EVALUATION OF SHELTER-IN-PLACE FROM A SMR HYPOTHETICAL ACCIDENT RELEASE

by

Yamato Sugitatsu

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STATEMENT OF COMMITTEE APPROVAL

Dr. Shripad T. Revankar, Chair

School of Nuclear Engineering

Dr. Robert Bean

School of Nuclear Engineering

Dr. Todd Smith

The United States Nuclear Regulatory Commission

Approved by:

Dr. Seungjin Kim

For my family, who always supported me in my pursuit of my goals. Your love and support have given me the strength to strive for perfection and overcome failures.

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SYMBOLS AND ABRREVIATIONS

Symbols

$c(x, y, z)$: Concentration of radioactivity at position (x, y, z) (Ci/m^3)

$C_{OA}(t)$: Outdoor radionuclide concentration (Ci/m^3)

$C(t_i)$: Ground concentration at time t_i (Ci/m^2)

$C'(t_i)$: Ground concentration at time t_i (Ci/m$^2 \cdot$ s)

$C''(t_i)$: Indoor concentration at time t_i (μCi/m^3)

D : Projected groundshine for sheltered cases (mSv)

D' : Projected groundshine for unsheltered cases at time t (mSv)

E : Removal efficiency of the supply air filter

E_i : Deposited energy from gamma ray which is emitted from nuclide i (MeV/g)

E'_i : Deposited energy from gamma ray which is emitted from nuclide i for unsheltered cases (MeV/g)

H : Stack release height (m)

Q : Contaminant emission rate of all radionuclides (Ci/s)

q_E : Mechanical ventilation exhaust flow rate (m^3/s)

q_{EXF} : Exfiltration flow rate (1/h)

q_{INF} : Infiltration flow rate (1/h)

q_S : Mechanical ventilation supply flow rate (m^3/s)

SF_t : Shielding factor at time t

u : Wind speed (m/s)

V : Volume of the building (m^3)

(x_0, y_0, z_0) : Position of center of the puff

λ : Decay constant of the nuclide (s^{-1})

σ_x : Horizontal plume dispersion parameter based on Pasquill-Gifford stability categories (1/m)

σ_y : Lateral plume dispersion parameter based on Pasquill-Gifford stability categories(1/m)

σ_z : Vertical plume dispersion parameter based on Pasquill-Gifford stability categories(1/m)

Abbreviations

EPA - Environmental Protection Agency

EPZ - Emergency Planning Zone

LOCA - Loss of Coolant Accident

LTSBO - Long Term Station Blackout

NRC - Nuclear Regulatory Commission

PAG - Protective Action Guide

PWR - Pressurized Water Reactor

RASCAL - Radiological Assessment System for Consequence Analysis

SMR - Small Modular Reactor

TEDE - Total Effective Dose Equivalent

ABSTRACT

Small modular reactors (SMRs) are expected as a suitable candidate to fulfill energy needs in the future. The regulation of the emergency planning zone (EPZ) has been a controversial issue. The possibility of smaller EPZs because of their small core size and passive safety functions is still under discussion. The major emergency responses to radiological incidents in the early phase are evacuation from the area and shelter-in-place within a building. Comparison between the dose incurred during evacuation and that with shelter-in-place is necessary to consider the proper protective actions. The effect of shelter-in-place from small modular reactor hypothetical accident was studied. The source term came from a long-term station blackout (LTSBO) and loss of cooling accident (LOCA), and the time change of air concentration and the ground deposition data through the atmospheric spread around the plant was calculated with Radiological Assessment System for Consequence Analysis (RASCAL), a software developed by United States Nuclear Regulatory Commission (NRC) to provide dose projection around the plant. Then general one-story and two-story houses were set up, and 6 wall materials were selected for calculating indoor doses. Cloudshine and groundshine were calculated with Monte Carlo methods. In addition, the conservation of mass, air flow model was established to evaluate the inhalation for sheltered cases. The shielding function of each house for each pathway was evaluated by comparing the indoor dose with outdoor dose. The projected dose for sheltered cases was much smaller than that for unsheltered cases. Even though the projected dose will not completely perish, it was quite effective to reduce radiation exposure and can be superior to evacuation. The result will be a basis for calculating the radiological dose for sheltered cases in case of nuclear emergency for SMRs, which will be valuable to have a more effective emergency planning.

CHAPTER 1. INTRODUCTION

1.1 Small Modular Reactors

SMRs are defined as advanced reactors that produce electricity up to 300MW(e) per module. [1] The interest in SMRs has increased because of the higher demand for affordable and scalable nuclear power operations. The components for SMRs can be built in factory and there is no need to build a module at the construction site, so that the advantage in terms of transportation is great. Their unique characteristics in modular construction and better adaptability to locations results in the high competitiveness in the nuclear industry, and they are expected as a suitable candidate to fulfill energy needs in the future. [2]

In the US, NuScale is leading the development of SMRs. In the latest progress, NRC completed phase 6 review of NuScale's reactor design certification application last August. [3] The concept of the NuScale SMR developed from a collaboration between Oregon State University and Idaho National Engineering Laboratory in 2003, and the review of the design certification by NRC started in 2011. NuScale's reactor has a rated thermal output of 160 MW and electrical output of 50 MW, and the design of their SMR is scalable, from one to 12 NuScale Power Modules within a single reactor building. [4] The power module model is shown in Figure 1.1.

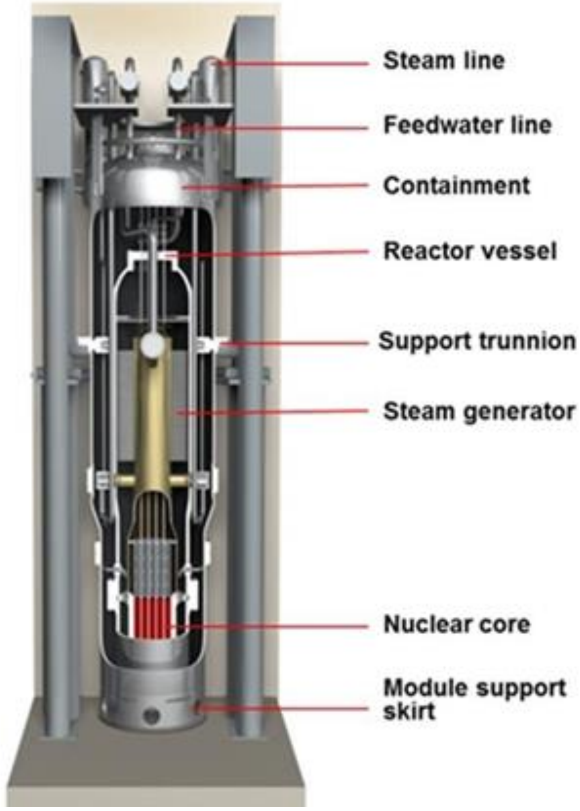

Figure 1.1. NuScale Small Modular Reactor [5]

NuScale developed a unique containment vessel which is submerged in the pool. Therefore, it provides a passive heat sink for the containment heat removal under LOCA conditions. Their plant is equipped with a new nuclear steam supply system composed of a reactor core, a pressurizer, and two steam generators integrated within the rector pressure vessel. [6] In addition, the reactor component is located entirely inside the containment vessel, which is immersed in water below ground, so that the reactor can be designed flexibly for seismic forces. Thank to this system, even under station blackout, the transition from water cooling to air cooling is achieved without any operator actions and the module does not need any recirculation pumps. Simulations of a small break loss of coolant accident with failure of passive safety functions and station blackout scenario using the NuScale reactor as their reference were already performed. [7,8] The studies showed that the safety functions of the reactor would work well to mitigate the severe accident progression.

1.2 Emergency Planning Zone

Although the reactor is equipped with various safety measurements, considering the possibility that a serious accident occurs is still important. Concerning the classification of the EPZ, the zone whose radius from the nuclear power plant is not more than 10 miles is described as plume exposure pathway. [9] Protecting communities from radiation exposure in the event of an accident is important in this zone. Concerning the zone whose radius is not more than 50 miles, the zone is described as ingestion exposure pathway where action plans to protect the public from radiological exposure through consumption of contaminated foodstuff are required. [9] Exact size and shape of the EPZ shall be determined in relation to local emergency response needs and capabilities. Figure 1.2 shows the typical EPZs.

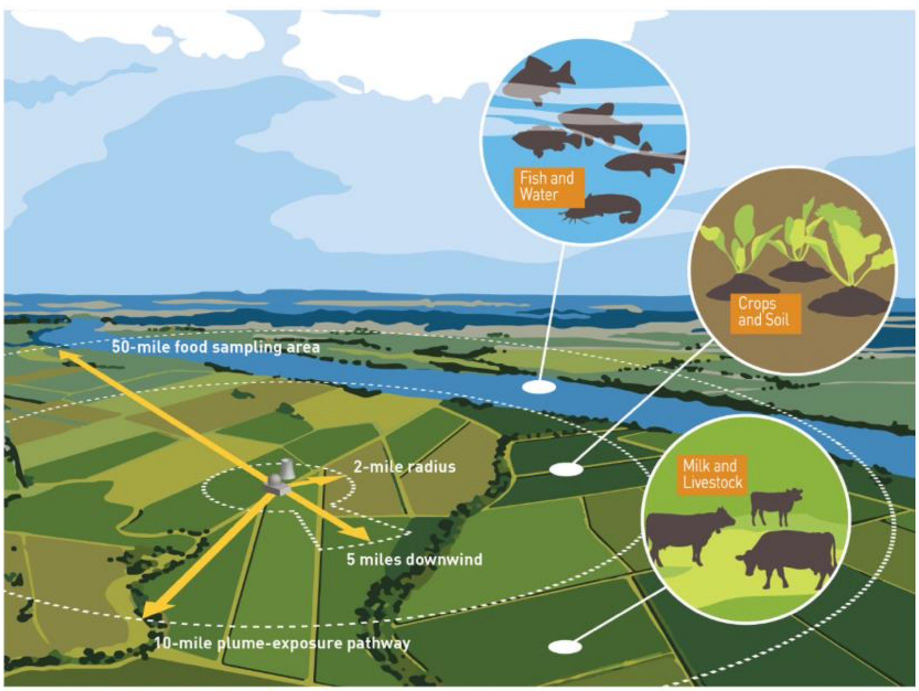

Figure 1.2. Emergency Planning Zone [10]

The current regulatory basis for the EPZ is based on atmospheric dispersion models and methodology, and the dispersion of radionuclides from the reactor is calculated with RASCAL. [11] Protective actions are informed by dose projections. RASCAL is a simulation code for making independent dose and consequence projections during radiological incidents. It was developed over 25 years ago to provide a tool for the rapid assessment of an incident or accident. The detail of RASCAL is to be mentioned later.

In the safety review of NuScale SMR, the regulation of the EPZ has been a controversial issue. Many SMRs are thought to require a much smaller emergency-planning zone (or none). It is because the amount of radioactivity in the core is quite small, or the timing for any release would always be much longer than that for large Light Water Reactors (LWRs). [12] It was shown that reducing the EPZ size from the conventional 10 miles to the very narrow range like the site boundary would significantly reduce offsite emergency planning cost. [13] Assuming that the EPZ is for a single unit plant with a nominal 40-year lifetime, there is an estimate that it costs approximately $10 million to establish an EPZ and an additional $2.25 million per year to maintain it[14]. Reducing the 10-mile plume-exposure pathway EPZ will significantly be able to reduce off-site emergency preparedness lifetime costs. Therefore, determining the size of the EPZ for SMRs has been one of the most critical topics.

1.3 Protective Action

According to the Environmental Protection Agency's (EPA) Protection Action Guides(PAGs), 10 to 50 mSv projected dose over 4 days would prompt individuals to take protective action. [15] A guiding principle of the PAGs is that the protective actions should result in more benefit than harm. Evacuation and shelter-in-place are effective actions to decrease radiation exposure, and it is important to find out which of them is practically better.

Table 1.1. Protective Action Standard [15]

Phase	Protective Action Recommendation	Protective Action Guideline
Early Phase	Shelter-in-place or evacuation of the public	10-50 mSv projected dose over the first 4 days

Selection of the protective action depends on the predictions of radiological incidents. The major emergency responses to radiological incidents in the early phase are evacuation from the area and shelter-in-place within a building. [15] Inhalation of radionuclides in the atmospheric plume and radiation exposure should be prevented as much as possible. In case of radiological release from a nuclear power plant, evacuation has long been considered as the best protective action to reduce the dose for those who live close to the plant. In theory, evacuation is a good response for completely preventing additional radiological exposure to the public. However, evacuation could come with its own consequences that can be even more harmful than the radiation exposure.

In case of Japan's Fukushima Daiichi Nuclear Plant incident which was precipitated by the Great East Japan Earthquake in 2011, the government issued a mandatory evacuation order to those who lived within a 20 km radius of the plant on the following day. Under a low radiation level, more than 16,000 people had to evacuate to another area. [16] A research of comparative assessment of mortality risk between elderly evacuees and non-evacuees after the incident shows that those who experienced evacuation had a substantially increased mortality risk. [17] Especially the initial evacuation for elderly people following the accident seemed to lead to the increased mortality. Subsequent evacuations did not show a large mortality impact due to their pre-planned and careful execution. Not starting the evacuation until temporary housing and other facilities were ready may have prevented such stress and physical harm.

The radiation exposure from this accident was actually much below the level that would cause acute injury. Consequently, the evacuation had a bigger impact on health than the radiation. Thus, one lesson learnt from the disaster is that shelter-in-place should be performed for at least sufficient time to adequately prepare the initial evacuation.

Looking at SMRs, they have relatively small output compared to existing LWRs. In addition, the probability of severe accident in SMRs are quite low due to the advanced safety functions. The smaller source term combined with the smaller core damage frequency would result in significantly reduced probability and consequence of accident. [18] Regulatory consideration for SMR about EPZ was previously reported by using the integrated PWR which has the same output as the NuScale SMR. [19] It concluded that the hypothetical SMR would produce less radioactivity after normalizing by thermal reactor power and containment volume than existing large-scale reactors and can meet the EPA-specified PAG lower limits for exposure.

1.4 Radiation Shielding

The calculated dose is composed of three exposure pathways: cluodshine, groundshine, and inhalation. Figure 1.3 shows how humans get radiation exposure from each pathway. It assumes that residents stay outside after the accident. The dose can be regarded for unsheltered cases. However, this calculation can be quite conservative when considering that the exposure to radiation will be significantly reduced by shelter-in-place. The effect of shelter-in-place has a significant dependence on the geometry and the wall material of the building. Therefore, clarifying such relationship is quite important to evaluate the result of shelter-in-place. In regard to inhalation dose for sheltered cases, accumulation of radionuclides inside a building is possible through infiltration, exfiltration and ventilation system with filters.

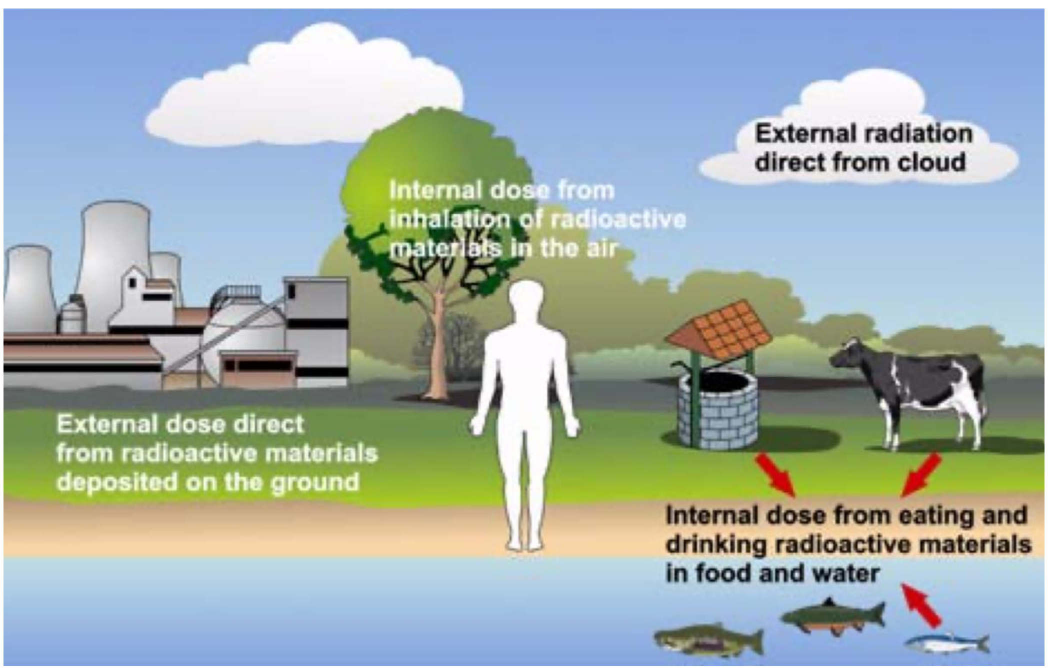

Figure 1.3. Exposure Pathways to Environmentally Released Radioactive Material [20]

Building shielding factors were calculated and applied to the output from RASCAL to calculate the dose for sheltered cases. The shielding by the wall of the building significantly reduces the exposures because most ionizing radiation cannot penetrate the wall. The values were used to evaluate the effect of shelter-in-place.

General one-story and two-story houses were set up, and 6 materials were selected as the outer wall for calculating indoor doses. Monte Carlo simulations were performed using Monte Carlo N-particle code (MCNP 6) to evaluate the cloudshine and groundshine for sheltered cases. [21] The shielding function was expressed by comparing the deposited energies in sheltered and unsheltered conditions. [22] The result will be a basis for calculating the radiological dose for sheltered cases in case of nuclear emergency for SMR, which will be valuable to have a more effective emergency planning. Shielding factor is commonly used as the factor which shows the radiation shielding capability of a building. It is described in Equation (1.1).

$$Shileding\ Factor = \frac{Absorbed\ Energy\ outside\ a\ building}{Absorbed\ Energy\ inside\ a\ building} \qquad (1.1)$$

Then general one-story and two-story houses were set up, and 6 materials were selected as the outer wall for calculating in this experiment. The shielding factors for cloudshine and groundshine were independently calculated following the calculation method noted above. Then, by multiplying the ground deposition and air concentration results with the time change of radioactivity coming from the RASCAL simulation, the total deposited energy for each condition was calculated. The ratio of total energies for unsheltered and sheltered cases were used as the shielding factors.

1.5 Objective: Evaluation of Effect of Shelter-in-Place

The previous research showed that smaller EPZs could be appropriate for hypothetical NuScale SMR because the possibility of a massive amount of radionuclides released from the plant was very low. In addition to that, the possible accident scenarios which could happen in an SMR has been studied. When it comes to determining practical emergency planning, research on projected dose for sheltered cases is also required. That is what this research focused on.

In this study, the effect of shelter-in-place was evaluated by considering projected dose for each pathway. Two different accident scenarios, LTSBO and LOCA, were developed in RASCAL by following the installed settings for existing PWRs. Then they were applied to the hypothetical SMR and the spread of released radionuclides within 10 miles of the plant was simulated. The projected dose based on the spread was the dose for unsheltered cases, and the dose with shelter-in-place was calculated by using the output from RASCAL and simulation with Monte Carlo methods.

The better protective action needs to be selected by comparing the comprehensive effect of evacuation and shelter-in-place. This study is beneficial for decision-making to significantly enhance public health and safety during a radiological emergency.

CHAPTER 2. MATERIALS AND METHODS

2.1 RASCAL

In a radiological release from a nuclear power plant, the amount of radioactivity and kinds of nuclides which are released to the atmosphere change depending on accident sequence. Each nuclide has a respective decay time and energy, so the proportion of the nuclides would affect the expected dose around the reactor. In this study, RASCAL was used to produce the source term and simulate the dispersion into the atmosphere.

LTSBO and LOCA were selected as the accident scenarios. They were both installed with RASCAL as the major accident scenarios for existing PWRs. RASCAL is equipped with only the existing commercial reactors in the US, so making use of the setting directly to reconstruct a possible accident in an SMR without considering the passive safety systems would be a conservative assumption. However, since the appropriate source term setting for the NuScale SMR was not available, they were applied as the hypothetical source term. In addition, the fuel composition for NuScale SMR was same as that for LWRs in the US, which backed the validity of using the reactor parameters of the existing reactors for simulating a potential SMR accident release.

The reactor parameters, release pathway, and the meteorology simulated with RASCAL was shown in Table 2.1. Nuclides would be leaked through a crack in the containment. The leak rate was assumed to be the design leak rate, 0.10% vol/d. The rainy condition was also selected to make the radiological dose to get high dose around the reactor and evaluate the reduction of projected dose due to shelter-in-place. Atmospheric stability class in RASCAL is Pasquill-Gifford stability class which is based on the method. [10] Class A to F corresponds to the different temperature gradient. Stability Class E means the temperature change per 100 meters is between -0.5℃ and +0.8 ℃.

Table 2.1. Reactor Parameters, Release Pathway, and Meteorology applied in RASCAL simulation

Reactor Power	160 MWt
Average Burnup	30000 MWd/MTU
Release Pathway	Dry containment leakage or Failure
Leak Rate	0.10% vol/d
Release Height	10 m
Stability Class	E
Wind speed	8 mph
Precipitation	Rain
Temperature	50 °F
Humidity	95%

In regard to construction of NuScale SMR, approximately 35 acres are planned to be used for building the power facility in the approved site. [12] Under the assumption that the plant area is a circle, the radius is estimated to be approximately 130 m. Even though the projected dose within 10 miles of the plant was simulated, the dose at locations very close to the reactor would be very crucial. The release of radionuclides to the atmosphere was assumed to continue for 4 hours. As the simulation output, RASCAL gave the ground deposition rate of each type of released nuclide during the period with 15-minute intervals. The time change of released radioactivity and the air concentration of I-131 were also given, and by assuming that the air concentration was simply proportional to the radioactivity, the air concentration of the other nuclides was calculated.

RASCAL integrates a Gaussian plume dispersion model as well as a Gaussian puff dispersion model for simulating the atmospheric dispersion. [11] The plume model is intended for shorter distances and uses a uniform wind field with respect to wind speed and wind direction. The puff model can handle changes of wind direction and wind speed.

The Gaussian dispersion model is widely used to calculate the concentration of pollutants including radiological release. The Gaussian plume equation shows the rate of change of a contaminant's airborne concentration due to advection and diffusion. It is described in Equation (2.1).

$$c(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} exp\left(-\frac{y^2}{2\sigma_z^2}\right)\left\{exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right\} \quad (2.1)$$

The plume is assumed to be reflected into the air when it hits the ground. The dispersion of pollutants in the atmosphere is determined by wind that carries the pollutants along the dominant direction of the wind and by the turbulent fluctuations that disperse the pollutants in all directions. The plumes' shape and size mainly depend on Pasquill-Gifford classes. [23]

The Gaussian puff model in RASCAL, called TADPUFF model, tracks the movement of individual puffs and calculates concentrations and doses based on puff positions. The normalized concentration in the vicinity of the puff is expressed in Equation (2.2).

$$c(x,y,z) = \frac{Q}{(2\pi)^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z} exp\left(-\frac{1}{2}\left(\frac{x-x_0}{\sigma_x}\right)^2\right) exp\left(-\frac{1}{2}\left(\frac{y-y_0}{\sigma_y}\right)^2\right) exp\left(-\frac{1}{2}\left(\frac{z-z_0}{\sigma_z}\right)^2\right) \quad (2.2)$$

This model behaves well in calm winds. RASCAL combines the two models, depending on the conditions for calculating a source term, dose and consequence projections for potential radiological releases from nuclear power plants and other nuclear facilities. [11] Parameters which give effects on the degree of dispersion are characteristics of emission (e.g. stack height and release height) and weather conditions (e.g. wind speed, wind direction, precipitation like rain and snow, temperature, pressure and humidity). [11] It supports the radiological response decision-making by providing context or supporting data. RASCAL's projection estimates are quite useful during the pre-release phase of a radiological emergency when an accident is possible. To make radiological dose projections with RASCAL practical, setting up the source term needs to be well considered with the reactor core design and the accident sequence.

2.2 Monte Carlo Methods

Figure 2.1 represents the appearance of one-story and two-story house used for calculating cloudshine and groundshine for sheltered cases. Their structures are almost the same except for the number of floors. House design parameters were shown in Table 2.2.

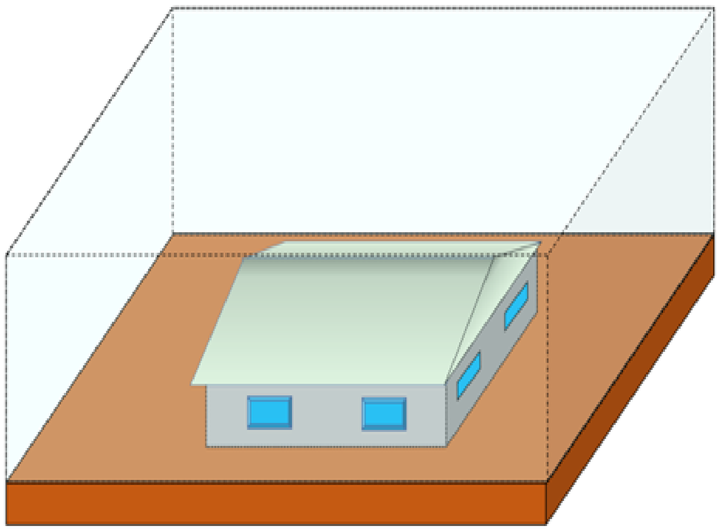

Figure 2.1. One-Story House

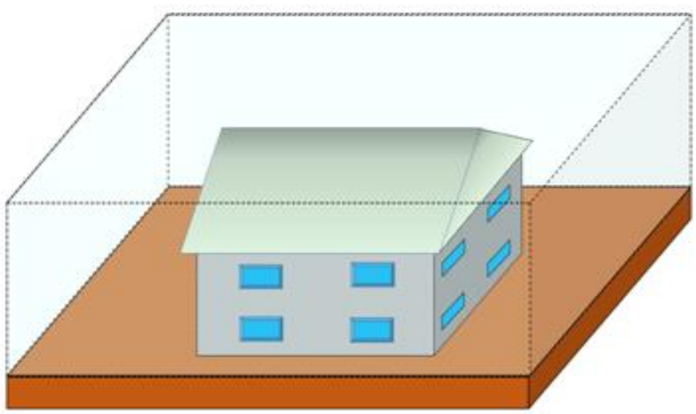

Figure 2.2. Two-Story House

Table 2.2. House Design Parameters

Room Size	4 m × 4 m × 3 m
Entire Space above Basement	16 m × 16 m × 16 m
Wall Thickness between Rooms and Floors	20 cm (Wood)
Window Size	2 m × 1 m × 2 cm
Roof Thickness	20 cm (Asphalt)
Roof Pitch	4 / 12
Basement Thickness	50 cm (Concrete)

There were 4 rooms on each floor in both houses. The sphere detector that was filled with air and had 30 cm radius was placed at the height of 1m above the ground in a room. In the case of a two-story house, the detector was placed in the room on either 1st or 2nd floor to know the differences between the floors.

In each simulation, radioactive sources were uniformly distributed in the air outside the house or on the ground and roof. Only the photon radiation from the cloudshine and groundshine pathways is important. Therefore, gamma rays emitted from radionuclides were focused to calculate the shielding factors for groundshine and cloudshine. The other types of radiation would not penetrate building wall and their contribution to indoor dose would be negligible. Only the gamma rays whose energies are at least 50 keV and intensities are at least 10% were taken into consideration. The data were taken from Nuclear Data Sheets and summarized in Appendix A. [23] The deposited energy on the detector was calculated with an F6 tally. The deposited energy for unsheltered cases were calculated by removing the house and placing only the detector at 1 m above the ground. For sheltered cases, the outer wall material was chosen from 6 materials: gypsum, wood, vinyl, clay brick, concrete, and glass. They are all common as building materials, but their densities range from 0.6 to 2.5 g/cm^3 and their compositions and densities are shown in Appendix B. Each calculation was performed while being careful to make a relative error less than 5%.

Table 2.3. Material Composition Parameters Applied in MCNP

Air			Asphalt			Clay brick			Concrete		
Density: 1.205×10^{-3} g/cm^3			Density: 1.1 g/cm^3			Density: 1.85 g/cm^3			Density: 2.3 g/cm^3		
Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction
C	6000	-0.000124	H	1000	-0.1094	O	8000	-0.499772955	H	1000	-0.010000
N	7000	-0.755267	C	6000	-0.8677	Na	11000	-0.005118820	C	6000	-0.001000
O	8000	-0.231781	N	7000	-0.0110	Mg	12000	-0.007236430	O	8000	-0.529107
Ar	18000	-0.012827	O	8000	-0.0200	Al	13000	-0.137605180	Na	11000	-0.016000
			S	16000	-0.0099	Si	14000	-0.313181397	Mg	12000	-0.002000
						P	15000	-0.000157111	Al	13000	-0.033872
						S	16000	-0.001882332	Si	14000	-0.337021
						K	19000	-0.017433103	K	19000	-0.013000
						Ca	20000	-0.000786160	Ca	20000	-0.044000
						Fe	26000	-0.020283449	Fe	26000	-0.014000

Gypsum			Glass			Vinyl			Wood		
Density: 0.6 g/cm^3			Density: 2.6 g/cm^3			Density: 1.5 g/cm^3			Density: 2.3 g/cm^3		
Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction	Symbol	Atomic Number	Weight Fraction
H	1000	-0.023416	O	8000	-0.463432	H	1000	-0.048380	H	1000	-0.057889
O	8000	-0.557572	Na	11000	-0.121075	C	6000	-0.384361	C	6000	-0.482667
S	16000	-0.186251	Si	14000	-0.345133	Cl	17000	-0.567260	O	8000	-0.459444
Ca	20000	-0.232797	Ca	20000	-0.070360						

2.3 Calculation of Groundshine

Ground concentrations of all 10 nuclides above were given with RASCAL. The values are given as the radioactivity per unit area per unit time. The time change of radioactivity was calculated by adding the new accumulation during the 15 minutes and the remaining amount of the previous accumulation.

$$C(t_{i+1}) = 900C'(t_{i+1}) + C(t_i)e^{(-900\lambda)} \qquad (2.3)$$

By combining the surface area of the ground and roof with the time change of radioactivity for each kind of nuclides, the total radioactivity on the ground and the roof was calculated. Although the roof was tilted, the density of the deposition was assumed to be uniform and the same as that on the ground. The surface deposition on the outer wall or the window of the houses was assumed to be very small and negligible.

The deposited energy on the detector from monoenergetic gamma-ray radiation was calculated with MCNP. By making use of the radiation energies and intensities emitted from a nuclide, the deposited energy from a nuclide which corresponded to each time step was calculated.

Next, from the values calculated in the process above, shielding factors were expressed with the following relationship.

$$SF = \frac{\sum_i C_i \cdot E_i}{\sum_i C_i \cdot E_i'} \qquad (2.4)$$

The time change of projected groundshine for unsheltered cases were given with RASCAL. Therefore, the projected groundshine for sheltered cases was calculated by dividing the unsheltered dose by the shielding factors.

$$D = \frac{D'}{SF_t} \qquad (2.5)$$

By adding up all the projected groundshine at each time step during the simulation period, the projected groundshine at each location was calculated.

2.4 Calculation of Cloudshine

Air concentration of I-131 was given with RASCAL. This was used to calculate the projected cloudshine in the same method as the groundshine calculation. On the other hand, the concentrations of the other nuclides were not accessible with RASCAL. In order to calculate them, the ratio of the air concentration of I-131 to the ground concentration of I-131 at each time and location were studied. Then by multiplying the ground concentration of the nuclides by the ratio at each time step and location, the air concentrations were obtained. In case of nuclides whose ground concentration were not available, the source term information was used. The ratio of released radioactivity of them to that of I-131 were first calculated, and then the air concentration of I-131 was multiplied by the ratios to obtain their air concentration.

Then the shielding factors were calculated in the same process as groundshine.

$$SF = \frac{\sum_i C_i' \cdot E_i}{\sum_i C_i' \cdot E_i'} \tag{2.6}$$

In this equation C_i' shows the radioactivity in the air. Then the projected cloudshine for sheltered cases was calculated from the following equation.

$$D = \frac{D'}{SF_t} \tag{2.7}$$

By adding up all the projected groundshine during the simulation period, the projected cloudshine for sheltered cases at each location was calculated.

2.5 Calculation of Inhalation

To calculate the projected inhalation for sheltered cases, the shelter control volume model was used. Figure 2.3 represents the appearance of one-story and two-story house and air flow. The entire rooms of each house were considered to be a control volume, and the time change of concentration of radionuclides inside house was calculated by taking the concentration that entered minus the concentration that exited into account. A mechanical ventilation system was assumed to be equipped with the house, and nuclides could enter the system. They also can reach inside the house by infiltrating the building wall. The mechanical ventilation system has an air filter to remove contaminants. The radioactive decay of nuclides inside the house was also considered.

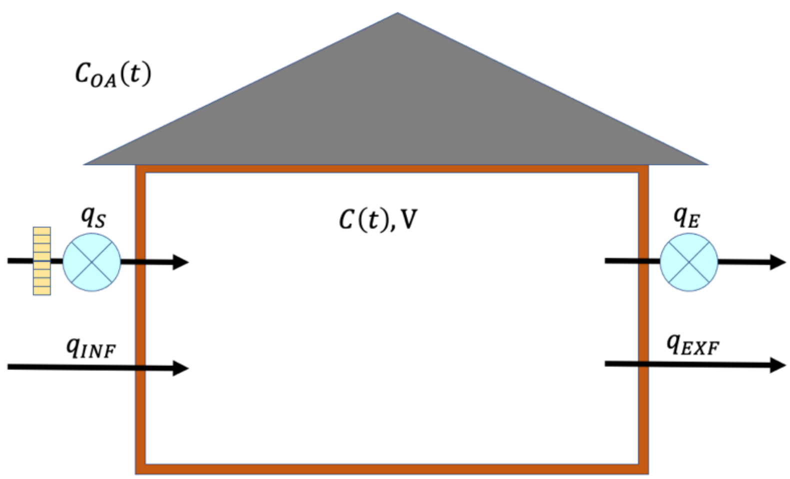

Figure 2.3. Shelter Control Volume Model

In order to find the time change of indoor concentration, the following equation was established.

$$V \cdot \Delta C = [q_{INF} C_{OA}(t_i) + q_S C_{OA}(t_i)(1 - E) - q_E C(t_i) - q_{EXF} C(t_i)] \cdot dt \qquad (2.8)$$

$$C(t_{i+1}) = C(t_i) + \Delta C \qquad (2.9)$$

In order to get the greatest effect of shelter-in-place, the mechanical ventilation system was assumed to be turned off so that the air flow via the pathway completely stopped.

$$q_E = q_S = 0 \quad (2.10)$$

Then the equation (2.9) was transformed into the equation (2.11).

$$V \cdot \Delta C = [q_{INF} C_{OA}(t_i) - q_{EXF} C(t_i)] \cdot dt \qquad (2.11)$$

By solving this equation, the indoor radionuclide concentration at time t_{i+1} was expressed as follows.

$$C(t_{i+1}) = C(t_i) + [q_{INF} C_{OA}(t_i) - q_{EXF} C(t_i)] \cdot \frac{dt}{V} \quad (2.12)$$

RASCAL showed the time change of air concentration at 15-minute intervals. Therefore, the time interval: $t_{i+1} - t_i = 0.25$ (h) was introduced into the equation (2.12).

$$C(t_{i+1}) = \frac{0.25 q_{INF}}{V} C_{OA}(t_i) + \left[1 - \frac{0.25 q_{EXF}}{V}\right] C(t_i) \quad (2.13)$$

Infiltration and exfiltration flow rate depend on the particle size of radionuclides. According to the paper which discussed the size distributions of airborne radionuclides from Fukushima nuclear power plant accident, the activity median aerodynamic diameters were ranging between 0.25 and 0.71 μm for Cs-137, from 0.17 to 0.69 μm for Cs-134, and from 0.30 to 0.53 μm for I-131. [25] I. Kulmala et al. developed a tool for modeling the indoor concentration due to outdoor contaminants. [65] There the particle penetration rate as a function of particle size was calculated. The air exchange rate for Cs and I whose diameter are up to 0.71 μm was calculated to be 0.53 (1/h). The infiltration and exfiltration flow rate were calculated by multiplying the value with the volume of the house. This procedure transformed the equation (2.13) into the equation (2.14).

$$C(t_{i+1}) = 0.1325 C_{OA}(t_i) + 0.8675 C(t_i) \quad (2.14)$$

The indoor concentration was simply calculated by using the outdoor and indoor concentration at the previous time step, and the values were common in both 1-story and 2-story houses.

The Shielding factors were calculated as the ratio of outdoor concentration to indoor concentration.

$$SF = \frac{\sum_i C_i'}{\sum_i C_i''} \tag{2.15}$$

Then the projected inhalation for sheltered cases was calculated from the following equation.

$$D = \frac{D'}{SF_t} \tag{2.16}$$

Therefore, the calculated dose on the 1st floor and the 2nd floor in 2-story house was same.

CHAPTER 3. RESULTS

3.1 RASCAL Results

By using the input shown in Chapter 2, the total effective dose equivalent (TEDE) in LTSBO and LOCA were calculated with RASCAL. TEDE is the summation of the committed effective dose equivalent, cloudshine, and 4-day groundshine. The maximum value of TEDE within 10 miles radius of the release point as a function of the distance is shown in Table 3.1.

Table 3.1. Projected TEDE in LTSBO and LOCA

LTSBO

Distance from the release (mile)	0.1	0.2	0.3	0.5	0.7	1	3	5	10
Total effective dose equivalent (mSv)	41	17	11	5.6	3.7	2.3	0.12	0.026	<0.01

LOCA

Distance from the release (mile)	0.1	0.2	0.3	0.5	0.7	1	3	5	10
Total effective dose equivalent (mSv)	13	5.5	3.3	1.7	1.1	0.7	0.043	0.011	<0.01

The doses in LTSBO were greater than those in LOCA at any location due to the greater source term. As the distance from the release went up, the projected dose exponentially decreased. In this calculation, the locations where the dose exceeded the PAGs are within 0.3 miles away from the release in LTSBO and 0.1 mile away in LOCA. In order to calculate the projected doses for sheltered cases, the time change of groundshine, cloudshine, and inhalation for 4 hours since the release started was discussed is to be mentioned later.

Figure 3.1 was another result from RASCAL which shows the accumulated TEDE in all directions during the calculation period.

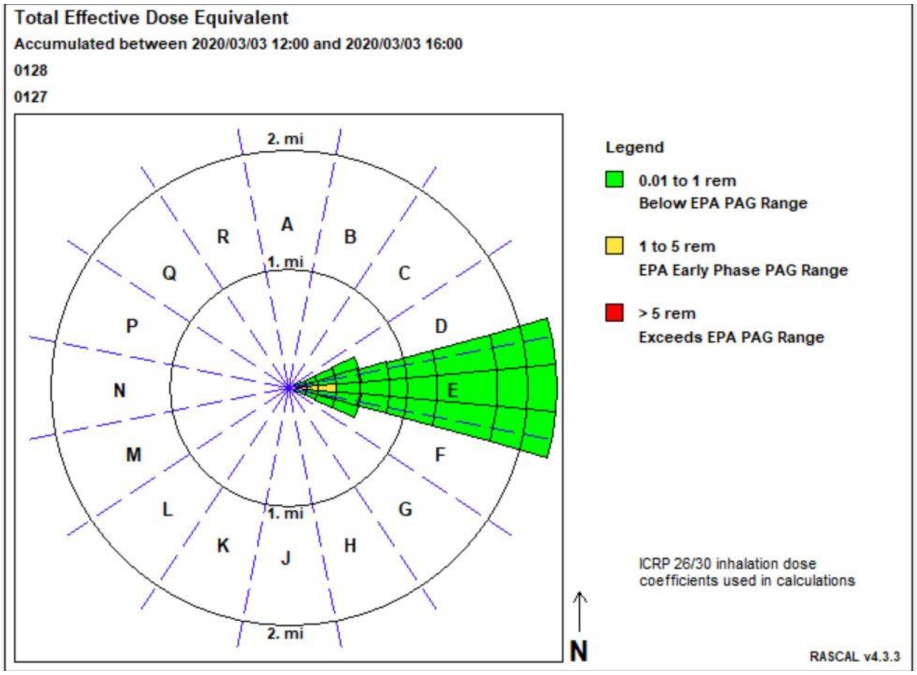

Figure 3.1. Accumulated TEDE within 2 Miles Radius of the Release in LTSBO

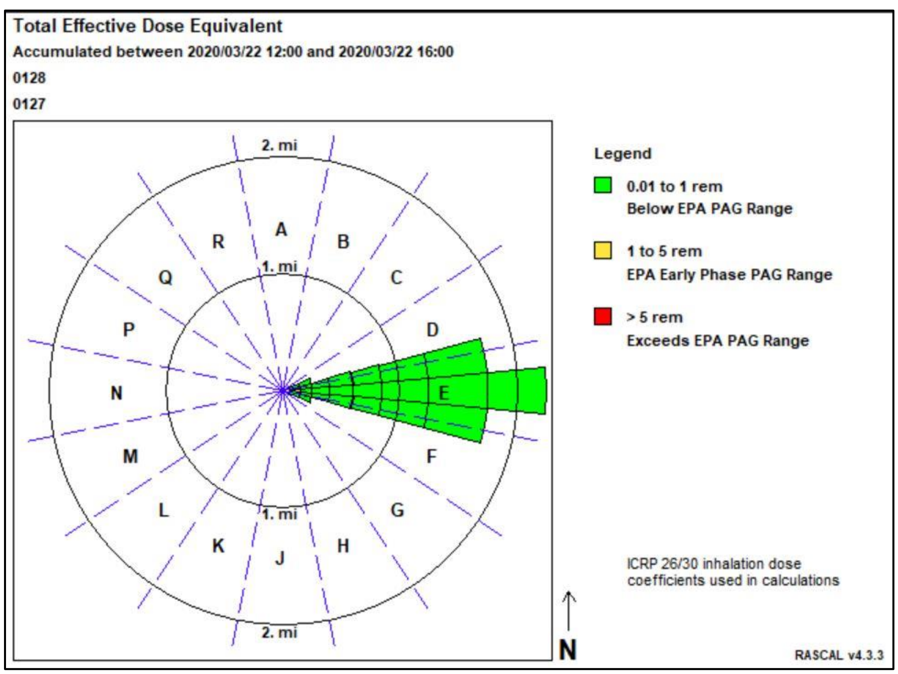

Figure 3.2. Accumulated TEDE within 2 Miles Radius of the Release in LOCA

Released radionuclides were carried to the east side by the wind. The area painted in green where the projected TEDE exceeded 0.1 mSv spread over the 2 miles radius of the release. However, the area painted in yellow where the dose exceeded 10 mSv were quite limited in both scenarios.

10 nuclides which contributed to groundshine, cloudshine, and inhalation for each pathway were shown in Table 4.2 and 4.3.

Table 3.2. Top 10 Nuclides Important to Dose in LTSBO

Groundshine		Cloudshine		Inhalation	
Nuclide	Importance	Nuclide	Importance	Nuclide	Importance
I-132	0.37	I-132	0.48	I-131	0.45
Te-132	0.10	I-133	0.12	Te-132	0.17
I-133	0.10	I-135	0.10	I-133	0.10
Cs-134	0.08	I-131	0.05	Cs-134	0.09
Te-131m	0.08	Xe-135	0.05	Ru-106*	0.05
I-135	0.07	Te-132	0.04	Cs-137*	0.04
I-131	0.04	Te-131m	0.03	Te-129m	0.02
Cs-136	0.04	Cs-134	0.04	Mo-99	0.02
Mo-99	0.03	Cs-136	0.01	Te-131m	0.01
Cs-137	0.02	Xe-133	0.02	Sr-90	0.01
Total	0.88	Total	0.94	Total	0.96

Table 3.3. Top 10 Nuclides Important to Dose in LOCA

Groundshine		Cloudshine		Inhalation	
Nuclide	Importance	Nuclide	Importance	Nuclide	Importance
I-132	0.24	I-132	0.26	I-131	0.29
I-133	0.11	Xe-135	0.16	Sr-90	0.16
Cs-134	0.10	I-133	0.11	Pu-241	0.09
I-135	0.08	I-135	0.09	Cs-134	0.07
La-140	0.07	Xe-133	0.09	Sr-89	0.07
Te-132	0.06	I-131	0.05	I-133	0.06
Cs-136	0.05	Kr-88	0.04	Cm-242	0.06
I-131	0.05	Cs-134	0.04	Te-132	0.05
Rb-88	0.05	La-140	0.03	Ce-144*	0.05
Te-131m	0.04	Cs-136	0.02	Cs-137*	0.03
Total	0.85	Total	0.29	Total	0.93

The total importance of the 10 nuclides shown above was between 85 and 96%. The energies and intensities of gamma rays emitted from them were used to calculate the dose for sheltered cases.

RASCAL also gave the time change of air concentration of I-131 and ground deposition of all nuclides within 10 miles of the plant. The concentrations of I-131 for 4 hours since the release started were shown from Figure 3.3 to Figure 3.10.

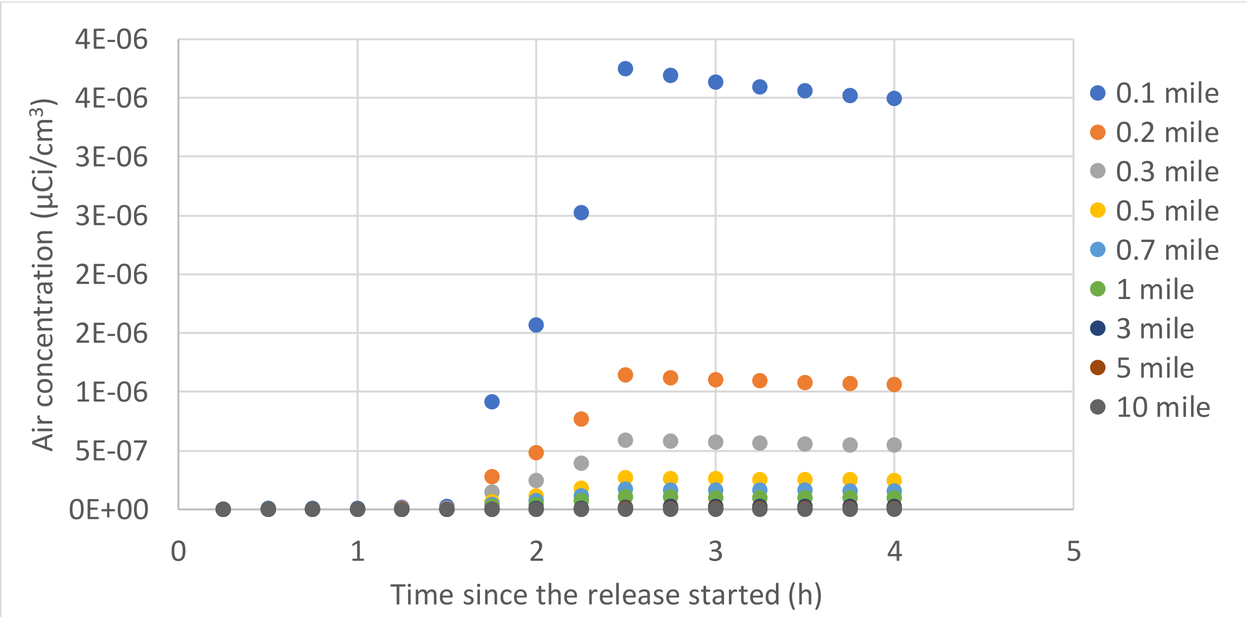

Figure 3.3. Time Change of Concentration of I-131 in the Air in LTSBO

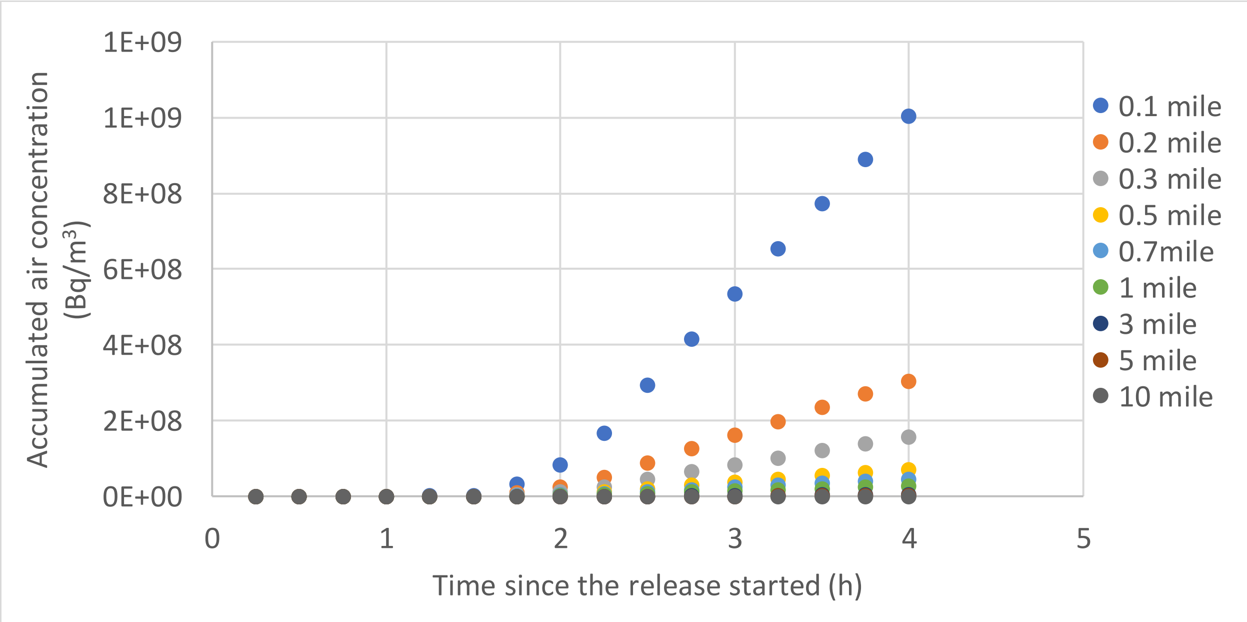

Figure 3.4. Accumulated Concentration of I-131 in the Air in LTSBO

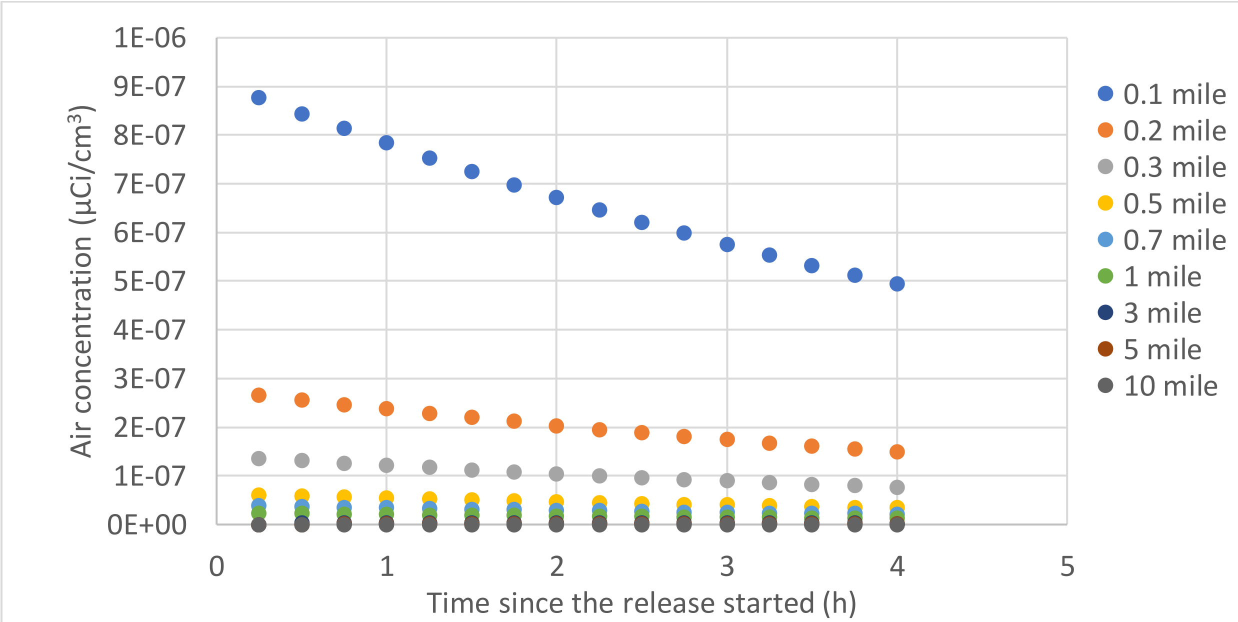

Figure 3.5. Time Change of Concentration of I-131 in the Air in LOCA

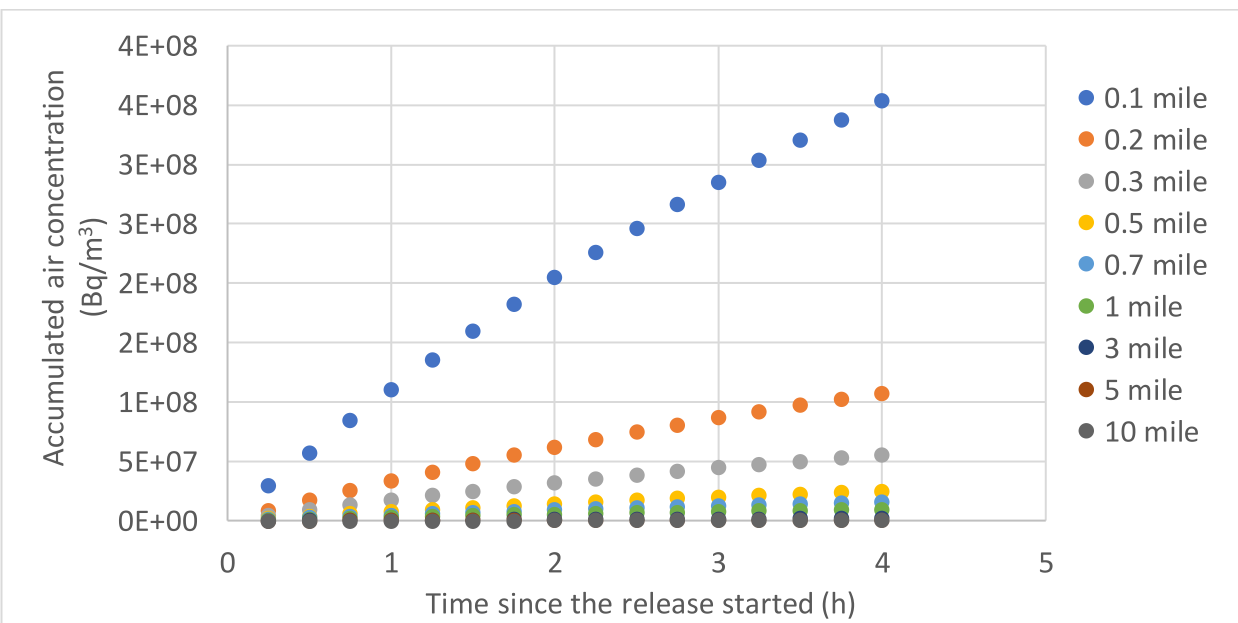

Figure 3.6. Accumulated Concentration of I-131 in the Air in LOCA

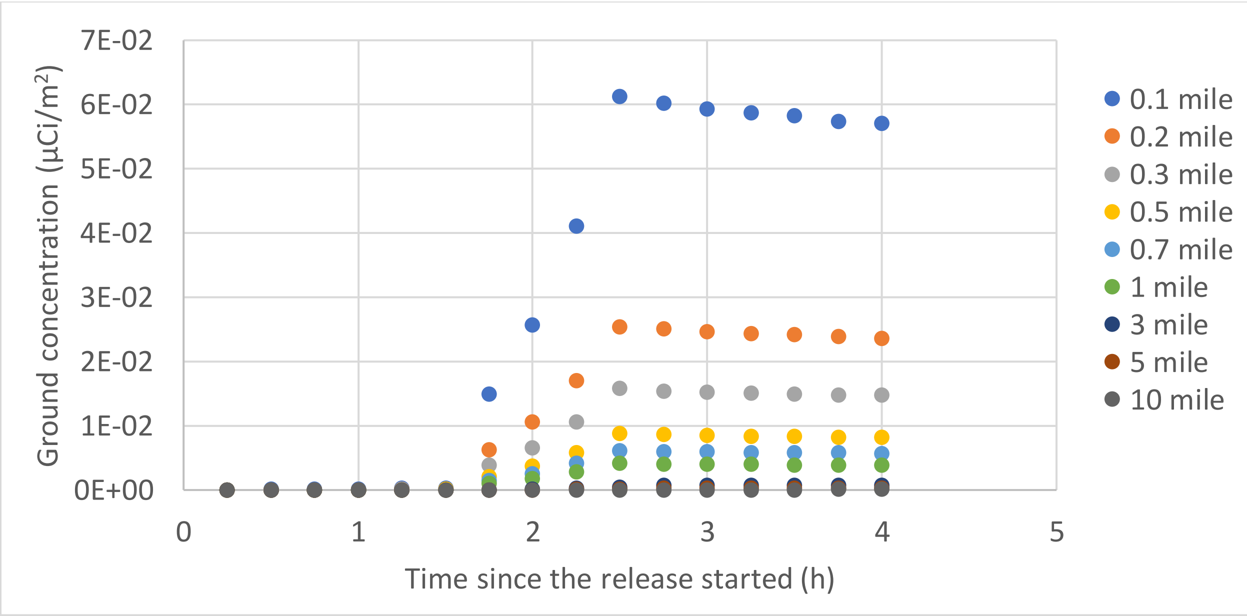

Figure 3.7. Time Change of Concentration of I-131 on the Ground in LTSBO

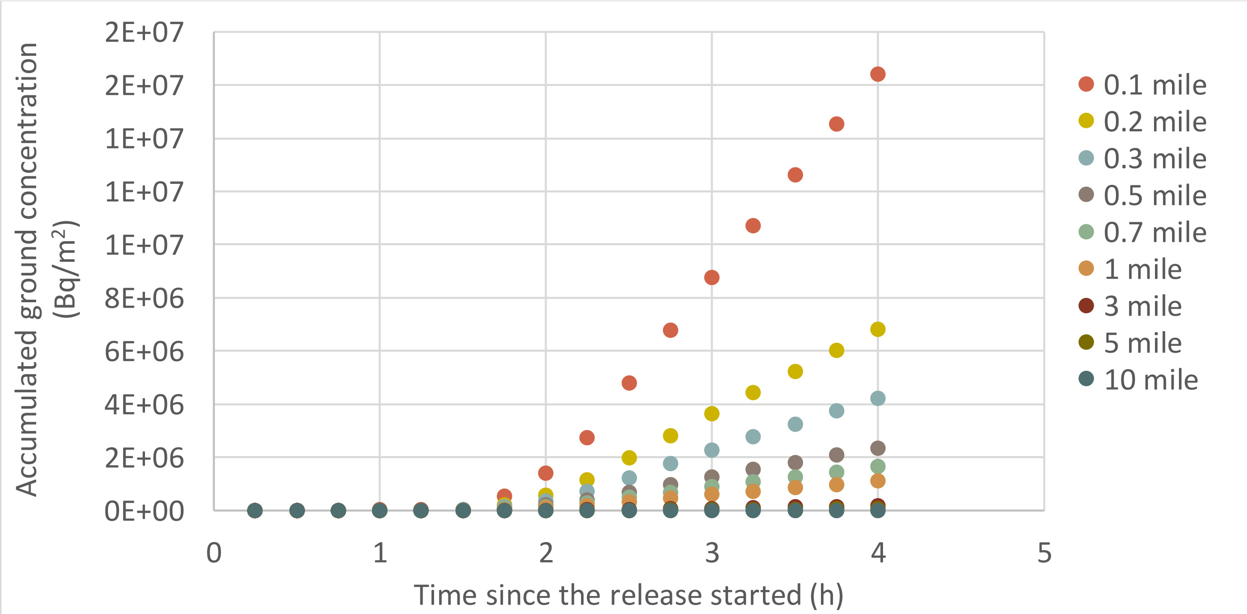

Figure 3.8. Accumulated Concentration of I-131 on the Ground in LTSBO

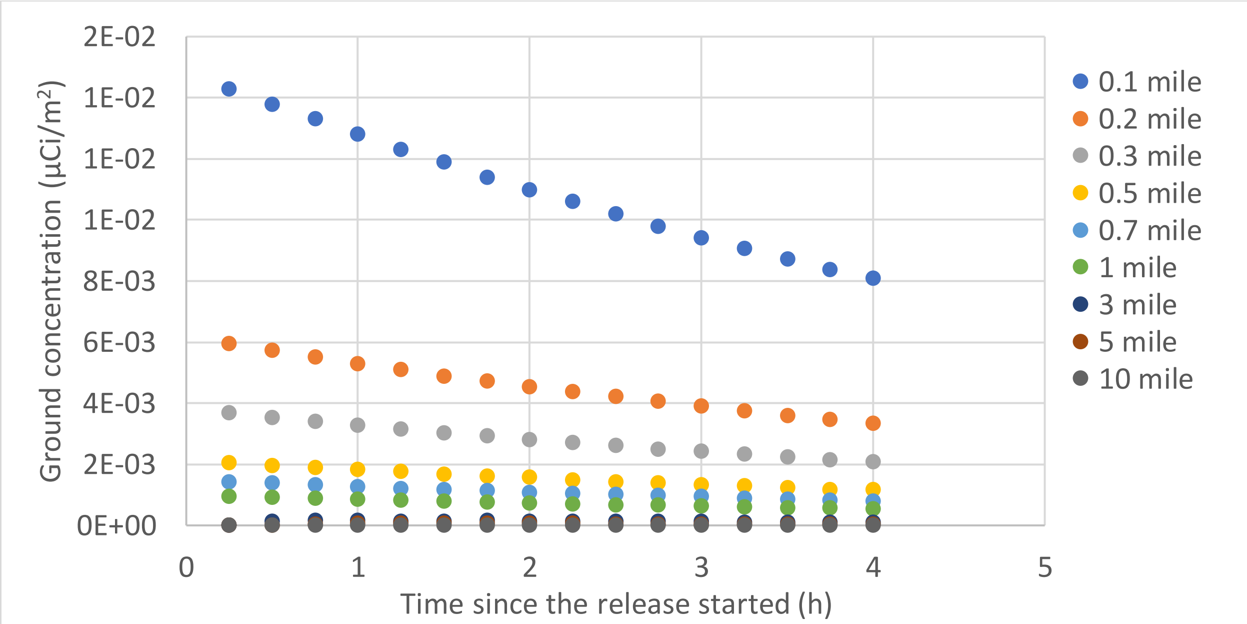

Figure 3.9. Time Change of Concentration of I-131 on the Ground in LOCA

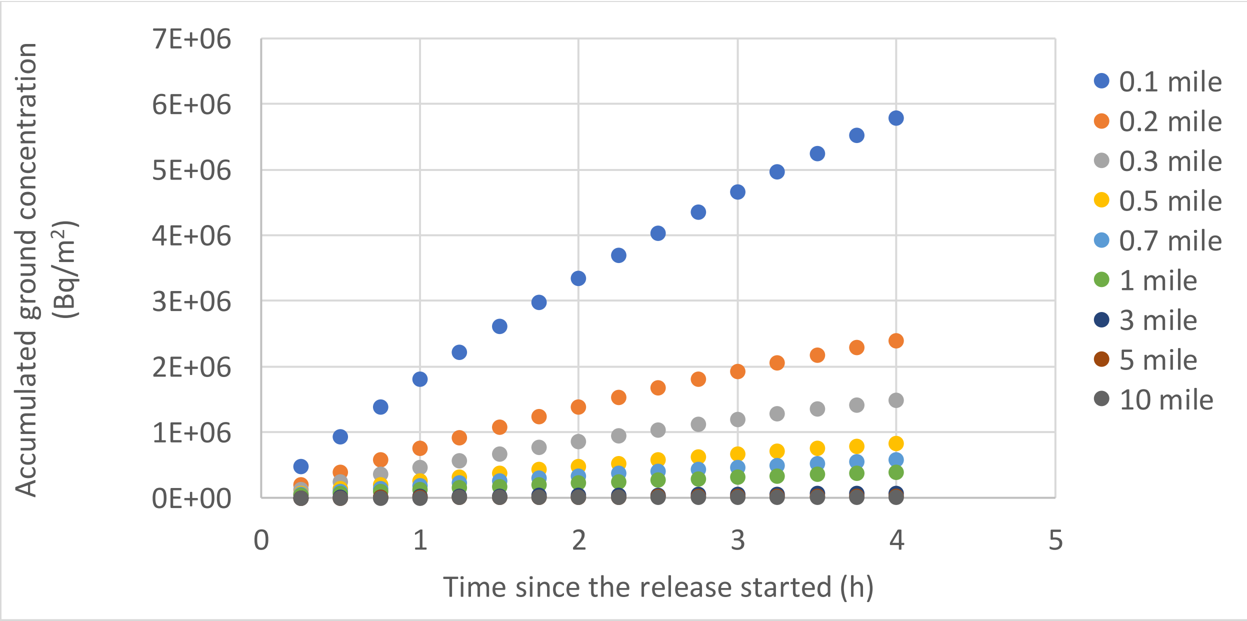

Figure 3.10. Accumulated Concentration of I-131 on the Ground in LOCA

In case of LTSBO, the release to the atmosphere was almost negligible for the first one hour and a half, but then the concentration rapidly increased. On the other hand, in case of LOCA, the largest change of concentration appeared. The difference of the release pathways resulted in this difference. In both cases, the values simply went down as the distance from the plant increased. The accumulated concentrations at 4 hours since the release started in LTSBO was larger than those in LOCA. Half-life of I-131 is approximately 8 hours, so the radioactive decay didn't have a large impact on the trend in either scenario. Calculating the air concentration of the other nuclides which largely contributed to dose is to be mentioned to later.

3.2 MCNP Results

Deposited energy on the detector from the selected gamma rays was simulated with MCNP. In order to calculate groundshine, the radiation source was placed uniformly on the ground and the roof. The deposited energy as a function of gamma ray energy was shown in Figure 3.11. to Figure 3.17. The value of energies which were used with MCNP are shown in Appendix A.

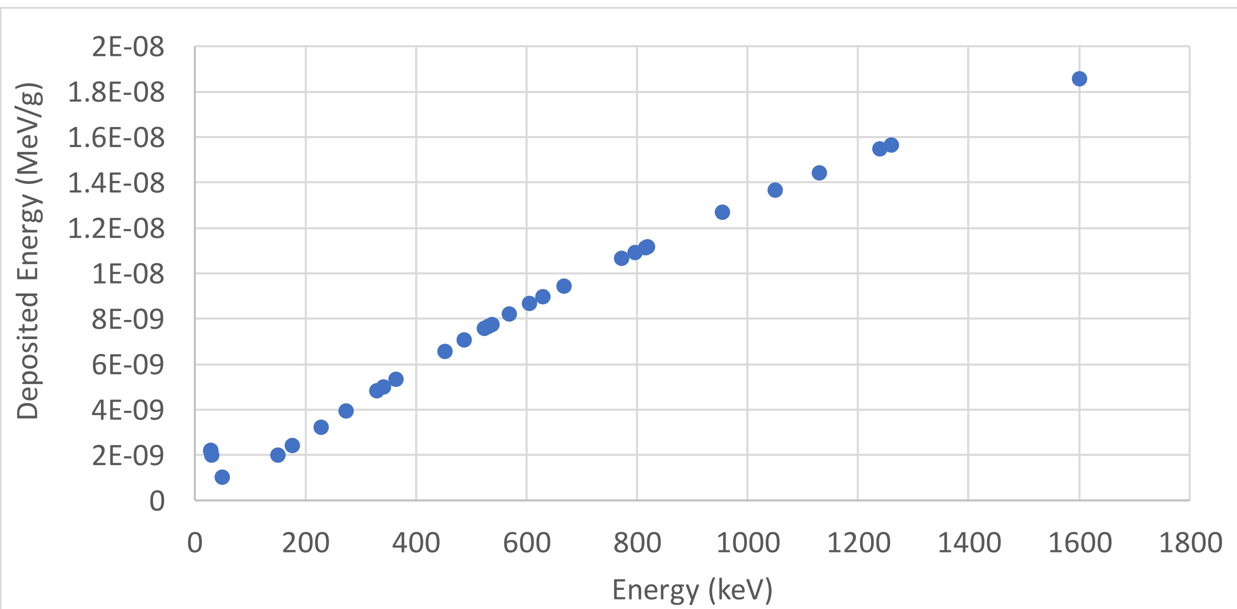

Figure 3.11. Deposited Energy on the Detector without a House from Radiation Emitted on the Ground

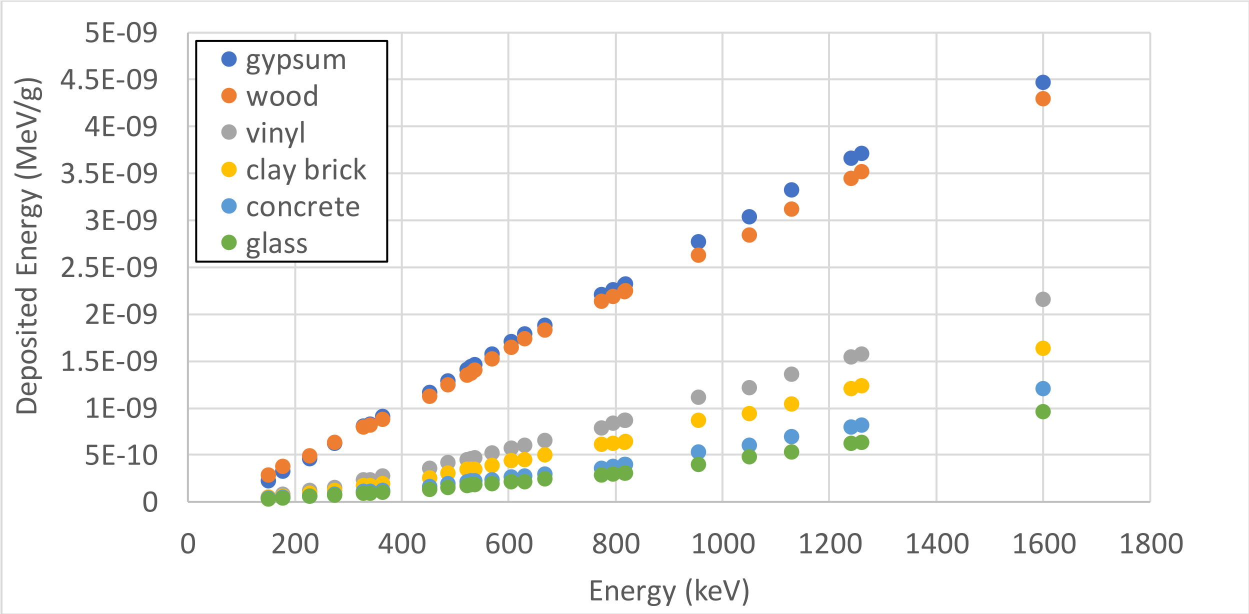

Figure 3.12. Deposited Energy on the Detector in 1-Story House from Radiation Emitted on the Ground

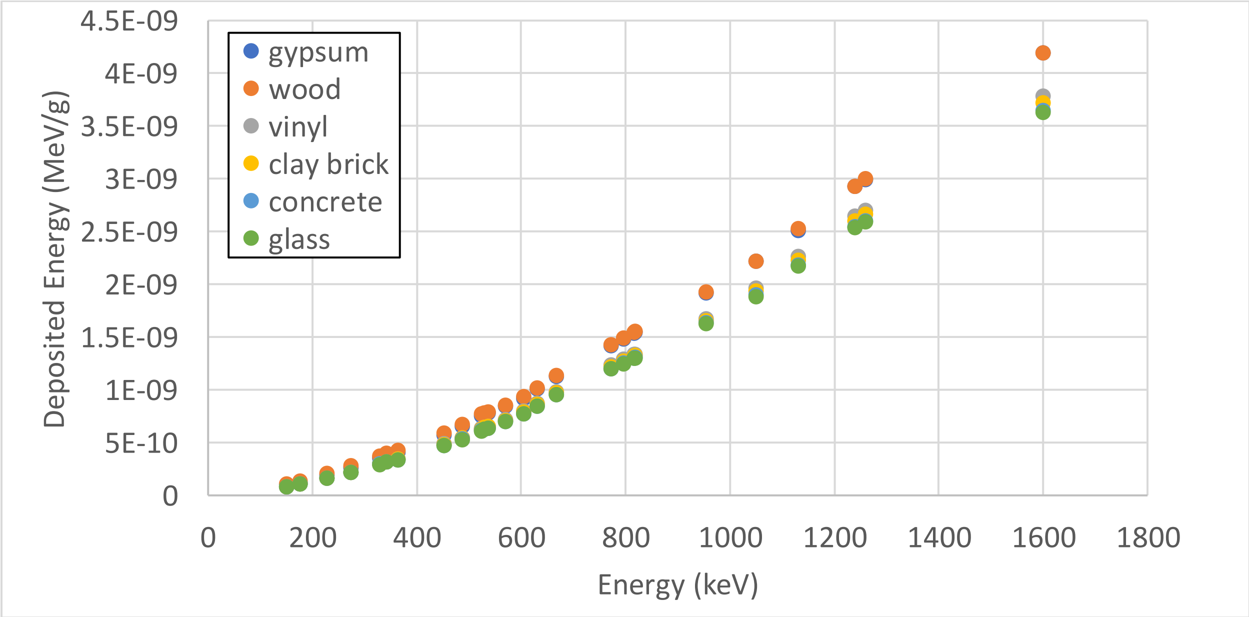

Figure 3.13. Deposited Energy on the Detector in 1-Story House from Radiation Emitted on the Roof

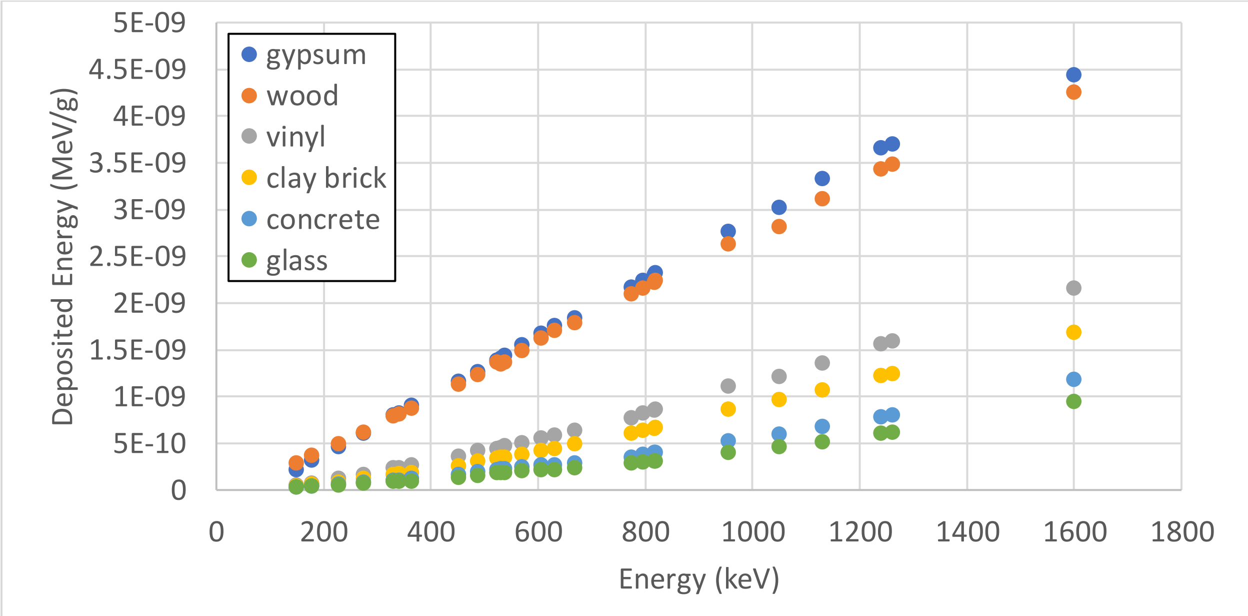

Figure 3.14. Deposited Energy on the Detector on the 1st Floor in 2-Story House from Radiation Emitted on the Ground

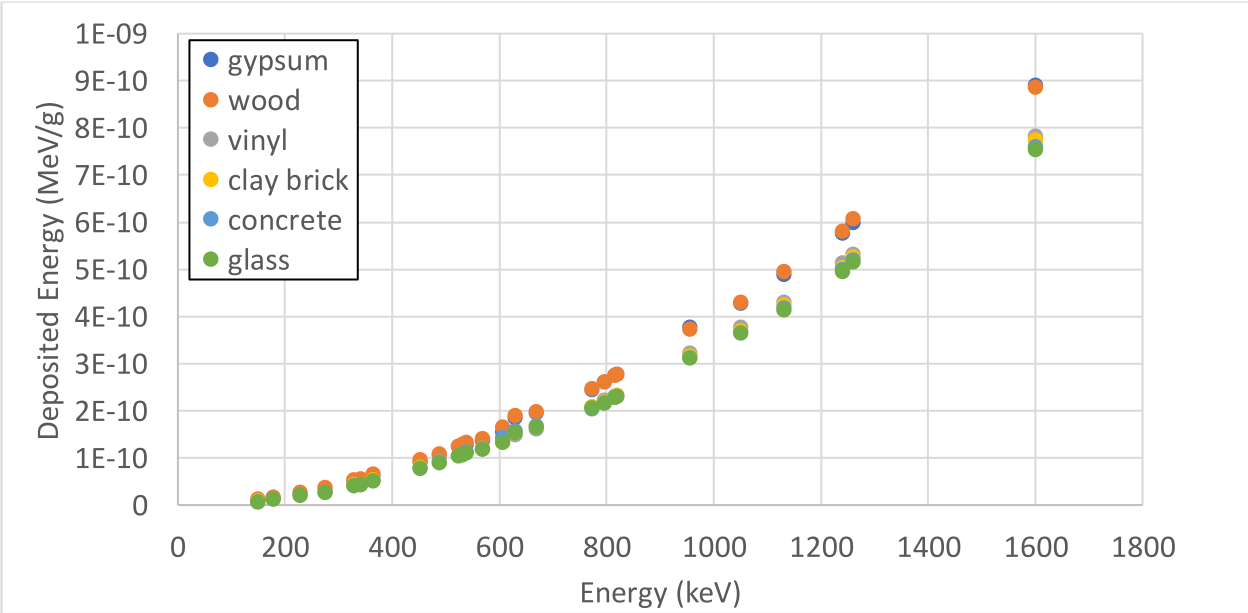

Figure 3.15. Deposited Energy on the Detector on the 1st Floor in 2-Story House from Radiation Emitted on the Roof

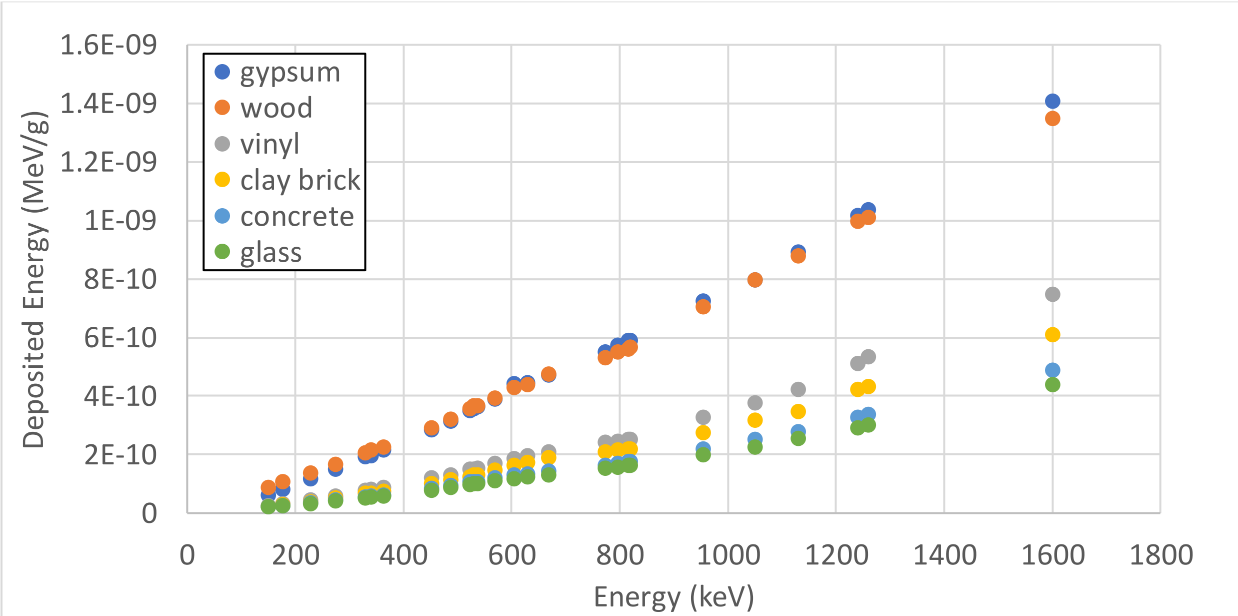

Figure 3.16. Deposited Energy on the Detector on the 2nd Floor in 2-Story House from Radiation Emitted on the Ground

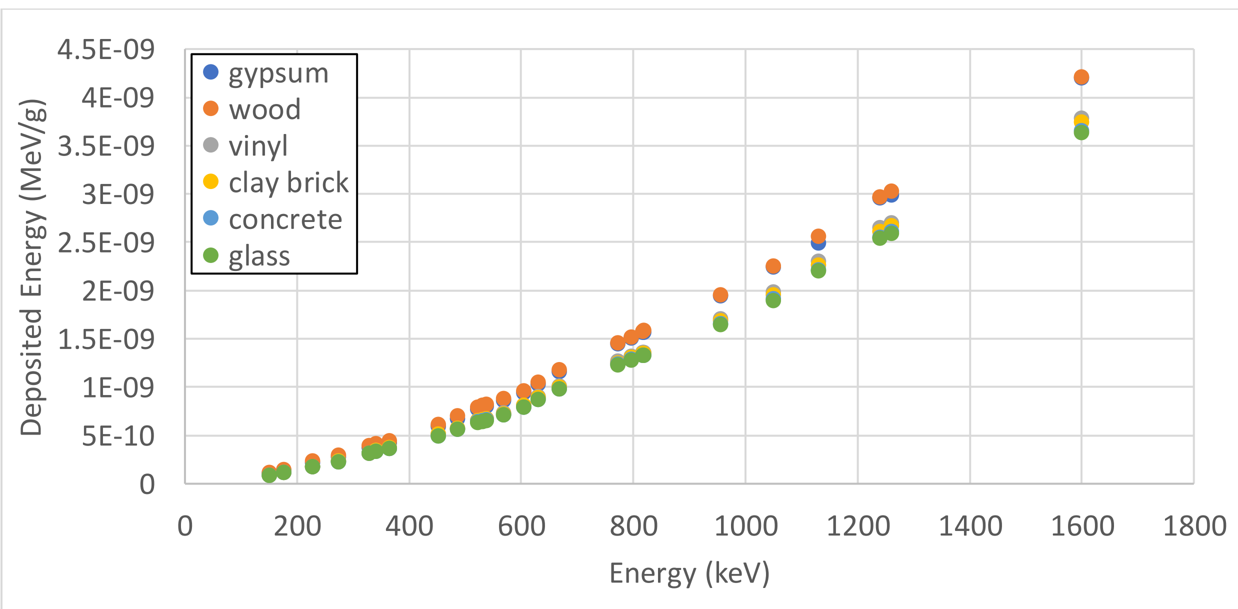

Figure 3.17. Deposited Energy on the Detector on the 2nd Floor in 2-Story House from Radiation Emitted on the Roof

The deposited energy was almost proportional to the radiation energy in every geometry. For sheltered cases, the wall made of concrete and glass worked best to minimize the deposited energy. The degree of decrease by the outer wall was clear by the deposited energy coming from the ground deposition. The deposited energies were almost the same when the detector was located in the 1-story house and on the 1st floor in the 2-story house due to the similar geometry. Placing the detector on the 2nd floor gave a smaller energy. This is thought to happen because the 1st floor functioned as the shielding and the distance from the ground increased. On the other hand, deposited energy coming from the roof changed little by the difference of wall material. In this case, the radiation needed to penetrate the roof and the ceiling between the floors and roof. Therefore, the involvement of the outer wall material to the deposited energy was quite limited. The deposited energy in 1-story house and on the 2nd floor in 2-story house were very close, and the energy on the 1st floor in 2-story house was smaller than those due to the shielding of the 2nd floor.

From the results above, the shielding factors for each nuclide were calculated with the emission probability.

Table 3.4. Shielding Factors for Groundshine in 1-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	6.4	6.5	15	17	24	26
Te-132	9.5	8.9	28	35	44	46
I-133	7.0	7.3	18	22	28	32
Cs-134	6.5	6.7	15	18	24	27
Te-131m	5.9	6.2	13	16	21	23
I-135	5.3	5.5	10	12	15	18
I-131	8.0	8.1	22	28	37	40
Cs-136	6.0	6.2	13	15	20	22
Mo-99	6.2	6.5	14	17	23	26
Cs-137	6.5	6.7	15	19	25	27
La-140	5.4	5.5	9.9	12	14	16
Rb-88	4.8	5.0	8.5	10	12	14

Table 3.5. Shielding Factors for Groundshine on the 1st Floor in 2-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	7.4	7.6	20	25	39	46
Te-132	10	9.8	38	51	69	77
I-133	8.1	8.4	24	30	45	53
Cs-134	7.4	7.7	20	26	40	48
Te-131m	6.8	7.3	18	23	35	42
I-135	6.2	6.6	14	17	25	31
I-131	8.8	9.1	28	39	59	69
Cs-136	7.0	7.3	17	21	33	40
Mo-99	7.4	7.7	20	26	40	47
Cs-137	7.6	7.8	21	26	42	49
La-140	6.4	6.7	13	17	23	28
Rb-88	5.9	6.2	12	15	20	24

Table 3.6. Shielding Factors for Groundshine on the 2nd Floor in 2-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	17	17	26	28	30	31
Te-132	27	24	50	52	56	57
I-133	19	19	32	34	37	38
Cs-134	17	17	27	29	31	32
Te-131m	15	16	23	25	27	28
I-135	12	12	18	19	21	22
I-131	23	22	40	42	46	47
Cs-136	15	15	23	24	26	27
Mo-99	16	16	25	27	29	30
Cs-137	17	17	27	28	31	32
La-140	12	12	17	18	20	20
Rb-88	10	11	14	15	17	17

Nuclides which emit only low energy radiation were likely to get high shielding factors. The values increased as the density of material rose. Shelter-in-place on the 1st floor in 2-story house gave higher factors than the other locations.

Next, radiation source was uniformly distributed in the air for calculating cloudshine. The results are shown in from Figure 3.18. to Figure 3.21.

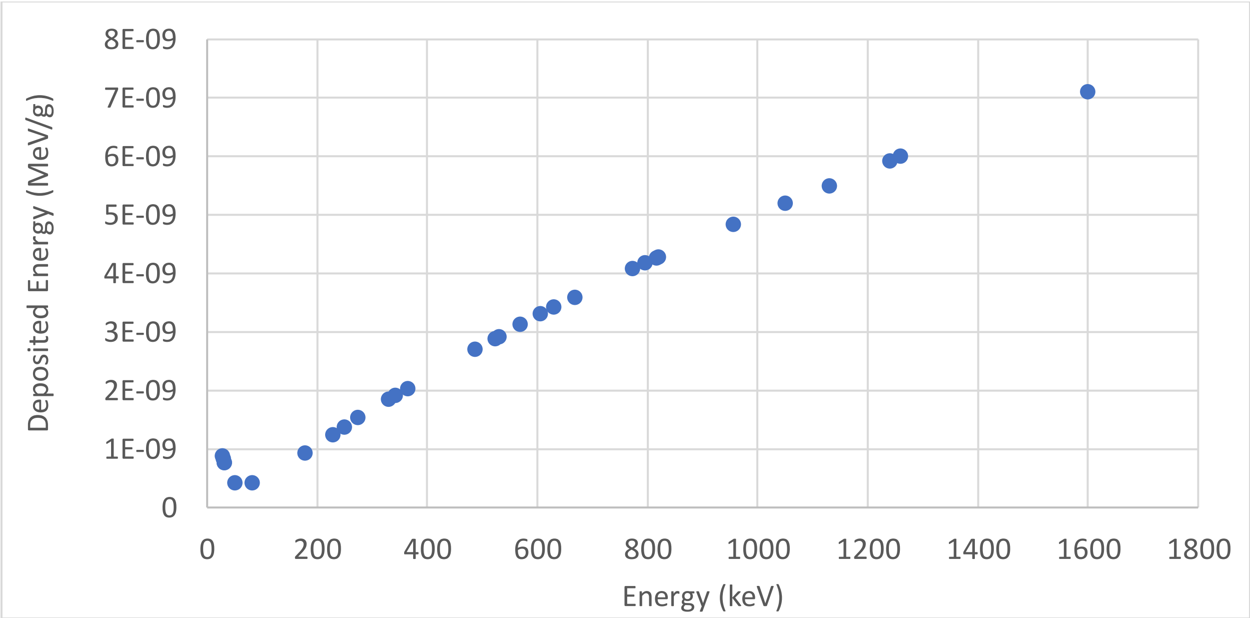

Figure 3.18. Deposited Energy on the Detector without a House from Radiation Emitted in the Air

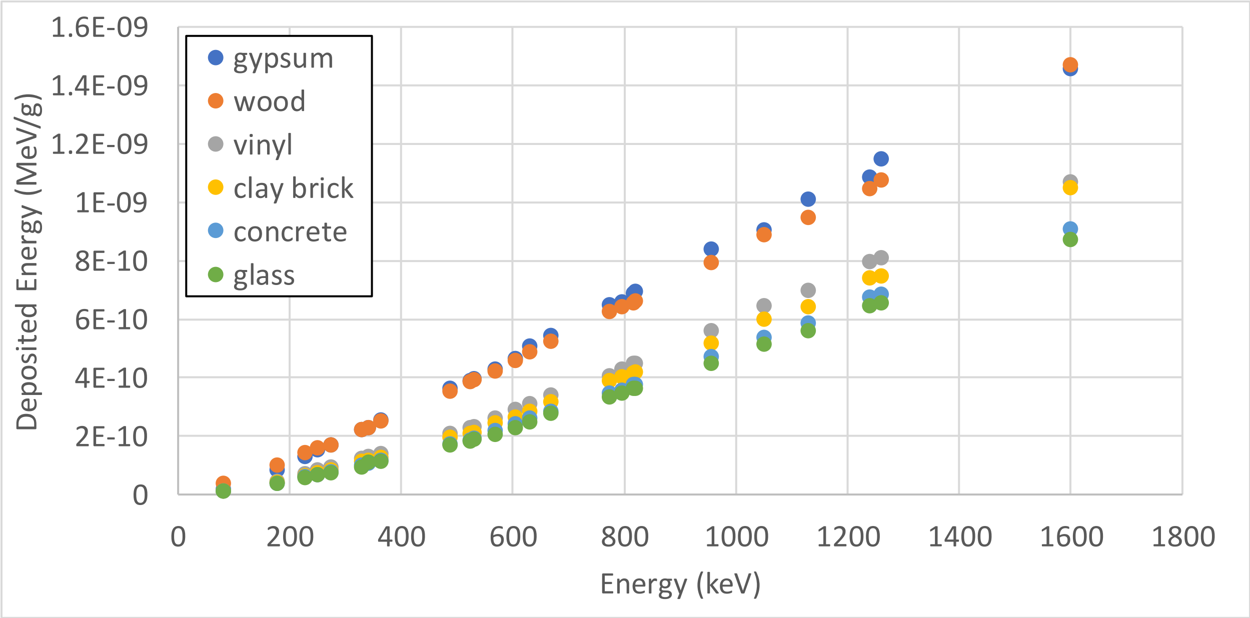

Figure 3.19. Deposited Energy on the Detector in 1-Story House from Radiation Emitted in the Air

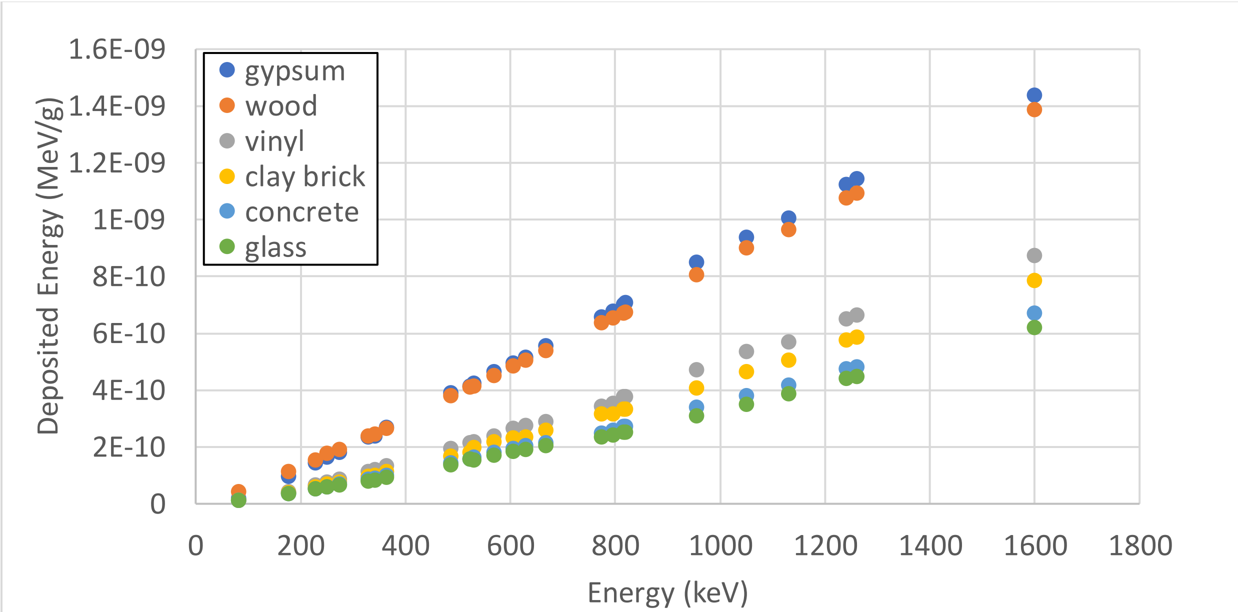

Figure 3.20. Deposited Energy on the Detector on the 1st Floor in 2-Story House from Radiation Emitted in the Air

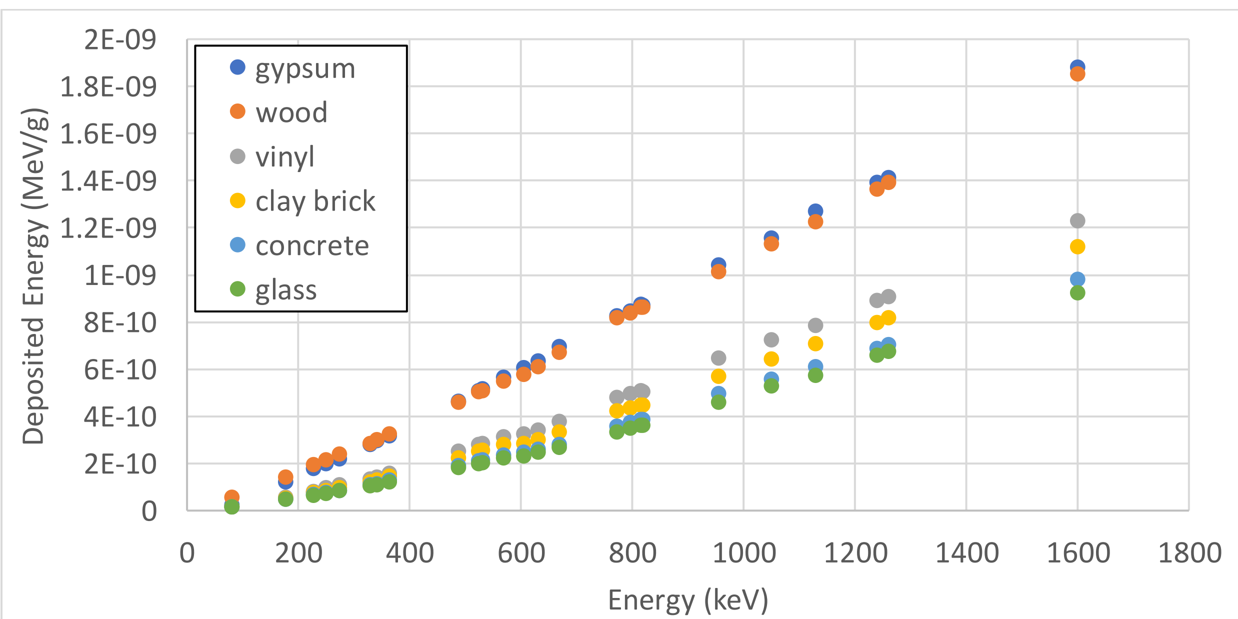

Figure 3.21. Deposited Energy on the Detector on the 2nd Floor in 2-Story House from Radiation Emitted in the Air

The deposited energy increased as the radiation energy increased. The denser wall material led to the smaller deposited energy on the detector for all geometries. Detectors placed in 1-story and on the 1st floor in 2-story house received a little smaller energy compared to that located on the 2nd floor.

From the results above, the shielding factors for each nuclide in cloudshine were also calculated with the emission probability.

Table 3.7. Shielding Factors for Cloudshine in 1-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	6.4	6.7	10	11	12	13
Xe-135	8.9	8.6	16	18	20	20
I-133	7.3	7.4	13	14	15	15
I-135	5.3	5.7	7.6	8.2	9	9.4
Xe-133	22	22	33	32	33	32
I-131	8.0	8.1	14	16	17	18
Kr-88	4.6	4.7	6.1	6.5	7.1	7.4
Cs-134	6.7	6.8	11	11	13	13
La-140	5.3	5.3	7.5	7.7	8.9	9.2
Cs-136	6.0	6.2	8.9	9.6	11	11

Table 3.8. Shielding Factors for Cloudshine on the 1st Floor in 2-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	6.3	6.5	12	14	16	17
Xe-135	8.4	7.8	18	20	23	23
I-133	6.9	7.1	14	15	18	19
I-135	5.3	5.6	9.3	11	13	14
Xe-133	22	23	38	36	38	38
I-131	7.6	7.7	16	18	21	22
Kr-88	4.8	4.9	7.4	8.4	9.9	11
Cs-134	6.4	6.6	12	14	17	18
La-140	5.3	5.5	9.1	10	12	13
Cs-136	5.9	6.1	11	12	15	16

Table 3.9. Shielding Factors for Cloudshine on the 2nd Floor in 2-Story House

Nuclides	gypsum	wood	vinyl	clay brick	concrete	glass
I-132	5.0	5.2	8.9	10	12	13
Xe-135	6.8	6.4	14	16	18	19
I-133	5.6	5.7	10	11	14	14
I-135	4.3	4.4	6.8	7.5	8.7	9.2
Xe-133	16	17	26	26	26	27
I-131	6.4	6.2	13	14	16	17
Kr-88	3.7	3.7	5.4	5.8	6.6	7.0
Cs-134	5.2	5.3	9.2	11	12	13
La-140	4.1	4.2	6.5	7.2	8.3	8.8
Cs-136	4.7	4.8	7.9	8.9	10	11

The shielding factors for cloudshine were generally smaller than those for groundshine. The values rose as the material density went up. For most data, shelter-in-place on the 1st floor in 2-story house gave the highest factors.

3.3 Groundshine

The projected groundshine for unsheltered cases was calculated by using the time change of groundshine at each location which were obtained from RASCAL. Groundshine for sheltered cases with each wall material were calculated from the ground concentration of nuclides in RASCAL output and the deposited energy on the detector obtained from MCNP. The results for both accident scenarios are summarized in the following tables.

Table 3.10. Comparison of Projected Groundshine with Shelter-in-place in 1-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place in 1-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-01	7.1E-02	6.9E-02	3.2E-02	2.7E-02	2.0E-02	1.8E-02
0.2	2.0E-01	3.1E-02	3.0E-02	1.4E-02	1.2E-02	8.9E-03	8.0E-03
0.3	1.2E-01	1.9E-02	1.9E-02	8.7E-03	7.2E-03	5.6E-03	5.0E-03
0.5	6.7E-02	1.0E-02	1.0E-02	4.6E-03	3.9E-03	3.0E-03	2.7E-03
0.7	4.5E-02	7.1E-03	6.9E-03	3.2E-03	2.6E-03	2.0E-03	1.8E-03
1	4.9E-02	4.6E-03	4.4E-03	2.1E-03	1.7E-03	1.3E-03	1.2E-03
3	2.4E-03	3.8E-04	3.7E-04	1.7E-04	1.4E-04	1.0E-04	9.3E-05
5	6.7E-04	1.0E-04	1.0E-04	4.5E-05	3.7E-05	2.8E-05	2.5E-05
10	4.1E-05	6.3E-06	6.1E-06	2.7E-06	2.3E-06	1.7E-06	1.5E-06

Table 3.11. Comparison of Projected Groundshine with Shelter-in-place on the 1st Floor in 2-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place on the 1st floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-01	6.1E-02	5.9E-02	2.4E-02	1.9E-02	1.3E-02	1.1E-02
0.2	2.0E-01	2.6E-02	2.6E-02	1.0E-02	8.1E-03	5.5E-03	4.6E-03
0.3	1.2E-01	1.7E-02	1.6E-02	6.4E-03	5.1E-03	3.4E-03	2.9E-03
0.5	6.7E-02	9.0E-03	8.7E-03	3.4E-03	2.7E-03	1.8E-03	1.5E-03
0.7	4.5E-02	6.1E-03	5.9E-03	2.3E-03	1.8E-03	1.2E-03	1.0E-03
1	4.9E-02	3.9E-03	3.8E-03	1.5E-03	1.2E-03	8.1E-04	6.8E-04
3	2.4E-03	3.3E-04	3.2E-04	1.2E-04	9.6E-05	6.3E-05	5.3E-05
5	6.7E-04	8.9E-05	8.6E-05	3.3E-05	2.6E-05	1.7E-05	1.4E-05
10	4.1E-05	5.4E-06	5.2E-06	2.0E-06	1.6E-06	1.0E-06	8.6E-07

Table 3.12. Comparison of Projected Groundshine with Shelter-in-place on the 2nd Floor in 2-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place on the 2nd floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-01	2.8E-02	2.8E-02	1.8E-02	1.7E-02	1.4E-02	1.5E-02
0.2	2.0E-01	1.2E-02	1.2E-02	7.9E-03	7.4E-03	5.9E-03	6.6E-03
0.3	1.2E-01	7.6E-03	7.7E-03	4.9E-03	4.6E-03	3.7E-03	4.1E-03
0.5	6.7E-02	4.1E-03	4.1E-03	2.6E-03	2.5E-03	2.0E-03	2.2E-03
0.7	4.5E-02	2.8E-03	2.8E-03	1.8E-03	1.7E-03	1.3E-03	1.5E-03
1	4.9E-02	1.8E-03	1.8E-03	1.2E-03	1.1E-03	8.9E-04	9.8E-04
3	2.4E-03	1.4E-04	1.5E-04	9.3E-05	8.7E-05	7.7E-05	7.8E-05
5	6.7E-04	3.9E-05	4.0E-05	2.5E-05	2.4E-05	2.1E-05	2.1E-05
10	4.1E-05	2.4E-06	2.4E-06	1.5E-06	1.4E-06	1.3E-06	1.3E-06

Table 3.13. Comparison of Projected Groundshine with Shelter-in-place in 1-Story House (LOCA)

distance (mile)	unsheltered cases	shelter-in-place in 1-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.9E-01	4.4E-02	4.3E-02	2.0E-02	1.6E-02	1.2E-02	1.1E-02
0.2	1.3E-01	1.9E-02	1.9E-02	8.5E-03	7.1E-03	5.4E-03	4.9E-03
0.3	7.9E-02	1.2E-02	1.2E-02	5.4E-03	4.4E-03	3.4E-03	3.1E-03
0.5	4.3E-02	6.6E-03	6.4E-03	2.9E-03	2.4E-03	1.9E-03	1.7E-03
0.7	2.9E-02	4.5E-03	4.3E-03	2.0E-03	1.6E-03	1.3E-03	1.1E-03
1	1.9E-02	2.8E-03	2.8E-03	1.3E-03	1.0E-03	8.0E-04	7.2E-04
3	1.6E-03	2.5E-04	2.4E-04	1.1E-04	9.0E-05	6.8E-05	6.2E-05
5	5.2E-04	7.8E-05	7.6E-05	3.4E-05	2.8E-05	2.1E-05	1.9E-05
10	5.2E-05	7.9E-06	7.7E-06	3.4E-06	2.8E-06	2.1E-06	1.9E-06

Table 3.14. Comparison of Projected Groundshine with Shelter-in-place on the 1st Floor in 2-Story House (LOCA)

distance (mile)	unsheltered cases	shelter-in-place on the 1st floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.9E-01	3.8E-02	3.7E-02	1.5E-02	1.1E-02	7.6E-03	6.4E-03
0.2	1.3E-01	1.7E-02	1.6E-02	6.3E-03	5.0E-03	3.3E-03	2.8E-03
0.3	7.9E-02	1.1E-02	1.0E-02	4.0E-03	3.1E-03	2.1E-03	1.8E-03
0.5	4.3E-02	5.7E-03	5.5E-03	2.2E-03	1.7E-03	1.1E-03	9.5E-04
0.7	2.9E-02	3.9E-03	3.7E-03	1.5E-03	1.2E-03	7.7E-04	6.4E-04
1	1.9E-02	2.5E-03	2.4E-03	9.3E-04	7.3E-04	4.9E-04	4.1E-04
3	1.6E-03	2.2E-04	2.1E-04	8.1E-05	6.4E-05	4.2E-05	3.5E-05
5	5.2E-04	6.8E-05	6.6E-05	2.5E-05	2.0E-05	1.3E-05	1.1E-05
10	5.2E-05	6.9E-06	6.6E-06	2.5E-06	2.0E-06	1.3E-06	1.1E-06

Table 3.15. Comparison of Projected Groundshine with Shelter-in-place on the 2nd Floor in 2-Story House (LOCA)

distance (mile)	unsheltered cases	shelter-in-place on the 2^{nd} floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.9E-01	1.7E-02	1.7E-02	1.1E-02	1.0E-02	9.4E-03	9.3E-03
0.2	1.3E-01	7.5E-03	7.6E-03	4.8E-03	4.5E-03	4.1E-03	4.1E-03
0.3	7.9E-02	4.7E-03	4.7E-03	3.0E-03	2.8E-03	2.6E-03	2.5E-03
0.5	4.3E-02	2.6E-03	2.6E-03	1.6E-03	1.6E-03	1.4E-03	1.4E-03
0.7	2.9E-02	1.7E-03	1.8E-03	1.1E-03	1.0E-03	9.4E-04	9.4E-04
1	1.9E-02	1.1E-03	1.1E-03	7.1E-04	6.6E-04	6.0E-04	5.9E-04
3	1.6E-03	9.6E-05	9.7E-05	6.1E-05	5.7E-05	5.3E-05	5.1E-05
5	5.2E-04	3.0E-05	3.0E-05	1.9E-05	1.8E-05	1.6E-05	1.6E-05
10	5.2E-05	3.0E-06	3.0E-06	1.9E-06	1.8E-06	1.6E-06	1.6E-06

The projected groundshine for unsheltered cases at 0.1 mile away from the plant for 4 hours since the release started are 0.45 mSv and 0.29 mSv in LTSBO and LOCA, respectively. For sheltered cases, the projected doses dropped to less than 0.1 mSv at every point in both scenarios. The values were at least 6 times smaller than those without a house. The outer wall made of concrete and glass had higher shielding factors due to their high density, but since the absorbed dose would not be so large even for unsheltered people, the difference of wall material would not be an important issue.

In regard to the location of shelter-in-place, staying on the 2nd floor was best to minimize the projected groundshine when the outer wall is made of relatively light material. When it is made of heavier material, sheltering on the 1st floor worked best.

3.4 Cloudshine

The projected cloudshine for unsheltered cases was calculated by using the air concentration of radionuclides with RASCAL and the shielding factors. The results for both accident scenarios were summarized in the following tables.

Table 3.16. Comparison of Projected Cloudshine with Shelter-in-place in 1-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place in 1-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-02	6.5E-03	6.4E-03	4.0E-03	3.7E-03	3.4E-03	3.3E-03
0.2	2.4E-02	3.4E-03	3.4E-03	2.1E-03	2.0E-03	1.8E-03	1.7E-03
0.3	1.6E-02	2.2E-03	2.2E-03	1.4E-03	1.3E-03	1.2E-03	1.1E-03
0.5	9.4E-03	1.3E-03	1.3E-03	8.2E-04	7.7E-04	6.9E-04	6.7E-04
0.7	6.6E-03	9.4E-04	9.3E-04	5.8E-04	5.4E-04	4.9E-04	4.7E-04
1	4.4E-03	6.2E-04	6.2E-04	3.8E-04	3.6E-04	3.2E-04	3.1E-04
3	8.0E-04	1.2E-04	1.1E-04	7.2E-05	6.7E-05	6.0E-05	5.8E-05
5	3.5E-04	5.1E-05	5.0E-05	3.1E-05	2.9E-05	2.6E-05	2.6E-05
10	6.3E-05	9.3E-06	9.1E-06	5.8E-06	5.4E-06	4.9E-06	4.7E-06

Table 3.17. Comparison of Projected Cloudshine with Shelter-in-place on the 1st Floor in 2-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place on the 1st floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-02	6.7E-03	6.6E-03	3.5E-03	3.1E-03	2.6E-03	2.4E-03
0.2	2.4E-02	3.5E-03	3.5E-03	1.8E-03	1.6E-03	1.4E-03	1.3E-03
0.3	1.6E-02	2.3E-03	2.3E-03	1.2E-03	1.1E-03	8.9E-04	8.4E-04
0.5	9.4E-03	1.4E-03	1.4E-03	7.1E-04	6.3E-04	5.3E-04	5.0E-04
0.7	6.6E-03	9.7E-04	9.6E-04	5.0E-04	4.5E-04	3.7E-04	3.5E-04
1	4.4E-03	6.4E-04	6.4E-04	3.3E-04	3.0E-04	2.5E-04	2.3E-04
3	8.0E-04	1.2E-04	1.2E-04	6.2E-05	5.5E-05	4.6E-05	4.4E-05
5	3.5E-04	5.2E-05	5.2E-05	2.7E-05	2.4E-05	2.0E-05	1.9E-05
10	6.3E-05	9.5E-06	9.4E-06	5.0E-06	4.5E-06	3.7E-06	3.5E-06

Table 3.18. Comparison of Projected Cloudshine with Shelter-in-place on the 2nd Floor in 2-Story House (LTSBO)

distance (mile)	unsheltered cases	shelter-in-place on the 2nd floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	4.5E-02	8.3E-03	8.3E-03	4.6E-03	4.1E-03	3.5E-03	3.4E-03
0.2	2.4E-02	4.4E-03	4.4E-03	2.4E-03	2.2E-03	1.9E-03	1.8E-03
0.3	1.6E-02	2.9E-03	2.9E-03	1.6E-03	1.4E-03	1.2E-03	1.2E-03
0.5	9.4E-03	1.7E-03	1.7E-03	9.5E-04	8.5E-04	7.3E-04	6.9E-04
0.7	6.6E-03	1.2E-03	1.2E-03	6.6E-04	6.0E-04	5.1E-04	4.8E-04
1	4.4E-03	8.0E-04	8.0E-04	4.4E-04	4.0E-04	3.4E-04	3.2E-04
3	8.0E-04	1.5E-04	1.5E-04	8.2E-05	7.4E-05	6.3E-05	6.0E-05
5	3.5E-04	6.5E-05	6.5E-05	3.6E-05	3.2E-05	2.8E-05	2.6E-05
10	6.3E-05	1.2E-05	1.2E-05	6.7E-06	5.9E-06	5.1E-06	4.8E-06

Table 3.19. Comparison of Projected Cloudshine with Shelter-in-place in 1-Story House (LOCA)

distance (mile)	unsheltered cases	shelter-in-place in 1-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.0E-02	2.7E-03	2.8E-03	1.7E-03	1.6E-03	1.5E-03	1.4E-03
0.2	1.1E-02	1.5E-03	1.5E-03	9.3E-04	8.6E-04	7.8E-04	7.6E-04
0.3	7.0E-03	9.7E-04	9.9E-04	6.1E-04	5.7E-04	5.2E-04	5.0E-04
0.5	4.2E-03	5.8E-04	5.9E-04	3.7E-04	3.4E-04	3.1E-04	3.0E-04
0.7	2.9E-03	4.1E-04	4.1E-04	2.6E-04	2.4E-04	2.2E-04	2.1E-04
1	2.0E-03	2.7E-04	2.8E-04	1.7E-04	1.6E-04	1.5E-04	1.4E-04
3	4.3E-04	5.6E-05	5.8E-05	3.5E-05	3.3E-05	3.0E-05	2.9E-05
5	2.2E-04	2.9E-05	3.0E-05	1.8E-05	1.7E-05	1.5E-05	1.5E-05
10	7.1E-05	9.1E-06	9.5E-06	5.6E-06	5.2E-06	4.8E-06	4.6E-06

Table 3.20. Comparison of Projected Cloudshine with Shelter-in-place on the 1st Floor in 2-Story House (LOCA)

distance (mile)	unsheltered cases	shelter-in-place on the 1st floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.0E-02	3.5E-03	3.7E-03	2.0E-03	1.8E-03	1.6E-03	1.5E-03
0.2	1.1E-02	1.9E-03	2.0E-03	1.1E-03	9.6E-04	8.3E-04	7.9E-04
0.3	7.0E-03	1.2E-03	1.3E-03	7.0E-04	6.3E-04	5.5E-04	5.2E-04
0.5	4.2E-03	7.4E-04	7.7E-04	4.2E-04	3.8E-04	3.3E-04	3.1E-04
0.7	2.9E-03	5.2E-04	5.4E-04	2.9E-04	2.7E-04	2.3E-04	2.2E-04
1	2.0E-03	3.5E-04	3.6E-04	2.0E-04	1.8E-04	1.5E-04	1.5E-04
3	4.3E-04	5.8E-05	6.1E-05	3.0E-05	2.7E-05	2.3E-05	2.2E-05
5	2.2E-04	3.0E-05	3.2E-05	1.6E-05	1.4E-05	1.2E-05	1.1E-05
10	7.1E-05	9.3E-06	9.9E-06	4.9E-06	4.4E-06	3.7E-06	3.6E-06

Table 3.21. Comparison of Projected Cloudshine with Shelter-in-place on the 2nd Floor in 2-Story House (LOCA)

distance (mile)	unsheltered	shelter-in-place on the 2nd floor in 2-story house					
	projected dose (mSv)	projected dose with wall material (mSv)					
		gypsum	wood	vinyl	clay brick	concrete	glass
0.1	2.0E-02	2.8E-03	2.9E-03	1.5E-03	1.3E-03	1.1E-03	1.1E-03
0.2	1.1E-02	1.5E-03	1.5E-03	7.9E-04	7.1E-04	6.0E-04	5.7E-04
0.3	7.0E-03	9.9E-04	1.0E-03	5.3E-04	4.7E-04	4.0E-04	3.8E-04
0.5	4.2E-03	5.9E-04	6.1E-04	3.1E-04	2.8E-04	2.4E-04	2.3E-04
0.7	2.9E-03	4.2E-04	4.3E-04	2.2E-04	2.0E-04	1.7E-04	1.6E-04
1	2.0E-03	2.8E-04	2.9E-04	1.5E-04	1.3E-04	1.1E-04	1.1E-04
3	4.3E-04	7.2E-05	7.6E-05	4.0E-05	3.6E-05	3.2E-05	3.0E-05
5	2.2E-04	3.7E-05	4.0E-05	2.1E-05	1.9E-05	1.6E-05	1.6E-05
10	7.1E-05	1.2E-05	1.3E-05	6.5E-06	5.9E-06	5.1E-06	4.9E-06

The maximum projected cloudshine for unsheltered cases were 0.045 mSv and 0.029 mSv in LTSBO and LOCA, respectively. They were relatively small compared to groundshine. For sheltered cases, the projected doses were at least several times smaller than those without a house, and outer wall made of concrete and glass had higher shielding factors than light materials. Just like groundshine, the absorbed dose would not be so large even for unsheltered people. Therefore the difference of wall material would be a small matter to evaluate the effect of shelter-in-place.

In both accident scenarios, the difference of projected doses with each sheltering location was not large. Staying on the 1st floor in 2-story house led to the minimum projected dose especially when the wall is made of heavy material.

3.5 Inhalation

Shielding factors for inhalation was considered to be the ratio of the outdoor concentration to the indoor concentration. The time change of indoor concentration of radionuclides were calculated from equation (2.12). Shielding factors in both scenarios are shown in Figure 3.22 and Figure 3.23.

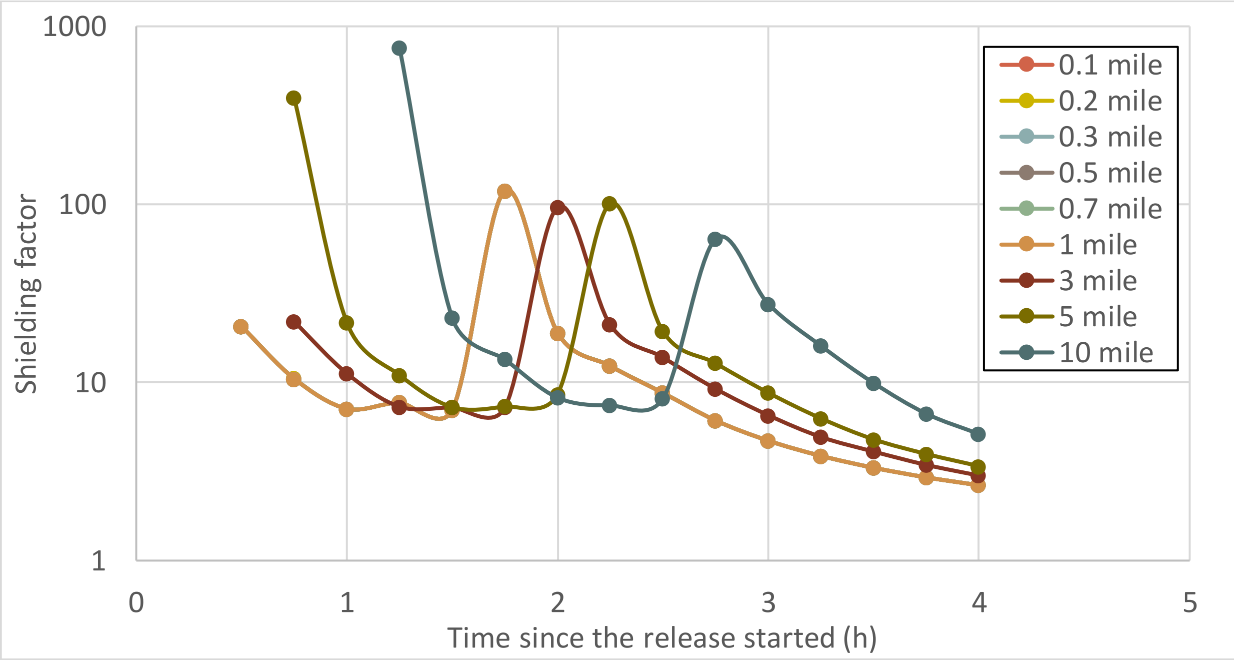

Figure 3.22. Shielding Factors for Inhalation in LTSBO

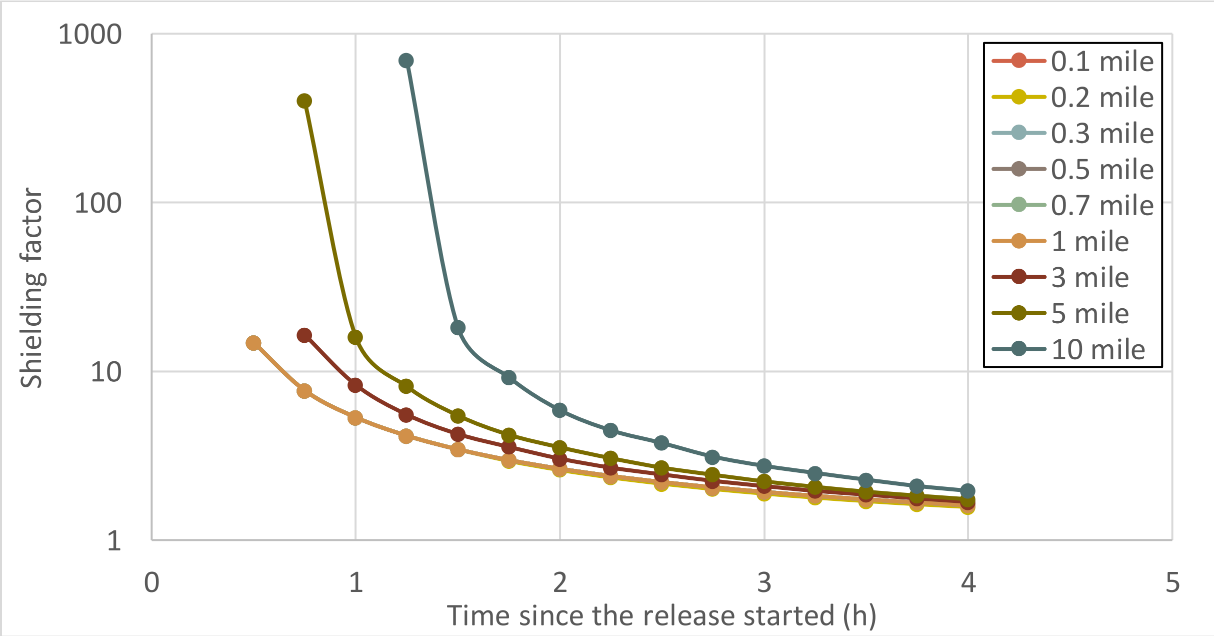

Figure 3.23. Shielding Factors for Inhalation in LOCA

In both scenarios, the shielding factors becomes smaller as the time passed and the outdoor concentration increased. In case of LTSBO, a mountain appeared at around 2 hours after the released started. This was because the released radioactivity was quite small in the first 2 hours, but then it suddenly rose and correspondingly the concentration around the reactor suddenly began to increase. On the other hand, the outdoor concentration gradually went up from the beginning, so the change of the shielding factors was smooth. The timing to calculate the shielding factors was delayed as the distance from the reactor went up because the outdoor concentration started to rise late in the region. The maximum values for inhalation were greater than those for groundshine and cloudshine, but as the time passed, the relationship reversed.

By using the shielding doses with shelter-in-place was calculated and compared with those for unsheltered cases. factors, the projected

Table 3.22. Comparison of Projected Inhalation with Shelter-in-place (LTSBO)

distance (mile)	unsheltered	shelter-in-place
	projected dose (mSv)	
0.1	6.5	1.4
0.2	2.0	4.3E-01
0.3	9.9E-01	2.2E-01
0.5	4.3E-01	9.5E-02
0.7	2.7E-01	5.8E-02
1	1.6E-01	3.4E-02
3	2.3E-02	4.5E-03
4	8.1E-03	1.4E-03
10	1.0E-03	1.3E-04

Table 3.23. Comparison of Projected Inhalation with Shelter-in-place (LOCA)

distance (mile)	unsheltered	shelter-in-place
	projected dose (mSv)	
0.1	3.5	1.2
0.2	1.0	3.5E-01
0.3	5.3E-01	1.7E-01
0.5	2.3E-01	7.5E-02
0.7	1.4E-01	4.5E-02
1	8.0E-02	2.6E-02
3	1.1E-02	3.6E-03
5	4.0E-03	1.2E-03
10	6.3E-04	1.7E-04

The maximum projected cloudshine for unsheltered cases was 6.5 mSv and 3.5 mSv in LTSBO and LOCA, respectively. They were more than 10 times greater than the corresponding groundshine and cloudshine. Therefore, the inhalation was considered as the most important pathway for TEDE. For sheltered cases, the projected doses decreased by more than 60%.

3.6 Effect of Shelter-in-place

The projected dose for each pathway was evaluated in the previous sections. In this section, the total dose was calculated as a function of distance and shown in from Figure 3.24 to 3.29.

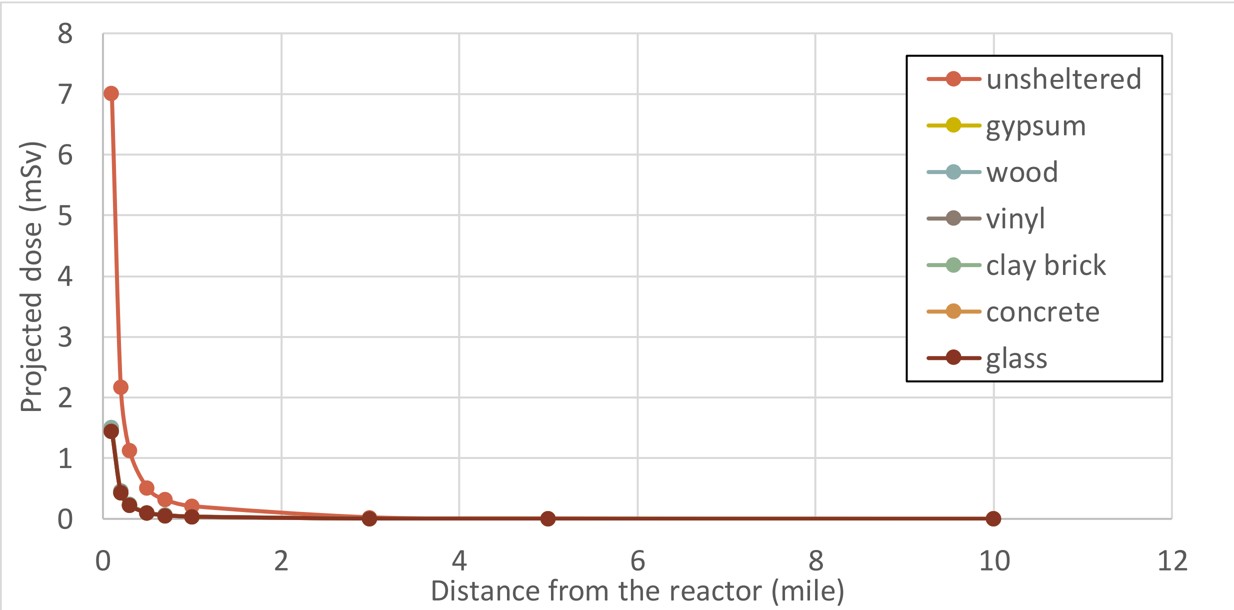

Figure 3.24. Projected Dose for Sheltering in 1-Story House (LTSBO)

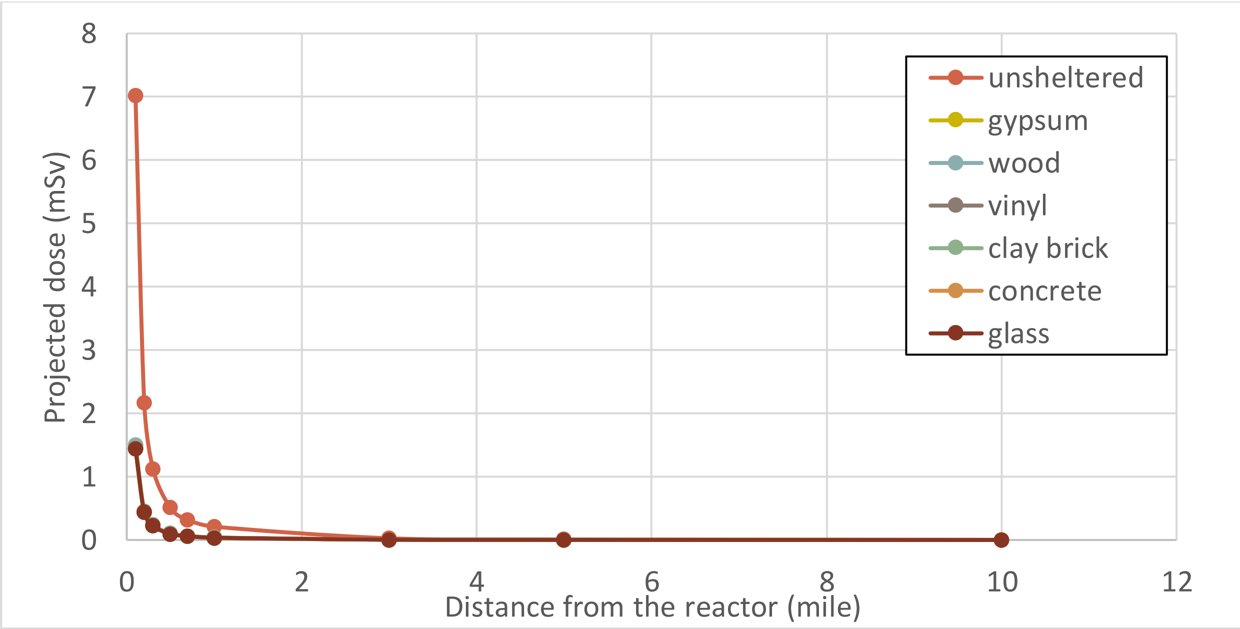

Figure 3.25. Projected Dose for Sheltering on the 1st Floor in 2-Story House (LTSBO)

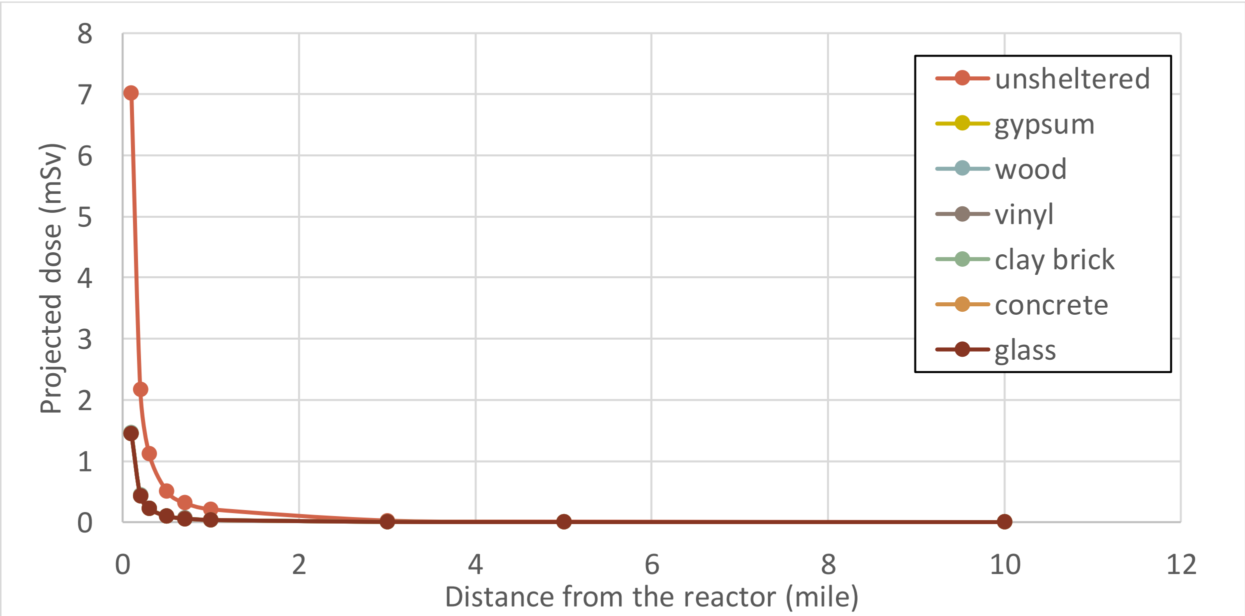

Figure 3.26. Projected Dose for Sheltering on the 2nd Floor in 2-Story House (LTSBO)

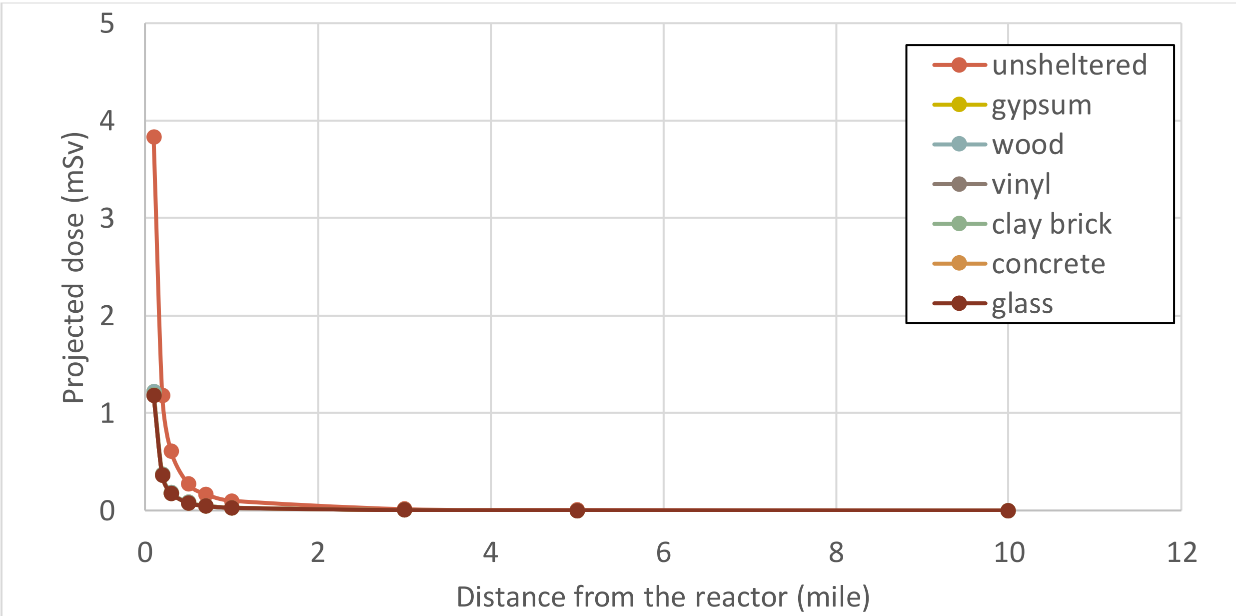

Figure 3.27. Projected Dose for Sheltering in 1-Story House (LOCA)

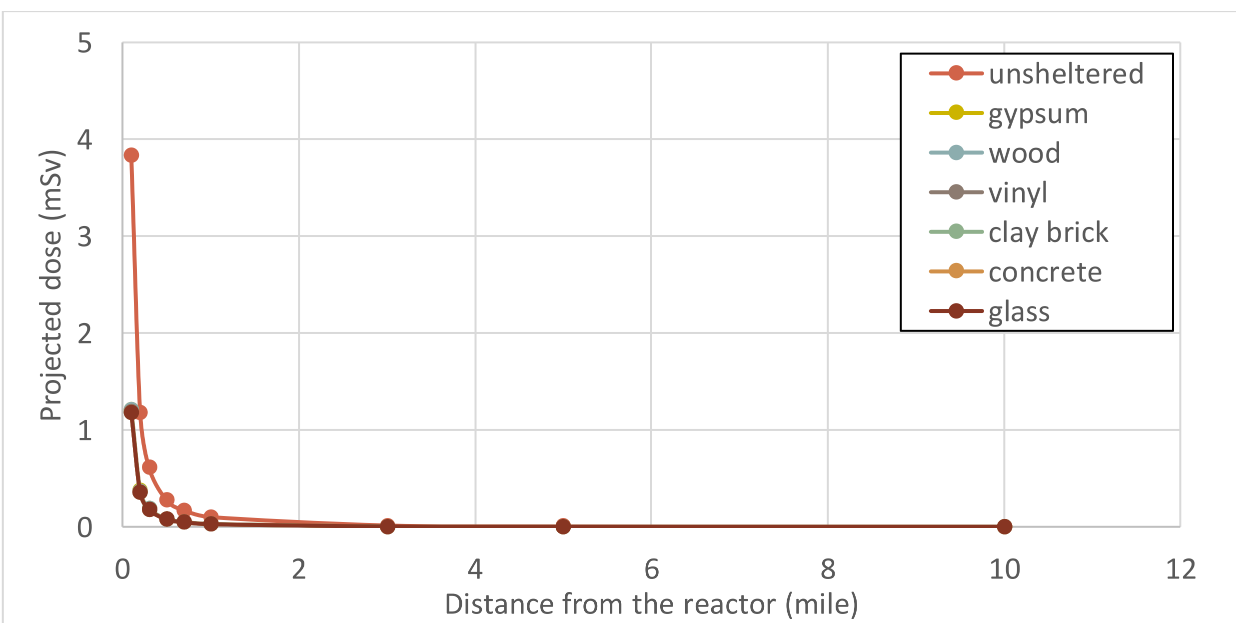

Figure 3.28. Projected Dose for Sheltering on the 1st Floor in 2-Story House (LOCA)

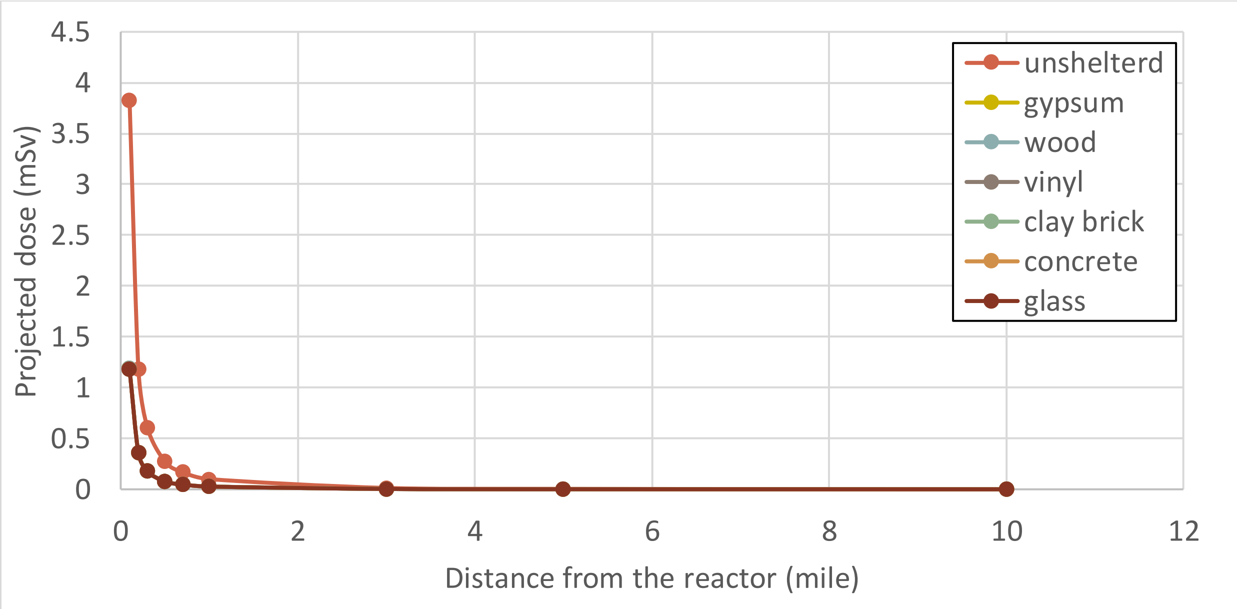

Figure 3.29. Projected Dose for Sheltering on the 2nd Floor in 2-Story House (LOCA)

All the projected doses for sheltered cases become smaller compared to the original doses for unsheltered cases due to the shielding of the houses. All the values were less than 1.5 mSv with any wall material at every location. Since the inhalation dose was the pathway which contributed to the dose the most for sheltered cases and the difference of the effect between outer wall materials were not considered, the projected doses for sheltered cases were almost same with any wall material. The projected doses went down as the distance from the reactor increased.

The short duration of exposure was assumed and so the assumed source term included relatively small radioactivity Therefore, the projected doses for unsheltered cases were rather small even at the very close locations to the reactor. The calculated doses at 10 miles away are in the magnitude of μVs. These values are significantly lower than the PAG standards to initiate protective actions, so there would be no necessity to evacuate or shelter-in-place for people who live there.

CHAPTER 4. CONCLUSIONS AND FUTURE WORK

4.1 Concluding Remarks

The effect of shelter-in-place was studied in case of a hypothetical accident in an SMR. Two potential source terms originating from LTSBO and LOCA were established with RASCAL following the installed PWR accident scenario. The leak rate was 0.10% vol/d in both scenarios, and the rainy weather condition was used. The calculation period since the release started was 4 hours, and during that time the reactor core was not recovered. Then, the atmospheric dispersion of the released radionuclides was calculated with Gaussian plume and puff models. The projected dose within 10 miles radius of the release point was calculated. The output was time-dependent, and the time interval was 15 minutes. The accumulated dose during the calculation period was regarded as the dose for unsheltered cases.

In regard to doses for sheltered cases, a general 1-story and 2-story house was built with MCNP. 6 materials were selected as the candidates of their wall material to study the impact of different material on reduction of projected dose inside the houses. The relationship between the gamma ray energy and deposited energy on the detector located inside the houses was calculated with MCNP simulation. Then by using the ground deposition rate and air concentration of the nuclides which were calculated with RASCAL, groundshine and cloudshine for sheltered cases was obtained. Expected dose with sheltering-in-place dropped to less than 20% of the corresponding dose for unsheltered cases in any location. Inhalation for sheltered cases was calculated by using the mass balance equation with the shelter control volume model. With the assumption that mechanical ventilation system completely shut down the air inflow and only infiltration and exfiltration through the wall could happen, the time change of indoor concentration of radionuclides were calculated. By considering the ratio of that to outdoor concentration as the shielding factors for inhalation the projected inhalation was obtained. The projected dose decreased by more than 60% compared to that for unsheltered cases.

From the results above, the inhalation was dominant pathway in TEDE for unsheltered cases. The inhalation was still the highest dose among the three in case of shelter-in-place and not affected by the different wall materials. Therefore the projected dose was almost same with any wall material. This result meant that staying in a general house with common wall material such as wood would be enough to significantly reduce the projected doses. This result strongly supports the effectiveness of shelter-in-place for reducing the radiological dose in case of an SMR severe accident for short duration of exposure. This study would be a useful basis for calculating the radiological dose for sheltered cases, which will be valuable to have more effective emergency planning for SMR.

4.2 Future Work

In this study, the source term was set with the established PWR accident scenario. The advanced safety features of the Unscaled SMR were not considered. The passive safety system enables the operator to keep cooling the core without any human work, so that the timing to start radioactivity release is expected to be rather delayed. Making use of the source term which is specific to SMRs would lead to more accurate calculation of projected dose. It would be very beneficial to determine the EPZ and emergency planning. Except for I-131, the calculation of air concentration was estimated by using the time change of the released radioactivity. The same dispersion style was assumed for every nuclide. However, the style could change depending on the kind of nuclides, so the other ways to calculate the air concentration may need to be studied.

Concerning the geometry of the house, adding a basement will be an option. Shelter-in-place in a basement would greatly work to make the expected dose very small. In addition, the detector to measure projected dose was located at the center of the room in the house. However, there would be a position dependency of radiological dose inside a room, so analyzing that would be interesting. Dose distribution in the room would be utilized to suggest the best position for sheltering.

In regard to the design of the building, the composite material can be used as the building wall material. It would need to fulfill the design requirement such as heat resistance and structural integration. The single layer wall was assumed as an outer wall and the effect was revealed in this research, so analyzing the effect of multilayer wall on the projected dose would also be important.

When it comes to comparing the effect of protective action, the combination of sheltering and evacuation should be focused. Shelter-in-place doesn't completely stop radiation exposure, so at some point people may have to start evacuation. Such action would be more practical than only evacuation or sheltering. Therefore, calculating the projected dose is also useful for decision-making in case of radiological accident in SMR.

APPENDIX A. GAMMA RAYS ENERGY AND INTENSITY USED FOR SIMULATION

Nuclides	energy (keV)	Intensity (%)
Ba-140	537	24.4
Cs-134	569	15.4
	605	97.6
	796	85.5
Cs-136	177	13.7
	274	12.7
	341	46.8
	819	99.7
	1048	80.0
	1235	20.0
Cs-137	662	85.1
I-131	364	81.5
I-132	523	16.0
	630	13.3
	668	98.7
	773	75.6
	955	17.6
I-133	530	87.0
I-135	1132	22.6
	1260	28.7
Kr-88	196	26.0
	835	13.0
	1530	10.9
	2196	13.2
	2392	34.6
La-140	329	20.3
	487	45.5
	816	23.3
	1596	95.4
Mo-99	740	12.2
Rb-88	898	14.4
	1836	22.8
Te-131m	774	36.8
	794	13.4
	852	19.9
	1125	11.0
Te-132	228	88.0
Xe-133	81	36.9
Xe-135	250	90.0

Data were cited from Nuclear Data Sheets. [24]

APPENDIX B. MCNP INPUT FILE

Geometry without a house

```
= = = = =
c GEOMETRY - CELLS
100 100 -0.001205 -10 imp:p=1 $ detector
200 200 -2.3 -20 imp:p=1 $ foundation made of concrete
300 100 -0.001205 +10 +20 -30 imp:p=1 $ air outside detector
400 0 +30 imp:p=0 $ void

c GEOMETRY - SURFACES
10 s 0 0 100 30 $ sphere-detector
20 rpp -800 800 -800 800 -50 0 $ foundation made of concrete
30 rpp -800 800 -800 800 -50 1600 $ air outside detector
= = = = =
```

Geometry of 1-story house

```
= = = = =
c GEOMETRY - CELLS
100 100 -0.001205 -10 imp:p=1 $ detector in room 1
200 100 -0.001205 +10 -20 imp:p=1 $ room 1
300 100 -0.001205 -30 imp:p=1 $ room 2
400 100 -0.001205 -40 imp:p=1 $ room 3
500 100 -0.001205 -50 imp:p=1 $ room 4
600 200 -0.65 -60 imp:p=1 $ wall between room 1,2
700 200 -0.65 -70 imp:p=1 $ wall from between room 1,3 to between room 2,4
800 200 -0.65 -80 imp:p=1 $ wall between room 3,4
900 200 -0.65 -90 imp:p=1 $ wall between floor 1 and roof
1000 500 -2.6 -100 imp:p=1 $ glass window 1 on room 1
1100 500 -2.6 -120 imp:p=1 $ glass window 2 on room 1
1200 500 -2.6 -140 imp:p=1 $ glass window 1 on room 2
1300 500 -2.6 -160 imp:p=1 $ glass window 2 on room 2
1400 500 -2.6 -180 imp:p=1 $ glass window 1 on room 3
1500 500 -2.6 -200 imp:p=1 $ glass window 2 on room 3
1600 500 -2.6 -220 imp:p=1 $ glass window 1 on room 4
1700 500 -2.6 -240 imp:p=1 $ glass window 2 on room 4
1800 100 -0.001205 +100 -110 imp:p=1 $ air around the glass window 1 on room 1
1900 100 -0.001205 +120 -130 imp:p=1 $ air around the glass window 2 on room 1
2000 100 -0.001205 +140 -150 imp:p=1 $ air around the glass window 1 on room 2
2100 100 -0.001205 +160 -170 imp:p=1 $ air around the glass window 2 on room 2
2200 100 -0.001205 +180 -190 imp:p=1 $ air around the glass window 1 on room 3
2300 100 -0.001205 +200 -210 imp:p=1 $ air around the glass window 2 on room 3
2400 100 -0.001205 +220 -230 imp:p=1 $ air around the glass window 1 on room 4
2500 100 -0.001205 +240 -250 imp:p=1 $ air around the glass window 2 on room 4
2600 100 -0.001205 -260 imp:p=1 $ air inside roof 1
```

2700 100 -0.001205 -270 imp:p=1 $ air inside roof 2
2800 600 -1.1 +260 -280 imp:p=1 $ roof 1
2900 600 -1.1 +270 -290 imp:p=1 $ roof 2
3000 300 -2.6 +110 +130 +150 +170 +190 +210 +230 +250 +300 -310 imp:p=1 $ wall outside the rooms
3100 400 -2.3 -320 imp:p=1 $ foundation made of concrete
3200 100 -0.001205 +280 +290 +310 +320 +330 -340 imp:p=1 $ air outside wall
3300 0 +340 imp:p=0 $ void

c GEOMETRY - SURFACES
10 s -210 210 100 30 $ sphere-detector
20 rpp -410 -10   10 410 0 300 $ room 1
30 rpp   10 410   10 410 0 300 $ room 2
40 rpp -410 -10 -410 -10 0 300 $ room 3
50 rpp   10 410 -410 -10 0 300 $ room 4
60 rpp -10 10   10 410 0 300 $ wall between room 1,2
70 rpp -410 410 -10 10 0 300 $ wall from between room 1,3 to between room 2,4
80 rpp -10 10 -410 -10 0 300 $ wall between room 3,4
90 rpp -410 410 -410 410 300 320 $ wall between 1st floor and roof
100 rpp -310 -110 419 421 100 200 $ glass window 1 on room 1
110 rpp -310 -110 410 430 100 200 $ air around the glass window 1 on room 1
120 rpp -421 -419 110 310 100 200 $ glass window 2 on room 1
130 rpp -430 -410 110 310 100 200 $ air around the glass window 2 on room 1
140 rpp 110 310 419 421 100 200 $ glass window 1 on room 2
150 rpp 110 310 410 430 100 200 $ air around the glass window 1 on room 2
160 rpp 419 421 110 310 100 200 $ glass window 2 on room 2
170 rpp 410 430 110 310 100 200 $ air around the glass window 2 on room 2
180 rpp -310 -110 -421 -419 100 200 $ glass window 1 on room 3
190 rpp -310 -110 -430 -410 100 200 $ air around the glass window 1 on room 3
200 rpp -421 -419 -310 -110 100 200 $ glass window 2 on room 3
210 rpp -430 -410 -310 -110 100 200 $ air around the glass window 2 on room 3
220 rpp 110 310 -421 -419 100 200 $ glass window 1 on room 4
230 rpp 110 310 -430 -410 100 200 $ air around the glass window 1 on room 4
240 rpp 419 421 -310 -110 100 200 $ glass window 2 on room 4
250 rpp 410 430 -310 -110 100 200 $ air around the glass window 2 on room 4
260 wed 0 -410 320 -410 0 0 0 0 137 0 820 0 $ inside roof 1
270 wed 0 -410 320 410 0 0 0 0 137 0 820 0 $ inside roof 2
280 wed 0 -480 320 -480 0 0 0 0 160 0 960 0 $ roof 1
290 wed 0 -480 320 480 0 0 0 0 160 0 960 0 $ roof 2
300 rpp -410 410 -410 410 0 320 $ temporary house
310 rpp -430 430 -430 430 0 320 $ outside wall
320 rpp -800 800 -800 800 -50 0 $ foundation made of concrete
330 rpp -800 800 -800 800 -50 1600 $ outside wall
= = = = =

Geometry of 2-story house

```
= = = = =
c GEOMETRY - CELLS
100 100 -0.001205 -10 imp:p=1 $ detector in room 1
200 100 -0.001205 +10 -20 imp:p=1 $ room 1
300 100 -0.001205 -30 imp:p=1 $ room 2
400 100 -0.001205 -40 imp:p=1 $ room 3
500 100 -0.001205 -50 imp:p=1 $ room 4
600 200 -0.65 -60 imp:p=1 $ wall between room 1,2
700 200 -0.65 -70 imp:p=1 $ wall from between room 1,3 to between room 2,4
800 200 -0.65 -80 imp:p=1 $ wall between room 3,4
900 200 -0.65 -90 imp:p=1 $ wall between 1st floor and 2nd floor
1000 500 -2.6 -100 imp:p=1 $ glass window 1 on room 1
1100 500 -2.6 -120 imp:p=1 $ glass window 2 on room 1
1200 500 -2.6 -140 imp:p=1 $ glass window 1 on room 2
1300 500 -2.6 -160 imp:p=1 $ glass window 2 on room 2
1400 500 -2.6 -180 imp:p=1 $ glass window 1 on room 3
1500 500 -2.6 -200 imp:p=1 $ glass window 2 on room 3
1600 500 -2.6 -220 imp:p=1 $ glass window 1 on room 4
1700 500 -2.6 -240 imp:p=1 $ glass window 2 on room 4
1800 100 -0.001205 +100 -110 imp:p=1 $ air around the glass window 1 on room 1
1900 100 -0.001205 +120 -130 imp:p=1 $ air around the glass window 2 on room 1
2000 100 -0.001205 +140 -150 imp:p=1 $ air around the glass window 1 on room 2
2100 100 -0.001205 +160 -170 imp:p=1 $ air around the glass window 2 on room 2
2200 100 -0.001205 +180 -190 imp:p=1 $ air around the glass window 1 on room 3
2300 100 -0.001205 +200 -210 imp:p=1 $ air around the glass window 2 on room 3
2400 100 -0.001205 +220 -230 imp:p=1 $ air around the glass window 1 on room 4
2500 100 -0.001205 +240 -250 imp:p=1 $ air around the glass window 2 on room 4
2600 100 -0.001205 -260 imp:p=1 $ room 5
2700 100 -0.001205 -270 imp:p=1 $ room 6
2800 100 -0.001205 -280 imp:p=1 $ room 7
2900 100 -0.001205 -290 imp:p=1 $ room 8
3000 200 -0.65 -300 imp:p=1 $ wall between room 5,6
3100 200 -0.65 -310 imp:p=1 $ wall from between room 5,7 to between room 6,8
3200 200 -0.65 -320 imp:p=1 $ wall between room 7,8
3300 200 -0.65 -330 imp:p=1 $ wall between floor 2 and roof
3400 500 -2.6 -340 imp:p=1 $ glass window 1 on room 5
3500 500 -2.6 -360 imp:p=1 $ glass window 2 on room 5
3600 500 -2.6 -380 imp:p=1 $ glass window 1 on room 6
3700 500 -2.6 -400 imp:p=1 $ glass window 2 on room 6
3800 500 -2.6 -420 imp:p=1 $ glass window 1 on room 7
3900 500 -2.6 -440 imp:p=1 $ glass window 2 on room 7
4000 500 -2.6 -460 imp:p=1 $ glass window 1 on room 8
4100 500 -2.6 -480 imp:p=1 $ glass window 2 on room 8
4200 100 -0.001205 +340 -350 imp:p=1 $ air around the glass window 1 on room 5
4300 100 -0.001205 +360 -370 imp:p=1 $ air around the glass window 2 on room 5
4400 100 -0.001205 +380 -390 imp:p=1 $ air around the glass window 1 on room 6
```

```
4500 100 -0.001205 +400 -410 imp:p=1 $ air around the glass window 2 on room 6
4600 100 -0.001205 +420 -430 imp:p=1 $ air around the glass window 1 on room 7
4700 100 -0.001205 +440 -450 imp:p=1 $ air around the glass window 2 on room 7
4800 100 -0.001205 +460 -470 imp:p=1 $ air around the glass window 1 on room 8
4900 100 -0.001205 +480 -490 imp:p=1 $ air around the glass window 2 on room 8
5000 100 -0.001205 -500 imp:p=1 $ air inside roof 1
5100 100 -0.001205 -510 imp:p=1 $ air inside roof 2
5200 600 -1.1 +500 -520 imp:p=1 $ roof 1
5300 600 -1.1 +510 -530 imp:p=1 $ roof 2
5400 300 -0.65 +110 +130 +150 +170 +190 +210 +230 +250 +350 +370 +390 +410 +430 +450
+470 +490 +540 -550 imp:p=1 $ wall outside the rooms
5500 400 -2.3 -560 imp:p=1 $ foundation made of concrete
5600 100 -0.001205 +520 +530 +550 +560 -570 imp:p=1 $ air outside wall
5700 0 +570 imp:p=0 $ void

c GEOMETRY - SURFACES
10 s -210 210 100 30 $ sphere-detector
20 rpp -410 -10   10 410 0 300 $ room 1
30 rpp   10 410   10 410 0 300 $ room 2
40 rpp -410 -10 -410 -10 0 300 $ room 3
50 rpp   10 410 -410 -10 0 300 $ room 4
60 rpp  -10  10   10 410 0 300 $ wall between room 1,2
70 rpp -410 410  -10  10 0 300 $ wall from between room 1,3 to between room 2,4
80 rpp  -10  10 -410 -10 0 300 $ wall between room 3,4
90 rpp -410 410 -410 410 300 320 $ wall between 1st floor and 2nd floor
100 rpp -310 -110 419 421 100 200 $ glass window 1 on room 1
110 rpp -310 -110 410 430 100 200 $ air around the glass window 1 on room 1
120 rpp -421 -419 110 310 100 200 $ glass window 2 on room 1
130 rpp -430 -410 110 310 100 200 $ air around the glass window 2 on room 1
140 rpp  110  310 419 421 100 200 $ glass window 1 on room 2
150 rpp  110  310 410 430 100 200 $ air around the glass window 1 on room 2
160 rpp  419  421 110 310 100 200 $ glass window 2 on room 2
170 rpp  410  430 110 310 100 200 $ air around the glass window 2 on room 2
180 rpp -310 -110 -421 -419 100 200 $ glass window 1 on room 3
190 rpp -310 -110 -430 -410 100 200 $ air around the glass window 1 on room 3
200 rpp -421 -419 -310 -110 100 200 $ glass window 2 on room 3
210 rpp -430 -410 -310 -110 100 200 $ air around the glass window 2 on room 3
220 rpp  110 310 -421 -419 100 200 $ glass window 1 on room 4
230 rpp  110 310 -430 -410 100 200 $ air around the glass window 1 on room 4
240 rpp  419 421 -310 -110 100 200 $ glass window 2 on room 4
250 rpp  410 430 -310 -110 100 200 $ air around the glass window 2 on room 4
260 rpp -410 -10   10 410 320 620 $ room 5
270 rpp   10 410   10 410 320 620 $ room 6
280 rpp -410 -10 -410 -10 320 620 $ room 7
290 rpp   10 410 -410 -10 320 620 $ room 8
300 rpp  -10  10   10 410 320 620 $ wall between room 5,6
```

```
310 rpp -410 410  -10  10 320 620 $ wall from between room 5,7 to between room 6,8
320 rpp  -10  10 -410 -10 320 620 $ wall between room 7,8
330 rpp -410 410 -410 410 620 640 $ wall between 2nd floor and roof
340 rpp -310 -110 419 421 420 520 $ glass window 1 on room 5
350 rpp -310 -110 410 430 420 520 $ air around the glass window 1 on room 5
360 rpp -421 -419 110 310 420 520 $ glass window 2 on room 5
370 rpp -430 -410 110 310 420 520 $ air around the glass window 2 on room 5
380 rpp  110  310 419 421 420 520 $ glass window 1 on room 6
390 rpp  110  310 410 430 420 520 $ air around the glass window 1 on room 6
400 rpp  419  421 110 310 420 520 $ glass window 2 on room 6
410 rpp  410  430 110 310 420 520 $ air around the glass window 2 on room 6
420 rpp -310 -110 -421 -419 420 520 $ glass window 1 on room 7
430 rpp -310 -110 -430 -410 420 520 $ air around the glass window 1 on room 7
440 rpp -421 -419 -310 -110 420 520 $ glass window 2 on room 7
450 rpp -430 -410 -310 -110 420 520 $ air around the glass window 2 on room 7
460 rpp  110 310 -421 -419 420 520 $ glass window 1 on room 8
470 rpp  110 310 -430 -410 420 520 $ air around the glass window 1 on room 8
480 rpp  419 421 -310 -110 420 520 $ glass window 2 on room 8
490 rpp  410 430 -310 -110 420 520 $ air around the glass window 2 on room 8
500 wed 0 -410 640 -410 0 0 0 0 137 0 820 0 $ inside roof 1
510 wed 0 -410 640 410 0 0 0 0 137 0 820 0 $ inside roof 2
520 wed 0 -480 640 -480 0 0 0 0 160 0 960 0 $ roof 1
530 wed 0 -480 640 480 0 0 0 0 160 0 960 0 $ roof 2
540 rpp -410 410 -410 410 0 640 $ temporary house
550 rpp -430 430 -430 430 0 640 $ outside wall
560 rpp -800 800 -800 800 -50 0 $ foundation made of concrete
570 rpp -800 800 -800 800 -50 1600 $ outside wall
= = = = =
```

Groundshine for unsheltered cases

```
= = = = =
c OTHER STUFF
mode p
nps 10000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=1
        cell=300
        par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 0.1 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
```

```
f6:p 100 $ Tally
= = = = =
```

Groundshine in 1-story house (radionuclides are distributed on the ground)

```
= = = = =
mode p
nps 5000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=0.774
        cell=3300
        par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 0.1 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $ Tally
= = = = =
```

Grounshine in 1-story house (radionuclides are distributed on the roof)

```
= = = = =
c OTHER STUFF
mode p
nps 10000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=0.452
        cell=3300
        eff=0.001
        par=p $ uniformly distributed source
si1 -480 0 $ x range
sp1 0 1 $Uniform distribution over x
si2 -480 480 $ y range
sp2 0 1 $ Uniform distribution over y
si3 320 480 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $ Tally
= = = = =
```

Groundshine in 2-story house (radionuclides are distributed on the ground)

```
= = = = =
c OTHER STUFF
```

```
mode p
nps 40000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=0.177
        cell=5600
        par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 0.1 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $ Tally
= = = = =
```

Grounshine in 2-story house (radionuclides are distributed on the roof)

```
= = = = =
c OTHER STUFF
mode p
nps 10000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=0.774
        cell=5500
        EFF=0.001
        par=p $ uniformly distributed source
si1 -480 0 $ x range
sp1 0 1 $Uniform distribution over x
si2 -480 480 $ y range
sp2 0 1 $ Uniform distribution over y
si3 640 800 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $ Tally
= = = = =
```

Cloudshine for unsheltered cases

```
= = = = =
mode p
nps 50000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
        erg=0.0283
        cell=300
```

```
      par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 1600 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $ Tally
= = = = =
```

Cloudshine in 1-story house

```
= = = = =
c OTHER STUFF
mode p
nps 5000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
      erg=0.081
    cell=3200
      par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 1600 $ z range
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $
= = = = =
```

Cloudshine in 2-story house

```
= = = = =
c OTHER STUFF
mode p
nps 10000000 $ number of source gammas
c SOURCE
sdef x d1 y d2 z d3
      erg=0.196
      cell=5600
      par=p $ uniformly distributed source
si1 -800 800 $ x range
sp1 0 1 $Uniform distribution over x
si2 -800 800 $ y range
sp2 0 1 $ Uniform distribution over y
si3 0 1600 $ z range
```

```
sp3 0 1 $Uniform distribution over z
c POINT DETECTOR
f6:p 100 $
= = = = =
```

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