Summary of Building Protection Factor Studies for External Exposure to Ionizing Radiation

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1. SUMMARY

Radiation dose assessments are used to help inform decisions to minimize health risks in the event of an atmospheric release of radioactivity including, for example, from a Radiological Dispersal Device, an Improvised Nuclear Device detonation, or a Nuclear Power Plant accident. During these incidents, radiation dose assessments for both indoor and outdoor populations are needed to make informed decisions. These dose assessments inform emergency plans and decisions including, for example, identifying areas in which people should be sheltered and determining when controlled population evacuations should be made.

US dose assessment methodologies allow consideration of the protection, and therefore dose reduction, that buildings provide their occupants. However, these methodologies require an understanding of the protection provided by various building types that is currently lacking. To help address this need, Lawrence Livermore National Laboratory, in cooperation with Sandia National Laboratories and the Nuclear Regulatory Commission, was tasked with (a) identifying prior building protection studies, (b) extracting results relevant to US building construction, and (c) summarizing building protection by building type. This report focuses primarily on the protection against radiation from outdoor fallout particles (external gamma radiation).

This study identified and summarized the results of approximately 400 building analyses in 26 previously published studies. This study's results were consistent with, and extend, prior studies of building protection by building type. The protection values, and a brief discussion on their use, provided in this report will be used to improve dose predictions and assessments generated by US Federal centers. As such, this work will potentially benefit government agencies nationwide that use these centers' dose assessments during emergencies, drills, and exercises.

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3. INTRODUCTION

Radiation dose assessments are used to help inform decisions to minimize health risks in the event of an atmospheric release of radioactivity from incidents such as a Radiological Dispersal Device (RDD), an Improvised Nuclear Device (IND) detonation, or a Nuclear Power Plant (NPP) accident. Prior to a release, these dose assessments can be used by emergency preparedness and response organizations, and their specialists, to develop response plans. During and after a release, dose assessment products support the incident commander and staff by providing information on (a) the expected radiation dose and associated health risks and (b) the efficacy of protective actions, such as population sheltering, evacuation, and relocation. Buildings can provide considerable protection (dose reduction) to their occupants. Prior research provides information on building protection for the purposes of (a) minimizing radiation exposure after nuclear explosions [1], [2] and (b) guiding the remediation of (or population relocation from) regional contamination caused by NPP accidents and RDD releases, e.g., see [3]–[6] and references therein.

For major events, United States Government agencies rely on dose assessments generated by the Department of Energy/National Nuclear Security Administration's (DOE/NNSA) National Atmospheric Release Advisory Center (NARAC), the Department of Homeland Security (DHS) led Interagency Modeling and Atmospheric Assessment Center (IMAAC), [1] and the Federal Radiological Monitoring and Assessment Center (FRMAC) [7]. However, US government estimates of radiation exposure assume, by default, that exposed individuals are outdoors and so do not account for building protection considerations, e.g., see references [8], [9]. Recent research [10] has focused on this gap and resulted in an operationally feasible methodology that provides an improved dose assessment while considering the variability of building protection and distribution of people within and among different building types [11]. This methodology is being incorporated into DOE NARAC and Department of Defense operational models. Similarly, recent updates to the DOE FRMAC dose assessment method have incorporated building protection and occupancy [8].

The successful implementation of these methodologies requires understanding the protection various buildings provide their occupants as this protection can vary considerably from building to building, at different locations within a given building, and at different times [1]. A comprehensive, recent literature review has been lacking and the specific properties required to accurately assess the building protection remains an active research area, e.g., [6].

To help address this need, Lawrence Livermore National Laboratory (LLNL), in cooperation with Sandia National Laboratories (SNL) and the Nuclear Regulatory Commission (NRC), was tasked with (a) identifying prior building protection studies, (b) extracting building protection results relevant to US construction, and (c) summarizing building protection by general building type. Due to the importance in the timely identification and procurement of adequate shelter after a nuclear explosion [2], [12], [13]; this report focuses primarily on the building protection against outdoor fallout particles (external gamma radiation).

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[1] DOE/NARAC is the primary provider of radiological/nuclear model predictions to the IMAAC.

To provide context to the building protection results, this study briefly discusses considerations when using these values, including (a) the relative importance of other exposure pathways, (b) the degree to which buildings are occupied, and (c) representativeness of these results to the building(s) being assessed. The latter point is important because many key building types have not been previously analyzed. While the information provided in this study is useful for incidents other than nuclear explosion fallout, additional factors must be considered for a complete RDD and NPP dose assessment (see the *Discussion* section).

The building protection results summarized in this study will be used to improve dose predictions and assessments generated by NARAC, IMAAC, and FRMAC. Therefore, this work will potentially benefit government agencies nationwide that use these Federal assets for dose assessments during drills, exercises, and emergencies.

4. METHODOLOGY

Based on previously collected literature and a new literature search, the authors generated a candidate list of prior studies that met the following criteria:

- *Detailed technical documentation was available*
  Only prior studies with detailed supporting documentation, such as a technical report or peer-review journal publication, were selected.
- *Primary source documents were used*
  In many cases, the same (or similar) building was discussed in several documents. All other considerations being equal, the document containing the original study (primary reference) was selected while the supplementary documents (secondary references) were used to provide additional detail (literature reviews such as *Spencer et al.* [1] and *Burson and Profio* [14] were used to identify studies and provide context).
- *Relevant to protection against nuclear explosion fallout and, secondarily, nuclear power plant accidents and radioactive dispersal devices in the US*
  Only prior studies whose results were judged relevant to US building construction and protection from nuclear explosion fallout, nuclear power plant accidents, and/or radioactive dispersal devices were selected. This criterion excluded studies that only partially analyzed the building protection, analyzed purpose built fallout shelters, and those whose results were reported in a form not readily applicable to calculating building protection
- *Documents have unlimited distribution*
  Prior studies and reports that had restricted access, e.g., Official Use Only, were excluded.

The list of selected studies was provided to the FRMAC Assessment Working Group and the NRC for review and a consensus list was generated. During the external peer review process, additional studies were identified. The key information (see below) was extracted and collated from the selected studies.

This process has identified approximately 400 building analyses and the authors believe that they have included most, but not all, of the publically available literature.[2] However, these buildings should NOT be considered to be a representative or comprehensive sample of all relevant buildings within the US because some building types were not well studied previously (see the *Discussion* section).

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[2] For example, we excluded studies that used the point-kernel (buildup factor) method as this calculation method only partially captured within-building radiation scatter.

This study identifies the prior studies by:

- *File name*
  Name of file contained in the electronic archive
- *Study reference (long form)*
  Full citation
- *Study reference (short form)*
  First author and publication year

This study categorized the prior building analyses by:

- Building type
  - *Realistic structure*
    Building was in use and not explicitly designed for fallout study or protection (often buildings were occupied)
  - *Other structure*
    Building was (1) explicitly constructed for fallout studies, (2) designed to protect against fallout radiation, and/or (3) not in use (e.g., lack contents)

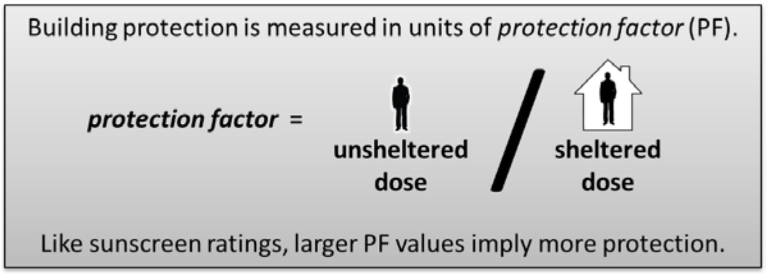
- Occupancy type
  - *Single family residence*
    Building occupied by a single family as their residence
  - *Multi-family residence*
    Building occupied by multiple families as their residence, e.g., apartment buildings
  - *Commercial*
    Building used for commercial purposes
    Subtypes are *Office, Factory, Laboratory, Shed, Supermarket,* and *Other*
  - *Public*
    Building used for government purposes
    Subtypes are *Hall, School,* and *Hospital*
  - *Other*
    Building not designed for normal occupancy, e.g., constructed solely to develop and test radiation shielding theory

- *Building height*
  Number of building stories (floors above the ground). Building height does not include basement level(s), if any.

- *Building description*
  A brief summary of the building studied

This study categorized the prior building analyses with regard to the analysis method used.

- *Experiment (E)*
  Study primarily based on experimental data. Many studies supplement experimental data with modeling or theoretical results.
- *Theory (T)*
  Study primarily based on modeling or theoretical results.



Building protection is measured in units of *protection factor* (PF).

Like sunscreen ratings, larger PF values imply more protection.

The protection buildings provide their occupants is often quantified in units of *protection factor.*[3] Protection factor is defined as the ratio of [the "open field" dose (or dose rate)] to [the dose (or dose rate) experienced within the building] where, for fallout radiation, "open field" dose is the radiation dose measured 1 m (approximately 3 ft) above an infinite flat plane uniformly contaminated with radioactive fallout. On occasion, building protection is reported in terms of *reduction factor* (also called *transmission factor*) which is the inverse of the protection factor.

$$Protection\ Factor = \frac{D_o}{D} = \frac{Unsheltered\ (Open\ Field)\ Dose}{Sheltered\ Dose}\ or\ \frac{Unsheltered\ (Open\ Field)\ Dose\ Rate}{Sheltered\ Dose\ Rate}$$

$$Reduction\ Factor = \frac{D}{D_o} = \frac{Sheltered\ Dose}{Unsheltered\ (Open\ Field)\ Dose}\ or\ \frac{Sheltered\ Dose\ Rate}{Unsheltered\ (Open\ Field)\ Dose\ Rate}$$

This study categorized the reported protection factors by:

- *Location within the building*
  Floor number (ground floor = 1st floor)

For each building location, this study collated the reported protection factors[4] and derived:

- *Typical/Median protection factor (Do/D)*
  Median of the reported protection factors. This value may or may not represent the typical protection that a building occupant would experience, which depends on several factors including the location of the person in the building.
- *Minimum protection factor (Do/D)*
  Smallest reported protection factor
- *Maximum protection factor (Do/D)*
  Largest reported protection factor

When a prior study reported reduction factors, the corresponding values were recorded.

- *Typical/Median reduction factor (D/Do)*
  Median of the reported reduction factors
- *Minimum reduction factor (D/Do)*
  Smallest reported reduction factor
- *Maximum reduction factor (D/Do)*
  Largest reported reduction factor

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

[4] If required, the reported results were converted to protection factors.

This study categorized prior building analyses with regard to the radiation source(s) used.

- Radiation type or isotope[5]
    - 1 hour post detonation
        - *^{60}Co*

          ^{60}Co emits 2 gamma rays per nuclear transition (1.17 MeV and 1.33 MeV). The effective photon energy (1.25 MeV) is similar to the effective penetration ability of 1-hour-old fallout [1].
        - *1-hour-old fallout*

          Modeling assuming the spectra of approximately 1-hour-old fallout
    - 1 to 3 days post detonation
        - *^{137}Cs* and *^{134}Cs*

          ^{137}Cs (and associated ^{137m}Ba decay product) emits, on average, 0.85 gamma rays per nuclear transition (0.662 MeV). ^{134}Cs decay yields similar energy (0.698 MeV) gamma rays. As the fallout radiation softens with time, ^{137}Cs radiation becomes more representative of the effective penetration of 1+ day-old fallout [1]. External exposure to ^{137}Cs (and ^{134}Cs) gamma rays can be a major contributor to the radiation exposures from nuclear power plant accidents [15].
        - *1-day-old fallout*

          Experiments performed at Nevada National Security Site (formerly Nevada Test Site) in approximately 1-day-old fallout
        - *3-day-old fallout*

          Experiments performed at Nevada National Security Site (formerly Nevada Test Site) in approximately 3-day-old fallout
- Radiation location
    - *Air immersion (A)*

      Radioactive gases or particles in air uniformly surrounding the building.
    - *Deposition (D)*

      Radioactive particles deposited on surfaces. These studies consider one or more of the following surfaces:
        - *Ground (G)*
        - *Roof (R)*

          Unless otherwise noted, roof and ground contamination levels are identical, i.e., equal Bq m^{-2}.
        - *Wall (W)*

          While not reported in the studies used here, wall contamination levels are typically much lower than roof and ground contamination levels, e.g., [16].

      Note: "GR" indicates both ground and roof contamination is present, and "GRW" indicates ground, roof, and wall contamination is present.

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[5] The radiation energy, and the degree to which radiation penetrates a building, depends on the type and amount of radioactive isotopes that are present (which changes with time). The effective penetration energy, which quantifies how effectively fallout radiation penetrates into buildings, is larger than the average radiation energy since higher energy radiation is more effective at penetrating buildings than lower energy radiation.

5. RESULTS

This study identified 382 distinct buildings in 26 prior studies that met the screening criteria.[6] There were 219 separate building analyses in which a unique building, radiation type, radiation location, analysis method, and building floor were specified (note that a building analysis sometimes summarized results derived from multiple buildings). The buildings and building analyses are grouped below by category. Note that (a) not all buildings/building analyses fit into a given categorization and (b) a single building/building analysis may contribute to multiple categories.

- Building type
    - *Realistic structures:* 298 buildings; 80 building analyses
    - *Other structures:* 84 buildings; 139 building analyses

- Occupancy type
    - *Single family residence:* 280 buildings; 92 building analyses
    - *Multi-family residence:* 45 buildings; 24 building analyses
    - *Commercial:* 31 buildings; 74 building analyses
    - *Public:* 13 buildings; 13 building analyses
    - *Other:* 16 buildings; 17 building analyses

- Location within the building
    - *Basement:* 36 buildings; 36 building analyses
    - *1st (ground) floor:* 320 buildings; 105 building analyses
    - *Upper floors:* 10 building; 25 building analyses
      (excludes the 2nd floor of single family residences)

- Radiation type
    - *1 hour post detonation:* 58 buildings; 109 building analyses
    - *1 to 3 days post detonation:* 324 buildings; 110 building analyses

- Analysis method
    - *Experiment:* 327 buildings; 125 building analyses
    - *Theory (model):* 63 buildings; 107 building analyses

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[6] A US Office of Civil Defense report, which quality assured National Fallout Shelter Survey protection estimates for 33 fallout shelters [17], was excluded from this analysis. This prior study only examined a single, well protected location (fallout shelter) in each building and thus was excluded to avoid biasing this study's typical building protection estimates. This Office of Civil Defense report's protection factors, which range from 45 to 1250, are consistent with the protection factor range identified in the present study for the corresponding (heavy construction) building type.

The **Appendix** and spreadsheet (Appendix - Building BF Studies.xlsx) describe the identified buildings and building analyses.

After examining the building analyses, the building analyses were regrouped by building construction type such that protection factors patterns were similar (more precisely, groups in which differences in building construction and resulting protection factor patterns could be distinguished). These groups are described in this section and summarized in **Table 1** (the typical values reported in Table 1 are rounded). The typical protection factor is the median of the corresponding building analyses' typical/median protection factors. This method was chosen to provide an equal weight to each prior building analysis as the number of (a) reported protection values and (b) buildings analyzed ranged widely from study to study. The reported maximum and minimum protection factors reflect the highest and lowest protection factors reported by any prior building analysis in a given group. The total number of building analyses used (n) for a given calculation is also reported.

Table 1. Summary of prior building protection factors for different types of building construction. Reported values are the typical value (and range of values) of the individual building analyses values and, where provided, consider the effects of both ground and roof contamination. The typical value is rounded. Lower stories correspond to ground floor (and second floor for the single family residences). Upper stories are second and higher floors for non-single-family buildings.

	Basement	*Lower stories*	*Upper stories*
Single family residence	10 (6 to 67)	2.5 (1.5 to 5.2†, 50‡)	n/a
Heavy construction	600 (12 to >10,000)	40 (2 to 2,200)	80 (9 to 1,500)
Empty supermarket	n/a	8.5	n/a
Empty shed	25 (11 to 72)	2 (1.6 to 4.2)	n/a

† This is the most protected position in lightweight construction (includes brick veneer).

‡ This is the most protected position in masonry construction.

Single family residences

The single family residence buildings identified are (relatively) small, free-standing, 1 or 2 story structures that may or may not have a basement. These houses have a variety of exterior walls (e.g., wood, stucco, brick veneer, and concrete) and roof types (e.g., asphalt shingle, wood shingle, and concrete). Large windows were common.

Above ground (1st and 2nd floor), the typical protection factor for single family residences was 2.4, rounded to 2.5, with a range of 1.5 to 50 (n = 70). When the analysis was limited to buildings with lightweight exterior walls (e.g., wood, vinyl, brick veneer), the typical protection factor was 2.2 with a range of 1.5 to 5.2 (n = 51).[7] The typical protection factor for heavier, masonry construction was 3.6 with a range of 1.7 to 50 (n = 12). The above ground portions of Russian and German houses (typical protection of 10 with range of 2.3 to 50; n = 10) were better protected than the above ground portions of the US and Japanese houses (typical protection of 2.2 with range of 1.5 to 25; n = 54).

Below ground (basement), the typical protection factor was 11, rounded to 10 (n = 17). However, the protection factors were more variable, ranging from 6 to 67, with (i) lower protection associated with relatively exposed basements (e.g., the building was on a slope and multiple walls were above ground) and early times after a detonation and (ii) higher protection associated with fully submerged basements (without windows) and later times after a detonation.

Moving from above ground to the basement increased the protection five-fold (the ratio of the typical protection factor for the basement to the typical protection factor for the other floors was 5.1 with a range from 2.8 to 29; n = 20). In contrast, moving away from windows and exterior doors provided only a modest increase in an individual's protection (the ratio of the typical to minimum above ground protection factor was 1.2 with a range from 1.1 to 2.8; n = 19).

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[7] A Russian wooden walled building, typical protection factor = 7.7, was excluded.

Heavy construction

These buildings were constructed from brick or concrete often with relatively thick (0.2 to 1+ m) walls and roofs and can be large, both in height and footprint. These buildings may be attached to, or surrounded by, similar buildings and have a variety of uses – including offices, laboratories, and multi-family residences (apartments).

The protection factors reported for these buildings varied widely, both between different buildings and within a given building (this study did not include purpose-built fallout shelters). Protection factors ranged from 2 to >10,000 with (i) lower protection associated with locations near windows and doors and (ii) higher protection associated with more sheltered interior (or basement) locations of the larger buildings.

The available data supports some differentiation by building floor:

- Basement: 623, rounded to 600, with range from 12 to >10,000 (n = 14)
- 1st (ground) floor: 35, rounded to 40, with range from 2 to 2,200 (n = 32)
- Upper floors: 80 with range from 9 to 1,500 (n = 29)

On any given building floor, moving away from windows and exterior doors doubled an individual's protection (the ratio of the typical to minimum protection factor was 2.0 with a range from 1.1 to 180; n = 52). Adequate protection (protection factor ≥ 10) was often observed throughout these buildings; however, protection factors > 1,000 were not observed on the top floor (just below the contaminated roof). Moving to a better protected floor within the same building increased the protection twenty-fold (the ratio of the typical protection factor for the best protected floor to the typical protection factor for the other floors was 23 with a range from 1 to 250; n = 38).

Empty shed

An empty Butler building was extensively studied at the Nevada National Security Site (formerly the Nevada Test Site). These analyses include fallout measurements from the Diablo and Shasta shots as well as more controlled experiments. This 84 m^2, single-story building was constructed of a steel-frame covered with 0.0005 m (26-gauge) steel panels. Wood joists separated the 1st floor from the basement below. Similar buildings are in use as storage sheds and warehouses. The studied building lacked contents, which, if present, could increase the protection relative to that reported here.

During one fallout experiment, contamination of the pitched, metal roof was measured to be approximately 10% of the nearby ground contamination levels [18]. The removal of the remaining roof fallout increased the measured protection factors by less than 10% (the values reported here include the roof fallout contributions). For context in a separate fallout experiment, the roof and ground contamination was similar on other buildings with (i) flat concrete and (ii) pitched asphalt shingle roofs.

Protection factors for the empty shed were similar to the lightweight construction single family residences. Above ground, the typical protection factor was 2.1, rounded to 2, with a range of 1.6 to 4.2 (n = 3). Below ground (basement), the typical protection factor was 25, with a range from 11 to 72 (n = 3), with (i) lower protection associated with measurements near the basement center and early times after detonation and (ii) higher protection associated with measurements near the basement edge and later times after detonations.

Theoretical studies of two similarly constructed, but much larger Japanese buildings suggest that protection increases with building size (1st floor protection factors of 3.2 and 7.1 were reported for 1,140 and 30,000 m^2 buildings, respectively [19]). Caution should be used in interpreting the latter results as the roof fallout contributions were not included in the analysis and may be significant for the larger, flat roof buildings.

Empty supermarket

A single study examined the protection associated with a supermarket.[8] Similar to other tall, large, warehouse (big-box) stores, this supermarket has relatively thick (0.2 m) concrete exterior walls; a thin, lightweight roof (0.05 m concrete); and a large front window. Notably, the studied building lacked contents. If there were contents, they may increase the protection relative to that reported here.

The reported protection factors were averaged over large areas of the empty supermarket and ranged from 8.2 to 8.6 (no protection factors were reported near the window). Radiation from the roof dominates indoor exposures, 66 to 89% of the total depending on the location.

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[8] A Japanese supermarket analysis was excluded since that analysis (a) did not consider roof contamination and (b) the galvanized steel exterior walls were atypical of US construction.

6. DISCUSSION

6.1 COMPARISON TO PRIOR BUILDING PROTECTION SUMMARIES

The results of this study are consistent with prior summaries of fallout protection, see **Table 2**. These summaries also collated prior building protection analyses and thus the agreement shown is expected since several, but not all, of the individual building analysis studies considered by this study were also considered by the prior summary studies.

Table 2. Comparison of protection factor values (and range) against ground and roof contamination between this study and prior building protection summaries for (a) US single family residences and (b) buildings with larger, heavier construction

(a)	This study	Glasstone [20]	Bursen [14]
Study category	Single family residence	Frame house	Single family residence
Basement	10 (6 to 67)	10 to 20	6 to 40
Above ground	2.5 (1.5 to 5.2[†], 50[‡])	1.7 to 3.3	2 to 5

[†] This is the most protected position in lightweight construction (includes brick veneer).

[‡] This is the most protected position in masonry construction.

(b)	This study	Glasstone [20]	Bursen [14]
Study category	Heavy construction	Multi-story apartment	Complex structures (offices and apartment buildings)
Basement	600 (12 to >10,000)	n/a	100 to 200
Lower stories	40 (2 to 2,200)	10	20 to 100
Upper stories	80 (9 to 1,500)	100	

6.2 APPLICABILITY

The following items should be considered when using this study's results.

- *Other exposure pathways*

  This study is focused on nuclear fallout building protection, i.e., external exposure to the gamma radiation emitted by relatively large fallout particles deposited on the building roof and surrounding area.

  For some RDD and NPP scenarios, contamination on other surfaces (e.g., walls, indoors, surrounding buildings, and trees) can contribute significantly to indoor radiation exposure and so need to be considered. In addition, other exposure pathways, such as inhalation (breathing contaminated air), immersion (being surrounding by contaminated air), and ingestion (eating contaminated food), may also be important, see [8], [15], [21], and references therein.

  For these scenarios, a complete dose assessment would require consideration of other types of building protection (e.g., air infiltration, protection from cloudshine) as well as additional fate and transport pathways (e.g., weathering and resuspension of deposited material, fomite transport), e.g., see [21]–[25].

- *Building occupation*

  Building protection can vary significantly from one building type to the next as well as within a given building. Thus, in general, a complete dose assessment requires characterizing both (a) the building protection of different occupied buildings and the variation within any given building as well as (b) the distribution of people among and within different building types, e.g., see [11], [15], [26], [27]. Complicating the dose assessment calculations further, both of these factors can vary over time. Thus this study informs, but does not completely consider all the building protection considerations (see the *Building Construction* discussion below).

  Other work informs the general understanding of population distribution, which is known to vary by location and time (e.g., many cities have a daily migration between outlying residences and commercial buildings in the urban core). Furthermore, government officials can influence population distribution changes (e.g., through zoning, sheltering, evacuation, and relocation) and, therefore, can potentially significantly minimize radiation dose during the planning, response, remediation, and recovery phases. For example, sheltering in the immediate aftermath of a low-yield nuclear detonation is estimated to save 10,000 or more lives [2], [12].

- *Building construction (and environmental) variability*

  There is a wide variety of different building construction within the United States and more generally, world-wide, see [28]–[32] and references within. While this study has identified approximately 400 previous building analyses, these buildings should NOT be considered to be a representative nor comprehensive sample of all (a) common building types within the US or worldwide, (b) relevant radiation spectra, nor (c) common building environments, e.g., rural vs. urban core. Indeed many common building types were not studied by any prior study including, but not limited to, glass walled office buildings found in many urban cores and earthen (adobe) buildings found worldwide. Similarly, only a few studies have examined the impact of radiation spectra or building surroundings (including other nearby buildings) on the building protection factors, e.g., [16], [17], [27], [33]. More broadly, the reviewed literature clearly indicates that a given building's protection depends on a combination of building, environmental, and radiation parameters.[9]

  The limited number of previous building analyses only partially characterizes the protection associated with specific building types in modern building distribution databases. For example, the DHS Hazards-United States (HAZUS) building database used in the Regional Shelter Analysis (RSA) demonstration capability [11] has 42 building types whose descriptions include several building properties; such as building height, size, internal structure and use; whose impact on the building protection factor have not been analyzed sufficiently in previous studies.[10]

  This study's results are broadly consistent with the protection factors used in the RSA demonstration capability. However, as noted above, building analyses covering a wider range of building construction and use are required to validate (or update) the building protection factors used in the current RSA demonstration capability.

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[9] The specific properties required to accurately assess the distribution of protection factors for a given building remains an active research area. It is known that the following properties can be important: mass (areal density) of external walls, roof, and floors; the presence of a basement; the number of stories; the internal building structure; location within the building; the presence of apertures (e.g., windows, doors); radiation spectra; and the surrounding environment, e.g., [1], [6], [16], [33]. For some buildings such as libraries and warehouses, building contents contain more mass than the building construction materials, e.g. [26], and there is some evidence that even in office and residential buildings, contents (and interior walls) may significantly alter building protection estimates [17]. Many of the prior protection factor assessments performed during the US civil defense program, e.g., [1] and references therein, or in nuclear power plant accident remediation studies, e.g. [16], [17], [19], [27], [33], do not consider building contents (studies of in-use buildings inherently include contents).

[10] This is due, in part, to the relatively limited number of non-single family residences that have been previously studied. Furthermore, these studies cover much of the variation of US single family residences, but neglect residence construction common in other parts of the world, e.g., earthen houses.

7. CONCLUSION

This study reviewed the previously published building protection literature and (a) identified prior building protection studies, (b) extracted the results relevant to US building construction, and (c) summarized building protection by building type. The summaries of building protection factors by building type were consistent with, and extend, prior published summaries. In using these results in radiation dose assessments, readers should consider (a) the relative importance of other radiation exposure pathways, (b) the degree to which buildings are occupied, and (c) representativeness of these results to the building(s) being assessed (e.g., many key building construction types have not been previously analyzed).

In future work, novel and efficient approaches may be needed to characterize the impacts of the broader array of building, population, environmental, and radiation parameters relevant to US (and worldwide) building stock and population distributions. While recent work has made progress on systematic methods of describing key building properties,[11] identification and standard descriptions of other properties are lacking. Furthermore, work remains to characterize the range, and reasonable combinations, of parameters associated with common building types. Finally, charactering the net effect of numerous interacting parameters will likely require a quality assured method that rapidly translates building, population, environmental, and radiation parameter sets into building protection factor distributions.

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[11] At an individual building level, the Global Earthquake Model building taxonomy [30] is currently being investigated by Oak Ridge National Laboratory for this application and shows promise in capturing the needed building parameters.

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9. APPENDIX

A. APPENDIX TABLE OF CONTENTS

B. PRIOR STUDY ABSTRACTS

Reference [A1]: *Experimental Evaluation of the Radiation Protection Afforded by Typical Oak Ridge Homes against Distributed Sources*

The protection afforded against simulated fallout radiation has been evaluated for several typical homes in the Oak Ridge area. Nine houses were chosen to represent a variety of construction materials, topographical conditions, and sizes; they included three types of Oak Ridge Cemesto houses, one concrete-block house with a basement "fallout shelter," and two woodframe houses. The protection factor (ratio of open-field exposure dose rate to exposure dose rate in the house) in all these houses ranged from 2 to 5 on the main floor and from 5 to 30 in the basements, except in the fallout shelter, where the protection factor was greater than 100. The analysis showed that sloping lots, common to Oak Ridge, do not appreciably affect the protection factor for the main floor. Owing to the generally increased exposure of the basement walls on such lots, the protection factors in the basements were typically lower than in similar basements built on level lots.

Reference [A2]: *Experimental Evaluation of the Fallout-Radiation Protection Afforded by a Southwestern Residence*

An experimental study was conducted to determine the fallout-radiation protection afforded by a residence representative of a type of construction much in favor in the Southwest: a single-story stucco and frame house with a heavy shake roof and no basement. This study was one of many such studies sponsored by Civil Effects Test Operations, Division of Biology and Medicine, U. S. Atomic Energy Commission, for the purpose of evaluating the protection presently afforded by ordinary homes and structures against the dangers of fallout radiation.

The protection afforded by the home was determined by simulating a fallout-radiation field above and immediately surrounding the house and measuring the radiation level within. The radiation field was simulated by pumping a sealed Co^{60} source through a long length of tubing evenly distributed over the test area. Highly sensitive dose-integrating ionization chambers were used to measure the radiation level inside the structure. The test was performed rapidly, easily, and safely. Valid statistical data were obtained even though the radiation level was of such low magnitude that it was unnecessary to evacuate any of the neighboring homes.

The protection factors within the house (ratio of exposure dose rate in the open field to exposure dose rate in the structure) ranged from 2.8 to 4.4, depending on the location. The results compare favorably with those found in previous exercises under similar conditions.

Reference [A3]: *Evaluation of the Fallout Protection Afforded by Brookhaven National Laboratory Medical Research Center*

An experimental study was made to determine the protection against fallout radiation provided by the Medical Research Center at Brookhaven National Laboratory. Shelter areas in the basement which could be used as emergency hospital wards were found to offer satisfactory shielding during a fallout situation.

This study also added data to the nuclear energy civil effects research being conducted by the Civil Effects Test Operations, Division of Biology and Medicine, United States Atomic Energy Commission, on the radiation shielding provided by structures.

A fallout radiation field was simulated by pumping a sealed Co^{60} source through a long length of evenly distributed tubing. Radiation measurements were made inside the Medical Center by dose-integrating ionization chambers.

In general, the protection factors (ratio of open-field exposure dose rate to structure exposure dose rate) varied from 200 to 400 throughout the basement and from 12 to 20 on the first floor. Two isolated areas in the basement indicated much higher protection factors (1400 and 4000). Since this was a large one-story structure with a flat roof, fallout on the roof would probably contribute more than 90 per cent of the total exposure dose rate at most points within the building during a fallout situation. Methods of significantly increasing the protection at most points of interest are limited to increasing the shielding material between the shelter areas and the roof or removing the contamination from the roof.

Reference [A4]: *An Experimental Evaluation of the Radiation Protection Afforded by a Large Modern Concrete Office Building*

An experimental study was made to determine the effective shielding provided by a modern reinforced-concrete office building (AEC Headquarters building) from nuclear fallout. Pocket ionization chambers were used for measurement of the radiation-field strength. Fallout was simulated with distributed and point-source configurations of Co^{60} and Ir^{192} sources.

Four typical sections were selected for study, and experiments were performed on each. These included an external wing with exposed basement walls and an external wing with a buried basement. Roof studies were made on an internal wing with a full basement and on the east end of wing A, which has a thin-roof construction. The thick-roof construction of 8 in. of concrete and 2 in. of rigid insulation covers all the building except the east end of wing A, which has 4 in. of concrete and 2 in. of insulation.

Reference [A5]: ***Experimental Evaluation of the Fallout-Radiation Protection Provided by Selected Structures in the Los Angeles Area***

An experimental study designed to provide a basis for estimating protection against fallout radiation was conducted on four diversified structures in the Los Angeles, Calif., area. This study was sponsored by the Civil Effects Test Operations (CETO), Division of Biology and Medicine, U. S. Atomic Energy Commission. The four buildings studied were (1) the Laboratory of Nuclear Medicine and Radiation Biology at the University of California at Los Angeles (UCLA); (2) a family fallout shelter; (3) the communications section of the Los Angeles Police Department building; and (4) a typical classroom located at North Hollywood High School.

A fallout radiation field was simulated by the Mobile Radiological Measuring Unit. The unit employed a single radioactive Co^{60} source, which was pumped at a uniform speed through a long length of tubing evenly distributed over the area of interest. Measurements of the radiation levels at selected points inside the structures were made with highly sensitive ionization-chamber detectors. Protection factors ranged from 10 to 2000 in the UCLA building, up to 10,000 in the family fallout shelter, from 50 to 150 in the communications section of the police building, and from less than 10 to approximately 20 in the high school classroom.

Reference [A6]: ***Shielding of Buildings in an Urban Environment***

The shielding of typical buildings, i.e. the reduction of outdoor to indoor exposure due to external radiation, has been measured in 41 Viennese dwellings. Buildings were selected to best represent the building structure of the city by establishing nine different building categories according to different construction periods. The measurements were performed by comparing the gamma flux outdoors to that indoors by *in situ* gamma spectroscopy and calculational correction for dose build-up. From the measurements the contribution of indoor contamination to indoor exposure was also derived, which ranged from <10% up to 50% of total indoor exposure 8 y after fallout. Immediately after fallout, therefore, possibly significantly higher contributions by indoor contamination may have to be expected. Exposure reduction factors amounted to 0.021 ± 0.006 on the average, old buildings from between the wars and after WW2 showing higher reduction factors of about 0.009, modern prefabricated buildings lower reduction factors of 0.025 and single-family houses displaying the lowest reduction factors of 0.11. Due to the experimental method these factors do not include any exposure reduction due to wash-off and other weathering effects which further decrease the exposure in urban areas as compared to initial fallout levels.

Reference [A7]: Dose rate survey inside and outside three public buildings located approximately 40 km northwest of the Fukushima Daiichi Nuclear Power Stations

We surveyed the reduction of the dose rate inside three public buildings compared to the dose rate outside in Kawamata-machi, Fukushima Prefecture. The three buildings – a wooden construction district meeting place, a steel construction public hall, and a reinforced concrete school building – are located approximately 40 km northwest of TEPCO’s Fukushima Daiichi Nuclear Power Stations. The dose rate measurement, performed with NaI(Tl) scintillation survey meter, was carried out on January 19, 2012. We evaluated the reduction of the dose rate inside the building using the reduction factor, which was determined to be the ratio of the dose rate inside the building to that outside the building. The reduction factors 1 m inside from the window were 0.51 – 0.56 for the wooden building, 0.34 – 0.51 for the steel construction building, and 0.27 – 0.31 for the concrete building. The reductions factors at the center of the room were 0.48 for the wooden building, 0.23 – 0.34 for the steel construction building, and 0.10 – 0.16 for the concrete building.

Reference [A8]: Radiation doses among residents living 37 km northwest of the Fukushima Dai-ichi Nuclear Power Plant

External and internal radiation doses were estimated for 15 residents who lived approximately 37 km northwest of the Fukushima Dai-ichi Nuclear Power Plant, which released radioactive plumes on March 11, 2011 as the result of the Tohoku earthquake and subsequent tsunami damage. Residents were interviewed on where they stayed and what they ate after the incident. To estimate external dose, the air dose rate around each person's home was measured, and cumulative effective doses up to 54 d after the deposition were calculated. To estimate committed effective dose, urinary bioassays were performed using a low-background Ge spectrometer on 54 d and 78–85 d after the deposition. The average cumulative effective dose was 8.4 mSv for adults and 5.1 mSv for children. The average committed effective dose from ^{134}Cs and ^{137}Cs was 0.055 mSv for adults and 0.029 mSv for children. Iodine-131 was observed from urinary samples of five residents, the equivalent doses for thyroid gland were 27–66 mSv at maximum. We discuss the necessity of reducing the risk of further exposure.

Reference [A9]: Measurements of air dose rates in and around houses in the Fukushima Prefecture in Japan after the Fukushima accident

Measurements of air dose rates for 192 houses in a less contaminated area (<0.5 μSv h^{-1}) of the Fukushima Prefecture in Japan were conducted in both living rooms and/or bedrooms using optically stimulated luminescence (OSL) dosimeters and around the houses via a man-borne survey at intervals of several meters. The relation of the two air dose rates (inside and outside) for each house, including the background from natural radionuclides, was divided into several categories, determined by construction materials (light and heavy) and floor number, with the dose reduction factors being expressed as the ratio of the dose inside to that outside the house. For wooden and lightweight steel houses (classed as light), the dose rates inside and outside the houses showed a positive correlation and linear regression with a slope-intercept form due to the natural background, although the degree of correlation was not very high. The regression coefficient, i.e., the average dose reduction factor, was 0.38 on the first floor and 0.49 on the second floor. It was found that the contribution of natural radiation cannot be neglected when we consider dose reduction factors in less contaminated areas. The reductions in indoor dose rates are observed because a patch of ground under each house is not contaminated (this is the so-called uncontaminated effect) since the shielding capability of light construction materials is typically low. For reinforced steel-framed concrete houses (classed as heavy), the dose rates inside the houses did not show a correlation with those outside the houses due to the substantial shielding capability of these materials. The average indoor dose rates were slightly higher than the arithmetic mean value of the outdoor dose rates from the natural background because concrete acts as a source of natural radionuclides. The characteristics of the uncontaminated effect were clarified through Monte Carlo simulations. It was found that there is a great variation in air dose rates even within one house, depending on the height of the area and its closeness to the outside boundary. Measurements of outdoor dose rates required consideration of local variations depending on the environment surrounding each house. The representative value was obtained from detailed distributions of air dose rates around the house, as measured by a man-borne survey. Therefore, it is imperative to recognize that dose reduction factors fluctuate in response to various factors such as the size and shape of a house, construction materials acting as a shield and as sources, position (including height) within a room, floor number, total number of floors, and surrounding environment.

Reference [A10]: Reduction factors for wooden houses due to external γ-radiation based on in situ measurements after the Fukushima nuclear accident

For estimation of residents' exposure dose after a nuclear accident, the reduction factor, which is the ratio of the indoor dose to the outdoor dose is essential, as most individuals spend a large portion of their time indoors. After the Fukushima nuclear accident, we evaluated the median reduction factor with an interquartile range of 0.43 (0.34–0.53) based on 522 survey results for 69 detached wooden houses in two evacuation zones, Iitate village and Odaka district. The results indicated no statistically significant difference in the median reduction factor to the representative value of 0.4 given in the International Atomic Energy Agency (IAEA)-TECDOC-225 and 1162. However, with regard to the representative range of the reduction factor, we recommend the wider range of 0.2 to 0.7 or at least 0.2 to 0.6, which covered 87.7% and 80.7% of the data, respectively, rather than 0.2 to 0.5 given in the IAEA document, which covered only 66.5% of the data. We found that the location of the room within the house and area topography, and the use of cement roof tiles had the greatest influence on the reduction factor.

Reference [A11]: External exposure of the population living in areas of Russia contaminated due to the Chernobyl accident

An updated version of external dose modeling is presented with reference to the population in Russian areas contaminated due to the Chernobyl accident. An earlier version has been modified by applying a study time interval with a starting point immediately after radionuclide deposition (rather than 4 years after the accident as applied earlier) and by introducing an estimate of individual dose distributions. New input data to the model are the nuclide-specific composition of the deposit, additional data about migration of caesium in soil, time dependence of location factors and uncertainty distributions of all input parameters. Model results (i.e. effective dose-rates and accumulated effective doses) from external exposure for the rural and urban populations in contaminated areas of Russia during 100 years after the accident are presented. Radionuclide contributions to the dose during various time intervals after the accident have been estimated. The model has been validated by measurements of absorbed dose-rate in air during the first 30 days after the accident and by TLD measurements of individual external doses among inhabitants of contaminated rural settlements in the year 1993. Both the measurements and model show that the geometric mean of individual external doses is about 10% lower than the arithmetic mean and the upper bound of the 95% confidence range is larger by a factor of about 2.

Reference [A12]: Measurements after the Chernobyl Accident in Relation to the Exposure of an Urban Population

After the Chernobyl accident *in-situ* gamma spectrometric measurements have been performed in Munich and in smaller towns in Southern Bavaria. At the measurement sites about two thirds of the total contamination was deposited by rain. For grassland, the attenuation of the radiation from ^{131}I, ^{103}Ru, ^{134}Cs, and ^{140}Ba due to the initial migration of the radionuclides in the ground and due to the surface roughness was found to be similar. However, large variations between the retention of the various elements on smooth surfaces have been observed. The absorbed dose-rate inside houses due to Chernobyl radionuclides was the range of one tenth to one hundredth of the absorbed dose-rate over open grassland, depending on the type of house and the location in the house, especially on the angle of view from the detector position to outside locations. The absorbed dose-rate in air due to caesium isotopes was measured over a period of 1 month to 8 years after the accident. To facilitate a use in models on radiation doses in urban environments, the time dependence of the results were approximated by analytical functions.

Reference [A13]: Pathway analysis and dose distributions

[document does not contain an abstract]

Reference [A14]: ***The Radiological Assessment and Recovery of Contaminated Areas***

The Civil Effects Test Operation Exercise CEX-57.1 following Operation Pumbbob was carried out to obtain information on decontamination procedures that could be used as radiological countermeasures. The test was conducted on D + 1 and D + 2 days after shot Coulomb C. Data were obtained on reclamation of land areas by scraping with a motorgrader, on fire-hosing and scrubbing a concrete-slab roof, and on fire-hosing a composition roof. In addition, some shielding data were obtained for a small building with 6-in.-thick concrete walls and roof.

The conceptual nature of a radiological defense system and the role of decontamination or reclamation in such a system are discussed. Most of the report deals with methods for reducing the observed data to interpretive form because the data were taken within a large contaminated area.

The decontamination effectiveness in terms of the fraction of contamination remaining was computed to be: (1) 0.2 to 0.3 for scraping with a motorgrader (1 pass with 1½ -in. cut); (2) 0.3 to 0.4 for fire-hosing a concrete roof (1 pass, 50-psi nozzle pressure); and (3) 0.3 to 0.4 for fire-hosing a composition shingle roof. No significant additional amount of fallout was removed from the concrete roof when it was scrubbed after fire-hosing. These results are high compared to other data owing to the low levels of contamination and error in the measurements and data analysis methods.

It is concluded that low levels of contamination at the Nevada Test Site could be utilized to advantage to obtain data on gamma-radiation properties, such as the effects of materials and source geometries on the attenuation of fission-product gamma rays. However, higher levels of fallout, in terms of the fallout particle mass, are required to obtain useful information and training on decontamination techniques; therefore, the use of low levels of contamination to conduct studies in this area is not recommended.

Reference [A15]: ***Experimental Radiation Measurements in Conventional Structure: Part II Comparison of Measurements in Above-Ground and Below-Ground Structures from Simulated and Actual Fallout Radiation***

An experimental study designed to provide a basis for estimating protection against fallout radiation was made on two types of structures at the Nevada Test Site. This study was sponsored by the Civil Effects Test Operations, Division of Biology and Medicine, U. S. Atomic Energy Commission. The two buildings studied were a lightly constructed building with a basement, and an underground group shelter.

An idealized fallout radiation field was simulated by the use of the Mobile Radiological Measuring Unit (MRMU). The unit employed a sealed radioactive Co^{60} source that was pumped at a uniform speed through a long length of flexible tubing evenly distributed over the area of interest. Radiation levels at selected points inside the structures were measured with sensitive ionization-chamber detectors.

These measurements were compared with measurements taken under actual fallout conditions at an earlier time and were also compared with the theoretical calculations.

Protection factors from fallout data and MRMU data at the basement structure compared roughly within a factor of 2. This was good, considering the limitations of the two sets of data and other factors affecting the differences. Comparisons between protection factors from fallout data and MRMU data at the underground group shelter were excellent. MRMU data and theoretical calculations also compared satisfactorily.

Reference [A16]: ***Protection Against Fallout Radiation in a Simple Structure***

A reinforced Butler building was exposed to fallout from Shots Diablo and Shasta, and the resulting dose rates and fallout deposition inside and outside the structure were measured with various instruments and techniques.

Protection factors and roof and ground contributions to the total dose rates at points within the structure were determined from the measurements. Comparisons were made with the results of theoretical and other experimental studies.

Information obtained from this experiment should be of value as basic experimental data for fallout protection work, although it is recommended that additional substantiative data be obtained under more controlled conditions.

Reference [A17]: ***Experimental Evaluation of the Fallout-Radiation Protection Provided by Structures in the Control Point Area of the Nevada Test Site***

Fallout radiation protection factors (PF's) were determined for six buildings within the CP complex of the U. S. Atomic Energy Commission's Nevada Test Site, four from experimental data with fallout simulation techniques and two derived from calculations. Data using ^{60}Co are applicable to a deposited 1-hr fission-product condition. Results are presented as PF contours on floor plans. These PF values at locations away from entrances are:

Building	PF range
CP-40, Communication Building	15 to 25
CP-45, Light Laboratory	
Upstairs	50 to 100
Downstairs	100 to 1000
CP-1, Main Control Building	
Upstairs	30 to 50
Downstairs	250 to 500
CP-1B, Main Control Building Addition	
Main floor	100 to 600
Basement	300 to 10,000
CP-2, Rad-Safe Building	
Upstairs	20 to 40
Downstairs	50 to 300
CP-14, Programmatic Building	2 to 3
CP-50, Radiological Sciences Building	5 to 10

Protection from 1-day-old fission products and from cloud passage was also estimated. These values are about the same for lightly constructed buildings (CP-14 and CP-50) but increase to as much as a factor of 3 higher for heavily constructed buildings (CP-1B).

Construction of a baffle wall around the west entrance to the main floor of CP-1B and provision of sandbags or concrete blocks to block up the north entrance to the basement are recommended to significantly improve protection factors in the Test Manager's Operations Room and the downstairs briefing room, respectively.

In addition to obtaining protection factor values for the buildings of concern, the experiment yielded much valuable information useful to a variety of radiation and shielding studies.

Reference [A18]: *Radiation Distribution within a Multistory Structure*

The evaluation of the methods currently proposed to calculate the protection afforded by a structure from radioactive contamination distributed on the ground and roof of structures has been the subject of past studies conducted at the Radiation Test Facility formerly Protective Structures Development Center. Investigations to date include an evaluation of dose variation with both location and size of the contaminated area; the attenuation afforded by a vertical wall adjacent to a semi-infinite field of contamination; the attenuation of roof based source of contamination; and the attenuation of radiation scattered into a basement area.

This report describes a series of experiments designed to measure the attenuated radiation dose within a structure from both an infinite field of contamination and limited strips of contamination. The experimental results are compared with results calculated on the basis of existing theories.

In the infinite field studies, the experiments were conducted on a structure having 49, 98, and 147 psf walls, but no floors. These experiments were designed to determine the dose distribution with different wall mass thickness. In the following series the structure was modified by adding floors of 48.6 psf and 97.2 psf with 49 and 98 psf walls. In this series, the effect of floors on the dose distribution was studied. Both structure center line and off center measurements were taken. Relatively good agreement, generally within 25%, was obtained between measured and computed reduction factors.

In the limited strip studies, the same floor and wall combinations were used. The agreement between calculational and experimental dose rates for limited strips of contamination is good for a simple box type structure; however, on upper stories of multi-story structures large differences were noted, especially for close in contamination. This difference is attributed partly to the scattered radiation emerging from the walls, which is assumed in the calculations to be symmetrical about the detector with respect to the horizon and unchanged with field widths. Experimental results indicated that the scattered radiation emerging from the walls is not symmetrical, but is more peaked in the upward direction.

Reference [A19]: *An Experimental Evaluation of Roof Reduction Factors within a Multi-story Structure*

Fallout contamination deposited on the roof of a structure is, in many cases, the source of the primary radiation component of the total dose obtained at any point within the structure. Experiments have been performed in which the doses from a source of radiation present on a roof were measured in many locations within a multi-story building.

This report presents the results of these experiments for roof and floor mass thicknesses of 48.6 and 97.2 psf. Comparisons of the experimentally measured gamma doses with those determined theoretically have been shown throughout this report. Agreement between experiment and theory has, in general, been found to be good.

Reference [A20]: *Modeling of an Industrial Environment: External Dose Calculations Based on Monte Carlo Simulations of Photon Transport*

External gamma exposures from radionuclides deposited on surfaces usually result in the major contribution to the total dose to the public living in urban-industrial environments. The aim of the paper is to give an example for a calculation of the collective and averted collective dose due to the contamination and decontamination of deposition surfaces in a complex environment based on the results of Monte Carlo simulations. The shielding effects of the structures in complex and realistic industrial environments (where productive and/or commercial activity is carried out) were computed by the use of Monte Carlo method. Several types of deposition areas (walls, roofs, windows, streets, lawn) were considered. Moreover, this paper gives a summary about the time dependence of the source strengths relative to a reference surface and a short overview about the mechanical and chemical intervention techniques which can be applied in this area. An exposure scenario was designed based on a survey of average German and Hungarian supermarkets. In the first part of the paper the air kermas per photon per unit area due to each specific deposition area contaminated by ^{137}Cs were determined at several arbitrary locations in the whole environment relative to a reference value of 8.39 x 10^{-4} pGy per gamma m^{-2}. The calculations provide the possibility to assess the whole contribution of a specific deposition area to the collective dose, separately. According to the current results, the roof and the paved area contribute the most part (approximately 92%) to the total dose in the first year taking into account the relative contamination of the deposition areas. When integrating over 10 or 50 y, these two surfaces remain the most important contributors as well but the ratio will increasingly be shifted in favor of the roof. The decontamination of the roof and the paved area results in about 80-90% of the total averted collective dose in each calculated time period (1, 10, 50 y).

Reference [A21]: ***Experimental Analysis of Interior Partitions, Apertures, and Nonuniform Walls***

The theory of radiation attenuation in complex structures has received much attention during the past few years. The principles have been worked out for application to simple configurations of floors and outside walls so that radiation intensities, within these idealized buildings, from plane fallout fields can be predicted with reasonable accuracy. For other situations, such as a multistory structure having interior partitions, apertures, and nonuniform walls, however, either experimental data do not agree well with computed values or the experimental data usually obtained from existing structures fail to indicate clearly which aspects of the theory require modification.

The purpose of the experimental work reported here was to evaluate systematically the present procedures for estimating the shielding influence of building components in real structures. Experimental data on the effects of interior partitions, apertures, and nonuniform walls in real geometries were obtained by a series of measurements made on the three-story test structure that was previously used in studies at the Radiation Test Facility (RTF). Two typical interior partition configurations were investigated: a box-shaped central core room and a 12-foot-wide corridor forming three rooms within the 24-by-36-foot test structure. In the aperture experiments, the exterior walls of the test structure were altered so that 1/9 of the wall area on the first and second stories consisted of apertures and 1/3 of the wall area on the third story remained open. The exterior walls of the structures for the nonuniform wall experiments consisted of 4-and-8-inch concrete slabs with 1/3 of the wall area occupied by 8-inch slabs.

Each building component was evaluated separately for its shielding influence on the structure. In addition, combinations of these components were investigated.

Major conclusions drawn from this study were:

<u>Interior Partitions</u>

1. For a given total wall thickness, experimental dose rates in the center of the structure increase as the partitions are moved toward the detector.
2. The reduction factors calculated for the structure with interior partitions are between 15 and 20 percent higher than experimental results for detector locations 3 feet above the floors.
3. The experimental reduction factors increase more rapidly with height above the floor than predicted by the calculations.

<u>Apertures</u>

1. The reduction factors calculated for the structure with apertures followed the general trend of the experimental results, but are conservative by as much as 30 percent.
2. The reduction factors calculated for the structure with apertures and interior partitions show the same trend as the experimental values, but are less conservative

than the results without the interior partitions. In locations below sill height the calculations were slightly nonconservative.

Nonuniform Walls

1. The use of azimuthal sectors in the calculations appears to be valid. The agreement with experiment is about the same as that noticed for experiments with uniform walls.
2. The presence of interior partitions in the structure with nonuniform exterior walls did not appreciably affect the accuracy of the calculational technique.

Reference [A22]: ***Shielding of Gamma Radiation by Typical European Houses***

The shielding of gamma radiation by typical European houses has been investigated using a Monte Carlo photon transport code. Sources of the gamma radiation are activity deposited on the building and its surroundings and air-borne radionuclides in an semi-infinite cloud. Results are given for different source energies and at various locations inside and outside of the buildings. The effects of deposition on nearby trees and of shielding by neighbouring buildings was investigated. A comparison has been made with results obtained for the same buildings by the point kernel buildup factor method. More than an order of magnitude underestimations by the point kernel method are shown to arise in certain cases.

Reference [A23]: ***Civic Improvement Program: Volume II - Fallout Protection Factor Analysis Capabilities***

The Vehicle Code System (VCS), originally developed to calculate initial radiation environments and protection factors for three-dimensional shield systems, has been modified to calculate protection factors for fallout radiation environments. This report describes the modifications to VCS and gives the results of several test case analyses performed to verify this fallout protection factor version.

Fallout radiation protection factor calculations were performed for a number of structures for which simulated fallout experiments had been performed in the late 1950’s and early 1960's. The comparisons were generally good, with about half of the results agreeing within 10 percent and three-quarters of the results agreeing within 20 percent. Disagreement was found in some cases where descriptions of the structure were not adequate. We believe, based on these overall results, that the fallout protection factor version of VCS is performing correctly.

Calculations were also performed to assess the potential effect on fallout protection factors of a number of variations in typical structures. Variations explored included the effects of internal partitions, attached garages, basement depth, structure length-to-width ratio, and fallout contaminated balconies.

Reference [A24]: *A University Design Study of Protection Factors in Typical American Houses*

Measurements were made of the ground contribution to the reduction factor at several locations in several typical American houses. Comparisons are made between experimental results and Engineering Manual calculations for the various locations. Comparisons are also made between different houses to observe the effects of changes in structural parameters, such as variations in exterior wall mass thickness.

In general, Engineering Manual results agree well with experimental results in the first story measurements of the ground contribution. The agreement for basement measurements seems to be a function of the location and elevation of the point in question. Agreement is good for locations in the lower half of the basement. However, as the locations approach the basement ceiling experiment and calculations may disagree by as much as a factor of two or three for the ground contribution. The calculations are usually on the conservative side when discrepancies are noted.

The Engineering Manual predicts a steady increase in the reduction factor as the detector location is moved toward the basement ceiling along the vertical centerline of the test structure. This trend was not observed experimentally. The reduction factors showed a weak dependance on the elevation in the lower half of the basement and displayed a significant decrease as the basement ceiling was approached.

Four types of Engineering Manual Calculations were performed for the purpose of comparison; a ^{60}Co energy spectrum was used in conjunction with Eisenhauer's floor attenuation factor and the usual floor barrier reduction factor; the same calculations were performed using a 1.12 hour fission product spectrum. It was found that the energy spectrum made little difference for above grade calculations, but significant differences were noted below grade.

Reference [A25]: Study of radiation dose reduction of buildings of different sizes and materials

The dependence of radiation dose reduction on the sizes and materials of buildings was studied by numerical analyses using the Monte Carlo simulation code, PHITS. The dose rates inside the buildings were calculated by simulating gamma-ray transport from radioactive cesium deposited at the ground surface. Three building models were developed: the wooden house, the open-space concrete building, and the thin-wall building, to study the effect of building size and construction material on dose reduction inside these structures. Here the floor-area sizes of the building models were varied to clarify the influence of building configuration on dose reduction. The results demonstrated that the dose rates inside the buildings linearly decreased with increasing floor area on a logarithmic scale for all types of buildings considered. The calculated dose distribution inside a building indicated that the distance from the outer walls was a determining factor for the dose rate at each position in the building. The obtained tendency was verified by comparison with data reflecting the dose reduction of typical buildings in Japan.

Reference [A26]: Analyses of radiation shielding and dose reduction in buildings for gamma-rays emitted from radioactive cesium in environment discharged by a nuclear accident

Precise dose assessment requires the factors for each building. In addition, the data were based on researches for foreign buildings, which may be different from Japanese buildings. We therefore surveyed building trends in Fukushima and selected representative houses and buildings. 3-D models of the buildings were constructed and the radiation doses inside the buildings were calculated by PHITS to derive the effects of shielding and dose reduction by the buildings. The results provide us useful knowledge for dose assessment of residents in Fukushima area.

Reference [A27]: Effect of Windows and Doors on the Gamma Shielding Factor for Typical Houses in Brazil

This study aims to determine the effect of windows and doors on shielding factors, defined as the ratios of the air kerma indoor to the air kerma in an open field, for typical building materials used in the southeast of Brazil due to radioactive material deposited on the surrounding field, walls, and ceiling external surfaces. The MCNP5 Monte Carlo radiation transport code was used in the simulation of photon shielding. The air kerma indoors for monoenergetic photons of 300 keV, 662 keV, and 3,000 keV has been determined for three different housing patterns, ranging from a poorly constructed house, at a density thickness of 5.5 g cm^{-2} for the walls, to a well-constructed house, at a density thickness of 13.1 g cm^{-2} for the walls, both with and without the presence of windows and doors. The shielding factor for the poorly constructed house type at an incident photon energy of 300 keV was found to be twice that of the well-constructed house type for the same energy. The presence of windows and doors showed very little or no significant increase on the shielding factors for the building materials studied. The maximum increase was found to be 9% for the well-constructed house type at a incident photon energy of 300 keV.

Reference [A28]: Building Protection- and Building Shielding-Factors for environmental exposure to radionuclides and monoenergetic photon emissions

We describe a simplified method for calculating both building protection- and shielding factors for generic one- and two-story housing-unit models that are source-term dependent. Typically, radionuclide-independent factors are applied generically to external dose coefficients to account for the radiation shielding effects of indoor residences. In reality, the shielding effectiveness of each housing-unit would change over time as the radionuclide mixture and gamma-ray energy spectrum change due to physical effects such as deposition, radioactive decay, weathering effects, and decontamination efforts. Thus, it is necessary to develop factors designed for multiple photon energy spectrums to generate a more realistic estimate of the shielding effectiveness of a particular building. It is impractical to develop factors specific to a spectrum of photons emitted by each radionuclide of interest. Therefore, Monte Carlo simulations have been performed for sixteen monoenergetic photon energies from 0.10 to 3.0 MeV to characterize the three-dimensional radiation fluence through each housing-unit produced by two idealized, yet realistic, environmental exposure scenarios. Results of these simulations were then used to develop fitted logarithmic functions (extrapolated to 0.0 MeV) to correlate an estimated factor to any monoenergetic photon energy up to 3.0 MeV. To verify these functions, another series of Monte Carlo simulations were performed for a select set of radionuclides to develop radionuclide-specific building protection- and shielding factors. Good agreement is achieved between factors estimated using the presented functions and those calculated directly using Monte Carlo methods. Factors predicted by these functions are found to be in general agreement with other study results reported on similar structures which applied various computational methods and source-terms.

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D. INDIVIDUAL BUILDING ANALYSIS RESULTS FOR REALISTIC STRUCTURES

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A1]	Oak Ridge type "D" (D1) house, partial basement, enclosed porch	1st floor	Single Family Residence	1	2.5 (2.3 to 3)	60Co	D	GR	E	
[A1]	Oak Ridge type "D" (D1) house, partial basement, enclosed porch	basement	Single Family Residence	1	8.5 (7 to 27)	60Co	D	GR	E	
[A1]	Oak Ridge type "D" (D2) house, partial basement, enclosed porch	1st floor	Single Family Residence	1	2.4 (2.1 to 2.8)	60Co	D	GR	E	
[A1]	Oak Ridge type "D" (D2) house, partial basement, enclosed porch	basement	Single Family Residence	1	8 (8.0 to 9.0)	60Co	D	GR	E	
[A1]	Oak Ridge type "D" (D3,D4) house, flat lot	1st floor	Single Family Residence	1	2.7 (2.2 to 2.7)	60Co	D	GR	E	
[A1]	Oak Ridge type "D" (D3,D4) house, sloped lot	1st floor	Single Family Residence	1	2.7 (2.2 to 2.7)	60Co	D	GR	E	
[A1]	Single story wood frame (WF1), full open basement, flat lot	1st floor	Single Family Residence	1	2.7 (2.3 to 2.8)	60Co	D	GR	E	
[A1]	Single story wood frame (WF1), full open basement, flat lot	basement	Single Family Residence	1	13 (12 to 13)	60Co	D	GR	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A1]	Single story wood frame (WF1), full open basement, sloping lot	1st floor	Single Family Residence	1	2.7 (2.4 to 2.8)	60Co	D	GR	E	
[A1]	Single story wood frame (WF1), full open basement, sloping lot	basement	Single Family Residence	1	7.5 (6.0 to 8.0)	60Co	D	GR	E	
[A1]	Single story wood frame (WF2), lot sloped up in front and down behind	1st floor	Single Family Residence	1	2.6 (2.1 to 2.6)	60Co	D	GR	E	
[A1]	Single story wood frame (WF2), lot sloped up in front and back	1st floor	Single Family Residence	1	2.5 (2.0 to 2.5)	60Co	D	GR	E	
[A2]	Single-story stucco and frame house, heavy shake roof, no basement	1st floor	Single Family Residence	1	4.1 (2.3 to 5.2)	60Co	D	GR	E	Determined infinite plane correction negligible (and therefore ignored)
[A1]	Oak Ridge type "B" Cemesto house, wood siding, crawlspace	1st floor	Single Family Residence	1	2.5 (2.3 to 2.8)	60Co	D	GR	E	
[A3]	BNL Med. Research Ctr., large 1-story reinforced concrete and brick structure	1st floor	Commercial (Laboratory)	1	16 (12 to 72)	60Co	D	GR	E	In/near low-level counting room (well shielded) reported PFs 100–120
[A3]	BNL Med. Research Ctr., large 1-story reinforced concrete and brick structure	basement	Commercial (Laboratory)	1	360 (29 to 4200)	60Co	D	GR	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A1]	Concrete block house, wood roof, partial basement, unfinished 'fallout shelter'	1st floor	Single Family Residence	1	3.9 (3.4 to 4.3)	60Co	D	GR	E	
[A1]	Concrete block house, wood roof, partial basement, unfinished 'fallout shelter'	basement	Single Family Residence	1	15 (11 to 15)	60Co	D	GR	E	
[A1]	Oak Ridge type "A" Cemesto house, wood siding, basement	1st floor	Single Family Residence	1	2.6 (2.3 to 2.8)	60Co	D	GR	E	
[A1]	Oak Ridge type "A" Cemesto house, wood siding, basement	basement	Single Family Residence	1	17 (14 to 21)	60Co	D	GR	E	
[A4]	AEC HQ Wing A, large multistory concrete office building	basement	Commercial (Office)	4	1900 (400 to 2300)	60Co	D	GR	E	
[A4]	AEC HQ Wing A, large multistory concrete office building	1st floor	Commercial (Office)	4	40 (30 to 100)	60Co	D	GR	E	
[A4]	AEC HQ Wing A, large multistory concrete office building	2nd floor	Commercial (Office)	4	100 (50 to 400)	60Co	D	GR	E	
[A4]	AEC HQ Wing A, large multistory concrete office building	3rd floor	Commercial (Office)	4	140 (70 to 440)	60Co	D	GR	E	
[A4]	AEC HQ Wing A, large multistory concrete office building	4th floor	Commercial (Office)	4	80 (60 to 120)	60Co	D	GR	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A4]	AEC HQ Wing B, large multistory concrete office building	basement	Commercial (Office)	4	1700 (1500 to 2500)	60Co	D	GR	E	
[A4]	AEC HQ Wing B, large multistory concrete office building	1st floor	Commercial (Office)	4	50 (30 to 140)	60Co	D	GR	E	
[A4]	AEC HQ Wing B, large multistory concrete office building	2nd floor	Commercial (Office)	4	160 (60 to 610)	60Co	D	GR	E	
[A4]	AEC HQ Wing B, large multistory concrete office building	3rd floor	Commercial (Office)	4	110 (70 to 400)	60Co	D	GR	E	
[A4]	AEC HQ Wing B, large multistory concrete office building	4th floor	Commercial (Office)	4	60 (50 to 130)	60Co	D	GR	E	
[A4]	AEC HQ Wing C, large multistory concrete office building	basement	Commercial (Office)	4	2000 (850 to 2400)	60Co	D	GR	E	
[A4]	AEC HQ Wing C, large multistory concrete office building	1st floor	Commercial (Office)	4	70 (30 to 1000)	60Co	D	GR	E	
[A4]	AEC HQ Wing C, large multistory concrete office building	2nd floor	Commercial (Office)	4	740 (250 to 1500)	60Co	D	GR	E	
[A4]	AEC HQ Wing C, large multistory concrete office building	3rd floor	Commercial (Office)	4	470 (240 to 1200)	60Co	D	GR	E	
[A4]	AEC HQ Wing C, large multistory concrete office building	4th floor	Commercial (Office)	4	110 (80 to 150)	60Co	D	GR	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A4]	AEC HQ Wing F, large multistory concrete office building	basement	Commercial (Office)	4	>10000 (>10000 to >10000)	60Co	D	GR	E	
[A4]	AEC HQ Wing F, large multistory concrete office building	1st floor	Commercial (Office)	4	40 (30 to 80)	60Co	D	GR	E	
[A4]	AEC HQ Wing F, large multistory concrete office building	2nd floor	Commercial (Office)	4	60 (50 to 250)	60Co	D	GR	E	
[A4]	AEC HQ Wing F, large multistory concrete office building	3rd floor	Commercial (Office)	4	120 (90 to 400)	60Co	D	GR	E	
[A4]	AEC HQ Wing F, large multistory concrete office building	4th floor	Commercial (Office)	4	90 (60 to 130)	60Co	D	GR	E	
[A4]	AEC HQ Wing G, large multistory concrete office building	basement	Commercial (Office)	4	>10000 (>10000 to >10000)	60Co	D	GR	E	
[A4]	AEC HQ Wing G, large multistory concrete office building	1st floor	Commercial (Office)	4	80 (30 to 1000)	60Co	D	GR	E	
[A4]	AEC HQ Wing G, large multistory concrete office building	2nd floor	Commercial (Office)	4	200 (50 to 1500)	60Co	D	GR	E	
[A4]	AEC HQ Wing G, large multistory concrete office building	3rd floor	Commercial (Office)	4	230 (70 to 1200)	60Co	D	GR	E	
[A4]	AEC HQ Wing G, large multistory concrete office building	4th floor	Commercial (Office)	4	80 (60 to 150)	60Co	D	GR	E	
[A5]	UCLA Laboratory of Nuclear Medicine and Radiation Biology; Large 2-story concrete building	basement	Commercial (Laboratory)	2	380 (12 to 3000)	60Co	D	GR	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A6]	Thick walled buildings in densely spaced town center	various	Multi-Family Residence, Commercial (Office)	5	59 (42 to 100)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 3 buildings; (d) reflects measurements in densely spaced center of town with massive outside walls; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.
[A6]	Pre WWI buildings with thick outer walls and small rooms	various	Multi-Family Residence	4	77 (48 to 200)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 5 buildings; (d) reflects measurements in preWWI buildings with thick outside brick walls and small rooms; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A6]	Buildings built between WWI and WWII with ~40 cm thick outer walls and medium (1.2 m^2) windows	various	Multi-Family Residence	4	110 (56 to n/a)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 7 buildings; (d) reflects measurements in buildings built between WWI and WWII with 38 to 51 cm thick outside brick walls and brick outer walls and medium (1.5 m^2) windows; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.
[A6]	pre WWII terraced houses	various	Multi-Family Residence	2	77 (71 to 83)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 2 buildings; (d) reflects measurements in preWWII terraced houses; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A6]	Post WWI with 45 cm thick outer walls and medium size (1.2 m^2) windows	various	Multi-Family Residence	3	110 (56 to n/a)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 4 buildings; (d) reflects measurements in postWWII houses with 40-50 cm thick walls and medium (1.5 m^2) windows; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.
[A6]	Prefabricated concrete buildings (30 cm walls) with large (4.8 m^2) windows	various	Multi-Family Residence	15	40 (n/a to n/a)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 5 buildings; (d) reflects measurements in prefabricated concrete buildings with 30 cm thick walls and larger (4.8 m^2) windows; (e) range not legible in available document; (f) ground, wall, and roof contamination levels (Bq m^2) may not identical.

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A6]	Cast concrete buildings with 45 cm walls	various	Multi-Family Residence	15	59 (30 to 1000)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 9 buildings; (d) reflects measurements in cast concrete buildings with 45 cm thick walls; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.
[A6]	Buildings built after 1980 with 35 cm walls and medium/large windows	various	Multi-Family Residence	7	50 (31 to 125)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 3 buildings; (d) reflects measurements in newer buildings with 35 cm thick walls; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A6]	Brick or concrete house	various	Single Family Residence	2	9.3 (7.9 to 11)	137Cs	D	GRW	E	(a) experimental study Viennese buildings 8yrs post Chernobyl; (b) values used were taken from Table 3 ("immediately after fallout") and do not include interior contamination; (c) average of 3 buildings; (d) reflects measurements in single houses with 12 to 16 cm thick brick or concrete walls; (e) ground, wall, and roof contamination levels (Bq m^2) may not identical.
[A7]	Japanese-style one-story meeting place (wooden house)	1st floor	Public (Hall)	1	2.0 (1.8 to 2.1)	137Cs 134Cs	D	GRW	E	(a) Japanese buildings 10 mo post-Fukushima; (b) data from Table 2; (c) building A, public meeting place; (d) isotope not reported
[A7]	Midsized public hall (steel construction)	1st floor	Public (Hall)	1	2.9 (2.0 to 4.3)	137Cs 134Cs	D	GRW	E	(a) Japanese buildings 10 mo post-Fukushima; (b) data from Table 2; (c) building B, public hall; (d) isotope not reported
[A7]	Reinforced concrete school	1st floor	Public (School)	2	7.1 (3.2 to 10)	137Cs 134Cs	D	GRW	E	(a) Japanese buildings 10 mo post-Fukushima; (b) data from Table 2; (c) building C, school building; (d) isotope not reported

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A8]	Japanese wooden house	n/a	Single Family Residence	n/a	2.5 (n/a to n/a)	137Cs 134Cs	D	GRW	E	(a) 6 houses; (b) approx 2 mo post-Fukushima
[A8]	Concrete school	n/a	Public (School)	n/a	10 (n/a to n/a)	137Cs 134Cs	D	GRW	E	approx 2 mo post-Fukushima
[A9]	Wooden and lightweight steel Japanese houses	1st floor	Single Family Residence	2	2.6 (n/a to n/a)	137Cs 134Cs	D	GRW	E	(a) average of 148 rural and urban houses in low dose region (< 0.5 μSv h^{-1}); (b) measurements near outside wall and 0.5 m above the floor; (c) unable to determine protection in heavy construction due to background radiation; (d) isotope not reported; (e) approx 3 yr post-Fukushima
[A9]	Wooden and lightweight steel Japanese houses	2nd floor	Single Family Residence	2	2.0 (n/a to n/a)	137Cs 134Cs	D	GRW	E	(a) average of 80 rural and urban houses in low dose region (< 0.5 μSv h^{-1}); (b) measurements near outside wall and 0.5 m above the floor; (c) unable to determine protection in heavy construction due to background radiation; (d) isotope not reported; (e) approx 3 yr post-Fukushima

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A10]	Japanese wooden house	1st floor	Single Family Residence	2	2.4 (1.9 to 3.0)	137Cs 134Cs	D	GRW	E	(a) median and inner quartile range of 69 houses; (b) measurements taken between 9 to 21 mo post-Fukushima
[A10]	Japanese wooden house	2nd floor	Single Family Residence	2	2.2 (1.8 to 2.6)	137Cs 134Cs	D	GRW	E	(a) median and inner quartile range of 69 houses; (b) measurements taken between 9 to 21 mo post-Fukushima
[A11]	Russian wooden house, rural area	1st floor	Single Family Residence	1	7.7 (5.6 to 13)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living area
[A11]	Russian brick house, rural area	1st floor	Single Family Residence	1	14 (9.1 to 33)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living and work areas
[A11]	Russian multi-story house, rural area	n/a	Multi-Family Residence	5	50 (25 to n/a)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living and work areas; (c) assumed to be similar to urban multi-story house
[A11]	Russian wooden house, urban area	n/a	Single Family Residence	n/a	11 (7.7 to 20)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living area
[A11] [A13]	Russian brick house, urban area	1st floor	Single Family Residence	1	20 (13 to 50)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living area; (c) building described in EUR 16541
[A11] [A13]	Russian multi-story house, urban area	n/a	Multi-Family Residence	5	100 (50 to n/a)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4, living area; (c) building described in EUR 16541

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A11]	Russian work building, urban area	n/a	Commercial (Other)	n/a	50 (33 to 100)	137Cs 134Cs	D	GRW	E	(a) 5 yr post-Chernobyl; (b) Table 4
[A12]	German (Munich) house 1	1st floor	Single Family Residence	n/a	9.1 (n/a to n/a)	137Cs 134Cs	D	GRW	E, T	(a) 1 mo post-Chernobyl; (b) Table 4; (c) attic and isotope data available; (d) wet dep.
[A12]	German (Munich) house 1	2nd floor	Single Family Residence	n/a	10 (n/a to n/a)	137Cs 134Cs	D	GRW	E, T	(a) 1 mo post-Chernobyl; (b) Table 4; (c) attic and isotope data available; (d) wet dep.
[A12]	German administration building	2nd floor	Commercial (Office)	n/a	50 (n/a to n/a)	137Cs	D	GRW	E, T	(a) 1.5 mo post-Chernobyl; (b) Table 4; (c) wet deposition
[A12]	German administration building	3rd floor	Commercial (Office)	n/a	50 (n/a to n/a)	137Cs	D	GRW	E, T	(a) 1.5 mo post-Chernobyl; (b) Table 4; (c) wet deposition
[A12]	German administration building	5th floor	Commercial (Office)	n/a	50 (n/a to n/a)	137Cs	D	GRW	E, T	(a) 1.5 mo post-Chernobyl; (b) Table 4; (c) wet deposition
[A12]	German (Munich) house 2	1st floor	Single Family Residence	n/a	n/a (11 to 13)	137Cs	D	GRW	E, T	(a) 2 mo post-Chernobyl; (b) Table 4; (c) wet deposition
[A12]	German (Munich) house 2	2nd floor	Single Family Residence	n/a	14 (n/a to n/a)	137Cs	D	GRW	E, T	(a) 2 mo post-Chernobyl; (b) Table 4; (c) wet deposition
[A12]	German (Grafing) house 3	1st floor	Single Family Residence	n/a	n/a (13 to 17)	137Cs 134Cs	D	GRW	E, T	(a) 2.5 mo post-Chernobyl; (b) Table 4; (c) attic and isotope data available; (d) wet dep.
[A12]	German (Grafing) house 3	2nd floor	Single Family Residence	n/a	14 (13 to 13)	137Cs 134Cs	D	GRW	E, T	(a) 2.5 mo post-Chernobyl; (b) Table 4; (c) attic and isotope data available; (d) wet dep.

E. INDIVIDUAL BUILDING ANALYSIS RESULTS FOR OTHER STRUCTURES

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A14]	Small precast concrete house with large windows	1st floor	Single Family Residence	1	7.1 (2. 6 to 25)	1-day old fallout	D	GR	E	Operation Plumbbob, Coulomb C shot - document contains decontamination efficiency data. PF estimated here as 3 ft reading outside / 3 ft reading.
[A15]	Butler building with basement	1st floor	Commercial (Shed)	1	2.1 (n/a to n/a)	60Co	D	GR	E	
[A15]	Butler building with basement	basement	Commercial (Shed)	1	13 (11 to 19)	60Co	D	GR	E	
[A16]	Butler building with basement	1st floor	Commercial (Shed)	1	2.1 (1.9 to 3.3)	3-day old fallout	D	G	E	Operation Plumbbob, Shasta shot
[A16]	Butler building with basement	basement	Commercial (Shed)	1	55 (33 to 67)	3-day old fallout	D	G	E	Operation Plumbbob, Shasta shot
[A16]	Butler building with basement	1st floor	Commercial (Shed)	1	2.0 (1.6 to 3.1)	3-day old fallout	D	GR	E	Operation Plumbbob, Shasta shot; roof contamination ~10% of ground contamination
[A16]	Butler building with basement	basement	Commercial (Shed)	1	40 (28 to 72)	3-day old fallout	D	GR	E	Operation Plumbbob, Shasta shot; roof contamination ~10% of ground contamination

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A16]	Butler building with basement	1st floor	Commercial (Shed)	1	4.9 (n/a to n/a)	1-day old fallout	D	G	E	Operation Plumbbob, Diablo shot
[A16]	Butler building with basement	basement	Commercial (Shed)	1	25 (16 to 31)	1-day old fallout	D	G	E	Operation Plumbbob, Diablo shot
[A16]	Butler building with basement	1st floor	Commercial (Shed)	1	4.2 (n/a to n/a)	1-day old fallout	D	GR	E	Operation Plumbbob, Diablo shot; roof contamination ~10% of ground contamination
[A16]	Butler building with basement	basement	Commercial (Shed)	1	25 (16 to 31)	1-day old fallout	D	GR	E	Operation Plumbbob, Diablo shot; roof contamination ~10% of ground contamination
[A17]	Heavy concrete building (building name is CP-40)	1st floor	Commercial (Other)	1	19 (4.7 to 29)	60Co	D	GR	E	NTS CP-40 Communication Building
[A17]	Heavy concrete building (building name is CP-40)	1st floor	Commercial (Other)	1	37 (29 to 110)	60Co	D	R	E	NTS CP-40 Communication Building
[A17]	Heavy concrete building (building name is CP-40)	1st floor	Commercial (Other)	1	67 (40 to 200)	137Cs	D	R	E	NTS CP-40 Communication Building

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A17]	Heavy concrete building (building name is CP-45)	2nd floor	Commercial (Laboratory)	2	66 (9.0 to 110)	60Co	D	GR	E	NTS CP-45 Light Laboratory
[A17]	Heavy concrete building (building name is CP-45)	1st floor	Commercial (Laboratory)	2	350 (25 to 2200)	60Co	D	GR	E	NTS CP-45 Light Laboratory; partially buried
[A17]	Heavy concrete building (building name is CP-1)	1st floor	Commercial (Other)	1	35 (11 to 60)	60Co	D	GR	E	NTS CP-1 Main Control Building
[A17]	Heavy concrete building (building name is CP-1)	basement	Commercial (Other)	1	330 (15 to 800)	60Co	D	GR	E	NTS CP-1 Main Control Building
[A17]	Heavy concrete building (building name is CP-1A)	1st floor	Commercial (Other)	1	45 (20 to 50)	60Co	D	GR	E	NTS CP-1A Main Control Building
[A17]	Heavy concrete building (building name is CP-1A)	basement	Commercial (Other)	1	93 (35 to 130)	60Co	D	GR	E	NTS CP-1A Main Control Building
[A17]	Heavy concrete building (building name is CP-1B)	mezzanine	Commercial (Other)	1	300 (230 to 400)	60Co	D	GR	E	NTS CP-1B Main Control Building Addition Mezzanine
[A17]	Heavy concrete building (building name is CP-1B)	1st floor	Commercial (Other)	1	250 (11 to 800)	60Co	D	GR	E	NTS CP-1B Main Control Building Addition Main Floor
[A17]	Heavy concrete building (building name is CP-1B)	basement	Commercial (Other)	1	2500 (14 to 12000)	60Co	D	GR	E	NTS CP-1B Main Control Building Addition Basement
[A17]	Heavy concrete building (building name is CP-2)	1st floor	Commercial (Other)	1	26 (8.0 to 59)	60Co	D	GR	E	NTS CP-2 Rad-Safe Building Upstairs
[A17]	Heavy concrete building (building name is CP-2)	basement	Commercial (Other)	1	230 (17 to 650)	60Co	D	GR	E	NTS CP-2 Rad-Safe Building Downstairs
[A17]	Wood frame, lightly constructed building (building name is CP-14)	1st floor	Commercial (Other)	1	n/a (2.0 to 3.0)	1-hr old fallout	A,D	GR	T	NTS CP-14 Programmatic Building (Engineering Manual range estimate, no median provided)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A17]	Concrete building (building name is CP-50)	1st floor	Commercial (Other)	1	n/a (2.0 to 10)	1-hr old fallout	A,D	GR	T	NTS CP-50 Radiological Sciences Building (Engineering Manual range estimate, no median provided)
[A18]	no building (no radiation in "building footprint")	overall building	Other	3	1.6 (1.5 to 1.7)	60Co	D	G	E	
[A18]	24'x36'x36' steel frame "building", no floors, roof, or walls	overall building	Other	3	2.1 (1.8 to 2.4)	60Co	D	G	E	
[A18]	24'x36'x36' concrete slab building, 49 psf walls, no floors or roof	overall building	Other	3	6.5 (4.9 to 7.9)	60Co	D	G	E	
[A18]	24'x36'x36' steel frame "building", 49psf floors, roof, and walls	overall building	Other	3	7.9 (5.3 to 12)	60Co	D	G	E	
[A19]	24'x36'x36' concrete slab building, 49 psf floors, roof, and walls	overall building	Other	3	230 (27 to 2000)	60Co	D	R	E	
[A18]	24'x36'x36' steel frame "building", 49psf walls and 97 psf floor and roof	overall building	Other	3	9.3 (5.1 to 14)	60Co	D	G	E	
[A19]	24'x36'x36' concrete slab building, 98 psf floors and roof, 49 psf walls	overall building	Other	3	190 (97 to 4800)	60Co	D	R	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A18] [A21]	24'x36'x36' concrete slab building, 98 psf floors and roof, 49 psf walls, Interior Configuration A1	overall building	Other	3	11 (6.4 to 35)	60Co	D	G	E	
[A18] [A21]	24'x36'x36' concrete slab building, 98 psf floors and roof, 49 psf walls, Interior Configuration A2	overall building	Other	3	22 (14 to 31)	60Co	D	G	E	
[A18] [A21]	24'x36'x36' concrete slab building, 98 psf floors and roof, 49 psf walls, Interior Configuration B	overall building	Other	3	14 (7.4 to 21)	60Co	D	G	E	
[A21]	24'x36'x36' concrete slab building - nonuniform walls type 1	overall building	Other	3	11 (6.9 to 17)	60Co	D	G	E, T	
[A21]	24'x36'x36' concrete slab building - nonuniform walls type 2	overall building	Other	3	23 (7.7 to 44)	60Co	D	G	E, T	
[A18]	24'x36'x36' steel frame "building", 98psf walls	overall building	Other	3	23 (17 to 29)	60Co	D	G	E, T	
[A18]	24'x36'x36' steel frame "building", 98psf walls, floors, and roof	overall building	Other	3	29 (16 to 42)	60Co	D	R	E, T	
[A18]	24'x36'x36' steel frame "building", 147psf walls	overall building	Other	3	77 (58 to 100)	60Co	D	G	E	

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A21]	24'x36'x36' concrete slab building - wall apertures	overall building	Other	3	9.5 (6.5 to 13)	60Co	D	G	E	
[A21]	24'x36'x36' concrete slab building - wall apertures and interior configuration A1	overall building	Other	3	15 (8.1 to 28)	60Co	D	G	E	
[A20]	Supermarket	middle of store	Commercial (Supermarket)	1	8.2 (n/a to n/a)	137Cs	D	GR	T	(a) includes roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	near exterior wall	Commercial (Supermarket)	1	8.6 (n/a to n/a)	137Cs	D	GR	T	(a) includes roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	office	Commercial (Supermarket)	1	8.6 (n/a to n/a)	137Cs	D	GR	T	(a) includes roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	parking lot (outside)	Commercial (Supermarket)	n/a	1. 5 (n/a to n/a)	137Cs	D	GR	T	(a) includes roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A20]	Supermarket	middle of store	Commercial (Supermarket)	1	7.9 (n/a to n/a)	137Cs	D	GRW	T	(a) includes walls, windows, doors, roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	near exterior wall	Commercial (Supermarket)	1	7.8 (n/a to n/a)	137Cs	D	GRW	T	(a) includes walls, windows, doors, roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	office	Commercial (Supermarket)	1	5.8 (n/a to n/a)	137Cs	D	GRW	T	(a) includes walls, windows, doors, roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)
[A20]	Supermarket	parking lot (outside)	Commercial (Supermarket)	n/a	1.4 (n/a to n/a)	137Cs	D	GRW	T	(a) includes walls, windows, doors, roof, air filter, and outdoor contamination; (b) similar to big box store; (c) does NOT consider store contents (which can be a considerable amount of mass)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A22]	Prefabricated house with wood walls and concrete roof	basement	Single Family Residence	1	67 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [A1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Prefabricated house with wood walls and concrete roof	1st floor	Single Family Residence	1	2.3 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A22]	Semidetached house (duplex) with concrete block walls and tile roof	basement	Multi-Family Residence	2	2000 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Semidetached house (duplex) with concrete block walls and tile roof	1st floor	Multi-Family Residence	2	12 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Semidetached house (duplex) with concrete block walls and tile roof	2nd floor	Multi-Family Residence	2	11 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A22]	Row house with 30 cm concrete walls and 20 cm concrete roof in an urban setting	basement	Multi-Family Residence	5	710 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Row house with 30 cm concrete walls and 20 cm concrete roof in an urban setting	1st floor	Multi-Family Residence	5	110 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Row house with 30 cm concrete walls and 20 cm concrete roof in an urban setting	2nd floor	Multi-Family Residence	5	160 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)
[A22]	Row house with 30 cm concrete walls and 20 cm concrete roof in an urban setting	4th floor	Multi-Family Residence	5	150 (n/a to n/a)	137Cs	D	GRW	T	(a) Values from Table 2 (other spectra available); (b) additional data available in follow on work [1 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 167-179 (1988); 2 - Meckbach et al., Radiation Protection Dosimetry, 25(3) 181-190 (1988)]; (c) includes elevated radiation sources and shielding (e.g., trees, surrounding houses)

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A23]	Single story wood frame house with basement	basement	Single Family Residence	1	8.3 (7.3 to 11)	1-hr old fallout	D	GR	T	(a) values from Table 5; (b) effects of structural variations studied
[A23]	Single story wood frame house with basement	1st floor	Single Family Residence	1	1.5 (1.5 to 1.7)	1-hr old fallout	D	GR	T	(a) values from Table 5; (b) effects of structural variations studied
[A23]	Two story brick veneer house with basement	basement	Single Family Residence	2	n/a (14 to 15)	1-hr old fallout	D	GR	T	(a) values from Table 10; (b) effects of structural variations studied
[A23]	Two story brick veneer house with basement	1st floor	Single Family Residence	2	n/a (3.2 to 3.6)	1-hr old fallout	D	GR	T	(a) values from Table 10; (b) effects of structural variations studied
[A23]	Two story brick veneer house with basement	2nd floor	Single Family Residence	2	n/a (3.4 to 3.5)	1-hr old fallout	D	GR	T	(a) values from Table 10; (b) effects of structural variations studied

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A23]	Four story brick veneer apartment building with basement and concrete floors and roof	basement	Multi-Family Residence	4	530 (n/a to n/a)	1-hr old fallout	D	GR	T	(a) values from Table 14; (b) effects of structural variations studied
[A23]	Four story brick veneer apartment building with basement and concrete floors and roof	1st floor	Multi-Family Residence	4	9.2 (n/a to n/a)	1-hr old fallout	D	GR	T	(a) values from Table 14; (b) effects of structural variations studied
[A23]	Four story brick veneer apartment building with basement and concrete floors and roof	2nd floor	Multi-Family Residence	4	17 (n/a to n/a)	1-hr old fallout	D	GR	T	(a) values from Table 14; (b) effects of structural variations studied
[A23]	Four story brick veneer apartment building with basement and concrete floors and roof	3rd floor	Multi-Family Residence	4	17 (14 to 18)	1-hr old fallout	D	GR	T	(a) values from Table 14; (b) effects of structural variations studied
[A23]	Four story brick veneer apartment building with basement and concrete floors and roof	4th floor	Multi-Family Residence	4	11 (n/a to n/a)	1-hr old fallout	D	GR	T	(a) values from Table 14; (b) effects of structural variations studied

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A24]	Single story wood frame house with basement and no interior partitions	1st floor	Single Family Residence	1	2.0 (n/a to n/a)	60Co	D	G	E	(a) all measurements taken at 3 ft above the floor; (b) corresponds to house 6: thin (5.5 psf) exterior walls, 1st floor 3 ft above grade, no interior partitions
[A24]	Single story wood frame house with basement and interior partitions	1st floor	Single Family Residence	1	2.1 (n/a to n/a)	60Co	D	G	E	(a) all measurements taken at 3 ft above the floor; (b) corresponds to house 10: thin (5.5 psf) exterior walls, 1st floor 3 ft above grade, interior partitions
[A24]	Single story brick veneer wood frame house with basement and interior partitions	1st floor	Single Family Residence	1	3.2 (n/a to n/a)	60Co	D	G	E	(a) all measurements taken at 3 ft above the floor; (b) corresponds to house 19: thick (45.5 psf) exterior walls, 1st floor 3 ft above grade, interior partitions

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A27]	Brazilian brick house (includes windows/doors)	1st floor	Single Family Residence	1	1.7 (n/a to n/a)	137Cs	D	GRW	T	Table 5, Brick house type with windows and doors
[A27]	Brazilian brick house with 1 layer of concrete (includes windows/doors)	1st floor	Single Family Residence	1	2.3 (n/a to n/a)	137Cs	D	GRW	T	Table 5, Brick_1L house type with windows and doors
[A27]	Brazilian brick house with 2 layers of concrete (includes windows/doors)	1st floor	Single Family Residence	1	3.0 (n/a to n/a)	137Cs	D	GRW	T	Table 5, Brick_2L house type with windows and doors
[A27]	Brazilian brick house (includes windows/doors)	1st floor	Single Family Residence	1	2.4 (n/a to n/a)	137Cs	D	GR	T	Tables 3 & 5, Brick house type with windows and doors neglecting the wall contamination
[A27]	Brazilian brick house with 1 layer of concrete (includes windows/doors)	1st floor	Single Family Residence	1	3.2 (n/a to n/a)	137Cs	D	GR	T	Table 3 & 5, Brick_1L house type with windows and doors neglecting the wall contamination
[A27]	Brazilian brick house with 2 layers of concrete (includes windows/doors)	1st floor	Single Family Residence	1	4.3 (n/a to n/a)	137Cs	D	GR	T	Table 3 & 5, Brick_2L house type with windows and doors neglecting the wall contamination

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A25] [A26]	Traditional urban house 1	1st floor	Single Family Residence	2	n/a (1.7 to 1.8)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Traditional urban house 2	1st floor	Single Family Residence	2	n/a (1.9 to 1.9)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Traditional urban house 3	1st floor	Single Family Residence	2	n/a (1.6 to 1.6)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Traditional suburban house 1	1st floor	Single Family Residence	2	n/a (1.9 to 2.3)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Traditional suburban house 2	1st floor	Single Family Residence	1	n/a (1.9 to 2.4)	137Cs	D	G	T	data from Table 1
[A25] [A26]	2 x 4 frame house	1st floor	Single Family Residence	2	n/a (1.9 to 2.0)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Prefabricated house	1st floor	Single Family Residence	2	n/a (1.9 to 2.0)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Lightweight concrete house	1st floor	Single Family Residence	2	n/a (2.1 to 2.3)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Concrete house	1st floor	Single Family Residence	2	n/a (5.3 to 8.3)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Wooden apartment	1st floor	Multi-Family Residence	2	n/a (2.0 to 3.7)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Concrete apartment	1st floor	Multi-Family Residence	5	n/a (7.1 to 33)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Kindergarten	1st floor	Public (School)	1	n/a (6.3 to 9.1)	137Cs	D	G	T	data from Table 1

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A25] [A26]	Primary school 1	1st floor	Public (School)	2	n/a (7.7 to 9.1)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Primary school 2	1st floor	Public (School)	2	n/a (7.7 to 9.1)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Junior high school	1st floor	Public (School)	3	n/a (7.7 to 9.1)	137Cs	D	G	T	data from Table 1
[A25] [A26]	High school	1st floor	Public (School)	3	n/a (8.3 to 50)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Gymnasium	1st floor	Public (School)	1	n/a (2.8 to 4.2)	137Cs	D	G	T	data from Table 1
[A25] [A26]	City hall	1st floor	Commercial (Office)	6	9.1 (n/a to n/a)	137Cs	D	G	T	(a) data from Table 1; (b) occupancy assumed to be administrative (i.e. offices)
[A25] [A26]	Town hall	1st floor	Commercial (Office)	2	5.6 (n/a to n/a)	137Cs	D	G	T	(a) data from Table 1; (b) occupancy assumed to be administrative (i.e. offices)
[A25] [A26]	Public hall	1st floor	Public (Hall)	3	14 (n/a to n/a)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Hospital 1	1st floor	Public (Hospital)	4	n/a (10 to 50)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Hospital 2	1st floor	Public (Hospital)	6	n/a (10 to 50)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Business office	1st floor	Commercial (Office)	5	6.7 (n/a to n/a)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Large factory	1st floor	Commercial (Factory)	1	7.1 (n/a to n/a)	137Cs	D	G	T	data from Table 1

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A25] [A26]	Small factory	1st floor	Commercial (Factory)	1	2.2 (n/a to n/a)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Shopping center	1st floor	Commercial (Other)	1	5.9 (n/a to n/a)	137Cs	D	G	T	data from Table 1
[A25] [A26]	Supermarket	1st floor	Commercial (Supermarket)	1	3.2 (n/a to n/a)	137Cs	D	G	T	data from Table 1
[A28]	Single story, vinyl sided house without a basement	1st floor	Single Family Residence	1	1.8 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, vinyl sided house without a basement	1st floor	Single Family Residence	1	2.0 (n/a to n/a)	137Cs	D	GR	T	data from Table 22
[A28]	Single story, vinyl sided house with a basement	basement	Single Family Residence	1	14 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, vinyl sided house with a basement	1st floor	Single Family Residence	1	1.9 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, vinyl sided house with a basement	basement	Single Family Residence	1	13 (n/a to n/a)	137Cs	D	GR	T	data from Table 22
[A28]	Single story, vinyl sided house with a basement	1st floor	Single Family Residence	1	2.0 (n/a to n/a)	137Cs	D	GR	T	data from Table 22
[A28]	Single story, brick sided house without a basement	1st floor	Single Family Residence	1	2.1 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, brick sided house without a basement	1st floor	Single Family Residence	1	2.6 (n/a to n/a)	137Cs	D	GR	T	data from Table 22

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A28]	Single story, brick sided house with a basement	basement	Single Family Residence	1	11 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, brick sided house with a basement	1st floor	Single Family Residence	1	2.1 (n/a to n/a)	60Co	D	GR	T	data from Table 22
[A28]	Single story, brick sided house with a basement	basement	Single Family Residence	1	11 (n/a to n/a)	137Cs	D	GR	T	data from Table 22
[A28]	Single story, brick sided house with a basement	1st floor	Single Family Residence	1	2.6 (n/a to n/a)	137Cs	D	GR	T	data from Table 22
[A28]	Two story, vinyl sided house without a basement	1st floor	Single Family Residence	2	1.8 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house without a basement	2nd floor	Single Family Residence	2	1.9 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house without a basement	1st floor	Single Family Residence	2	1.9 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house without a basement	2nd floor	Single Family Residence	2	2.0 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house with a basement	basement	Single Family Residence	2	14 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house with a basement	1st floor	Single Family Residence	2	1.8 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house with a basement	2nd floor	Single Family Residence	2	1.9 (n/a to n/a)	60Co	D	GR	T	data from Table 23

Reference	Building description	Location	Occupancy	Height (floors above ground)	Protection factor median (min to max)	Radiation type or isotope	Air immersion (A) or deposition (D)	If deposition, includes ground (G), roof (R), and/or wall (W)	Method primarily experiment (E) or theory (T)	Notes
[A28]	Two story, vinyl sided house with a basement	basement	Single Family Residence	2	11 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house with a basement	1st floor	Single Family Residence	2	1.9 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, vinyl sided house with a basement	2nd floor	Single Family Residence	2	2.0 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, brick sided house without a basement	1st floor	Single Family Residence	2	2.0 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, brick sided house without a basement	2nd floor	Single Family Residence	2	2.0 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, brick sided house without a basement	1st floor	Single Family Residence	2	2.5 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, brick sided house without a basement	2nd floor	Single Family Residence	2	2.6 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	basement	Single Family Residence	2	10 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	1st floor	Single Family Residence	2	2.0 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	2nd floor	Single Family Residence	2	2.0 (n/a to n/a)	60Co	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	basement	Single Family Residence	2	10 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	1st floor	Single Family Residence	2	2.5 (n/a to n/a)	137Cs	D	GR	T	data from Table 23
[A28]	Two story, brick sided house with a basement	2nd floor	Single Family Residence	2	2.6 (n/a to n/a)	137Cs	D	GR	T	data from Table 23