Lawrence Livermore National Laboratory

Regional Shelter Analysis – External Gamma Radiation Exposure Methodology

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Regional Shelter Analysis – External Gamma Radiation Exposure Methodology

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Abstract

During normal operations, buildings can protect their occupants from outdoor hazards, including nuclear fallout and other external gamma radiation hazards. Purposeful sheltering can increase this protection. The physics of building protection against external gamma radiation is relatively well understood and we can characterize the protection afforded by individual buildings. However, an operationally efficient, regional-scale methodology to account for building protection effects has not previously been available. Such a method is necessary because (a) the overwhelming majority of the US population is indoors at any given time and (b) a regional-level building protection methodology could better estimate populations truly at risk in emergencies, support improved decision-making (shelter vs. evacuation decisions), and help guide resources towards those most at risk.

The Regional Shelter Analysis (RSA) methodology provides a comprehensive, yet operationally efficient method for population-based risk analyses. Specifically, it accounts for (a) building protection distributions (within and among different buildings) and (b) population postures (how people are distributed within and outside of buildings). The RSA method could support a common operating picture by providing user specific results that have the resolution appropriate for individual user's needs while still being consistent with the information being provided to the other users. The method employs existing building and population databases and is compatible with most modern exposure and injury assessment tools.

This report presents the RSA methodology and discusses general operational considerations, with a focus on external gamma radiation exposures. To place this work in the context of prior efforts and current initiatives, a focused literature review is provided that identifies the relevant literature, scientific findings, and datasets from a variety of scientific fields. Other reports in this series will discuss (a) the inhalation exposure pathway and (b) specific RSA implementations.

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1. Introduction

Buildings can protect their occupants from outdoor hazards. In some cases, this protection can reduce hazardous exposures by an order of magnitude or more. The degree to which indoor exposures are reduced, relative to being outdoors, depends upon the specific building, hazardous material, and exposure pathway.[1] This report considers building protection from exposure to external gamma radiation (gamma radiation that originates from outside the body). Radiation emergencies may also involve atmospheric releases of inhalable radioactive particles and gases. Building protection for this case is covered in a separate report [2], [3].

Because, on average, the US population spends about 87%, 8%, and 5% of their time indoors, outdoors, and in vehicles, respectively [4]; it is essential that population-level public health and emergency response exposure and risk assessments incorporate an accurate building protection component. However, as discussed in the (*2. Historical Perspective*) section below, building protection considerations are often limited (or entirely omitted) in current exposure and casualty assessments. This may be due, in part, to the complexity of the problem, as a comprehensive solution needs to address building construction and operations, population distributions (both within individual buildings and among different buildings in a given region), the physics of the external gamma radiation exposure pathway and its hazard dose-response relationships against a variety of potential health outcomes. Regardless, current US Federal exposure assessment tools and guidance have limited ability to assess the degree to which buildings protect individuals, e.g., [5]–[9].[2] Because of this, exposure assessments can over-estimate population exposures and health risks – which is potentially problematic as protective actions could be applied to a much wider population than required. In situations in which only limited resources are available, the use of outdoor-only assessment models and / or imprecise building protection modeling could inadvertently allocate resources to low risk populations and so reduce the levels of assistance provided to the populations most at risk or most amenable to assistance [16], [17].

[1] Unless otherwise noted, we interchangeably use the term outdoors, unprotected, and unsheltered to simplify the discussion. Individual outdoor exposures can, and do, vary for a variety of reasons [1]. The theory developed in this report is capable of handling regional variation in both outdoor and indoor exposures.

[2] The US Department of Defense Hazard Prediction and Assessment Capability (DoD HPAC) model contains an optional fallout protection capabilities [10]–[13]. Similarly, the United Nations, US EPA, and the US Department of Energy, including the National Atmospheric Release Advisory Center (NARAC) model, provide optional, operational estimates to which indoor populations are shielded from outdoor radiological hazards [5], [14], [15]. All of these cases, except HPAC and NARAC which are in the process of upgrading their building protection capabilities using elements of the RSA method, use single estimates for broad, building-class-based categories, e.g., residential vs. commercial buildings, rather than the more relevant protection factor distributions for the detailed range of building classes or types currently in use.

The Regional Shelter Analysis (RSA) methodology described here aims to partially address these issues. Initially developed as a stand-alone tool, elements of the RSA methodology are currently being integrated into operational emergency response models including the US Department of Energy National Atmospheric Release Advisory Center (NARAC) and US Department of Defense Hazard Prediction and Assessment Capability (HPAC), see **Figure 1**. This RSA method thus represents a new, operationally feasible model that incorporates both building protection and population distributions - in contrast to most prior work, which has primarily focused on elucidating the processes and parameter values to assess (and improve) individual building protection.[3] The RSA methodology is intended to provide practical assistance to government officials in designing and implementing multi-hazard, multi-exposure pathway strategies that reduce population exposures to many important types of hazardous materials, including gamma radiation – both for emergency situations requiring rapid decisions, e.g., sheltering, evacuation, remediation, and/or relocation, as well as for public health responses to ongoing chronic hazardous exposures, e.g., [19], [20]. Such an integrated analysis framework may be of practical use when minimizing acute (emergency) and chronic hazardous exposures through changes in the building protection and changing population locations. These could be accomplished in advance of actual emergencies through changes in zoning and building code standards; urban and transportation planning; and developing in advance plans for moving at-risk populations using sheltering, evacuation, and relocation strategies [14], [15], [21]. The RSA method is (a) spatial scale independent (suitable for use on scales ranging from individual rooms, buildings, neighborhoods, cities, to entire countries), (b) compatible with current building and population databases as well as most current exposure and health effect models and measurements, and (c) computationally efficient during operational use (RSA methodology typically determines the distribution of indoor exposures by multiplying the outdoor exposure(s) by a set of predetermined linear scaling factors, see **Figure 2**).

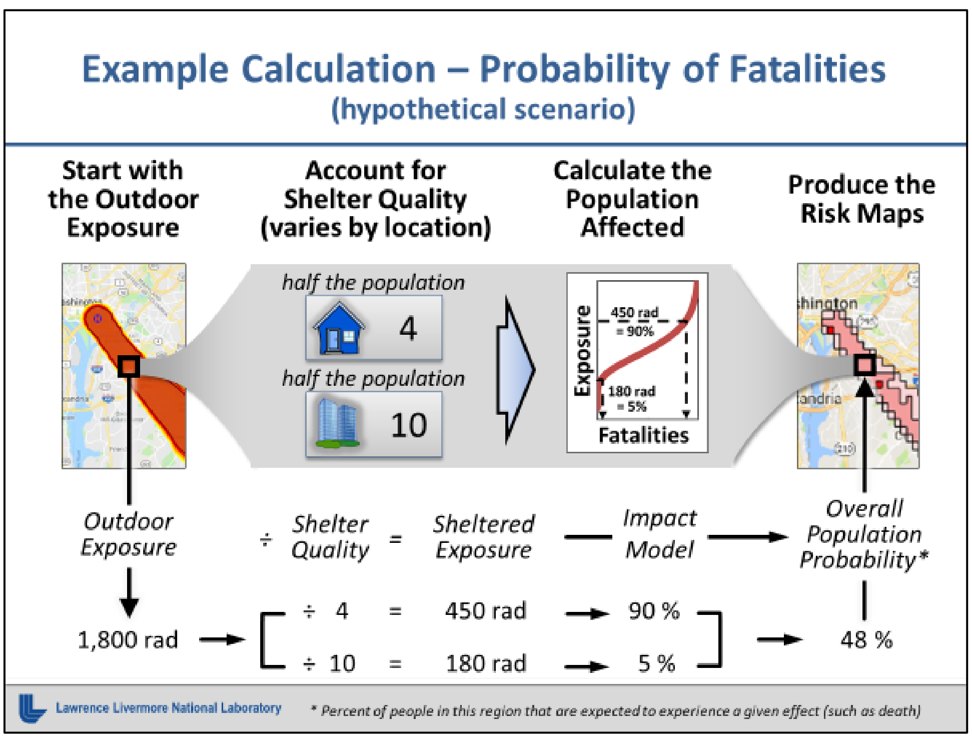
This report is part of a series of reports describing the Regional Shelter Analysis methodology and application. This report, which focuses on external gamma exposures, describes (a) prior key building protection and sheltering research, (b) the physical basis of building protection, (c) the general RSA methodology, which combines the protection provided by buildings with the population distribution within and among the different buildings, and (d) general, operational equations for calculating population impacts for external gamma exposure. Separate reports (a) describe the RSA methodology for hazardous inhalation exposures [2], (b) illustrate, for planning officials and a general scientific audience, the key considerations that govern building protection against inhalation hazards [22], and (c) demonstrate the applications of the RSA methodology for (i) inhalation particulate hazards [3] and, in the future, (ii) external gamma

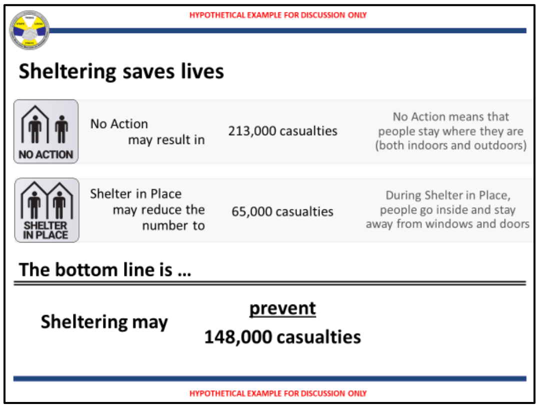
[3] As discussed further in the (*6. Discussion*) section, accounting for distributions of building protection can be critical for accurate assessments as the degree of protection provided by buildings can be highly variable, both within a given building and among different buildings, see [1], [18].

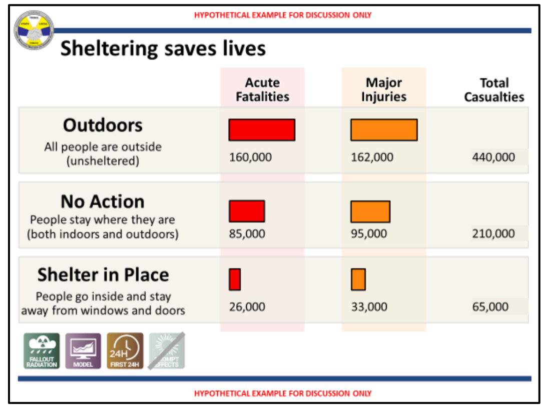
exposures. To allow each report to function as a stand-alone document, this report contains some information that is also duplicated in other reports.

Figure 1 (next page). Examples of draft products that illustrate possible output from the Regional Shelter Analysis method. At the time of writing, product development and review is on-going and so final products may be different than those shown here. Modeling results shown are illustrative and only consider the impacts of fallout radiation.

Figure 2 (this page). Schematic illustrating how the use the Regional Shelter Analysis method to calculate the fraction of the total population impacted given (a) an outdoor exposure, (b) shelter quality estimates for the region of interest, (c) a model that translates exposure to the probability of impact (fatalities for this example). Modeling results shown are illustrative and only consider the impacts of fallout radiation.




HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY
Sheltering saves lives
NO ACTION
No Action may result in
213,000 casualties
No Action means that people stay where they are (both indoors and outdoors)
SHELTER IN PLACE
Shelter in Place may reduce the number to
65,000 casualties
During Shelter in Place, people go inside and stay away from windows and doors
The bottom line is …
Sheltering may
prevent
148,000 casualties
HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY


HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY
Sheltering saves lives
Acute Fatalities
Major Injuries
Total Casualties
Outdoors
All people are outside (unsheltered)
160,000
162,000
440,000
No Action
People stay where they are (both indoors and outdoors)
85,000
95,000
210,000
Shelter in Place
People go inside and stay away from windows and doors
26,000
33,000
65,000
HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY


Outdoor
OUTDOOR
All people are outside (unsheltered)
worse
protection
better
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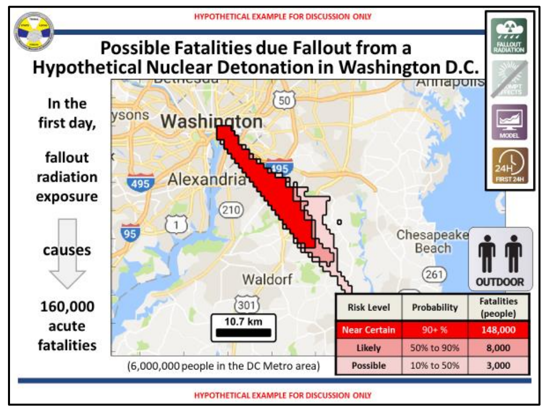
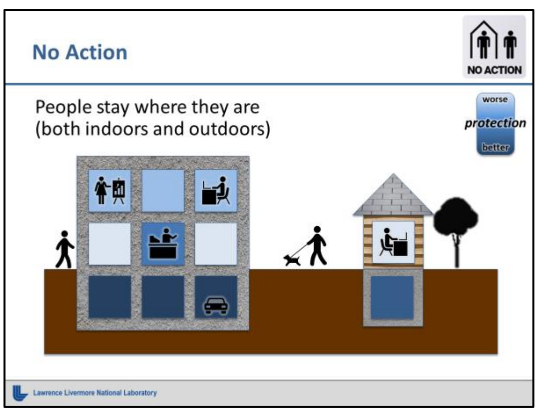
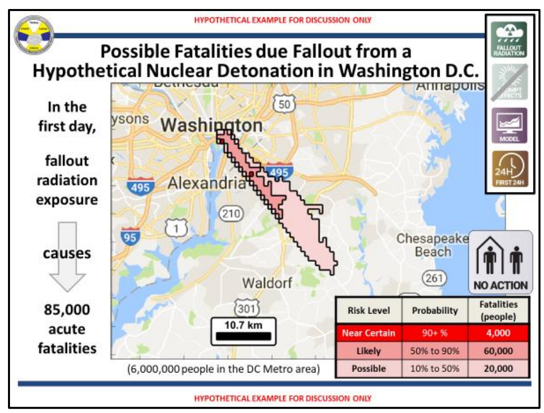
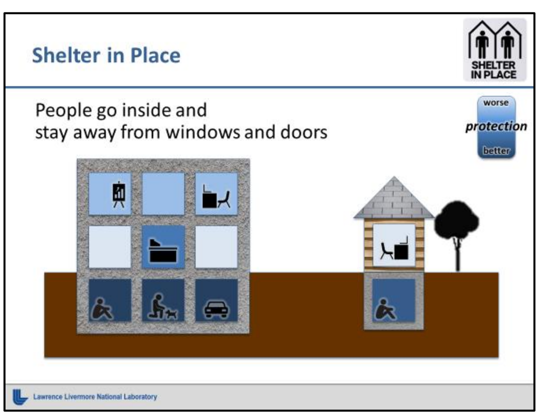

HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY
Possible Fatalities due Fallout from a Hypothetical Nuclear Detonation in Washington D.C.
In the first day,
fallout radiation exposure
causes
160,000 acute fatalities
Washington
Alexandria
Chesapeake Beach
Waldorf
10.7 km
OUTDOOR
Risk Level | Probability | Fatalities (people)
Near Certain | 90+ % | 148,000
Likely | 50% to 90% | 8,000
Possible | 10% to 50% | 3,000
(6,000,000 people in the DC Metro area)
HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY


No Action
NO ACTION
People stay where they are
(both indoors and outdoors)
worse
protection
better
Lawrence Livermore National Laboratory


HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY
Possible Fatalities due Fallout from a Hypothetical Nuclear Detonation in Washington D.C.
In the first day,
fallout radiation exposure
causes
85,000 acute fatalities
Washington
Alexandria
Chesapeake Beach
Waldorf
10.7 km
NO ACTION
Risk Level | Probability | Fatalities (people)
Near Certain | 90+ % | 4,000
Likely | 50% to 90% | 60,000
Possible | 10% to 50% | 20,000
(6,000,000 people in the DC Metro area)
HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY


Shelter in Place
SHELTER IN PLACE
People go inside and
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worse
protection
better
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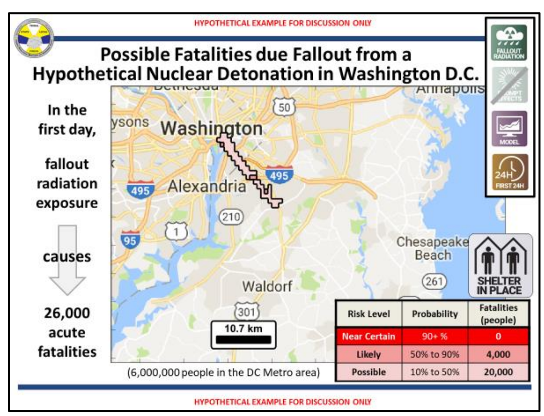

HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY
Possible Fatalities due Fallout from a Hypothetical Nuclear Detonation in Washington D.C.
In the first day,
fallout radiation exposure
causes
26,000 acute fatalities
Washington
Alexandria
Chesapeake Beach
Waldorf
10.7 km
SHELTER IN PLACE
Risk Level | Probability | Fatalities (people)
Near Certain | 90+ % | 0
Likely | 50% to 90% | 4,000
Possible | 10% to 50% | 20,000
(6,000,000 people in the DC Metro area)
HYPOTHETICAL EXAMPLE FOR DISCUSSION ONLY

2. Historical Perspective

This section provides the historical context of both (a) the scientific understanding of building protection against external gamma radiation and (b) the use of building protection, including sheltering, within the context of public policies and practice in radiation emergencies. In this section, we make particular note of (a) key theoretical concepts and (b) the strengths and weakness of existing theory and data. Prior building protection approaches are reviewed here at a general level. We note that due to the large volume of prior work, this report highlights key literature and data, but does not provide a comprehensive, detailed review of all prior work.

2.1. External Gamma Radiation Exposures

In the 1950s, the US government initiated a civil defense program intended to mitigate the consequences of a nuclear explosion on its homeland [23]. While all nuclear weapon effects were considered, the hazard posed by fallout radiation, i.e., gamma rays emitted from radioactive particles deposited from a passing nuclear (mushroom) cloud, was of particular concern. Extensive experimental and theoretical studies were conducted to understand the protection that individual buildings provide their occupants [24]. By the 1960s, the science was sufficiently mature that the National Fallout Shelter System (Program) was set up to identify shelter locations nationwide [23]. By 1968, the US Office of Civil Defense reported that spaces for more than 160 million people had been identified [25]. Over time, the US response strategy evolved due to changes in the (a) the number and yield of USSR nuclear weapons; (b) reductions in the expected warning time for a nuclear attack; (c) financial constraints; and (d) national priorities [23]. However, shelter remained a key component of the US response strategy, either by itself or in combination with other strategies, such as evacuation [23]. Also, sheltering's potential to avoid 10+ million fatalities by reducing short-term exposure to fallout radiation has been consistently recognized, e.g., [26]. Eventually however, attention turned to all-hazards planning, with a focus on natural disasters, and the US fallout shelter program was scaled down and finally discontinued [23]. However, other countries, such as Switzerland, do currently maintain extensive civilian fallout shelters [27].

More recently, concerns over nuclear terrorism sparked a resurgence of interest in the impacts of, and appropriate civilian response to, an urban nuclear explosion, e.g., [28]–[31]. Modern fallout shelter research has typically focused on computationally intensive analyses of individual buildings and urban cores a few km in extent, e.g., [29], although recent work by Lawrence Livermore National Laboratory has developed novel fast-running codes that estimate fallout building protection [32]. Work on building protection over wider geographic regions existed previously as the US Department of Defense (US DoD) developed a world-wide fallout protection assessment capability for warned populations by combining (a) fallout protection estimates for 6 shelter categories (5 building/shelter types and open terrain) with (b) the geographic distribution of these building/shelter types [33]. Motivated in part by earlier RSA developments (e.g., [18], [32], [34]–[36]), the US DoD is updating and greatly expanding these capabilities, e.g., [10]–[13].

The above research has contributed to the current US guidance to: “take shelter in the nearest and most protective building or structure” in the immediate aftermath of a nuclear explosion [21]. In assessing the expected efficacy of this protective action, current US civilian guidance and practice provides building protection factors for a small number (2 to 10) of building types, each of which is associated with a single (or narrow range of) protection estimate(s) [5], [14], [21]. However, we note that the degree to which these estimates cover the expected range of US (or worldwide) building types is unclear since some of these building types, such as large office or residential buildings, have a wide range of protection factors (orders of magnitude), both within a given building and among different buildings [18] and some modern building types have not been previously studied. Indeed, on-going research suggests that the buildings examined in the prior studies are not representative of current US building stock. This on-going research may inform updates to the current practice.

Starting in the late 1960s, nuclear fallout shelter assessment capabilities were adapted and extended for use in planning for, responding to, and remediating nuclear power plant (NPP) accidents and radiological dispersal devices (RDD). As part of that extension, *Slade* [37] and *Spencer* [24] provided the initial theoretical basis for assessing exposure by, and building protection against, external radiation emitted from airborne and ground-based radioactive materials (termed cloudshine and groundshine, respectively). Motivated in part by the need to respond to, and remediate the impacts of, the Chernobyl and Fukushima NPP accidents, the early *Slade* [37] work was later extended by other researchers to include consideration of additional building (also called location or environment) types, a range of radioisotopes, a broad array of contaminated surfaces (including walls and nearby buildings/trees), as well as the movement of radioactive materials after deposition (weathering, resuspension, decontamination, remediation), e.g., [18], [38]–[45] and references therein. Analogous to the modern fallout shelter situation, these risk analysis capabilities continued to rely upon a relatively small number of representative building types that have either a single protection factor or a small set of protection estimates. The distribution of population within these building types (called population occupancy) was often left to the judgment of the individual analyst although broad estimates for some regions have been published and are available, e.g., [39], [40], [46], [47]. As an illustrative example, the 2013 UN assessment of long-term radiation exposure due to the Fukushima accident considered three types of buildings (wooden houses, fire-proof wooden houses, and concrete buildings) and two types of outdoor surfaces (paved and unpaved) [38]. Based on Chernobyl studies, these locations were predicted to initially reduce the external gamma radiation dose from ground contamination (groundshine). Individuals in (or standing on) these locations received 40%, 20%, 10%, 60%, and 75%, respectively, of the dose received by an individual standing on a reference surface (i.e., a uniformly contaminated, smooth, flat plane).[4] The fraction of time individuals spent within these locations was estimated based on census data and subject matter expertise. Recent research has highlighted the importance of including both realistic building protection estimates and population locations when assessing external dose [1].

The early nuclear power plant (NPP) accident research also provided a theoretical basis for assessing building protection in nuclear emergencies, either from external gamma radiation or from the inhalation of radioactive gases and airborne particles [37], [46], [48], [49]. These early efforts may have had limited utility due, in part, to the limited understanding of many practical details and the difficulty of accurately estimating building protection for a specific location, particularly for inhalation exposures which were being studied alongside external gamma radiation exposures. During this period, shelter came to be regarded as a low-cost, low-risk alternative for situations in which evacuation was not appropriate, e.g., severe weather, damage to transportation infrastructure, immobile populations (e.g., the injured, institutionalized, and/or elderly), and/or insufficient evacuation time [50]. Improvements in scientific understanding and a desire for a consistent, all-hazards response have resulted in the modern guidance that recommends shelter be considered in a broader array of situations, often in concert with other protective actions including evacuation [14], [15].

This historical trend in planning policy parallels the use of shelter as a protective action in responding to NPP accidents. The response to the Three-Mile-Island accident used evacuation as the primary protective action [51]. Similarly, sheltering was not significantly used during the response to the Chernobyl accident [52]; however, *Likhtarev et al.* [53] estimates that its use would have halved the collective radiation dose for individuals within 30 km of the reactor and it is reasonable to expect that individuals who were indoors for all or part of the time the radioactive plume passed by experienced reduced radiation exposure relative to those standing outside. Subsequent research supports this view and recommends more nuanced shelter-evacuation strategies depending on the extent of the release and other relevant conditions [54]. The response to the Fukishima accident used a combined shelter-evacuation strategy in which populations at successively greater distances from the NPP were initially sheltered and later evacuated [55], [56].

2.2. Building Characteristics, Populations, and Geographic Distributions

An RSA exposure assessment requires characterizing (a) the building protection of different occupied buildings, (b) the variation of protection within any given building as well as (c) the distribution of people among and within different building types, e.g., see

[4] For the Chernobyl/Fukushima scenarios, more radioactive material is expected to deposit on unpaved outdoor surfaces, such as lawns, than on paved outdoor surfaces, such as roads. Thus, an individual standing on an unpaved surface would receive a larger radiation exposure than an individual standing on a paved surface.

[34], [57]–[59]. The first two items require identifying and characterizing key building attributes (see the (*3. Building Protection Physics*) section). The latter requires understanding the purposes for which the building is used (also called occupancy). Complicating the calculations further, each of these factors can vary over time. For example, building operating conditions can change; and many cities have a daily migration pattern between outlying residences and commercial buildings in the urban core. There is currently a substantial, yet incomplete, set of databases to estimate these parameters, which are summarized here to provide context to the later development of the RSA method.

Prior research on time use has tracked where and how people spend their time during a normal day. These studies have been performed over many decades and in numerous countries, e.g., [60], and provide the foundation for characterizing the degree to which different types of buildings are occupied at various times. Natural hazard, e.g., earthquake, planning and response tools have extended these time use study results by correlating time use categories with the geographical distribution of building structural characteristics. *Brzev et al.* [61] and *Gamba* [62] provide a recent survey of global, regional, and local building databases (for the purposes of earthquake risk assessment) including key considerations on their use within an integrated analysis framework similar to that discussed here. We note that more detailed population estimates, either through examining individual building databases or harvesting social media, e.g., [63], are becoming available.

To provide the reader context for this report, we summarize here a few notable examples of local and regional building databases that provide structural and/or population attributes. The US Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) system provides estimates of how global populations are distributed into each of 89 model building types (e.g., small, lightweight wood frame; unreinforced masonry) and 2 building occupancy types (i.e., residential, non-residential) within the urban and rural regions of each country [64]–[67]. The related US Department of Homeland Security HAZUS model provides similar, but higher fidelity, estimates for US populations with 45 building construction and 33 building occupancy types delineated at US Census tract and Census block scales [68]–[71]. [5] The US Census, US Department of Energy, US Environmental Protection Agency, and independent researchers provide additional, supplemental information on US residential and commercial building properties and occupancy, although many of these sources have limited geographic distribution information [72]–[78]. In other countries, similar broad area information is also available [62]. Finally, detailed construction and occupancy information on large numbers of individual buildings is available for some locations. For example, local municipalities within the US often collect detailed occupancy,

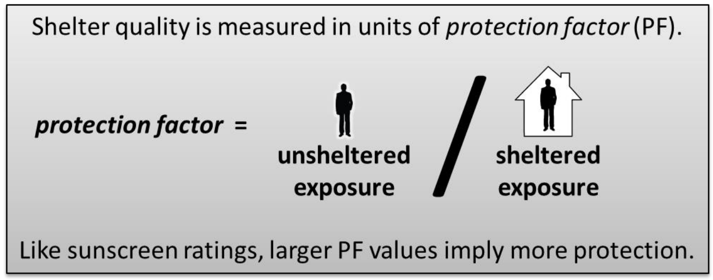
[5] Nominally HAZUS has 36 distinct building construction types. However, 6 building types may have basements. In this report we have separated the buildings with basements into separate building types. There are also outdoor and transportation (commuting) locations.

construction, and geographic location information for the purposes of assessing property taxes (the amount, type [e.g., year built, square footage, occupancy category], and quality of these data varies widely). Similarly, significant effort has gone into characterizing building stock for the purposes of energy efficiency. While access to this information can be limited, publicly available and research focused examples do exist, e.g., [79], [80]. Notably, this type of data has recently been adapted to estimate building protection for approximately 11.5 million UK residences [81], [82].

The authors are unaware of general estimates of the distribution of people within buildings. The number of people that can be present in a given room is well known to vary with room use and the maximum allowed population densities (occupancy loads) have long been codified within building construction and fire codes, e.g., (a) Table 1004.1.2 in the International Building Code and (b) Table 7.3.1.2 in the Life Safety Code [83], [84]. A limited number of building occupancy load surveys, such as [85] and references therein, have characterized typical (as opposed to maximum) occupancy loads (see also the occupancy discussion in [77]). When coupled with building floor plans and expert judgment, maximum and typical occupancy load estimates provide insight into the relative distribution of people within a given building. We note that, analogous to regional population distributions, building population distributions may vary with time, e.g., workday vs. weekend; night vs. day; and population posture (e.g., normal use vs. shelter in place).

3. Building Protection Physics

3.1. Building Protection and Assessment Metrics



The Regional Shelter Analysis methodology measures protection in terms of protection factor and transmission factor (see **Equations 1a** and **1b**). *Protection factor* (PF) is defined as the ratio of the unsheltered to sheltered exposure.[6] Similar to sunscreen and personal protective respirator rating systems, higher protection factor values indicate lower exposures and thus increased protection. The *transmission factor* (also called the location factor or the building exposure ratio) is the inverse of the protection factor and is used during modeling calculations. Within the context of sheltering from radioactive fallout from nuclear detonations, the US government has defined adequate shelter as a protection factor of 10 or more [21].

(Equation 1a)

$$Protection\ Factor = \frac{Unsheltered\ (Outdoor)\ Exposure}{Sheltered\ (Indoor) Exposure}$$

(Equation 1b)

$$Transmission\ Factor = \frac{1}{Protection\ Factor}$$

For the purposes of a Regional Shelter Analysis, the unsheltered exposure is defined as the exposure present 1 m above an infinite, flat plane. For some health effect models, additional assumptions may be required, see the *(5. Radiation Hazard Health Effects)* section below. The unsheltered exposure can be determined either through direct measurement or calculated by an exposure model. We note that care should be taken in estimating the unsheltered exposure as individual outdoor exposures in a particular region can, and often do, vary for a variety of reasons. For example, environmental features; including trees, hills, valleys, and even buildings; and non-homogenous environmental contamination are well known to affect outdoor exposures. The RSA method developed in this report can account for these variations in outdoor exposures

[6] In the nuclear power plant accident literature, some studies use the term protection factor to indicate other quantities.

by defining one or more outdoor locations with their corresponding protection factors and population distribution. Thus, the impact of local outdoor environment can readily be included in building protection calculations.

3.2. Buildings and External Gamma Radiation Exposures

Once released, radioactive material can travel from the release site and deposit on a variety of surfaces including the ground, vegetation, exterior building walls, interior surfaces, and roofs. Both during transport and after deposition, radioactive material will decay, releasing potentially harmful radiation. Indoor individuals can be exposed to this radiation after it has traveled through building materials. In the immediate aftermath of a nuclear explosion, gamma ray photons (radiation) emitted from nuclear fallout deposited on outdoor surfaces can result in life-threating exposures. For radiological dispersal devices and many nuclear power plant accident scenarios, external radiation exposures contribute significantly to (or dominate outright) the lingering hazards that may require environmental remediation and/or population relocation. In all three cases, the primary radiation hazard is often gamma ray photons, with energies between 0.5 to 3 MeV. These gamma ray photons are the primary focus of this report.

As discussed in the (*2. Historical Perspective*) section, the building protection against external gamma radiation hazards has been long studied. *Dillon and Homann* [32] have recently reviewed the fallout shelter physics and the key building attributes needed to accurately assess protection factors for many building types. This review is briefly summarized here. When traveling through building materials, gamma radiation interacts with electrons through a process called Compton scattering, in which the overall scattering increases with increasing number of electrons encountered. This scattering has a limited dependence on the specific type of building material, e.g., wood vs. concrete. Compton scattering affects an indoor individual's radiation dose by (a) attenuation, decreasing the radiation dose by reducing amount of radiation traveling in a direct path between the source and the individual; and (b) buildup, increasing the radiation dose by deflecting non-direct path radiation towards the individual. The degree to which buildings reduce occupant dose depends on (a) the location of the occupant within the building; (b) specific building properties including building size and geometry; exterior wall, floor, roof, ceiling, and interior densities; and the number and size of windows and doors; and (c) radiation source characteristics including the radiation energy and location(s).

Several methods exist for estimating building protection against external gamma radiation, e.g., [24], [32], [44], [86]–[89]. These methods and experimental studies demonstrate that (a) indoor exposures can be determined by linearly scaling outdoor exposures, i.e., a protection factor approach, and (b) an order of magnitude or greater protection is possible when large amounts of mass are between the external radiation source(s) and indoor individuals.[7] Examples of the latter include underground locations or the interior of buildings constructed with heavy materials. *Dillon et al.* [18] provides a summary of prior external gamma radiation exposure building protection factors for nuclear explosion and NPP scenarios circa 2016. We note that active research continues, particularly with respect to managing major nuclear power plant accidents, e.g., [44], [45] and references therein. Notable recent work include the (a) first assessment of the protection associated with a modern, glass-wall office building [90] and (b) Japanese experimental studies on (i) the protection associated with about 200 additional buildings, (ii) the potential for the surrounding environment (e.g., slopping terrain) to affect the building protection, and (iii) the potential for strong variability in dose rate within a single building and the nearby outdoor environment [1], [91], [92].

[7] Buildings can also reduce radiation exposures by increasing the distance between radioactive sources and at-risk individuals. However, this reduction is often minor as relatively large distances are needed to adequately reduce radiation exposures. For example, a person standing in a plane contaminated with fallout radiation needs to be in the middle of a 150 m radius contamination-free disk to obtain a factor of 10 reduction in radiation exposure. See [32] for more details.

4. Regional Shelter Methodology

Regional Shelter Analysis method estimates *shelter quality* – defined as the (distribution of) protection for a given region, time period, and population posture.[8] A *region* is defined as a geographic area in which the geographic distribution of protection cannot be (or is not) resolved further. The scale or size of a region can vary with input(s) and/or application(s). Specific examples range from individual buildings, neighborhoods, and cities as well as much larger administrative regions (counties, states, countries, etc.). In the shelter quality database discussed later, each grid cell is a region. A *population posture* describes how people are distributed among and within various locations within a region. Population postures can change as people respond to a hazardous event and examples include unwarned scenarios, where people go about their normal day; shelter-in-place (often called minimally warned), where people shelter in the most protected portion of the nearest building; and neighborhood sheltering, where people go to the most protective building in the nearby area. A *time period* is defined as a specific time range during a day or day of the week with examples including weekday rush hour or weekend early morning hours. The population posture can vary with the time period, e.g., typically few people are in commercial buildings during the middle of the night.

4.1. Calculating Shelter Quality

The RSA method calculates regional shelter quality by (a) identifying the locations in which people are present; (b) characterizing, for each location: the (i) building protection factors, and (ii) fraction of the regional population; and (c) combining the location specific protection factors and population fractions into a regional shelter quality estimate. A *location* is defined as a place within a region in which people are present. Like regions, the size of a location can vary depending on the application and examples include a room in a building; an individual building; all residential buildings; or varying outdoor locations.

The details of the steps (a) and (b) vary by method implementation as several different types of (i) location definitions and (ii) associated protection factors and population fractions are available to develop a shelter quality database. A general discussion of these topics is provided in the (1) (*2.2. Building Characteristics, Populations, and Geographic Distributions*), (2) (*3. Building Protection Physics*), and (3) (*6. Discussion*) sections of this report. Illustrative examples are provided in [34], [57].

Calculation of shelter quality (step (c) above) is described as follows for a single region, population posture, and time period. This is illustrated in **Figure 3** using the example input dataset shown in **Table 1**.

[8] To enhance readability, the discussion here is restricted to population-weighted quantities. The RSA method can also use other importance weighting metrics including, but not limited to, area, building number, and monetary value. For example, area-weighted calculations can be used to assess the distribution of protection (populated or not) available in a given region.

First, the location protection factor cumulative probability distribution (black dashed line, **Figure 3**) is determined by (a) sorting the set of location-specific protection factors in order of decreasing value and (b) summing the corresponding population percents. **Table 2** illustrates this calculation using the example input dataset.

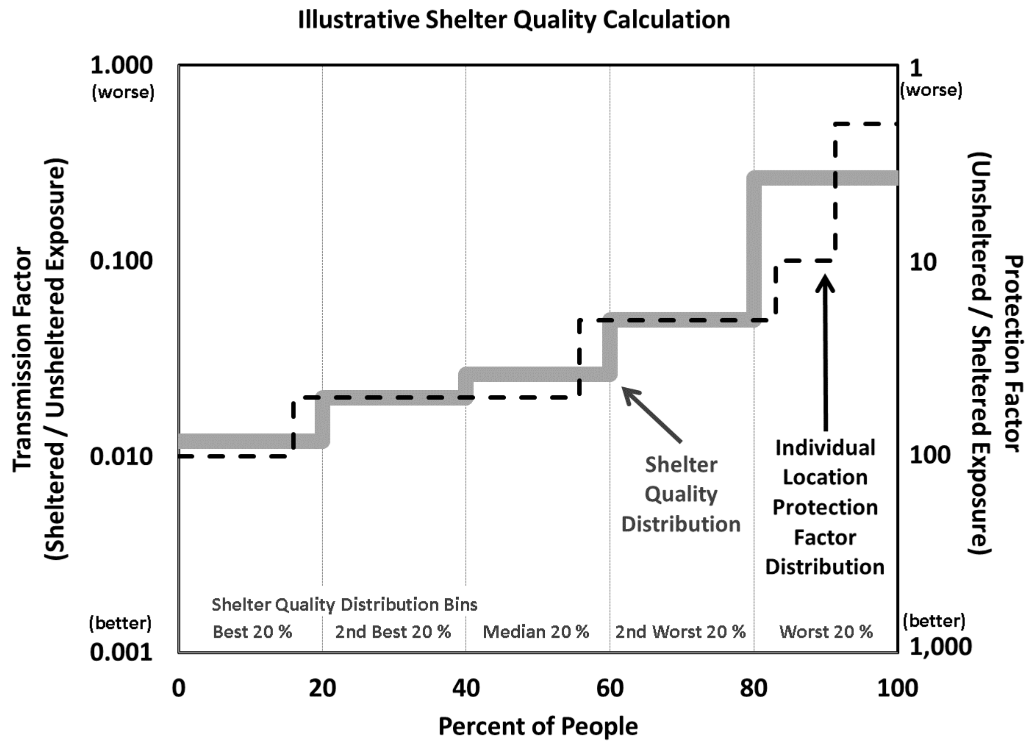


Figure 3. Illustrative shelter quality calculation for a single time, region, and population posture.

Second, five shelter quality probability bins were created in successive quintiles[9] and the shelter quality transmission factors (grey-shaded horizontal bars in **Figure 3**) were then determined by a population-weighted average of the location transmission factors in each shelter quality probability bin. **Table 3** illustrates this calculation using the example input dataset**.** In the case in which a sorted location probability spans more than one shelter quality probability bin, e.g., location 5 spans the best 20% and 2nd best 20% probability bins; the location is divided into sub-locations such that the resulting sub-location

[9] Although in general the number and magnitude of the shelter quality probability bins can vary, five, equal shelter quality probability bins are used in this example for illustrative purposes and are also used in subsequent reports to demonstrate operational calculations. A small, consistent set of probability bins streamlines the operational use of the RSA method and facilities communication at different operational levels.

probabilities align with the shelter quality probability bin division(s). This case is denoted by the “a” and “b” notation in **Table 3** locations.

Third, the shelter quality protection factor for each probability bin was determined by inverting the corresponding shelter quality transmission factors (see **Equation 1b)**.

Table 1. Example input dataset

Location number	1	2	3	4	5	6	7	8
Protection factor	50	50	20	10	50	100	2	20
Population (percent)	22.1	5.4	13.5	8.2	12.3	16.0	8.7	13.8

Table 2. Example location protection factor cumulative probability distribution

Location number	6	5	1	2	8	3	4	7
Protection factor	100	50	50	50	20	20	10	2
Population (percent)	16.0	12.3	22.1	5.4	13.8	13.5	8.2	8.7
Start cumulative population (percent)	0.0	16.0	28.3	50.4	55.8	69.6	83.1	91.3
Stop cumulative population (percent)	16.0	28.3	50.4	55.8	69.6	83.1	91.3	100

Table 3. Example shelter quality transmission factor cumulative probability distribution

Location number	Location transmission factor (1 / protection factor)	Relative weight† (dimensionless)	Shelter quality transmission factor‡ (1 / protection factor)	Shelter quality probability bin name
6	0.01	0.80 (= 16/20)	0.012	best 20%
5a	0.02	0.20 (= 4/20)		
5b	0.02	0.42 (= 8.3/20)	0.020	2nd best 20%
1a	0.02	0.59 (= 11.7/20)		
1b	0.02	0.52 (= 10.4/20)	0.026	median 20%
2	0.02	0.27 (= 5.4/20)		
8a	0.05	0.21 (= 4.2/20)		
8b	0.05	0.48 (= 9.6/20)	0.050	2nd worst 20%
3a	0.05	0.52 (= 10.4/20)		
3b	0.05	0.16 (= 3.1/20)	0.27	worst 20%
4	0.10	0.41 (= 8.2/20)		
7	0.50	0.44 (= 8.7/20)		

† Calculated by dividing (a) the Table 2 location population percent (adjusted to align with the shelter quality probability bin) by (b) 20% (the probability associated for each shelter quality probability bin).

‡ Calculated by (a) multiplying (i) the location transmission factor by (ii) the relative weight and then (b) summing the resulting values associated with the locations within each shelter quality probability bin.

4.2. Shelter Quality Databases

Shelter quality estimates can be conveniently stored within a database, where each geographically distinct grid cell is a separate region, and later used to generate population-level risk analyses when combined with outdoor exposure estimates and health effect models. Visualizing the shelter quality database provides a graphical depiction (map) of the shelter quality for an area of interest (e.g., a city). This approach allows the shelter quality database to be derived from higher fidelity data sources, such as individual building data, where these higher fidelity data are available and lower fidelity data sources, such as the PAGER database, in the case where higher fidelity data are not available. *Dillon et al.* [57] and *Dillon et al.* [34] provide worked (hypothetical) examples that (a) use publicly available information about individual buildings to calculate shelter quality distributions for individual building and neighborhood-scale regions and, separately, (b) demonstrate how the higher fidelity HAZUS and lower fidelity PAGER databases can be combined into a single, multi-resolution shelter quality database.

The shelter quality database can have multiple data layers where each data layer has a specific spatial resolution and shelter quality probability bin values defined for each grid cell.[10] As a practical matter, a set of data layers that are self-consistent, but have different spatial resolutions enables computationally efficient exposure assessments by using the shelter quality layer resolution closest to the unsheltered exposure analysis resolution, see also [34] and the (*6. Discussion*) section.

The method to generate lower spatial resolution shelter quality data layers, e.g., 10 km x 10 km grid cells, from higher spatial resolution shelter quality data layers, e.g., 1 km x 1 km grid cells, is described here.

> First, the higher resolution grid cells that geographically overlap each lower resolution grid cell are identified, see **Figure 4**. The lower and higher resolution grid cells boundaries do not necessarily align and so in some cases a given higher resolution grid cell may only partially overlap, and thus only partially contribute to, a given lower resolution grid cell.
>
> Second, **Equation 2** is used to calculate the population within the lower resolution grid cell. As an example, the lower resolution grid cell shown in **Figure 4** contains 20 people if there are 5 people in every higher resolution grid cell.
>
> Third, the lower resolution grid cell shelter quality distribution is calculated for each time period and population posture using the algorithm described in the

[10] (1) The grid cell resolution is not required to be constant in a given data layer. (2) While often the case, grid cells are not required to be square.

(*4.1. Calculating Shelter Quality*) section. For this calculation, the (a) input locations are the higher resolution grid cell probability bins, (b) input location protection factors are the protection factors associated with the higher resolution grid cell probability bins, and (c) input population is the fraction of lower resolution grid cell population associated with each input location as determined by **Equation 3**.

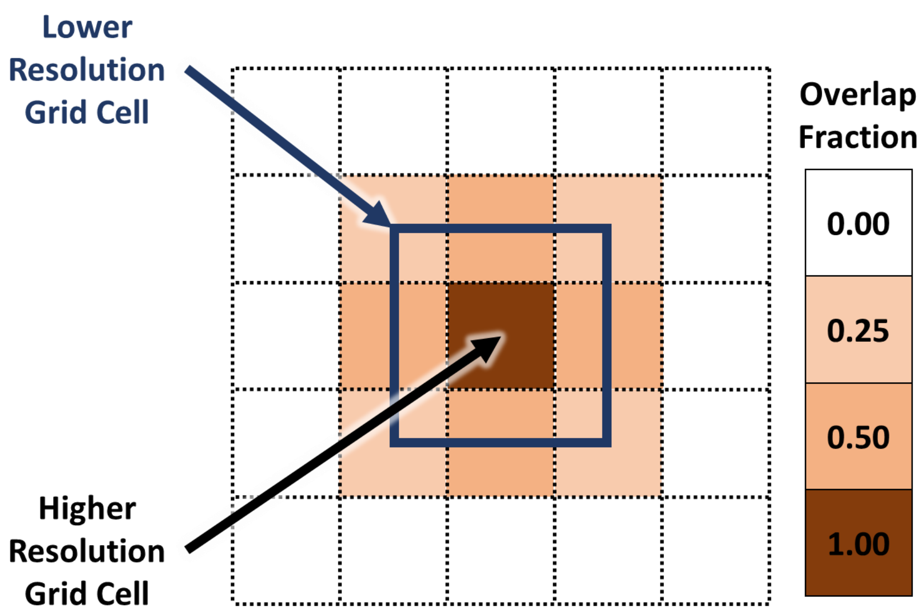


Figure 4. Illustration of higher resolution grid cells (outlined with dashed lines) overlapping a lower resolution grid cell (outlined with a solid blue line). In this illustration, the higher resolution grid cells can overlap the lower resolution grid cell fully, partially, or not at all.

(Equation 2)

$$Low\ Res\ Population_j = \sum_i \left(High\ Res\ Population_i \times Overlap\ Fraction_{i,j}\right)$$

(Equation 3)

$$Location\ Probability_{i,j,p} = \frac{High\ Res\ Population_i \times Overlap\ Fraction_{i,j} \times Probability\ Bin\ Value_p}{Low\ Res\ Population_j}$$

where

i is a high spatial resolution grid cell (dimensionless),

j is a low spatial resolution grid cell (dimensionless),

p is the high spatial resolution population bin (dimensionless),

$Low\ Res\ Population_j$ is the population for lower resolution grid cell j (people),

$High\ Res\ Population_i$ is the population for higher resolution grid cell i (people),

$Overlap\ Fraction_{i,j}$ is the fraction of higher resolution grid cell i area that overlaps the lower resolution grid cell j (dimensionless),

$Location\ Probability_{i,j,p}$ is the location probability for lower resolution grid cell j associated with the probability bin p from higher resolution grid cell i (dimensionless), and

$Probability\ Bin\ Value_p$ is the value of the probability bin p (dimensionless).

4.3. Population Impact Calculations

The Regional Shelter Analysis methodology can adjust existing model predictions of (a) unsheltered exposure and (b) health effects to estimate the impacts on sheltered individuals. For a given region, the general process occurs in the following four steps. First, the sheltered exposures for each probability bin are calculated by dividing the unsheltered exposure by the corresponding probability bin protection factor. Second, the fraction of affected individuals in each probability bin is determined from the sheltered exposure and the appropriate health effect model. Third, the fraction of affected individuals in the region is determined from the weighted average of the individual probability bin estimates. Finally, the total number of affected people is determined by multiplying the regional population by the affected fraction. For some RSA applications, certain parameter input details are hazard and/or exposure pathway specific and these are described in more detail in following subsections.

External radiation exposure estimates can be combined with RSA shelter quality estimates to calculate population impacts. These can be calculated using the following equations: **Equation 4** calculates the sheltered exposure by dividing the unsheltered exposure by the RSA shelter quality estimates. **Equation 5** calculates the fraction of people impacted in a given region via a weighted average of the fraction of people impacted in each probability bin, which in turn, is calculated using a health effect model (a model that relates exposure to one or more health outcome(s) of interest) and the sheltered exposures. **Equation 6** calculates the affected people in a given region by multiplying the fraction of people affected with the corresponding population estimate. **Equation 7** calculates the total number of affected people.

(Equation 4)

$$Sheltered\ Exposure_{r,p} = \frac{Unsheltered\ Exposure_{r}}{Shelter\ Quality_{r,p}}$$

(Equation 5)

$$Impact\ Fraction_{r} = \sum_{p\,\in\,probabilty\ bins} \frac{Health\ Effect\ Model\left(Sheltered\ Exposure_{r,p}\right)}{Probability\ Bin\ Value_{p}}$$

(Equation 6)

$$Regional\ Impacts_{r} = Impact\ Fraction_{r} \times Population_{r}$$

(Equation 7)

$$Total\ Number\ of\ Impacted\ People = \sum_{r \in regions} Regional\ Impacts_r$$

where

$Sheltered\ Exposure_{r,p}$ is the average (population weighted) exposure in region r and probability bin p (Gy or Sv),[11]

$Unsheltered\ Exposure_r$ is the unprotected exposure in region r (Gy or Sv),

$Shelter\ Quality_{r,p}$ is the (population weighted) protection factor for probability bin p and region r (dimensionless),

$Impact\ Fraction_r$ is the fraction of people impacted in region r (dimensionless),

$Health\ Effect\ Model\ (Exposure)$ is the probability of a health effect for given exposure (dimensionless),

$Regional\ Impacts_r$ is the number of people impacted in region r (people),

$Population_r$ is the number of people in region r (people), and

$Total\ Number\ of\ Impacted\ People$ is the total number of people affected (people).

Additional discussion on directly adjusting population-level risk estimates is provided in ***Regional Shelter Analysis – Inhalation Exposure Methodology*** [2].

[11] Radiation doses are measured in units of Grey (Gy) or Severts (Sv).

5. Radiation Hazard Health Effects

5.1 Overview of Ionizing Radiation Injury Mechanisms and Modeling

Health effects due to ionizing radiation exposure are classified as either stochastic or tissue effects (the latter are also called deterministic or non-stochastic effects). Stochastic effects, which are of concern primarily at low radiation doses and/or dose rates, can result from injury to a single cell or small number of cells and the principal consequences are carcinogenic and/or heritable effects. Tissue effects, which occur at higher doses and dose rates, result from the collective injury of a substantial number of cells in the affected tissues. This collective injury can result, among other injuries, in eye cataracts, non-malignant skin damage (radiation burns), cell depletion in the bone marrow causing hematological deficiencies, and/or gonadal cell damage leading to fertility impairment. Stochastic or deterministic health effect models typically, although not always, use different types of radiation dose metrics (discussed below) – however both metrics are determined by a summing of the individual contributions from each radiation exposure pathway.[12] The likelihood of both stochastic or tissue health effects increases with dose. For a given dose, shorter time period exposures are more hazardous than longer time periods as there is less time for the radiation damage to be repaired. For example, a 5 Gy to bone marrow dose would likely be lethal if received in 1 day while the same 5 Gy dose received evenly over 50 years would likely not result in any acute health effects.

Although there is no strict time boundary to distinguish between radiation exposure time periods relevant to human health effects, these environmental exposures are commonly classified as acute or chronic when received in < 30 d and > 60 d, respectively (exposure periods between 30 to 60 d may be categorized differently depending on the specific study). The boundary between acute and chronic exposures is substantially longer than the timescales by which building structures prolong either the external or inhalation exposures and so the RSA methodology is compatible with the exposure timescales, and hence dose rates, used in current radiation health effect models.

Tissue health effect models typically use the absorbed dose to either an individual organ/tissue or to the whole body which is measured in Gy (SI unit) or rad [14], [34], [93]. Absorbed dose is the total amount of energy deposited (absorbed) per gram of matter, e.g., bone, tissue, air, over a specified time period.[13] Acute radiation syndrome (ARS) describes the combination of effects associated with tissue damage incurred

[12] Individuals can be exposed to ionizing radiation through a variety of pathways including external exposure and/or internal exposure through inhalation, ingestion, or direct contact, e.g., absorption through intact or broken skin.

[13] For human tissue, the relative effectiveness by which different radiation types, such as alpha particles, beta particles, and gamma rays, damage biological tissue can be considered. For this case, the adsorbed dose is reported in units of Gy-equivalents. This is related to, but distinct from, the equivalent dose concept discussed in the context of stochastic effects.

during an acute exposure(s) [14].[14] For lower doses, i.e., 1 Gy; ARS can present clinically in the first minutes to weeks after exposure with diarrhea, vomiting, fever and decreased number of blood cells due to damage to the most sensitive organs (bone-marrow, small-intestine wall, and lungs). High, acute, whole-body doses of radiation (> 8 Gy) are likely fatal (without medical attention) and exposed individuals may present within minutes of exposure with disorientation or coma. Below ~0.5 Gy, no tissue effects are expected.

Stochastic health effect models typically use either an equivalent (organ/tissue) dose and/or an effective (whole body) dose which are typically measured in Sv (SI unit) or rem – although a few models use absorbed dose [93]–[95]. The equivalent dose is estimated for individual organs by summing the contribution of each radiation exposure pathway and is weighted by the relative amount of damage caused by different types of radiation (radiation weighting factor). The effective dose is estimated by summing the individual equivalent doses for each organ/tissue as weighted by the sensitivity of the individual organ/tissue to radiation damage (tissue weighting factor). The US Environmental Protection Agency (US EPA) estimates general population lifetime cancer incidence risk to be ~10^{-4} per mSv [14]. Based on this dose-response relationship, the US EPA protective action guidelines, which are a form of exposure guideline level, recommend considering the relocation of the general population when the projected dose (which does not consider building protection) is above 20 mSv in the first year or 5 mSv in the second and subsequent years (corresponding to an increased lifetime cancer incidence risk of > 0.16% and 0.04% per year, respectively) [14].[15]

5.2 Dose Conversion Factors and Building Protection

Radiation Dose Conversion Factors (DCFs), also called Dose Coefficients, are commonly used to scale air and ground contamination levels to both adsorbed and equivalent/effective doses [5], [14], [94], [98]–[103]. DCFs vary with radiation type and energy (radionuclide) and can also vary with the timescale over which the health effect is being considered, e.g., likelihood of illness over a 10 yr period. The DCFs are based on a set of assumptions concerning the radiation source, environment, and the exposed individual. For the external radiation pathway, the radiation source is assumed to be: (a) an infinite, uniformly contaminated, flat plane for the case of exposure to freshly deposited radioactive material (groundshine); (b) uniform contamination from the ground surface to a specified depth for exposure to contaminated soil; or (c) an infinite, uniformly contaminated hemisphere for submersion within a radioactive cloud (cloudshine). The surrounding environment is also assumed to have specific atmospheric and soil compositions. Finally, DCFs are referenced to the anatomy of the reference adult person and so estimated internal, e.g., organ, doses implicitly assume

[14] External radiation burns may also occur, but are not considered part of the ARS.

[15] This standard is comparable to the IAEA standard of 20 mSv per yr to transition from an emergency to an existing exposure situation [96] and lower than typical exposures seen in locations with naturally high levels of background radiation, e.g., [97].

shielding of the adult body. The use of "modification factors," which linearly scale the provided DCFs, is recommended when the source geometry, environment, and exposed population differ from these standard assumptions.

For most use cases, the assumptions used in deriving the DCFs are consistent with the assumptions used in the RSA methodology. For example, the RSA unsheltered exposure definition of an exposure present 1 m above an infinite, flat plane is consistent with the DCFs definition of individual standing in an infinite, flat plane – indeed *Eckerman et al.* [99], [101] provides factors to scale the dose at 1 m above ground level (agl) to an effective (whole body) dose. Therefore, DCFs can be directly used in the RSA casualty calculation by setting the RSA exposure to be equal to an adsorbed, equivalent, or effective radiation dose as appropriate. Furthermore, the RSA location transmission (and protection) factors, which linearly scale the unsheltered dose, are functionally identical to the DCF modification factors used to adjust the standard DCFs to local conditions. Thus the RSA building protection estimates can function as DCF modification factors to readily account for changes in source geometry, e.g., a roof radiation source; exclusion of deposited radiation by the building footprint, environmental effects (e.g., ground roughness) and the effects of other nearby buildings.[16] The references in this report, including but not limited to [3], [18], [32], provide improvements over the original modification factors. We note as a reminder that RSA shelter quality, which also has units of protection factor, further incorporates the distribution of population among different RSA locations.

5.3 Additional Considerations

As with all uses of dose-conversion factors in the built environment, a detailed accounting for changes to the relative distribution of radiation over the indoor human body may be required. For example, the legs of an individual standing next to window may be well shielded from outdoor radiation by the windowsill while the window glass may provide the torso and head with less shielding.[17] For this case, the RSA implementation may need to use (a) building protection factors that vary with both exposure location and height within the building and type of dose being assessed and (b) detailed, within-building population distribution estimates. These issues may be of limited concern for the important case of estimating fatal exposures to nuclear fallout. In this case, the lowest-dose threshold fatality pathway is damage to the femur bone-marrow. As the femur is located approximately 1 m above the floor for individuals standing, sitting in a chair, or lying on a bed, protection factors referenced 1 m above the floor are sufficient for risk estimation (an analogous argument is also valid for injury to the small intestine associated with many prodromal radiation exposure symptoms).

[16] Factors analogous to RSA location protection factors can be used to scale health effect reference values for the reference man to other men as well as women and children, e.g., [94].

[17] It is unclear the degree to which this affects a significant portion of the building population as individuals closer to the building core may be more uniformly irradiated than those near the outer walls [32].

6. Discussion

Buildings can provide significant protection to their occupants – in some cases reducing acute and chronic exposures by orders of magnitude relative to exposures received by individuals outside. The scientific understanding of how buildings protect their occupants is in many respects quite mature, however an operationally efficient method suitable for assessing regional-level built environment protection, as opposed to individual building-level protection, has not been previously available.

While sheltering is a well-recognized protective action, no general-purpose sheltering decision support tool currently exists to assist decision makers in external gamma radiation exposure emergency situations. This technical gap poses a challenge to both risk assessments in general, and emergency response planning in particular, as it inhibits the more nuanced use of sheltering including optimizing assessments by region, time period, and/or hazard as well as the development and use of more advanced shelter-evacuate strategies. The Regional Shelter Analysis methodology presented here attempts to address this need by extending prior research to provide a practical method that accounts for the protection that buildings provide their occupants against external hazards on a regional scale. Applications are specifically discussed in companion reports, e.g., [3].

The Regional Shelter Analysis method presented here provides practical operational impact calculation capabilities for a variety of different types of exposures. In a given region, significant localized differences in exposures and health risks can exist and can be modeled using RSA shelter quality values. A separate shelter quality value is defined for each distinct group of people in the built environment (i.e., modeling multiple probability bins).[18] The RSA method also allows for more accurate consequence assessments for hazards whose health effects do not vary linearly with exposure or population demographics, such as acute radiation exposure. **Figure 5** illustrates the value of assessing regional variability in risk analyses using a hypothetical example for outdoor external gamma radiation exposure of 1000 rads, in which almost all injuries (impacts) are predicted to occur in the "worst" protected 20% of the population while the "typical" (median exposure) individual is not injured. In this case, a global population assessment, i.e., a risk estimation that relies on calculating an "average" regional population-level protection factor, would not capture the fact that 20% of the regional population were injured, since the overall median population exposure is low. We note that the overall accuracy of the RSA method will depend, in part, upon the degree to which the probability bin specification accurately resolves the underlying shelter quality distribution.

[18] We note that uncertainty can be treated (a) analytically (error propagation) or (b) statistically using Monte Carlo methods or by adding an additional uncertainty axis analogous to the variability axis (i.e., shelter quality distribution) discussed in this report.

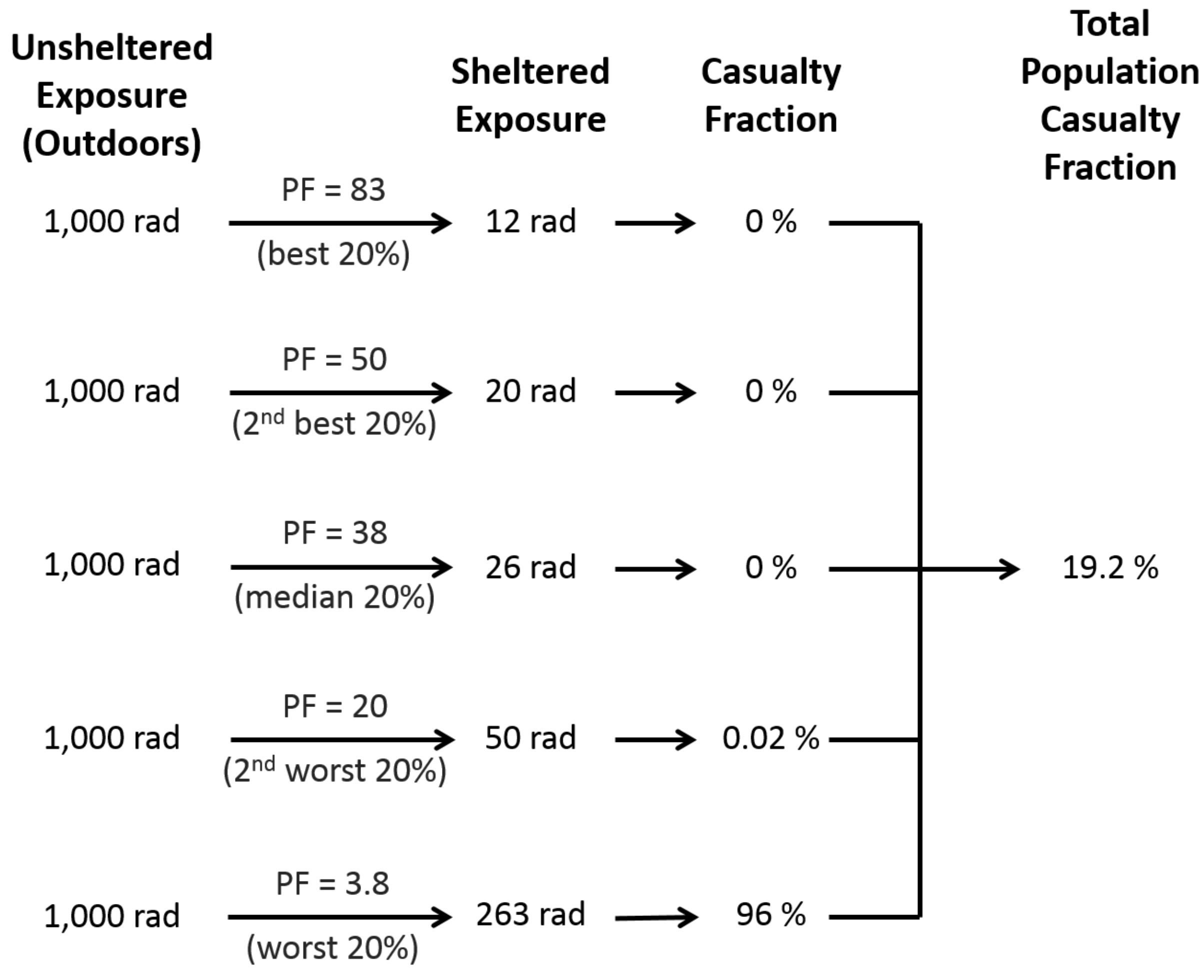


Figure 5. Illustrative casualty (impact) calculation. PF = protection factor

A more comprehensive RSA model could facilitate broader operational efforts to manage hazardous exposures. For example, the RSA method is intended to further the all hazards emergency response initiative by developing a consistent framework for considering how buildings affect both the external gamma radiation and inhalation exposure pathways [19], [20]. For management of complex radiation emergency response scenarios, a variety of RSA datasets may be used simultaneously. Effective risk management may require a response coordinated across a wide range of decision makers at different levels, such as a country president, state governor, county supervisor, city mayor, precinct captain, and neighborhood-level emergency responders. For these cases, RSA estimates need to be self-consistent across multiple regions of control/interest, i.e., a common operating picture, so that decisions and resource allocations are well aligned. These requirements can be met by constructing a set of self-consistent, hierarchal (and potentially overlapping) RSA databases, We note that this type of implementation provides exposure estimates (and the underlying data) in a manner that is sufficiently precise, but not overly precise as to overwhelm each analyst and/or decision maker with unnecessary amounts of data – even if ultimately the underlying input data used for the RSA is detailed and high-resolution.

Over a longer time horizon, a RSA approach can inform more general public health planning efforts to maximize the protective benefits provided by the built environment by assessing the impact of proposed government policies on building protection (through updated building code standards) and population postures (through updated zoning ordinances and transportation infrastructure planning), e.g., [104]–[106] and references therein. We note also RSA's potential ability to be adapted to provide exposure assessments for specific demographic subgroups including, but not limited to, economically and socially vulnerable populations [106], [107]. In performing such targeted assessments, consideration should be given on the degree to which the subpopulation of interest may be distributed within the built environment, i.e., whether it differs from the overall population.

6.1 Limitations

The Regional Shelter Analysis method relies on a small set of technical assumptions which, while reasonable, deserve mention and comment. First, the RSA methodology, as described in this report, implicitly assumes that the location protection factors do not vary with time. Theoretical extensions to the current method are required when considering the effects of (a) a change in building properties, including temporary measures to improve the fallout shelter quality such as adding sandbags in strategic locations; (b) changes over time in the distribution of the radiation hazard in the outdoor environment, e.g., nuclear fallout washing off of a roof in a rainstorm; and (c) other nuclear explosion effects, e.g., prompt radiation, blast, thermal effects and injuries due to building damage, e.g., building collapse and glass breakage. Also, the current report focuses on human health impacts. We note that social and economic disruptions are also major concerns in emergency planning [104]. Finally, we are unaware of any studies that provide broadly applicable estimates of the distribution of people within buildings (limited information exists for some building types).

Finally, the RSA method presented in this report applies to stationary population exposures and risk assessments. Many of the more complex population responses, including some combined shelter and evacuation strategies, require consideration of dynamic (mobile) populations. Dynamic population considerations may either decrease hazardous exposures, e.g., individuals with poor shelter may move to higher quality shelters, or increase hazardous exposures, e.g., individuals with good shelter may temporarily go outside (where they may be less protected) to assist in rescue operations or obtain food and medical assistance [30]. While the RSA method is compatible with existing tools that consider dynamic populations, e.g., [108]; these tools are computationally intensive and/or require significant analyst time and skill. As such, use of these tools is typically restricted to advanced assessments or work within a specific research context, e.g., [31], [109]–[112]. Extensions to the RSA methodology (or other methodologies) that provide a more operationally practical solution in this regard would be of significant benefit. We note that such an effort should include an understanding of government policy, warning dissemination and compliance, and human behavior, e.g., [113]–[118], as government emergency communications and actions have the potential to significantly influence population locations (and hence shelter quality) via evacuation, relocation, and sheltering as well as in a preventive sense by zoning and building code planning, e.g., [104]–[106] and references therein.

7. Conclusion

Buildings can protect their occupants from outdoor hazards during normal operations. Sheltering, a widely recognized protective action, can increase this protection. However, building protection is not routinely incorporated into modern regional exposure, risk, and casualty assessments. This may have important consequences for radiation emergency response planning and operations. In such cases, population exposures may be overestimated, potentially leading to both miscommunication as to the risk extent and misallocation of resources away from those most at risk in both the management of emergencies and chronic public health issues assessments.

The Regional Shelter Analysis (RSA) method developed here accounts for the distribution of building protection (both within and among buildings), the population posture (how people are distributed among and within buildings) and temporal considerations (e.g., night vs. workday). The RSA method could support a common operating picture by providing user specific results that have the resolution appropriate for individual user's needs while still being consistent with the information being provided to the other users. The method employs existing building and population databases and is compatible with most modern exposure and injury assessment tools.

This report develops the general methodology and places the RSA method in context of prior work and current initiatives. The other reports in this series discuss the specific implementations for the inhalation pathway and include exposure pathway-specific discussion of key scientific gaps and the degree to which current building descriptions (taxonomies) describe the relevant building properties of interest. More generally, we note that while building characterization and occupancy is an active area of research in numerous fields; we are unaware of any studies that provide broadly applicable estimates of the distribution of people within buildings. Finally, we note that multiple RSA implementations may need to be created to support different sets of operational and/or scientific assessment requirements. These requirements include accuracy; resolution at multiple spatial and temporal scales; computational efficiency; compatibility with existing exposure and health effect models and measurements; all-hazards emergency response planning and messaging; and clear, timely, simultaneous results provided to different operational domains as needed to coordinate and support decision making by officials and staff.

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9. Attestations

Ethics statement
No humans or animals were used this in work

Data accessibility
No primary data were used in this analysis.

Competing interests
The author has no competing interests for the material provided in this manuscript beyond (a) being employed at Lawrence Livermore National Laboratory and (b) receiving funding from the acknowledged sources.

Author's contributions

Michael Dillon (MBD) was responsible for the study concept and design, including method and theory development, discussion, historical perspectives, building protection physics, and discussion. MBD, with valuable help from Steve Homann, also developed the radiation health effect section (i.e., Steve Homann was a co-author on the radiation health effect section).

All authors give approval for publication.

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