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Analysis of Sheltering and Evacuation Strategies for an Urban Nuclear Detonation Scenario

Larry D. Brandt, Ann S. Yoshimura

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Sandia National Laboratories
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Larry D. Brandt
Ann S. Yoshimura

Sandia National Laboratories
P.O. Box 969
Livermore, CA 94551-0969

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. This study examines shelter-evacuate policies and effectiveness focusing on a 10 kt scenario in Los Angeles. The goal is to provide technical insights that can support development of urban response plans. Results indicate that extended shelter-in-place can offer the most robust protection when high quality shelter exists. Where less effective shelter is available and the fallout radiation intensity level is high, informed evacuation at the appropriate time can substantially reduce the overall dose to personnel. However, uncertainties in the characteristics of the fallout region and in the exit route can make evacuation a risky strategy. Analyses indicate that only a relatively small fraction of the total urban population may experience significant dose reduction benefits from even a well-informed evacuation plan.

Acknowledgements

The authors gratefully acknowledge the insights and support of Lindsay Klennert and John Fulton of Sandia National Laboratories, and Brooke Buddemeier and Michael Dillon of Lawrence Livermore National Laboratory in this study. The contributions of Rob Allen of Sandia were also key in the understanding of the role and importance of situational assessment following an urban nuclear detonation.

Executive Summary

A nuclear detonation in an urban area can result in large downwind areas contaminated with radioactive fallout deposition. Early efforts by local responders must define the nature and extent of these areas, and advise the affected population on strategies that will minimize their exposure to radiation. These strategies will involve some combination of sheltering and evacuation actions. Options for shelter-evacuate plans have been analyzed for a 10 kt scenario in Los Angeles. These analyses have informed the response guidance under development by the DOE national laboratory team addressing this issue. The focus has been on reducing the number of people who receive very high radiation doses that might lead to acute radiation sickness. The quality of the shelter immediately available to protect from fallout radiation exposure has been shown to be a key determinant of the preferred action. Other important variables that determine shelter-evacuate strategy effectiveness are the evacuation departure time, and the accuracy with which the best evacuation route is known.

Results from the analyses documented in this report point to the following conclusions:

- When high quality shelter (protection factor ~10 or greater) is available, shelter-in-place for at least 24 hours is generally preferred over evacuation.
- Early shelter-in-place followed by informed evacuation (where the best evacuation route is employed) can dramatically reduce harmful radiation exposure in cases where high quality shelter is not immediately available.
- Evacuation is of life-saving benefit primarily in those hazardous fallout regions where shelter quality is low and external fallout dose rates are high. These conditions may apply to only small regions within the affected urban region.
- External transit from a low quality shelter to a much higher quality shelter can significantly reduce radiation dose received if the move is done soon after the detonation and if the transit times are short.

Situation assessment by local responders to confirm the characteristics of the high dose rate fallout zone is essential for successful implementation of an evacuation strategy. Plume modeling predictions based only on uncertain source parameters and external meteorological databases are unlikely to provide fallout zone characterization to the accuracy required for highly effective evacuation.

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. Analysis of a broader spectrum of scenarios is a recommended next step in the confirmation of the conclusions drawn by this study.

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1. Introduction

The prospect of a nuclear detonation 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, efforts to prepare for the aftermath of a detonation have also been recommended.[1]

While the detonation of even one, unsophisticated, terrorist nuclear device in a major U.S. city would be an unprecedented catastrophe, past studies have indicated that an informed response in the first 72 hours following the detonation could significantly reduce casualty levels. Advice to individuals within the fallout hazard zone downwind of the detonation is a particularly important response consideration. Both sheltering inside structures and evacuation away from the fallout hazard zone can reduce total radiation exposure. However, 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.

The work documented in this report provides a detailed examination of a 10 kt nuclear detonation scenario in Los Angeles. The primary objective of this study is to recommend shelter and evacuation response strategies that will minimize the number of individuals who receive high doses of radiation due to fallout exposure. To accomplish this, the analyses determine the distribution of population dose levels resulting from a variety of shelter-evacuate strategy options. The work also highlights the impact of uncertainties and implementation shortcomings through the examination of a series of exemplary points within the overall scenario space.

Following a review of the problem context and earlier studies in this area, this report begins with a summary of the analysis approach and modeling tools that have been developed as a part of this work to estimate both the population dose distributions due to fallout radiation exposure, as well as more focused analyses of specific exemplary points. Four general strategies representing a range of shelter-evacuate decision alternatives are examined. The overall population impacts of various evacuation plans are summarized along with the sensitivities to implementation variables such as evacuation timing. A spatial analysis identifies those areas in which evacuation will have the greatest lifesaving value. Analysis of exemplary points in the Los Angeles scenario focuses on the implementation issues in these most critical areas. The important role of situation assessment by local responders is also discussed.

1 For example, see Perry, William J. et al, "After the Bomb," New York Times Op-Ed, June 12, 2007. This concern and resulting recommendations are documented more fully in Carter, Ashton B., Michael M. May, and William J. Perry, "The Day After: Action Following a Nuclear Blast in a U.S. City," The Washington Quarterly, 30:4, Autumn 2007, pp. 19-32.

2. Background

2.1. Earlier Studies

An extensive set of tools and results based on both experiments and analyses performed during the Cold War has provided a scientifically sound 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 past work has focused on damage levels and phenomena, with less emphasis on prescriptive response planning.[2]

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] In 2006, the DHS Radiological and Nuclear Response and Recovery (RNRR) program commissioned a project executed by Sandia National Laboratories and Lawrence Livermore National Laboratory to provide a sound scientific basis for preparedness and response decision making following an urban nuclear detonation. The first phase of that project culminated in a workshop in February 2007, attended by the nation's leading nuclear effects experts, to identify nuclear effects issues impacting post-detonation state and local response decisions.[4] The decision to shelter or evacuate from fallout areas was one of the areas highlighted in this workshop.

The issues surrounding the shelter-evacuate decision were examined by Sandia during the second phase of the RRNR project.[5] That work identified four general shelter-evacuate strategies and examined factors that influence the effectiveness of each. Meteorological conditions were identified as a primary source of uncertainty, and data on wind speed and direction variability were assembled. Calculations for a Washington DC scenario modeled using the DoD Hazard Prediction and Assessment Code (HPAC) yielded dose estimates for each of the postulated strategies at several points within the fallout zone. "Informed evacuation", whereby evacuees from the fallout zone are able to evacuate at the right time using accurate route information was identified as a promising strategy. The difficulties associated with determining and communicating the information to enable this approach were also discussed.

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[2] One study addressing the DHS 10 kt national planning scenario was completed in 2005-06: Berning, Doug et al, "Nuclear Effects Planning Factors to Aid Preparedness for Emergency Response to a Detonation of a Nuclear Weapon," Los Alamos National Laboratory, Report LA-CP-06-1166, October 2, 2006, Limited Distribution.

[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. Also notable is the National Defense University workshop series intended to identify key response issues and initial expert feedback: see Caves, John P. Jr. et al, "Project on Nuclear Effects & Response Questions", Project Summary Paper, Center for the Study of Weapons of Mass Destruction, National Defense University, November 2006, Official Use Only.

[4] Dombroski, Matthew et al, "Radiological and Nuclear Response and Recovery Workshop: Nuclear Weapon Effects in an Urban Environment; February 15-16, 2007," Sandia National Laboratories and Lawrence Livermore National Laboratory, LLNL Report UCRL-TR-232119, Official Use Only.

[5] Law, Karen H, et al, "Shelter-Evacuate Strategies and Consequences Following an Urban Nuclear Detonation," Sandia National Laboratories Report SAND2008-0390, March 2008, For Official Use Only.

2.2. Goals of the Current Analysis

The goals of the current study are twofold:

- **To evaluate the regional, population impacts of shelter-evacuate strategy options:** Previous work has emphasized specific points within the hazardous fallout area to show the relative benefits of various shelter-evacuate strategies. However, to evaluate the effectiveness of a strategy, the distribution of radiation exposures to regional inhabitants in executing the strategy is required. This project has developed and exercised the NUclear EVacuation Analysis Code (NUEVAC) to estimate this distribution.

- **To understand the robustness of shelter-evacuate strategies:** The baseline analyses for population effectiveness calculations make many idealized assumptions regarding knowledge of the fallout hazard zones, ability to determine and communicate a shelter-evacuate strategy, and compliance by the affected population. In a real event, many of these enabling factors would be imperfectly implemented due to a wide range of technical and human factors. While a full uncertainty analysis is beyond the scope of this project, exemplary points are analyzed to illustrate the sensitivities to key technical issues, such as those outlined below.

Previous studies have highlighted several technical issues that are addressed by the analyses documented here. These include the following:

- **Assessment of evacuation timing and its dependence on shelter quality:** Avoidance of the initial fallout particulate by seeking shelter early after an event has been a core recommendation of researchers. The duration of time this shelter should be occupied depends on the quality of the shelter and the hazards anticipated during the transit away from the fallout zone. In some cases, shelter quality may be high enough that evacuation is not a desirable option.

- **Identification of high priority evacuation zones:** The urgency associated with evacuation actions to save lives will depend on both the fallout intensity and the ease of evacuation to safe regions. Identification of the most essential evacuation priorities can guide situation assessment and operational response activities following a nuclear event.

- **Examination of evacuation route sensitivities:** Evaluation of the accuracy with which evacuation paths must be described will guide situational assessment activities. Delayed evacuation may be the preferred strategy where uncertainties in the fallout extent and magnitude are great.

The analyses in this work are intended principally to inform the federal guidance documents that were under development during this research.[6] Applied, actionable guidelines incorporating the insights and conclusions developed in this work are also under development by the national laboratories involved in this research.[7] The tools and scenario analyses described here can also serve as orientation and training inputs to urban first responders and response planners who are seeking to prepare for the possibility of an IND event.

This work does not seek to advance the science of fallout phenomenology modeling. The extensive effects knowledge documented[8] and implemented in existing models[9] are used to provide the fallout radiation field within which the response actions are evaluated. The NUEVAC software, developed as a part of this project, uses the externally modeled fallout data to calculate the path, shelter, and time dependent integrated dose for those exposed to the radiation field.

3. Technical Approach

3.1. 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.

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[6] Coordination of the current work with the recent first edition of the "Planning Guidance for Response to a Nuclear Detonation," released by the Homeland Security Council Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats occurred through the Modeling and Analysis Coordination Working Group (MACWG) which was chartered by the DHS Office of Health Affairs to coordinate technical research related to this topic.
[7] Buddemeier, B.R. et al, "Key Planning Factors for Response to the Aftermath of Nuclear Terrorism," Lawrence Livermore National Laboratory Report, LLNL-TR-410067, in process.
[8] A primary reference is Glasstone, S. and P.J. Dolan, *The Effects of Nuclear Weapons, Third Ed*., 1977. A more detailed technical reference is Bridgman, Charles J., *Introduction to the Physics of Nuclear Weapon Effects*.
[9] Domestic responses within the domain of the Department of Homeland Security employ a suite of models (including the KDFOC fallout code) housed and executed at the Interagency Modeling and Atmospheric Assessment Center (IMAAC) at Lawrence Livermore Laboratory. The Defense Threat Reduction Agency model is the Hazard Prediction and Assessment Code (HPAC) that is a standard for DoD applications.

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 emphasis on reducing acute radiation sickness or death leads to a focus on individuals who might receive high radiation doses (~150 rem or greater). This is consistent with the expected emphasis on life saving measures immediately following the event. Other evacuation operations may be deemed useful at later times to reduce longer term, lower intensity, radiation exposure.

The analyses here make several important assumptions. These include:

- **Knowledge of fallout plume characteristics:** The determination of evacuation plans in this analysis assumes complete knowledge of the fallout plume location and intensity for setting evacuation zones and strategies.
- **Communication and execution of evacuation strategies:** The ability to communicate the resulting shelter-evacuate strategy and complete compliance with the strategy by the affected population are assumed. It is also assumed that the supporting infrastructure (e.g., communication facilities, roads, shelters, etc.) are adequate to enable the prescribed shelter-evacuate strategy. For example, no explicit modeling of congestion or roadway blockage has been employed. Such factors are, however, incorporated indirectly through the relatively slow evacuation speeds employed in the analysis.

These assumptions of perfect information and perfect compliance offer an upper bound on the effectiveness of evacuation measures under consideration. If the estimated benefits of evacuation are not significant with these assumptions, then the actual benefits may be much lower. The impacts of imperfect knowledge and execution are addressed through the examination of the exemplary analysis points.

3.2. Modeling Regional Strategy Effectiveness

The NUclear EVacuation Analysis Code (NUEVAC) was developed to calculate integrated doses resulting from exposure to fallout radiation during shelter and evacuation. 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).[10] A range of scenarios has been generated by IMAAC in support of DHS within the last year, including a number of scenarios supporting HSPD-18 consequence assessment studies. The baseline scenario used in this analysis is a 10 kt detonation in downtown Los Angeles. The data files from IMAAC specify the fallout dose rate at selected times following the detonation (15, 30, and 45 minutes; 1, 2, 4, 12, and 24 hours) and integrated dose for other times (2, 4, 6, 12, and 24 hours). These data are specified for each point on a square grid with a resolution of 250

[10] NUEVAC can also employ outputs from the DTRA HPAC model, although that capability was not exercised in the analyses documented here.

meters that covers the fallout area. The data included in the scenarios reflects 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.[11] More detailed information regarding the modeling assumptions and outcomes for this scenario may be requested through IMAAC.[12]

The NUEVAC software can calculate the population dose distributions for a wide range of prospective shelter-evacuate plans. The major features of the model are illustrated using the simplified example in Figure 1. A set of possible evacuation zones and several evacuation path options are illustrated for a standard Gaussian plume extending downwind beyond the prompt effects region. Evacuation zones in this modeling approach consist of areas defined by circular arcs and lines extending outward from the detonation point. An illustrative set of six zones is shown in Figure 1 to cover the Gaussian fallout region shown there. In the models developed for this study, the fallout region can be covered by any number of evacuation zones bounded by circular arcs and radial lines. 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
- Movement in specified direction at specified velocity

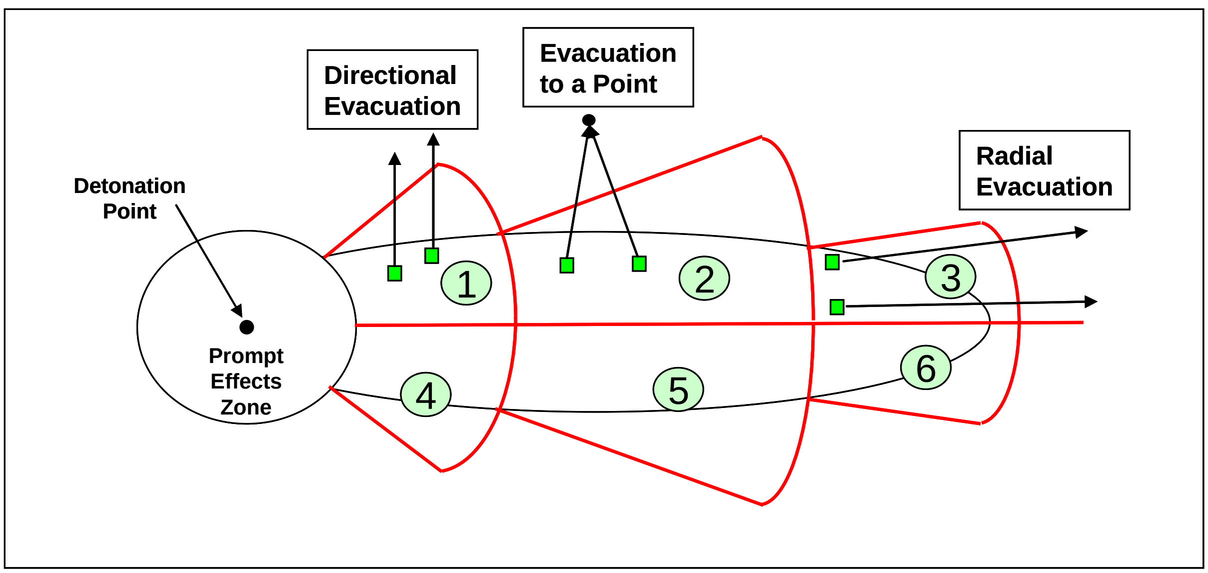

Figure 1. Exemplary evacuation regions for a typical Gaussian plume. (Alternative movement options are illustrated.)

[11] 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.
[12] Consequences Report, 10 kt LA, 15 July 2006, 18Z-Standard, NARAC/IMAAC Internal Report.

The radial and directional movements can be designated for a specified time interval and distance. Piecewise linking of the three 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 fitted curve matches all IMAAC dose rate points by a transition from the forward calculation of the earlier point and the reverse calculation of the upcoming point within any time interval. The initial ramp of the dose rate from zero up to its maximum value is also fit with power law curve in such a way that the integrated dose under the fitted curve matches the two hour value provided for each grid point by the IMAAC data. The shape of the early dose rate curves (including the discontinuities at the input data points) is only an approximate representation of the deposition phase of the fallout. However, the integrated dose calculations for all evacuation departure times past the peak dose rate (i.e., less than a half hour in high dose rate regions) are accurately modeled, relative to the IMAAC model data, by this protocol.

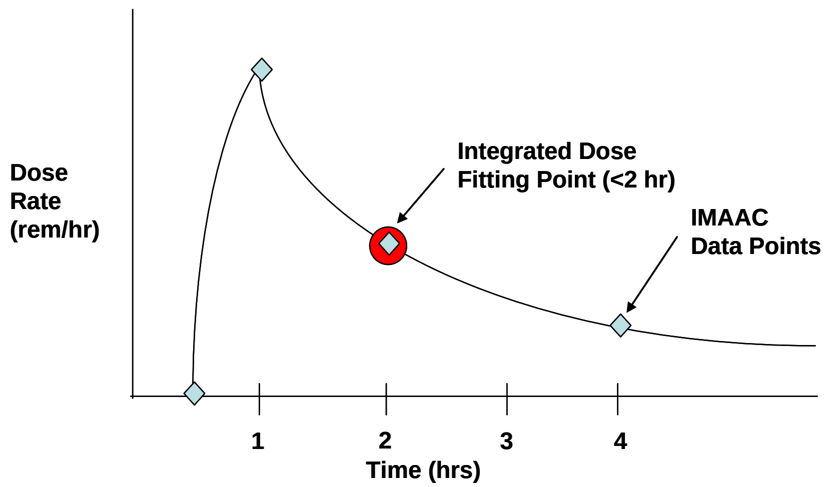

Figure 2. Temporal fitting protocol for IMAAC dose rate data.

NUEVAC includes both temporal decay and spatial variations in radiation levels in its calculation of dose accumulated within a shelter or along an evacuation path. The way this is accomplished is illustrated in Figure 3. The figure illustrates the evacuation path through a small section of the 250 meter by 250 meter high resolution data field. The dose rate at any time for any of the data grid points is provided by the temporal interpolation calculation described above. For a walking evacuee proceeding through the grid at 3 km/hr, dose integration occurs at one minute (50 meter) intervals, shown as the circular waypoints on the evacuation path. At each integration point, a bi-linear interpolation of the dose rate from the four closest points in the data field is used to update the integrated dose. In this fashion, both the temporal and spatial changes are updated for each 50 meter waypoint along the path.

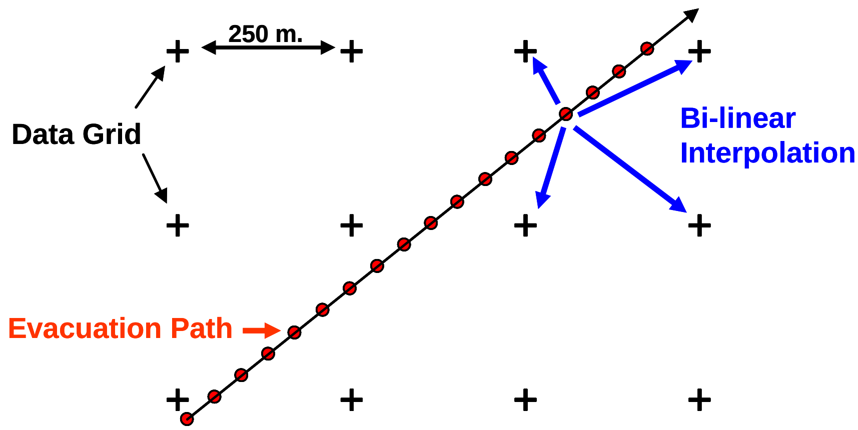

Figure 3. Integration of evacuation dose along prescribed evacuation route.

3.3. Modeling and Analysis of Exemplary Point Sensitivities

NUEVAC calculations of the dose profiles during transit for exemplary point analyses utilize the same path integration protocol described above for the regional analyses. However, a broader range of outputs are generated, including integrated total, sheltering, and evacuation doses as a function of time for the prescribed sheltering and evacuation strategy. The exemplary analysis tools also have sensitivity options that will calculate the variation of the total integrated dose as a function of the duration of the initial sheltering period at the start of the shelter-evacuate action. This provision allows for rapid examination of shelter departure time sensitivities for the exemplary points under consideration.

4. Los Angeles Scenario – Regional Effectiveness Analysis

4.1. LA Scenario and Evacuation Options

Analysis of the regional evacuation options for Los Angeles was based on a 10 kt detonation assumed to occur in the downtown area on July 15, 2006. At the time of the detonation, the winds were light. Lower level winds (below 1000 m.) were generally from the southeast with velocities generally less than 10 km/hr. Higher level (5000 to 7000 m.) winds were also light, and were from the southwest with velocities of ~10-20 km/hr. This high level range includes the altitudes to which large quantities of fallout particulate are lofted following a 10 kt ground detonation. The light wind velocities and the extensive wind shear (change in wind direction with altitude) resulted in a very wide fallout deposition plume. The plume shape at one hour following the detonation is shown in Figure 4. Deposition of the most active fallout particles was in the early-forming plume area northwest of the detonation point. Later deposition of the lighter particulate was northeast of the detonation point, forming a bi-lobed plume structure encompassing a total arc of approximately 90 degrees.

The analysis of the Los Angeles scenario examines a number of shelter-evacuate protocols. These include:

1. **Shelter-in-Place Followed by Early, Informed Evacuation:** 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:** One frequently recommended strategy[13] 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 Move to Better Shelter:** 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. **Radial Evacuation Away from Detonation Location:** Radial evacuation has been used as a surrogate for uninformed evacuation away from the detonation area.

The baseline evacuation plan established for the Los Angeles scenario is illustrated in the diagram in the lower right in Figure 4. The blue lines in the diagram illustrate the general evacuation direction for each zone. For zones that lie between the two lobes of the plume structure, evacuees are assumed to move outward to lower dose areas between the two lobes, and then to complete their evacuation by moving radially out of the region. Movement in the other

[13] 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.

evacuation zones is toward the nearest edge of the fallout area. The evacuation paths do not attempt to follow the road network or adapt to geographic obstructions in this regional analysis. To compensate for inefficiencies due to these factors, a slow average evacuation speed is assumed (nominally 3 km/hr for walking evacuation). While the baseline cases do not specify paths through the mountainous region north of the hazardous fallout area, a further reduction in evacuation speed through these hills, or an alternate path to the northwest to avoid the obstructions could be specified. However, such modifications of the plan would not significantly change the integrated dose distributions because of the low radiation levels in these areas. More detailed analyses of route selection and its impacts are included in later exemplary point analysis sections.

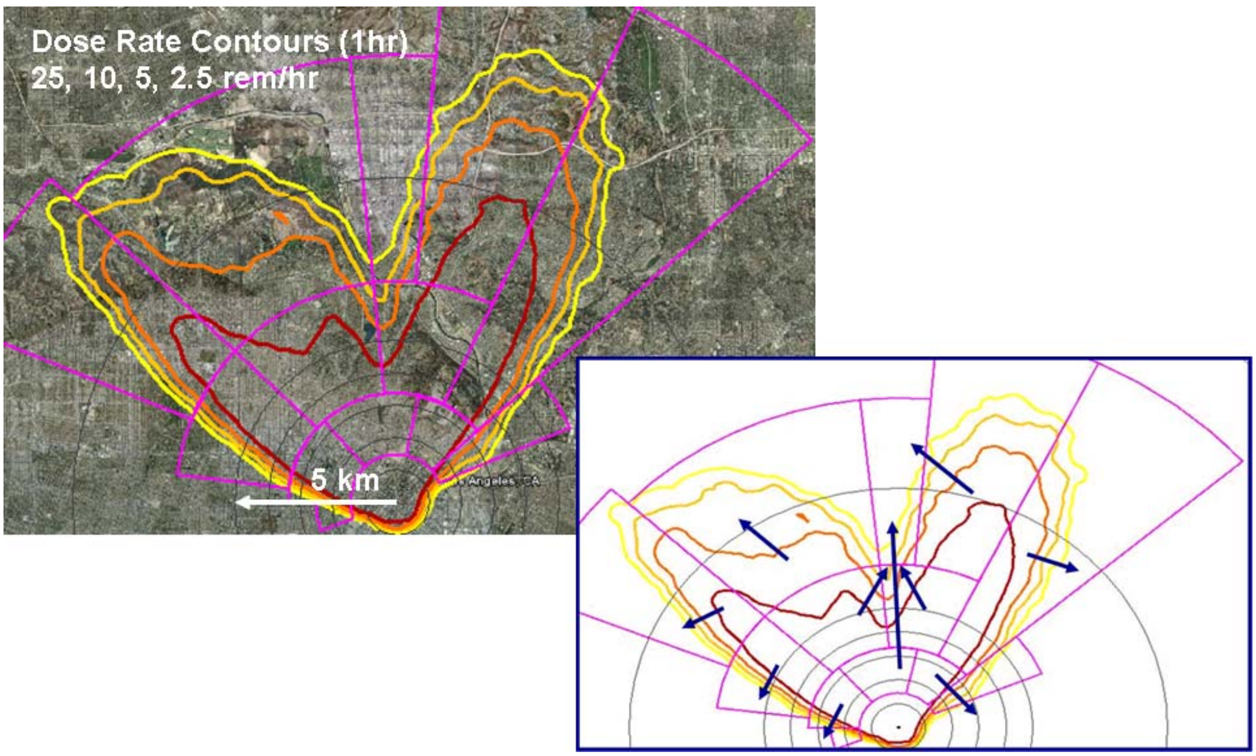

Figure 4. Los Angeles 10 kt scenario with baseline evacuation zones and routes.

The shelter quality for structures in the fallout hazard zone can vary over a wide range. The quality of shelter is prescribed by a “shelter factor” or “protection factor” that is equal to the ratio of outside dose rate divided by inside dose rate. In this report, the term shelter factor will generally be used, and will be designated by the abbreviation “SF”. Shelter factors for various types of structures are illustrated in Figure 5. In general, the quality (as a shield to fallout radiation) of available shelter in the residential areas of Los Angeles may be lower than in the urban areas of the eastern U.S. due to the lighter, wood frame construction (without basements) which characterizes the typical, western, residential structure. In this study, the sheltering sensitivities are generally calculated for shelter factors of four and ten. The SF=4 case applies to predominantly residential sheltering, recognizing that single family homes in Los Angeles may have protection factors as low as two or three, but that many live in multi-story structures that permit protection factors above four. The SF=10 case applies to the daytime work environment, particularly in multi-story office buildings in downtown or commercial areas. Large facilities such as hospitals also offer options for shelter factors even greater than ten.

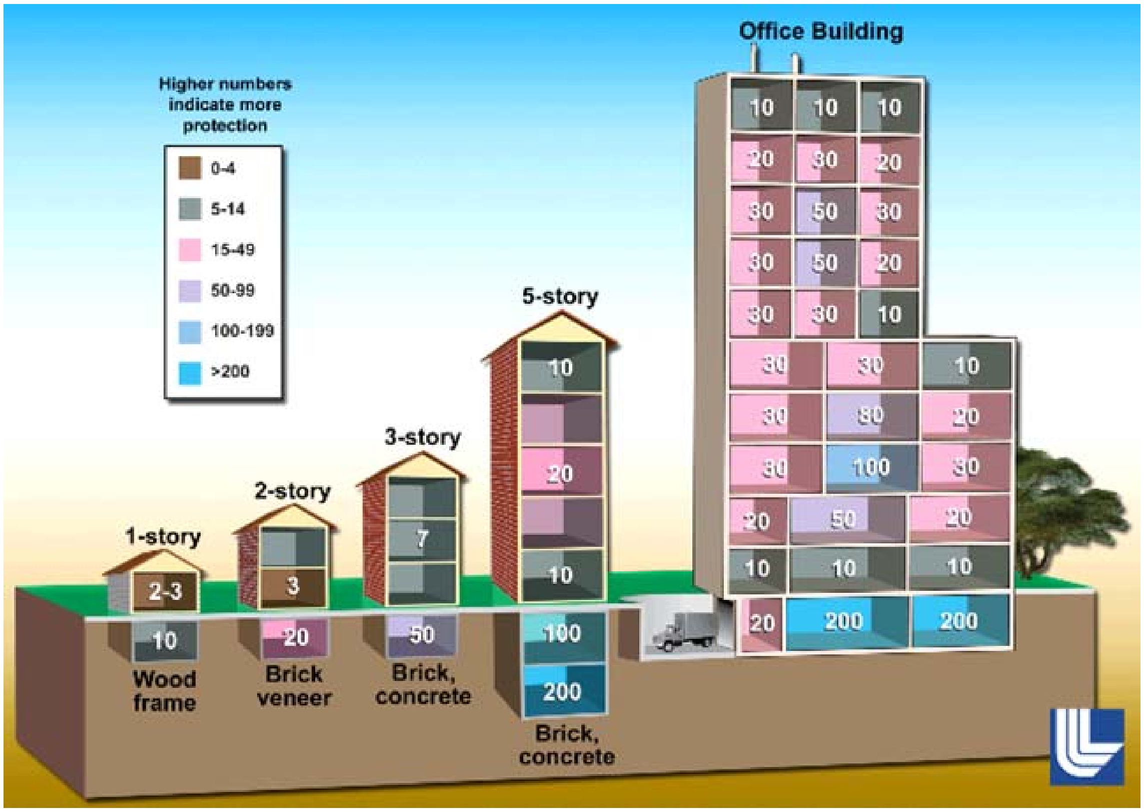

Figure 5. Variations in shelter factors for residential and office structures. (Illustration provided courtesy of Brooke Buddemeier, Lawrence Livermore National Laboratory)

4.2. Regional Results – Baseline Evacuation Plan

The regions in Los Angeles where residents would receive an integrated dose of greater than 100 rem in the 24 hours following the 10 kt detonation are illustrated in Figure 6 for various shelter and evacuation options. The "sheltered" levels are the 24 hour integrated dose to those who remain inside a shelter of the indicated quality for a full day following the detonation. For the informed evacuation case, individuals are assumed to remain sheltered (SF=4) until three hours after the detonation, at which time they evacuate. An exemplary, high resolution histogram of the integrated dose distribution produced by NUEVAC for the informed evacuation case is also included in the figure.

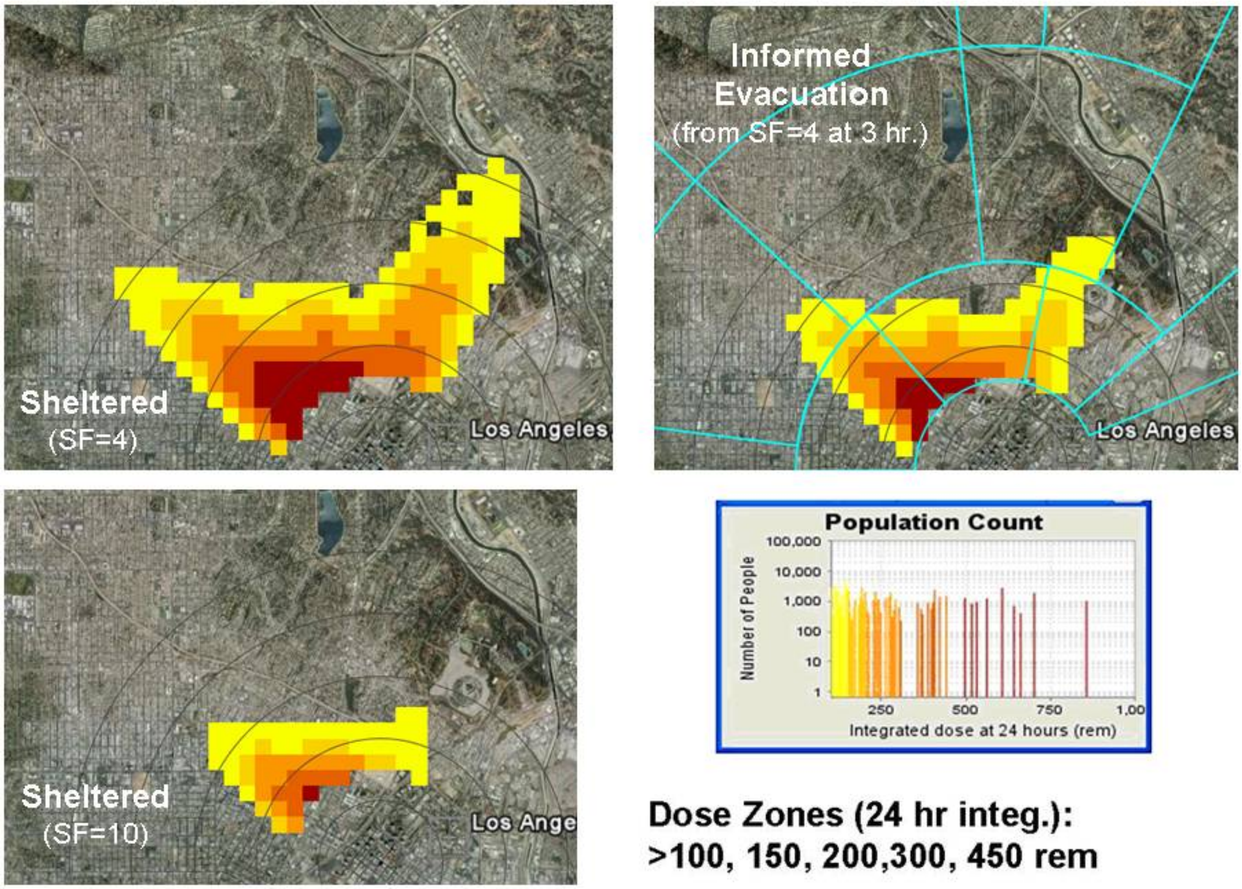

Figure 6. Geographic distribution of integrated dose for shelter-in-place and informed evacuation strategies. (Departure time = 3 hours; 24 hour integrated dose).

Comparisons of sheltering and evacuation options in this report will often be made through use of cumulative bar charts as shown in Figure 7. For each strategy, the bars represent the number of individuals receiving the threshold integrated dose or greater. For example, the 300 rem bar indicates all those who receive doses above that level, including those included in the 450 rem bar. Similarly, the 200 rem bar includes all those in the 300 rem and 450 rem bars.

Figure 7 shows the number of people impacted at various radiation dose levels for the strategies under consideration. These results highlight the potential effectiveness of planned responses in reducing the population that receives dangerous fallout exposures. A threshold of 150 rem is assumed to be the comparison level for highly hazardous exposures that could potentially lead to acute radiation sickness. Over 194 thousand receive greater than 150 rem if they remain outside during the 24 hours following the detonation. This number falls to 71 thousand for shelter in a lower quality shelter (SF=4) and to 27 thousand for high quality shelter (SF=10). Informed evacuation beginning three hours following the detonation assists particularly those in lower quality shelter. A total of about 40 thousand receive greater than 150 rem following an informed evacuation from a lower quality shelter (SF=4). Evacuation is less useful for those exiting from a high quality shelter. A total of 21 thousand receive greater than 150 rem when evacuating from high quality shelters (SF=10).

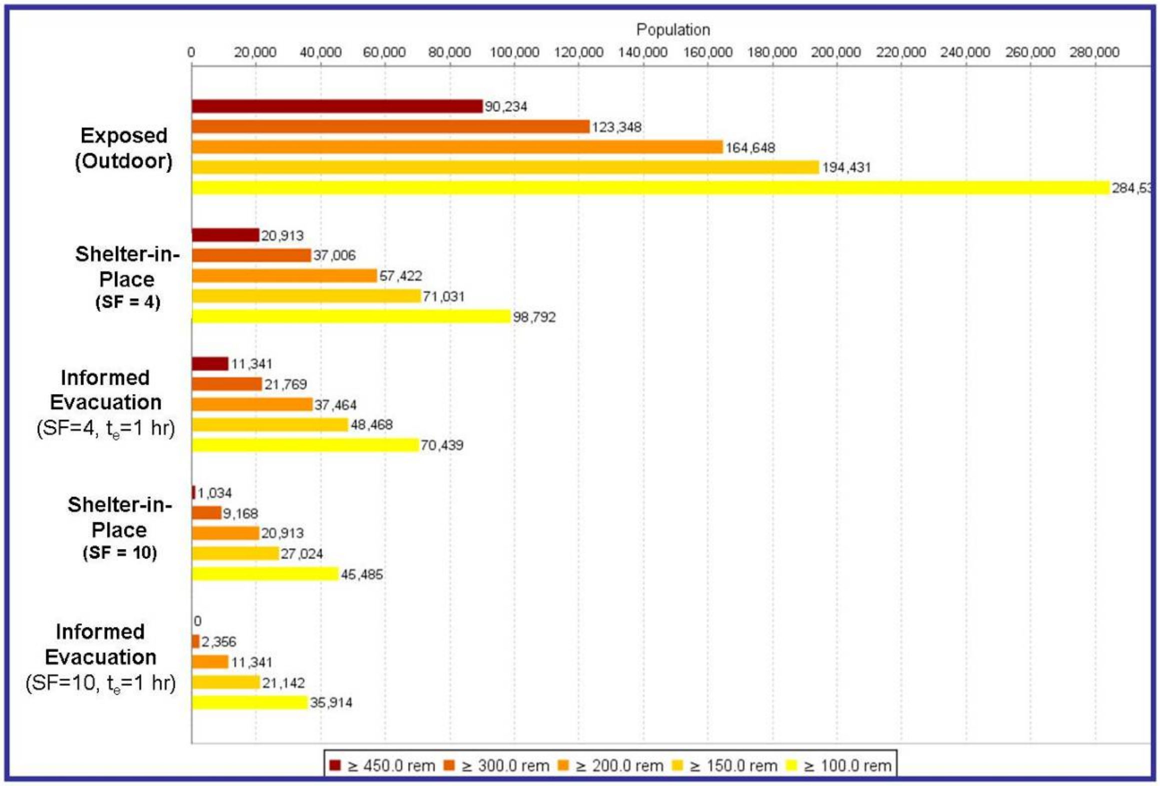

Figure 7. Comparison of populations exposed to dose thresholds for various sheltering and evacuation strategies (Evacuation time = 3 hours; 24 hour integrated dose).

4.3. Spatial Variation of Evacuation Effectiveness

Results of the previous section show that sheltering or informed evacuation can significantly reduce fallout doses, and hence the number of people subject to acute radiation sickness or death. In light of constraints on response resources, an effective evacuation strategy should target those who will receive the greatest benefits. The spatial variations in the relative effectiveness of alternative shelter-evacuate strategies can be compared through geographic, difference diagrams that plot the absolute change in integrated dose resulting from one strategy versus a second strategy. For example, Figure 8 shows the improvement when individuals execute an informed evacuation from a SF=4 shelter beginning three hours following detonation, as compared to remaining in that shelter for 24 hours. Only dose reductions above 25 rem are identified since this is likely to be the lowest threshold level that might logically motivate action in the early hours following the detonation. There are significant risks due to any evacuation operation, including erroneous understanding of the extent and intensity of the fallout area leading to inappropriate evacuation routes. In light of these risks, it is likely that an improvement of 25-50 rem in the expected exposure would reasonably be required to offset the potential regrets.

Figure 8 indicates that there is a large area between 1.5 km and 3 km of the detonation point where informed evacuation from a shelter with a protection factor of 4 will reduce integrated exposure by over 50 rem. However, as shown by Figure 9, if a shelter with protection factor of 10 is available, the area in which informed evacuation is beneficial shrinks significantly. In only a few of the highest dose rate cells does the benefit due to evacuation from a protection factor 10 exceed 50 rem. Note that these results assume integration of the shelter-in-place dose to 24 hours. This integration interval implicitly assumes that situation assessment actions will be complete enough by 24 hours to enable informed evacuation from areas that remain hazardous. If such evacuation were delayed, sheltered individuals would continue to receive some exposure to radiation. The additional dose resulting from occupancy of a lower quality shelter (SF=4) from 24 hours to 72 hours after the detonation is shown in Figure 10.

These results are quite important in highlighting operational considerations surrounding evacuation operations. If the major benefits due to evacuation occur in the high dose region close to the prompt effects region, more focused evacuation plans for these regions will have the highest leverage in saving lives. Evacuations from these high dose rate zones will probably need to be individually initiated since movement into these areas will be unsafe for responders. In addition, walking will likely be the only viable evacuation option, due to the blast-induced rubble and debris that is to be expected within 3 km of the detonation point. The route sensitivity for evacuation from these high dose rate regions will be addressed in the exemplary point analyses reviewed later in this report.

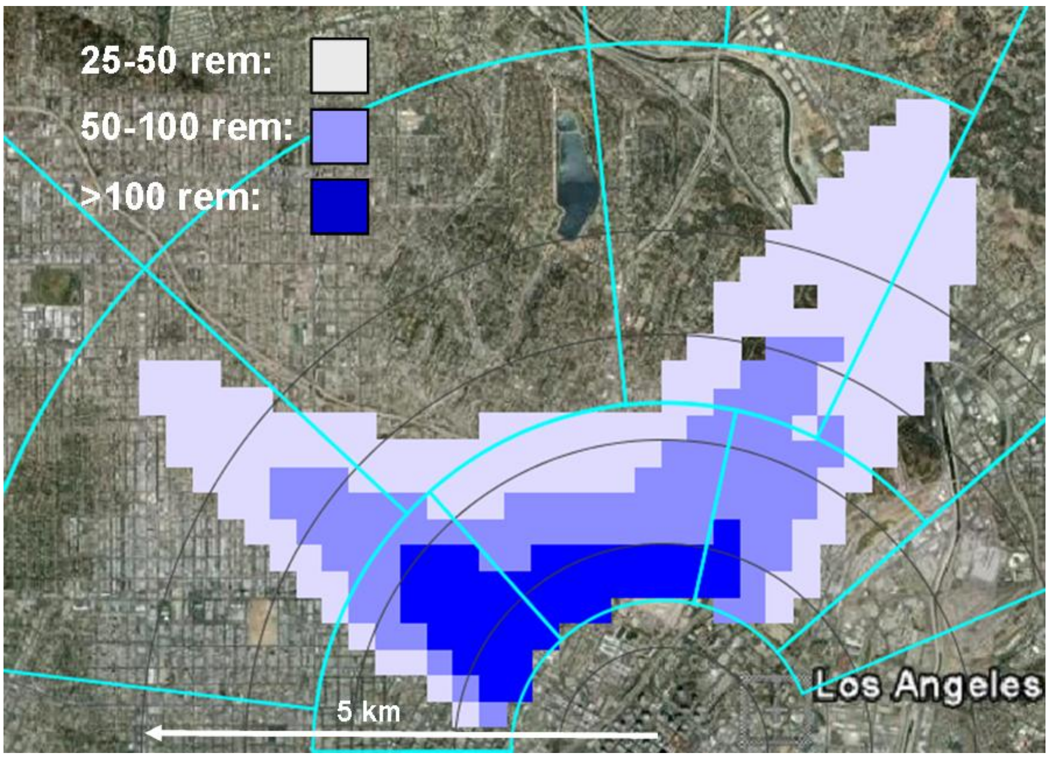

Figure 8. Informed evacuation dose reductions over shelter-in-place with SF=4 (Departure time = 3 hours; 24 hour integrated dose; Cell size: 250 m x 250 m).

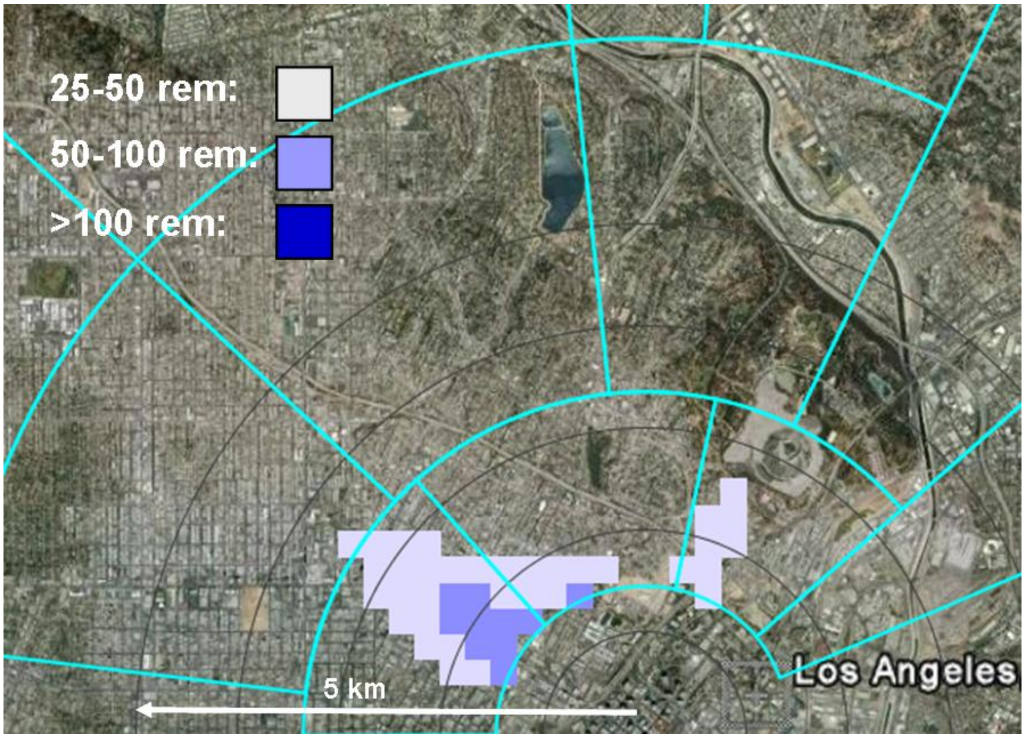

Figure 9. Informed evacuation dose reductions over shelter-in-place with SF=10 (Departure time = 3 hours; 24 hour integrated dose; Cell size: 250 m x 250 m).

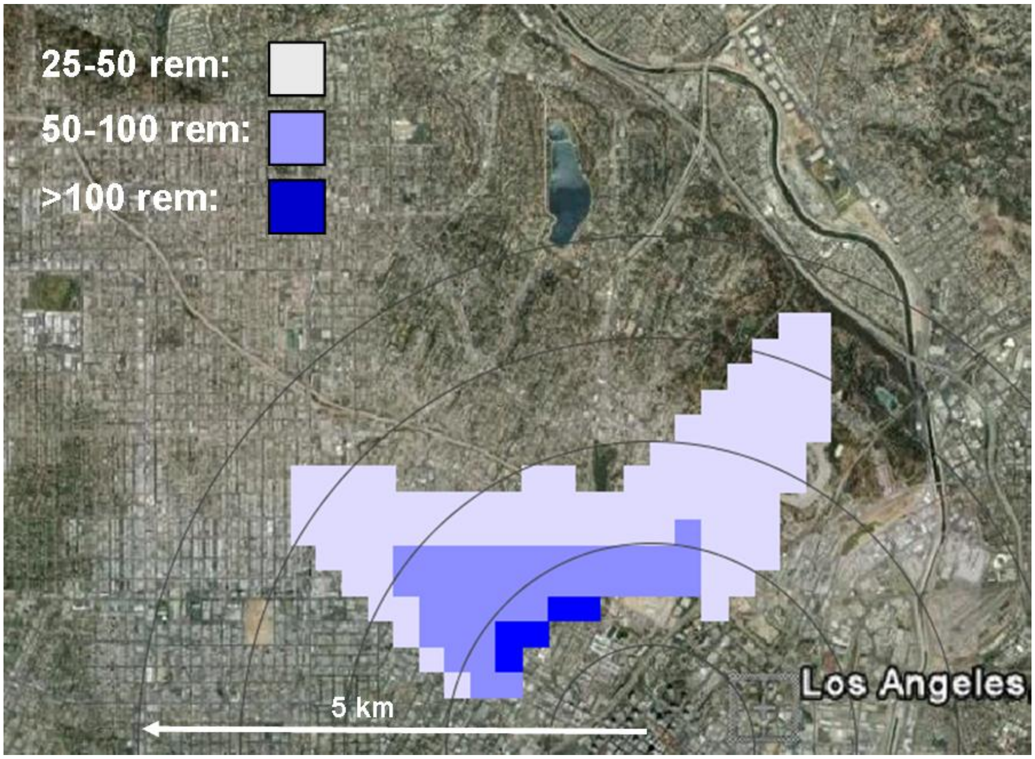

Figure 10. Differential dose from 24 hours to 72 hours for shelters with SF=4. (Cell size: 250 m x 250 m)

4.4. Other Regional Evacuation Sensitivities

Several sensitivity studies are included here to illustrate how the effectiveness of regional evacuation is impacted by critical policy and execution parameters. First, the impact of "uninformed evacuation", modeled here by radial evacuation away from the detonation, is discussed. Then, sensitivities in informed evacuation effectiveness to changes in the departure time are shown. Finally, initial results for the strategy of early movement to a higher quality shelter are reviewed. Where indicated in the results shown below, a modified baseline evacuation plan is employed that reduces the size of the outlying evacuation zones to eliminate areas where integrated doses for the analyzed strategies are well below the 150 rem analysis threshold.

Uninformed (Radial) Evacuation

Many who have imagined the fear and chaos surrounding an urban nuclear detonation have argued that sheltering may be a difficult strategy to implement. Instead, it has been suggested that inhabitants of the area – whether in the hazardous fallout region or not – will seek to gather their family together and evacuate on major roadways out of the area. An accurate assessment of the population dose distribution for immediate, uninformed evacuation by a large urban population would require examination of the effects of obstructions, congestion, and choke points on vehicular traffic, and is beyond the scope of this study. However, it might be reasonable to assume that, in the absence of other information, individuals will generally move away from the detonation point. Hence, radial evacuation at a velocity consistent with the congestion and obstructions associated with mass evacuation might serve as a surrogate for a more detailed evacuation analysis.

Figure 11 shows the results of just such an analysis, assuming radial evacuation at a walking velocity (3 km/hr) for all those in the baseline evacuation zones. The results compare the dose distributions for radial evacuation (at 1 hour and 3 hours after detonation) with the baseline informed evacuation and shelter-in-place strategies. A shelter factor of 4 was used for shelter prior to evacuation and for shelter-in-place. The calculation results indicate that radial evacuation effectiveness is midway between the shelter-in-place strategy and the informed evacuation strategy. The radial evacuation results for a 1 hour departure time are very similar to those for a 3 hour departure time. It is notable that the numbers exposed at high dose levels (i.e., >300 rem and >450 rem) are only about 10% to 15% higher for the radial strategy than for the informed strategy. This would imply that radial evacuation works almost as well to reduce high level exposures as a more finely tuned plan. This conclusion should be generalized with caution, since radial strategies for this particular two-lobe plume lobes turn out to be optimal for the evacuees between the two lobes. This circumstance, which favors the radial evacuation strategy, will not be the case for many other plume shapes.

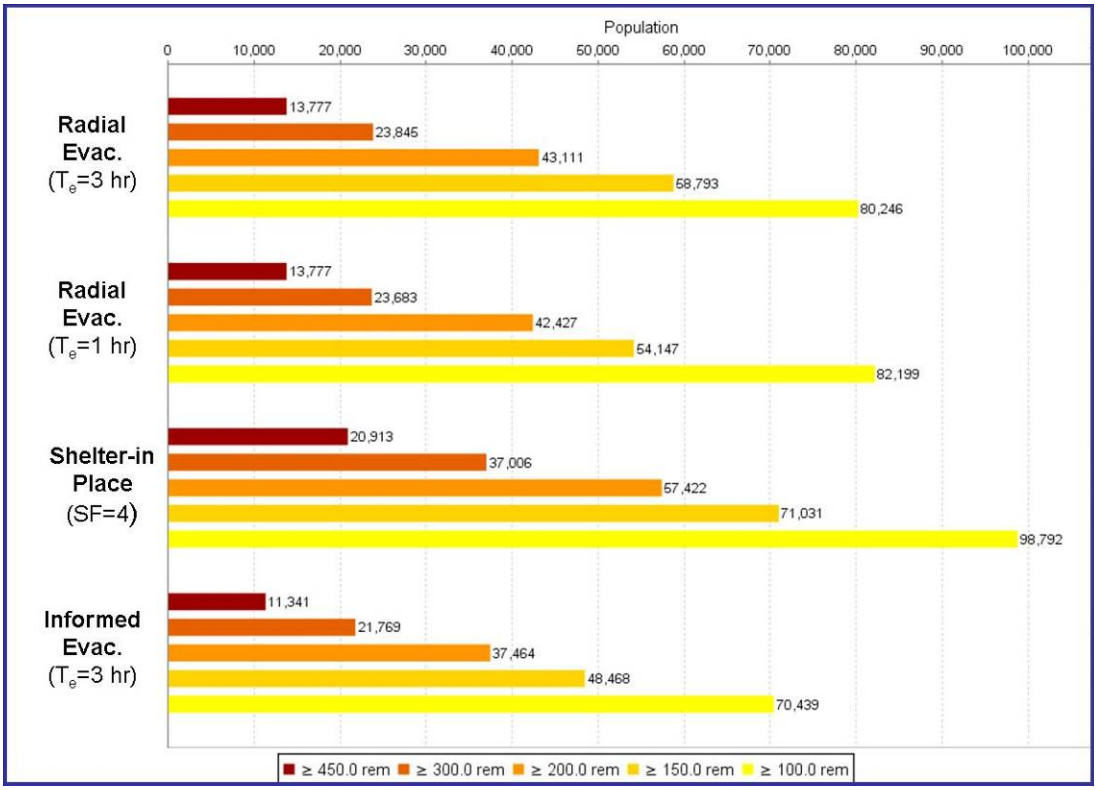

Figure 11. Comparison of uninformed (radial) evacuation with informed evacuation and shelter-in-place (SF=4) strategies.

Departure Time Sensitivities

The baseline analysis results presented earlier assumed a departure time for informed evacuation of three hours. It may be optimistic to presume that a complex evacuation plan can be executed in the early hours following the detonation. Results comparing effectiveness for several departure times are shown in Figure 12. The results in the figure illustrate the earlier conclusion that there is little to be gained by evacuation from a high quality (SF=10) shelter. In addition, two points should be emphasized from the SF=4 results. First, early evacuation significantly lowers the number of people exposed at 150 rem or above. Many of these people are in less intense dose rate regions, and are able to exit to safety with small evacuation doses. Second, evacuation from the higher dose rate regions (i.e., those resulting in doses >300 rem) can be delayed with minimal regrets until the outside dose decays to make all transit routes less hazardous. These sensitivities will be reviewed in greater depth in the exemplary point analyses documented later in this report.

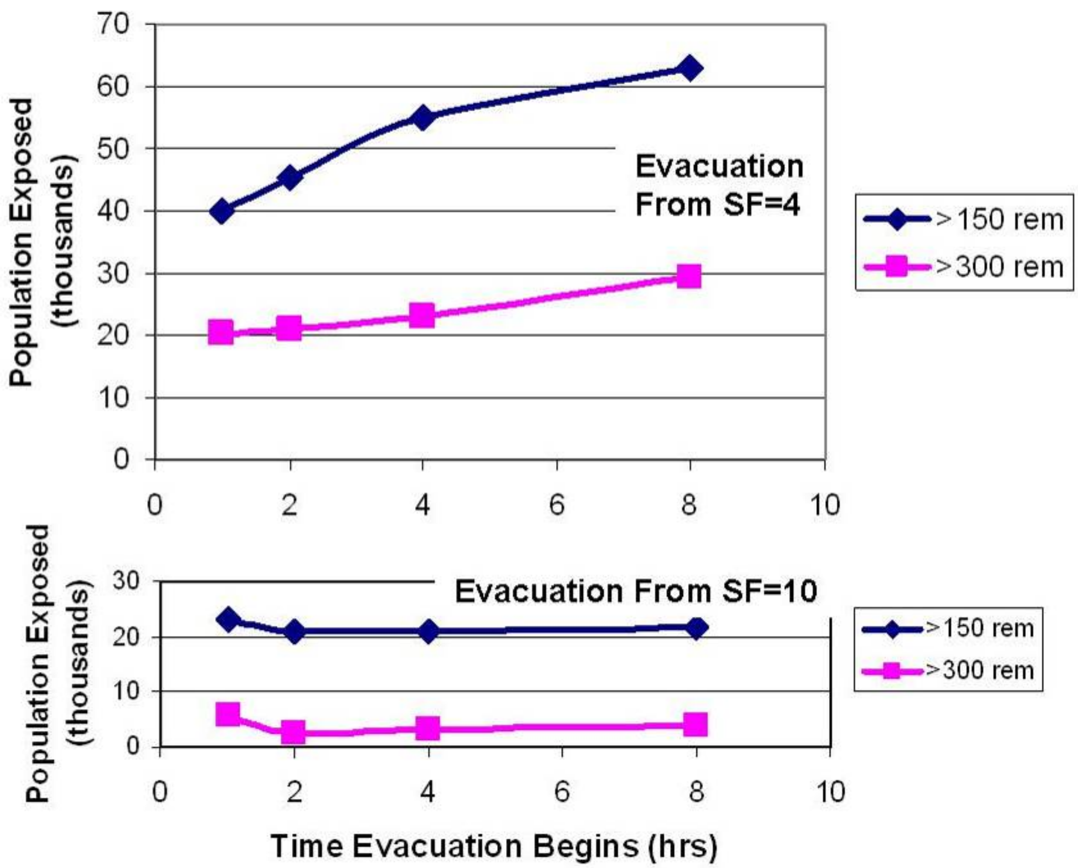

Figure 12. Departure time sensitivities for informed evacuations from shelters with SF=4 and SF=10. (Modified baseline evacuation plan employed.)

Transit to Higher Quality Shelter

In some cases, individuals may find themselves in a relatively poor quality shelter (i.e., protection factor of 2 to 4), but close to another structure that might afford much better sheltering opportunities. These might include a multi-story office building or hospital, a subway station, or an underground parking garage. This shelter transit strategy is relatively easy to implement, since it requires no knowledge of the specific nature of the fallout hazard extent or intensity. If the strategy is implemented outside of the fallout zone, it can be easily abandoned when the nature of the fallout hazards are better known. However, the strategy is not without risks. These include:

- Direct exposure to fallout particulate, particularly if outdoor transit occurs within the first half hour following the detonation
- Very large outside doses if transit time is long or is through a very high dose rate area
- Surface contamination of shoes, clothing, or skin during transit through fallout area
- Uncertainties about the quality and life support capability of the destination shelter

An estimate of the improvement of the population dose distribution can be made by assuming that individuals in each cell of the fallout area begin in a poor quality shelter (say SF=4), move outside for the transit interval (SF=0), and then enter a high quality shelter (SF=10). Using this approximation, any change in radiation levels due to spatial movement during transit to the better shelter is ignored. However, reduction in radiation intensity due to decay is still included in the calculations. For short transit intervals this is likely to be a reasonable assumption, at least from a statistical perspective, since it approximates equally likely transit in any direction from the starting point. Figure 13 compares the number of exposed individuals (>150 rem) for the pure shelter-in-place (SIP) strategy with the number exposed for the shelter transit strategy. The population numbers are for a 24 hour dose integration period. The calculations for this figure employed a modified baseline evacuation plan focused on the highest impact areas identified in the differential analyses reviewed earlier.

The results highlight the importance of short transit times in achieving the payoffs of the improved radiation protection following the movement to the new shelter. When transit time is 24 minutes, there is little improvement in the number receiving 150 rem, particularly for early movement times. At a transit time of ~12 minutes, the improvement in exposed population numbers is relatively insensitive to departure time. Early movement will result in earlier occupancy of the high quality shelter, but also exposes the individual to very high, unshielded, dose rates during the transition. These two effects are almost balanced for a transit time of ~12 minutes. If transit time is zero and the transit is done early, large reductions in the exposed population can occur, approaching the SF=10 shelter-in-place levels.

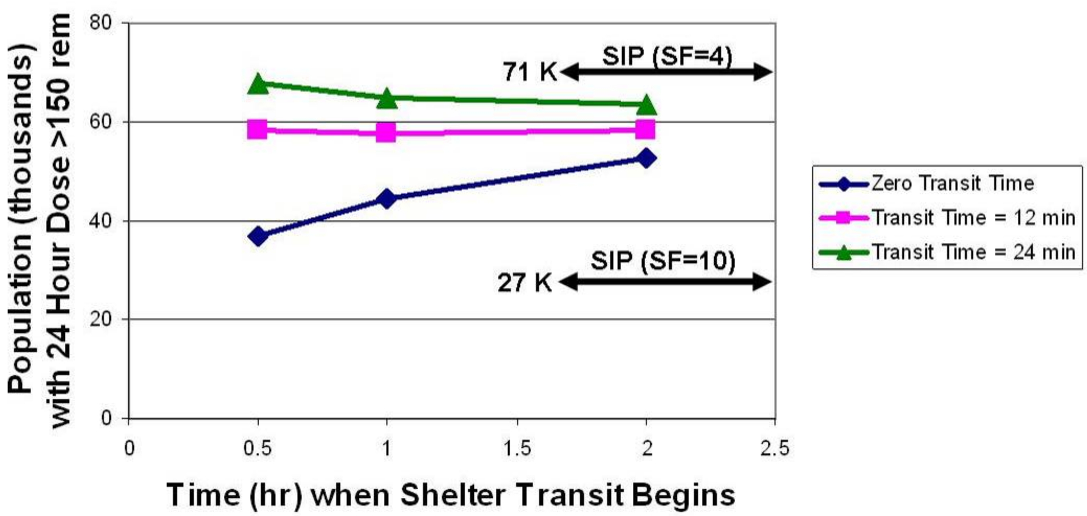

Figure 13. Regional integrated dose improvements due to transition from lower quality (SF=4) to higher quality (SF=10) shelter. (Modified baseline evacuation plan employed.)

5. Los Angeles Scenario – Exemplary Point Analyses

5.1. Selection of Exemplary Points

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. The exemplary analyses will particularly address 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 for the exemplary points seek to inform 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 representative points chosen for analysis in the Los Angeles scenario are listed in Table 1 and their locations are shown in Figure 14 along with the dose rate contours one hour following the detonation. These include several points within the highest dose rate region to the northwest of the detonation where the heaviest and most radioactive of the fallout particulate falls soon after the detonation. The points were also chosen based on their relative position within the fallout plume, with some being selected from the center of the plume and some relatively close to the edges.

Table 1. Los Angeles scenario exemplary analysis points.

Pt. #	Dose Rate (rem/hr at 1 hr)	Location
1	**780**	**Wilshire Blvd. at S. Union St.**
2	**560**	**St. Vincent's Hospital** (near W. 3rd Ave. and S. Alvarado)
3	**370**	**Los Angeles Fire Department – Station 11** (near W. 7th Ave. and S. Bonnie Brae)
4	**340**	**Hollywood Fwy (US-101) at E. Edgewood Rd.**
5	**200**	**Wilshire Blvd. at S. Commonwealth St.**

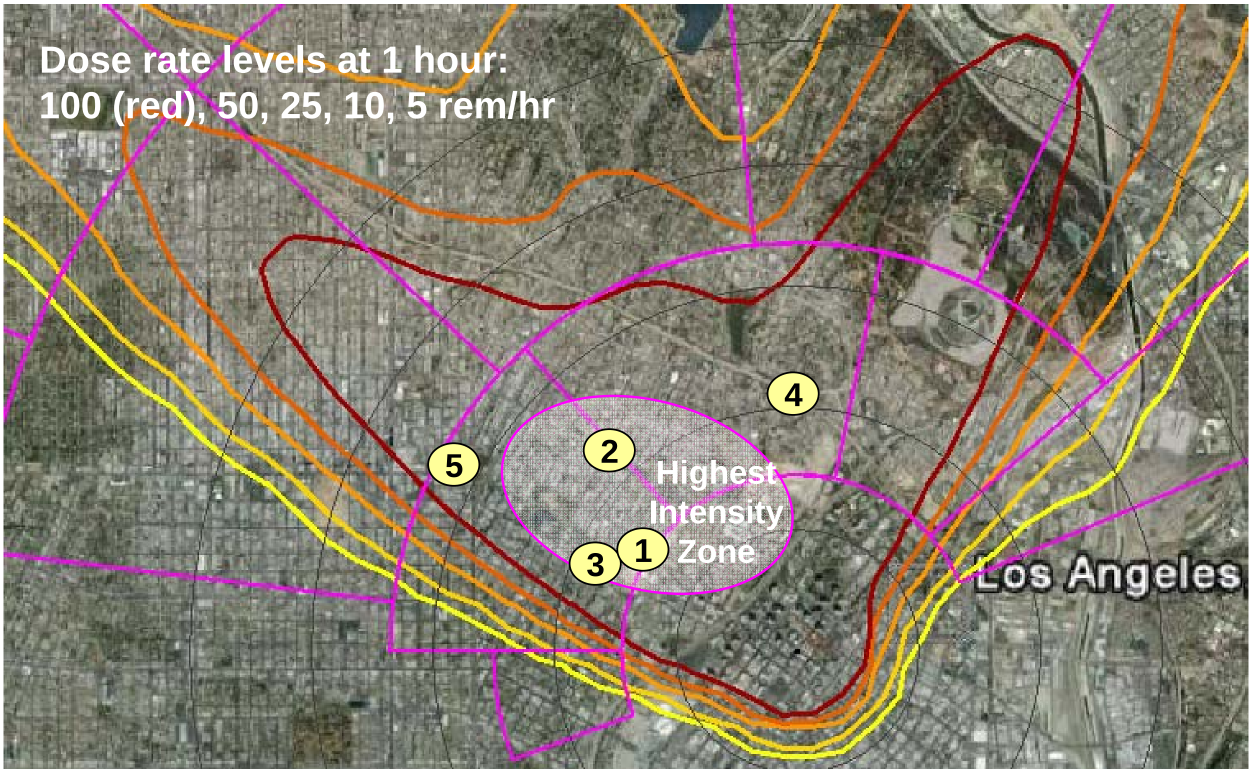

Figure 14. Los Angeles scenario exemplary analysis point locations.

5.2. Exemplary Point Sensitivities

Review of the exemplary points will focus first on those in highest intensity zone. Here the sensitivities and regrets due to uncertainties in, or improper execution of, the evacuation plans are the greatest. To introduce the discussions of the initial three points, Figure 15 shows a depiction of the relative dose rates along the baseline evacuation paths analyzed for each of these points plotted against a Google Earth background. The baseline path is the best of the three route options analyzed for each point.

Figure 15. Depiction of relative dose rates during evacuation from exemplary analysis points 1, 2, and 3 along baseline evacuation routes. (View is looking to the northwest from above and slightly west of the detonation point. The color coding indicates outside dose rates (100-red, 50, 25, 10, 5-yellow rem/hr) for a 3 hour evacuation departure time. The vertical lines along the route in the figure represent evacuation progress at 50 meter intervals - one minute transit for the 3 km/hr evacuation speed assumed in the analyses.)

Point 1 – Wilshire Blvd. at S. Union St.

The intersection of Wilshire Blvd and S. Union Street is ~1.55 km from the detonation point and lies near the center of the highest fallout deposition area outside of the prompt effects radius. The unshielded dose rate is 780 rem/hr at one hour following the detonation. The three evacuation routes analyzed for this location are shown in Table 2.

Table 2. Evacuation Routes for Point 1(Wilshire Blvd at S. Union).

Route	Description
Baseline	South on S. Union St. to S. Hoover St.
Alternate-1	Northwest then west on Wilshire Blvd.
Alternate-2	North on Union St. to Hollywood Fwy (US-101), then northwest on US-101

The routes chosen for analyses for Point 1 highlight the hazards of poor route selection during early evacuation. As shown in Figure 16, the baseline (BL) route is along the most direct path out of the contaminated area. By contrast, alternate route 2 (Alt-2) proceeds north through the most intense fallout region. Alternate route 1 (Alt-1) is less effective than baseline due to its long transit through the northwest lobe of the plume.

Figure 16. Dose rate profiles for evacuation from Point 1

The exemplary point analyses determine the total individual dose as a function of key variables, including evacuation route taken and time that evacuation begins. The total dose includes both the initial dose during sheltering prior to evacuation and the dose received during the evacuation itself. Figure 17 shows these results for evacuation from Point 1. The two plots in the figure represent departures from shelters with SF=4 and SF=10 for times between 0.5 hours and 24 hours. Also shown in the upper (SF=4) plot are the evacuation doses for each of the routes as a function of departure time. The evacuation dose is that received only during the evacuation process. It includes the effects of radiation decay and the geographic changes in dose rate as a result of movement out of the plume as described Section 3.2 above. As shown in Figure 17, this evacuation dose is a major component of the total dose for early evacuations, but it decays to low levels within 8-12 hours following the detonation for even the most hazardous evacuation routes.

For early departure times, the Alt-2 evacuation dose is very high and is the dominant component of total dose received by evacuees. For the SF=4 case, the quick exit enabled by the baseline route makes early departure best. However, for the wrong route (e.g., Alt-2), early evacuation causes much higher doses. It is important to note that the very large dose rate gradients in the highest fallout region make the early choice of an evacuation route critically dependent on the accuracy of the assessment of the fallout intensity in the area. This can be illustrated by noting from Figure 16 that the distance from Point 1 to the peak of the fallout intensity is only 300 to 400 meters. This corresponds to an angular displacement of the plume of only 10 to 15 degrees. In other words, if the plume models were in error, and the actual plume were rotated between 10 and 15 degrees counter-clockwise from that shown on earlier figures, then the preferred evacuation route from point 1 would shift. For plume shifts of even smaller angular amounts, the relative route effectiveness will change significantly. This highlights both the risks associated with evacuation in the high dose rate regions, and the need to seek ground truth radiation intensity measurements in the formulation of evacuation guidance for these regions.

The optimal time for evacuation depends both on shelter quality and on the dose received during evacuation. The optimal departure time for SF=4 and the Alt-2 route is approximately 3 hours. The optimal departure times are longer for SF=10 shelter, but these times also depend upon the evacuation route chosen. Note that the dose level curves are relatively flat beyond the optimal departure time, particularly for higher quality shelter. This means that those who are sheltering in preparation for evacuation need not be overly concerned about staying beyond the optimal time.

Figure 17 also indicates the long term (100 hour) shelter-in-place (SIP) dose for both sheltering levels using horizontal, arrowed lines. The significant gap between even the 24 hour departure dose and the long term shelter-in-place dose for SF=4 shelters indicates that evacuation is still preferred to continuing shelter-in-place, even well after the optimal evacuation time is past. In addition, the evacuation dose for later evacuations becomes very small, as does the difference in the dose received on the different evacuation routes. Hence, for later evacuations, determination of the best route for leaving the area becomes a much less significant concern. For SF=10 shelters, the difference between the 24 and 100 hour dose is small, indicating very modest benefit for those who evacuate after a full day of sheltering.

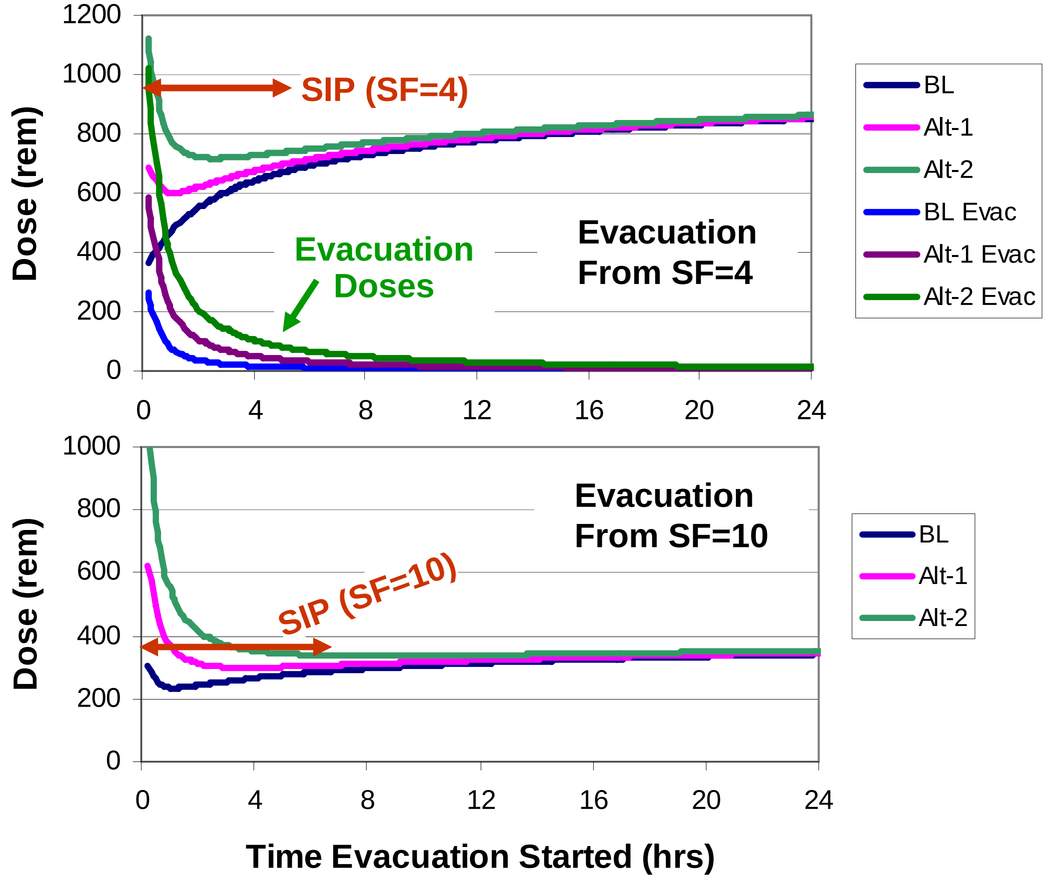

Figure 17. Shelter-Evacuate Route Analysis for Point 1.

Point 2 – St. Vincent's Hospital

St. Vincent's Hospital is ~2.24 km to the northwest of the detonation point. While it lies close to the centerline of the maximum fallout deposition zone, its increased distance results in lower radiation intensity than for Point 1. The unshielded dose rate here is 560 rem/hr at one hour following the detonation. The three evacuation routes analyzed for this location are shown in Table 3.

Table 3. Evacuation routes for Point 2 (St. Vincent's Hospital).

Route	Description
Baseline	North on Alvarado to Hollywood Fwy (US-101), then northwest on US-101
Alternate-1	South on S. Alvarado to S. Hoover, then south on S. Hoover
Alternate-2	Northwest, then west on W. 3rd Ave.

The evacuation routes away from St. Vincent's illustrate the situation of an evacuee who starts relatively near the center of the fallout area. As shown in Figure 18, the baseline route avoids transit through the highest dose rate regions, but the imbalance among routes is not as extreme as was seen earlier for Point 1.

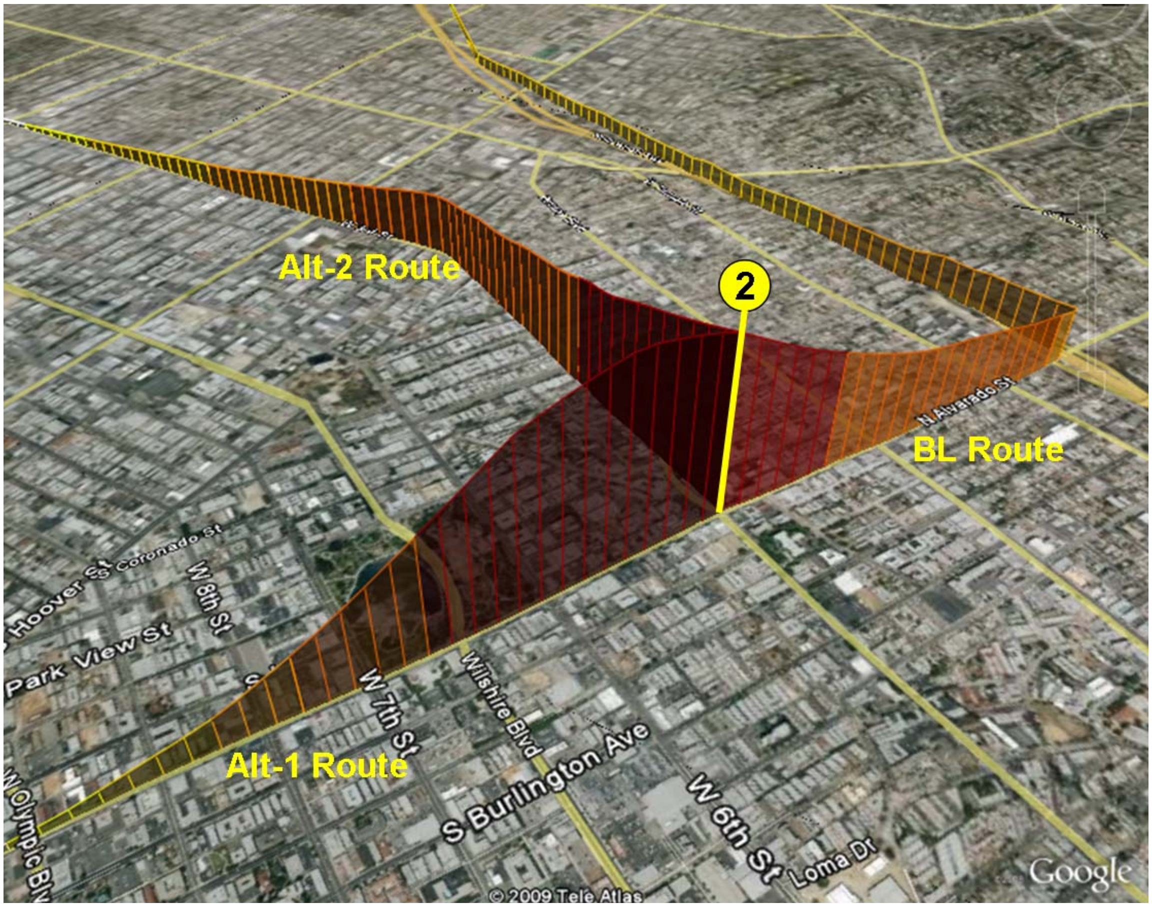

Figure 18. Dose rate profiles for evacuation from Point 2 (St. Vincent's Hospital).

The route results shown in the plots of Figure 19 reflect the lower sensitivity to evacuation route from Point 2 (although there may be more undesirable routes that were not analyzed for this point). As was the case for Point 1, the optimal departure time depends on shelter quality and on the evacuation dose. Since the dose rate profiles for the three routes are not dramatically different, the optimal evacuation times are also similar for all routes. This optimal departure time is low (~ 1 hour) for those in lower quality shelters (SF=4). Comparison of the total dose values at and following the optimal evacuation times with the 100 hour shelter-in-place dose show that there is value for evacuations after the optimal time, particularly from poorer shelters. The gains due to evacuation from similar quality shelters and evacuation times are smaller here than at Point 1 due to the differences in maximum external dose rates. In the case of hospitals, the likelihood of long term sheltering beyond the first 24 hours is high due to the difficulties and heightened risks associated with evacuation of patients.

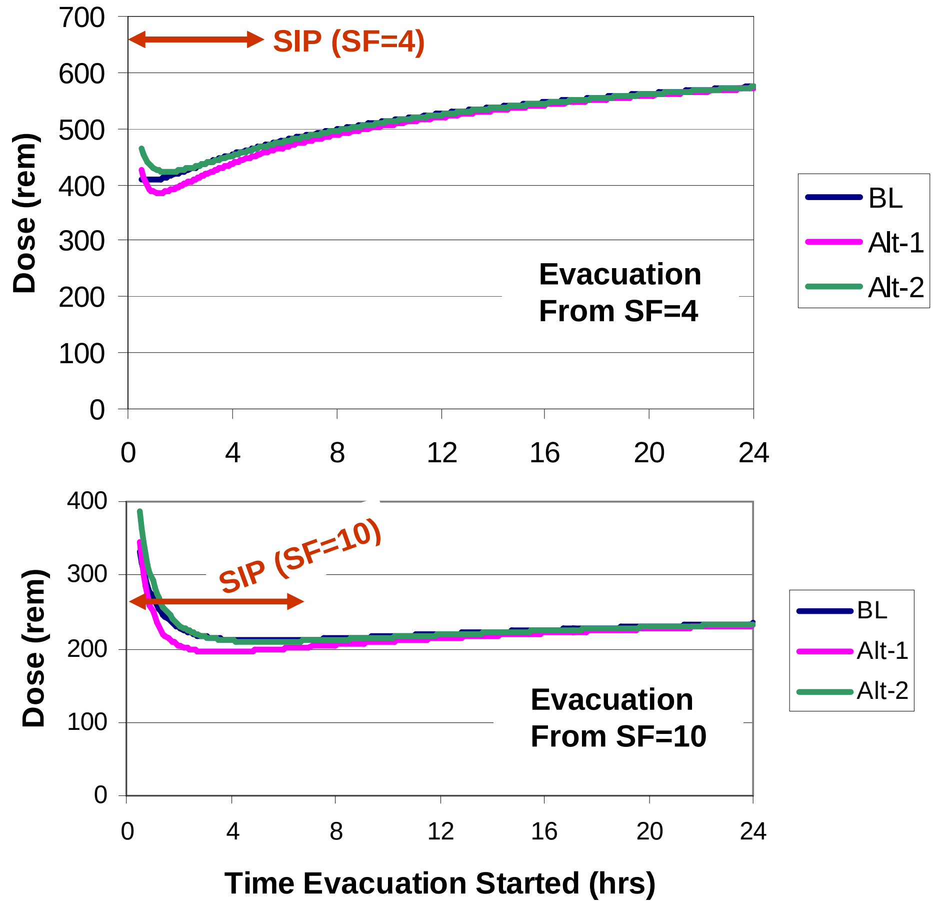

Figure 19. Shelter-Evacuate Route Analysis for Point 2 (St. Vincent's Hospital).

An examination of the shelter transition strategy from SF=4 to SF=10 was completed for this point to assess the attractiveness of the hospital as a shelter for those nearby with inadequate sheltering options. Figure 20 compares the total 100 hour dose to an individual sheltering in place with both SF=4 and SF=10 with that resulting from a six minute transit from a nearby SF=4 shelter to a SF=10 shelter at the hospital location. The total dose depends on the time at which the outside transit occurs. While earlier transitions are better, there is still significant benefit to making the transition between five and twelve hours following the detonation. For later transits (at times greater than 8 hours), similar gains can be achieved by evacuation out of the region along various routes. These results may slightly understate the value of shelter transition, since shelter factors greater than 10 could likely be found within the hospital.

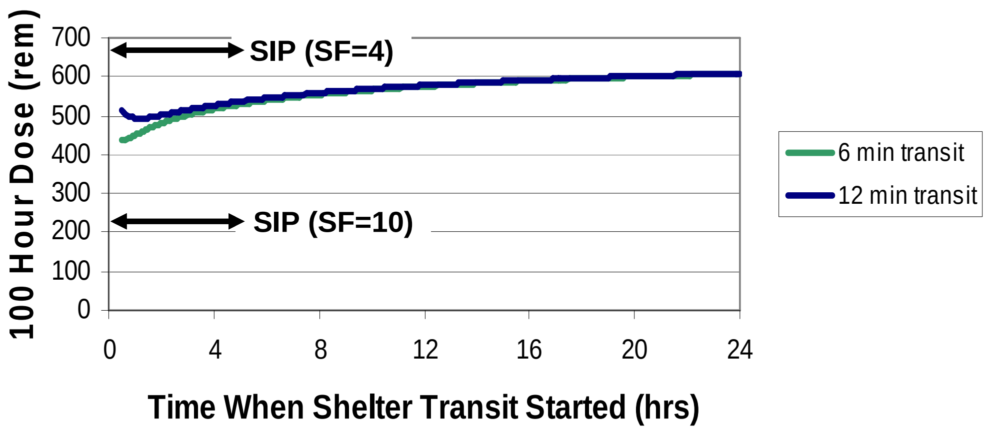

Figure 20. Total 100 hour doses for shelter-in-place and shelter transit strategies for Point 2 (St. Vincent's Hospital).

Point 3 – Los Angeles Fire Department Station #11

The LAFD Station 11 is located near the intersection of S. Bonnie Brae and 7th Ave. It is ~1.92 km from the detonation point, and is at the edge of the intense fallout zone to the northwest of the detonation. The unshielded dose rate here is 370 rem/hr at one hour following the detonation. The three evacuation routes analyzed for this location are shown in Table 4.

Table 4. Evacuation routes for Point 3 (Los Angeles Fire Department Station #11).

Route	Description
Baseline	South on S. Bonnie Brae to 11th, northwest on 11th to S. Hoover, then south on S. Hoover
Alternate-1	Northeast (on S. Bonnie Brae and others to Hollywood Fwy (US-101), then northwest on US-101
Alternate-2	Northwest on 7th, north on Hoover, then west on Wilshire

The dose rate profiles for the route options from Point 3 are illustrated in Figure 21. Since Point 3 is at the edge of the intense fallout region, similar route sensitivities exist for this case as were seen in the Point 1 analysis. The baseline (BL) route requires only a few hundred meters before it is outside of the significant fallout hazard area. By contrast, the first alternate (Alt-1) route proceeds north into the most intense portion of the fallout area, resulting in very high dose levels during transit. The second alternate (Alt-2) is less effective than baseline due to its long transit near the center of the northwest lobe of the plume.

Figure 21. Dose rate profiles for evacuation from Point 3 (LAFD Station 11)

The analysis plots in Figure 22 show that optimal evacuation times vary across a significant range for this case, due to the wide variation in route effectiveness. For SF=10 shelter, there is virtually no benefit for evacuation using the Alt-1 route during the first 24 hours. Also note that the payoff due to late evacuation versus shelter-in-place is reduced for comparable cases relative to that seen for earlier exemplary points. This is due to the reduced peak fallout intensity at Point 3 as compared to Points 1 and 2. The 100 hour shelter-in-place (SIP) doses are shown by the horizontal, arrowed lines in the plots of Figure 22.

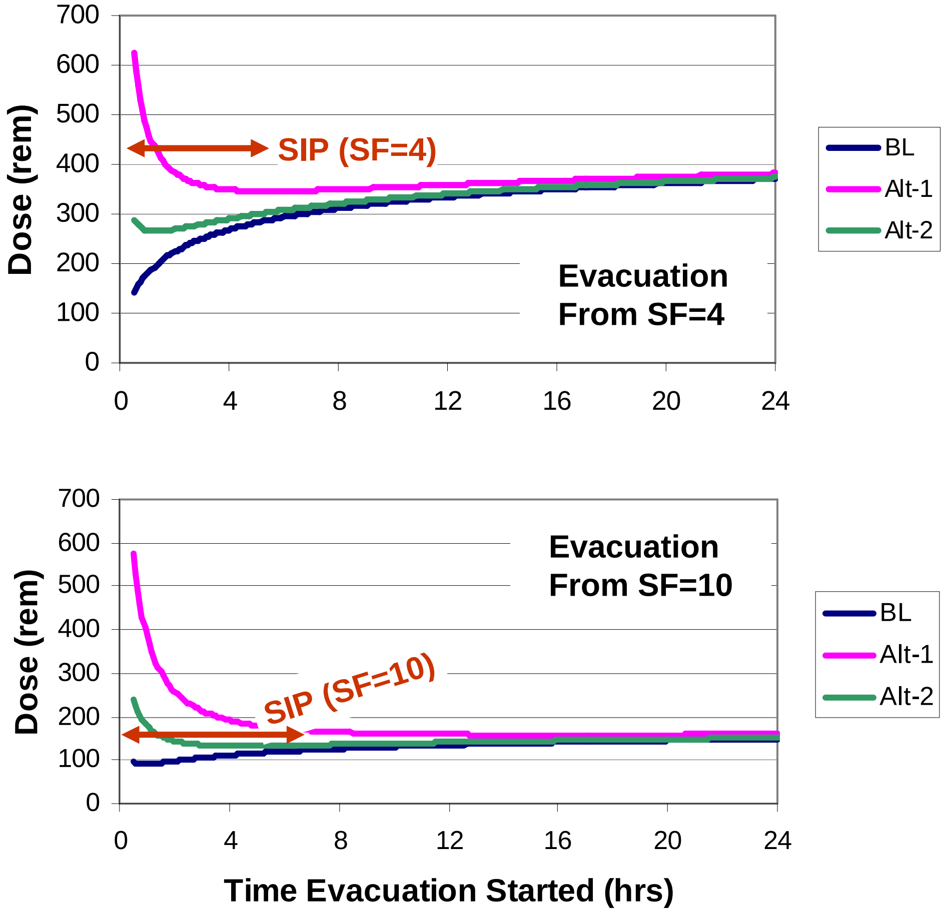

Figure 22. Shelter-Evacuate Route Analysis for Point 3 (LAFD Station #11).

Point 4 – Hollywood Freeway (US 101) at E. Edgewood Road

The next exemplary analysis point was chosen in the second, later-developing lobe of the fallout plume. The intersection of the Hollywood Freeway and E. Edgewood Road is ~2.03 km from the detonation point. The unshielded dose rate is 340 rem/hr at one hour following the detonation. The three evacuation routes analyzed for this location are shown in Table 5.

Table 5. Evacuation routes for Point 4 (Hollywood Fwy at E. Edgewood Rd).

Route	Description
Baseline	Southeast on Hollywood Fwy (US-101); then east on San Bernadino Fwy (I-10)
Alternate-1	To Glendale Fwy via Marion and W. Sunset Blvd, north on Glendale Fwy, then northwest on I-5
Alternate-2	Northwest on Hollywood Fwy (US-101)

Point 4 is near the center of the second lobe of the fallout plume. As a result, the three routes offer comparable effectiveness, as shown in Figure 23. The similar evacuation times reflect the small differences in the routes. There is no route in this case that is so close to the edge of the plume that very early evacuation would be recommended. This case is close to Point 3 in the absolute value of evacuation at times after the optimum due to the comparable fallout intensity at the two points (one hour rate of 370 rem/hr at Point 3 as compared to 340 rem/hr at Point 4).

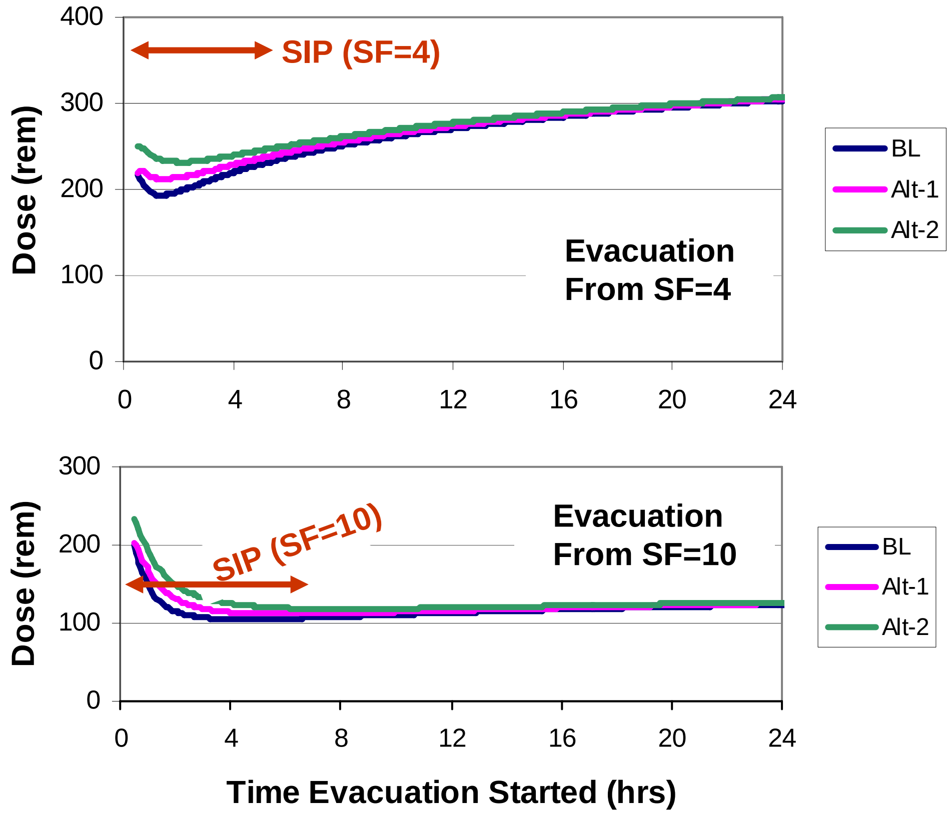

Figure 23. Shelter-Evacuate Route Analyses for Point 4.

Point 5 – Wilshire at S. Commonwealth

The intersection of Wilshire Blvd. and S. Commonwealth St. is ~3.14 km from the detonation point. The unshielded dose rate is ~200 rem/hr at one hour following the detonation. The three evacuation routes analyzed for this location are shown in Table 6.

Table 6. Evacuation routes for Point 5 (Wilshire Blvd at S. Commonwealth).

Route	Description
Baseline	West on Wilshire Blvd.
Alternate-1	East to S. Hoover, then south on S. Hoover
Alternate-2	North on Commonwealth to Hollywood Fwy (US-101), then northwest on freeway

This exemplary point is similar to Points 1 and 3 in its proximity to the edge of the fallout area. As a result, very early departures on the effective routes (BL and Alt-1) result in lower total doses, as shown in Figure 24. Even from higher quality shelter (SF=10), the optimum evacuation time for these good routes is between two and three hours, generally shorter than for most other evacuation cases from SF=10. This case also illustrates the penalties for early choice of a poor evacuation route. Evacuation on Alt-2 proceeds into the peak plume area, causing higher total doses and lengthening the optimal shelter time. Comparison of the doses for late evacuation with the 100 hour SIP dose indicates a small benefit for evacuation. As the near-peak fallout intensity drops lower than 200 rem/hr (as measured 1 hour following detonation), the benefits of delayed evacuation also drop. These benefits are almost negligible for late evacuation from high quality (SF=10) shelter at this point.

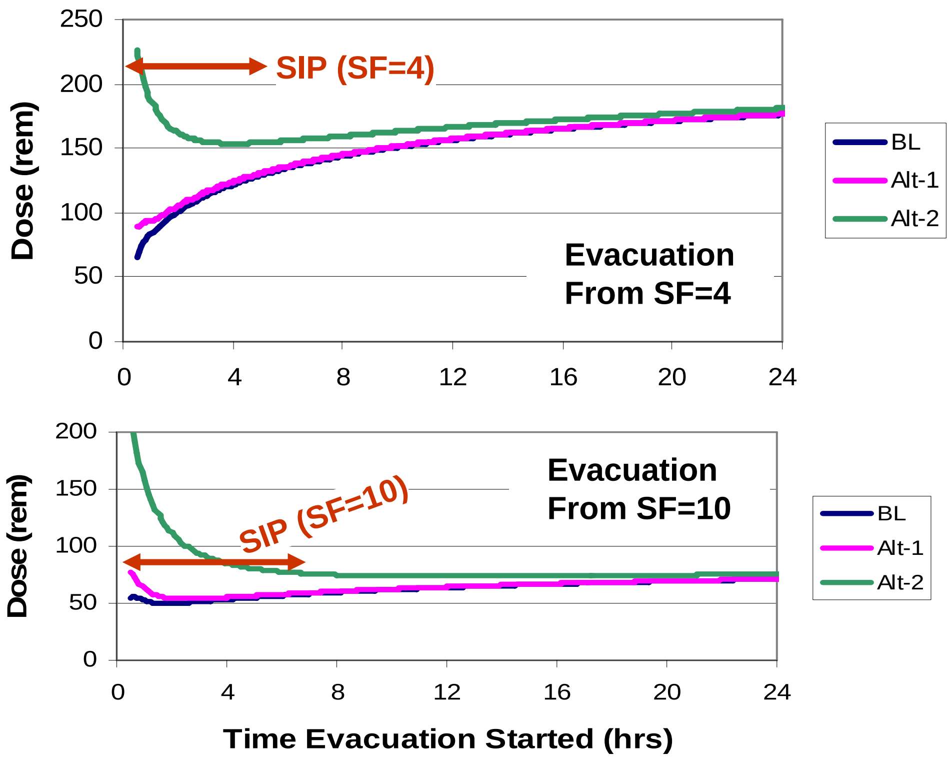

Figure 24. Shelter-Evacuate Route Analyses for Point 5.

5.3. Conclusions from Exemplary Point Analyses

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.

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.

6. Situational Assessment and Evacuation

6.1. Requirements for Situational Assessment

Following an improvised nuclear device (IND) attack, many of the characteristics of the IND will not be immediately clear. Key, initially uncertain, parameters that will significantly influence the fallout plume include detonation location, height of burst, and device yield. Even if both surface and high altitude meteorology were known perfectly, these uncertainties mean that early calculations of the nature of the fallout plume will likely be in error. As the response progresses, observations and radiation measurements on the ground and in the air must be directed toward identification of burst conditions and ground truth regarding the extent of fallout areas. This situational assessment will provide the basis for guiding responder rescue operations near hazard zones and for informing evacuation strategies for individuals within fallout areas.

The information requirements that provide the basis for effective evacuation away from the highest dose regions of the fallout hazard area can be quite demanding. The exemplary point analyses indicate that significant reductions in evacuation effectiveness can occur if fallout plume projections are just a few degrees in error. This can be contrasted with current guidance for fallout area operations proposed in earlier program meetings with first responder communities.[14] This guidance, based on a keyhole-shaped exclusion area, is illustrated in Figure 25. The buffer areas reflecting uncertainties in initial modeling of the fallout plume have not been quantified in this or earlier studies. The size of the buffer zone depends on weapon, detonation location, meteorological conditions, and the quality of the model used in making the plume estimates.

[14] The "keyhole" exclusion region model for guiding response operations was developed in earlier DHS studies and has been presented to responder communities as a part of the focus group meetings in the first half of the DHS/OHA program that sponsored the current research.

It is notable that a buffer zone enclosing the bi-lobed plume used as a baseline in the Los Angeles scenario would encompass more than a full quadrant. An initial keyhole exclusion zone of this size does little to assist in the definition of a detailed evacuation plan such as the one employed for baseline analyses documented here. In order to define and execute the baseline plan, more detailed measurements using local measurements or federal assets (e.g., Civil Support Team, DOE Consequence Management) will be required.

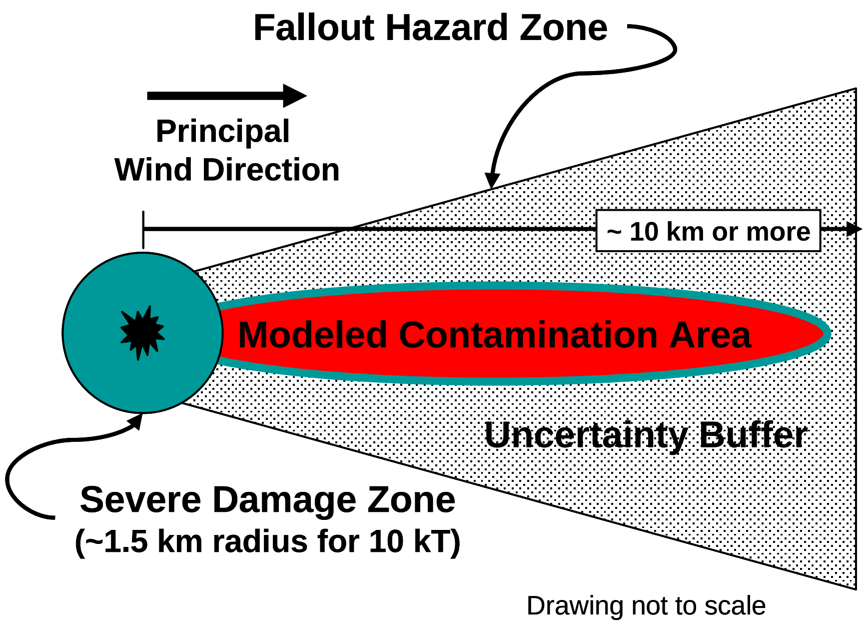

Figure 25. Keyhole model recommended for guidance prior to situational assessment and operational evacuation planning.

6.2. Use of Local Assets in Situational Assessment

Local responders will bear the primary responsibility for development and execution of any evacuation plan during the first hours following a detonation. Federal assets, particularly aerial detection platforms for direct mapping of the fallout hazard area, will be valuable contributors of ground truth, but may not significantly impact response decisions within the first 24 hours. Local responders have a wide array of radiation detection assets that might be applied immediately after the event. An initial review of detectors being purchased by major urban areas indicate that some have very high dose rate capabilities suitable for use in surveying radiological or nuclear event. However, local responders have not developed and exercised concepts of operation that would allow them to safely and effectively utilize these assets to characterize the fallout hazard area. These operations are made more complex since responders must avoid exposure to the highest hazard areas during the assessment process. In some cases, useful assets are available locally to support assessments (e.g., Civil Support Team aerial capabilities in Los Angeles). However, plans for the deployment of these assets and the utilization of the resulting data remains a gap that should be addressed by local responders.

7. Key Findings and Recommendations

The analyses performed on the Los Angeles nuclear detonation scenario have pointed toward the following key recommendations:

Utilization of High Quality 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.

Early Informed Evacuation from High Dose Rate Regions: 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.

Evacuation from Lower Dose Rate Regions: Early evacuation from lower dose rate regions (<100 rem/hr at one hour after detonation) will generally not significantly reduce the likelihood of acute radiation sickness as compared with a shelter-in-place strategy.

Impact of Uncertainties in Fallout Zone Characterization: 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.

Transit to Higher Quality Shelter: Transit from lower quality (e.g., SF~4) to nearby, higher quality (SF~10) shelter can reduce radiation doses to individuals in the fallout zone. For significant benefit, transit must be rapid (less than ~6 minutes) and occur in the first hours following the detonation. However, this strategy faces several uncertainties, including heightened exposure during transit to shelter, possible contamination, and less effective human support services in the destination shelter.

8. Future Technical and Capability Needs

8.1. Evaluation of Current Analyses

The current analyses have provided an in-depth examination of a single urban detonation scenario. Simplifying assumptions, most favoring evacuation strategies, have been made. Exemplary cases have been employed to understand sensitivities, rather than a more detailed risk-based analysis to quantify the impact of the many uncertainties surrounding the event. Perhaps the greatest limitation of the current study is the focus on a single scenario. The best shelter-evacuate strategy will depend critically upon both the weapon (especially the yield and detonation location) and upon the meteorological conditions at the time of the attack. Many aspects of a real attack will be unknowable in advance, so operational plans for situation assessment coupled with a provision for handling uncertainty in the response processes will be essential. The results flowing from this study are a first step in understanding the overall impacts and key drivers following a nuclear detonation. Hence they inform post-event decisions, but represent only one of a very large number of scenarios that might unfold.

A particularly important element of the problem is the implementation of an effective shelter-evacuate strategy. Gaps exist in operational situation assessment protocols needed to define the strategy. The ability to communicate to individuals in the fallout hazard zone may be compromised by the detonation. Evacuation hazards include exposure to the falling particulate (if evacuation is attempted immediately after the detonation). Transition to high quality shelters runs the risk of contamination spread plus potential shortcomings in the ability of the shelter to support evacuees for the duration of the sheltering period. In some cases, the best strategy may not be the one that yields the lowest integrated dose assuming ideal implementation, but rather the strategy that faces the lowest risk of more catastrophic outcomes.

8.2. Next Steps

The shortcomings outlined above suggest several areas for future investigation. These include the following:

Broader Scenario Set: A much more diverse scenario set incorporating different detonation parameters and weather patterns is essential to generalize the results of this study and to provide a foundation for the risk-based assessments discussed above.

Impacts of Shelter Quality Spatial Distribution: The current analyses have shown how important immediate or nearby shelter quality is to the determination of shelter-evacuate policy. Consideration of the spatial and quality distribution of shelters within an evacuation zone is particularly important in the further analysis of shelter-in-place, shelter transition, and evacuation strategies.

Situation Assessment Operational Plans: Current studies have indicated the importance of local situation assessment activities. Realistic operational protocols to accomplish this have not been developed by U.S. urban response planners. This is a serious shortcoming that will impact not only shelter-evacuate implementation but the broader response as well.

Risk-based Assessments: A more complete attempt to balance the risks faced by individuals in the population at various locations and times following the detonation is needed. The likely accuracy of early plume predictions and the availability of ground truth measurements should calibrate what might reasonably be known in the first few hours following a detonation. One part of this risk assessment should address the variability of plume modeling accuracy with the prevailing meteorological conditions at the time of the detonation.

Distribution (Electronic Copies):

Department of Homeland Security/S&T/CBD
Attn: Sara Klucking [Sara.Klucking@dhs.gov]

Department of Homeland Security/OHA
Attn: Charles Blue [Charles.Blue@dhs.gov]

Department of Homeland Security/FEMA
Attn: Don Daigler [Donald.Daigler@dhs.gov]
Sean Crawford [Sean.Crawford@dhs.gov

Department of Homeland Security/OPD
Attn: John MacKinney [John.Mackinney@dhs.gov]

Office of Science and Technology Policy
Attn: Tammy Taylor [ttaylor@ostp.eop.gov]

Defense Threat Reduction Agency
Attn: Michael Schick [Michael.Schick@dtra.mil

Lawrence Livermore National Laboratory
Attn: Brooke Buddemeier [buddemeier1@llnl.gov]
Michael Dillon [dillon7@llnl.gov]

Los Alamos National Laboratory
Attn: Randy Bos [mbos@lanl.gov]

Institute for Defense Analysis
Attn: Deena Disraelly [ddisrael@ida.org]

Applied Research Associates
Attn: Kyle Millage [kmillage@ara.com]

Noblis
Attn: John Mercier [John.Mercier@noblis.org]

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Department of Homeland Security
Attn: DHS/S&T/CBD/Sara Klucking
245 Murray Lane SW
Washington, DC 20528

Department of Homeland Security
Attn: DHS/OHA/Charles Blue
245 Murray Lane SW
Washington, DC 20528

Lawrence Livermore National Laboratory
Attn: Brooke Buddemeier
P.O. Box 808, L-171
Livermore, CA 94551-0808
(10 copies)

Lawrence Livermore National Laboratory
Attn: Michael Dillon
P.O. Box 808, L-xxx
Livermore, CA 94551-0808

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