazardous portions of the fallout region. The frame on the left shows the transmission factors for the median 20% of buildings, and the frame on the right shows transmission factors for the worst 20%. (Note that the protection factor is the inverse of the transmission factor, that is transmission of 0.25 corresponds to PF = 4, and transmission of 0.1 to PF = 10.) The median protection factor (as shown on the left) is generally well above the adequate level (PF = 10). Even the worst 20% of the areas closer to the detonation point have protection factors of >4 (as shown on the right).

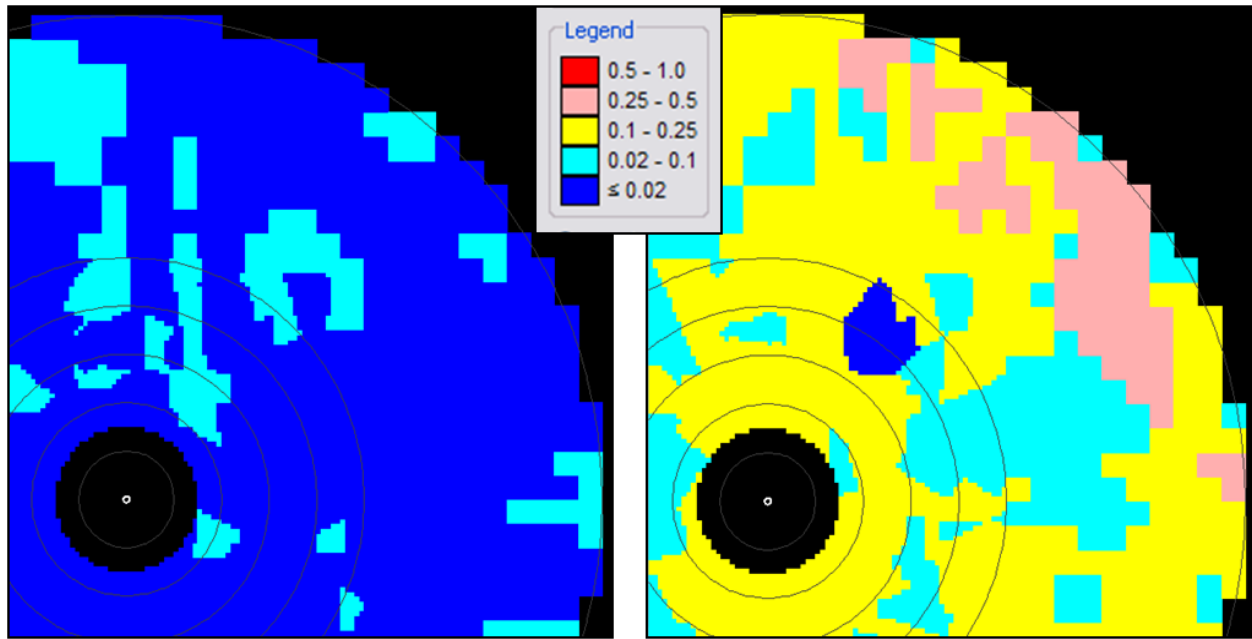


Figure 10. Svalin shelter quality data for the NCR

Shelter-in-Place (S-i-P) Results Using Svalin Data

Total regional casualty estimates for shelter-in-place comparing two fixed shelter factors (PF = 2 and 10) with the regional Svalin data are shown in Figure 11. In Figure 11, the Svalin non-responsive (NR) results assume that individuals remain at the point in the building where they are at detonation time. The Svalin shelter-in-place (S-i-P) results assume that individuals seek the best sheltering area in that building after the detonation. These results show that the shelter quality in the NCR is quite good relative to the threshold adequate shelter level (PF ~ 10). The significance of these results is highlighted by comparison to results in Figure 6. The shelter-in-place results for the NCR indicate that the casualty level drops from ~130,000 individuals if the population is exposed outdoors, to about 2% of that level if all adopt an immediate shelter-in-place strategy at the best location in the building they occupy at the time of the detonation.

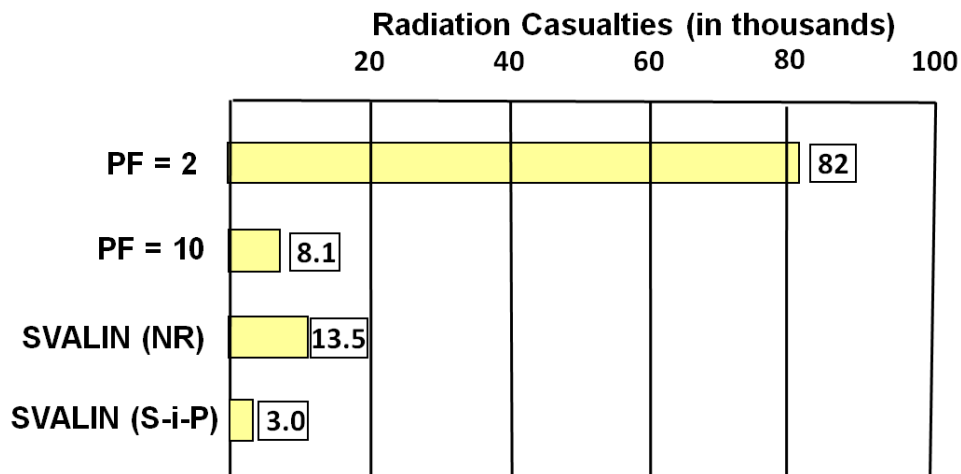


Figure 11. Shelter-in-Place casualties for fixed and Svalin protection factors

It is important to remember that there remains considerable uncertainty both in the actual protective capability of specific buildings, the position of occupants of the building, and the spatial distribution of the fallout particulate in the area. In spite of these limitations, the Svalin data provide the best currently available approach to the assessment of regional shelter quality on shelter-evacuate strategy effectiveness.

Shelter-Dependent Transit Using Svalin Data

The shelter quality distributions for the NCR permit evaluation of a shelter transit strategy in which only individuals in the least protective shelters transit to better shelters or evacuate out of the region. This strategy assumes the following:

1. Individuals in poor shelters know the shelter quality of the building in which they find themselves at the time of detonation, and;
2. They can find their way to better quality shelter in a short period of time

Figure 12 shows the reduction in casualties resulting from individuals in shelters with $PF < 10$ leaving those shelters to find better protection nearby. Note that the plot is of casualties avoided, so larger numbers are improvements. The transiting individuals are assumed to move to a shelter with $PF = 20$ in the transit time shown. The upper (red) curve assumes departure one hour after the detonation, and the lower (dark blue) curve departure thirty minutes after detonation. Compared to the lives saved by shelter-in-place in regional (Svalin) shelters, even the best casualty reductions in Figure 12 are small by comparison. Furthermore, the transit must occur within just a few minutes and departure must be delayed to one hour past the detonation to minimize exposure to the highest dose rate times in the hazardous fallout region. Furthermore, these improvements can disappear if transit is too soon following the detonation, or the transit time is too long. Hence, errors in the implementation of this strategy may well eliminate its effectiveness. While individuals in inadequate shelters may be best served by evacuation or shelter transit, their numbers are small for the NCR based on the Svalin data used in this analysis.¹²

¹² The analyses in Figure 12 assume that all those in $PF < 10$ depart for better shelter. A more optimized strategy is possible, where each individual determines whether and when to transit to a better shelter based on the quality of his current shelter, quality of the destination shelter, and expected transit time. While this kind of strategy would achieve better results than those shown in Figure 12, implementation difficulties and likelihood of error are also expected to be high.

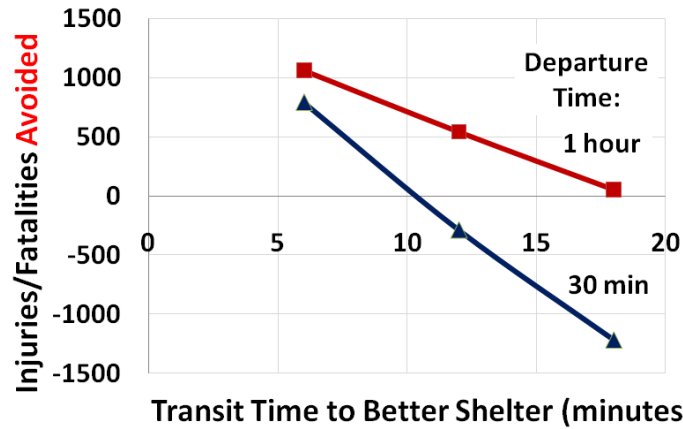


Figure 12. Utility of shelter-dependent transit strategies (NCR Svalin Data)

Late Time Departure from NCR (Svalin) Shelters

Departure from shelters at later times when the dose rates in the fallout region have decayed significantly will reduce acute radiation casualties. Reductions in overall (Svalin S-i-P) casualties due to shelter departure between 8 and 36 hours after the detonation are shown in Figure 11. These calculations assume that evacuation employs the Route-Based Evacuation (RBE) protocol illustrated in Figure 6. Previous shelter-in-place results have assumed that individuals stay sheltered for four days (96 hours). However, evacuation away from the highest hazard areas well before completion of that four day interval can often be beneficial. This earlier departure is also consistent with the expected needs of individuals to seek food, water, or medical care as soon as possible following the event.

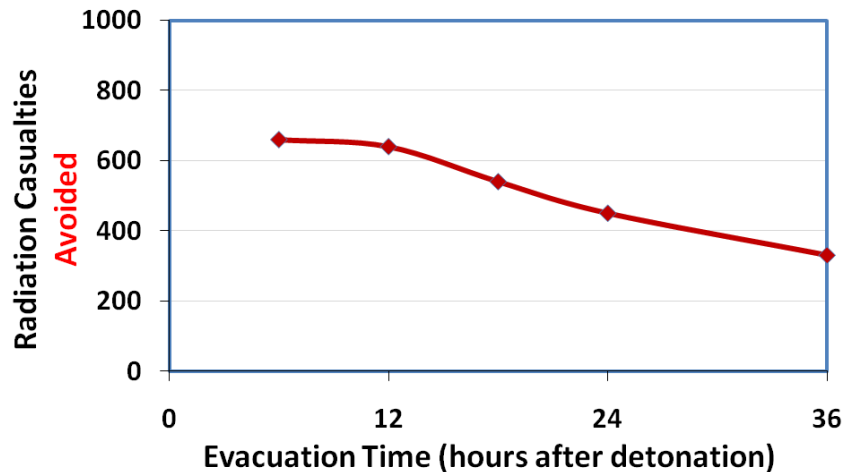


Figure 13. Delayed shelter departure times (RBE from NCR Svalin shelters)

NCR (Svalin) Results Summary

An overall comparison of the results of NCR Svalin analyses is shown in Figure 14. These results show that improvements over shelter-in-place (Svalin “S-i-P” data) can be made, but with significant demands on situational assessment and individual decision making. If informed evacuation route information were known and communicated three hours of the detonation (perhaps an optimistic assumption) a reduction of approximately 1200 radiation casualties might be achieved. As discussed earlier in conjunction with Figure 11, even a delay to twelve hours in evacuation would reduce casualties by approximately 740 over an extended shelter-in-place strategy. The fact that relatively early informed evacuation is of value should motivate the earliest possible situation awareness of fallout hazard areas as a key aspect of the regional planning process. The final bar on Figure 14 shows that a shelter-dependent strategy will reduce casualties as compared to S-i-P, but at the cost of increasing complexity. This includes identification of initial and destination protection factors and determination of departure timing criteria.

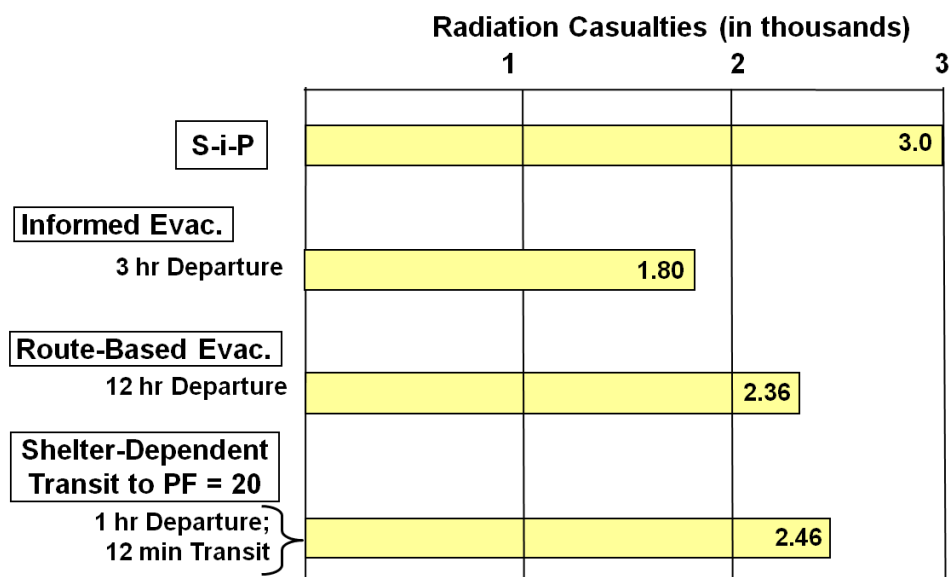


Figure 14. Summary data for Svalin shelter-evacuate strategies

4. NCR Scenario – Exemplary Point Analysis

4.1. Role of Exemplary Point Analysis

Regional analysis results presented above have highlighted the overall effectiveness of shelter-evacuate strategy options. The goal of the exemplary point analyses is to identify uncertainties and implementation issues that might impact the benefits due to evacuation identified in these regional results. Exemplary analyses are particularly useful in addressing the decision environment within high dose rate regions of the fallout area. The time urgency and accuracy requirements for decision making in these regions are particularly critical, since a relatively short external exposure can result in life-threatening acute radiation sickness. The sensitivity studies at exemplary points can inform many issues, including the following key questions:

- **Evacuation route sensitivity:** How accurately must evacuation routes out of the high dose rate regions be specified? What are the regrets for selecting the wrong route?
- **Evacuation departure time:** What determines the optimal shelter time before evacuation should begin? How will delays in departure to allow for more complete understanding of the evacuation route impact exposure?
- **Assessment requirements:** How sensitive is evacuation to uncertainties in the plume shape or errors in situation assessment?

The detailed review of a few points cannot provide absolute guidelines, particularly for other scenarios that may have very different fallout plume shapes and intensity contours. However, the analyses can provide insight into the most important determinants of evacuation success. Furthermore, the review of such points with first responders and emergency planners can serve as an effective approach for improving their knowledge of the phenomenology and overall decision issues associated with definition of a shelter-evacuate policy.

The NCR exemplary point analyses focus on a single case study, evacuation from Cardozo High School. Many of the benefits of exemplary point analysis are illustrated by this case. Other points with different locations relative to the highest dose rate regions may also be of interest in the planning process. Such points have been examined for other urban areas in previous studies.¹³

4.2. Exemplary Point Sensitivities – Cardozo High School

Cardozo High School is in a critical position relative to the NCR scenario fallout region. It is to the east of the centerline of the plume and the highest dose rate areas. The sensitivities associated with evacuation timing and routes from this point illustrate several challenging problems associated with movements near the highest dose rate portions of the fallout area.

¹³ For a broader discussion of a more diverse set of exemplary points, see Brandt, L.D., and A. S. Yoshimura, “Analysis of Sheltering and Evacuation Strategies for an Urban Nuclear Detonation Scenario” (for Los Angeles exemplary points) and “Analysis of Sheltering and Evacuation Strategies for a Chicago Nuclear Detonation Scenario” (for a Chicago exemplary point).

The three evacuation routes analyzed for Cardozo High School are shown in Table 1.

Table 1. Evacuation Routes for Cardozo High School
(1330 Clifton St. NW, Washington, DC)

Route	Description
Route 1	West via city streets to Calvert Bridge across Rock Creek; West to Connecticut Ave.; Northwest on Connecticut Ave.
Route 2	North on 13 th to Euclid St. NW; West on Euclid to 16 th St. NW; North on 16 th St. (DC EMA route for Cardozo HS)
Route 3	East to Sherman Ave. NW; North to Columbia Rd. NW; East to Kenyon St; Northwest across golf course to N. Capitol St. NE; North on N. Capitol St (~ Informed Evacuation path)

The routes chosen for analyses for Point 1 highlight the hazards of uninformed route selection during early evacuation. Route 1 is the most direct path to the west away from the fallout area. Route 2 is the official evacuation path for Cardozo High School as designated on the DC Emergency Management Agency website (<http://dcatlas.dcgis.dc.gov/evac/>). Route 3 is one implementation of the informed evacuation strategy that directs evacuees between the two lobes of the plume to travel northeast away from the highest dose rate regions. The dose rates encountered during evacuation along these routes for a departure time of thirty minutes are illustrated in Figure 15. Vertical lines along the routes depict evacuation progress at one minute intervals (50 meters for the assumed evacuation velocity of 3 km/hr).

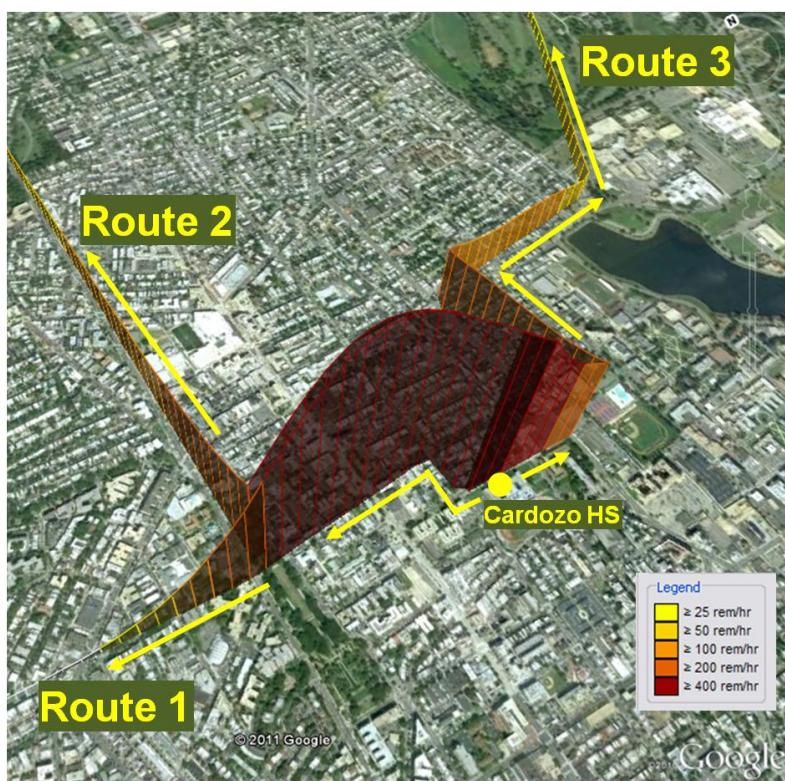


Figure 15. Dose rate profiles for evacuation from Cardozo High School

This depiction in Figure 15 of the radiation exposure levels along the routes provides a particularly compelling illustration of the impacts of alternative route selections, and the rapid changes in radiation levels at locations near the highest dose rate regions of the plume.

Evacuation results shown in Figure 16 for Cardozo High School show both the dose received during evacuation as well as the total dose that includes dose received during sheltering prior to the evacuation. These are plotted as a function of the time at which evacuation begins. The evacuation dose plots in the upper graph show that evacuation along Route 2 (the official evacuation route for Cardozo High School) is worse than the other two routes analyzed here. This is because Route 2 follows the centerline of the northern plume during departure from the area. Routes 1 and 2 are generally equivalent for later departures. Route 1 takes a shorter path through the most intense radiation field, but soon emerges into uncontaminated area. Route 3 takes a somewhat longer path through lower dose rate regions. For very early evacuation prior to the decay of the highest dose rate regions, Route 1 is substantially more hazardous than Route 3. Note that the magnitude of the evacuation doses decrease dramatically eight to twelve hours following the detonation, making the choice of route less critical for delayed evacuations.

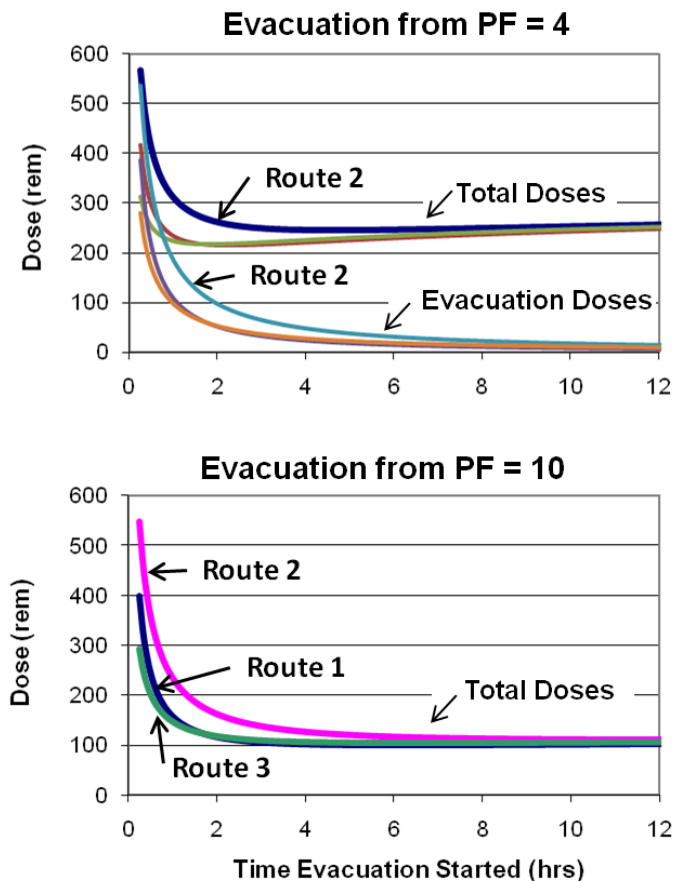


Figure 16. Evacuation analyses for Cardozo High School

The results in Figure 16 highlight the potentially large risks associated with early evacuations near high dose rate regions. For all of the cases illustrated, evacuation prior to twelve hours offers relatively small benefits, even from relatively poor shelters (i.e., PF = 4). Of course, this

conclusion does not hold true for all points in or near the highest fallout regions. However, in the absence of excellent situational awareness coupled with an ability to estimate the expected evacuation dose, early evacuation is a high risk strategy.

The desirability of alternative evacuation routes is critically dependent on the direction in which the fallout plume moves. The center of the peak fallout intensity lies less than a half mile to the west of Cardozo High School. If the plume direction were shifted just a few degrees clockwise, the best evacuation route of the three (by far) would be Route 1, over the informed evacuation path (Route 3). This dramatic shift in preferred evacuation route for small angular shifts in the plume direction again highlights both the risks associated with evacuation in the high dose rate regions, and the importance of early situation assessment.

4.3. Implications of Exemplary Point Analysis

Occupants of the most intense fallout region downwind of a nuclear detonation face many life threatening risks. These exemplary analyses have illustrated some of the risks associated with each of the principal strategies under evaluation in this study. The following points are a recap of the observations made in this section:

- Choice of route can make very large differences in the total integrated dose during evacuation. In some cases, the choice of an incorrect route can make evacuation a less desirable option than remaining in a relatively poor (SF ~ 4) shelter. The regrets due to poor route selection drop rapidly with time and can be ignored 8-12 hours following the detonation.
- The precision with which fallout dose rate contours must be known to prescribe informed evacuation routes may challenge available information. Just a few degrees error in the angular location of the plume can result in dangerous evacuation paths for those who are directed through the center of the high dose rate area, rather toward lower dose rate areas.
- The uncertainties associated with the shelter-in-place or transit to better shelter outcomes will likely be lower than evacuation strategies in the early hours following a detonation when accurate fallout hazard mapping is unavailable.
- When relatively good shelter (SF~10) is available, the preferred strategy is to remain in that shelter to avoid the uncertainties of evacuation.
- Use of official evacuation routes defined for other hazards may lead evacuees into high dose rate fallout regions when employed following an IND detonation.

These exemplary results point toward the need for a more thorough risk assessment of shelter-evacuate strategies. For those at the edge of the intense fallout region, very large benefits will result from informed evacuation actions. Unfortunately, it is not clear that this information can be either collected or communicated soon after the detonation, and the penalties for inappropriate evacuation decisions can be high.

5. Key Findings and Recommendations

The following findings and recommendations have resulted from analyses performed on the baseline NCR nuclear detonation scenario:

Confirmation of Planning Guidance Recommendations: The principal shelter-evacuate recommendations included in Federal IND guidance have been confirmed for the NCR scenario. These include:

- *Shelter-in-Place in Adequate Shelter:* Extended shelter-in-place within a high quality shelter (Shelter Factor > 10) is almost always preferred over evacuation. Even under the idealized evacuation assumptions used in this study, a very small fraction of occupants of even the highest dose rate regions will benefit by evacuating from SF>10.
- *Shelter Transit or Evacuation from Inadequate Shelter:* Early evacuation from lower quality shelters in a high dose rate region (>100 rem/hr at one hour after detonation) can be life saving when the edge of the fallout zone is nearby, and when an effective evacuation route is known. Evacuation should be deferred until at least an hour following detonation to avoid direct contact with fallout particulate during deposition.
- *Delayed Transit in Hazardous Fallout Regions:* Errors in the identification of the boundaries of high dose rate regions in the fallout hazard zone can result in non-optimal evacuation routes that eliminate the benefits of evacuation. In the absence of accurate situational assessment, evacuation from lower quality shelters should be delayed until approximately 8 hours following detonation to avoid transit into very hazardous fallout areas.

NCR Route-Based Evacuation: Evacuation using the official evacuation routes out of Washington, DC, rather than routes specifically tailored to a particular fallout scenario result in modest increases in radiation casualties for the baseline case examined here. However, for some points, evacuation using the official routes will result in very significant increases in the evacuation dose as compared to informed evacuation.

NCR Shelter Quality: The radiation protective capabilities of buildings in the hazardous fallout region of the baseline NCR scenario are generally very good, based on the available Svalin data. This results in the following findings:

- *Utility of NCR Shelter-in-Place Strategy:* The effectiveness of shelter-in-place strategies in the NCR is very good. The overall Svalin S-i-P casualty levels (~3,000) are well below those that would occur if all occupants of the fallout region had access only to adequate shelters (PF~10). Modest (but easily implemented) improvements to the Svalin S-i-P strategy result from evacuation beginning 8 to 12 hours following the detonation.
- *Shelter Transit Effectiveness:* High shelter quality in Washington, DC makes shelter transit useful only for the small number of people who find themselves in the poorest shelters (including outdoors and in vehicles). Some improvement in casualty numbers can be achieved using shelter-dependent strategies that involve transit by these individuals.

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