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Analysis of Sheltering and Evacuation Strategies for a Chicago Nuclear Detonation Scenario

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Prepared by
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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 Chicago. The work utilizes a single scenario to examine regional impacts as well as the shelter-evacuate decision alternatives at selected exemplary points. For many Chicago 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 and Michael Dillon of Lawrence Livermore National Laboratory in this study. Their assessment of shelter quality through the Svalin project provided key inputs underlying many of the primary conclusions of this study.

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 downtown Chicago have been completed. A range of strategies that include shelter-in-place, shelter transit, uninformed evacuation, and informed evacuation are included. 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 confirmed for the Chicago scenario. 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.
- The radiation protection capabilities of many structures in the Chicago region 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 ~3,600, as compared to ~100,000 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.

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1. Introduction

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 at 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 Chicago. 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 data of the shelter quality distribution in the Chicago region. A representative baseline scenario is employed to illustrate the key tradeoffs faced by response planners for such an event.

Following, this report begins with a review of the problem context and 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 specific exemplary points, are reviewed. Several general strategies representing a range of shelter-evacuate decision alternatives are then examined.

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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.

2. Background

2.1. 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. Most recent published results address 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. Many of the key results that supported Federal response guidance[5] evolved from the initial Los Angeles results.

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[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] 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. Note that a more extensive discussion of the background of the scientific analysis activities is included in this reference. 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", paper presented at the American Nuclear Society Special Session on Risk Management, Washington, DC, November 18, 2009. To be included in the upcoming ANS publication: "Risk Management – Expanding Horizons".

[5] See "Planning Guidance for Response to a Nuclear Detonation," Chapter 3.

2.2. Goals of the Chicago Analysis

The analyses documented in this report incorporate key data specific to the Chicago region to provide tailored results in support of Chicago region planning activities. As compared to past shelter-evacuate studies, the high resolution regional shelter quality inventory available for Chicago enables more accurate assessment of regional 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.

- **Recommendation of Chicago-specific strategies:** Available national response guidance provides a foundation for response planning. However, the data available from region-specific analyses can assist Chicago planners in assessing the unique factors that will impact their planning.

A number of key technical issues are addressed in the Chicago analyses. These include the following:

- **Sensitivities to key implementation factors:** Many implementation factors impact the effectiveness of alternative shelter-evacuate options. One element examined in detail here is the timing of potential evacuation or shelter transit options.

- **Impact of situational awareness uncertainties:** The availability of accurate information on the fallout hazard areas and the ability to communicate that information will determine the ability to execute alternative shelter-evacuate strategies. The impact of shortcomings in the ability to acquire and communicate enabling information will be discussed relative to each strategy option.

- **Depiction of region-specific guidance:** Graphical tools to depict outcomes for both regional and exemplary point analyses are employed to facilitate understanding of the key determinants of shelter-evacuate strategy effectiveness.

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.

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.

3.2. 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.[6] 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 Chicago. 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 (400 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.[7] Note that the NEUVAC 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

[6] 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.
[7] 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 to specified point at specified velocity
- Movement in specified direction at specified velocity
- Movement to a designated line (shortest path)

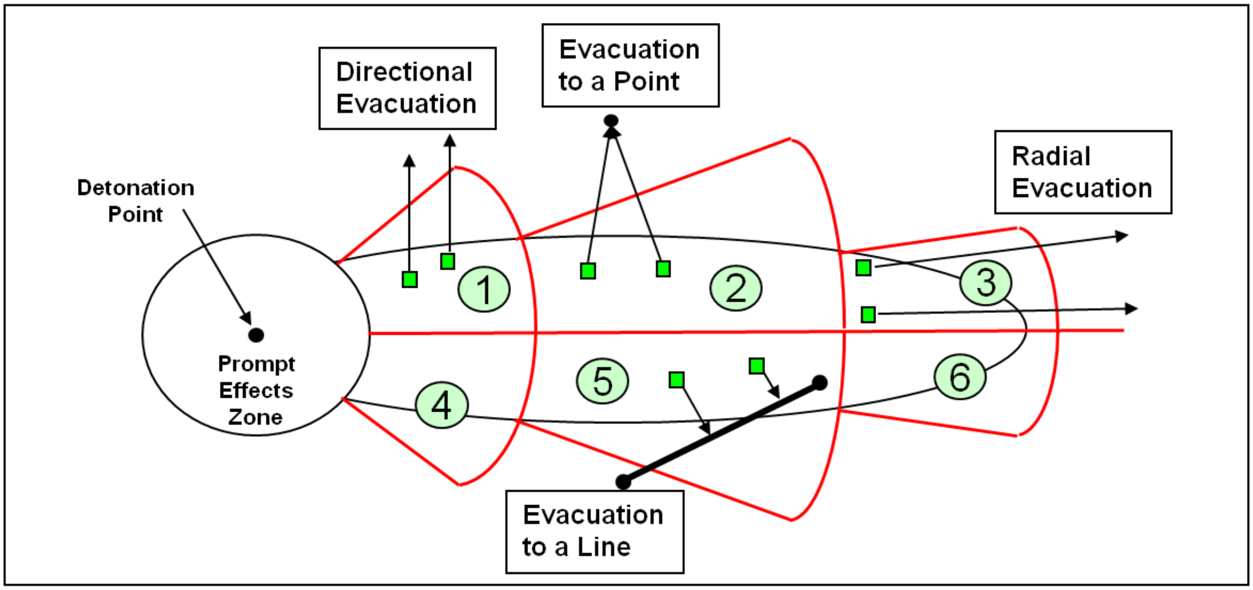

Figure 1. Exemplary evacuation regions and movement options for a typical Gaussian plume

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.[8]

[8] 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.

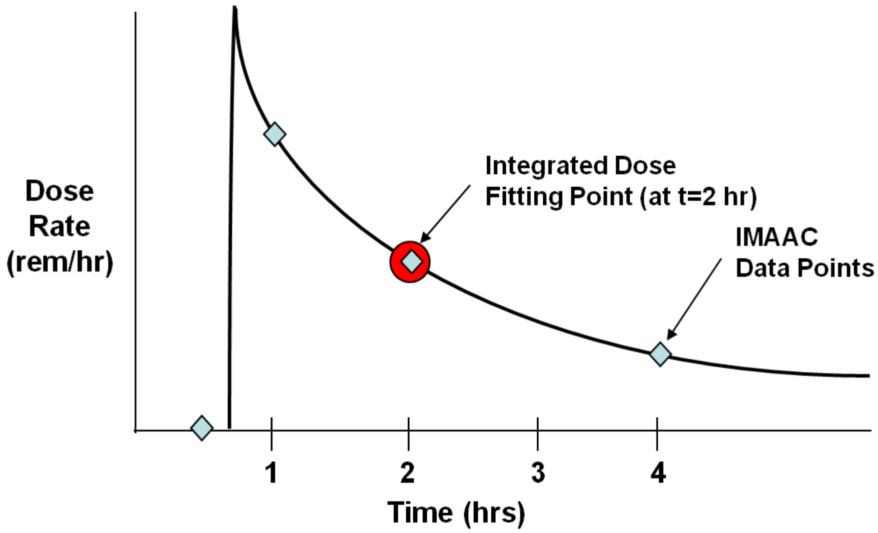

Figure 2. Temporal fitting protocol for IMAAC dose rate data

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 of Chicago is shown in Figure 3.

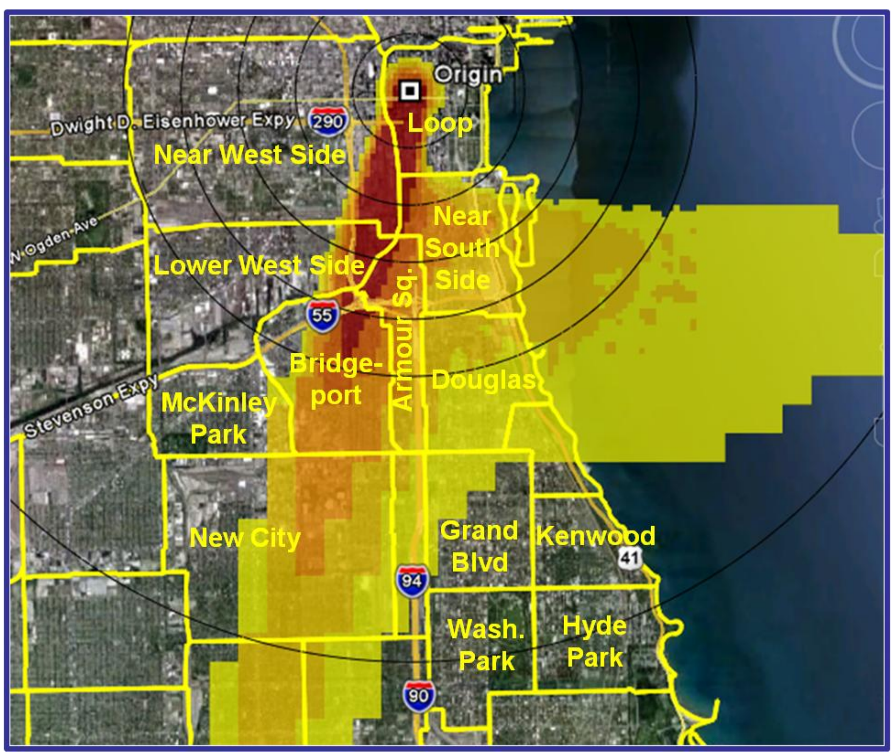

Figure 3. Illustrative Chicago neighborhood zones for evacuation planning

3.3. 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 factor of buildings in many areas of Chicago is 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.[9]

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 Chicago region have been incorporated into the sheltering calculations performed by NUEVAC. NUEVAC permits the easy display of the shelter quality data, as shown in Figure 4, and employs the data in various sheltering and evacuation strategies as described later in this report.

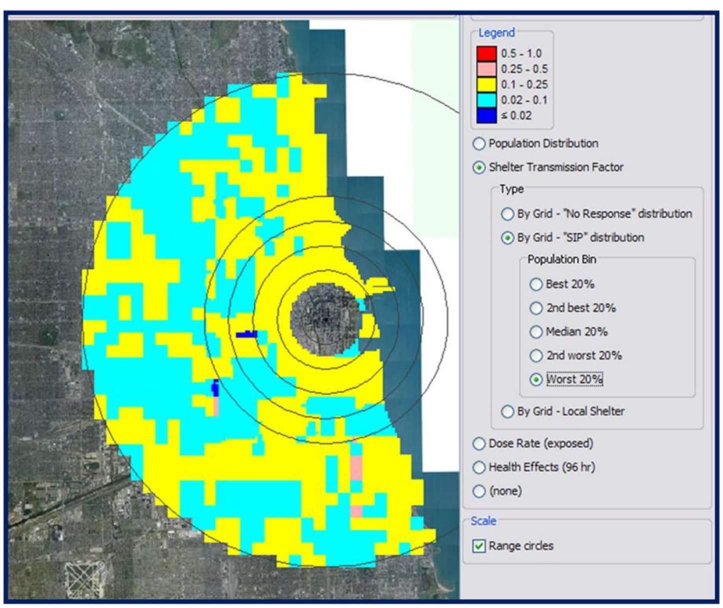

Figure 4. Example of NUEVAC display of Svalin shelter quality data

[9] For more discussion of shelter protection factors of various structures see references identified in footnotes 1 and 2.

4. Chicago Baseline Scenario – Regional Results

4.1. Chicago Baseline Scenario and Evacuation Options

Analysis of the regional evacuation options for Chicago was based on a 10 kt detonation assumed to occur in the downtown area on January 14, 2009. At the time of the detonation, the winds are generally from the north, causing the central area of the plume, with the highest concentration of radioactive particles, to extend south from the detonation point in downtown Chicago. However, some wind shear is present, causing a side lobe of the plume, having a lower deposition level, to extend to the east over Lake Michigan. The plume shape at one hour following the detonation is shown in the left diagram in Figure 5.

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

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[10] 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. **Shelter-Dependent Transit or Evacuation:** 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 must be used to calculate the effectiveness of this strategy.
5. **Radial Evacuation Away from Detonation Location:** Radial evacuation has been used as a surrogate for uninformed evacuation away from the detonation area.

The informed evacuation plan for the Chicago scenario is illustrated in the diagram in the lower right in Figure 5. The white lines in the diagram at the right illustrate the general evacuation direction for each zone. Occupants of the zones west of the centerline of the plume travel westward away from the highest dose rate zones. Those in the zones east of the centerline travel to the shore of the lake and then proceed southeast to exit the hazardous 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).

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[10] 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.

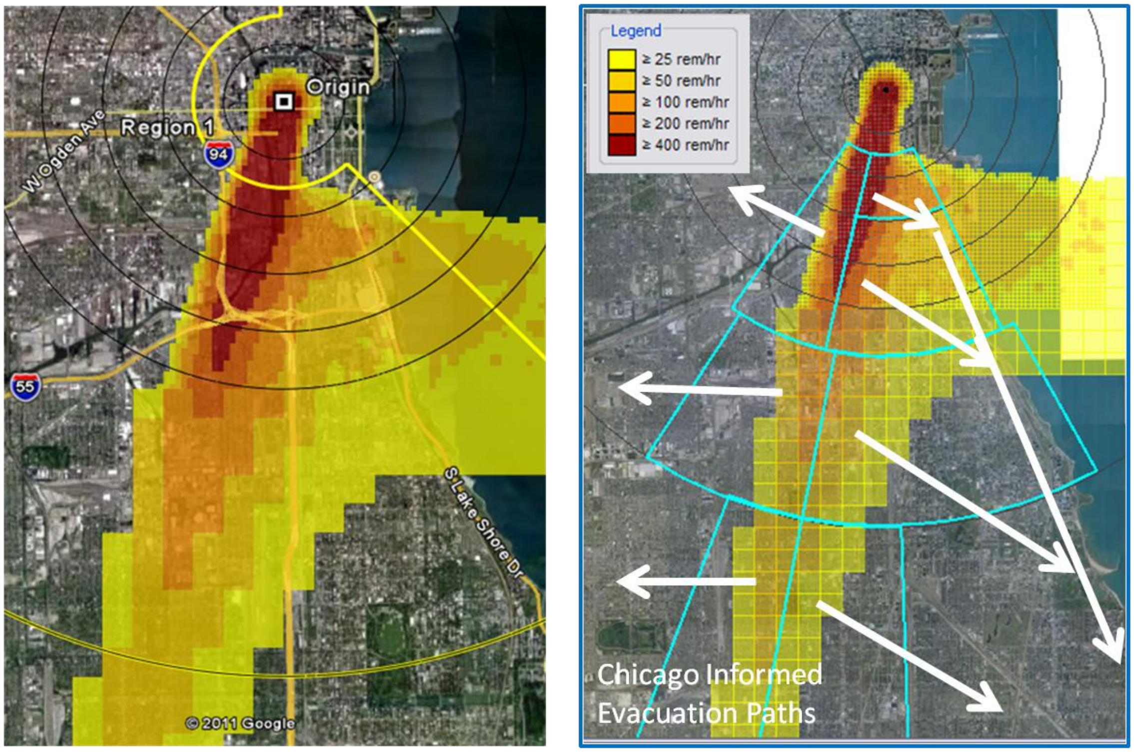

Figure 5. Chicago baseline 10 kt scenario (left) with informed evacuation routes (right)

4.2. Regional Results – Sensitivities to Shelter Quality

The casualty levels (numbers of injuries and deaths) caused by the baseline Chicago scenario for various sheltering and evacuation strategies are shown in Figure 6. 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 100 thousand casualties. If only inadequate shelter (PF=2) is available, sheltering in place is not the best strategy. Where information on the plume location is available, early informed evacuation away from inadequate shelter and out of the region will reduce casualties. Even uninformed (radial) evacuation will reduce casualties below those resulting from remaining in inadequate shelter. If the entire population had adequate shelter (PF=10), the total casualty level is reduced to ~8,600. Even the use of informed evacuation will reduce the casualty level to only ~6,000. Casualties will be higher if the informed evacuees leave too early (i.e., at 1 hour after detonation) and transit the radiation field before the highest dose rates have decayed.

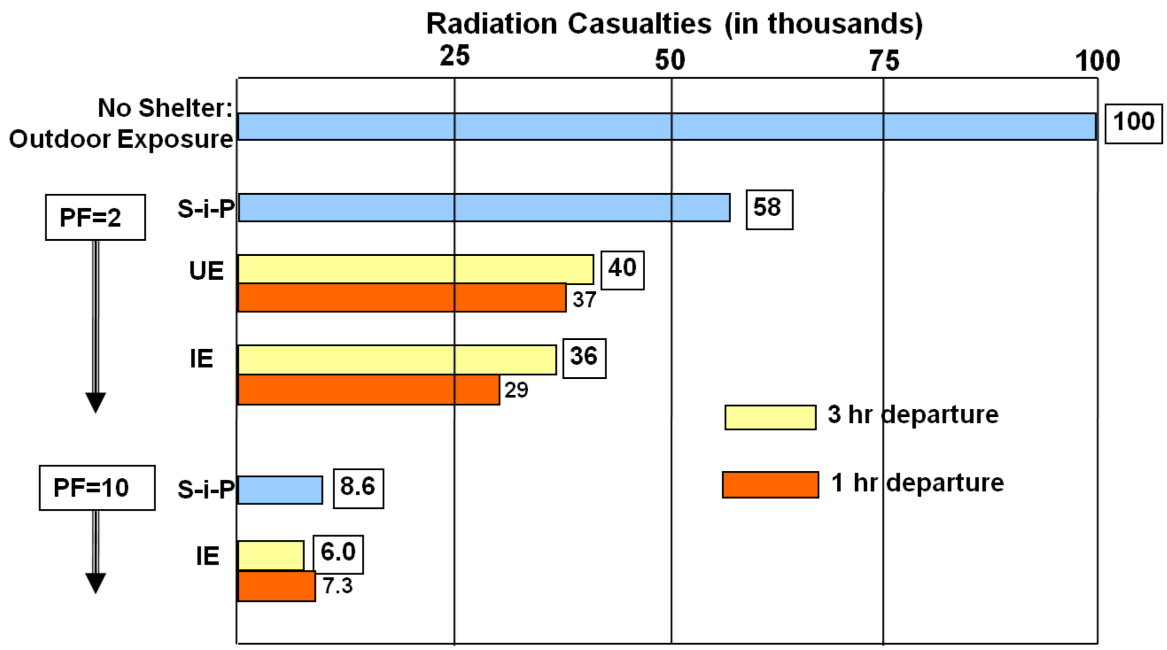

Figure 6. Casualty numbers for alternative shelter-evacuate strategies

For those who find themselves in poor or inadequate shelter, transit to better shelter can reduce total integrated dose, thereby reducing the number of casualties from those shown in Figure 6. 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 7 shows the reduction in radiation casualties (as compared to shelter-in-place) from inadequate or poor shelters resulting from shelter transit or uninformed evacuation. (Note that a higher number in Figure 7 represents a good outcome – the REDUCTION in injuries and fatalities.) The greatest improvements occur when transiting or evacuating from the worst shelters (PF=2). Individuals will often 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.

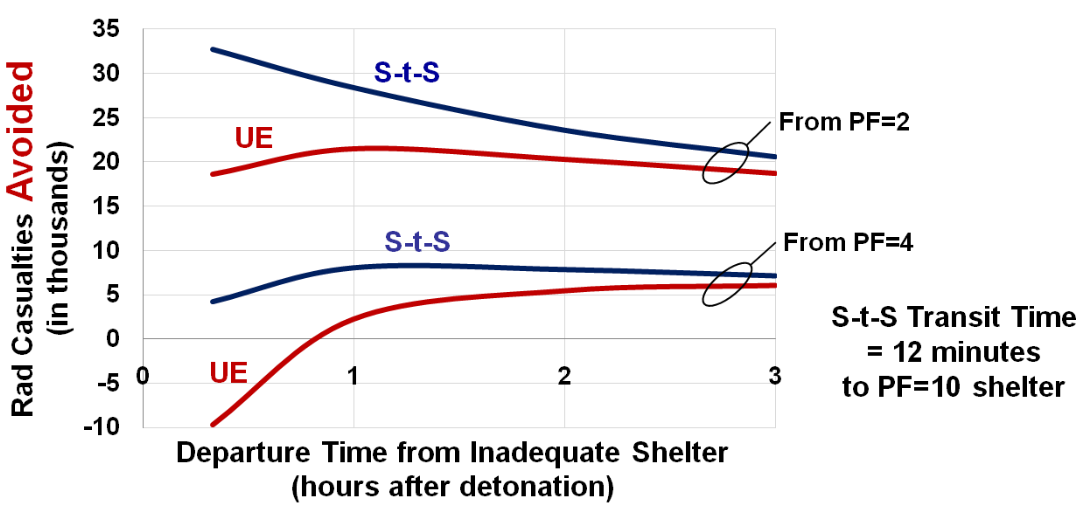

Figure 7. Evacuation time sensitivities from inadequate shelters

When comparing two evacuation strategies, it is often useful to understand the geographical areas in which differences in casualties occur, in addition to the overall magnitude of expected casualties. 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 8.

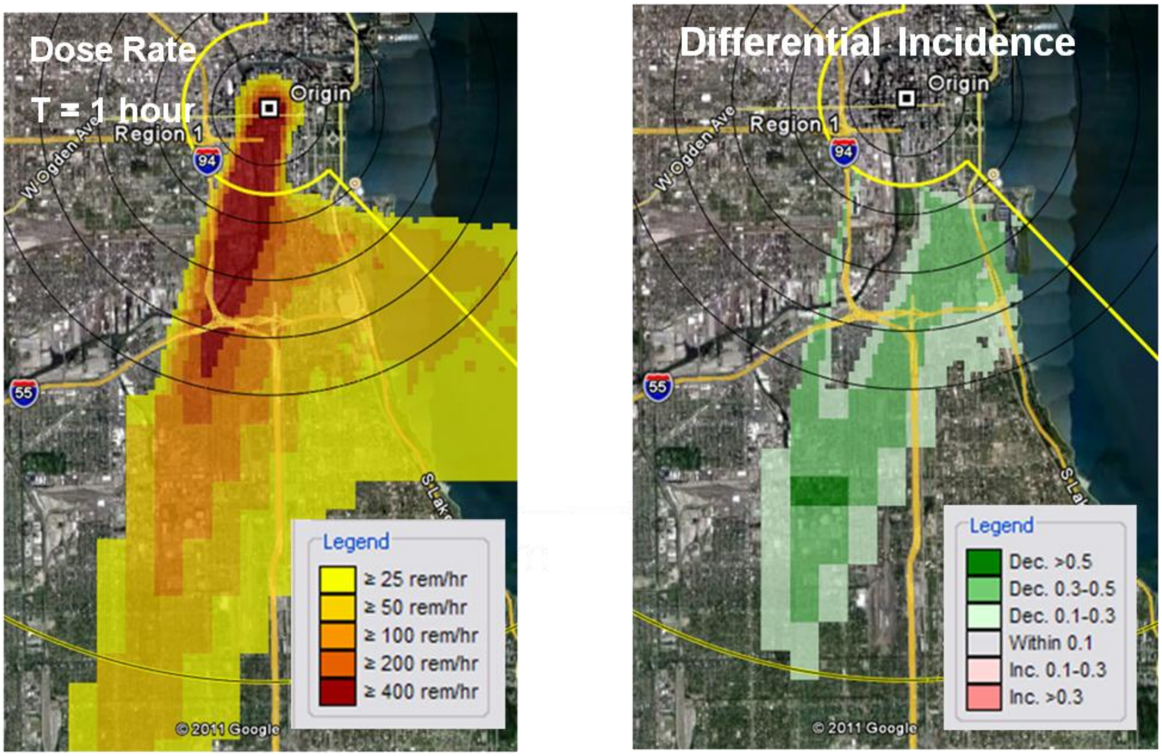

Figure 8. Differential casualty incidence; (Reduction due to shelter transit from PF=2 to PF=10, at T_d=1 hour with T_t=12 min, as compared to shelter-in-place with PF=2)

As is often the case with evacuation or shelter transit, the greatest improvement due to movement away from poor shelter occurs at the edge of the highest dose rate region (i.e., where the dose rate one hour after detonation ~100 rem/hr). This region where incidence of radiation sickness or death decreases becomes smaller as the shelter quality of the region improves, almost disappearing for adequate shelter levels. The use of this and similar incidence spatial profiles can assist planners in understanding the relative impacts of their sheltering and evacuation recommendations.

4.3. Regional Results with Chicago Svalin Data

The use of the Svalin data for the Chicago area permits a more realistic calculation of total regional casualties than can be achieve by presuming some nominal regional protection factors, as was done in the last section.

Shelter-in-Place (Svalin) Results

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 9. These results show that the shelter quality in the Chicago region is quite good relative to the threshold adequate shelter level (PF ~ 10). The significance of these results is further highlighted in reference to Figure 6. The shelter-in-place results for Chicago indicate that the casualty level drops from ~100,000 individuals if the population is exposed outdoors, to 3.6% of that level if all adopt an immediate shelter-in-place strategy.

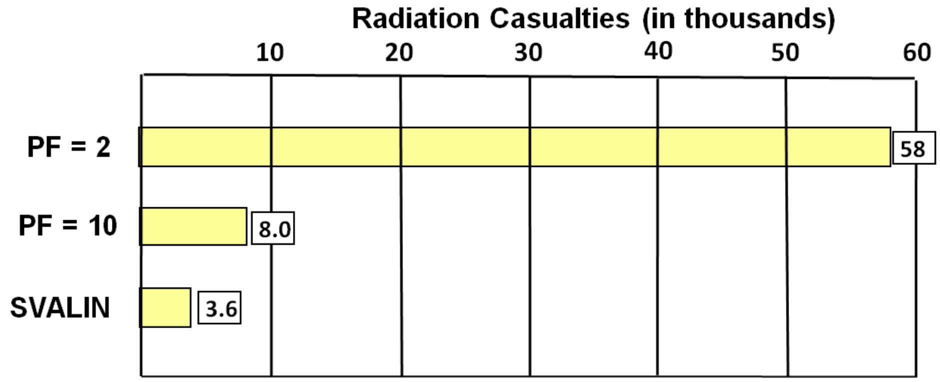

Figure 9. Shelter-in-place casualties for fixed and Svalin protection factors

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 Shelter Quality Estimates

The availability of shelter quality distributions for Chicago permits 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

Two analysis cases are illustrated in Figure 10. The first case assumes that individuals in poor shelters are able to find nearby adequate shelter (PF = 10). These individuals are assumed to depart when the transmission factor of their shelter is less that PF = 6.7.[11] The blue lines in Figure 10 show the reduction in the number of casualties due to this transit. Compared to the number of Svalin shelter-in-place casualties, the reductions in the blue lines represent relatively

[11] Sensitivity analysis using various departure criteria within NUEVAC showed that the specified departure criteria offered the greatest reduction in casualty levels. Note that the optimal departure criterion depends on the quality of the destination depends on the quality of the destination shelter. Hence the criterion for a destination with PF=20 is different, and results in a greater number of transits.

small improvements. 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. These are fairly demanding requirements to expect of a population in the confusing and uncertain environment following the detonation. The situation is somewhat improved if the destination shelter has a higher quality. Results for a destination quality of PF = 20 are shown in the red lines in Figure 10. For this case, individuals who find themselves in shelters worse that PF = 10 depart for better shelter. Greater improvements are possible here. However, the requirement for short transit times and the need to delay departure past the peak dose rate remains. While individuals in the poorest shelters are best served by evacuation or shelter transit, their numbers are small for the Chicago area under consideration in this analysis.

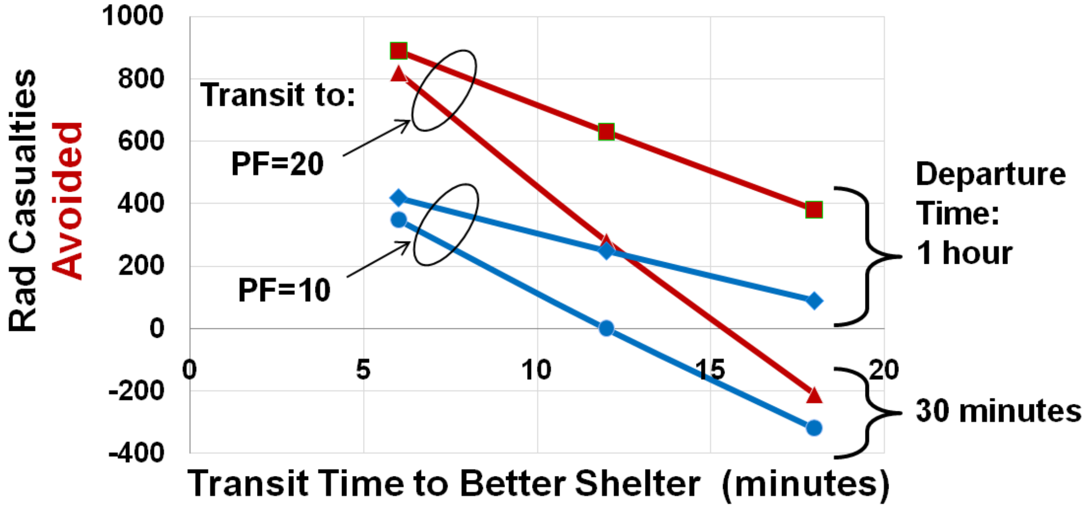

Figure 10. Utility of shelter-dependent transit strategies (Chicago Svalin Data)

Late Time Departure from Chicago (Svalin) Shelters

Departure from Chicago shelters at later times when the dose rates in the fallout region have decayed significantly will reduce acute radiation casualties. The reduction in overall (Svalin) casualties resulting from shelter departure between 6 and 36 hours following the detonation is shown in Figure 11. These calculations assume that evacuation occurs via the informed routes illustrated in Figure 5. Earlier evacuation away from the highest hazard areas can reduce casualties since the sheltering occupants escape the doses estimated in the baseline calculations, which integrate exposures over a 100 hour sheltering interval. 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.

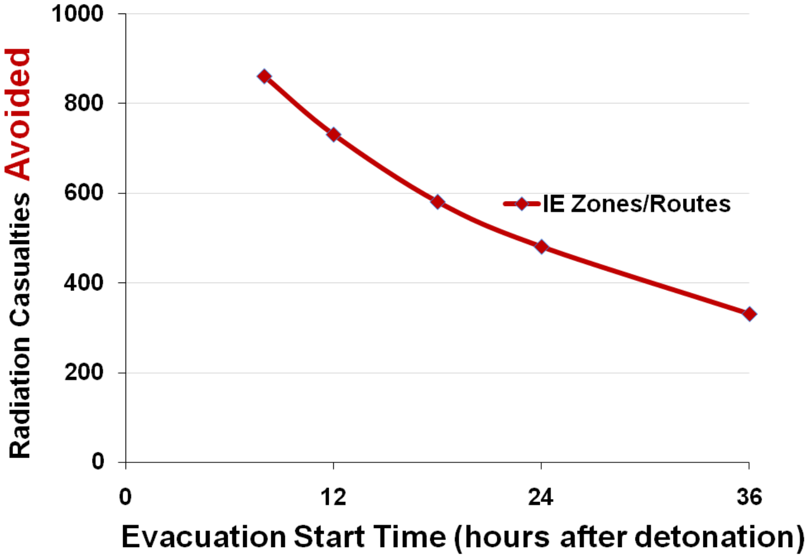

Figure 11. Delayed shelter departure time sensitivity (Chicago Svalin Data)

Chicago (Svalin) Results Summary

An overall comparison of the results of Chicago Svalin shelter-evacuate options is shown in Figure 12.

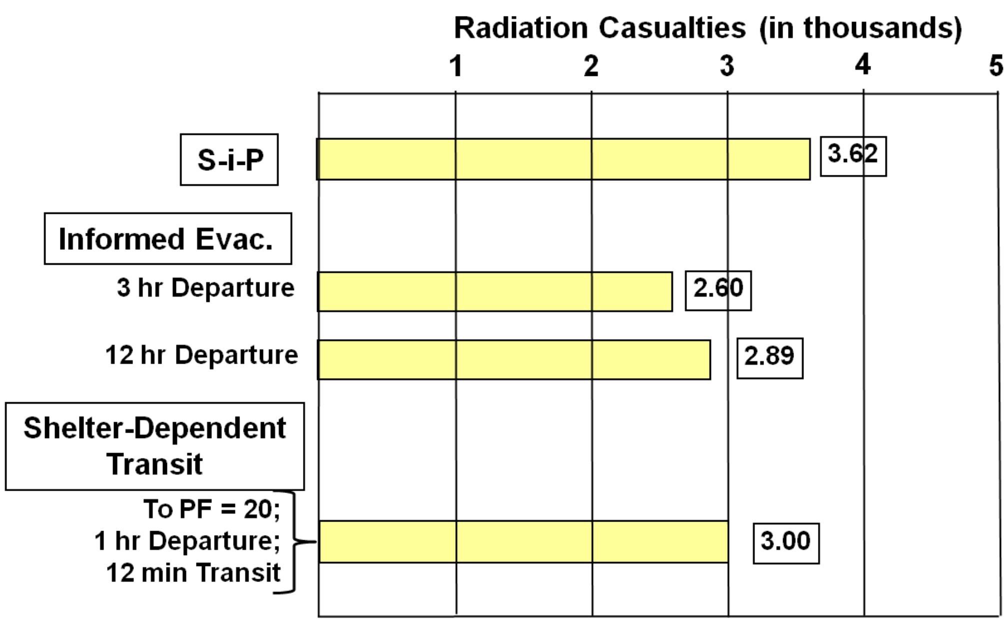

Figure 12. Summary data for Svalin shelter-evacuate strategies

The results in Figure 12 show that improvements over Svalin shelter-in-place can be made. However they result in demanding situational assessment and individual decision making functions. Svalin shelter-in-place (S-i-P) is considerably more effective that even informed evacuation from adequate (PF = 10) shelter. It is possible to improve on the pure shelter-in-place option. If excellent information on the hazardous fallout region can be acquired and communicated, then informed evacuation using the routes shown in Figure 5 could occur. If that could be done within three hours of the detonation (perhaps an optimistic assumption) a reduction of approximately 1000 acute radiation casualties might be achieved. As discussed earlier in conjunction with Figure 11, even a delay to twelve hours in the informed evacuation would reduce casualties by approximately 700 over an extended shelter-in-place strategy. The fact that relatively early informed evacuation is of some value should motivate the earliest possible situation awareness for fallout hazards as a key aspect of the regional planning process. The final bar on Figure 12 shows that improvement is possible using a shelter-dependent strategy, but at the cost of increasing complexity, including the need to identify initial and destination protection factors, as well as a departure criteria that results in only those transits that would be beneficial.

5. Chicago Scenario – Exemplary Point Analysis

5.1. 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 Chicago exemplary point analysis focuses on a single case study, the Chinatown fire station. 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.[12]

5.2. Exemplary Point Sensitivities – The Chinatown Fire Station

The Chinatown fire station is in a critical position relative to the Chicago scenario fallout region. It is to the east of the centerline of the plume and the highest dose rate areas. However, since it is also relatively near the shoreline of Lake Michigan, the natural tendency of occupants of the region near the fire station might be to evacuate to the west, particularly if early situational assessment activities showed that the plume was being deposited generally south of downtown. However, this would turn out to be an incorrect presumption. The sensitivities associated with

[12] For a broader discussion of a more diverse set of exemplary points in the Los Angeles area, see Brandt, L.D., and A. S. Yoshimura, "Analysis of Sheltering and Evacuation Strategies for an Urban Nuclear Detonation Scenario."

evacuation timing and routes from this point illustrate several challenging problems associated with movements near the highest dose rate portions of the fallout area.

The three evacuation routes analyzed for the Chinatown fire station are shown in Table 1.

Table 1. Evacuation Routes for the Chinatown Fire Station (212 W. Cermak Road)

Route	Description
Baseline	East on E. Cermak; South on Martin Luther King to I-55; East to South Lakeshore; Continue Southeast on South Lakeshore Drive
Alternate-1	South on I-94
Alternate-2	West on W. Cermak to S. Archer Ave.; South-West on S. Archer to enter I-55; West/Southwest on I-55

The routes chosen for analyses for Point 1 highlight the hazards of poor route selection during early evacuation. The baseline (BL) route is the implementation of the informed evacuation route that reduces exposure to high radiation levels to the degree possible. Alternate route 1 (Alt-1) approximates the uniformed evacuation route, since it proceeds in a radial path away from ground zero. Alternate route 2 (Alt-2) might be appealing since it proceeds away from the barrier offered by Lake Michigan. In fact, Alt-2 would be the best route if the plume direction were only a few degrees counterclockwise from the baseline scenario. The dose rates encountered during evacuation along these routes for a departure time of three hours are illustrated in Figure 13. This depiction of the radiation exposure levels along the routes provides a particularly compelling illustration of the impact of incorrect route choice and the rapid changes in radiation levels at locations near the center of the plume.

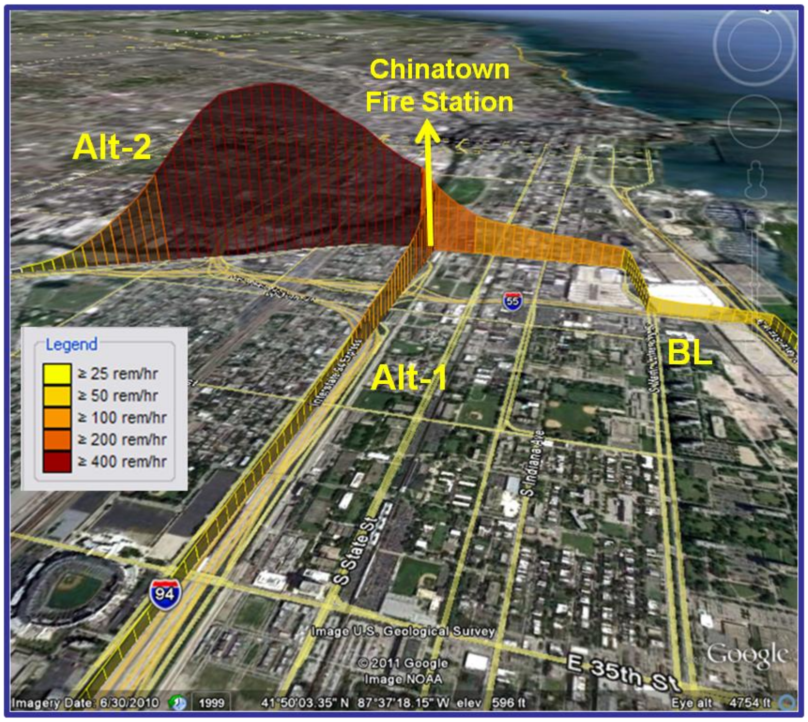

Figure 13. Dose rate profiles for evacuation from the Chinatown fire station

Evacuation results shown in Figure 14 for the Chinatown station 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 confirm the intuitive message from Figure 13 – that departure along the Alt-2 route soon after the detonation is much worse than the other two options. Evacuation doses from the baseline and Alt-1 routes are almost equal. Note that the magnitude of the evacuation doses decrease dramatically by twelve hours following the detonation, making the choice of route somewhat less critical for delayed evacuations. The results in Figure 14 highlight the very large risks associated with early evacuations from 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.

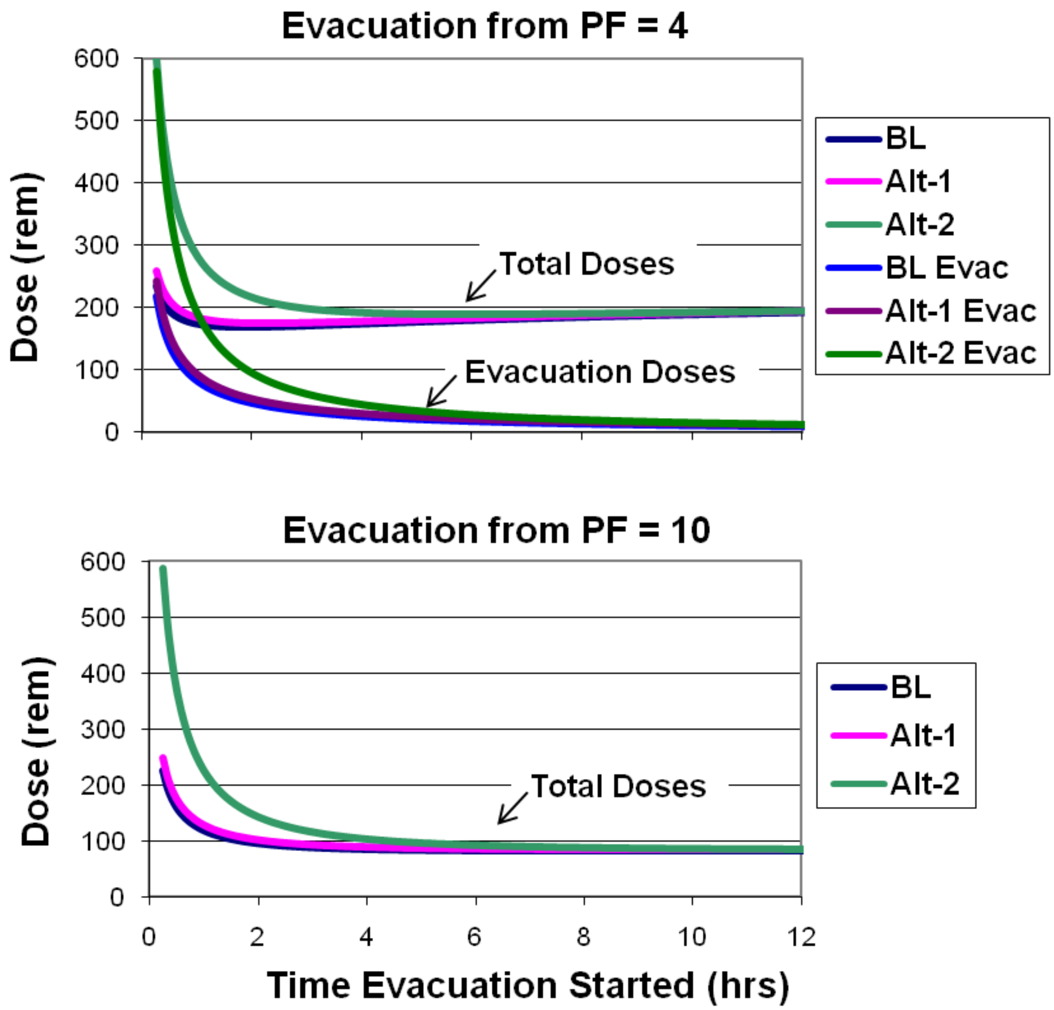

Figure 14. Evacuation analyses for the Chinatown fire station

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 the Chinatown fire station. If the plume direction were shifted less than 10 degrees counterclockwise, the best evacuation route of the three would be Alt-2, out I-55. 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.

5.3. 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.

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. Key Findings and Recommendations

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

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

Chicago Region Shelter Quality: The radiation protective capabilities of buildings in the hazardous fallout region of the baseline Chicago scenario are generally very good. This results in the following findings:

- *Utility of Chicago Shelter-in-Place Strategy:* The effectiveness of shelter-in-place strategies in Chicago exceeds informed evacuation strategies even for very optimistic assumptions regarding information availability and implementation compliance. The overall casualty levels (~3,600) are well below those expected for the threshold adequate shelter levels (PF~10).
- *Shelter Transit Effectiveness:* High shelter quality in Chicago makes shelter transit useful only for the small number of people who find themselves in the poorest shelters (including outdoors and vehicles). Some improvement in casualty numbers can be achieved using shelter-dependent strategies that involve shelter transit by these individuals.

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