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Title: Transforming Protective Action Strategies for Radiological Emergencies—Exacting the Science of Sheltering-in-Place.

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Steven R. Reese

Radiological emergency plans ensure that protective actions can and will be taken in the event of an accident. Principle protective actions for the early phase of an emergency are evacuation and sheltering-in-place. While evacuations are generally safe, there are deterministic, long-term health consequences from prolonged displacement that outweigh the stochastic radiological health risk. Implementation strategies require balancing the risk to ensure protective actions do more good than harm. In many cases, sheltering-in-place provides a viable alternative to evacuation, yet guidance and tools are lacking to aid decision-makers on the best choice of action during an emergency. Therefore, a method is proposed to exact the science of sheltering-in-place. A model to predict the radiological protection afforded by a typical residential shelter was developed and incorporated into a tool to examine the sensitivity of parameters important to shelter effectiveness. The resultant analysis tool—named PARatus for the Latin word for “prepared”— provides valuable insights into the parameters important to effective sheltering. Transformation is possible, but science and innovation are not enough. A cultural change is needed within the radiation protection community to embrace the future. Then, the process of deliberation can be used to better risk-inform protective action strategies for radiological emergencies.

Transforming Protective Action Strategies for Radiological Emergencies—
Exacting the Science of Sheltering-in-Place

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Todd Ryan Smith, Author

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DEDICATION

To my wife and children. I owe you back for the time.

To everyone else, may you find this work useful and may you never have to use it.

Chapter 1 – Introduction

Radiological emergency preparedness has reached a tipping point. As described by Malcolm Gladwell, author of *The Tipping Point*, the tipping point is about change. And this change is like an epidemic—things happen all at once, and little changes can make a huge difference. The tipping point is about how ideas are spread. A long-standing idea used in radiation protection is the linear hypothesis for low-level radiation exposure. The linear no-threshold (LNT) hypothesis was widely used in risk assessments that formed the bases for protective actions. But within the radiation protection community, a tipping point has been reached, and for many the LNT hypothesis is no longer seen as supported by the available scientific evidence. In addition, responses to real-world events have provided a new understanding of the actual risk of protective actions—risks that outweigh the hypothetical risk from radiation. Even the guiding philosophy of the Precautionary Principle is being questioned (Neidell, 2019). These ideas are quickly spreading and change is coming to the fundamental philosophy, science, and practice of radiological emergency preparedness and response. But once past the tipping point, things start rolling downhill. The question is, *in which direction should we go? Do we need big changes, or are there small changes that can have a big impact?*

The answer to these questions starts with what we already know. While radiation is a unique hazard, it is not special. Radiological emergencies do not require extraordinary measures in emergency planning above the planning and resources needed for other types of hazards (NRC, 1978). Protective action strategies in place to respond to a radiological emergency include the commonplace actions of evacuation and sheltering-in-place. Radiological protective action strategies are intended to balance the risk of the hazard against the risk of the protective action itself to ensure adequate protection of public health and safety. But preparing for the worst-case or overreacting to an actual radiological emergency will upset this balance, resulting in actions that are likely to do more harm than good. To prevent this from happening, a deliberative approach is needed for the changes that are occurring within the radiation protection community.

This thesis proposes that expanded use of sheltering-in-place in response to a radiological release will help balance protective action strategies to ensure that protective actions do more good than harm. This idea will be supported by evidence that current practice will likely result in an overreaction in terms of the number of people evacuated in response to a radiological event. It will then be demonstrated that the basis for the risk/cost/benefit trade-off for choosing between evacuation or shelter-in-place is unbalanced. To address this imbalance, a more exact science is needed. A radiological protection model will be developed to demonstrate the effectiveness of sheltering-in-place and the need for addressing the current gaps in knowledge. It will be shown that a small change in implementing sheltering-in-place over evacuation could make a huge difference for public health and safety. But how can this theory translate into practice? This will be addressed, in part, by an examination of the cultural changes that need to take place within the radiological emergency preparedness community. It will be argued that the prudent philosophical approach to risk communication should be to move away from unsupported messages of “no safe dose” and to freely share knowledge of the risks with decision-makers and the public to better inform decisions to act. As a whole, this thesis is a critical examination of the past *practice*, *science*, and *philosophy* and a roadmap for transforming the future. A change in direction for protective action strategies in support of radiological emergency preparedness for both new and existing reactor technologies is proposed—a change that seeks to tip the balance in the direction needed to ensure protective actions will do more good than harm.

1.1 A Brief Overview of Radiological Emergency Preparedness

The objective of radiological emergency preparedness is to ensure that adequate protective actions can and will be taken in the event of an emergency at a nuclear power plant (NPP). After the accident at Three Mile Island (TMI), it became clear that more robust emergency planning was needed to ensure protective measures could be implemented to protect the public health and safety. As a result, the NRC added emergency preparedness (EP) as the final layer of a robust defense-in-depth strategy and published regulatory standards for emergency planning at commercial nuclear power plants in 10 *Code of Federal Regulation*s 50.47 “Emergency Plans”. The planning basis for EP, developed by a joint U.S. Nuclear Regulatory Commission (NRC) and Environmental Protection Agency (EPA) Task Force in 1978, is documented in NUREG-0396, “Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants” (NRC 1978). The recommendation of the joint Task Force was that planning should be based on knowledge of the potential consequences, timing, and release characteristics of a spectrum of accidents. Additionally, the Task Force introduced the concept of emergency planning zones (EPZs), which are areas within which planning is needed to ensure that prompt and effective actions can be taken to protect the public in the event of an accident (NRC 1978).

EPZs are planning mechanisms to ensure that appropriate protective actions can be implemented in a timely manner in the event of an actual emergency. Two emergency planning zones exist around each nuclear power plant. A plume exposure pathway EPZ, which is an area about 10 miles in radius around a site, and an ingestion pathway EPZ which extends about 50 miles in radius around a site. The primary pathway of concern within the plume exposure pathway EPZ is exposure to and inhalation of airborne radioactive contamination. The primary concern in the ingestion pathway EPZ is the ingestion of contaminated food and water.

Within the plume exposure EPZ, prompt protective actions may be necessary to reduce the risk to the public in the event of a significant radiological release. The size of the plume exposure EPZ is based primarily on the following considerations (NRC, 1980; NRC, 2019):

- *Projected doses from the traditional design basis accidents would not exceed Federal Protective Action Guide (PAG) levels outside the zone.*
- *Projected doses from most core melt sequences would not exceed Federal PAG levels outside the zone.*

- *For the worst-case core-melt sequences, immediate life-threatening doses would generally not occur outside the zone.*
- *Detailed planning within the zone would provide a substantial base for expansion of response efforts in the event that this proves necessary.*

Extensive provisions are made for action within the plume exposure pathway EPZ. These include provisions for prompt decision-making regarding protective actions for the public and implementation of evacuation plans. The EPZ is sufficiently large to provide for substantial reduction in early health effects associated with radiological exposure in the event of a worst-case core melt accident. Additionally, the detailed planning for the plume exposure pathway EPZ provides a basis for *ad hoc* response beyond the EPZ boundary.

The response to an event at a nuclear power plant begins with the emergency classification. Emergency classifications indicate both the degree of departure from safe operations and the potential for a radiological release. Nuclear power plants use the four emergency classifications listed below in order of increasing severity (NRC, 1978; NRC 2019):

> ***Notification of Unusual Event –*** *Events are in process or have occurred which indicate potential degradation in the level of safety of the plant. No release of radioactive material requiring offsite response or monitoring is expected unless further degradation occurs.*
>
> ***Alert –*** *Events are in process or have occurred that involve an actual or potential substantial degradation in the level of safety of the plant. Any releases of radioactive material from the plant are expected to be limited to a small fraction of the Environmental Protection Agency (EPA) PAGs.*
>
> ***Site Area Emergency (SAE) –*** *Events are in process or have occurred that result in actual or likely major failures of plant functions needed for protection of the public. Any releases of radioactive material are not expected to exceed the EPA PAGs except near the site boundary.*
>
> ***General Emergency (GE) –*** *Events involve actual or imminent substantial core damage or melting of reactor fuel with the potential for loss of containment integrity. Radioactive releases can reasonably be expected to exceed the EPA PAGs for more than the immediate site area.*

The ultimate purpose of recognizing an emergency condition is to ensure that appropriate protective actions are taken both onsite and offsite (Elkmann, 2017). To accomplish this, licensees are required to make a protective action recommendation (PAR) to offsite response organizations. The cognizant offsite authority will then make a protective action decision (PAD) and inform the public of the need to act. Both the PAR and the PAD are driven by protective action guides (PAGs). A PAG is the projected dose to an individual from a release of radioactive material at which a specific protective action to reduce or avoid that dose is recommended (EPA, 2017a).

Reasonable assurance of adequate protection of the public health and safety is maintained by demonstrating that plans for coping with emergencies are adequate and that they can be implemented. NPP licensees are required to demonstrate the capability for implementing emergency plans by conducting an emergency preparedness (EP) exercise every two years. Likewise, offsite radiological emergency response plans are required to be exercised every two years with participation by each offsite authority having a role under the plans. These biennial exercises provide opportunity to demonstrate proficiency in the key skills necessary to implement principal functional areas of emergency response including protective action recommendation development and protective action decision-making. The NRC evaluates the licensee performance, and the Federal Emergency Management Agency (FEMA) evaluates the performance of the offsite response organizations and documents evaluation of the exercise in an after action report (AAR) provided to the NRC. The NRC is charged with the authority to ensure that overall reasonable assurance is maintained.

1.2 Protective Action Strategies

Protective actions considered for a radiological emergency include evacuation, sheltering, and, as a supplement to these, the prophylactic use of potassium iodide (KI), as appropriate. Under most conditions, evacuation may be the preferred action to prevent further exposure to radioactive material. But an evacuation does not always call for the complete removal of the entire population within the 10-mile plume exposure EPZ. In most cases, an atmospheric radioactive release would move with the wind and the resulting plume would not cover the entire EPZ. The release also expands and becomes less concentrated as it travels away from a plant. Therefore, evacuations can be planned to anticipate the path of the release. In the event of a General Emergency, as a default protective action, a 2-mile ring around the plant is evacuated, along with people living in the 5-mile zone directly downwind and just to either side of the projected path of the release. This "keyhole" pattern (shown in Figure 1-1) helps account for potential wind shifts and fluctuations in the release path (NRC, 2020a). The initial evacuation may also be performed in a staged manner by evacuating the 2-5 mile zones after evacuation of the 2-mile zone. The need for expanded evacuations is assessed as the accident progresses. An EPZ is typically subdivided into Protective Action Zones (PAZ) or Emergency Response Planning Areas (ERPAs) to facilitate evacuation planning and response actions. In an emergency, residents within affected zones would be advised to take specific protective actions of evacuation or sheltering-in-place. Other people living in the remainder of the EPZ may be advised to go inside, stay inside, and tune-in. Precautionary protective actions may have been issued prior to the declaration of a General Emergency and may include early dismissal of schools, evacuation of special populations, closing of public areas, and placing livestock on stored food and water (NRC, 2020a).

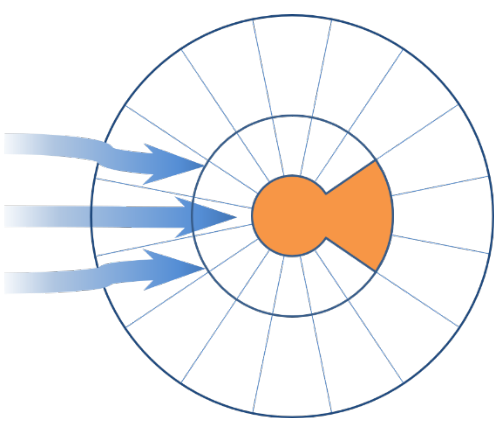

Figure 1-1 Example keyhole evacuation

Under some conditions, people may be instructed to take shelter in their homes, schools, or office buildings. Sheltering may be more appropriate than evacuation when the release of radioactive material is known to be short-term or controlled by the nuclear power plant operator. A supplemental protective action in the plume exposure EPZ involves taking potassium iodide (KI), a compound that helps prevent the thyroid from absorbing radioactive iodine. If taken properly, KI blocks the radioactive iodine from being absorbed by the thyroid gland and reduces the risk of thyroid cancer. Potassium iodide does not protect against any other inhaled radioactive materials, nor will it offer protection from external exposure to radiation.

1.3 Protective Action Guides

The PAGs promulgated by the EPA are a tool for balancing the radiological risk against the physical risk of taking the protective action. The EPA and Food and Drug Administration (FDA) have established PAGs that are applicable to severe reactor accidents. Emergency management officials use PAGs for making decisions regarding actions to protect the public from exposure to radiation during an emergency. Such actions include, but are not limited to, evacuation, shelter-in-place, temporary relocation, and food restrictions. Development of the PAGs was based on the following principles, which also apply to the selection of any protective action during an emergency:

- *Prevent acute effects*
- *Reduce risk of chronic effects*
- *Balance protection and ensure that actions result in more benefit than harm*

The PAGs are designed to prevent adverse health effects by triggering public safety measures—protective actions, such as evacuation—and minimizing unnecessary exposures. PAGs are set at a level where the health risk from radiation exposure that could be avoided with protective action outweighs the risk associated with taking the safety measures: e.g., traffic accidents, trips and falls, or anxiety associated with dislocation or the separation of family members.

The effectiveness of a protective action is related to the timing of the action in relation to the timing of the radiological release. The EPA established PAGs for early phase protective actions low enough to meet the objective of reducing dose. It is important to emphasize that PAGs and EPZs are implemented as guidance tools and planning mechanisms, respectively. EPA intends that the PAGs be used as guidance for triggering appropriate protective actions in order to protect public health and safety and to minimize exposures to the general public and emergency workers; PAGs do not represent limits between safe and unsafe dose. PAGs are based on projected doses that can be avoided by the specific protection action being considered. Doses incurred prior to initiation of the protective action are not considered. Similarly, in considering early protective actions such as evacuation or sheltering, doses that could be avoided by an intermediate or long term protective action, such as control of contaminated food and water, are excluded.

1.4 Protective Action Recommendations and Decisions

The NRC guidance for developing protective action strategies is contained in Supplement 3, "Guidance for Protective Action Strategies," to NUREG-0654/FEMA-REP-1, Revision 1, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants" (NRC, 2011a). This guidance is based on a study known as "the PAR study" (NRC, 2007). The PAR study provided a technical basis for enhancing protective action strategies including the use of staged evacuation and actions for rapidly progressing scenarios. Some key results from the PAR study for enhancing protective action strategies include:

- *Radial evacuation should remain the major element of protective action strategies. Evacuations are effective in protecting public health and safety, and the public is seldom injured during evacuation.*
- *Sheltering in place (SIP) should receive more emphasis in protective action strategies. SIP is more protective than radial evacuation under rapidly progressing severe accidents at sites with long evacuation times.*

- *Precautionary actions, such as evacuating schools and parks during a Site Area Emergency, can be prudent.*
- *Strategies that reduce evacuation time also reduce public health consequences. Staged evacuation can reduce evacuation times by allowing the early movement of some people while traffic and access control points are being set up to further direct road use. Staged evacuation is most beneficial if shadow evacuation is minimized.*

The PAR guidance provides a protective action logic development tool intended for use by nuclear power reactor licensees to develop site-specific PAR procedures. Offsite response organizations can use Supplement 3 to develop protective action strategy guidance for decision-makers. Although a General Emergency is a serious event that warrants protective action, it is not necessarily synonymous with a severe accident. The PAR guidance recognizes the disparity between a severe accident with an early release and other General Emergency conditions and so provides scenario-specific protective action decision guidance. Additionally, guidance is provided for determining when the immediate evacuation of those closest to the nuclear plant is necessary and criteria for the expansion of initial protective actions. This guidance is intended to simplify initial protective action decision-making and implementation and to allow additional time for evacuation management if the expansion of evacuated areas is necessary (NRC, 2011a).

NPP licensees are responsible for making timely PARs in accordance with regulations, Federal guidance, and plant conditions and for providing the PARs to offsite response organizations (OROs) to allow them to make timely and well-informed protective action decisions. The PAR must be made rapidly, in accordance with approved procedures. Licensees develop these procedures in partnership with the ORO(s) responsible for protective action decision-making. OROs are responsible for deciding which protective actions to implement. As demonstrated in biennial evaluated exercises, NPP emergency response organizations (EROs) typically include a PAR with the General Emergency notification. Although there is no explicit regulatory requirement on the time allowed to determine a protection action recommendation, the NRC and FEMA have historically communicated an expectation that decisions are completed within about 15 minutes of the onset of conditions requiring a PAR (Elkmann, 2017). After a General Emergency declaration has been made, a 15-minute notification requirement remains in effect to ensure timely notifications are made to OROs.

Emergency response personnel perform radiological assessments throughout the emergency and recommendations are made to OROs on the need to take or expand protective actions if dose projections show that protective action criteria could be exceeded. Dose projections that are based on effluent monitor data and verified by field monitoring data would provide the strongest basis for a PAR; however, effluent monitor data alone can be sufficient if other data (e.g., plant conditions, area or process monitors) verify the occurrence of a radiological release.

1.5 Risk of Evacuation and Relocation

In the event of a radiological release from a nuclear power plant, evacuation has long been considered the key protective action to reduce the dose to the population living in the surrounding area. In theory, evacuation is a good response as it helps prevent additional radiological exposure to the public. However, evacuation, and prolonged relocation, have longer term consequences that can be more harmful than the radiation exposure.

The accident at the Fukushima Daiichi nuclear plant, initiated by the March 11, 2011, Great East Japan Earthquake and tsunami, ultimately resulted in widespread evacuations of the local population. Over 100,000 people were evacuated as a result of the accident (UNSCEAR, 2014; WNA, 2021). A chronology of evacuation and shelter-in-place orders following the accident show that protective measures, including compulsory evacuations, were carried out in a staged manner over the course of several days (NAS, 2016). These measures were taken based on radiation safety considerations and the massive damage to the infrastructure and facilities following the earthquake and tsunami.

The World Health Organization has reported on the public health consequences related to the response actions to the disaster (WHO, 2016).

Protective measures resulted in a wide range of social, economic, and public health consequences. A sharp increase in mortality among elderly people who were put in temporary housings has been reported, along with increased risk of non-communicable diseases, such as diabetes and mental health problems. The lack of access to health care further contributed to deterioration of health. According to the WHO (WHO, 2016):

> *There were public health consequences related to the response actions to the disaster, such as evacuation and relocation of people. These measures were taken based on radiation safety considerations and the massive damage to the infrastructure and facilities following the earthquake and tsunami. These measures resulted in a wide range of social, economic, and public health consequences. A sharp increase in mortality among elderly people who were put in temporary housings has been reported, along with increased risk of non-communicable diseases, such as diabetes and mental health problems. The lack of access to health care further contributed to deterioration of health.*
>
> *Similar to what was observed and reported for the Chernobyl population, the displaced Fukushima population is suffering from psycho-social and mental health impact following relocation, ruptured social links of people who lost homes and employment, disconnected family ties and stigmatization. A higher occurrence of post-traumatic stress disorder (PTSD) among the evacuees was assessed as compared to the general population of Japan. Psychological problems, such as hyperactivity, emotional symptoms, and conduct disorders have been also reported among evacuated Fukushima children. While no significant adverse outcomes were observed in the pregnancy and birth survey after the disaster, a higher prevalence of postpartum depression was noted among mothers in the affected region.*

A number of recent studies have examined the risk of evacuation and relocation following the few severe reactor accidents that have occurred world-wide. The resounding conclusion of all of these studies is that unnecessary evacuations may have led to more harm than good. A study by J. Callen and T. McKenna noted that evacuations and relocations following the accident at Fukushima Daiichi resulted in deaths and injuries but prevented only exposures that were too low to result in meaningful observable radiation-induced health-effects (Callen, 2018). Their paper calls for a new system of radiation protection that justifies protective actions through a graded approach that balances the meaningful health effects of radiation exposure against those of the protective actions taken to avert the exposure (Callen, 2018).

A study of voluntary nursing home evacuations in response to the Fukushima accident looked at the risk trade-off between evacuation and radiation exposure using loss of life expectancy (LLE) as a detriment indicator of four evacuation scenarios: rapid evacuation, deliberate evacuation, 20-mSv exposure, and 100 mSv exposure (Murakami, 2015). The highest LLE of residents was 11,000 person-days, due to evacuation-related risks in a rapid evacuation scenario; this greatly exceeded the LLE in the other scenarios: 27 person-days for deliberate evacuation, 1100 person-days for 20 mSv exposure, and 5800 person-days for 100 mSv-exposure. The authors concluded that the most important point of their study is the need to take evacuation-related risk into account together with radiation exposure risk, and that compulsory evacuation needs to be better balanced with the trade-off against radiation risk.

A study by Waddington et al., quantified the value of the protective actions taken at Chernobyl in 1986 and Fukushima Daiichi in 2011 (Waddington, 2017). Radiation induced loss of life expectancy was evaluated through use of a judgment-value (J-value) framework to assess the cost-effectiveness of safety schemes that reduce risk to human life. Their analysis supported the findings from previous studies concluding that the relocation of 220,000 members of the public could not be justified on the ground of radiological health benefit. Additionally, the initial relocation of 115,000 people was only found to be economically defensible for between 26 to 62 percent of that population. In total, the J-value analysis found that only 9 to 22 percent of the roughly 335,000 people relocated after Chernobyl were justifiable.

1.6 Reconsidering Protective Action Strategies

The current state-of-practice of radiological dose projection is to assume no protection from evacuation or shelters when deciding upon the need to act. This is done in order to ensure that the risks of radiation are not overlooked, and also to ensure adequate dose savings are provided by taking protective actions. As a result, people may be advised to evacuate promptly from the immediate area, even if no release has occurred. Although protective actions are not intended to cause more harm than they avoid, evacuation can be more dangerous if not properly employed. An example of this would be trying to evacuate individuals who are residing in either a hospital or nursing home, as the machinery necessary to support bodily functions or access to other specialized care is not always portable. And for the population in general, the long-term risks of prolonged evacuation or relocation could result in adverse health effects including worsening of existing conditions, development of new issues, or even death.

There is an alternative to the immediate evacuation of the population at risk, which is sheltering-in-place. Sheltering-in-place is the action of remaining inside of a building for a period of time during a radiological release, closing all windows, shutting off the HVAC and moving to the most sheltered location of the home, typically a basement. Current dose projection models and protection guides conservatively assume that an individual will be outside both during and after the release. Therefore, it is assumed that the individual will receive a large dose, when in reality the dose received may be significantly reduced by the protection afforded by the structure.

Evacuation and sheltering-in-place are proven protective actions in an emergency. But how they are implemented makes all the difference in the outcome. The best-laid plans are to no avail without the trust of the decision-maker and the public. In the wake of the Fukushima Daiichi nuclear accident—considering the risk of evacuation and relocation—it is time to re-examine protective action strategies for radiological emergencies. This starts with an examination of current practice.

Chapter 2 – Implementing Protective Actions

This chapter examines how protective action strategies are implemented in practice during radiological emergency preparedness exercises and drills. Initial protective action decision-making in response to simulated radiological releases from commercial nuclear power plants is demonstrated during periodic drills and exercises. A study was performed of the PARs and PADs made during biennial exercises to assess how well they comport with the EPA PAGs. Trends in precautionary actions and the use of potassium iodide were also investigated. A review of biennial exercise after action reports (AARs) was used to gather data on protective action decision-making during evaluated biennial exercises. Figure 2-1 shows the methodology used for this study. The sections below describe each step in more detail.

Figure 2-1 Study methodology

2.1 Review of Biennial Exercise After Action Reports

This study primarily consists of a review of FEMA after action reports of offsite response organization performance in biennial exercises.[1] Supplemental population information and dose projection data was taken from site-specific NPP Evacuation Time Estimate (ETE) studies and exercise scenarios, respectively. All reports are publicly available in the NRC's Agencywide Documents Access and Management System (ADAMS).[2] AARs dating back to the 1980s were available for

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[1] AARs are available on the NRC's public web site at https://www.nrc.gov/about-nrc/emerg-preparedness/related-information/fema-after-action-reports.html html.

[2] ETE studies and exercise scenarios are available in the NRC's web-based ADAMS (WBA) site at https://www.nrc.gov/reading-rm/adams.html.

review. However, this review focused on AARs for exercises conducted after 2011 to capture current practices in protective action decision-making and to align with the latest revision to the NRC's PAR guidance issued in November 2011 (NRC, 2011a).

A total of 54 AARs were reviewed from biennial exercises that occurred between 2012 and 2018. The AARs represent data from 51 unique sites spread across the various NRC and FEMA regions. Data from 40 AARs provided useful information regarding the PAR and PAD, precautionary protective actions, meteorological conditions, and dose projection data. A partial summary of the data is provided in Appendix A. Table 2-1 summarizes the number of references to PARs and PADs found in the reports: 52 AARs had information on precautionary measures; detailed information on the PAD was found in 40 reports; 31 had information on the PAR; 16 AARs contained dose projection data from the exercise scenario. Data regarding the decision to use KI was also available. In general, KI decisions were made for emergency workers and in some cases, members of the public.

Table 2-1 Protective action information in after action reports

Number of AARs with Reported Protective Action Strategy Element					
Initial PAR	**Expanded PAR**	**Initial PAD**	**Expanded PAD**	**Precautionary Measures**	**Potassium Iodide**
31	8	40	12	52	40

A radiological release was simulated to occur in all but two scenarios. In most scenarios a release was in progress at the time the PAR and PAD were made. In a few scenarios, the offsite release did not start until after the General Emergency was declared. Delayed releases typically started within the hour after the GE declaration. Release durations were assumed to either be ongoing or to end after a few hours.

The AARs contain PAR and PAD information concisely communicated in terms of the affected zones (e.g., ERPA or PAD) or evacuation areas. This information was converted into population using data from site-specific ETE studies. An ETE contains population data on permanent, transient, and special populations within the EPZ. All ETE studies contained population data based on the latest (2010)

U.S. Census Bureau data. For comparison purposes, only the resident population data was used to estimate the number of potential evacuees. Transient populations, while important to any evacuation, are typically people that reside outside of the EPZ, and may not be significantly impacted in the long-term by an evacuation order. Special populations were not considered under the general evacuation because they represent much smaller portions of the overall population and they may have been already relocated as a precautionary measure.

Many AARs contained pertinent exercise scenario information including meteorological conditions that would be considered in making dose projections for informing protective actions. Some AARs contained PAD data but no information on the PAR. In those cases, available wind direction data from the exercise scenario was used to determine a default PAR based on an assumed keyhole evacuation of the 0-2 mile region and adjacent sectors 5-miles downwind. ETE studies typically report the sectors or emergency response planning areas (ERPAs) that would be evacuated in a keyhole strategy for various wind directions. Wind direction at the time a GE was declared was cross-referenced to the site-specific ETE study to determine a default PAR based on a keyhole evacuation in 13 cases.

The AARs contained references to over 120 different decisions on precautionary measures that would be taken in response to a radiological emergency (see Appendix A). Examples of precautionary measures include relocation of schools and special populations; livestock advisories recommending animals be placed on stored feed and water; agricultural advisories; air, water, and rail restrictions; bans on hunting and fishing; and closing of public areas. These were categorized and tallied by emergency classification level in order to assess what precautionary measures are typically considered and when they would be initiated.

2.2 Estimated Keyhole Evacuations

The population density surrounding NPPs varies greatly within the 10-mile zone. In general, the 2-mile area surrounding NPPs is a low population zone and population tends to increase further away from the site. An estimate of the average number of people recommended for evacuation using a default keyhole PAR strategy can be obtained from reported population data. Using the ETE studies, data on the geographic distribution of the permanent, transient, and special populations within the EPZ were analyzed. Following the method outlined in the NRC's study of evacuation time estimates, NPP sites were divided by EPZ population into three categories representing small, medium and large populations of 0-50,000; 50,000-200,000; and > 200,000 residents, respectively (NRC, 2020b). Permanent resident population data, available in 1-mile increments, was compiled from 58 ETE reports. Figure 2-2 illustrates the change in average incremental permanent resident population verses the radial distance from the plant for small, medium, and large sites.

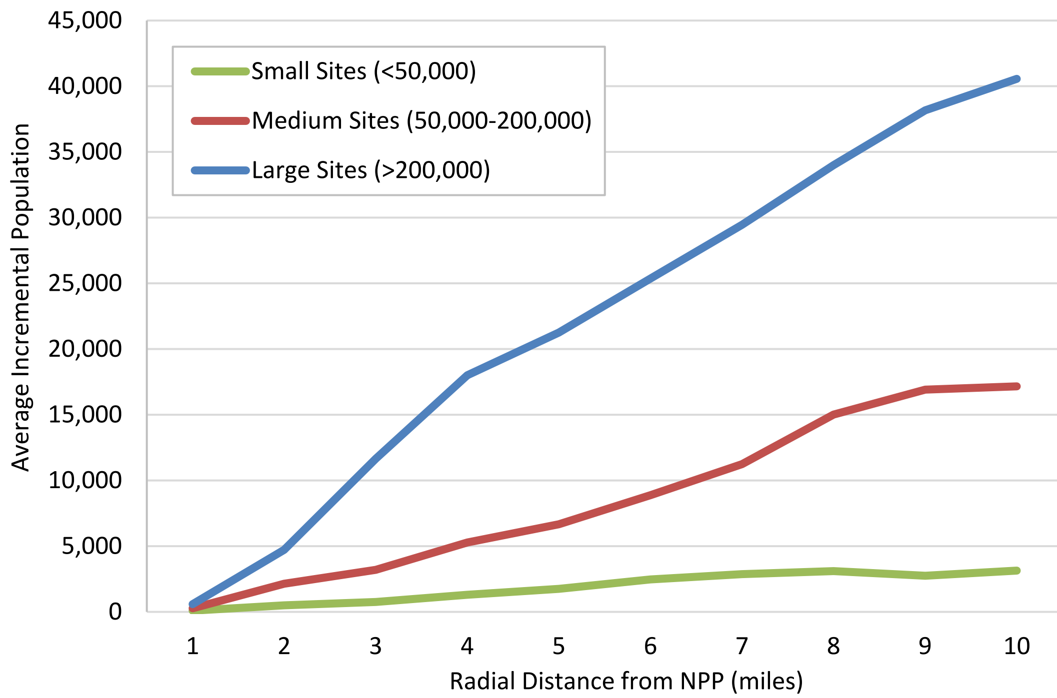

Figure 2-2 Radial distance from NPP versus average resident population for small, medium, and large NPP sites

The estimated keyhole strategy was assumed to include the 0-2 mile area, and 5 mile downwind sectors that include three 22.5 degree sectors. This represents 3/16th (approximately 19 percent) of the downwind area from 2-5 miles. The keyhole PAR was based on the average population within this geometric area and did not consider the actual size and shape of the ERPAs.

2.3 Radiological Dose Projections

Limited dose projection data performed during the exercise was available in the AARs, although the corresponding exercise scenarios include extensive radiological data for use in the exercise and for demonstration of performance objectives. This data often included dose projections for the EPZ from the time of the GE declaration. A review of the exercise scenarios associated with the 54 AARs reviewed from 2012-2018 yielded 27 site-specific dose projections. This data was used to supplement the AAR data for comparison to the PARs and PADs.

Dose projection data from exercise scenarios is typically presented in terms of the radial distance from the plant and the projected whole body dose to the individual (TEDE) at the distance, as shown in the example in Table 2-2. Because a large release is often prevented due layers of defense-in-depth built into the design of nuclear plants, dose projection data is often reported in units of mrem vice rem; as such care was taken to ensure the correct units were identified in order not to over- or under-state the projected dose when pulling data from AARs. Accident scenarios vary widely in terms of initiating conditions and postulated events leading up to a release, but in most scenarios a radiological release is assumed to be in progress at the time the GE is declared.

Table 2-2 Example exercise scenario dose projection data

Distance	TEDE (mrem)	CDE (mrem)
Site Boundary	143	634
2 Miles	9.55	42.9
5 Miles	2.41	6.41
10 Miles	1.2	3.1

Figure 2-3 provides a comparison of the dose projection data from 27 different accident scenarios. The dose projections in Figure 2-3 are best fit lines from data representing either conditions at the time the GE was declared or the maximum dose projection during subsequent time periods following the start of the release. As shown in Figure 2-3, most dose projections are well below the PAG limits within 2 miles from the point of release. Nine of the 27 dose projections (only one-third) exceeded PAGs at the site boundary, and only one exceeded PAGs beyond 5 miles.

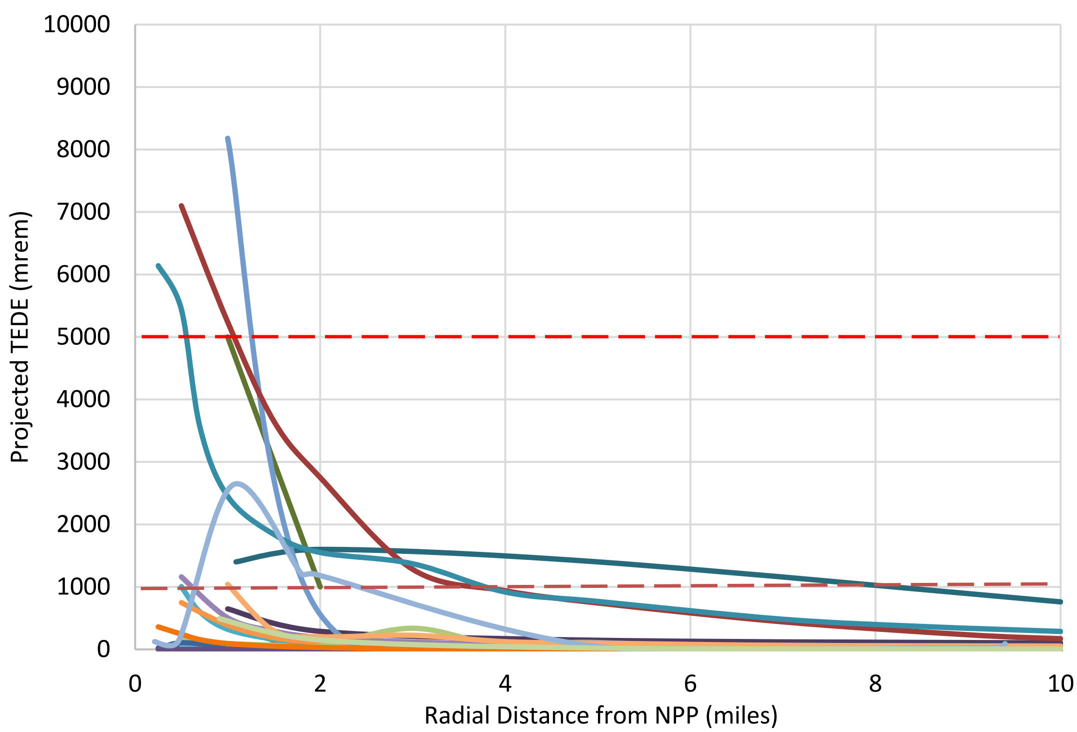

Figure 2-3 Dose projections versus radial distance from point of release

Dose projections included data for a range of radial distances and points within the plume. The 27 dose projections reviewed include a total of 196 projected locations. A histogram of this data, shown in Figure 2-4, reveals that only 14 percent of all dose projections exceeded PAGs. This data demonstrates that in many cases PAGs are not exceeded offsite even after a General Emergency is declared. Regardless, because of the anticipatory response to a General Emergency, default plant condition-based PARs are issued, and PADs are declared based on an independent assessment of the accident. A few exercise scenarios had no release, but during the exercise, PARs and PADs were issued anyway based on declaration of the General Emergency.

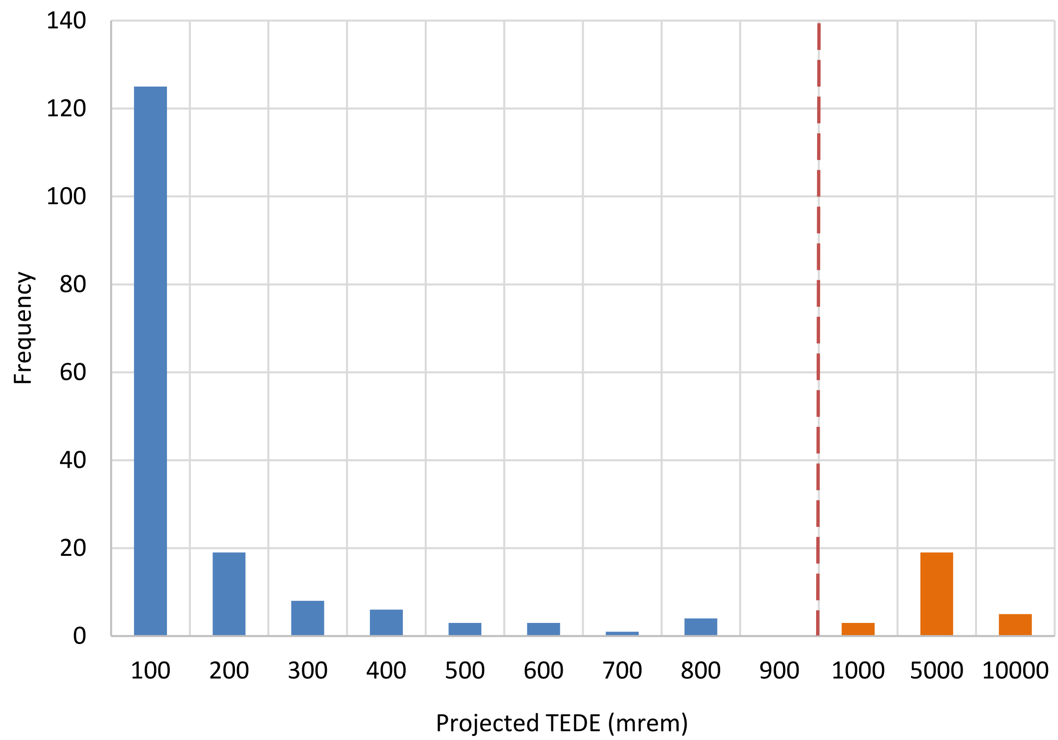

Figure 2-4 Frequency of exercise scenario dose projections exceeding PAGs

2.4 Comparison of PARs and PADs

A comparison of PARs to PADs is provided in Table 2-3. The data was divided into categories of small, medium, and large population for comparison to the estimated keyhole PAR values. In certain jurisdictions, the default PAD for the protective action strategy is full evacuation of the EPZ (0-10 miles, 360 degrees). The population in sites that evacuate the entire EPZ ranges from 75,000 to over 300,000 people. Removing these sites from the data reduces the average PAD for all sites to 12,498, which still exceeds the average default PAR by a factor of 1.5.

Table 2-3 Comparison of PARs and PADs

Estimated Average Number of Evacuees for PARs and PADs				
Site Population	**Keyhole PAR**	**Average PAR**	**Average PAD**	**Percent Difference**
< 50,000	1308	4953	5980	120%
50,000 – 200,000	5250	10441	29131	280%
> 200,000	14849	27916	217624	780%
Average	4272	8029	27883	350%

Figure 2-5 illustrates the comparison of site-specific PARs and PADs in order of smallest to largest PAR in terms of impacted population. Examination of the data showed that the tendency for the PAD to exceed the PAR goes up with EPZ population. This figure illustrates that even excluding the three PADs exceeding 100,000 people, there is still a significant number of PADs that exceed the PAR. A direct comparison shows that out of 40 PARs and PADs, 21 PADs exceeded the default PAR, 19 PADs were equal to the PAR, and 1 PAD was less than the PAR. Most of the PARs and PADs involve evacuation of the public close to the NPP and sheltering-in-place for remaining individuals in the plume path. However, the need for such action early-on may be pre-mature for two reasons: (1) a release of radioactive material does not always exceed PAG levels offsite, and (2) even when PAGs are exceeded, the initial impacted areas are not as extensive as the recommended PARs and PADs. The impact of this can be illustrated by comparing the population impacted by the PAG to the population impacted by the PARs and PADs, which will be done next.

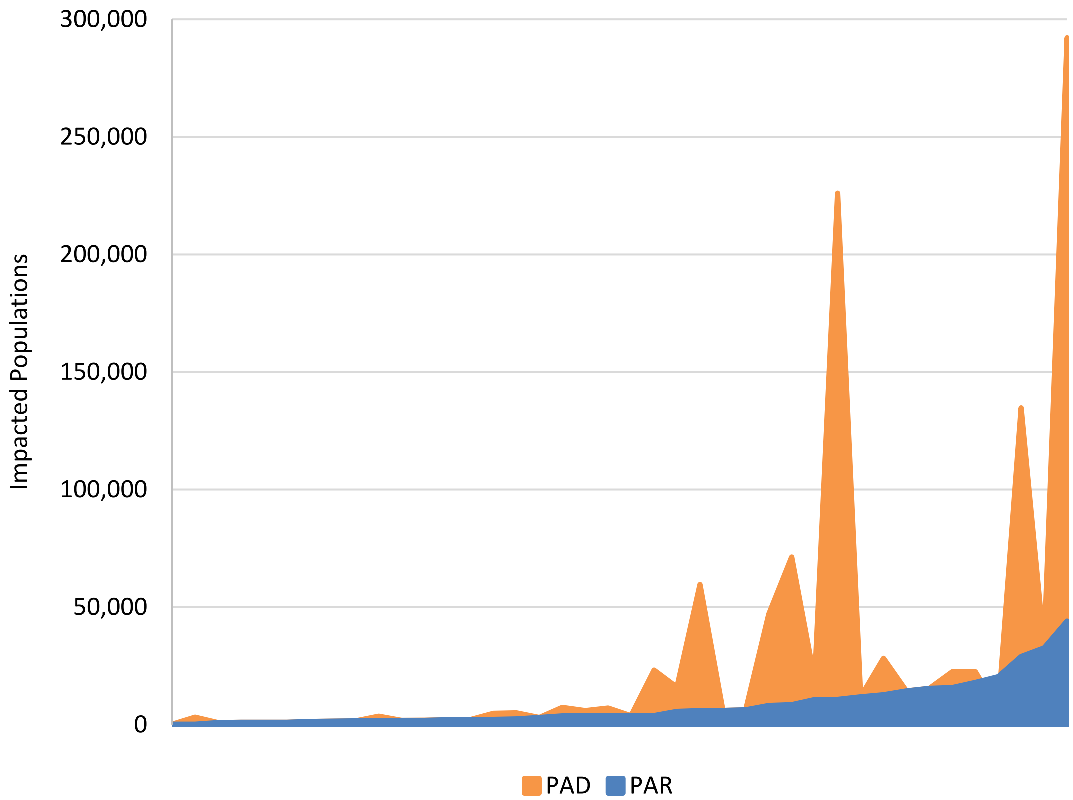

Figure 2-5 Comparison of impacted population size for PARs and PADs

2.5 Dose Projection Data and Comparison to PAGs

The comparison of PARs to PADs shows that protective action decisions typically exceed the protective action recommendation resulting in an increase in the number of potential evacuees. This reveals a level of conservatism in the decision-making process for protective actions. However, available dose projection data reported in exercise after action reports may not support such conservative protective action decisions based on consideration of the protective action guides. It was found that PAGs were exceeded offsite in only about one-third of the available initial dose projection data. In theory, the PARs and PADs should be based on the EPA PAGs. As such, the degree of conservatism involved in these decisions can be assessed by a comparison to the PAG.

The relative size of the population impacted by the PAG was developed considering that PAGs are generally not exceeded beyond the extent of the keyhole area of 0-2 miles and adjacent sectors 5 miles downwind—an area encompassed by the keyhole PAR. As such, the site-specific population data used to determine the impacted population for the PAR (Table 2-3) was multiplied by a factor of 1/3 to account for the percent of the scenarios in which PAGs were initially exceeded beyond the site boundary.

Table 2-4 shows the comparison of PAGs, PARs, and PADs in terms of potentially impacted populations. This data shows the level of conservatism added to the already conservative PAG level. Of note, the keyhole PAR (evacuation of the 0-2 mile area and 5 mile downwind adjacent 22.5 degree sectors) is comparable to the average number of people that would be affected by exceeding the PAG. The actual PARs conservatively involve more of the population mostly because the structure of ERPAs within the EPZ are such that adjacent sectors span larger areas and include more of the population than an idealized keyhole. A comparison of the Keyhole PAR to the Average PAR shows this approximately doubles the number of potential evacuees. PADs increase this number by a factor of 1.2 to 7.8 by including areas outside of the PAR into the PAD. As a result, PADs may encompass 4 to 24 times more of the population than the impacted population as indicated by the PAG. On average, the PAD represents a population group that is 6 times larger than the PAG. The comparison between the average number of evacuees impacted by the PAGs, PARs, and PADs is illustrated in Figure 2-6. The impacted populations were converted to areas to emphasize the dramatic difference in the number of individuals that would be evacuated based on the PAGs, the recommended PAR, and the PAD.

As described in the EPA PAG Manual, PAGs do not establish an acceptable level of risk for normal, non-emergency conditions, nor do they represent the boundary between safe and unsafe conditions (EPA, 2017a). PAGs were developed using a risk-benefit balancing process, designed to prevent acute effects, reduce the risk of chronic effects, and balance protection with other important factors to ensure that actions result in more benefit than harm. Such a risk-benefit balancing incorporates a level of precaution into the PAGs. As stated in the PAG Manual (EPA, 2017a):

> *Assumptions made to generate default parameters and derived response levels…include some worst-case assumptions to ensure PAGs are appropriate emergency guides for all members of the public, including sensitive subpopulations such as young children. For example, early phase derived levels are based on the assumption that a person is outdoors 24 hours a day for four days being exposed to the plume. Intermediate phase derived levels also conservatively do not account for shielding provided by being indoors part of each day of the projection year. People are assumed to remain in the contaminated area during the entire time (not going to work or school in an uncontaminated area, for instance.) Another example of conservatism is assuming that radionuclides are in the chemical and physical form that yields the highest dose (e.g., the particle size is one micrometer mean aerodynamic diameter). These conservatisms allow dose assessors to project whole body doses or total effective dose (TED) to a reference person, for simplicity, and then decision-makers can make protective action decisions that apply to entire communities including children, adults and the elderly.*

In essence, PAGs are already conservative. As such, dose projections should use realistic inputs when information is available to limit the amount of conservatism added into the calculations. The EPA PAG manual warns that overly conservative dose estimates may lead to unnecessary protective actions. However, the analysis of this section shows that conservatism in dose projections does not appear to be the driving factor leading to potentially unnecessary protective actions. Rather, the added conservatism comes from the nature of the PARs and PADs. The factors that may have led to this added level of conservatism are discussed later on.

Table 2-4 Comparison of PAGs, PARs, and PADs

Estimated Average Number of Evacuees for PAGs, PARs and PADs				
Site Population	**Average PAG**	**Keyhole PAR**	**Average PAR**	**Average PAD**
< 50,000	1651	1308	4953	5980
50,000 – 200,000	3480	5250	10441	29131
> 200,000	9305	14849	27916	217624
All Sites Average	4812	4272	8029	27883

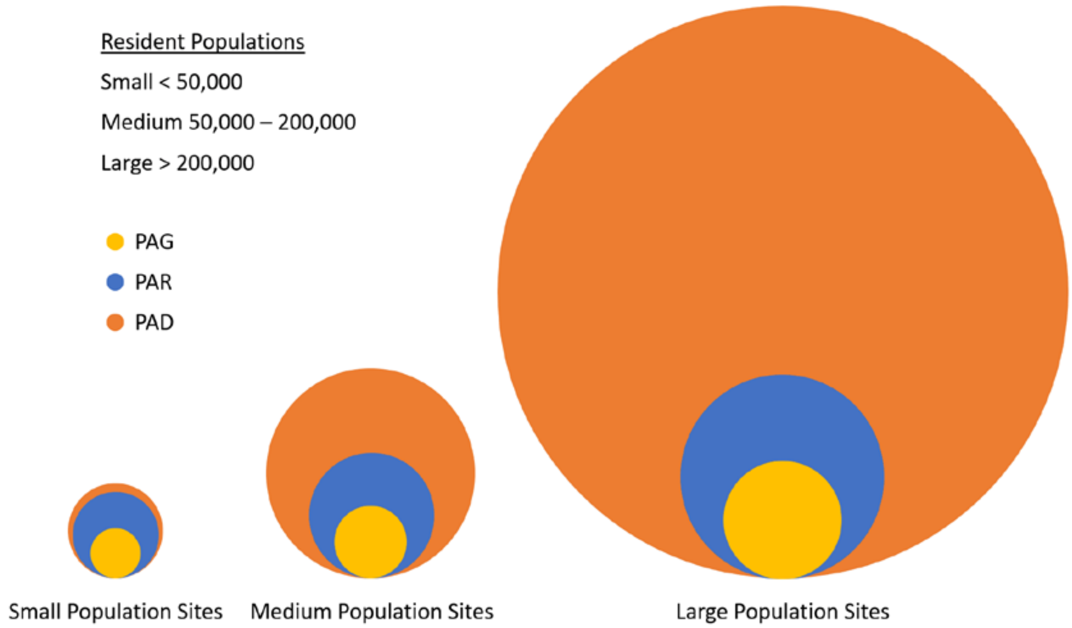

Figure 2-6 Visual comparison of the average population size that could be impacted by evacuating in accordance with PAGs, PARs, and PADs for small, medium, and large population sites

2.6 Precautionary Measures

Prominent considerations for precautionary measures include evacuation (or early dismissal) of schools and special populations, livestock and agricultural advisories, restricting access to public areas, and restricting air, water, and rail traffic within the EPZ. Table 2-5 provides the number of references found for each type of precautionary measure and the corresponding emergency classification level when the action was initiated. Precautionary measures are anticipatory, and, as the data shows, most precautionary measures are initiated during the SAE, and before a significant offsite release is expected. However, almost one-fifth of the precautionary measures were implemented at the Alert. In particular, evacuation or early dismissal of schools was often considered early in the event, often starting at the Alert phase when no release is expected to occur offsite. After the General Emergency declaration, other precautionary measures were typically initiated for schools and special populations in areas outside of the declared evacuation zone.

Table 2-5 Summary of precautionary measures

Initiation of Precautionary Measures			
Precautionary Measure	**Alert**	**SAE**	**GE**
Alert Schools	3	2	-
Evacuate Schools and Special Populations	7	21	7
Air, Water, Rail Restrictions	4	13	8
Restrict Access to Public Areas	4	20	6
Livestock/Agricultural Advisory	3	27	9
Total	21	83	23

2.7 Evacuation as a Protective Action

Evacuations are typically classified as no-notice or noticed events (FEMA, 2019a). No-notice events occur with little or no warning and require rapid assessment, decision-making, communication, and implementation of protective actions. Examples of incidents that might cause a no-notice evacuation include a hazardous material spill, explosion at a chemical plant, a terrorist attack, a flashflood, or even an earthquake (FHWA, 2007). In a noticed event, jurisdictions have warning of an impending hazard and officials have time to prepare in advance, assess, communicate, and implement protective measures. Typically, initial preparation discussions occur as soon as the jurisdiction receives notification of an impending hazard (FEMA, 2019a). Examples of noticed events include hurricanes and slowly moving wildfires, and emergencies at nuclear power plants.

A distinguishing feature between noticed and no-notice events is that no-notice events are often in response to hazards that are immediately dangerous to life and health. In general, radiological emergencies at nuclear power plants, are not immediately dangerous to life and health, and any evacuation would likely be a noticed event as indicated by state-of-the-art analyses of potential accident and release timings (NRC, 2012). The NRC has studied evacuations and has concluded that evacuations in the United States, whether preplanned or ad hoc, are effective and successfully save lives and reduce the potential number of injuries associated with the hazard (NRC, 2005). Additionally, the NRC found that effectiveness in implementation of emergency plans is directly related to the level of planning (NRC, 2008). Issues with evacuations were found when authorities deviated from emergency plans and procedures. However, such deviations are not likely to occur within radiological emergency preparedness programs because of frequent training, drills, and exercises which are regularly inspected.

The AARs did not provide enough information to be able to assess the rationale for specific PADs. In general, it can be assumed that EROs follow their procedures for issuing a PAR and that PADs are based on information provided by the ERO and by independent evaluation by offsite agencies in accordance with an approved plan. Even so, it is worth considering whether PARs and PADs are driven by other factors such as exercise artificiality and preconditioning and even the planning basis for radiological emergency preparedness.

2.8 Potential Factors Influencing Protective Action Decision-Making

The scenario timing and protective action decision-making observed during biennial exercises might indicate that protective action decision-making is a time-critical event for any radiological emergency. However, exercise scenarios are largely artificial in that accidents are always allowed to get progressively worse with little chance for operator success in mitigating the event in the earlier stages of the emergency. In reality, an accident would take much longer to progress to the point of a radioactive release with offsite consequences, if at all. NPP operators are highly trained to manage accidents, and as demonstrated in real-life, most events will not progress to the point of an actual release. Even so, the disparity between PARs and PADs, particularly in relation to the PAG, indicate that should a radiological release occur, a strong potential exists for evacuations to involve more people than necessary.

As demonstrated with many other hazards, rapid evacuations are typically required for events that are immediately dangerous to life and health. But in a radiological emergency, evacuations are triggered by PAG levels at which there is no immediate risk of harm and the stochastic risk is merely assumed. In such a situation, evacuation of more people than necessary could result in doing more harm than good, especially if people are not allowed to expeditiously return home. The prolonged risks of evacuation and relocation should be factored into the decision-making, but exercise scenarios rarely offer additional time to consider the need for action or the opportunity to decide when to terminate those actions.

2.8.1 Exercise Artificiality and Preconditioning

Drill and exercise scenarios are required to encompass a wide spectrum of events and conditions to avoid anticipatory responses resulting from participant preconditioning. Prior to 2011, the NRC became aware that the scenarios used in drills and exercises had become predictable and were preconditioning responders to event sequences that did not represent credible accidents (NRC, 2011b). In particular, exercise scenarios may have preconditioned responders toward anticipatory response in the escalation of emergency classification and the expectation that every emergency results in a radiological release. Further, in order to have time to demonstrate performance of key skills and fulfill exercise objectives, the timing of exercise scenarios typically do not resemble credible reactor accidents and most scenarios included improbable containment failure leading to substantial offsite release. This may result in negative training, including the potential to assume that worst-case releases are in progress requiring immediate decisions be made to move populations before PAGs are exceeded.

In the 2011 enhancement to EP rule, the NRC revised biennial exercise requirements to ensure that the eight-year exercise cycle contained a variety of scenarios (NRC, 2011b). The intent of this enhancement was to prevent pre-conditioning to the exercise. While the 1980 EP regulations were successful in ensuring a high level of preparedness at every NPP site, the NRC believed that exercise scenarios should be enhanced because, as the scenarios were implemented previously, responders may have been preconditioned to accident sequences not likely to resemble the accidents they could realistically face. Shortcomings of exercise scenarios included: the unlikely timing of simulated accident events in the scenarios; the inevitability of large radiological releases; and the failure to incorporate a wide spectrum of events, including hostile action.

Biennial exercise scenarios are by necessity, time-compressed. This is needed in order demonstrate key skills and abilities to meet exercise objectives. A downside to this time compression is the potential for pre-conditioning of responders. A review of the exercise timelines documented in the AARs reveals a fairly predictable progression from Unusual Event, Alert, Site Area Emergency, to General Emergency. The average time to progress from an Alert to SAE was 92 minutes and the average time to a GE from the SAE was 76 minutes; additional timing data is provided in Table 2-6.[3] Thus, even though scenarios are designed to minimize pre-conditioning, the timing of exercises introduces artificialities that may create a false sense of urgency for making protective action decisions.

Table 2-6 Progression of emergency classification levels in biennial exercise scenarios

Progression of Emergency Classification Levels		
Time Measure (minutes)	**Alert to SAE**	**SAE to GE**
Average time until next classification	92	76
Minimum time between classifications	56	18
Maximum time between classifications	189	145
Standard deviation of classification times	29	28

[3] Times for declaration of the Unusual Event are typically not recorded in the AAR, since this is typically below the response level for any offsite actions.

2.8.2 Planning Basis Assumptions and Actual Events

The planning basis for emergency preparedness (NUREG-0396), in particular the planning time frames, are based on design basis accident considerations and the severe accidents considered in the 1975 Reactor Safety Study (WASH-1400) (NRC, 1975; NRC, 1978). The WASH-1400 Reactor Safety Study assumed that a major release could begin anytime within 30 minutes to 30 hours after an initiating event and that release durations could exceed several days. Contrary to the accelerated progression of events driving drill and exercise scenarios, real-world events can be slow developing and are often quickly resolved. As demonstrated in the events at the Fukushima Daiichi plant and as shown in the NRC's SOARCA studies, reactor accidents are more likely to progress over the course of days, rather than a few hours (NRC, 2013a; NRC, 2013b). Table 2-7 shows the core damage frequency (CDF) in events per year and the atmospheric release timing of unmitigated severe accident scenarios from the SOARCA study in comparison to the 1982 siting source term (SST1). The SOARCA data clearly shows that the expected frequency of events is much lower and the releases would start much later and last much longer than predicted in early studies. Only under highly unlikely circumstances would an accident lead to an actual release. In the U.S., this assurance is provided through a robust defense-in-depth strategy in which emergency preparedness is the final layer.

Table 2-7 SOARCA scenario comparison to siting study source term (SST1)

Scenario	CDF (Events/yr)	Atmospheric Release Timing	
		Start (hr)	End (hr)
Peach Bottom (PB) LTSBO	$3x10^{-6}$	20.0	48.0
PB STSBO w BS	$3x10^{-7}$	16.9	48.0
PB STSBO w/o BS	$3x10^{-7}$	8.1	48.0
Surry STSBO	$2x10^{-6}$	25.5	48.0
Surry STSBO w/TISGTR	$4x10^{-7}$	3.6	48.0
Surry LTSBO	$2x10^{-5}$	45.3	72.0
Surry ISLOCA	$3x10^{-8}$	12.8	48.0
Siting Source Term 1 (SST1)	$1x10^{-5}$	1.5	3.5

Still, every year, a number of emergencies are declared at NPP sites. Information on the number and type of emergency declaration can be found on the NRC's public webpage.[4] The frequency of event declarations for the different emergency classes were tabulated for the time period covering the AAR review of this study, and a histogram of the results are shown in Figure 2-7. All declared emergencies for this time frame never moved beyond an Unusual Event or Alert. The majority of these events were declared due to fires or toxic gas releases—as would be experienced at any industrial facility—and never challenged the integrity of the plant. Only rarely is there an escalation from one classification level to another, and even then, only from an Unusual Event to an Alert. This is contrary to the planning basis for EP which assumes, based on the Reactor Safety Study, that a release could occur as soon as within 30 minutes of the initiating event. This leaves open the opportunity to take more deliberate protective actions for events that are not determined to be rapidly progressing severe accidents. And it also brings into question the utility of taking early precautionary measures at the Alert stage without more information as to the severity of the event and prognosis for worsening conditions. Of note, during these actual Alert events, no precautionary actions were reported taken offsite.

[4] https://www.nrc.gov/reading-rm/doc-collections/event-status/event/

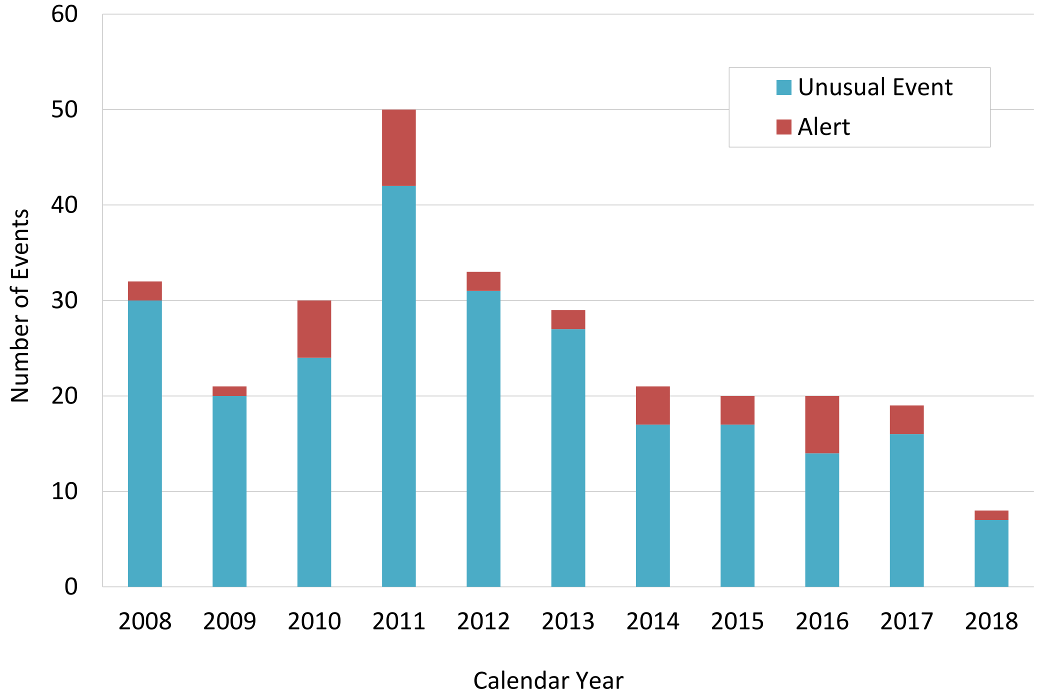

Figure 2-7 Frequency of actual emergency declarations per calendar year[5]

2.9 Are We Doing More Harm Than Good?

This chapter looked at protective action recommendations and protective action decision-making demonstrated during NPP biennial exercise evaluations. The current practice of protective action decision-making is driven by artificialities in exercise scenarios and a spectrum of accidents used in the planning basis for emergency preparedness which assumes that a release could occur within 30 minutes of the initiating event, requiring a capability to take prompt protective actions. A comparison to the EPA PAGs against available dose projection data indicates that in many scenarios, PAG levels were not exceeded in declared evacuation areas.

[5] The higher number of emergency declarations in 2011 is due to multiple plants reporting 13 Unusual Events and 1 Alert in response to one common initiating seismic event.

There is general acceptance that avoiding unnecessary radiological dose is desirable. This might lead some to believe that in a radiological emergency this goal is best achieved by maximizing the evacuation. However, evacuating populations that are not at risk from a radiological release exposes them to the costs and risk of evacuation with no perceived benefit (Hammond, 2015). While the current protective action strategy is designed to be anticipatory, taking actions too early or unnecessarily may not equate to real savings in dose and could result in doing more harm than good in the long term. In any emergency, the prolonged displacement of people from their homes adds additional challenges and presents real risks to the individual.

Advanced reactors, including light water reactors with passive safety features and small modular reactors, have a number of design features that would preclude a release from occurring within a short time frame. For these advanced plants, EP is part of the initial design consideration and there are multiple layers of defense-in-depth to ensure public safety such that potential accident sequences will look much different from the large light water reactors of the past. In anticipation of these advanced technologies, consideration should be given now to the formulation of appropriate protective action strategies. Should there ever be a severe accident in an advanced plant design, there may be significantly more time to respond. Additionally, small modular reactors have a much smaller source term, and doses are very unlikely to exceed PAGs for any appreciable distance from the site. In such a case, sheltering-in-place may prove just as effective as evacuation. As such, the protective action strategies developed for light water reactors may need to be reconsidered for application to future plant designs. This reconsideration must include a realistic examination of the benefits of sheltering-in-place and the potential long-term detriments of evacuation and relocation so that the risks are properly balanced and that protective actions do not result in more harm than good. How those risks are balanced will be examined next.

Chapter 3 – Balancing the Risks

The EPA Protective Action Guides are based on the overarching premise that protective actions should do more good than harm. This chapter presents a thorough history of the development of the PAGs including the studies that informed the basis for the PAG levels. This is followed by a critical examination of the basis and implementation guidance for the PAGs. The PAG Manual contains a variety of PAGs for early, intermediate, and late phases of response, and food and water interdiction. This discussion is focused on the early phase PAGs, particularly the 1-5 rem PAGs for evacuation or sheltering-in-place and the relocation PAG of 2 rem in the first year and 0.5 rem in subsequent years.

3.1 History of the PAGs

The many incarnations of the EPA PAG Manual received their start in the Civil Defense programs of the 1960s and the early Federal guidance for protective actions from nuclear fallout. The Federal Radiation Council (FRC) set out to establish a Radiation Protection Guide (RPG), defined as the radiation dose which should not be exceeded without careful consideration of the reasons for doing so. The FRC recommended that yearly radiation exposure to the whole body of individuals in the general population (excluding background and medical exposures) should not exceed 0.5 rem. Although it was expected that reasonable efforts should be made to keep exposures below this level, it was the considered judgment of the FRC that, "…it is obviously appropriate to exceed this level if a careful study indicates that the probable benefits will outweigh the potential risk" (FRC, 1960). The idea behind this is that the effort expended to control exposure increases in magnitude with the dose.

It is instructive to examine the mindset and beliefs that informed the development of this early standard of radiation protection. The Federal Radiation Council (FRC) provided a number of useful observations and considerations in

Federal Guidance Report No. 1, "background material for the development of radiation protection standards," including (FRC, 1960):

> *The delayed effects produced by ionizing radiation in an individual are not unique to radiation and are for the most part indistinguishable from those pathological conditions normally present in the population and which may be induced by other causes.*
>
> *If one assumes a direct linear relations between biological effect and the amount of dose, it then becomes possible to relate very low dose to an assumed biological effect even though it is not detectable. It is generally agreed that the effect that may actually occur will not exceed the amount predicted by this assumption.*
>
> *Even if the injury should prove to be proportional to the amount of radiation the individual receives, to the best of our present knowledge, the new permissible levels are thought not to constitute an unacceptable risk.*
>
> *Therefore, some balance must be struck between risk and benefit.*

These points are summarized as follows. First, radiation was not to be viewed as fundamentally different from other causes of pathological conditions; i.e., radiation is a unique hazard, but radiation does not produce unique consequences. Second, the LNT hypothesis was generally agreed to be conservative and not a powerful model in terms of its predictive capabilities. Third, permissible levels of exposure are acceptable risks. And finally, there must be some balance between the risk and benefit of radiation exposure. Consistent with these principles the FRC recommendation was that no exposure to radiation should be permitted unless it satisfied two criteria (FRC, 1961):

1. *the various benefits to be expected as a result of the exposure, as evaluated by the appropriate responsible group, must outweigh the potential hazard or risk; and,*
2. *the reasons for accepting or permitting a particular level of exposure rather than reducing the exposure to a lower level must outweigh the decrease in risk to be expected from reducing the exposure.*

In this second criteria, we see the genesis of the rationale that protective actions should do more good than harm.

The FRC Reports No. 1 and No. 2 were primarily concerned with environmental exposure in normal peacetime operations of nuclear technology and controlling annual intake of radioactive material. The FRC considered emergency exposure situations in FRC Report No. 5 (FRC, 1964). Although primarily concerned with future ingestion of contaminated foods, the principles to be used in the development of guidance for taking protective actions in an emergency considered (FRC, 1964):

1. *the possible risk to health associated with the projected dose to the population from the fission products.*
2. *the amount by which the projected doses can be reduced by taking certain protective actions.*
3. *the total impact, including risks to health associated with these protective actions.*
4. *the feasibility of taking the action.*

Taking protective actions was considered appropriate when the health benefit associated with the reduction in dose that can be achieved is considered sufficient to offset the undesirable factors associated with the action (FRC, 1964). Again, there is an evolution of the idea that protective actions should do more good than harm.

Balancing the risk of the radiation exposure against the impact of the protective action would involve consideration of factors such as the degree of departure from usual practice, the length of time over which the action is applied, the relative ease with which the action could be executed, and the possible health risks associated with the action (FRC, 1964). FRC Report No. 5 expanded on this idea of doing more good than harm by noting that protective actions will yield a greater return in relation to their disadvantages if projected doses are high rather than low. As such, protective actions were to be applied to small areas of high dose levels rather than over large regions.

In 1972, the EPA's Office of Radiation Programs published the "National Radiation Protection Program – Strategy and Plan," to describe a revised mission for the protection of the environment and population against unwarranted radiation injuries (EPA, 1972a). As an overarching framework, the EPA emphasized that there is no absolute "justifiable risk" that is good for all time and place (EPA, 1972b). Rather, what constitutes "justifiable risk" is a societal decision that requires a method for reaching *a priori* decisions on what risk/cost/benefit balance society would ultimately select if all subsequent information were made available (EPA, 1972b). As a generic approach, the risk/cost/benefit consideration enters into all areas of radiological protection from reactor accidents to laser applications. The overall pathway, exposure, dose/health effects, and benefit models developed for evaluating risk and benefits could be applied to specific applications with appropriate modification of parameters.

The application areas to be addressed—including reactor accidents—were explored further in Appendix C of the National Radiation Protection Program (EPA, 1972b). Preparedness for radiological emergencies was to be done on a cost-effective basis, consistent with the expected risk and consequences. This included the need to develop protective action guides (PAGs) that would seek to balance the risk/cost/benefit to society for reactor accidents. As an example, a PAG was needed to weigh the risks and costs of evacuation against reductions in exposure for various population groups (EPA, 1972b). Continuing from that point, guidance to the states would be developed for when to recommend evacuation or shelter-in-place.

The EPA produced a legal compilation in January of 1973, to provide background material for the development of radiation protection standards and protective action guides. In this legal compilation, the EPA emphasized principles from FRC Reports No. 1, No. 2, and No. 5. Specific to FRC Report No. 5 in the application of PAGs, the following guidance was provided (EPA, 1973):

1. *If the projected dose exceeds the PAG, protective action is indicated.*
2. *The amount of effort that properly may be given to protective action will increase as the projected dose increases.*
3. *The objective of any action is to achieve a substantial reduction of dose that would otherwise occur—not to limit it to some prespecified value.*

Because the justification for protective actions depended on the dose averted, use of the projected dose as a basis for implementation of a proposed action is valid only if it is expected that most of the projected dose will be averted. In a particular situation actions with low impact are justifiable at low values of projected dose, but as the projected dose becomes less, the net benefit of public well-being from reduction of exposure becomes less. If only high impact protective actions are needed, such actions should be justified at projected doses higher than the PAG level (EPA, 1973).

Although primarily concerned with normal peacetime and accidental exposures through longer-term environmental pathways (e.g., food and milk), the EPA recommended that, “caution should be exercised in decisions to take protective actions in situations where projected doses are near the numerical values of the RPG[s], since the biological risks are so low that the actions could have a net adverse rather than beneficial effect on the public well-being” (EPA, 1973). The RPGs were not to be used as firm safe/not safe limits. These ideas were also reflected in the early considerations of PAGs for radiological emergencies as part of the EPA’s National Radiation Protection Program, within which the EPA recognized that decisions to evacuate populations should not be made lightly. In regard to the development of the PAGs, the EPA identified a real need for guidance on the anticipated risks due to an evacuation (EPA, 1972b).

Recognizing that evacuation, like radiation exposure, can impose risks upon the affected population, in 1974, the EPA published an assessment of evacuation risks in EPA-520/6-74-002, “Evacuation Risks – An Evaluation” (EPA, 1974). Information was compiled on over 500 evacuation events in the U.S. after 1960. Reasons for the evacuation included floods, fires, hurricanes, explosions, and toxic substances, providing a broad base for making useful comparisons. The study focused on the risk of death, the risk of injury, and the costs associated with evacuation events. The results showed that the risk of injury or death to evacuees did not change as a function of the numbers of persons evacuated, and that these risks could be approximated by the National Highway Safety Council statistics for motor vehicle accidents. It was noted that in most emergency evacuation events, the observed numbers of injury or death was likely to be lower than values predicted using the National Motor Vehicle Accident Death and Injury Rate data (EPA, 1974). Because the risk of death or injury due to an evacuation event is so low, projections of deaths and injuries (much like projections of stochastic effects of radiation exposure) are not statistically valid for population sizes likely to be involved in single evacuation events. The conclusion of the study was that large or small population groups can be effectively evacuated with minimal risk of death or injury. Populations were likely to be able to take care of themselves provided plans were developed to minimize location-specific problem areas. Costs would likely not be a deterrent to evacuation, but only in the short term (EPA, 1974). It should be noted that the risk of injury or death was considered only in the context of the miles travelled during an evacuation event. The long term physical health effects of evacuations and relocations did not factor into the evacuation risk assessment used to form the basis for the PAGs.

As a precursor to the PAG Manual, the EPA published a review of radiation protection activities from 1974 (EPA, 1975a). The term Protective Action Guide was defined within as the projected absorbed dose to individuals in the general population that warrants protective action following a contaminating event. Table 2-2 of this report provided PAGs for emergency response of nonessential personnel in a range of 1 to 5 rem projected whole body gamma dose (EPA, 1975a). The protective measures considered appropriate for achieving the objectives of the PAGs included evacuation, sheltering, prophylaxis, respiratory protection, and controlled access. If a projected dose exceeded the PAG, protective action was indicated. This did not mean immediate evacuation. The nature of the protective action was to vary depending on the circumstances and the nature of competing risks. A range of PAG values was specified to account for local constraints in implementing protective actions. Critical exposure pathways were assumed to be from airborne exposure and contamination of foodstuff and property. Within the framework of these PAGs, it was assumed that (EPA, 1975a):

1. *the PAGs applied to acute exposure from a gaseous cloud released to the atmosphere from a reactor accident.*
2. *the PAGs would not be applied to large communities (e.g., over 200,000 population) for which reasonable estimates had not been made of the health risks related to massive movement of people.*

3. *the PAGs applied only to the taking of initial protective actions for the first 2 to 4 days; and,*
4. *insufficient information about the source term and probable duration of exposure preclude quantification of shelter as an effective protection action.*

Regarding this last point, sheltering was considered an appropriate action but was believed to be ineffective against continuous gaseous releases after about two hours in the absence of shelters with ventilation control (EPA, 1975a). Source term information mostly came from the AEC-sponsored Reactor Safety Study (RSS) performed by Dr. Rasmussen of MIT. The Reactor Safety Study (WASH-1400; also known as the Rasmussen Study) helped formulate the basis for emergency planning for reactor accidents (NRC, 1978). During this time, the EPA was working on a more detailed review of the Reactor Safety Study, with a draft published as EPA-520/3-75-012, "Reactor Safety Study (WASH-1400): A Review of the Draft Report," (EPA, 1975b) and a final version published in EPA-50/3-76-009, "Reactor Safety Study (WASH-1400): A Review of the Final Report" (EPA, 1976). Although the RSS gave estimates of the probabilities of various nuclear accidents, for radiological protection the problem remained to determine the level of risk acceptable to society.

The first edition of the PAG Manual was published in 1975 (EPA, 1975c). The PAG Manual was prepared to provide practical guidance to state, local, and other officials on criteria to use in planning protective actions for radiological emergencies. Within this document, the balance between risk, benefit, and cost of protective actions really began to take shape. The PAGs for whole body exposure to airborne radioactive materials are shown in Figure 3-1 (EPA, 1975c). It should be noted (as discussed in later versions of the PAG Manual) that these PAG values are for external gamma dose to the whole body. For inhalation, a projected thyroid dose of 5-25 rem was the recommended PAG for the general population. A protective action was to be taken to avoid or reduce projected dose when the benefits derived from such action were sufficient to offset any undesirable features of the protective action. The PAG was not to be used to imply a certain level of acceptable dose, rather the PAG was to be used in an *ex post facto* effort to minimize the risk from an event which is occurring or has already occurred. PAGs balanced the risks and costs against the benefits obtained from the protective action. An important assumption behind the PAG at this time is that it was assumed the event has occurred and the projected exposure is expected as a result. On this basis, the EPA stated there was no relationship between acceptable levels of societal risk of radiation exposure and the PAG (EPA, 1975c). This is a subtle point of the 1975 PAG Manual that was not carried forward into future revisions.

Population at Risk	Projected Whole Body Gamma Dose (Rem)
General population	1 to 5[a]
Emergency workers	25
Lifesaving activities	75

[a]When ranges are shown, the lowest value should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations. Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action.

Figure 3-1 PAGs for whole body exposure to airborne radioactive materials

Within the general framework of the PAG Manual, the accident scenarios of the RSS led to the belief that protective action decisions needed to be made in a short time. Significant releases of radioactivity were expected to occur within 1.5 to 2.5 hours of the initiating condition; therefore, if protective actions were to be effective, they must be taken promptly. Given the assumed time restrictions, it was further assumed that the information needed to select the optimum alternative may not be readily available. In such a case, officials needed to be ready to rapidly select the best of several alternatives. As such, planning activities were to be focused on the resources required to promptly implement viable alternatives in emergency situations (EPA, 1975c).

For planning purposes, the EPA recommended the following sequence of events to minimize population exposure (EPA, 1975c):

1. *Notification by the facility operator that an incident has occurred that is expected to cause offsite projected doses that exceed the PAG.*
2. *Immediate evacuation of a predesignated area.*
3. *Monitor gamma exposure rates in the environment.*
4. *Calculate plume centerline exposure rate vs. distance.*
5. *Use exposure rate and estimated exposure duration to convert to projected dose.*
6. *Compare projected dose to the PAGs and adjust actions as indicated.*
7. *Continue to make adjustment as more data becomes available.*

To assist in determining appropriate actions under Step 6, the EPA provided recommended protective actions in Table 5.2 of the 1975 PAG Manual; this table is shown in Figure 3-2 (EPA, 1975c).

Table 5.2 Recommended protective actions to avoid whole body and thyroid dose from exposure to a gaseous plume.

Projected Dose (Rem) to the Population	Recommended Actions[a]	Comments
Whole body <1 Thyroid <5	·No protective action required. ·State may issue an advisory to seek shelter and await further instructions or to voluntarily evacuate. ·Monitor environmental radiation levels.	Previously recommended protective actions may be reconsidered or terminated.
Whole body 1 to <5 Thyroid 5 to <25	·Seek shelter and wait further instructions. ·Consider evacuation particularly for children and pregnant women. ·Monitor environmental radiation levels. ·Control access.	
Whole body 5 and above Thyroid 25 and above	·Conduct mandatory evacuation of populations in the predetermined area. ·Monitor environmental radiation levels and adjust area for mandatory evacuation based on these levels. ·Control access.	Seeking shelter would be an alternative if evacuation were not immediately possible.
Projected Dose (Rem) to Emergency Team Workers		
Whole body 25 Thyroid 125	·Control exposure of emergency team members to these levels except for lifesaving missions. (Appropriate controls for emergency workers, include time limitations, respirators, and stable iodine.)	Although respirators and stable iodine should be used where effective to control dose to emergency team workers, thyroid dose may not be a limiting factor for lifesaving missions.
Whole body 75	·Control exposure of emergency team members performing lifesaving missions to this level. (Control of time of exposure will be most effective.)	

[a]These actions are recommended for planning purposes. Protective action decisions at the time of the incident must take into consideration the impact of existing constraints.

Figure 3-2 Recommended protective actions from 1975 EPA PAG Manual

The interesting takeaways from this table are the PAG levels for which particular actions were recommended. A mandatory evacuation of the population within a predetermined area[6] was not recommended unless the projected dose exceeded 5 rem whole body. Within the range of 1 to 5 rem, evacuation for children and pregnant women was to be considered, but the primary action was to seek shelter and await further instructions. Shelters were thought to provide good protection from inhalation of gases for a short period of time (i.e., one hour or less) but were assumed to be generally ineffective after about two hours due to natural ventilation of the shelter (EPA, 1975c).

The 1975 PAG Manual also addressed lifting of protective actions. The lifting of protective actions could be justified on the basis of cost savings when the corresponding health risks had been adequately reduced (EPA, 1975c). The restoration phase, including reentry, was allowed to begin at any time as appropriate. Time was not a constraint on reentry except as a factor for the cost of remaining out of the evacuated area. In regard to the evacuated population, people were to be allowed reentry when the radiation risk had been averted or reduced to guide levels for the general population. More importantly, this concept of the restoration phase assumed there would be additional accumulation of dose. That is, it was expected that the affected population would continue to receive some amount of exposure from contamination in the environment. This is shown in Figure 3-3, which is taken from Figure 1.1 of the 1975 EPA PAG Manual (EPA, 1975c). Timeline 8 shows that dose accumulation as a result of the accidental release of radionuclides was an expected part of the restoration phase. No additional protective actions were needed, provided the doses accumulated during this time remained below guide levels.

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[6] The predesignated area for immediate action was the downwind sector and two adjacent sectors (22.5 degrees sector widths) extending radially to the outer edge of the low population zone. The low population zone is defined by the NRC in 10 CFR 100.3 as the area immediately surrounding the exclusion area which contains residents, the total number and density of which are such that there is a reasonable probability that appropriate protective measures could be taken in their behalf in the event of a serious accident.

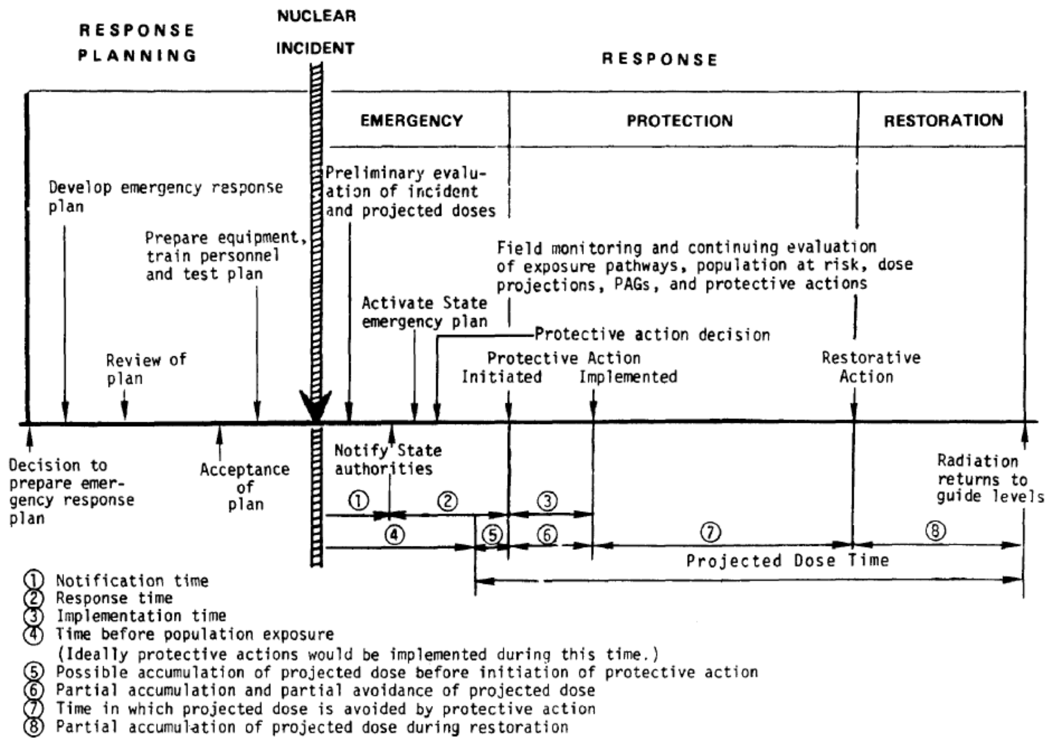

Figure 3-3 Sequence of events for responding to a nuclear incident

The 1975 PAG Manual was only partially completed. As described in a subsequent annual report on Radiation Protection Activities, the EPA was planning to provide additional PAGs for the intermediate and long term phases of response (EPA 1977). But more importantly, a basis for the PAGs was needed to quantify the risk/cost/benefit of protective actions. An evaluation of evacuation risks had already been completed, and the EPA would soon complete a study on the effectiveness of shelters and an examination of the relative benefits of shelter and evacuation. Within the next decade, the EPA would publish additional studies to assess the costs associated with evacuation and relocation, culminating in the formulation of a complete basis for the PAGs.

The EPA study on shelter effectiveness was published in 1978 as two parts: Protective Action Evaluation Part I (EPA-520/1-78-001A) and Part II (EPA-520/1-78-001B), "The Effectiveness of Sheltering as a Protective Actin Against Nuclear Accidents Involving Gaseous Releases" (EPA, 1978a; EPA, 1978b). Part I of the study described an analysis to estimate the benefit that might be derived from sheltering following a release of gaseous fission products from a nuclear power plant facility. The analysis focused on the essential parameters and general characteristics of small and large shelters available to the public. Shelter effectiveness was defined in terms of the dose reduction factor (DRF), which is the ratio of the dose that may be incurred with sheltering to that without sheltering. DRF estimates were made for the whole body and thyroid doses based on exposure to time-varying levels of gaseous radionuclide sources of krypton, xenon, and iodine. As with many of these early studies, the magnitude of the release and dose estimates were based on data from the Reactor Safety Study (WASH-1400).

A simple shelter model was constructed which accounted for representative attenuation factors and the specific geometry for cloudshine and groundshine exposure. For inhalation, no structural-filtering was assumed to hold up infiltration of gaseous xenon and krypton. For radioiodine in all its various chemical forms, a filtering value of 0.51 was assumed to approximate the filtering value of the shelter structure. The shelter effectiveness model also considered source deposition outside and inside the shelter. The analysis results primarily focused on the change in DRF over time as the shelter becomes less attractive for providing protection. The analysis also provided a number of practical insights. For example, the extent to which sheltering is an attractive option depends on the ratio of the projected dose to the PAG. Generally, when that ratio is comparable to the reciprocal of the DRF, sheltering is effective as a protective action (EPA, 1978a). However, the extent to which the results for shelter effectiveness could be applied to an actual incident could not be estimated for two reasons: (1) the analysis ignored the dose contribution from particulate radionuclides, and (2) the analysis was based on incomplete knowledge of the ingress of fission product material into a shelter. With a better understanding of these attributes, sheltering could be demonstrated to be much more effective.

Part II of the shelter effectiveness study evaluated sheltering and evacuation from the standpoint of providing guidance for emergency planning. Based on idealized calculational models of shelter and evacuation, the analysis in Part II showed that evacuation would provide the greatest margin of protection and should be the primary means of protective action (EPA, 1978b). However, this margin would vary depending on a number of factors, such that both actions should be considered when projected dose exceeded PAG levels. In an attempt to synthesize the analysis results, the EPA included a procedure for providing guidance in making decisions for protection of the public through evacuation or sheltering. The symbolic representation of this procedure is shown in Figure 3-4 (EPA, 1978b). For perhaps obvious reasons, this procedure does not appear in subsequent radiological planning guidance.

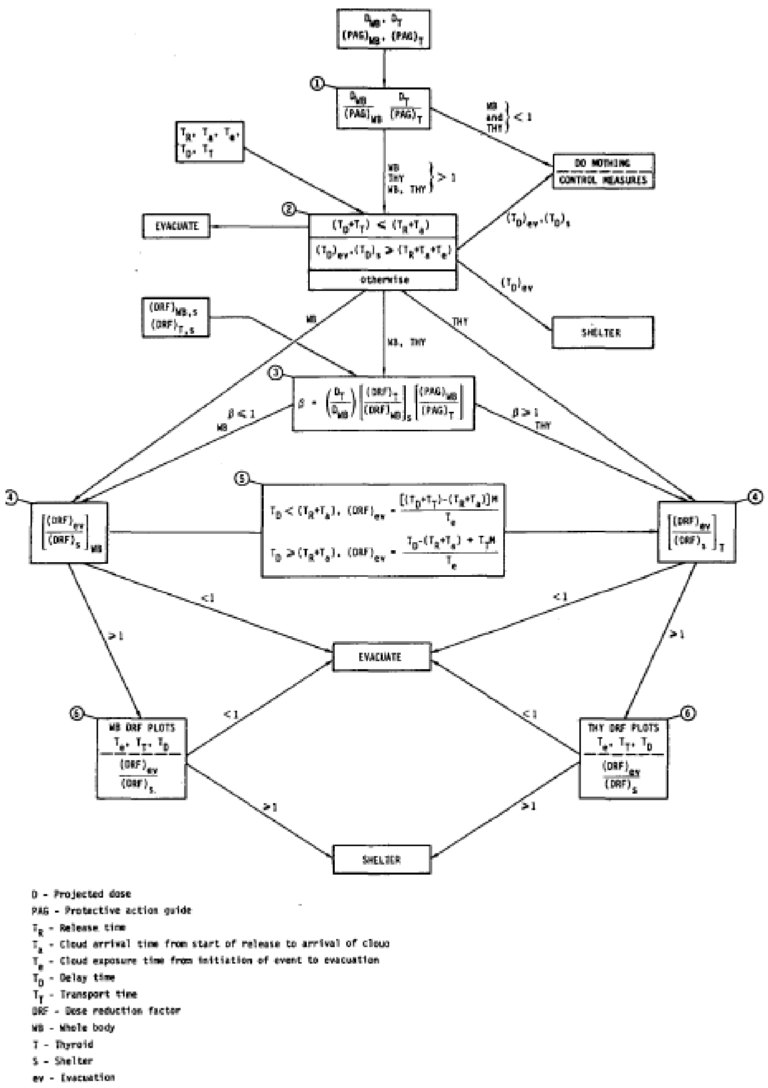

Figure 3-4 Procedure for assessing and recommending evacuation or shelter

The shelter effectiveness study concluded that principle considerations in making tradeoff evaluations for protective actions relied on detailed knowledge of the accident source term, evacuation dynamics, and shelter effectiveness. Despite the valiant effort at developing a practical decision-making tool, the EPA concluded that additional work—experimental and analytical—was needed to develop complete guidelines for evacuation and sheltering (EPA, 1978a).

Another critical piece of information needed to refine protective action decision-making was a better understanding of the accident source terms. These efforts were happening at the NRC as part of a rulemaking effort for the siting of nuclear power reactors. In the early 1980s, the NRC published a series of NUREGs in support of siting nuclear power reactors including, NUREG-0771, "Regulatory Impact of Nuclear Reactor Accident Source Term Assumptions," NUREG-0772, "Technical Basis for Estimating Fission Product Behavior During LWR Accidents," and NUREG-0773, "The Development of Severe Reactor Accident Source Terms: 1957-1981" (NRC, 1981a; NRC, 1981b, NRC, 1982a). NUREG-0773 presented a detailed description of the considerations that went into the development of a spectrum of siting source terms (SSTs) compiled from the results of probabilistic risk assessments available at the time (NRC, 1982a). NUREG/CR-2239, "Technical Guidance for Siting Criteria Development," examined the use of these representative source terms in the development of generic siting criteria, uncoupled from a specific plant design (NRC, 1982b). The three most severe siting source terms—SST-1, SST-2, and SST-3—and the information contained in these NUREGs would soon find use by the EPA.

In 1987, the EPA published EPA 520/1-87-023, "An Analysis of Evacuation Options for Nuclear Accidents" (EPA, 1987). The objective of this report was to establish relationships between radiation dose and the cost of evacuation under a wide variety of conditions. This would serve as a database for evaluating whether implementation costs and risks averted could be used to justify evacuation at lower doses than would be required based on acceptable risk of health effects alone (EPA, 1987). Cost/dose relationships were developed for 54 scenarios based on 3 severe reactor accidents, 6 meteorological conditions, and 3 angular widths of the evacuation zone corresponding to 70, 90 and 180 degrees (which translated into the number of people evacuated or exposed). The accident scenarios came from the siting source terms SST-1, SST-2, and SST-3 recently developed by the NRC. Evacuation costs were estimated at $182.90 (expressed in 1982 dollars) per individual for a 4-day evacuation period. The radiological risk was estimated at 3×10^{-4} cancer deaths per person-rem. Using a range of $400,000 to $7,000,000 as an acceptable range of costs for avoiding a statistical death from pollutants other than radiation, this amounted to $120 to $2000 per person-rem avoided. These values were then compared to the marginal cost-effectiveness of evacuation over an angle of 90 degrees. No conclusions were drawn within this study; rather it served as a database for use in formulating a basis for the PAGs.

In 1989, the EPA published a cost estimate for relocation in EPA 520/1-89-015, “Economic Criteria for Relocation” (EPA, 1989). This report provided background information on the social cost of relocating households away from contaminated areas as a result of a radiological release from a nuclear power plant and the cost of remaining within these areas for households that were not relocated. The cost of relocating a household was estimated at $66.01 per day, with additional moving costs of $1693 per accident. Results of this analysis were to be used in the development of a relocation PAG. The projected dose limit for the relocation PAG was to be established by evaluating the costs and benefits of relocation. Specifically, the net cost of relocation of $27/person/day was to be compared to the health risk to the non-relocated individual due to radioactive contamination for the period of time from the beginning of relocation (for the relocated households) through decontamination and onto the end of the relocation (EPA, 1989). The health risk cost was not estimated in this report. As with the analysis of evacuation options, these reports served to develop the basis for the PAGs that would appear in the next revisions to the PAG Manual.

The next widely used version of the PAG Manual was published in May of 1992 as EPA-400-R-92-001, “Manual of Protective Action Guides and Protective

Actions for Nuclear Incidents" (EPA, 1992a). A few precursors to the 1992 PAG Manual also exist. Although the 1992 PAG Manual contains reference to a 1980 version of the PAG Manual this version may not have been widely published but was an update to the 1975 PAG Manual in the areas to be developed.[7] A 1988 and 1990 version of the PAG Manual are available which show the evolution of the PAGs, much of which is contained in the 1992 PAG Manual (EPA, 1988; EPA, 1990).

The 1992 PAG Manual divided a nuclear incident into three phases within which different considerations would apply with regard to protective actions. These phases are termed the early, intermediate, and late phase[8], and although they do not represent precise periods of time, they provide a useful framework for considerations in emergency planning. PAGs for the early phase of a nuclear incident, taken from Table 2-1 of the 1992 PAG Manual, are shown in Figure 3-5 (EPA, 1992a).

Table 2-1 PAGs for the Early Phase of a Nuclear Incident

Protective Action	PAG (projected dose)	Comments
Evacuation (or sheltering[a])	1-5 rem[b]	Evacuation (or, for some situations, sheltering[a]) should normally be initiated at 1 rem. Further guidance is provided in Section 2.3.1
Administration of stable iodine	25 rem[c]	Requires approval of State medical officials.

Figure 3-5 1992 PAG Manual Early Phase PAGs

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[7] An extensive search was performed to look for a 1980 PAG Manual. The National Service Center for Environmental Publications (NSCEP) search results return a PAG Manual with a 1980 publication date, but the attached version is from 1988. Based on discussions in the 1988 PAG Manual, the only marked revision appears to be the incorporation of Appendix D "Technical Bases for Dose Projection Methods," into Chapter 5 of the eventual 1992 PAG Manual. This Appendix D appears as "to be developed" in the 1975 PAG Manual.

[8] The 1975 PAG Manual also divided the incident into three phases called emergency, protection, and restoration. The distinguishing events of these phases do not directly align with the emergency phases as defined in later versions of the EPA PAG Manual.

The EPA established the following four principles for PAGs in the 1992 PAG Manual:

1. *Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which such effects are not likely to occur) should be avoided.*
2. *The risk of delayed effects on health (primarily cancer and genetic effects for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health under emergency conditions, and are reasonably achievable.*
3. *PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health achievable at acceptable cost should be carried out.*
4. *Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.*

It was noted by the EPA at the time, that Principles 1, 3, and 4 had been proposed for use by the international community as the essential bases for decisions to intervene and that Principle 2 was recognized as an additional consideration (EPA, 1992a).

With the completion of a number of studies to inform selection of the PAGs, the 1992 PAG Manual included appendices to describe the risk/cost/benefit basis for the PAGs. As part of the basis for early phase PAGs, it was believed that the radiation risk avoided is usually much greater than the risk from evacuation itself. As such, evacuation of the public was recommended at a projected dose of 1 rem to an individual. The 1 rem projected dose of the 1992 PAG Manual is the sum of the committed effective dose equivalent from inhalation of radionuclides and effective dose equivalent from exposure to external radiation. This was a slight modification of the previously published PAG values for evacuation, which were based on 1 rem external gamma dose from the plume and 5 rem committed dose to the thyroid from inhalation (EPA, 1975c). The EPA performed a comparison of the PAGs and determined that the old and new PAGs provided the same level of protection; and for releases with smaller fractions of radioiodines, the new PAGs would be slightly more protective (EPA, 1992a).

Although PAG levels remained essentially the same, the 1992 guidance on protective action implementation differed from the 1975 PAG Manual in which evacuation at 1-5 rem was to be considered for pregnant women and children, and mandatory evacuation of the general public from a predetermined area was recommended when projected dose exceeded 5 rem. The exact reasons for this shift in philosophy is complex as the time period between 1975 and 1992 was significant for radiological emergency planning, and many changes came about in a short period of time as a result of the seminal events at Three Mile Island (TMI) and Chernobyl. In particular, just a few years after TMI, the NRC published the 16 planning standards for onsite and offsite emergency plans in 10 CFR Part 50. Along with these regulations came the supporting guidance document NUREG-0654/FEMA-REP-1, Revision 1, “Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants” (NRC, 1980). As the nuclear power industry and government at all levels worked to implement these new programs and exercise radiological emergency plans, a number of lessons learned continued to shape development of the EP program. Some informative discussions on these lessons learned and perspectives on radiological emergency planning for light water reactors at the time are found in the proceedings from a workshop on implementing protective actions for other radiological incidents, published in EPA 402-R-92-001, “Implementing Protective Actions for Radiological Incidents at Other Than Nuclear Power Reactors” (EPA, 1992b).

Despite the change in implementation guidance, the 1992 PAG Manual is clear that some judgment is needed when considering the taking of protective actions. Special situations or groups for which evacuation may not be appropriate at 1 rem include: severe weather, competing disasters (e.g., hurricane, earthquake), institutionalized persons who are not readily mobile, and when factors exist that may impede an evacuation. Additional guidance and some examples were provided to decision-makers for determining when sheltering may be preferable to evacuation. The 1992 PAG Manual also states, “In general, sheltering should be preferred to evacuation whenever it provides equal or greater protection” (EPA, 1992a); however, the guidance lacks clear quantification of the effectiveness of shelters and evacuation in order for a direct comparison to be made. The lack of a quantifiable understanding of the dose reduction afforded by protective actions could possibly lead to poor choice of action. For example, the PAG Manual states that evacuation is seldom justified at less than 1 rem, but also states, "in some cases evacuation may be useful at projected doses below the PAGs" (EPA, 1992a). Without a detailed understanding of the protection afforded by shelters, especially at projected doses around 1 rem, decision-makers would have little information on which to weigh the decision for protective actions.

The 1992 PAG Manual also provided PAGs for the intermediate phase, shown in Figure 3-6 (EPA, 1992a). The objective of the intermediate phase PAG was to assure that: (1) doses in any single year after the first will not exceed 0.5 rem, and (2) the cumulative dose over 50 years (including the first and second years) will not exceed 5 rem (EPA, 1992a). Based on expected source terms from a nuclear reactor accident, a PAG of 2 rem projected dose in the first year was expected to meet both objectives through radioactive decay, weathering, and normal part time occupancy in structures within contaminated areas. Implementation of relocation at this PAG value would provide reasonable assurance that a person relocated would avoid an exposure rate that would result in a first year dose of 1.2 rem. This was based on the EPA estimate that an additional 0.8 rem of exposure could be avoided through normal occupancy of homes and other structures. Additionally, for persons residing outside of the relocation zone, the implementation of simple dose reduction techniques was expected to reduce exposures to less than 1 rem in the first year. Three important points on the basis for the relocation PAG should be emphasized:

1. The 2 rem is based on meeting the objectives of not exceeding 0.5 rem in any single year after the first and not exceeding 5 rem over 50 years.
2. The 2 rem was the result of dose calculations developed from three postulated severe reactor accident source terms.
3. The expected avoided dose from relocation is actually 1.2 rem in the first year, not 2 rem.

Table 4-1 Protective Action Guides for Exposure to Deposited Radioactivity During the Intermediate Phase of a Nuclear Incident

Protective Action	PAG (projected dose)[a]	Comments
Relocate the general population.[b]	$\geq$2 rem	Beta dose to skin may be up to 50 times higher
Apply simple dose reduction techniques.[c]	$<$2 rem	These protective actions should be taken to reduce doses to as low as practicable levels.

Figure 3-6 1992 PAG Manual Intermediate Phase PAGs

Updated versions of the PAG Manual were released in 2013, 2016, and 2017. The 2013 version was a draft for interim use (EPA, 2013). An approved version was signed out in 2016 (EPA, 2016), and a final updated EPA PAG Manual was released in January 2017 (EPA, 2017a). The updated PAG Manual contains many key changes to expand use of the guidance to radiological events beyond reactor accidents and to incorporate advancements in the scientific understanding of radiation dose and risk to human health. The 2017 PAG Manual provides a refined summary of the PAG principles:

1. *Prevent acute effects.*
2. *Balance protection with other important factors and ensure that actions result in more benefit than harm.*
3. *Reduce risk of chronic effects.*

Here, a concise statement is made that protective actions should do more good than harm.

As shown in Figure 3-7, most of the PAGs and corresponding protective actions from the 1992 PAG Manual remained unchanged in the current PAG Manual (EPA, 2017a). In regard to sheltering or evacuation, PAG levels for the early phase remained the same at 1-5 rem projected dose over 4 days. The early phase thyroid PAG was revised to adopt the 5 rem projected child thyroid dose from exposure to radioactive iodine, as recommended by the FDA. And the relocation PAG of 2 rem projected dose in the first year was modified to include a projected dose of 0.5 rem/year in the second and subsequent years.[9] The EPA also stated that the updated PAG Manual removed the intermediate phase relocation PAG of 5 rem over 50 years to avoid confusion with long term cleanup, as numeric PAGs would not be used to guide restoration and recovery of areas impacted by a radiological incident (EPA, 2017a).

Table 2-1. PAGs and Protective Actions for the Early Phase of a Radiological Incident[a]

Protective Action Recommendation	PAG	Comments
Sheltering-in-place or evacuation of the public[b]	PAG: 1 to 5 rem (10 to 50 mSv) projected dose over four days[c]	Evacuation (or, for some situations, sheltering-in-place) should be initiated when projected dose is 1 rem (10 mSv).
Supplementary administration of prophylactic drugs – KI[d]	PAG: 5 rem (50 mSv) projected child thyroid dose[e] from exposure to radioactive iodine	KI is most effective if taken prior to exposure. May require approval of state medical officials (or in accordance with established emergency plans).

[a] This guidance does not address or impact site cleanups occurring under other statutory authorities such as the United States Environmental Protection Agency's (EPA) Superfund program, the Nuclear Regulatory Commission's (NRC) decommissioning program, or other federal or state cleanup programs.

[b] Should begin at 1 rem (10 mSv) if advantageous except when practical or safety considerations warrant using 5 rem (50 mSv); take whichever action (or combination of actions) that results in the lowest exposure for the majority of the population. Sheltering may begin at lower levels if advantageous.

[c] Projected dose is the sum of the effective dose from external radiation exposure (e.g., groundshine and plume submersion) and the committed effective dose from inhaled radioactive material.

[d] Provides thyroid protection from radioactive iodines only. See the complete 2001 FDA guidance, "Potassium Iodide as a Thyroid Blocking Agent in Radiation Emergencies" (FDA 2001). Further information is also available in "KI in Radiation Emergencies – Questions and Answers" (FDA 2002), and "Frequently Asked Questions on Potassium Iodide (KI)." For information on radiological prophylactics and treatment other than KI, refer to http://www.fda.gov/Drugs/EmergencyPreparedness/BioterrorismandDrugPreparedness/ucm063807.htm, https://www.emergency.cdc.gov/radiation, and www.orau.gov/reacts.

[e] Thyroid dose. See Section 1.4.2. The one-year old age group is expected to receive the largest dose to the thyroid from exposure to radioactive iodine. Therefore, it is recommended that the one-year old age group is considered when considering the administration of prophylactic KI.

Figure 3-7 2017 PAG Manual Early Phase PAGs

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[9] In the 1992 PAG Manual 0.5 rem/year in the second and subsequent years was not a PAG but was an objective of the relocation PAG of 2 rem in the first year.

Considerations on implementing evacuation vs. sheltering-in-place are described in Section 2.2.2 of the 2017 PAG Manual. During the time between PAG Manual revisions, the NRC completed a number of studies to demonstrate the effectiveness of evacuations, but no wide-scale studies of the effectiveness of shelters were performed during this time. However, because the 2017 PAG Manual serves all types of radiological incidents, information on typical shelter dose reduction factors in response to a nuclear detonation is provided, as shown in Figure 3-8 (EPA, 2017a). Despite the additional information on shelter DRFs, shelter effectiveness is assumed to be no better than what it was assessed to be 40 years prior. Specifically, shelters are assumed to be ineffective after a few hours. Consequently, the implementation guidance remains largely the same as in early PAG Manuals. The EPA did clear up evacuation guidance stating that evacuation is not recommended for dose projections of less than 1 rem over four days, and that evacuation is not justified below 0.5 rem. But in regard to sheltering, although the guidance supports use of shelters below 1 rem, for projected dose above 1 rem, sheltering is recommended over evacuation only for special populations and under special circumstances for the general population.

At this point it is worth pausing to consider a hypothetical question. Suppose the projected dose is 1-2 rem for a significant portion of the general population and that no special circumstances exist—*which protective action is better*? What the guidance needs is definitive data to support interpretation of the statement that, "Sheltering-in-place should be preferred to evacuation whenever it provides equal or greater protection" (EPA, 2017a). But in this regard the PAG Manual simply opines, "Selection of evacuation or sheltering-in-place is far from an exact science…" (EPA, 2017a). Clearly, the opportunity exists to improve the science.

Figure 2-1. Exposure Reduction from External Radiation from Nuclear Fallout as a function of Building Type and Location

The numbers represent dose reduction factors. A dose reduction factor of 10 indicates that a person in that area would receive 1/10th of the dose of a person in the open. A dose reduction factor of 200 indicates that a person in that area would receive 1/200th of the dose of a person out in the open.

Figure taken from "Planning Guidance for Response to a Nuclear Detonation," Second Edition, National Security Staff, Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats, June 2010, courtesy of Lawrence Livermore National Laboratory. The protection factors in this figure are specific to nuclear detonation fallout, but the variations in factors throughout typical buildings may be informative for other airborne radiological releases.

Figure 3-8 Building dose reduction factors for nuclear fallout

Since the introduction of the PAG in the 1960s, a key concept has remained that the decision to implement protective actions is based on the projected dose to be avoided by taking the action. It has always been upheld that PAGs could be developed to justify the risk/cost/benefit to society. The 2017 PAG Manual reiterates the principles that formed the basis for the PAGs in the following (EPA, 2017a):

1. *Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which such effects are not likely to occur) should be avoided.*
2. *The risk of delayed effects on health (primarily cancer and genetic effects for which linear nonthreshold relationships to dose are assumed) should not*

exceed upper bounds that are judged to be adequately protective of public health under emergency conditions, and are reasonably achievable.

3. *PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health achievable at acceptable cost should be carried out.*
4. *Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.*

The development of the PAGs from the 1960s to today has held to these core principles in one form or another. The information needed to form the basis for the PAGs was developed throughout the 1970s and 1980s and by the late 1980s, the basis for the PAGs was established and has remained largely unchanged since 1992. It now remains to examine whether this basis and the current PAG levels are still valid.

3.2 Examination of the Early Phase PAG Basis

The following sections are a critical examination of the principles and technical basis of the early phase PAGs to assess the degree to which the historical basis holds up and to uncover the driving principles for the recommended PAG values that have remained largely unchanged since the 1960s.

3.2.1 Principle 1 – Prevent Acute Effects

The prevention of acute effects has no practical influence on the selection of early phase PAG levels. This is so much the case that the 2017 PAG Manual states that the avoidance of acute health effects requires no additional consideration. One has to go back to earlier versions of the PAG Manual to find any further discussion. The 1992 PAG Manual states that the assumed threshold for prompt effects is much higher (50 to 300 rads) than any PAG that would satisfy the remaining principles and, "Thus, Principle 1 has no effect on the choice of the PAG level" (EPA, 1992a). Although the PAGs accomplish the intent behind Principle 1, it is clear that early phase PAG levels are so low that no balance to the risk of acute effects was used to establish the upper PAG limits.

3.2.2 Principle 2 – Risk of Delayed Effects

The EPA analysis of the risk of delayed effects has changed very little over the years and the 2017 PAG Manual simply refers back to the basis in the 1992 PAG Manual. Based on Principle 2, evacuation of the public is not justified below 0.5 rem. The statistical risk of delayed effects is estimated at 0.0003 cancer deaths per person-rem, which represents a risk of 0.00015 for fatal cancer at 0.5 rem. Maximum lifetime risk levels considered acceptable by EPA range from 0.000001 to 0.0001 for routine operations (EPA, 1992a). These risk estimates result in a maximum dose in the range of 100 to 200 millirem under normal conditions. Since there was no clear precedent for choosing different acceptable risks for normal versus emergency conditions, the EPA assumed a factor of 5 to 10 was not unreasonable and concluded that a projected dose of 1 rem would satisfy Principle 2 (EPA, 1992a). Although the EPA has published a revised risk estimate of 5.8×10^{-4} cancer deaths per person-rem (EPA, 2011a), even if this value were used in the PAG basis it would only increase the risk estimate by a factor of 2 and would still be within the EPA's estimated range of acceptable risk for emergency situations.

Part of the difficulty in establishing a dose level to satisfy Principle 2 results from use of the linear no-threshold hypothesis. Since it is assumed there is no threshold dose for delayed health effects, the determination of a dose value that is adequately protective of the public under emergency conditions is a judgment on acceptable risk. As such, the only basis EPA had in setting this standard was to compare the risk of delayed effects to the acceptable risks for other carcinogens.

The literature is saturated with the criticisms and short-comings of the LNT hypothesis to the point that no effort is needed to remind the reader herein. Instead, two points must be made in regard to the use of low-dose models in the PAG basis. First, as an understanding of the biological effects of radiation at low dose increases, this knowledge can and should be used to replace the LNT hypothesis. This could result in a different PAG level that, presumably, would be more scientifically supported. Secondly, radiation effects at low dose have been so extensively studied that regardless of which low-dose model prevails, the risk of delayed effects from doses as low as PAG levels are likely to remain vanishingly small, to the point of being indistinguishable from other causes. The 1992 PAG Manual included a chart (shown in Figure 3-9) to compare the risk associated with radiation to those associated with several other risks to which the public is commonly exposed (EPA, 1992a). The lifetime risk of accidental death in even the safest occupations is comparable to the lifetime cancer risk associated with a dose of 5 rem. So why was 1 rem chosen as the PAG level at which to consider taking action? Would not 5 rem also be an acceptable level of risk? It needs to be emphasized that regardless of the dose response model chosen, the basis for Principle 2 *is also driven by a presumed level of acceptable risk*. But what constitutes acceptable risk? That question will be examined later, it now remains to examine if Principle 2, based on acceptable risk, is balanced against Principle 3 (cost) and Principle 4 (health effect of protective action).

3.2.3 Principle 3 – Balance of Cost

To estimate the upper and lower bounds on dose for evacuation based on cost, the EPA considered common values placed on avoiding risk. The EPA used $400,000 to $7,000,000 as an acceptable range of costs for avoiding a statistical death. Using an assumed risk of $3x10^{-4}$ cancer deaths per person-rem, a resultant range of $120 to $2000 per person-rem avoided was compared to the marginal cost-effectiveness of evacuation over an angle of 90 degrees. The cost basis considered three generic siting source terms (SST-1, SST-2, and SST-3) over a range of atmospheric stabilities and evacuation scenarios. An example for SST-2 is shown in Figure 3-10 (EPA, 1992a). The overall results are summarized in Table 3-1, taken from Table C-4 of the 1992 PAG Manual (EPA, 1992a). From this analysis, the EPA concluded that under Principle 3, evacuation is only justified at values equal to or greater than 0.5 rem (maximum evacuation cost), and not justified above 5 rem (minimum evacuation cost).

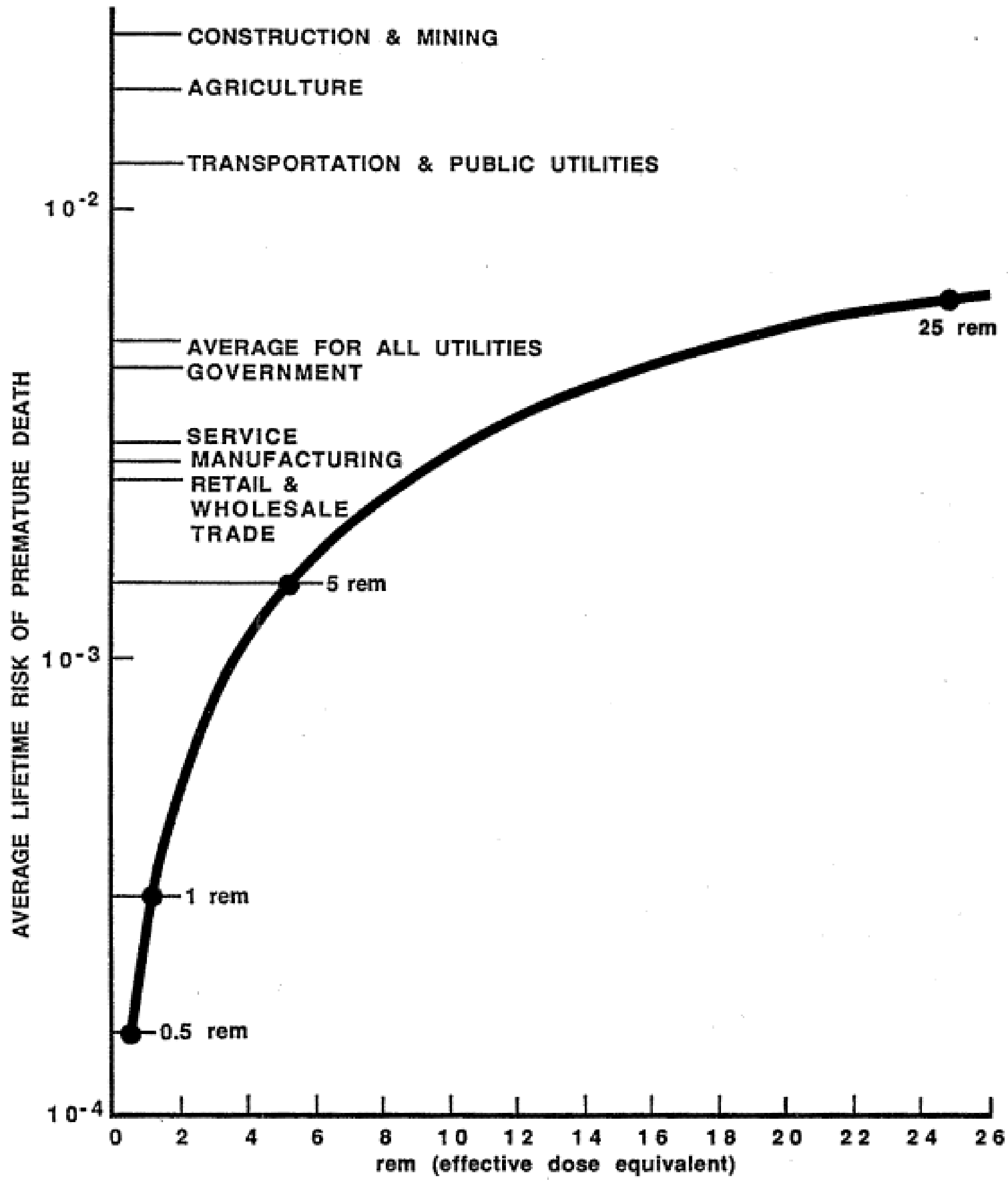

Figure 3-9 Chart of risk comparisons

Table C-2 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class C)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	Δ Cost (dollars)	Δ Dose avoided (person-rem)	Δ Dollars/ Δperson-rem avoided
70	0.5	4.95E+7	1.13E+5	439	3.71E+7	4.95E+4	750
	1	1.23E+7	6.31E+4	195	9.87E+6	2.58E+4	382
	2	2.46E+6	3.73E+4	66	1.68E+6	1.02E+4	165
	5	7.82E+5	2.71E+4	29	3.89E+5	6.15E+3	63
	10	3.93E+5	2.10E+4	19	1.32E+5	4.75E+3	28
	20	2.60E+5	1.62E+4	16	3.40E+4	2.50E+3	10
	50	(a)	(a)	(a)			
90	0.5	6.35E+7	1.13E+5	564	4.77E+7	4.95E+4	964
	1	1.58E+7	6.32E+4	250	1.27E+7	2.58E+4	491
	2	3.11E+6	3.74E+4	83	2.16E+6	1.02E+4	212
	5	9.48E+5	2.72E+4	35	5.00E+5	6.16E+3	81
	10	4.47E+5	2.10E+4	21	1.70E+5	4.76E+3	36
	20	2.77E+5	1.63E+4	17	3.40E+4	2.50E+3	14
	50	(a)	(a)	(a)			
180	0.5	1.25E+8	1.13E+5	1110	9.44E+7	4.95E+4	1910
	1	3.10E+7	6.32E+4	491	2.51E+7	2.58E+4	971
	2	5.95E+6	3.74E+4	159	4.28E+6	1.02E+4	419
	5	1.68E+6	2.72E+4	62	9.90E+5	6.16E+3	161
	10	6.87E+5	2.10E+4	33	3.36E+5	4.77E+3	70
	20	3.51E+5	1.63E+4	22	6.70E+4	2.50E+3	27
	50	(a)	(a)	(a)			

[a] The 4-day dose does not exceed the PAG outside the 2-mile radius of the accident site. The total cost of evacuation within this radius is 2.02E+5 dollars; the total dose avoided is 2.78E+3 person-rem; and the total cost per person-rem avoided is $73.

Figure 3-10 Example costs for implementing PAGs for SST-2 type accident

Table 3-1 Cost basis for evacuation

Table C-4 Upper Bounds on Dose for Evacuation, Based on the Cost of Avoiding Fatalities[a]

Accident Category	Atmospheric Stability Class	Dose Upper Bounds[b,c] Maximum (rem)	Minimum (rem)
SST-1	A	5	0.4
	C	5	0.4
	F	10	0.8
SST-2	A	1	0.15
	C	3.5	0.25
	F	10	0.7
SST-3	A	(d)	(d)
	C	(d)	(d)
	F	5	0.45

[a] Based on data from EP-87a.

[b] Windspeeds typical of each stability class were chosen.

[c] Based on an assumed range of $400,000 to $7,000,000 per life saved.

[d] For stability classes A and C, the dose from an SST-3 accident is not predicted to exceed 0.5 rem outside a 2-mile radius. It is assumed that evacuation inside this radius would be carried out based on the emergency condition on the site. No differential evacuation costs were calculated within this area.

However, like the estimate of the cancer risk, the cost estimates for evacuation used to justify the PAGs have remained unchanged since the 1980s. The cost of evacuation used in the basis is the 1987 estimate of $183.90 per person for a 4-day evacuation (actually expressed in 1982 dollars). It is reasonable to expect that this analysis will not hold up if factors such as inflation, adjusted cost of statistical value of life, and cancer risk estimates are adjusted. A brief examination of those factors will now be considered.

The EPA currently recommends a central estimate of $7.4 million be used in all benefits analyses.[10] This value is based on 2006 dollars, and EPA has provided guidance for use of this value, including how to adjust the base year, in “Guidelines for Preparing Economic Analyses” (EPA, 2010a). Appendix B of these Guidelines shows this estimate to have a Weibull distribution with standard deviation of $4.7 million (EPA, 2010b). Using the 2006 value, assuming a normal distribution with one standard deviation, and assuming a cancer-related risk of 0.0003, results in a range of $810 to $3630 per person-rem avoided. This represents an increase of about 2 to 6 times the cost of the 1987 estimate. The NRC provides their own estimate of this cost-benefit analysis to monetize the health detriment of radiation in dollars per person-rem of collective dose. The NRC analysis is based on total health detriments including mortality and morbidity. The current analysis provided in NUREG-1530, Revision 1, “Reassessment of NRC’s Dollar Per Person-Rem Conversion Factor Policy,” estimates the dollar per person-rem conversion factor as $5100 per person-rem (NRC, 2015a). This is based on a statistical life value of $9.0 million and a nominal risk coefficient factor of 5.7×10^{-4} per person-rem. In general, as the dollars per person-rem increases, the justified value of the PAG should decrease. In comparing this updated range of costs to Table 3-1, a value of 0.5 rem would likely be an upper limit to the PAG based on dollars per person-rem avoided.

[10] https://www.epa.gov/environmental-economics/mortality-risk-valuation#whatvalue

But the PAG should also be balanced against the cost of evacuation, which has also increased. The 1987 cost analysis primarily considered four components to the evacuation cost: lodging, food, transportation, and lost income. Lodging accounts for the hotel rooms necessary to house the evacuated population, food covers a set cost per person per day, transportation is the amount of gas necessary to move out of and back into the evacuation zone (assumed 100 miles round trip), and lost income provides an amount of money for those who have to miss work due to the evacuation order.

A revised cost estimate can be made using current Federal rates and wage data. The costs were estimated for two representative NPP locations, representing both rural and urban demographics. The cost for food and lodging are taken from the U.S. General Services Administration per diem rates for the selected regional locations (GSA, 2021). Population information was gathered from the site-specific ETE studies which are based on the 2010 Census data. Based on this data, the average number of individuals per household, is approximately 2.5 for both locations. A single household is assumed to share a vehicle for transportation and lodging. The costs associated with lodging for the two NPP locations were estimated at $110.00 per day and $96.00 per day. An average cost of $103 per day was converted into a per person number by dividing by the number of individuals per household (2.5) resulting in a final lodging cost of $41.20 per person per day. Food costs were estimated at $55.00 per person per day using the GSA per diem rates. The transportation cost is assumed to account for 100 miles roundtrip, 50 miles out of the zone and then 50 miles back in as was assumed in the 1987 cost analysis (EPA, 1987). The Internal Revenue Service (IRS) issues standard mileage rates, which was 57.5 cents per mile as of January 1, 2020. This value was used to estimate an average cost of $57.50 for the roundtrip of 100 miles. This amount is divided by the number of individuals per household to find a single-time cost of $23 per person per evacuation. The lost income per person per day is slightly more nuanced than the other three cost areas. Wage was specifically considered, as it does not account for the income in the population such as unemployment insurance, child support payments, liability payments, and similar supplements. Therefore, the Average Wage Index provided by the Social Security Administration was used to find both the average wage and the ratio of the population that is employed (SSA, 2021). The amount of lost income per person per day was found to be $87.30. Combining the daily and one-time costs results in the following equation for estimating evacuation costs for a specified number of days,

$$\text{Evacuation cost (dollars/person over } d \text{ days)} = 183.5 \cdot d + 23$$

Using this equation, a 4-day evacuation cost is estimated as $757 per person. This is approximately 4 times higher than the 1987 4-day cost estimate of $183 per person. As evacuation costs increase, the justified PAG should also increase. But the 2017 PAG Manual does not provide any revised cost estimates or discussion on why the cost basis from the 1992 PAG Manual should remain valid.

From the updated estimates of the health cost per person-rem and evacuation cost per person-rem, it can be seen that these cost factors are diametrically opposed in regard to the PAG. An increase in the health cost per person-rem supports evacuation at lower values than the current PAG, yet an increase in the 4-day evacuation cost suggests evacuation may not be justified at current PAG levels. Over time, it is possible that the divide between the upper and lower PAGs supported by this cost analysis would further increase, until eventually no meaningful comparisons could be made to the other PAG Principles in order to balance the overall risk/cost/benefit. As it is, both average costs have increased by a factor of about 4 since 1987. As such, an updated cost estimate might result in only a minor adjustment of the justified PAG. However, there is one glaring assumption that needs to be addressed. The foregoing cost analysis assumes a 4-day evacuation. Experience shows a prolonged evacuation duration is more likely. If so, then how might that affect the PAG?

The cost basis for the PAGs compares two dissimilar costs. The cost associated with the risk of radiation exposure is a lifetime risk. The cost associated with evacuation is an assumed cost over 4 days. Using the cost equation above, the estimated cost per person for different evacuation durations is shown in Table 3-2.

As seen in the table, the cost of evacuation exceeds the NRC estimate of the health detriment cost after 30 days.[11]

Table 3-2 Evacuation cost per-person for various evacuation durations

Evacuation Duration (Days)	Evacuation Cost (Dollars per-person)
4	$757
7	$1308
10	$1858
30	$5528
60	$11033
90	$16538

The cost basis for the PAGs makes the explicit assumption that the evacuation only lasts 4 days. Evacuation, in theory, is expected to be only temporary—just enough time is needed to avoid exposure to the plume. However, the return of evacuees to their residences (outside of restricted zones) is assumed to occur within a week or more from the time of the incident (EPA, 1992a). The longer the affected population remains evacuated, the less the PAG remains justified in terms of cost, but these costs were not considered in development of the early phase PAG. Presumably, any cost beyond four days would be accounted for in relocation costs for the population; however, as will be shown later, relocation costs are also out of date and underestimated.

Principle 3 is also problematic in that the historical cost basis is only used to justify the PAG level as it pertains to evacuation. No effort was made to assess the dose that could be avoided by sheltering and to balance the risk of sheltering against the cost. From this, it can be concluded that Principle 3 has significant limitations. First, the cost estimates are not expressed in current dollar values and do not make use of updated estimates of the statistical value of life or cancer risks. Next, the cost

[11] The NRC estimate of $5100 per person-rem is higher than the 1992 EPA estimate of $2000 per person-rem.

analysis is only valid for a 4-day evacuation, yet an actual evacuation would likely extend for a much longer period of time, which would alter the cost/risk/benefit balance. Finally, the cost benefit of sheltering has not been quantified. Consequently, it remains to be seen if an updated cost analysis would continue to support PAGs at the current levels. But perhaps that point is moot after consideration of the final PAG principle, that the risk of the protective action should do more good than harm.

3.2.4 Principle 4 – Risk of Protective Action

Principle 4 states that above all the other principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided. The EPA study of transportation incidents resulted in a risk from travel of about 9×10^{-8} per person mile. For the assumed 100-mile round trip, this resulted in a fatality risk of 9×10^{-6} per person. For an assumed risk of fatal cancer of 3×10^{-4} per person-rem, the evacuation risk is then equivalent to 0.03 rem. For populations more at risk from an evacuation (e.g., elderly populations), the risk equivalent is 0.15 rem (based on a factor of 5 for at-risk populations). Over the years, enhancements in vehicle safety have only lowered the risk of fatal car accidents. In fact, current estimates of transportation fatalities are almost half of what they were in 1978, as shown in Figure 3-11 from data provided by the U.S. Department of Transportation (DOT, 2021). As such, an updated analysis in support of the PAG basis would likely lead to the conclusion that the evacuation mortality risk is equivalent to about 0.015 rem. Similar to the principle of avoiding acute risks, Principle 4 does not influence the PAG level (EPA, 1992a; EPA, 2017a), even as a lower bound.

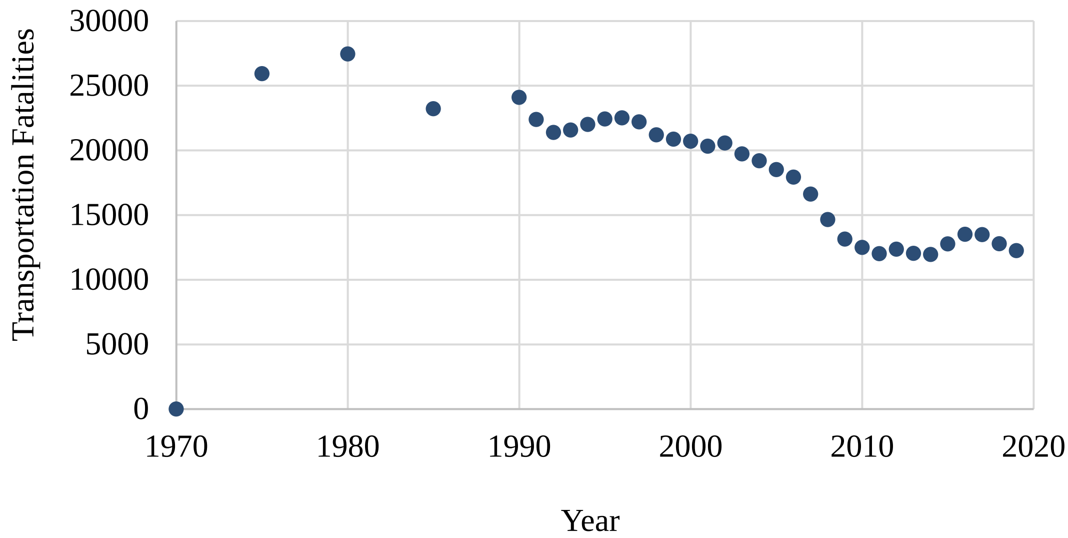

Figure 3-11 Passenger car fatalities by year

The EPA estimate of the evacuation risk is practical as it applies to an assumed short duration evacuation (perhaps 4 to 7 days). However, the longer a population stays displaced from its home community, the larger the impact of the protective action becomes in terms of health effects. An assessment of the long term health effects due to evacuation and relocation, and even sheltering, has not been applied to the basis for the PAGs. If included in the PAG basis, these long term health effects would have an important impact on the justified PAG level.

An estimated 100,000 people evacuated Fukushima Prefecture, of which approximately 80,000 were evacuated by the authorities and the rest evacuated on their own. It is also estimated that at least 2000 people died from the effects of evacuations ordered as necessary to avoid radiation exposure from the Fukushima event. Although this is a singular event, the mortality risk from this evacuation is roughly estimated as 0.02. This risk is more than 2000 times the risk of death from a traffic incident during the evacuation or relocation. Assuming a fatal cancer risk of 0.0003 per person-rem, and an evacuation fatality risk of 0.02, the evacuation risk equivalent is 67 rem. If the majority of the population at risk were elderly—for whom the health risk of prolonged displaced is higher—then it is reasonable to reduce this value a factor of 5 to find an equivalent projected dose level for the general population.[12] This results in 13 rem as the minimum justifiable projected dose for an evacuation.

Since Principle 4 surpasses all other principles, a PAG that accounted for a holistic view of the health effects of protective actions would likely result in a much higher projected dose level for evacuation than prescribed by the current PAG levels. Although the added risk considerations described herein are related to the long-term health consequences of evacuations and relocations, even the mortality risk of evacuation, estimated by the EPA to be in the range of 30 to 150 mrem, is perhaps underestimated. In one study, a survey of the risks associated with 320 evacuation events from 1972 to 1985 found an individual's mortality risk to be equal to a radiation dose between 110 and 5800 mrem, depending on the dose response model used to assess the risk for a roundtrip evacuation (Witzig, 1987). It was also found that the risks associated with an evacuation of a 16-km radius area was approximately 100 times greater than the risks associated with a 3.2-km radius evacuation (Witzig, 1987). In addition, this study compiled data on the risk and cost of injury related to the evacuation. These study results suggest that the lower bound on the PAG level based on Principle 4 should actually be higher than current estimates. Certainly, this study supports the idea that an evacuation should involve the smallest response area necessary in order to reduce the risk of mortality or harm during the evacuation event. Minimizing the number of evacuees would have the added benefit of reducing the long-term negative health consequences of an evacuation. These longer-term health consequences also extend to the risk of relocation. Although relocation is a more deliberate protective action, the relocation PAG is based on the same principles as the early phase PAG. As such, the basis for the relocation PAG will be examined next.

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[12] This factor of 5 is based on the PAG range of 1 to 5 rem and on the factor of 5 applied to persons at high risk of evacuation used to satisfy Principle 4 for the early phase and relocation PAGs as described in Appendix C and E of the 1992 PAG Manual and Section 2.3.4 "Higher PAGs for Special Circumstances" of the 2017 PAG Manual.

3.3 Examination of the Relocation PAG Basis

Appendix E of the 1992 PAG Manual provides the basis for the intermediate phase PAG of 2 rem in the first year. A summary of the considerations for selecting the PAGs for relocation are shown in Figure 3-12 (EPA, 1992a). The same basis is carried forward to the 2017 PAG Manual which added the additional PAG of 0.5 rem in subsequent years. The major considerations for the intermediate phase are the same four principles of the early phase (EPA, 1992a). However, the EPA stated that considerations for the intermediate phase PAGs differed from those for the early phase with regard to implementation. Specifically, Principles 3 and 4 differ in regard to the cost of avoiding dose and the practicability of leaving special populations in the restricted zones. A critical examination of the PAG principles as they apply to relocation are provided in the following.

Table E-5 Summary of Considerations for Selecting PAGs for Relocation

Dose (rem)	Consideration	Principle
50	Assumed threshold for acute health effects in adults.	1
10	Assumed threshold for acute health effects in the fetus.	1
6	Maximum projected dose in first year to meet 0.5 rem in the second year[a].	2
5	Maximum acceptable annual dose for normal occupational exposure of adults.	2
5	Minimum dose that must be avoided by one year relocation based on cost.	3
3	Minimum projected first-year dose corresponding to 5 rem in 50 years[a].	2
3	Minimum projected first-year dose corresponding to 0.5 rem in the second year[a].	2
2	Maximum dose in first year corresponding to 5 rem in 50 years from a reactor incident, based on radioactive decay and weathering only.	2
1.25	Minimum dose in first year corresponding to 5 rem in 50 years from a reactor incident based on radioactive decay and weathering only.	2
0.5	Maximum acceptable single-year dose to the general population from all sources from non-recurring, non-incident exposure.	2
0.5	Maximum acceptable dose to the fetus from occupational exposure of the mother.	2
0.1	Maximum acceptable annual dose to the general population from all sources due to routine (chronic), non-incident, exposure.	2
0.03	Dose that carries a risk assumed to be equal to or less than that from relocation.	4

[a]Assumes the source term is from a reactor incident and that simple dose reduction methods are applied during the first month after the incident to reduce the dose to persons not relocated from contaminated areas.

Figure 3-12 Considerations for relocation PAG

3.3.1 Principle 1 – Prevent Acute Effects

Based on the avoidance of acute effects (Principle 1), an upper bounds on the dose for relocation of the general population was set at 50 rem for adults and 10 rem for fetuses. The analysis supporting these lower dose bounds for acute effects is described in Appendix B of the 1992 PAG Manual. The same analysis is used to support both the early and intermediate phase PAGs, but it is not clear why this should be the case, particularly for the intermediate phase. Early phase PAGs are based on a 4-day dose and the intermediate phase dose is projected over 1 year. The duration of exposure matters when it comes to the biological effects of radiation. But the EPA did not provide an explanation as to why the 50 rem and 10 rem bounds are appropriate over an assumed exposure duration of 1 year. Also unclear is how such a large dose could be accumulated. The primary exposure pathway for the intermediate phase is external whole body gamma radiation. Inhalation is expected to be minimal, and ingestion exposure from contaminated food and water are not considered in the relocation PAG. The siting source terms used by the EPA were the three most severe accident types based on core inventory and release fractions (NRC, 1982a). Yet, it was not demonstrated that these source terms could be expected to produce an annual dose on the order of 10 to 50 rem. Similar to the early phase PAG, Principle 1 had little influence on the chosen PAG.

3.3.2 Principle 2 – Risk of Delayed Effects

On the basis of control of chronic risks (Principle 2) 5 rem was assigned as an upper bound on the acceptable controllable lifetime exposure to radiation from accidentally deposited radioactive materials (EPA, 1992a). This value seemed reasonable to the EPA, since over a period of 50 years, 5 rem corresponded to an average annual exposure of 100 mrem—a value commonly accepted as an upper bound for chronic annual exposure of the public from all sources of exposure other than natural background and medical radiation. Aside from this, there is no real basis for an upper bound of 5 rem. As shown in Figure 3-9, 5 rem was believed to be comparable to other risks faced by society. In comparison to the risk of premature death normally confronting the public, similar risk of death from radiation-induced cancer was expected in a range of doses from about 0.07 to 33 rem (EPA, 1992a). It can be seen then that 5 rem is in the middle of this range with respect to order of magnitude.

For projected doses from nuclear reactor accidents, a 5 rem lifetime dose was estimated to corresponded to about 1.25 to 2 rem from exposure during the first year and 0.4 to 0.5 rem, or less, in subsequent years (EPA, 1992a). From this, the PAG level of 2 rem became the derived value representing the maximum dose in the first year that would ensure less than 5 rem over 50 years as shown in Figure 3-13 (EPA, 1992a).

The first year and subsequent year dose estimates leading to 5 rem over 50 years are worth further examination. Figure 3-13 shows the annual doses corresponding to 5 rem in 50 years. From this figure it can be seen that a PAG of 2 rem in the first year and 0.5 rem in the second and subsequent years would limit the 50 year exposure to 5 rem. However, there are some nuances to consider. To start, these siting source terms are based on WASH-1400 reactor inventories and release fractions. No effort has been made to update this analysis using state-of-the-art source term information. This is important because the values derived below are based only on the mix of radionuclides from the release and do not represent the actual severity and probability of exceeding these doses for the event listed. This is obvious, because as shown in Table E-3 of the 1992 PAG Manual, SST-3 has estimated release quantities that are four orders of magnitude lower than SST-1 and two order of magnitude lower than SST-2. Yet, because the source terms were normalized to yield 5 rem over 50 years, SST-3 is shown as the limiting case for relocation even though this accident sequence is not expected to exceed a dose of 0.5 rem outside a 2-mile radius as shown in Table C-4 of the 1992 PAG Manual.

The relocation PAG set on Principle 2 suffers from limitations similar to the early phase PAG. First, the whole basis for the relocation PAG rests on an arbitrary

50 year dose of 5 rem, judged to be the acceptable level of lifetime risk. The relocation PAG was also chosen to ensure subsequent year doses do not exceed 0.5 rem. The value of 2 rem was chosen to meet these limits, but this value is based on outdated source term data from WASH-1400. It may be worth re-examining the basis for the PAGs using updated source terms, but the 2017 PAG Manual introduced another problem that would complicate the analysis.

Section 1.3.5 of the 2017 PAG Manual describes key changes to the updated manual. Among the changes, the EPA removed the intermediate phase relocation PAG of 5 rem over 50 years to avoid confusion with long-term cleanup (EPA, 2017a). The rationale for this decision is further described in Section 4.2.1. The removal of this “PAG” raises several questions and creates a few problems. First, it should be remembered that the PAG of 2 rem is based on meeting the objectives of not exceeding 0.5 rem in any single year after the first and not exceeding 5 rem over 50 years. As such the 5 rem over 50 years was never a PAG. In removing this “PAG” the EPA effectively removed the basis for the 2 rem. Yet the EPA retained 2 rem projected over the first year as the relocation PAG and added another PAG of 0.5 rem projected over any subsequent year to “keep emergency management decisions as simple as possible” (EPA, 2017a). In other words, the primary basis for the relocation PAG was removed and the other basis was added as a PAG itself. This means there is no longer an established basis for the relocation PAG based on Principle 2. As such, while the relocation PAG may simplify decision-making, there is no basis that ensures this is the correct decision. Presumably, the relocation PAG is at least balanced by the other principles—however an examination of Principles 3 and 4 will show this not to be the case.

Table E-3 Annual Doses Corresponding to 5 Rem in 50 Years[a]

Year	Dose According to Accident Category[b] (rem)		
	SST-1	SST-2	SST-3
1	1.25	1.60	1.91
2	0.52	0.44	0.38
3	0.33	0.28	0.24
4	0.24	0.20	0.17
5	0.18	0.16	0.13
6	0.14	0.12	0.11
7	0.12	0.11	0.090
8	0.10	0.085	0.070
9	0.085	0.075	0.065
10	0.080	0.070	0.060
11	0.070	0.060	0.050
12	0.060	0.055	0.050
15	0.055	0.045	0.040
20	0.045	0.040	0.030
25	0.040	0.035	0.025
30	0.030	0.030	0.025
40	0.025	0.020	0.020
50	0.020	0.015	0.010

Figure 3-13 Annual doses corresponding to 5 rem in 50 years

3.3.3 Principle 3 – Balance of Cost

On the basis of cost alone, Principle 3 would not drive the relocation PAG to values of less than 5 rem (EPA 1992a; EPA, 2017a). As described earlier, the EPA published background information on the social cost of relocating households away from contaminated areas (EPA, 1989). Household estimates of the relocation cost amounted to \$66.01 per day and included a one-time cost per accident of \$1693. This resulted in a net cost of relocation of \$27 per person per day (EPA, 1989). To satisfy Principle 3, the quantity of interest is the dose at which the value of the risk avoided is equal to the cost of relocation. The equation for this is given as (EPA, 1992a),

$$D = \frac{C}{VR}$$

where D is the effective dose, C is the cost of relocation, V is the value of avoiding a statistical death (estimated at \$400,000 to \$7,000,000 in 1992), and R is the statistical risk of death from radiation (0.0003). Based on these numbers, the dose to be avoided to justify the cost of relocation would be about 5 to 80 rem.

A conservative estimate of an updated cost that would justify relocation can be made using the EPA 2006 baseline statistical value of life of $7.6 million, giving $2280 per person-rem as the quantity VR, and assuming that relocation costs, C, have increased over the years by a factor of 4 (as estimated for evacuation). These assumptions result in a first year dose of 17 rem. Even using the higher NRC published dollars per person-rem conversion factor of $5100 results in a first year dose of 8 rem. The conclusion is obvious, the relocation PAG of 2 rem is not balanced according to Principle 3.

3.3.4 Principle 4 – Risk of Protective Action

The EPA did not perform a separate estimate of the risk of relocation. This was partly because no data was available on differing risks of relocation for different population groups (EPA, 1992a). Instead, the traffic incident risk used to assess the risk of evacuation was assumed to apply to relocation as well. This provided a lower bound for relocation of 0.15 rem, which is the dose equivalent to the risk for persons at high risk of evacuation. Given the arbitrary nature of the derivation, the EPA stated that, “it is fortunate that this value is much lower than the PAG selected, and is therefore not an important factor in its choice” (EPA, 1992a). As shown for the early phase PAG, if the true health risks of relocation are accounted for, the justified dose to ensure that relocation does more good than harm would exceed 10 rem.

Like the early phase PAG, the relocation PAG is primarily based on Principle 2, but is set at a level that does not satisfy Principles 3 and 4 and does not consider Principle 1. As such, the PAG is not justified. On top of this, the basis for the relocation PAG was removed from the PAG Manual. This is an important point that seems to have been overlooked. In addition to the PAG principles, a planning group consisting of Federal, state, and industry officials provided recommendations in 1982 which the EPA considered in the development of the relocation PAG. These recommendations included (EPA, 1992a):

1. *The PAGs should be based primarily on health effects.*
2. *The PAGs should be established as high as justifiable…*
3. *PAGs should apply only to exposure during the first year after an incident.*

It is obvious that the relocation PAG fails to meet all of these recommendations. The PAG was never justified on the basis of the health risk of relocation. The PAG was not set as high as justifiable, even though Principle 3 supports a higher level. And a PAG for exposure in subsequent years after the first year was added to the PAG Manual.

3.4 Risk Balance of the PAG Basis

In summary, the basis for the early phase and relocation PAGs do not hold up under examination. Fundamentally, the PAG level is set by Principle 2 alone. There is no balance to the radiological risk. Furthermore, the stochastic radiological risk is based on an acceptance of the LNT hypothesis, which is an incomplete model of the biological effects of radiation at low dose. Principle 2 is also based on the concept of acceptable risk. But the acceptable risk is set by the EPA at a level much lower than other acceptable levels of risk tolerated by society. The uncertainty in the assumptions and models supporting Principle 2 alone are enough to question the PAG levels and certainly deserves more attention by academics, policy-makers, and the public.

Principles 1, 3, and 4 should support the PAG level set by Principle 2, yet this is not the case. Principle 1, as directly stated by the EPA, has no impact on the PAG level. Principle 3 is based on outdated cost estimates and fails to consider the cost of a prolonged evacuation in justifying the PAG level for the early phase PAG. For relocation, Principle 3 is largely ignored, when it could have been used to justify establishing a higher PAG level. And Principle 4—the overriding principle that protective actions should do more good than harm—fails to account for a realistic and holistic view of the public health risks of evacuations and relocations. If based on Principle 4 alone, evacuations and relocations would likely not be justified for doses below 10 rem. Simply put, the current balance of the risk does little to inform making practical decisions on protective action implementation.

3.5 Restoring the Balance

The purpose of this review of the PAGs and their bases was to examine the historical development of the PAG Manual in order to reveal the fundamental principles that should drive protective action decision-making and to take a critical look at the factors that have changed through the years. While the principles remain valid, the historical basis for the PAGs do not hold up, so what can be done? One option would be to revise the PAG levels to reflect the current understanding of the risk/cost/benefit tradeoff. Certainly, it would appear that raising the PAG level for evacuation or relocation to a range 5-10 rem could be justified.

But perhaps the EPA is stuck between a rock and a hard place when it comes to the PAGs. There is a general consensus among scientists and professional organizations that 10 rem (100 mSv) represents the boundary between low and high dose. The reference levels for early phase protective action contained in International Atomic Energy Agency (IAEA) guidance and as recommended by the International Commission on Radiological Protection (ICRP) are generally not to exceed 100 mSv (IAEA, 2011; IAEA, 2015; ICRP, 2020). Most people might also agree that an evacuation is warranted to reduce dose and prevent deterministic and stochastic health effects above a 4-day projected dose of 10 rem. There is also a general sense that below 1 rem, the risk is low enough not to warrant protective actions such as evacuation and relocation. This leaves the range of 1-10 rem within which to decide upon the best course of action. Even if the PAGs were revised to the upper end of this range (i.e., 5-10 rem) the problem remains to decide upon which action to take. PAGs are trigger levels; the PAGs are there to help decide when to take action. But numerical PAGs alone do not indicate *which* action to take. For this reason, the PAG

Manual provides considerations for how best to implement evacuation and sheltering-in-place once a PAG is projected to be exceeded. Currently, evacuation is still the preferred initial course of action. But given the increasing attention to the long term health risks of evacuation and relocation, maybe it's time to give sheltering-in-place another look.

3.6 Reconsidering Sheltering-in-Place

Sheltering involves staying inside a structure with doors and windows closed and ventilation systems shut off. Sheltering-in-place is a low-cost, low-risk protective action that can provide protection with an efficiency ranging from up to 100 percent, depending on the circumstances (EPA, 1992a). The protection afforded by shelters is often characterized by a dose reduction factor, defined as,

$$DRF = \frac{dose\ with\ protective\ action}{dose\ without\ protective\ action}$$

Estimated dose reduction factors for external exposure to gamma radiation are shown in Table 3-3 (EPA, 1992a). These values are the assumed initial values prior to infiltration of radionuclides into the building interior; as such, they were considered applicable only for a short duration plume. However, the reduction in shelter efficiency is not dramatic since most of the exposure comes from the contamination outside of the shelter and not from the small volume of contamination deposited inside; as such most shelters retain their efficiency as shields against gamma radiation (EPA, 1992a). But if that is the case, then why does the PAG Manual state, "It is apparent that staying in a shelter for more time than that required for one or two complete air exchanges is not very effective for reducing inhalation exposure" (EPA, 1992a). This statement comes from the analysis of inhalation dose.

The inhalation dose is affected by the inside/outside air exchange rate. Using the assumptions of constant atmospheric and source conditions and no effects from filtration, deposition, or radioactive decay, the EPA model for the buildup of indoor concentration is given as (EPA, 1992a),

$$C_i = C_o(1 - e^{-Lt})$$

where C_i is the concentration inside, C_o is the concentration outside, L is the ventilation rate (h^{-1}) and t is the elapsed time (h). Based on this model, and typical air exchange rates in the range of 0.2 to several air changes per hour, the indoor air concentration can be seen to quickly approach the outdoor concentration within a few hours. The change in DRFs for inhalation dose is shown in Table 3-4 (EPA, 1992a).

The consequence of this simplified model is that the shelter guidance in the PAG Manual has been colored by the assumed inefficiency of using shelters for an extended duration during a radiological emergency. Although removed from the 2017 PAG Manual, the summary of planning guidance for evacuation and sheltering in the 1992 PAG Manual states that sheltering is usually not appropriate for exposure lasting longer than two complete air changes of the shelter (EPA, 1992). And although the 2017 PAG Manual shows that some shelters can provide dose reduction factors of more than 100, the manual states the shelters should not be relied upon and heavy caveats are placed on implementing sheltering-in-place, including recommending that it be followed by evacuation when feasible (EPA, 2017a).

Table 3-3 Representative dose reduction factors for external radiation

Table C-6 Representative Dose Reduction Factors for External Radiation

Structure	DRF	Effectiveness (percent)
Wood frame house (first floor)	0.9	10
Wood frame house (basement)	0.6	40
Masonry house	0.6	40
Large office or industrial building	0.2 or less	80 or better

Table 3-4 Dose reduction factors for sheltering from inhalation

Table C-7 Dose Reduction Factors for Sheltering from Inhalation of Beta-Gamma Emitters

Ventilation rate (air changes/h)	Duration of plume exposure(h)	DRF
0.3[a]	0.5	0.07
	1	0.14
	2	0.25
	4	0.41
	6	0.54
1.0[b]	0.5	0.21
	1	0.36
	2	0.56
	4	0.75
	6	0.83

[a]Applicable to relatively "airtight" structures such as well- sealed residences, interior rooms with chinked doors and no windows, or large structures with outside ventilation shut off.

[b]Applicable to structures with no special preparation except for closing of doors and windows.

Very little information on the effectiveness of shelters has changed within the PAG Manual over the years, and the basis for the implementation of the PAGs still relies on the analysis from the late 1970s (EPA, 1978a). Despite its benefits, sheltering-in-place remains underestimated as an alternative to evacuation in response to a radiological release from a nuclear power plant. Much of this has to do with a dearth of research and studies into the effectiveness of sheltering-in-place, as it pertains to radiological emergencies. But shelter effectiveness has been widely studied for other hazards and atmospheric pollutants. The benefits of both sheltering-in-place and evacuation in response to a variety of emergency events is well understood in the context of all-hazards emergency planning. The current Federal guidance on protective actions to support comprehensive emergency plans published by FEMA in *Planning Considerations: Evacuation and Shelter-in-Place* states that, “jurisdictions should always consider shelter-in-place as the first/default option, when feasible” (FEMA, 2019a). If this is true for all-hazards planning, should it not apply to radiological events as well? Why, in radiological emergency planning, is the emphasis placed on prompt evacuation rather than prompt sheltering-in-place?

The difficulty lies in the lack of information. The PAG Manual states, “sheltering-in-place should be preferred to evacuation whenever it provides equal or greater protection” (EPA, 1992a; EPA, 2017a). Unfortunately, after more than 40 years since the issuance of the first PAG Manual, the conditions for which this statement is true remain unclear. Considering dose savings alone, at some point before or during a release, an evacuation would almost always seem to be the preferred action. But are there situations when sheltering-in-place would be preferred even if it did not provide equal or greater protection? Under what conditions might that be true? The PAG Manual notes that selection of evacuation or sheltering-in-place is far from an exact science. But, if that’s the case, then the remedy is obvious…we need a more exact science!

Chapter 4 – Exacting the Science

This section describes the development of a model to assess the relative effectiveness of sheltering-in-place and evacuation in response to a radiological release. The authorities and individuals that must decide on a course of action need to have the best information available to direct actions that provide the most benefit to the public and the environment. This can only be done if the risks faced by the public and the benefits of protective actions are understood so that the best decisions can be made. Critical to this is an understanding of the science supporting the use of various protective actions.

Both sheltering-in-place and evacuation can be used to reduce or avoid dose following a radiological release. Shelter efficiency depends on several factors including radionuclide characteristics, ventilation rates, particle infiltration and filtration, and shelter location inside the building, among other factors. The effectiveness of an evacuation depends primarily on the time to mobilize and time to travel away from the plume. The purpose of this study is to examine the key parameters and practical aspects of implementing sheltering-in-place and evacuation in order to identify the factors that are of primary importance for reducing dose. Various models were developed to capture relevant physical phenomena involved with protective actions. Dose projections were performed to provide the source term and unsheltered dose resulting from an assumed severe accident in representative boiling water reactor (BWR), pressurized water reactor (PWR), and small modular reactor (SMR) plants. The approach to modeling the effectiveness of protective actions is described in terms of the dose savings resulting from: (1) building protection factors for cloudshine and groundshine dose, (2) shelter reduction of inhalation dose, and (3) evacuation. A composite model was coded into a MATLAB application. The application can be used to evaluate the effectiveness of sheltering-in-place and evacuation during the early phase of a radiological release. A novel feature of this application is the ability to vary many of the input parameters to examine the relative importance to radiological protection.

4.1 RASCAL Source Terms and Dose Projections

Dose projections for the early phase of a radiological release are the combined result of three main exposure pathways: cloudshine, groundshine, and inhalation. These exposure pathways are illustrated in Figure 4-1. Cloudshine is the direct exposure to radioactive materials from an atmospheric plume. Groundshine is the exposure from material deposited on the ground and continues to be important even after a plume has passed. Inhalation results from breathing in radioactive materials while immersed in a plume or from resuspension of ground-deposited material. Inhaled radionuclides may be retained in the lungs or move to the bloodstream and to other organs prior to elimination from the body. Thyroid dose due to radioiodine is a particular inhalation pathway concern for a radiological release.

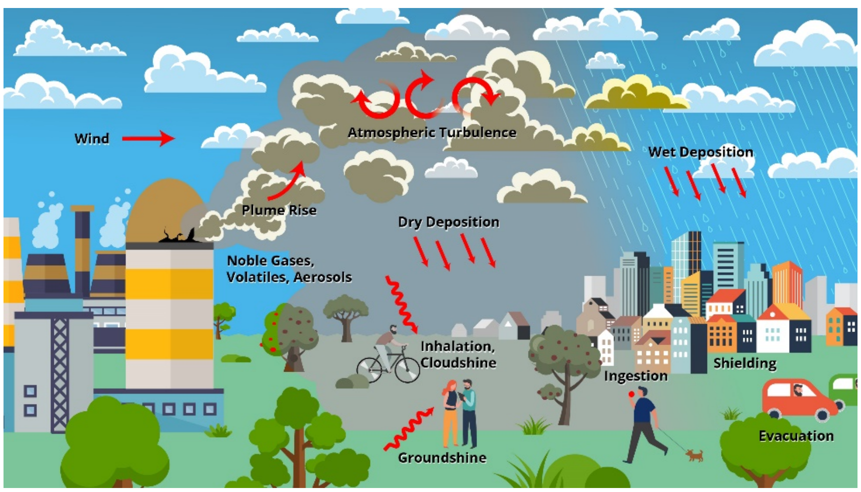


Figure 4-1 Pathways of exposure during a radiological release[13]

Protective actions are informed by radiological dose projections by comparing the projected dose to the EPA PAG. However, the EPA PAGs assume that the reference person is unprotected during the release and early phase derived PAGs assume that a person is outdoors 24 hours a day for 4 days being exposed to the

[13] https://maccs.sandia.gov/maccs.aspx

plume (EPA, 2017a). While the EPA evaluated certain guidelines for different subpopulations, these primarily apply to the PAGs for KI, food, and water. The PAGs for evacuation, sheltering-in-place, and relocation are based on adult populations and are assumed to be applicable to all age groups.

The RASCAL code is a tool for making dose projections during radiological emergencies. RASCAL was developed by the NRC over 25 years ago to provide a tool for the rapid assessment of an incident at an NRC-licensed facility and to aid decision-making such as whether the public should evacuate or shelter-in-place (NRC, 2021). Dose projection software such as RASCAL can evaluate atmospheric releases from nuclear power plants, spent fuel storage pools and casks, fuel cycle facilities, and radioactive material handling facilities. State and local authorities may use RASCAL or similar dose projection tools to aid protective action decision-making, although dose projection data is not the only criterion for making decisions.

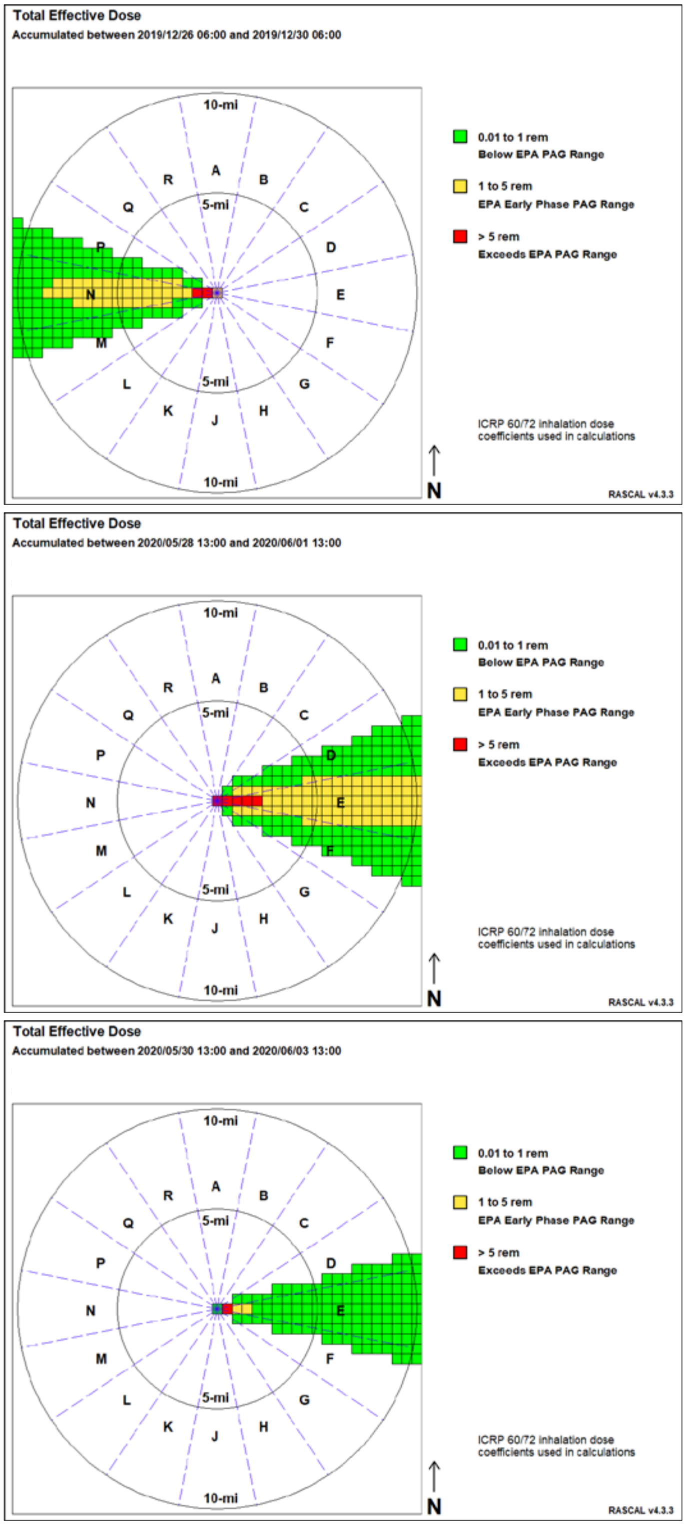
RASCAL version 4.3 provides predefined source terms for a variety of potential accident sequences. The details of the models and methods used in RASCAL are described in NUREG-1940, “RASCAL 4.3: Description of Models and Methods” (NRC, 2015b). The *Source Term to Dose* module in RASCAL 4.3 was used to produce the needed dose projections. *Source Term to Dose* uses pre-determined, time-dependent source terms for specific nuclear power plant accident sequences such as a loss of cooling accident (LOCA) and long term station blackout (LTSBO). Representative PWR and BWR plants plant were selected from the pre-populated NPP sites. Three case-studies were selected and developed in RASCAL to provide the unprotected dose projection data. These cases are:

- BWR Long Term Station Blackout (LTSBO)
- PWR Loss of Coolant Accident (LOCA)
- SMR Loss of Coolant Accident (LOCA)

Because RASCAL does not yet contain models for the various small modular reactor designs currently in development, the SMR case was modeled by using the large light water reactor PWR model and scaling the core to 250 MW. The parameters of the accident sequence (time to core damage, degree of core damage, release pathway, leakage rate, release height, meteorology) were adjusted to produce dose projections conducive to further evaluation of protective action effectiveness. In all cases, the accident scenario was allowed to progress to the point of a radiological release and the release was allowed to persist. Each accident scenario was allowed to progress for 96 hours.

Standard meteorological conditions (Class D neutral stability, 4 mph wind speed, 70 F, 50% relative humidity, and no precipitation) with winds coming from a single direction were assumed to persist for 96 hours. Although unrealistic to assume there is no change in the weather, this modeling approach is appropriate to this study as it results in a fixed dose projection in terms of weather conditions so that the sensitivity of other parameters can be evaluated. This assumption is also conservative, as changes in wind direction, increased wind speed, and less stable atmospheric conditions would result in more atmospheric dispersion which would reduce the projected dose at any location. The impact of weather on radiological dose projections has been described in many other studies and is not examined further here. Dose projection data was produced in RASCAL for close-in distances and out to 25 miles, in half-mile increments. For the accident scenarios considered, useful dose projection data extended to about 15 miles. As such, a cutoff of 15 miles was applied to the model. Dose conversion followed the ICRP 60/72 methods embedded in RASCAL. Details of the accident scenarios and source terms are provided in the Appendix B.

RASCAL provides useful details of the dose calculations. The projected maximum dose (calculated as the total effective dose equivalent, TEDE) at various distances from the release point are provided in Appendix B. In addition to maximum projected dose values, RASCAL provides a graphical footprint of the plume with shaded values of the projected dose. The projected plume for the three sample cases are shown in Figure 4-2 below. At each computational grid point, RASCAL also provides the instantaneous dose rate (rem/h) and cumulative dose (rem) for the various dose pathways. Figure 4-3 provides an example for the inhalation CED at 5 miles from the release point of the BWR LTSBO accident.



BWR LTSBO

PWR LOCA

SMR LOCA

Figure 4-2 Plume footprint (10 miles) for BWR LTSBO, PWR LOCA, and SMR LOCA accident scenarios

The data for the contributions to TEDE as a result of 96 hours of exposure from inhalation, cloudshine, and groundshine was extracted along the plume centerline in half-mile increments from the point of release out to 10 miles, and in slightly larger increments out to 15 miles. The rate data was used in the model developed here to recalculate the cumulative TEDE for an unprotected reference person at a downwind location and to provide the instantaneous values of dose rate of accumulation to which the reduction afforded by protective actions could be applied.

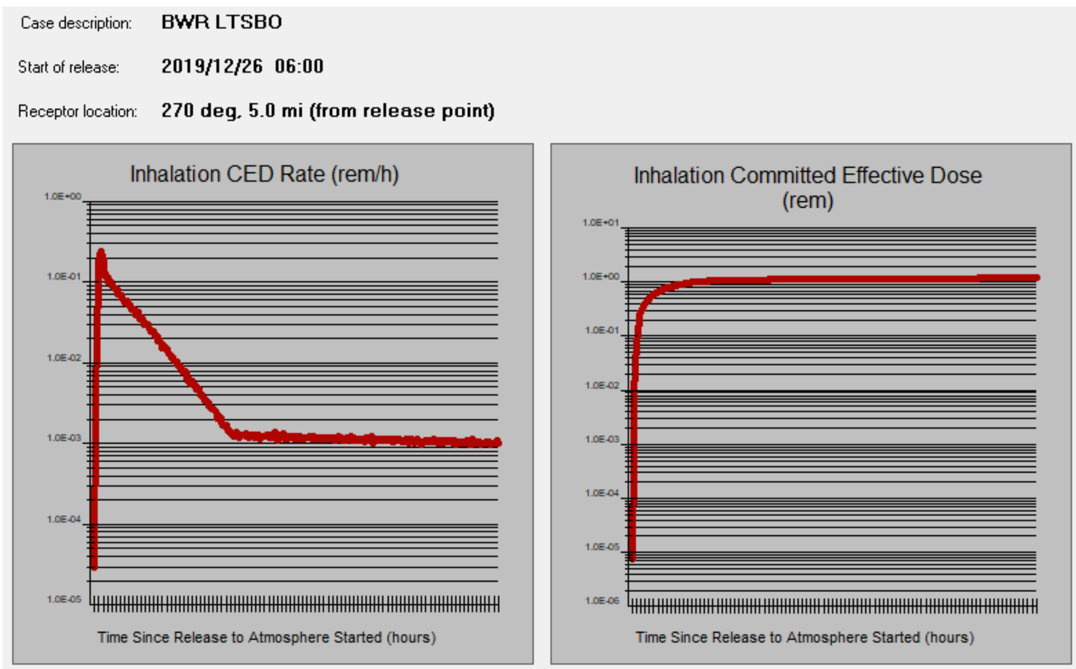


Figure 4-3 RASCAL inhalation dose rate and cumulate dose versus time since release at 5.0 miles from the point of release

4.2 Cloudshine and Groundshine Building Protection Factors

The protection from external exposure afforded by shelters can be expressed in terms of a building protection factor. A protection factor is simply the ratio of the protected response D to the unprotected response D_0 at a particular location, given as,

$$PF = \frac{D}{D_0} \tag{4-1}$$

Effectively, the building protection factor represents the alteration of the radiation field due to the shielding properties of the structure materials and variation of the photon fluence. The building protection factor can be applied to radiological consequence analyses that relate the radionuclide specific exposure to dose through dose conversion factors. As such, building protection factors can be applied to RASCAL projected dose values for cloudshine and groundshine.

Building protection factor correlations for environmental exposure to monoenergetic photon emissions, developed by Dickson and Hamby at Oregon State University (Dickson, 2016), were applied to the time-dependent cloudshine and groundshine dose output from RASCAL. The protection factor correlations developed by Dickson are suitable for use in a wide-area release and are dependent on photon energy, building material, and location within the building (Dickson 2016). The protection factor correlations were developed for typical residential single family homes; as such, the dose reduction is likely conservative with regard to larger residential structures such as apartment complexes, although potentially less conservative in comparison to other types of dwellings, such as a mobile home.

Dickson developed simulation models for four standard housing structures with two types of siding, for a possibility of eight house models. The four housing structures are: (1) one-story house with a basement, (2) one-story house without a basement, (3) two-story house with a basement, and (4) a two-story house without a basement. The options for siding material were vinyl and brick. Construction of the house models assumed industry standard stud spacing (16 in/40.64 cm on center) for exterior walls with typical thickness (0.5 in/1.27 cm) exterior oriented strand board (OSB) panels. Exterior walls assumed typical fiberglass batt insulation between studs. Vinyl siding was directly mounted to the OSB like in typical home construction. For brick homes there is an air gap (1 in/2.54 cm) between the OSB and weather barrier for air circulation. For detailed specifications of the standard construction house models refer to Table 2 in Dickson (Dickson, 2016). The dimensions of the residential structures developed by Dickson were applied to the model developed here using an assumed ceiling height of 9 ft to estimate the volume; the dimensions are shown in Table 4-1.

Table 4-1 Residential housing unit dimensions

	One-story	One-story w/ Basement	Two-story	Two-story w/ Basement
Area (ft^2)	17177	30955	15478	22366
Ceiling (ft)	9	9	9	9
Volume (ft^3)	1722	3444	1722	2583

If a large release of radioactive material were to occur as a result of an accident, a variety of radionuclides could be released. Each radionuclide is characterized by its decay modes, decay times and decay energy. The penetrating power of radiation and the biological damage are both related to this energy. The protection factors for monoenergetic photon emissions developed by Dickson are energy-dependent to account for this penetrating power. Shielding effectiveness was modeled using Monte Carlo simulation applied to sixteen mono-energetic photon energies ranging from 0.1 MeV to 3.0 MeV (Dickson, 2016). Protection factor data was generated for each floor and then a weighted average was determined for the entire house. The data was then fit to a logarithmic curve to develop a series of equations that provide the protection factor as a function of photon energy in MeV. The protection factor equations for the various house models are repeated in the tables below (Dickson, 2016).

Based on the specified photon energy (MeV), the energy dependent protection factor for the particular shelter type and shelter location (Tables 4-2 to 4-5) are applied to the cloudshine and groundshine dose from RASCAL. The protection afforded by the shelter from external sources of radiation is illustrated in Figure 4-4 (Dickson, 2016). The protection factor is applied to the instantaneous unsheltered dose rate (given in 15 minute intervals) and added to the cumulative sheltered dose.

Table 4-2 One-story building cloudshine protection factors

Vinyl		Brick	
No basement		No basement	
First Floor	0.084 ln(x) + 0.7698	First Floor	0.1167 ln(x) + 0.5897
Weighted Average	0.084 ln(x) + 0.7698	Weighted Average	0.1167 ln(x) + 0.5897
Basement		Basement	
First Floor	0.0836 ln(x) + 0.7604	First Floor	0.1187 ln(x) + 0.5827
Basement	0.0871 ln(x) + 0.4442	Basement	0.076 ln(x) + 0.2937
Weighted Average	0.0875 ln(x) + 0.6019	Weighted Average	0.0973 ln(x) + 0.4382

Table 4-3 Two-story building cloudshine protection factors

Vinyl		Brick	
No basement		No basement	
Second Floor	0.0936 ln(x) + 0.8741	Second Floor	0.1335 ln(x) + 0.6201
First Floor	0.0821 ln(x) + 0.7349	First Floor	0.1240 ln(x) + 0.4224
Weighted Average	0.0879 ln(x) + 0.8045	Weighted Average	0.1288 ln(x) + 0.5212
Basement		Basement	
Second Floor	0.0935 ln(x) + 0.8714	Second Floor	0.1336 ln(x) + 0.6186
First Floor	0.1028 ln(x) + 0.7217	First Floor	0.1240 ln(x) + 0.4176
Basement	0.0879 ln(x) + 0.4035	Basement	0.0730 ln(x) + 0.2070
Weighted Average	0.0950 ln(x) + 0.6654	Weighted Average	0.1102 ln(x) + 0.4144

Table 4-4 One-story building groundshine protection factors

Vinyl		Brick	
No basement		No basement	
First Floor	0.0590 ln(x) + 0.5420	First Floor	0.0699 ln(x) + 0.2799
Weighted Average	0.0590 ln(x) + 0.5420	Weighted Average	0.0699 ln(x) + 0.2799
Basement		Basement	
First Floor	0.0484 ln(x) + 0.5410	First Floor	0.0706 ln(x) + 0.2775
Basement	-0.014 ln(x) + 0.0774	Basement	0.0040 ln(x) + 0.0583
Weighted Average	0.0224 ln(x) + 0.3083	Weighted Average	0.0306 ln(x) + 0.1681

Table 4-5 Two-story building groundshine protection factors

Vinyl		Brick	
No basement		No basement	
Second Floor	0.0395 ln(x) + 0.5401	Second Floor	0.0740 ln(x) + 0.2815
First Floor	0.0491 ln(x) + 0.5557	First Floor	0.0905 ln(x) + 0.2683
Weighted Average	0.0405 ln(x) + 0.5484	Weighted Average	0.0822 ln(x) + 0.2749
Basement		Basement	
Second Floor	0.0466 ln(x) + 0.5378	Second Floor	0.0740 ln(x) + 0.2803
First Floor	0.0491 ln(x) + 0.5540	First Floor	0.0905 ln(x) + 0.2668
Basement	-0.016 ln(x) + 0.0604	Basement	0.0039 ln(x) + 0.0405
Weighted Average	0.0333 ln(x) + 0.3900	Weighted Average	0.0570 ln(x) + 0.2009

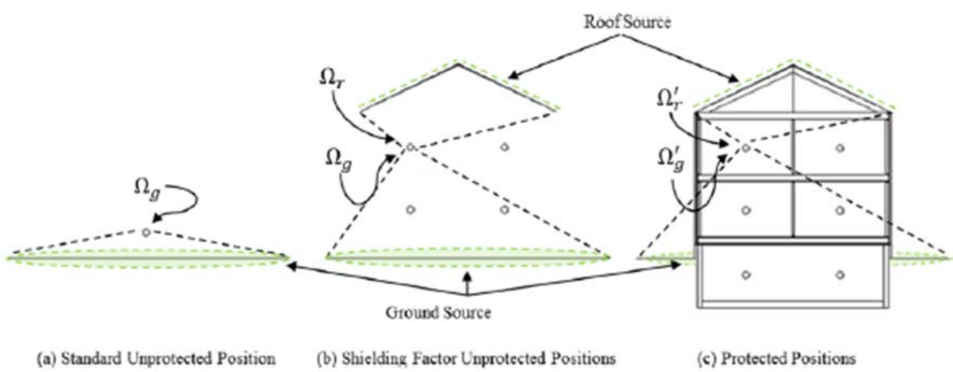


Figure 4-4 Protection factor application to location in shelter

While the protection factors account for attenuation at specific photon energies, a range of photon energies will be present in a release. The specific photon energy dependence can be accounted for by using the radionuclide importance data from RASCAL. RASCAL contains source importance information and lists the percentage each nuclide contributes to a specific dose pathway over time. Since the source importance changes over time due to the presence of short-lived radionuclides, the shelter protection factors will have a time dependence associated with them as well. RASCAL provides this source term importance data for day 0, day 1, and day 7 after the accident, from which energy- and time-dependent protection factors for the 96 hour exposure period could be developed. Although it would be possible to incorporate weighted protection factors into the model, for research purposes a single photon energy of 0.75 MeV is applied. This value was derived from the top 10 nuclides important to cloudshine and groundshine dose provided by RASCAL (see Appendix A) by weighting the energy of the dominant gamma emitted during decay by the nuclide importance. Average emitted photon energy for the PWR and BWR cases examined ranged from 0.67 to 0.95 MeV with an overall average of 0.78 MeV.

4.3 Shelter Inhalation Dose Model

To model the inhalation dose received inside of the shelter, a basic conservation of mass approach was used to capture the important physics. The shelter is treated as a single control volume and instantaneous and uniform mixing is assumed. Various mechanisms affect the buildup of activity in the shelter over time including infiltration through the building envelope and mechanical ventilation. The airborne activity of radionuclides inside of the control volume changes with time. Assuming no internal source terms, a mass balance leads to a simple equation to express the rate of change of airborne radionuclide activity in the shelter as,

$$V_s \frac{dC_s}{dt} = rate\ in - rate\ out \quad (4\text{-}1)$$

where C_s is the concentration of the contamination inside the shelter of volume V_s.

Infiltration and mechanical ventilation are considered to be the primary means by which airborne contaminants can enter the shelter. Once inside the shelter volume, radionuclides are conservatively assumed to remain suspended in the air. Additional losses through exfiltration or by deposition onto surfaces (and potential resuspension) are not considered. Other possible means of bringing contamination into the shelter from the outside—which could result in resuspension of particulates—are considered to be minor factors affecting inhalation dose.

One way that contamination can enter a building is through infiltration of the building envelop. Particle infiltration refers to air and particulates coming in through openings like cracks, loose windows and doors. The concentration of contamination that enters the shelter in this way can be estimated by multiplying the outdoor air concentration by the rate at which the air infiltrates and by a factor to represent what fraction of the contamination particles are able to penetrate the building envelope. Outdoor concentration will be given by $C_o(t)$, infiltration rate will be given by q_{inf}, and the penetration factor will be given by PF_{inf}. The infiltration rate and penetration factor are assumed to be constant with time but are adjustable. This gives the first entrance term as, $C_0(t)q_{inf}PF_{inf}$. In reality, this term will depend on weather conditions at the time of release among other factors. Representative values for the infiltration and exfiltration rates and penetration factors will be described later.

The other way in which contamination can enter the shelter is through mechanical ventilation. Mechanically ventilated buildings take in air from the outside in order to heat or cool the building and to provide fresh air. The model for mechanical ventilation assumes there is an HVAC system that draws in outside air through an air filter. Air filters have an efficiency based on the percentage of contaminants of a particular size they are able to filter out. A variety of commercial air filters are available for home use; as such, the HVAC filter efficiency is an adjustable parameter in the model. The radionuclide contribution entering via this pathway can be calculated by taking the outdoor concentration at a certain time and multiplying by the supply air flow rate from the HVAC system and the percentage of contaminants not stopped by the air filter. The HVAC supply air flow rate will be given by q_{vent} and the filter efficiency will be given by ε_f (or given by f). The fraction of contaminants that are not stopped by the filter is simply $(1 - \varepsilon_f)$. Therefore, the second entrance term is, $C_o(t)q_{vent}(1 - \varepsilon_f)$. Although radionuclides will likely deposit onto other surfaces within the ventilation system, these additional losses are not modeled.

To maintain balanced air flow, the inlet and outlet airflow rates are assumed equal. That is, the infiltration rate equals the exfiltration rate through the building envelope ($q_{inf} = q_{exf}$) and the ventilation air is assumed to be exhausted at the same intake rate of q_{vent}. For loss by exfiltration through the building envelope, the penetration factor could again be applied; however, radionuclides are assumed to stay immobile within the building envelop and not become airborne again. Additionally, there are no holdup mechanisms to the ventilation outflow. As such, these outflows expel the shelter air containing the airborne contaminants at the concentration level of $C_s(t)$. The exfiltration rate is then given by $C_s(t)q_{exf}$ and the mechanical ventilation outflow is given by $C_s(t)q_{vent}$

Another factor that would influence the inhalation dose is the loss rate from the air due to deposition of material onto surfaces within the shelter. A deposition term could be added, but by assuming the radionuclides remain airborne inside the shelter, the resultant inhalation dose is more conservative. Although the deposition loss rates from the air inside the shelter would further reduce the inhalation dose, radionuclides deposited inside the shelter would contribute to external whole body dose. The EPA study on shelter effectiveness from 1978 considered this internal deposition contribution to whole body dose to be very minor (EPA, 1978a; EPA, 1978b). As such, it was not important to complicate the model to capture minor external contributions to dose from sources deposited inside the shelter. However, in reality, the possibility of hotspots inside the shelter and the potential contamination issues should not be ignored. For now, these effects are not considered.

Combining the various mechanisms, the mass balance (Equation 4-1) becomes,

$$V_s \frac{dC_s}{dt} = q_{inf} PF_{inf} C_o(t) + q_{vent}\left(1 - \varepsilon_f\right) C_o(t) - q_{exf} C_s(t) - q_{vent} C_s(t) \quad (4\text{-}2)$$

This equation can be discretized for use in a numerical model. For the *i*th time-step, the concentration in the shelter is equal to the concentration in the previous timestep, plus the change in concentration as,

$$C_s(t_i) = C_s(t_{i-1}) + \Delta C_s(t_i) \quad (4\text{-}3)$$

where,

$$\Delta C_s(t_i) = \begin{pmatrix} q_{inf} PF_{inf} C_o(t_i) + q_{vent}\left(1 - \varepsilon_f\right) C_o(t_i) \\ -q_{exf} C_s(t) - q_{vent} C_s(t_i) \end{pmatrix} \frac{\Delta t}{V_s} \tag{4-4}$$

In using Equations 4-3 and 4-4 it was assumed that effective dose in rem is proportional to airborne concentration by virtue of the applied dose conversion factors in RASCAL. For this reason, the model operates on the dose rate output from RASCAL as previously described, and not airborne radionuclide concentration. The inhalation model just described is illustrated in Figure 4-5.

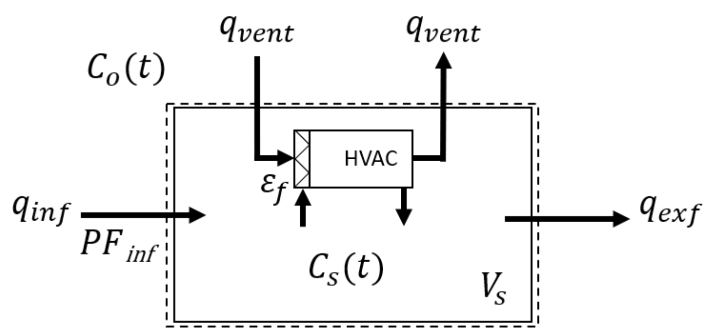


Figure 4-5 Shelter control volume model for inhalation dose

The shelter model was developed to examine the sensitivity of various parameters important to the use of sheltering-in-place during a radiological release. No experimental work was performed as part of this work to validate this simplified model. However, similar models have been developed for investigations into the penetration of particles into buildings; see for example: Kulmala, 2016; Thornburg, 2001; He, 2005; Mosely, 2010; Diapouli, 2013; and Bennett, 2006. Kulmala et al., developed a model for use in determining shelter efficiency of mechanically ventilated buildings against outdoor hazardous agents (Kulmala, 2016). The Kulmala model, written in terms of the parameters already described above, is expressed as,

$$\Delta C_s(t_i) = \begin{pmatrix} q_{inf} PF_{inf} C_o(t_i) + q_{vent}\left(1 - \varepsilon_f\right) C_o(t_i) \\ -q_{exf} C_s(t) - q_{vent} C_s(t_i) \\ -q_{AC} E_{AC} C_s(t_i) - \beta V C_s(t_i) + G \end{pmatrix} \frac{\Delta t}{V_s} \tag{4-5}$$

Comparison to Equation 4-4 shows that the Kulmala model differs by three additional terms:

- $q_{AC}E_{AC}C_s(t_i)$ is the removal of contaminants from the indoor air by an air cleaner (AC) with flow rate q_{AC} and removal efficiency E_{AC}. The Kulmala model was validated experimentally without this term. The shelter model developed here also does not model this optional filtration method.

- $\beta V C_s(t_i)$ is the removal of contaminants by surface deposition at a deposition velocity of β. This removal mechanism was intentionally left out of the model developed here to add conservatism to the results. Although this does create the potential for hotspots inside the shelter and more whole-body exposure, the EPA study on shelter effectiveness showed the internal deposition contribution to dose to be very minor (EPA, 1978a; EPA, 1978b).

- G is the indoor contaminant generation rate. The Kulmala study set this term equal to zero to study the effects of penetration of outdoor contaminants. Similarly, no radionuclides are generated indoors for the model developed here.

The Kulmala study included field tests to determine key parameters and to validate the model. Figure 4-6 shows the results of estimated infiltration rates based on measured indoor and outdoor concentrations of 0.3-0.5 μm particles used in the field study (Kulmala, 2016). Good agreement was obtained between the measured and predicted results.

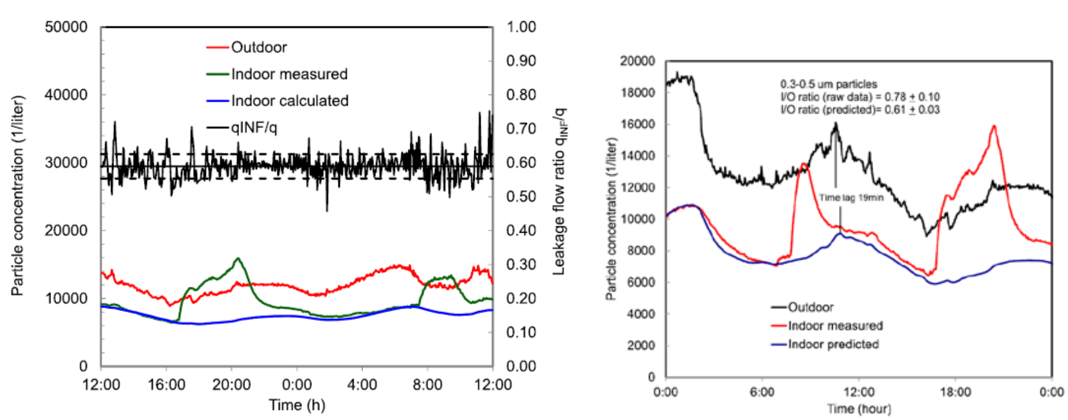


Figure 4-6 Measured and calculated outdoor and indoor particle concentrations in the size range of 0.3-0.5 μm

Kulmala cited measurements from the Fukushima accident showing the air contained radioactive particles with activity median aerodynamic diameters (AMAD) ranging between 0.25 and 0.71 μm for ^{137}Cs and 0.30 to 0.53 μm for ^{131}I (Kulmala, 2016). The released particle sizes are comparable to the range of particles studied by Kulmala; this suggests that the model developed here—which is similar to the validated Kulmala model—is suitable to estimate the effectiveness of shelters during a radiological release. To complete the model for the shelter inhalation dose, typical values for the model parameters were developed as described in the following.

4.3.1 Air Exchange Rate

Air exchange is the balanced flow into and out of a building and is composed of three processes: (1) infiltration—air leakage through random cracks, and other unintentional openings in the building envelope, (2) natural ventilation—airflows through open windows, doors, and other designed openings, and (3) forced ventilation—controlled air movement driven by mechanical means (EPA, 2011b). Chapter 19 of the EPA Exposure Factors Handbook provides an overview of the major transport pathways for airborne substances in buildings and recommendations on volumes and air exchange rates for use in modeling (EPA, 2011b). The air exchange rate is generally expressed in terms of air changes per hour (ACH), defined as the ratio of the airflow (ft^3/hour) to the volume (ft^3). The distribution of airflows across and within the building envelope is largely determined by the interior pressure distribution. Various forces cause air flows including temperature differences, wind, mechanical ventilation systems and interior fans. While natural ventilation and forced ventilation contribute at times to the indoor/outdoor air exchange in homes, infiltration is the dominant mechanism for residential structures. (Koontz, 1995).

Table 19.1 of the EPA Exposure Factors Handbooks provides a mean residential volume of 492 m^3 (17375 ft^3). This volume compares well to the volume of the one-story (17177 ft^3) and two-story (15478 ft^3) house models developed by Dickson and used to develop the cloudshine and groundshine protection factors.

Table 19.1 also provides a mean air exchange rate of 0.45 ACH, with 0.18 ACH as the lower 10^{th} percentile. Various distributions of air exchange rates in houses are reported with geometric mean ± standard deviations of 0.90 ± 2.13 ACH, 0.53 ± 1.71 ACH, and 0.68 ± 2.01 ACH (EPA, 2011b). For modeling inhalation exposure in residential settings, the 10^{th} percentile value of 0.18 ACH is recommended as a conservative value (Koontz, 1995). However, for the model developed here, the indoor air concentration has already been made conservative by the exclusion of the deposition loss. Adding additional conservatism is unnecessary and would continue to skew the results away from a best-estimate value. As such, the mean value of 0.45 ACH is used as the default for both the infiltration rate and mechanical ventilation rate. This value is recommended when a typical value is desired (Koontz, 1995). For the one and two-story house models, this corresponds to ventilation rates in the range of 116-232 ft^3/min.

4.3.2 Penetration Factor

Particle infiltration is a very dynamic process and an important factor in the effectiveness of shelters. There is epidemiological evidence showing a strong relationship between exposure to outdoor particles and adverse health including lung dysfunction, asthma, myocardial infarction and mortality has led to important research in ways to predict particle penetration into buildings. Because people spend roughly 90% of their lifetime indoors, there are ongoing efforts to develop effective strategies to mitigate the adverse health effects of indoor exposure to particles with an outdoor origin (Chen, 2011). Early studies into particle infiltration were mostly experimental and data was taken after steady state conditions had developed. However, a radiological plume release is more dynamic in space and time; as such, estimates of the penetration factor under dynamic conditions is desirable. Good summaries of the early experimental studies and efforts to develop mechanistic indoor air quality models are provided in technical review papers by Lange, Wallace, and Diapouli (Lange, 1995; Wallace, 1996; Diapouli, 2013). Another good review of the relationship between indoor and outdoor particle concentrations was performed by Chen and Zhao (Chen , 2011).

Chen et al., developed a mechanistic model to predict particle penetration by considering three of the major loss mechanisms through cracks of various lengths: Brownian diffusion, gravitational settling, and inertial impaction (Chen, 2012). For particles in the range of 0.5-6 mm diameter, penetration factors varied from 0.2 to 1 (Chen, 2012). The model was validated through experimental work in an office and a student dormitory as shown in Figure 4-7 (Chen, 2012). The Chen model was not validated for particles with diameters less than 0.5 mm. In a nuclear power plant accident, particles of various sizes may be released into the environment.

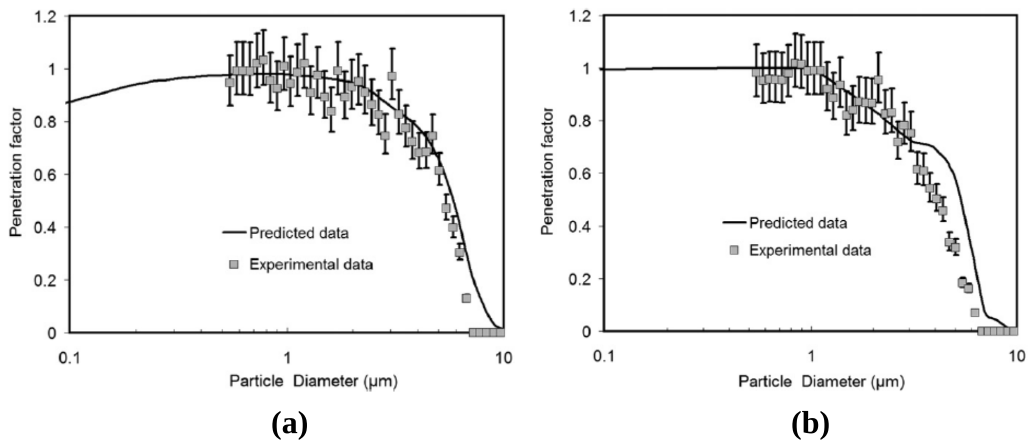


Figure 4-7 Comparison of predicted penetration factors with experimental data for (a) office, and (b) dormitory

Measurements from the Fukushima accident provide distributions of observed particle diameters with distance from the Fukushima Daiichi Nuclear Power Plant (FDNPP) as shown in Figure 4-8 (Martin, 2019). Average particle diameters with distance are also available for specific radionuclides (Martin, 2019). These results suggest that close-in to the point of release, median particle sizes tend toward diameters greater than 1 μm, with a decreasing trend to an average particle diameter smaller than 1 μm with distance. However, at any distance from the point of release, particles diameters in a range of 0.1-10 μm are observed. Hence, some estimate of the penetration factor for smaller particles is needed.

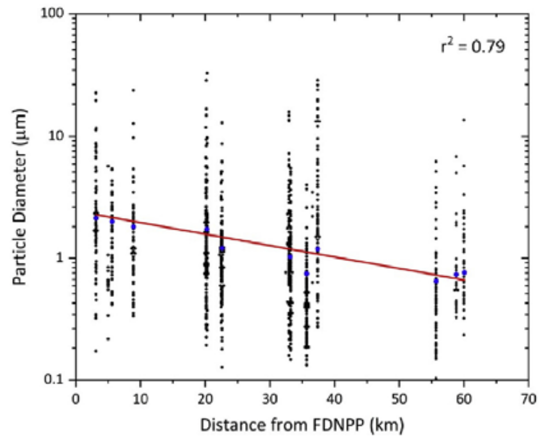


Figure 4-8 Observed particle diameter reduction with increasing distance from FDNPP

Bennett and Koutrakis developed a method of calculating the dynamic penetration factor using time-dependent concentrations and air-exchange measurements (Bennett, 2006). Dynamic penetration factors were calculated for seven houses over various times. The mean infiltration factor across homes was 0.49, increasing up to 0.76 for the 0.2-0.3 μm size fraction and then decreasing steadily to 0.32 for the largest size fraction (4-6 μm). Data from an example house is provided in Figure 4-9. Bennett and Koutrakis also found that the penetration factor is highly dependent on the air exchange rate. Air exchange was the greatest predictor of dynamic infiltration as shown in Figure 4-10 for representative particle size fractions of 0.02-0.03 and 2.0-3.0 μm (Bennett, 2006).

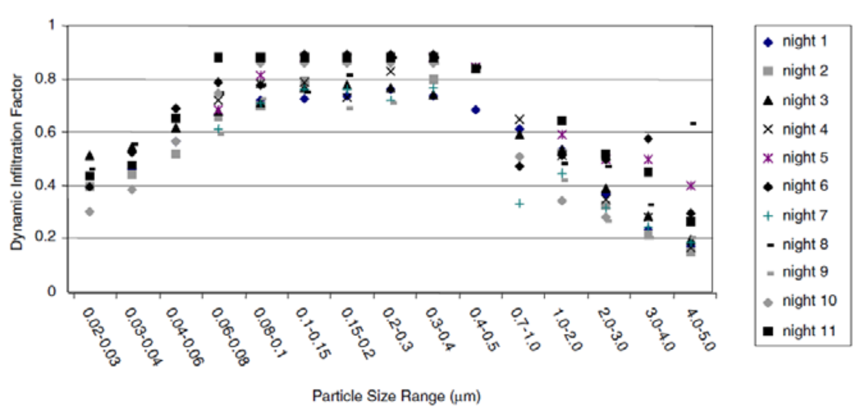
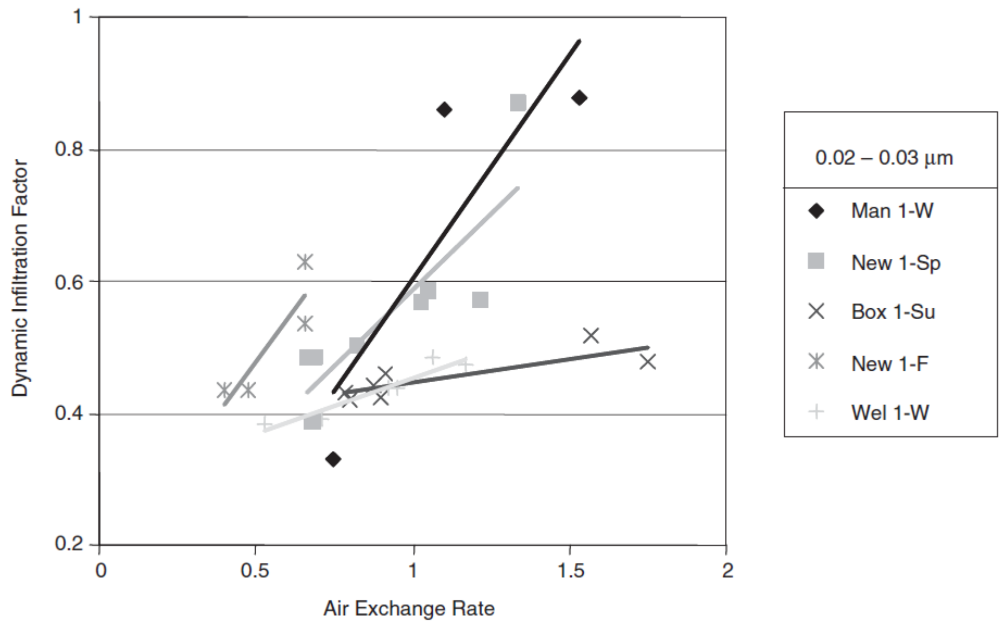
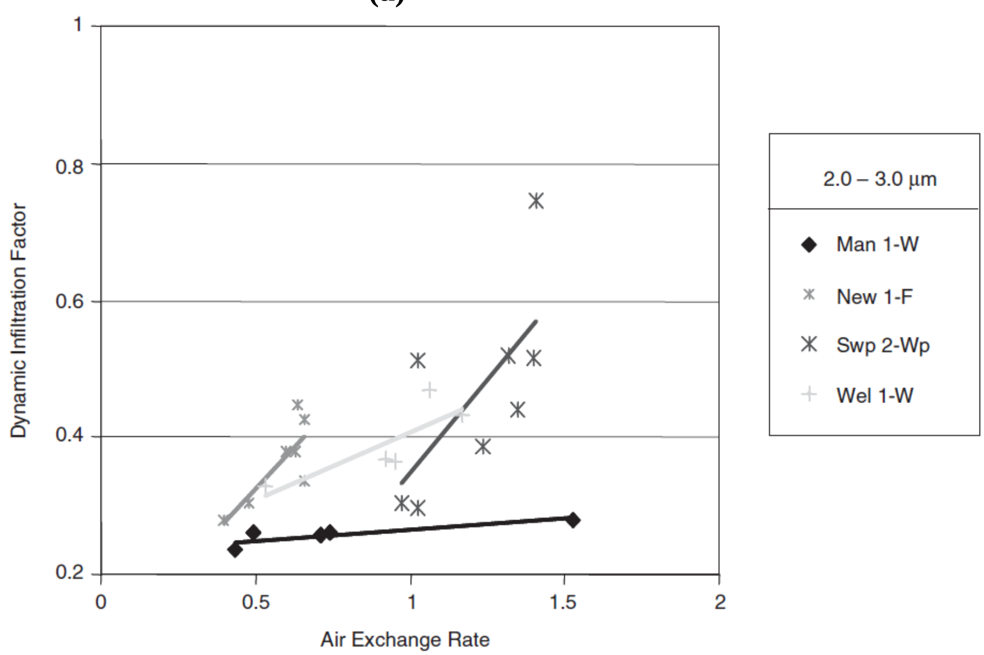


Figure 4-9 Relationship between dynamic penetration factor and particle size



(a)



(b)

Figure 4-10 Dynamic penetration factor versus air exchange rate for particle size fractions (a) 0.02-0.03 µm, and (b) 2.0-3.0 µm

Liu and Nazaroff performed laboratory experiments to measure particle penetration through surrogates of cracks in building envelopes (Liu, 2003). The particle penetration factor was determined for particle sizes 0.02-7 μm as shown in Figure 4-11. Consistent with prior modeling results, the penetration factor is closer to unity for particles of diameter 0.1-1.0 mm for large cracks (> 0.25 mm crack height) (Liu, 2003). Supporting these laboratory findings, a study of 40 homes in Germany found a distribution of penetration factors and that the median penetration factors were relatively low, not exceeding 0.5 for any size particle in the range of 0.01-10 μm (Zhao, 2020).

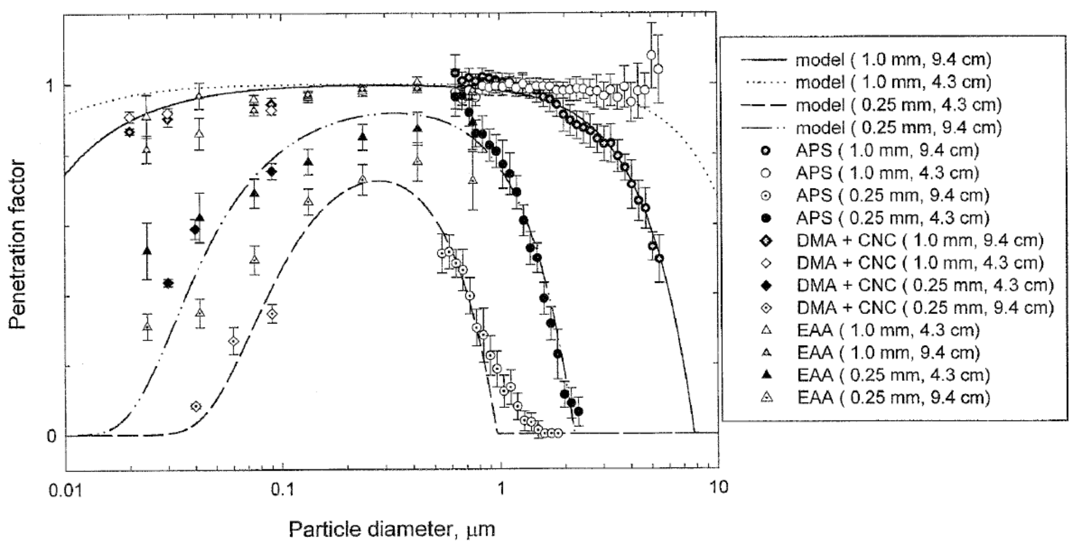


Figure 4-11 Comparison of model predictions with experimental data for aluminum cracks

For modeling purposes in this study, the penetration factor will be variable between 0 and 1. A sensitivity study will be performed to assess the importance of this parameter in reducing inhalation dose. For specific cases when use of a single penetration factor value is desirable, values of 0.5 and 0.2 will be used. These values were arrived at considering the particle size distribution data from the Fukushima release and the experimental and model prediction results presented here, including the effect of the air exchange rate.

4.3.3 HVAC Filter Efficiency

Filters consist of porous structures of fibers or stretched membrane material to remove particles from airstreams.[14] The fraction of particles removed from air passed through a filter is termed the "filter efficiency" and is provided by the Minimum Efficiency Reporting Value (MERV) under standard conditions. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides standards for MERV ratings and filter testing. Table 4-6 provides the MERV ratings and minimum efficiencies for various particle size ranges (ASHRAE, 2017). A typical home furnace filter may only have a MERV rating of 4 to 7, with efficiencies around 20%. The informational graphic provided in Figure 4-12 shows the relationship between MERV rating, particle size efficiency, and types of airborne contaminants removed. For modeling purposes, the HVAC filter efficiency will be variable between 0 and 1, and a sensitivity study will be used to assess the importance of this parameter in reducing inhalation dose.

Table 4-6 Minimum efficiency reporting values (MERV)

ASHRAE Standard 52.2-2017 -- Minimum Efficiency Reporting Value (MERV)

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, μm			
	Range 1 0.30 to 1.0	Range 2 1.0 to 3.0	Range 3 3.0 to 10.0	Average Arrestance, %
1	N/A	N/A	$E_3 < 20$	$A_{avg} < 65$
2	N/A	N/A	$E_3 < 20$	$65 \le A_{avg}$
3	N/A	N/A	$E_3 < 20$	$70 \le A_{avg}$
4	N/A	N/A	$E_3 < 20$	$75 \le A_{avg}$
5	N/A	N/A	$20 \le E_3$	N/A
6	N/A	N/A	$35 \le E_3$	N/A
7	N/A	N/A	$50 \le E_3$	N/A
8	N/A	$20 \le E_2$	$70 \le E_3$	N/A
9	N/A	$35 \le E_2$	$75 \le E_3$	N/A
10	N/A	$50 \le E_2$	$80 \le E_3$	N/A
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$	N/A
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$	N/A
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$	N/A
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	N/A

[14] https://www.ashrae.org/technical-resources/filtration-disinfection

MERV Rating	Air Filter will trap Air Partiles size .3 to 1.0 microns	Air Filter will trap Air Particles size 1.0 to 3.0 microns	Air Filter will trap Air Particles size 3 to 10 microns	Filter Type ~ Removes These Particles
MERV 1	< 20%	< 20%	< 20%	Fiberglass & Aluminum Mesh
MERV 2	< 20%	< 20%	< 20%	~
MERV 3	< 20%	< 20%	< 20%	Pollen, Dust Mites, Spray Paint,
MERV 4	< 20%	< 20%	< 20%	Carpet Fibres
MERV 5	< 20%	< 20%	20% - 34%	Cheap Disposable Filters
MERV 6	< 20%	< 20%	35% - 49%	~
MERV 7	< 20%	< 20%	50% - 69%	Mold Spores, Cooking Dusts,
MERV 8	< 20%	< 20%	70% - 85%	Hair Spray, Furniture Polish
MERV 9	< 20%	Less than 50%	85% or Better	Better Home Box Filters
MERV10	< 20%	50% to 64%	85% or Better	~
MERV 11	< 20%	65% - 79%	85% or Better	Lead Dust, Flour, Auto
MERV 12	< 20%	80% - 90%	90% or Better	Fumes,Welding Fumes
MERV 13	Less than 75%	90% or Better	90% or Better	Superior Commercial Filters
MERV 14	75% - 84%	90% or Better	90% or Better	~
MERV 15	85% - 94%	95% or Better	90% or Better	Bacteria, Smoke, Sneezes
MERV 16	95% or Better	95% or Better	90% or Better	
*MERV 17 = HEPA 13	99.97%	99% or Better	99% or Better	HEPA & ULPA
*MERV 18 = HEPA 14	99.997%	99% or Better	99% or Better	~
*MERV 19 = U15	99.9997%	99% or Better	99% or Better	Viruses, Carbon Dust, < 0.3 µ
*MERV 20 = U16	99.99997%	99% or Better	99% or Better	*ASHRAE does not recognize Merv 17-20
Illustration Provided by LakeAir / www.lakeair.com				

Figure 4-12 Relationship between MERV rating, efficiency, and contaminants[15]

4.4 Evacuation Model

Estimating evacuation times typically involves the use of traffic simulation models and the development of an evacuation time estimate (ETE). The ETE is an estimate of the time to evacuate various distances and sectors within the plume exposure pathway emergency planning zone. The NRC study on evacuation time estimates documented in NUREG/CR-7269, "Enhancing Guidance for Evacuation Time Estimate Studies," provides insight into the factors of traffic supply and demand that control the dynamics of an evacuation (NRC, 2020b). Evacuations can be divided into two major periods of activity: mobilization time and travel time. Mobilization time is defined as the period from the time an evacuation order is received to the time

[15] https://www.lakeair.com/merv-rating-explanation/comp

vehicles depart from their origins. Travel time is the time it takes to move from the point of origin to a specific destination. As described in Appendix 4 to NUREG-0654, Rev. 1, a simple approach to estimating the evacuation time is to assume these actions are sequential and simply add the maximum time for each component (NRC, 1980). This modeling approach is applied here. From this, the dose and protection factors applied during the mobilization phase and evacuation phase can be assumed based on the location of the activity. Origin points are specified as distances from the point of release, along the plume centerline, ranging from 0 to 15 miles, in 0.5 mile increments. During the mobilization period, individuals are assumed to be at home (at the specified distance) preparing to evacuate. As such, the sheltered dose accumulated during this time is counted toward the evacuation dose. Within the model, mobilization time can be specified for any time between 0 and 24 hours. After the set mobilization time, evacuees are assumed to exit the EPZ at a defined speed. The evacuation speed can be specified for any value between 0 and 60 miles per hour. The speed is translated to dose by considering the time spent within the plume or travelling through a contaminated area. First, the travel time is calculated as the difference in linear miles between the point of origin, D_O, and the model boundary of 15 miles, divided by the speed,

$$travel\ time = \frac{15 - D_O}{speed} \tag{4-6}$$

During each 15 minute time step, the evacuee location is updated to reflect the distance travelled away from the point of release, along the direction of the plume centerline. The dose accumulated during travel includes contributions from groundshine, cloudshine, and inhalation, as appropriate to the location with respect to the plume. During the travel time, a vehicle protection factor equal to 0.9 is applied to the groundshine and cloudshine dose rate of accumulation at the current vehicle location, but no protection is assumed for the inhalation dose (NRC, 2014). This assumption is appropriate as vehicles are not particularly air-tight and cabin filters are assumed to be ineffective. The total evacuation dose is the sum of the dose received during the mobilization time and the dose accumulated during the travel time from the point of origin out to 15 miles.

Table 3-16 of the NRC's study of evacuation time estimates provides summary evacuation metrics for representative small, medium, and large population EPZs (NRC, 2020b). The average evacuation speed for evacuees ranges from 13 to 43 mph. Table 3-16 also contains the vehicle miles traveled by evacuees within the representative site models that spanned a distance of 20 miles from the site of the nuclear power plant. This translates to average travel times of 30 minutes to 90 minutes from the point of origin out to 20 miles. Additionally, Appendix C of the ETE study provides an illustration of the general relationship between population within the EPZ and the ETE taken from site-specific ETE studies, as shown in Figure 4-13 (NRC, 2020b). The evacuation model parameters applied here can produce evacuation times consistent with these studies.

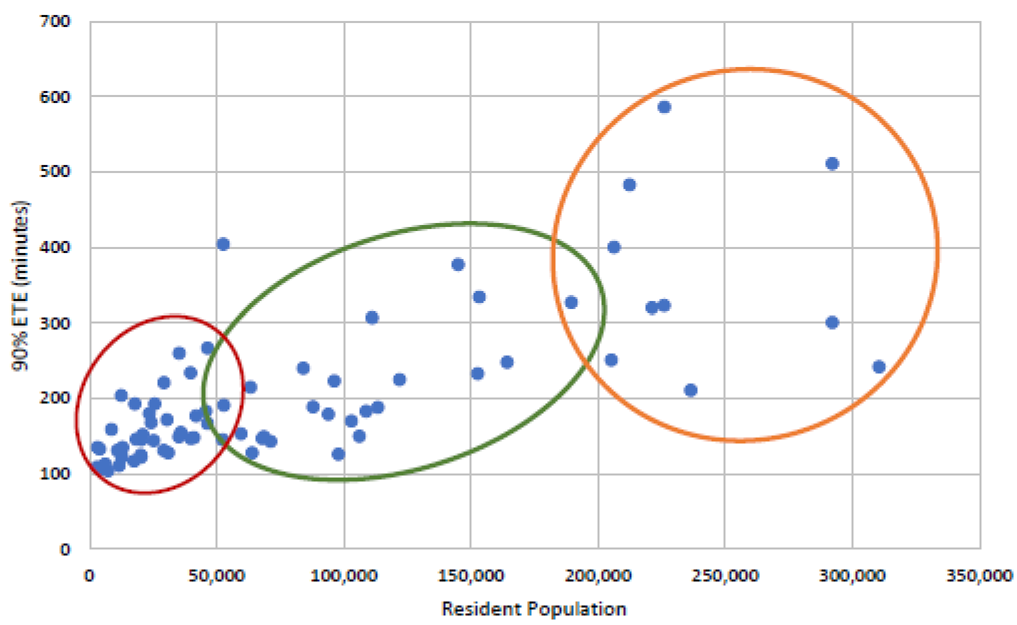


Figure 4-13 Relation between evacuation time and EPZ resident population

4.5 PARatus Application Development

The RASCAL data and protection models just described were built into an application using the Application Designer in MATLAB. A graphical user interface (GUI) was developed to provide an intuitive way for users to adjust the various model parameters and examine the impact on the dose projection. The application tool is aptly named **PARatus** after the Latin word for “prepared”. The PARatus GUI is shown in Figure 4-14. The GUI provides control over a variety of the model inputs previously described. These include the scenario, photon energy, shelter model, ventilation parameters, and evacuation model parameters. Scenarios include selection of BWR LTSBO, PWR LOCA, or SMR LOCA. The average photon energy can be specified as any amount in MeV, with a default value of 0.75 MeV applied. Shelter model selections include vinyl or brick siding, one or two story homes, with or without basement, and shelter location within the home. Ventilation parameters provide for separate contributions due to particle infiltration and mechanical ventilation. Infiltration rate is specified in ACH and the resulting air flow in cfm is displayed. The penetration factor, which is applied to the infiltration rate, can be specified to any value between 0 and 1. Similarly, mechanical ventilation rates are specified in ACH and an HVAC filter efficiency value (between 0 and 1) is applied. In addition, the mechanical ventilation can be secured for any specified duration. This is done by setting the ventilation blower time off (Vent T-off) to any hour from the start time of release (t = 0) and resuming operation any subsequent hour (Vent T-on). The default values assume the HVAC system is secured during sheltering in place. The evacuation model parameters set the distance from the point of release as both the reference point for the dose projections and origin point for an evacuation. Mobilization time is specified for any value between 0 and 24 hours. Evacuation speed ranges from 0 to 60 mph. Of note, an evacuation speed of zero assumes the reference person has left their home and is in their vehicle but has not traveled anywhere. This would provide less protection from dose than a shelter. Once all the inputs are specified, the user may evaluate the scenario.

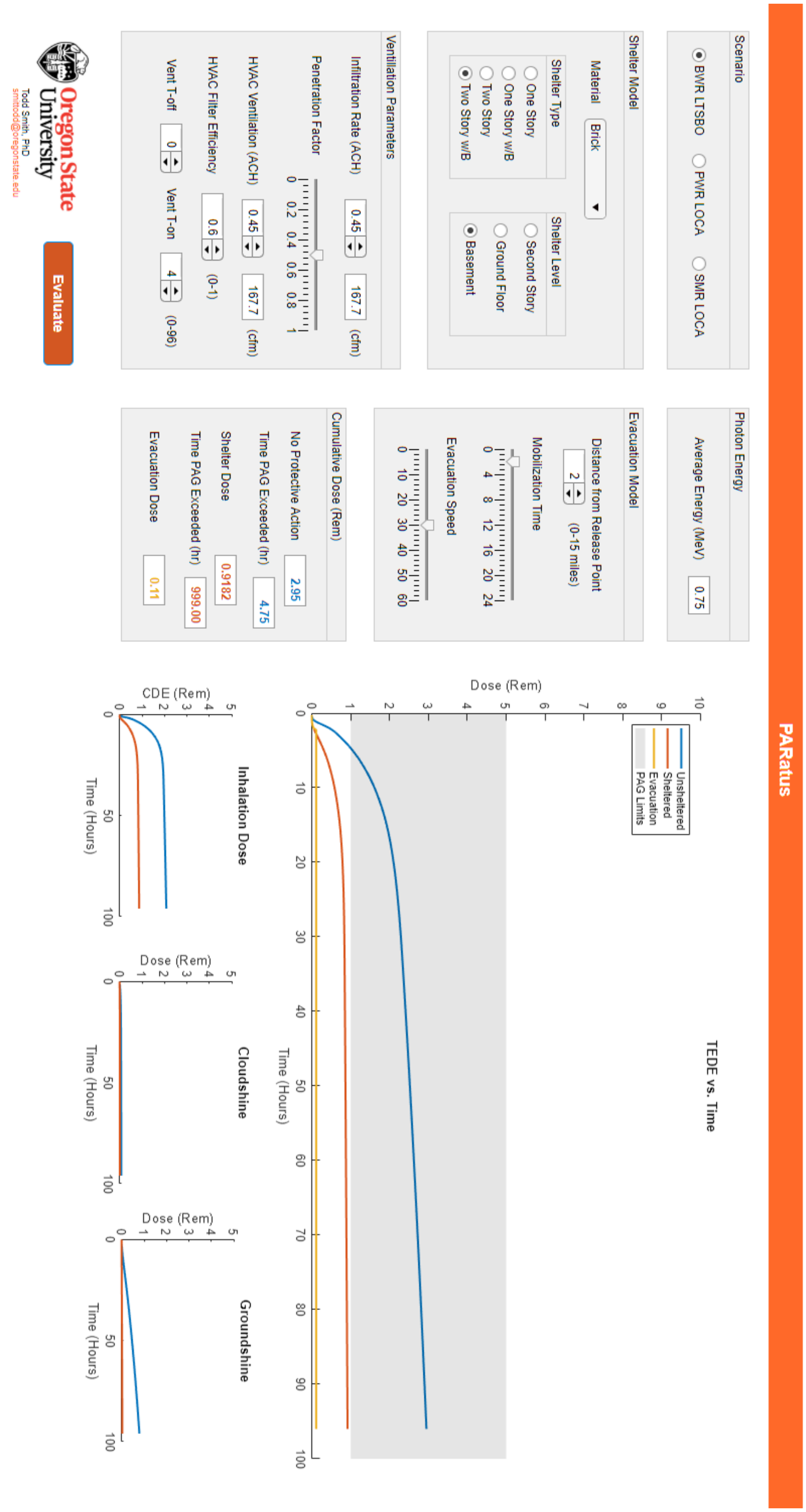


Figure 4-14 PARatus graphical user interface (GUI)

The output of PARatus provides both a summary and visual comparison of the dose assuming no protective actions are taken to the dose reductions afforded by shelter-in-place and evacuation. The Cumulative Dose table provides the integrated TEDE for 96 hours of exposure including the time PAGs are expected to be exceeded at that particular location. The results are shown in a combined graph of TEDE vs. time along with individual dose vs. time graphs for each pathway. This provides for a better understanding of the relative importance of the different dose pathways over time.

4.6 Model Results.

The PARatus tool was used to explore the effectiveness of sheltering-in-place and the sensitivity of various parameters important to radiological protection using shelters. As a first comparison, the shelter effectiveness was evaluated for the BWR, PWR, and SMR scenarios assuming an average photon energy of 0.75 MeV, on the ground floor of one-story house with vinyl siding located 2 miles from the point of release, with an infiltration rate of 0.45 ACH (232.2 cfm), a penetration factor of 0.2, and no HVAC ventilation. For the evacuation, a mobilization time of 2 hours is assumed along with an evacuation speed of 30 mph.

As shown in Figure 4-15, for the BWR LTSBO, the inhalation dose is the primary component of the total dose, with groundshine gradually building up over time. If unprotected, PAG levels will be exceeded at this location approximately 4.75 hours from the start of release; but, if sheltering-in-place is promptly implemented, PAGs would not be exceeded for even the first 4 days after a release. For the PWR LOCA scenario, inhalation is still the largest component of the total dose, as shown in Figure 4-16. However, the PWR LOCA scenario has a strong cloudshine component, due mostly to Xe-133. Under the assumed conditions, cloudshine becomes the largest contributor to the total dose after accounting for the effects of sheltering. Because the PWR release scenario is more severe than the BWR scenario, PAGs are exceeded in 2 hours if unprotected. Sheltering extends this time by a few hours.

While evacuation is seen to be protective in the BWR and PWR scenarios, sheltering-in-place provides considerable dose savings. For the PWR scenario, the evacuation dose for an evacuee starting 2 miles from the point of release is almost 1 rem. In terms of dose savings, evacuation saves approximately 4.7 rem, but sheltering-in-place also provides a substantial savings of 3.6 rem. In this scenario, evacuation would save only about 0.9 additional rem of dose; although this margin is highly dependent on the mobilization time and evacuation speed. For the BWR scenario, evacuation provides an additional dose savings of 0.8 rem. In terms of dose savings, this suggests that both the absolute and relative dose savings afforded by evacuation and sheltering-in-place might be important in helping to decide upon a course of action.

For the SMR LOCA scenario shown in Figure 4-17, inhalation is again dominant, but even left unprotected, the PAG level is not projected to be exceeded until the groundshine contribution causes the projected dose to exceed 1 rem after almost 3 days (66 hours) from the start of release. Again, sheltering-in-place proves effective even at 2 miles. Interestingly, the evacuation dose is projected at 0.07 rem, which is now in the range of 0.03 to 0.15 rem which the EPA estimated as the equivalent accident risk during an evacuation. This would suggest that evacuation should never be a preferred option for dose savings this inconsequential.

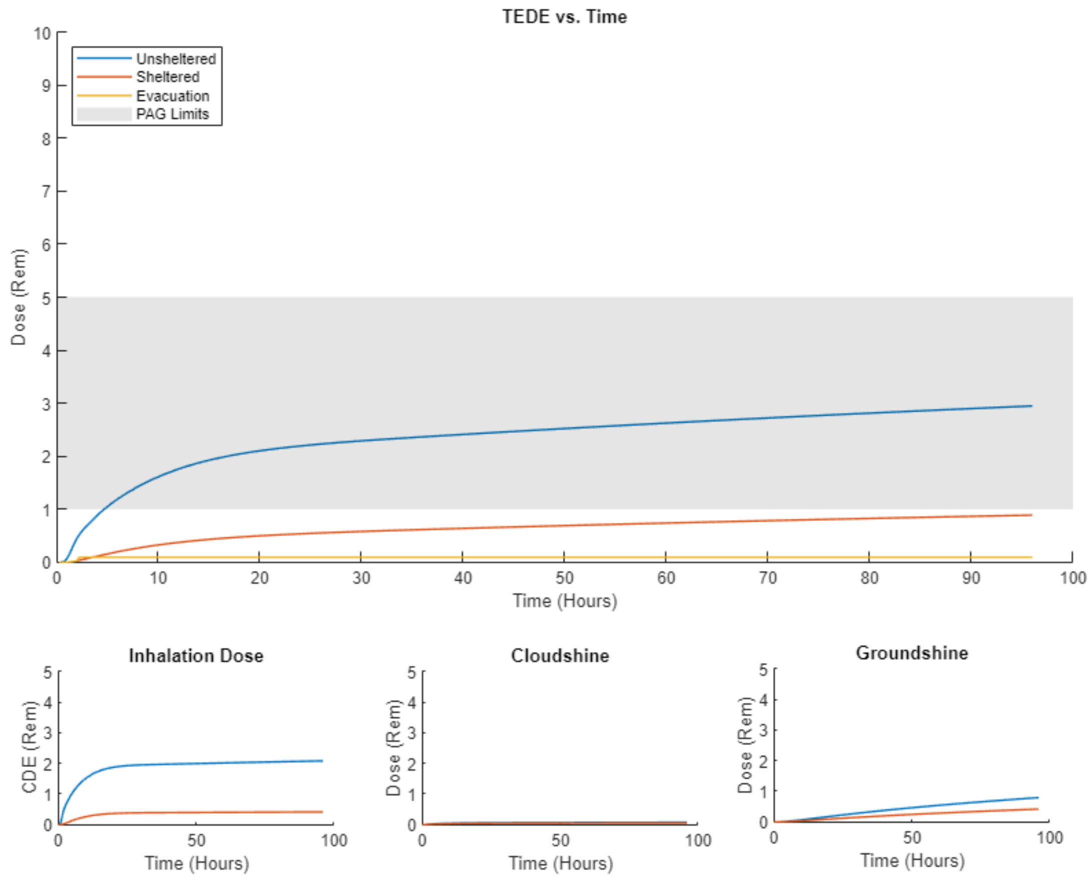


Figure 4-15 BWR LTSBO – One story vinyl siding, ground floor, natural ventilation 0.45 ACH penetration factor = 0.2, no HVAC

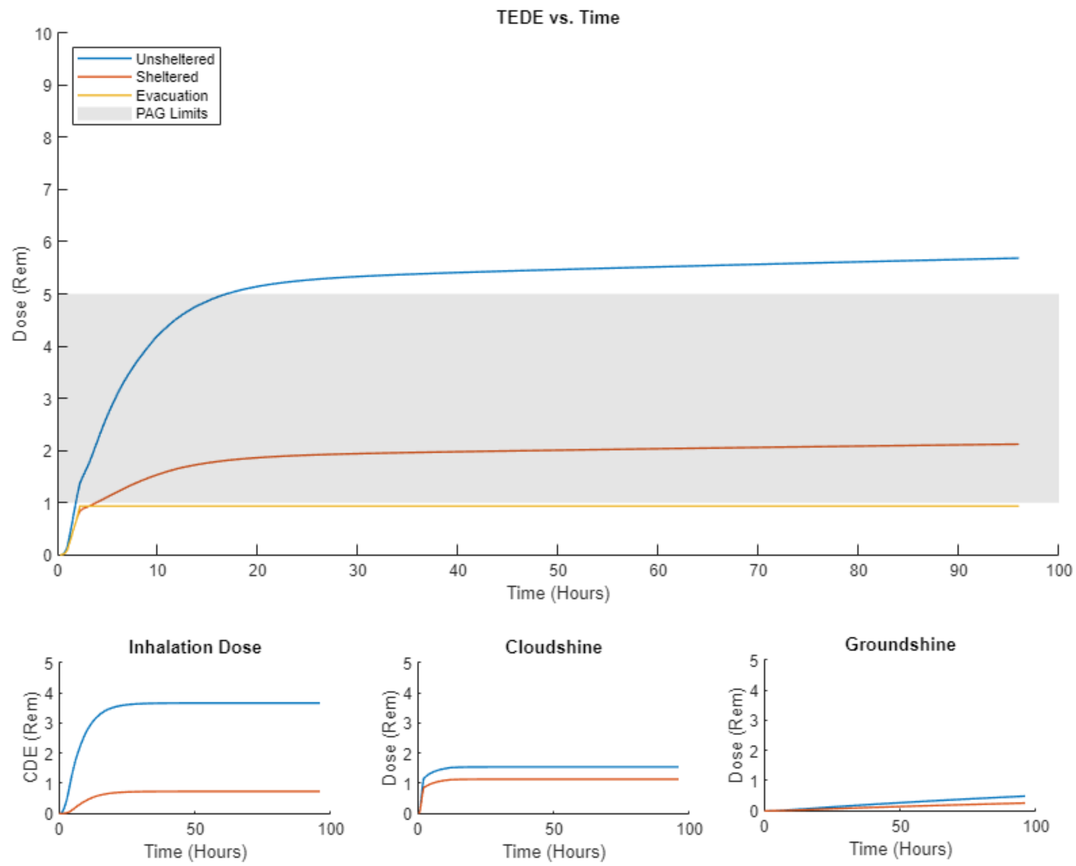


Figure 4-16 PWR LOCA – One story vinyl siding, ground floor, natural ventilation 0.45 ACH penetration factor = 0.2, no HVAC

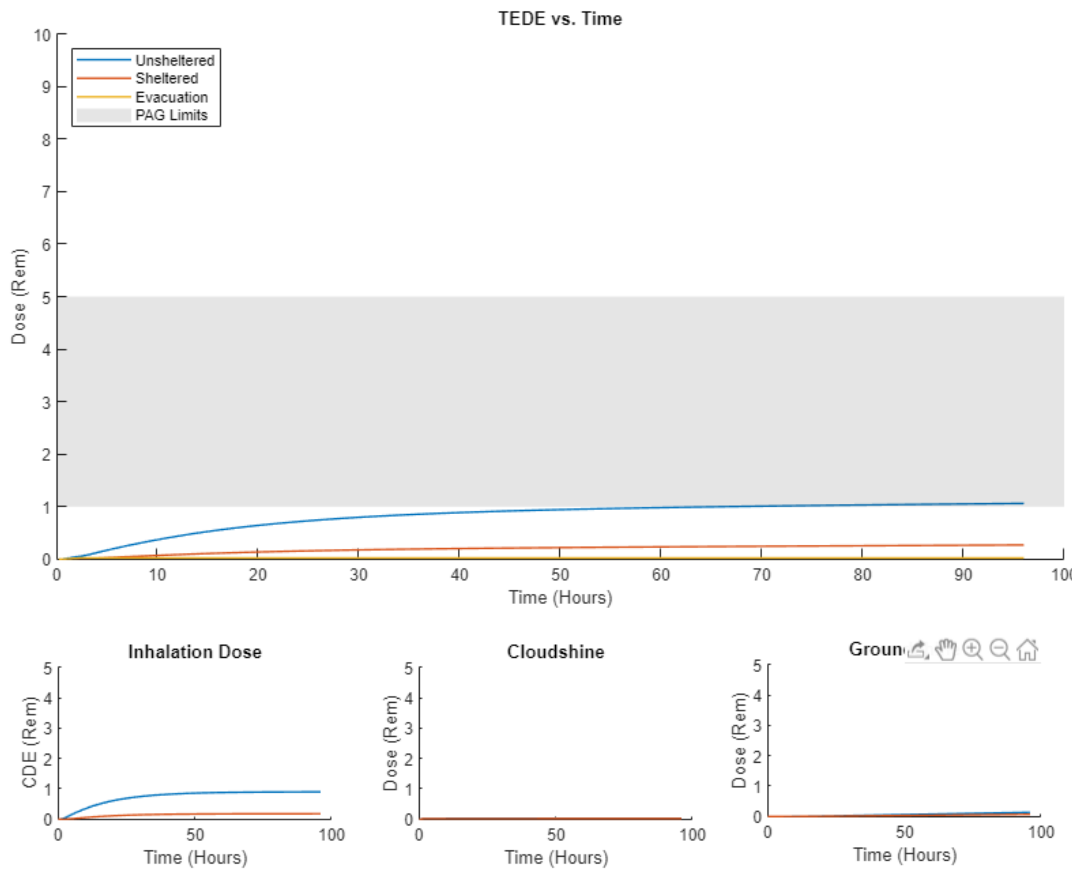


Figure 4-17 SMR LOCA – One story vinyl siding, ground floor, natural ventilation 0.45 ACH penetration factor = 0.2, no HVAC

Overall, the protection afforded by shelters is estimated to be greater and more practical over a longer duration than estimated in early studies. Table 4-7 compares dose reduction factors for sheltering from inhalation dose from Table C-7 of the 1992 EPA PAG Manual with the results of the current study. Dose reduction factors from the PARatus model are estimated to be at least twice as protective.

Shelters are also more protective against cloudshine and groundshine dose than estimated in Table C-6 of the 1992 EPA PAG Manual. For the BWR LTSBO event, the contribution due to cloudshine is minimal, and the average dose reduction factor determined using PARatus is 3.3 at the ground floor and 5.7 in the basement for the vinyl-sided house. For the PWR LOCA, the average dose reduction factor is 2.8 at the ground floor and 4.3 in the basement. For brick homes, the protection factor is slightly higher, and peaks around 6.2. This gives a nominal does reduction factor range of 3 to 6 for a typical one-story house. This level of protection is consistent with the dose reduction factors provided in the 2017 EPA PAG Manual and are 3 to 4 times more protective than what was provided in Table C-6 of the 1992 version of the PAG Manual (EPA, 1992a). This analysis demonstrates that sheltering remains a viable alternative to evacuation. Methods to improve implementation of sheltering can be further assessed by examining the sensitivity of various parameters important to dose.

Table 4-7 Comparison of shelter dose reduction factors for inhalation

Ventilation rate (ACH)	Duration of plume exposure (hr)	1992 EPA PAG Manual DRF	PARatus 0.5 miles DRF	PARatus 2 miles DRF
0.3	0.5	0.07	0.0058	0
	1	0.14	0.0521	0.0221
	2	0.25	0.1747	0.1267
	4	0.41	0.3155	0.2998
	6	0.54	0.3673	0.3608
	96	-	0.436	0.437
1.0	0.5	0.21	0.0193	0
	1	0.36	0.1043	0.0477
	2	0.56	0.2870	0.2218
	4	0.75	0.4031	0.3940
	6	0.83	0.4300	0.4268
	96	-	0.464	0.464

4.6.1 Shelter Effectiveness with Distance

Dose rates generally drop off with an approximate $1/r^2$ behavior from the point of release (NRC, 1978). As such, sheltering-in-place can be effective for reducing dose below PAG levels within just a few miles from the point of release for even severe beyond design basis accidents. Figures 4-18, 4-19, and 4-20 show the benefit of sheltering-in-place in a one-story vinyl-sided house at the ground and basement levels versus distance from the release point for the postulated BWR, PWR, and SMR severe accident scenarios. In all cases, dose can be controlled to levels below the PAGs after a few miles from the point of release through effective use of sheltering-in-place. This finding suggests that prompt evacuations, if needed, should commence in the area closest-in to the site and that evacuations may not require a keyhole or staged component. For example, a prompt evacuation in the 0-2 mile zone surrounding the PWR or BWR site would be effective at reducing dose while minimizing the number of people evacuated. A shelter-in-place order for the 2-5 mile downwind sectors would provide significant dose savings and provide time for detailed measurements to be taken before expanding the evacuation order. For the SMR scenario, evacuation would provide dose savings, but may not be justified; sheltering-in-place even within a half-mile from the point of release is a viable initial protective action to take while confirmatory measurements are made to assess the need for additional action.

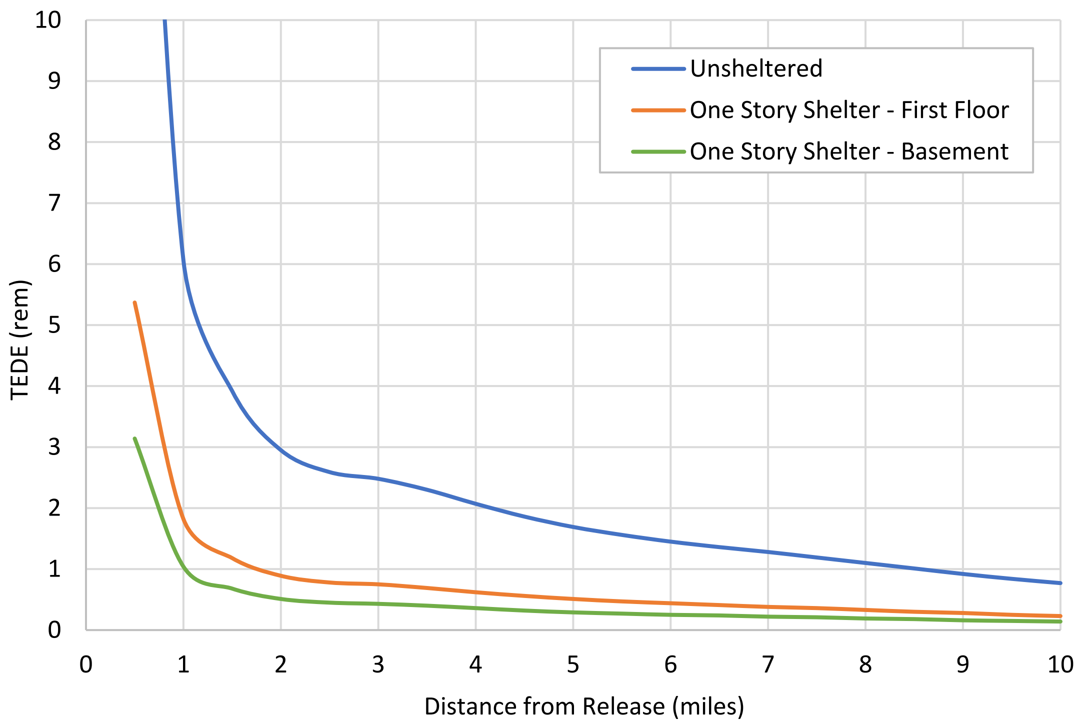


Figure 4-18 BWR LTSBO shelter effectiveness versus distance

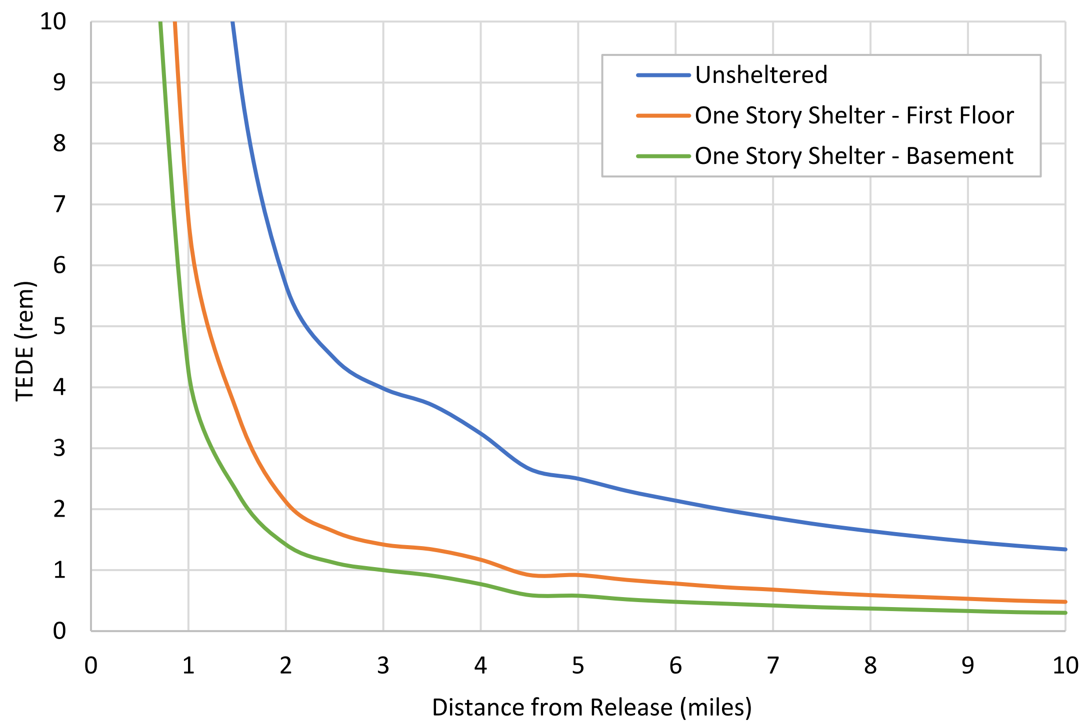


Figure 4-19 PWR LOCA shelter effectiveness versus distance

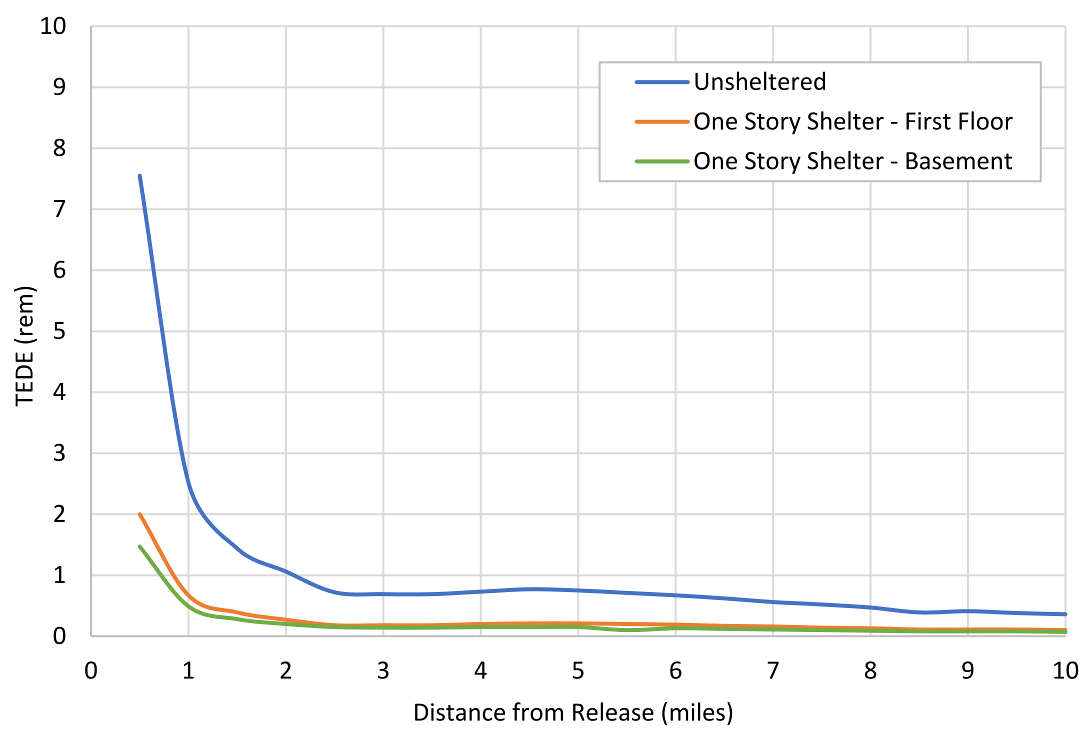


Figure 4-20 SMR LOCA shelter effectiveness versus distance

4.6.2 Effect of Photon Energy

Building protection describes the change in KERMA within the housing-unit with respect to the standard unprotected position. The effect of photon energy on shelter effectiveness is captured in the protection factor models which are useful over an energy range of 0 to 3 MeV (Dickson, 2016). Figures 4-21 through 4-24 show the sensitivity of the photon energy on the combined 4-day cloudshine and groundshine dose. Over the range of 0.1-3 MeV, photon energy can vary the projected dose by as much as 0.5 rem, or slightly more. Practically, there will be a mix of photon energies in the release. While higher energy photons are more penetrating, average photon energies did not exceed 1 MeV for the radionuclides important to cloudshine and groundshine. A fortunate result of the various accident source terms is that photon energies of the radionuclides important to cloudshine and groundshine are emitted in the range where shelters are more protective. Table 4-8 shows the average photon energy weighted by radionuclide importance to cloudshine and groundshine dose for the BWR, PWR, and SMR scenarios.

Table 4-8 Average photon energy by pathway

Scenario	Cloudshine	Groundshine
	Average Photon Energy (MeV)	
BWR LTSBO	0.71	0.67
PWR LOCA	0.81	0.95
SMR LOCA	0.81	0.97

The impact of elevation on shelter effectiveness is clearly shown in Figures 4-23 and 4-24 for the PWR scenario. The difference from the BWR scenario is due to the higher cloudshine component. Differences between groundshine and cloudshine protection factors with elevation are described in detail by Dickson (Dickson, 2016). The clear application for protective actions is to shelter in basements whenever possible. Shelters are also particularly useful when the cloudshine contribution to dose is expected to be low.

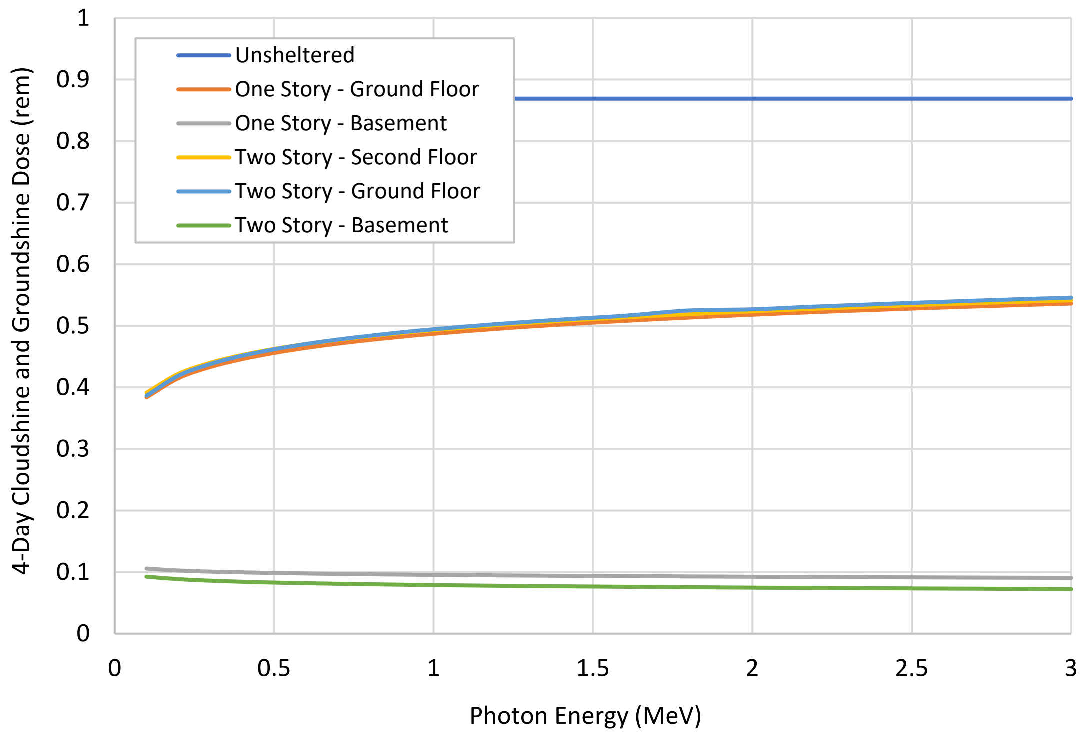


Figure 4-21 Effect of photon energy on shelter dose, BWR LTSBO, 2 miles downwind, vinyl-sided

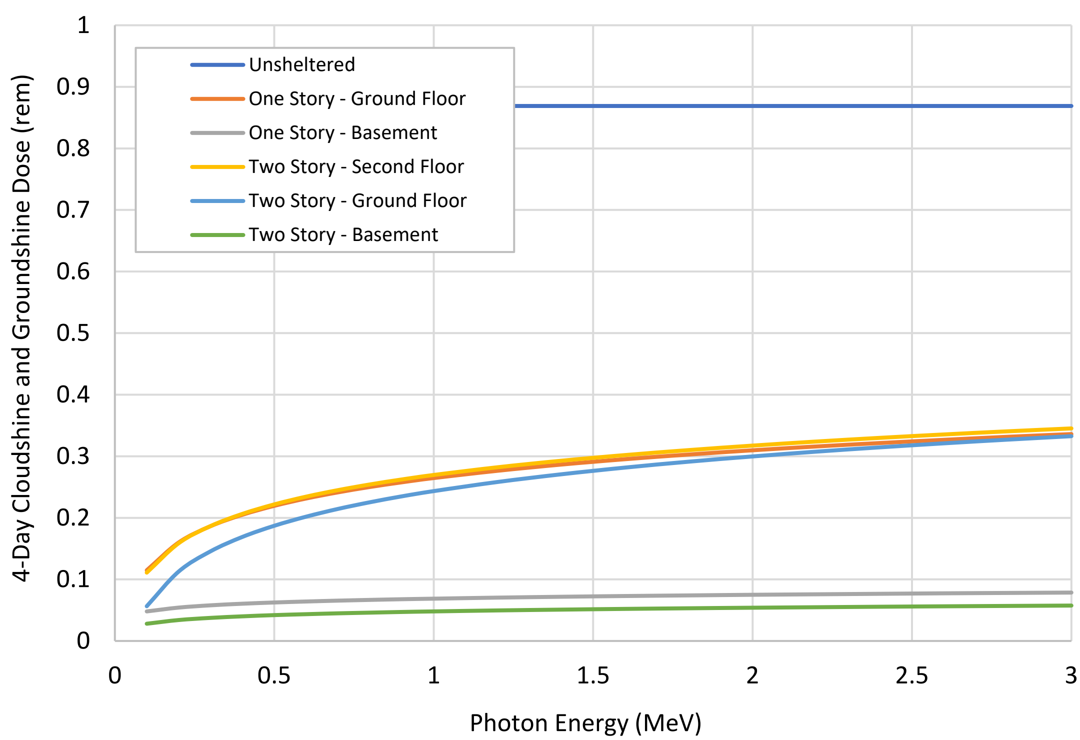


Figure 4-22 Effect of photon energy on shelter dose, BWR LTSBO, 2 miles downwind, brick-sided

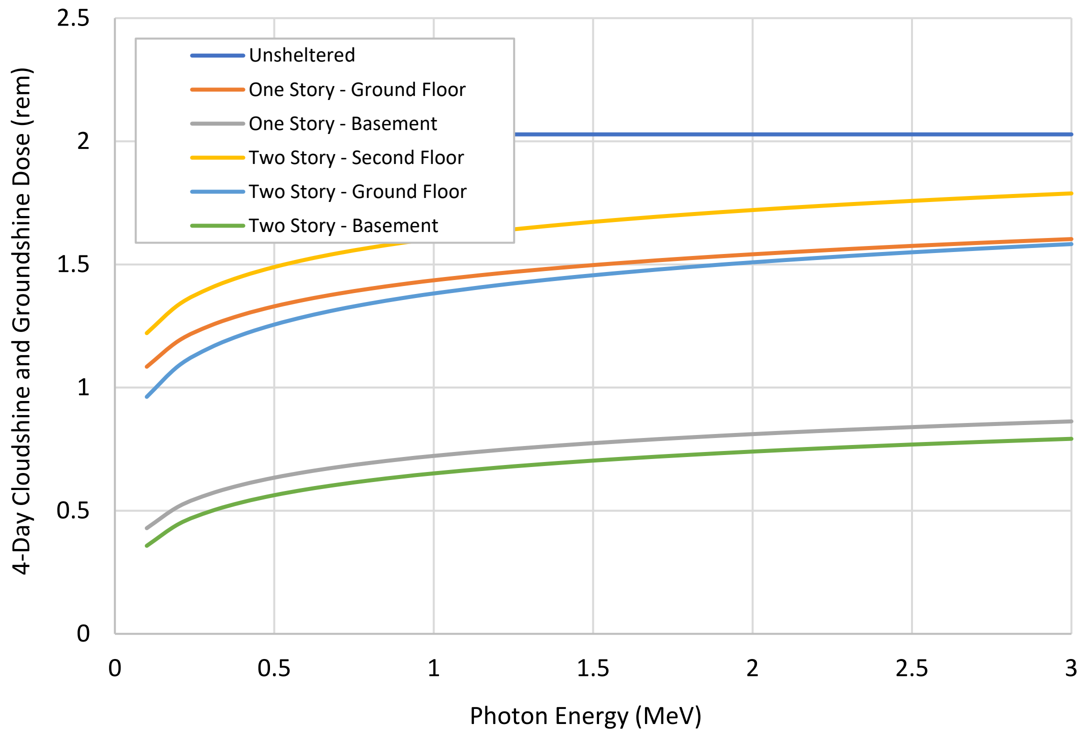


Figure 4-23 Effect of photon energy on shelter dose, PWR LOCA, 2 miles downwind, vinyl-sided

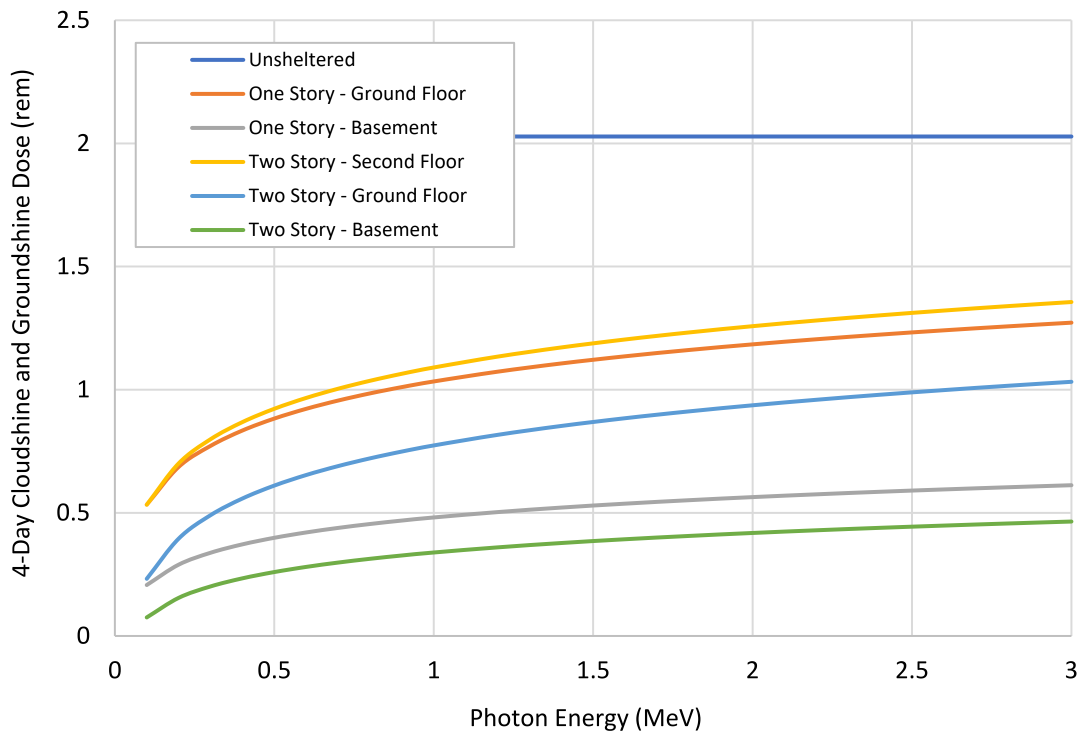


Figure 4-24 Effect of photon energy on shelter dose, PWR LOCA, 2 miles downwind, brick-sided

4.6.3 Effect of Ventilation Rate

The inhalation dose is highly dependent on the rate at which the inside and outside air mix. This exchange of air is primarily due to infiltration and mechanical ventilation. Because the activity in the plume and the plume passage are time dependent, dose savings can be achieved by reducing the exchange of air while the plume is overhead. Assuming no loss through filtration, Figure 4-25 shows the impact air exchange rates have on dose for the BWR scenario at a location 2 miles from the point of release. This figure shows that exchange rates as low as 0.05 ACH will result in inhalation doses almost equal to the unsheltered dose. This result is specific to this example, and there is likely a dependency on the plume passage time and rate of release, but those parameters were not investigated further. However, this does illustrate that it takes very little air exchange between the shelter and the outside air for the inhalation dose to eventually reach the unsheltered inhalation dose value.

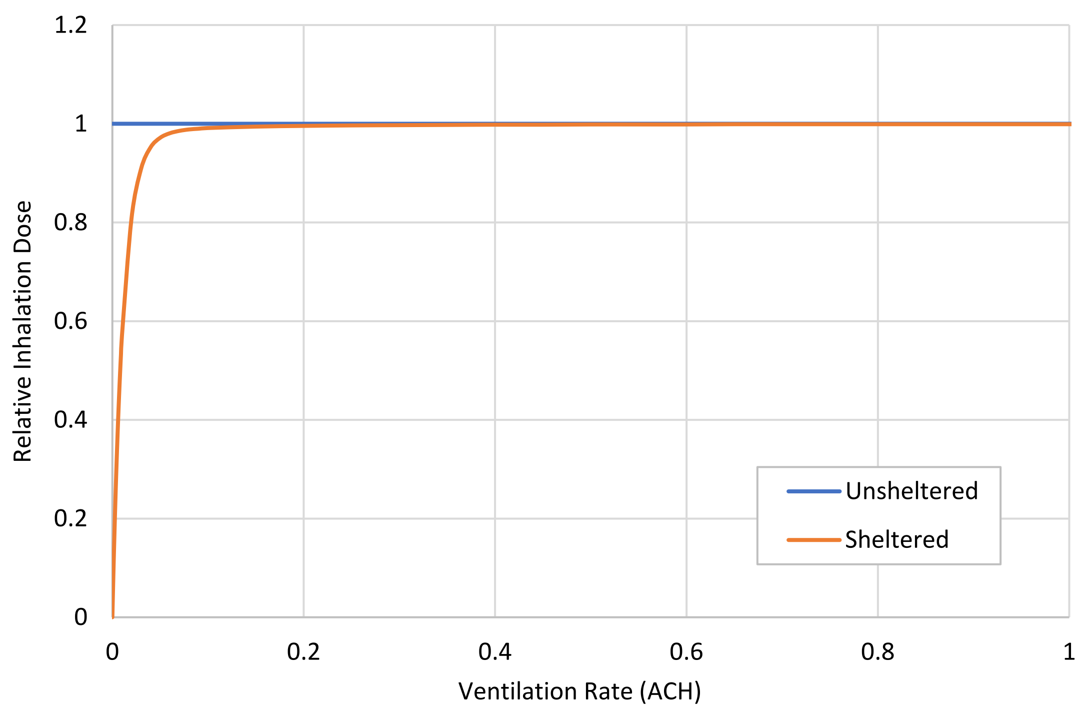


Figure 4-25 Effect of ventilation rate on inhalation dose

Lowering the air exchange rate does offer a benefit though, which is an increase in the time before PAGs are exceeded. As shown in Figure 4-26, a ventilation rate as low as 0.2 ACH would double the amount of time available before PAGs were exceeded. In actual hours at this location, if left unsheltered, PAGs would be exceeded 4.75 hours from the time of release, but 9.75 hours would be available if ventilation rates can be reduced to 0.2 ACH. The gain in time increases exponentially the lower the air exchange rate becomes. However, there is a practical limit to how well a house can be sealed, particularly if little to no notice is provided before the release. Fortunately, reducing the ventilation rate is not the only means of reducing inhalation dose. The penetration factor and HVAC filter efficiency also prove to be important.

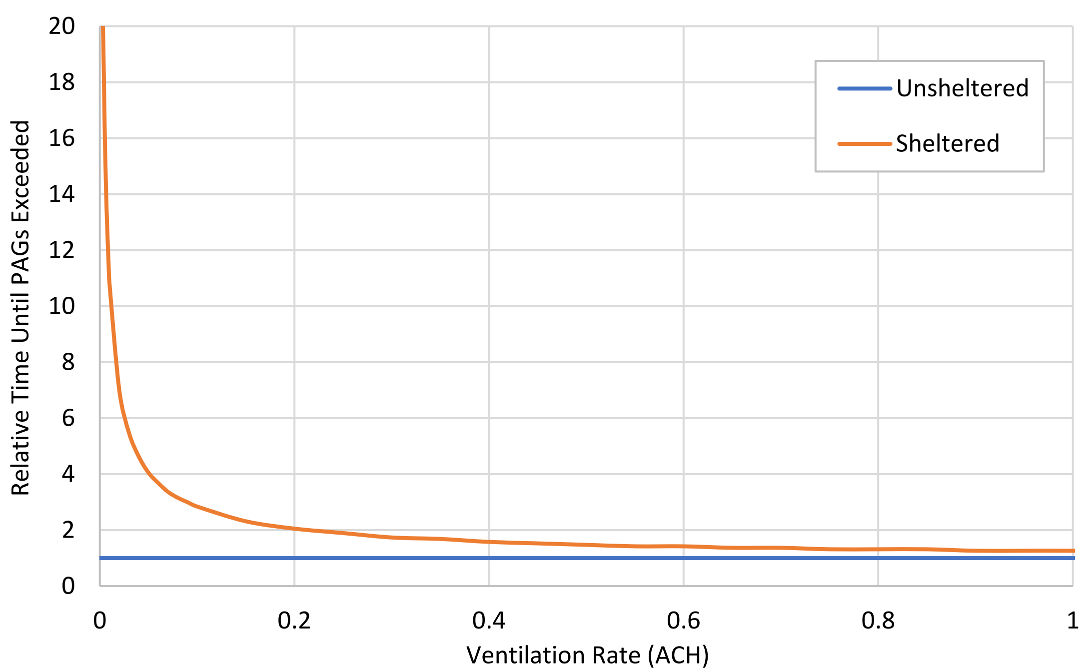


Figure 4-26 Effect of ventilation rate on time to exceed PAGs

4.6.4 Impact of Penetration Factor and Filter Efficiency

Filtration effects play an important role in reducing inhalation dose. Conceptually, the penetration factor is simple enough, and dose is reduced by a factor approximately equal to the penetration factor value.[16] For the natural infiltration of air into the house, particulates will be captured in the building envelope. Similarly, some HVAC units have filters to purify the air drawn in from the outside before further conditioning and distribution and which also filter the recycled air inside the house. For the BWR and PWR scenarios, the following cases were evaluated at 2 miles and 5 miles from the point of release to assess the importance of the penetration factor:

1. No Protective Actions: the unprotected dose projection over 96 hours.
2. Evacuation – the dose received assuming a 2 hour mobilization time and evacuation speed of 30 mph.
3. Sheltering (HVAC=0 ACH): sheltering in a one story house on the ground floor with a natural infiltration rate of 0.45 ACH.
4. Sheltering (HVAC=0.45 ACH; f=0): sheltering in a one story house on the ground floor with a natural infiltration rate of 0.45 ACH and a mechanical ventilation rate of 0.45 ACH but with no filter).
5. Sheltering (HVAC=0.45 ACH; f=0.8): sheltering in a one story house on the ground floor with a natural infiltration rate of 0.45 ACH and a mechanical ventilation rate of 0.45 ACH with filter efficiency of 0.8).

For each case, the penetration factor, which acts only on the infiltration rate, is varied from 0 to 1 and plotted against the total effective dose equivalent. The effect of the penetration factor and HVAC filter efficiency are shown in the following figures. In addition to the dose reduction, the filtration effects have a strong influence on the time before PAGs are exceeded. This is plotted in the accompanying figures for each scenario (BWR and PWR) and location (2 and 5 miles downwind).

As expected, the penetration factor plays an important role in reducing dose from the natural infiltration of outside air. It is not unrealistic to assume the

[16] This is approximate since the ventilation rate also contributes to a reduction in dose for sufficiently low rates of air exchange with respect to the plume passage time.

penetration factor may be as low as 0.2 or lower as described earlier. For the BWR scenario, even at 2 miles, sheltering can be effective at reducing dose below the PAG levels. This is, of course, source term dependent, as illustrated by the PWR scenario which has approximately the same dose levels at 5 miles as the BWR scenario at 2 miles. The more important result is to examine how sheltering-in-place compares to evacuation. For the assumed evacuation parameters, evacuation is clearly effective at avoiding dose. Yet, effective sheltering actions can bring the difference in TEDE to less than 1 rem. In other words, the difference in dose for an individual who evacuates versus an individual that shelters-in-place is likely to be less than 1 rem. For the SMR scenario, even at distances close-in (~ 2 miles from the point of release), sheltering is effective at reducing dose.

Ventilation by mechanical means and the additional filtration capabilities of HVAC systems provide additional considerations for implementing sheltering-in-place. If no amount of filtration is available (f=0), then increasing the rate of air exchange from the outside to the inside reduces the shelter effectiveness. However, even an inexpensive filter (around $50) with an 80% filtration efficiency (f=0.8) for micron-sized particles would assist in reducing the inhalation dose, even if the penetration factor is higher. Of course, this would mean contamination would be spread through the house, however, some amount of contamination will occur anyway. There may be advantages to forcing the air through HVAC systems that are designed to provide filtration. If the HVAC system is running it will likely accumulate particulates on the filter, which can easily be disposed of and replaced; and contamination in the HVAC ducts, which is likely to accumulate on horizontal runs and bends, can be removed later on. For these scenarios, the reduction in building protection factors for contamination inside the house is assumed to be negligible, so no adjustments were made to the cloudshine and groundshine components to dose.

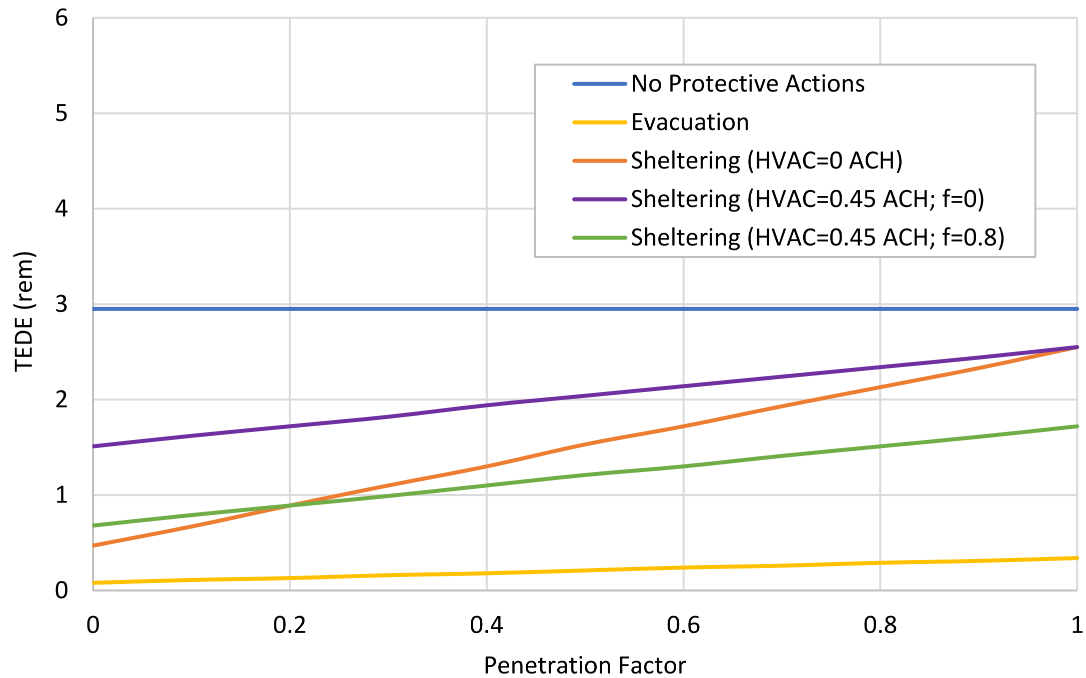


Figure 4-27 Effect of penetration factor and filter efficiency on dose; BWR scenario at 2 miles

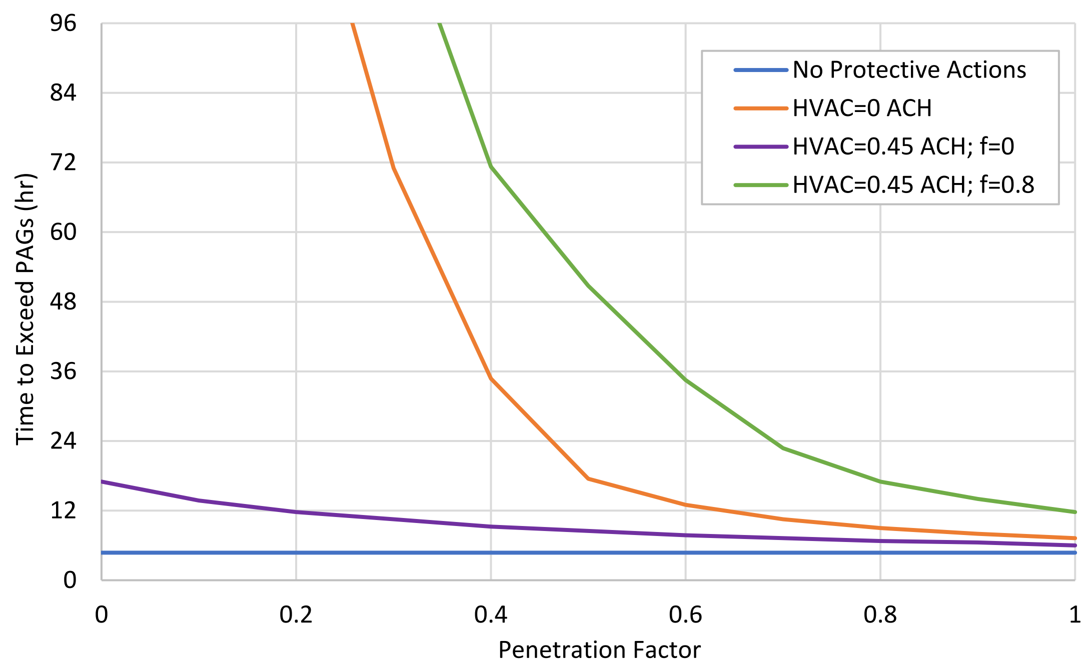


Figure 4-28 Effect of penetration factor and filter efficiency on time to exceed PAGs; BWR scenario at 2 miles

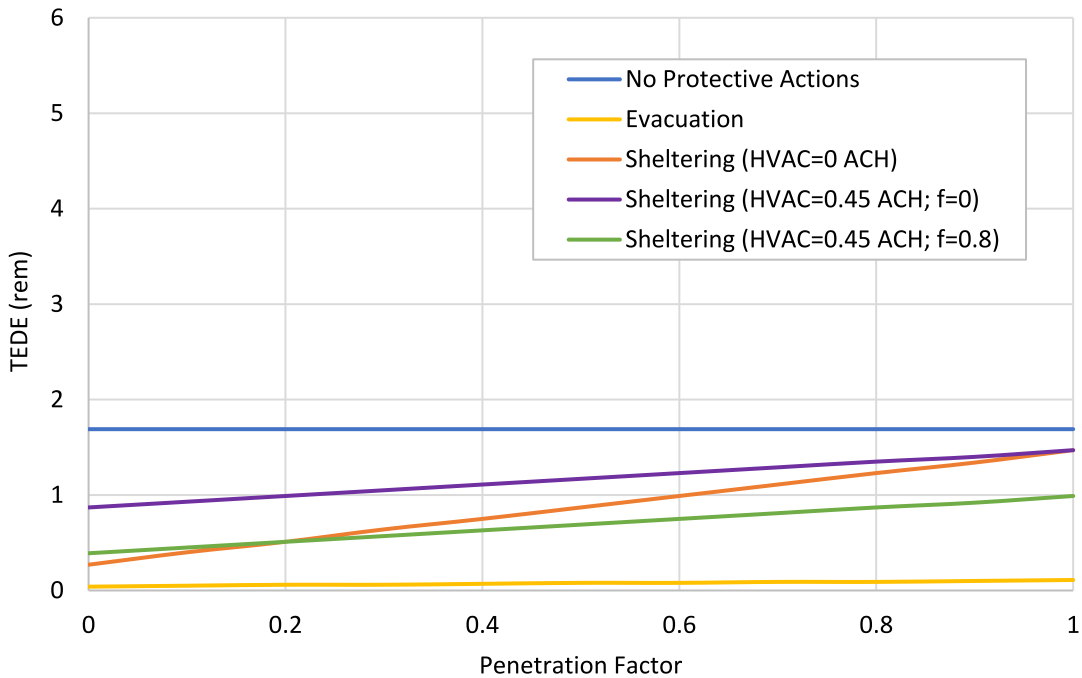


Figure 4-29 Effect of penetration factor and filter efficiency on dose; BWR scenario at 5 miles

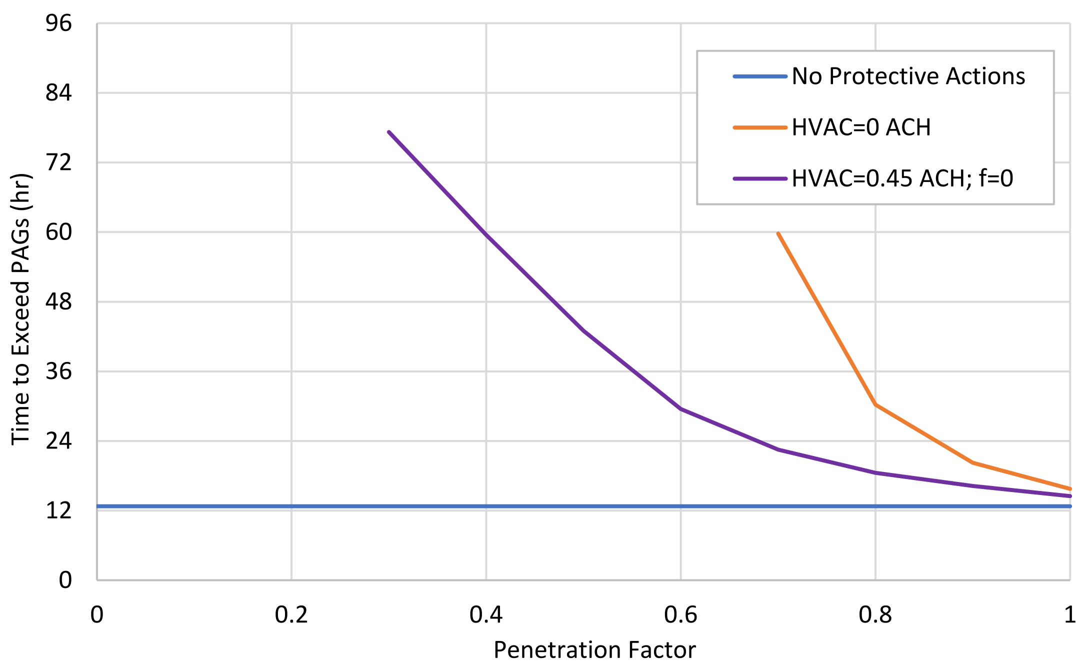


Figure 4-30 Effect of penetration factor and filter efficiency on time to exceed PAGs; BWR scenario at 5 miles

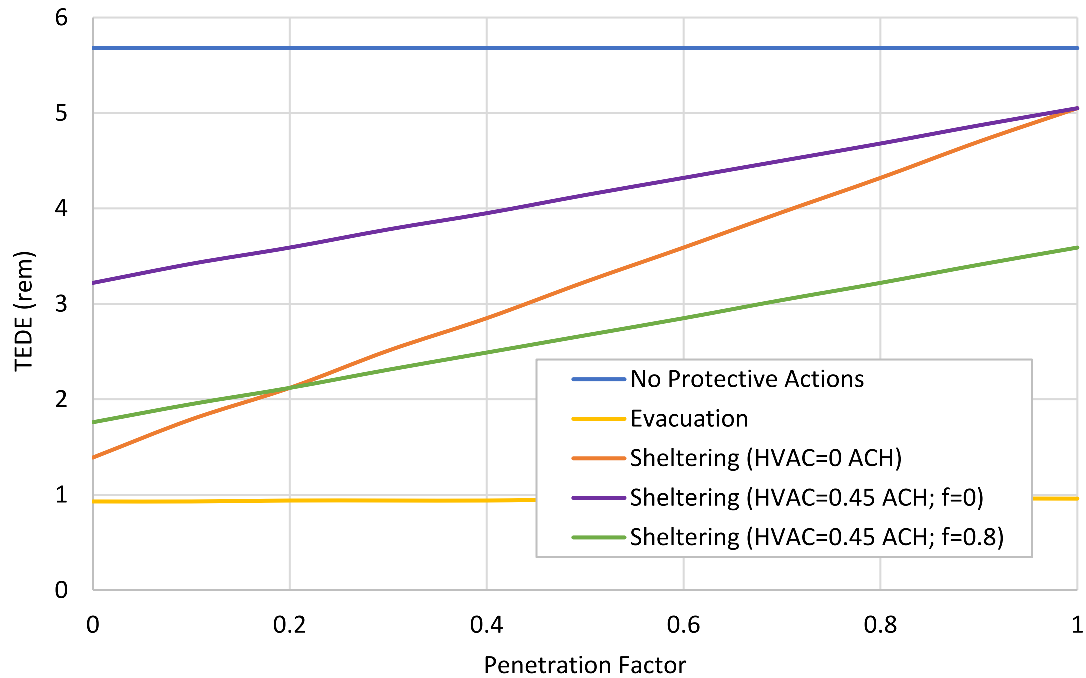


Figure 4-31 Effect of penetration factor and filter efficiency on dose; PWR scenario at 2 miles

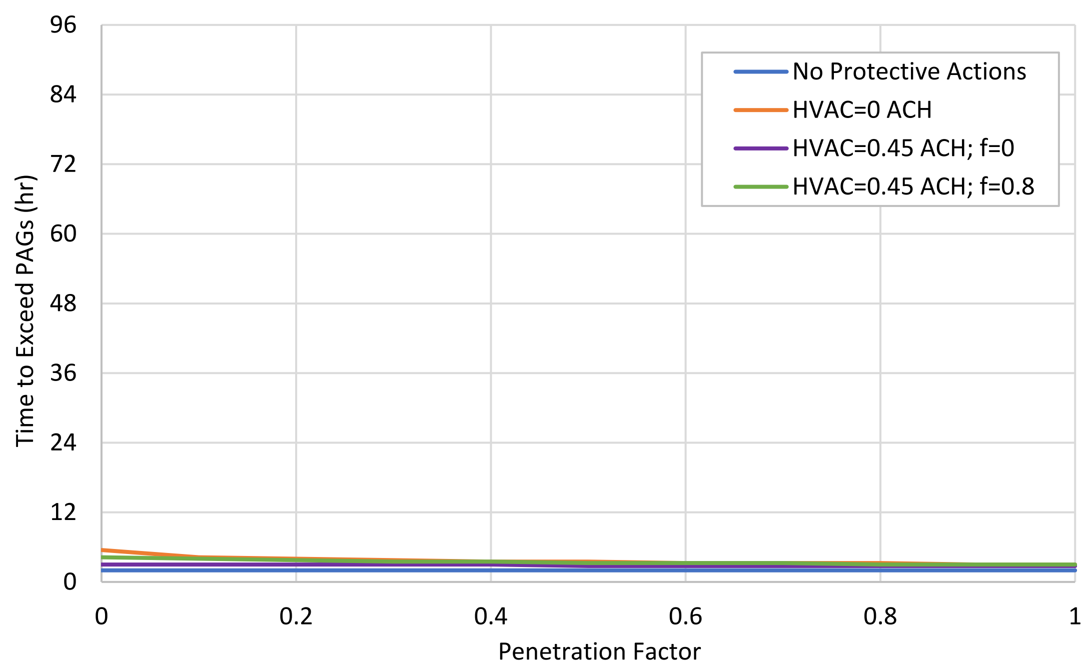


Figure 4-32 Effect of penetration factor and filter efficiency on time to exceed PAGs; PWR scenario at 2 miles

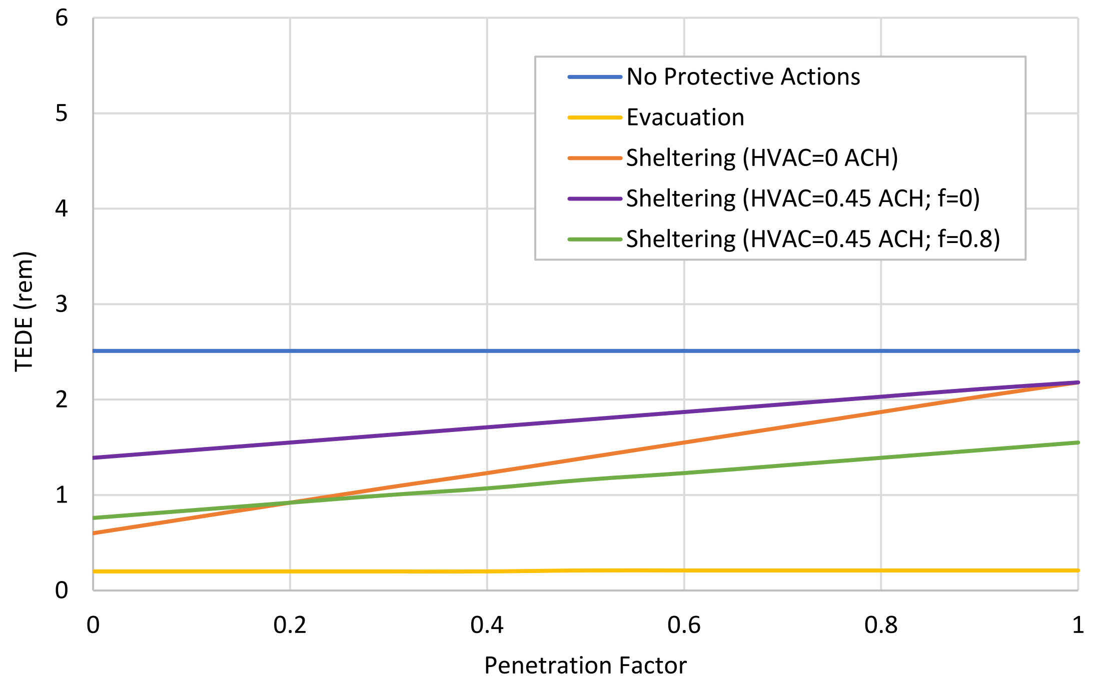


Figure 4-33 Effect of penetration factor and filter efficiency on dose; PWR scenario at 5 miles

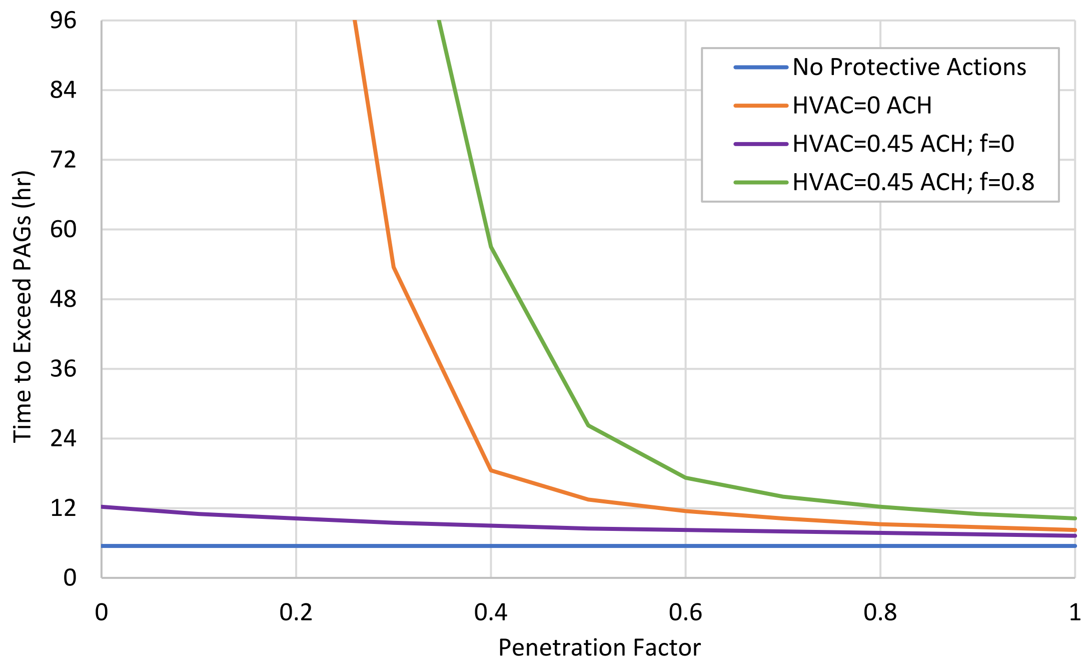


Figure 4-34 Effect of penetration factor and filter efficiency on time to exceed PAGs; PWR scenario at 5 miles

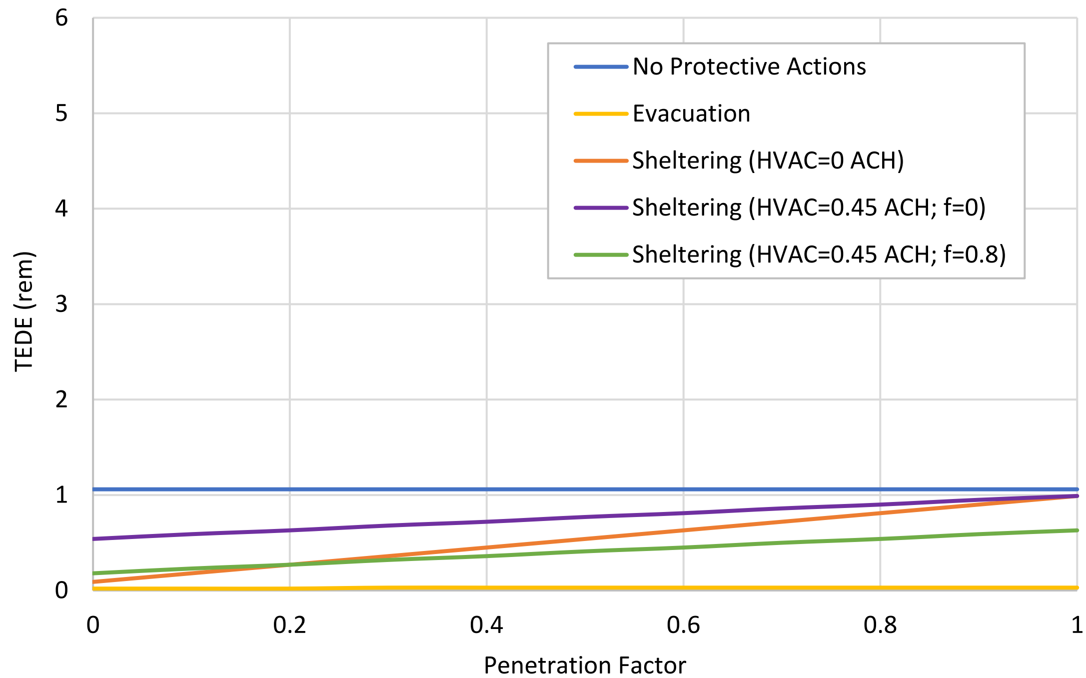


Figure 4-35 Effect of penetration factor and filter efficiency on dose; SMR scenario at 2 miles

The greatest advantage that filtration of radionuclides offers is in the form of additional time to decide upon action. This is illustrated in Figures 4-28, 4-30, and 4-34 for the BWR and PWR scenarios. An incremental change in the amount of filtration provided by the building envelope and HVAC system provides an exponential increase in the time available before PAGs are exceeded. This provides an enormous advantage in that, unlike evacuation which assumes a prompt public response once recommended, sheltering provides protection and additional time to assess the accident prognosis and conditions on the ground to better inform the need for further protective actions. Even a moderate amount of filtration can extend the time before PAGs are exceeded to 12 hours or longer. However, this again is dependent on the magnitude of the release, as the PWR scenario at 2 miles illustrates (Figure 4-32). Close-in to the point of release, PAGs may be exceeded within a few hours for a very low probable, high consequence accident. But in the SMR scenario, which has a smaller source term, a similar loss of coolant accident resulted in consequences that were easily managed using shelter-in-place such that dose would not exceed PAG levels even 2 miles downwind. This was not illustrated in a figure, because all sheltering cases resulted in not exceeding PAGs at 2 miles within the first four days. This result emphasizes the importance of a graded approach to emergency preparedness and the need to consider the specific risk of the facility when developing and implementing protective action strategies.

4.6.5 HVAC Considerations

PAG Principle 4 is intended to ensure that protective actions do more good than harm. Considerable attention and research has been devoted lately to the health consequences of evacuation and relocation. However, sheltering has its own inherent risk. HVAC systems provide important functions, not just for comfort, but to counter environmental conditions such as extreme heat and cold that could be detrimental to health. Although rare, heat stroke can raise the body's temperature to 106 °F or higher within 10 to 15 minutes, resulting in death or permanent disability.[17] Older adults are more prone to sudden changes in temperatures and less susceptible to the effects of radiation at low dose. This would suggest that sheltering strategies for locations in warmer climates, where large retiree populations live, should consider whether or not to secure air-conditioning, particularly if a release were to occur on an extremely hot day. Sheltering-in-place typically involves recommendations to secure HVAC units. If HVAC systems offer limited filtration, then it may prove beneficial keeping the mechanical ventilation secured to minimize air exchange until the plume has passed. But operation of HVAC units provide advantages in terms of protection from the environment, in which case it may prove beneficial to keep them running. As such, the factors that determine this balance will be explored next.

An analysis was performed to assess the inhalation dose sensitivity to the duration for which mechanical ventilation is secured. Figure 4-36 shows example cases using the PWR scenario in which air exchange occurs only through the HVAC unit and different values of the filter efficiency are assumed with values of f=0, 0.4,

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[17] https://www.cdc.gov/niosh/topics/heatstress/heatrelillness.html

and 0.8. The total inhalation dose, unprotected, is a projected 3.66 rem. The results show that the dose savings are dependent on the timing of the plume passage and the amount of filtration afforded by the HVAC system. In all cases, the longer the air exchange can be secured, the more beneficial this appears to be for reducing inhalation dose. However, this benefit decreases over time after the plume has passed overhead. In these specific scenarios, there is no substantial benefit to securing the HVAC for more than 24 hours.[18] In addition, as filtration efficiency improves, the time needed to ensure inhalation dose remains below PAG levels is decreased. For this scenario, to get below 1 rem, with no filtration the HVAC system would need to be secured for about 10 hours; at a filter efficiency of 40%, ventilation would need to be secured for 7 hours; and with a filter efficiency of 80%, inhalation dose can be controlled below 1 rem for the duration of the plume passage.

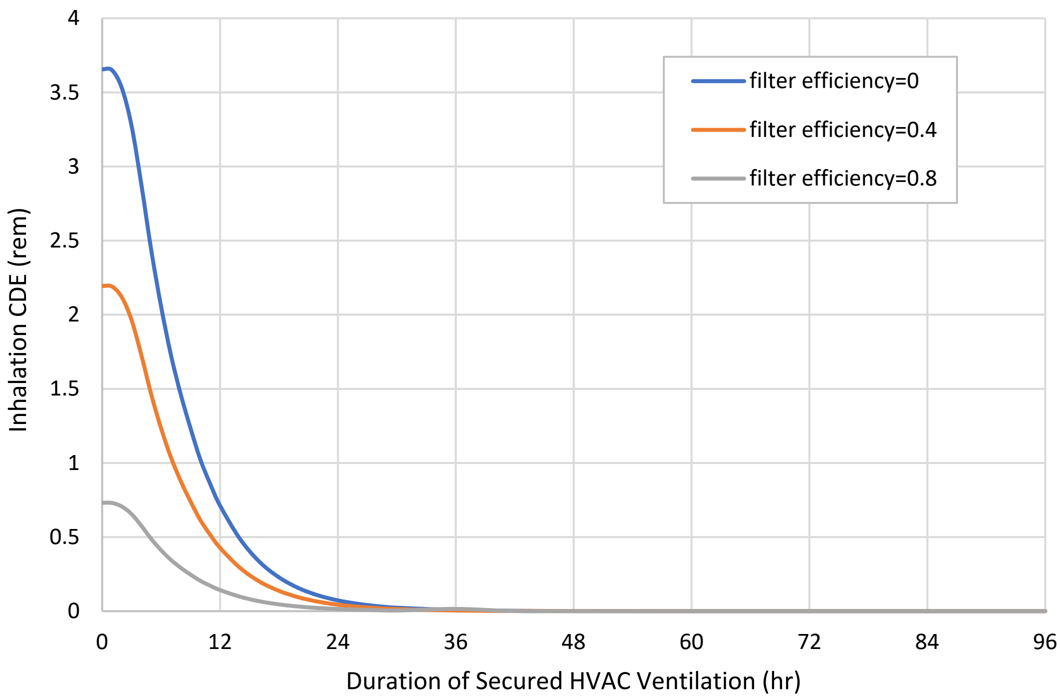

Figure 4-36 Effect of Securing HVAC Ventilation on Inhalation Dose

[18] The significant portion of the plume release lasted for roughly 24 hours in each scenario.

In reality, it is very difficult to completely avoid all air exchange, and the effect of the natural infiltration was not considered in the previous analysis. The analysis was repeated assuming an infiltration rate of 0.45 ACH with a penetration factor=0.5 and for various cases of HVAC filter efficiency. Again, the unprotected inhalation dose was 3.66 rem. In all cases, because of the natural infiltration, an asymptotic inhalation dose of 1.83 rem is projected to be incurred sheltering. For comparison purposes, the doses for each case were normalized to the asymptotic value of 1.83 rem. The results are shown in Figure 4-37. Ventilation is secured starting at the time of release at t=0 for the duration of time in hours shown along the x-axis, after which time the HVAC system is started in the model at an assumed rate of 0.45 ACH and with the various filter efficiencies shown. As before, there is negligible benefit in securing forced ventilation for more than 24 hours. This figure illustrates that the decision to operate the HVAC unit, and for how long, is highly dependent on the ability to filter out particulates. For a limited ability to filter out particulates, it remains prudent to secure HVAC operations to maximize the dose savings by minimizing the air exchange. In this scenario, securing ventilation for at least 24 hours would result in dose savings of 1800 rem; however, with even a standard furnace filter (f=0.1-0.2) the additional benefit of keeping the HVAC system secured for more than 6 hours is less than 100 mrem, about 5% of the total dose savings. This suggests that HVAC systems can be restored, if needed, once a significant portion of the plume has passed overhead. But there may be an advantage to operating the HVAC unit for the duration of the event. For moderate to high levels of filter efficiency, securing ventilation for more than a few hours may actually prove detrimental to dose savings. For very high filter efficiencies, the increased time of air exchange is outweighed by the removal of particulates from the air. This result is counter-intuitive to the notion that HVAC units should be secured to maximize the shelter effectiveness. But if increased dose savings can be provided by an HVAC system with a high efficiency filter, this offers an attractive implementation strategy that is particularly useful when the risk of potential harm from prolonged indoor exposure to extreme environmental conditions is also present.

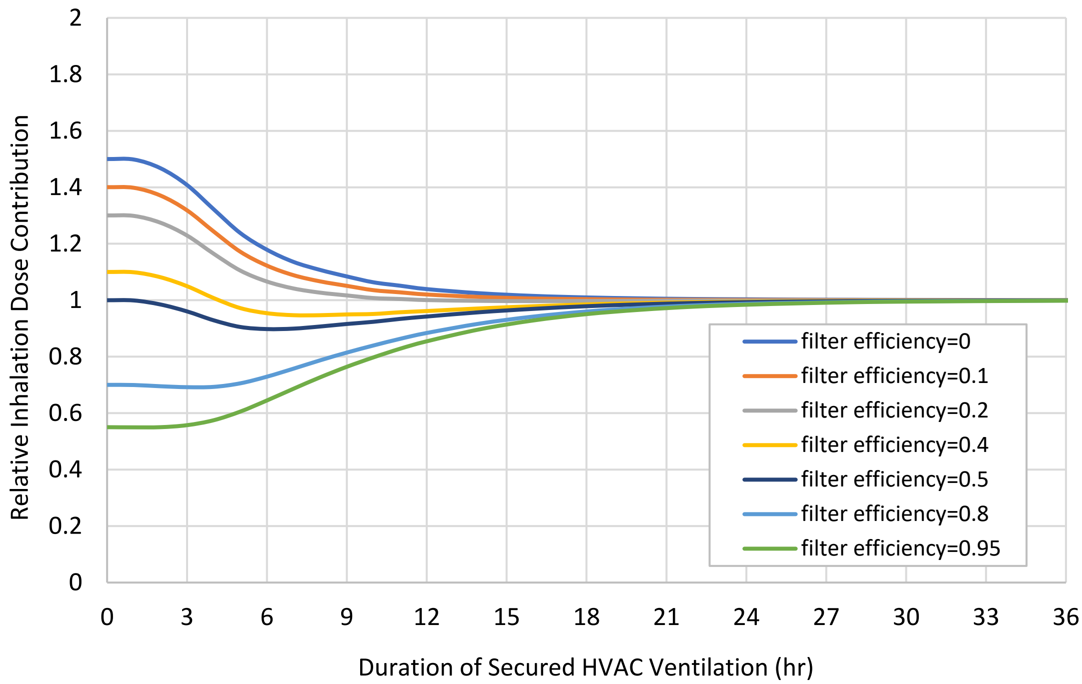

Figure 4-37 Relative effects of infiltration and HVAC ventilation and filtration on inhalation dose

4.7 Model Summary and Comparison of Shelter Effectiveness

The model results presented are not intended to be used directly to develop new protective action strategies. Rather, these results are intended to provide important considerations for the development and implementation of protective action strategies. Overall, these results suggest that shelter-in-place is effective at reducing dose to below PAGs levels when protected doses are in the range of 1-5 rem. These results further illustrate that sheltering can provide substantial dose savings such that additional dose savings provided by evacuation may not be warranted. As an initial protective action, sheltering-in-place offers substantial protection from a radiological release and would typically extend the time available before PAG levels are reached. This would provide more time to gather ground-truth data and base additional protective action decisions on actual measurements rather than dose projections.

The Fukushima Daiichi accident has resulted in a number of studies examining various factors related to shelter efficiency. An indoor air survey of 53 buildings within the evacuation area near the FDNPP showed that concentrations of ^{137}Cs in indoor air decreased with decreasing particle aerodynamic mean diameter and was inversely related to the square of the distance from the FDNPP (Shinohara, 2019). The relationship between cesium surface contamination and distance from the FDNPP matches measurements at homes in the towns of Okuma, Futaba, and Tomioka (Yoshida-Ohuchi, 2016). The indoor air survey attempted to isolate the contribution to dose from indoor surface contamination. Estimates of indoor ambient dose equivalent rates indicated that surface contamination contributed only about 3.0% to the indoor ambient dose rate.[19] This suggests that the indoor dose rate is strongly affected by the outdoor contamination levels and less by indoor surface contamination. This study also provided data to show that the indoor steady state dose rates were about a factor of 2 or more lower than the outdoor rates in most locations (Yoshida-Ohuchi, 2016). Similar dose reduction factors have been reported elsewhere. A median reduction factor of 0.43 (0.34-0.53) was found based on a survey of 69 detached wooden houses in evacuation zones in the Iitate village and Odaka district (Yoshida-Ohuchi, 2014). Dose reduction efficiencies of various other structures in the Fukushima Prefecture have been reported. The dose reduction factor for gamma radiation from cloudshine and groundshine based on indoor and outdoor absorbed dose rates in wood, aluminum, and reinforced concrete structures were reported as 0.55±0.04, 0.15±0.02, and 0.19±0.04, respectively (Monzen, 2014). These results are based on measurements after a relative steady state had been reached between the indoor and outdoor contamination levels, and the authors noted that factors related to the time variation of dose reduction efficiencies warranted further studies for radiation safety management (Monzen, 2014).

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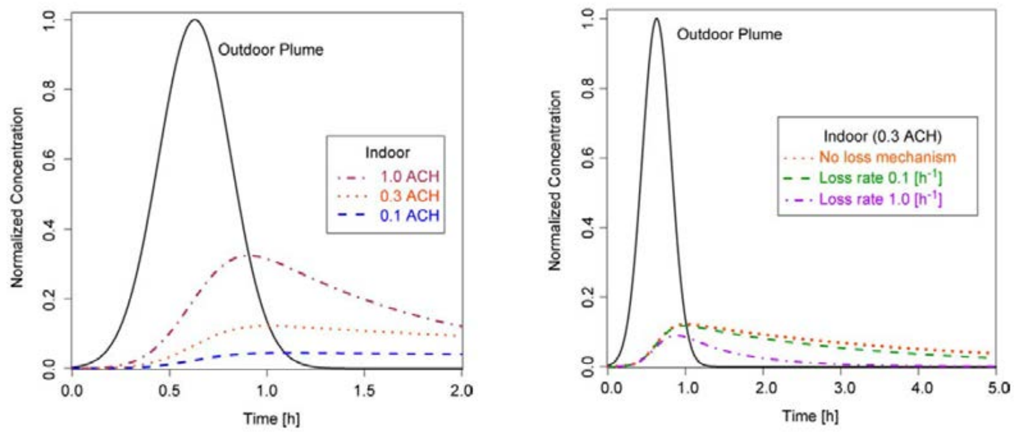
[19] This result also confirms the conclusion by the EPA that indoor deposition is a minor contribution to whole body dose (EPA, 1978) supporting its use as a modeling assumption.

In regard to the shelter effectiveness of airborne particles, Tan et al., developed a model to estimate the airborne sheltering factor (ASF) accounting for the air exchange rate, interior air volume, and inner surface area of dwellings for inhalation of ^{137}Cs and ^{131}I (Tan, 2015). Based on measured outdoor and indoor air concentrations, the model predicted an air exchange rate of 0.15 h^{-1} and fraction loss rates of radionuclides from the indoor air of 0.28 h^{-1} and 0.25 h^{-1} for Iodine and Cesium, respectively. At steady state, the model predicted ASF of 0.54 for ^{131}I and 0.60 ^{137}Cs (Tan, 2015). The importance of the indoor/outdoor airborne radionuclide concentration for radioiodine was demonstrated by researchers in Japan who showed that the committed effective dose to adults and the committed equivalent dose to the thyroid of infants staying indoors would likely be about 1/6 and 1/9 of the provisional doses from outdoor concentrations (Takeyasu, 2013). Overall, these studies support the results of the PARatus model. In addition, they support use of the cloudshine and groundshine protection factor correlations used in this study and the modeling approach for estimating inhalation dose. These studies also support the assumption that the indoor surface contamination is not a significant exposure pathway for dose.

The overarching principle of the PAGs is that protective actions should do more good than harm. Prolonged displacement of individuals from their homes is now known to result in significant health consequences, irrespective of the hazardous event leading to the evacuation or relocation. As such, the risks of evacuation should be carefully considered before unnecessarily moving people simply out of an abundance of caution. The results presented here demonstrate that sheltering-in-place provides a viable alternative to the use of wide-scale evacuation in the event of a radiological release. In addition, the increased dose savings provided by an HVAC system and high efficiency filter, and the risk of potential harm from prolonged indoor exposure to extreme environmental conditions warrant further investigation into the use of HVAC systems during a radiological release. These benefits of sheltering are illustrated by insights provided from other fields of study.

4.8 Additional Insights on Sheltering

Except for the unique radioactive properties, an environmental release of radionuclides exhibits phenomena similar to and is subject to the same physics as other airborne particulates. An extensive amount of research exists in the study of indoor and outdoor concentrations of airborne particles. Primarily this is driven by the recognition of the health risks of respirable particulate matter (PM). Many studies focus on the daily fluctuations in environmental levels of contaminant for a broad geographical area; but radiological events are sudden releases, and the plume behavior will have large geospatial and temporal variations. Chemical releases are a good analogy, and previous studies on sheltering in buildings from a large-scale outdoor chemical release have demonstrated the benefit that reducing the air exchange rates and natural removal mechanisms have on minimizing the indoor concentration levels. Figure 4-38 shows the results of a study to characterize the effects of air infiltration (ACH) and loss rates due to surface deposition (Chan, 2004). Similar results were obtained in another study of expedient sheltering-in-place against airborne hazards, which found protection factors ranged from 1.3 to 539, depending on the conditions (Jetter, 2005). In a chemical release the toxic nature of the hazard may warrant efforts to secure ventilation and reduce infiltration through taping of doors and vents, and placing plastic sheets over windows; however, after the passing of the plume some residuals will remain indoors. It is therefore important to terminate shelter-in-place to minimize exposure to toxic materials soon after the plume has passed (Chan, 2004).



(a) **(b)**

Figure 4-38 Indoor concentration profiles for a typical dwelling with (a) different air exchange rates, and (b) different air loss rates

The EPA PAG Manual recognizes that after the plume has passed, continued sheltering-in-place should be re-evaluated; shelters may be opened to vent any airborne radioactivity trapped inside (EPA, 2017a). However, the guidance does not appear to be operationalized. The NRC guidance on protective action strategies describes the use of sheltering-in-place and when it should be recommended by the licensee, but the termination of protective actions is the responsibility of the offsite response organizations (NRC, 2011a). Thus, the licensee has no regulatory impetus to recommend termination of protective actions based on knowledge of the release and plant conditions. In its study on protective actions in the intermediate phase of a radiological emergency the NRC asked state emergency managers if alternatives to evacuation or relocation are considered in the plan (NRC, 2018). States replied that sheltering-in-place is considered with specific considerations given to a puff release, weather, population density, traffic, and time of day, but no information on how such actions would be terminated was documented in the study (NRC, 2018). Although emergency plans provide all the capabilities for making prompt decisions with regard to sheltering, it is not clear how prompt decisions would be made to resume ventilating shelters once the plume has passed. The FEMA REP Program Manual provides guidance to ensure state and local radiological response plans include considerations for sheltering-in-place, but detailed guidance on operational considerations are not provided (FEMA, 2019b).

The use of HVAC systems and openings to control airborne contaminants is part of research efforts to control indoor levels of particulate matter. Thornburg et al., studied the penetration of particles into buildings through Monte Carlo simulations and found that a house with an HVAC unit in operation results in smaller indoor/outdoor (I/O) concentration ratios as shown in Figure 4-39 (Thornburg, 2001).

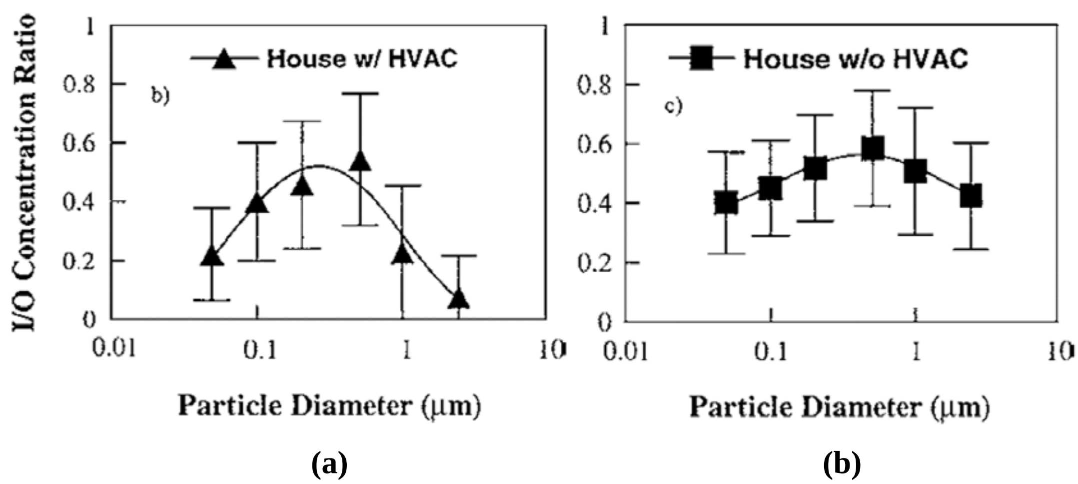
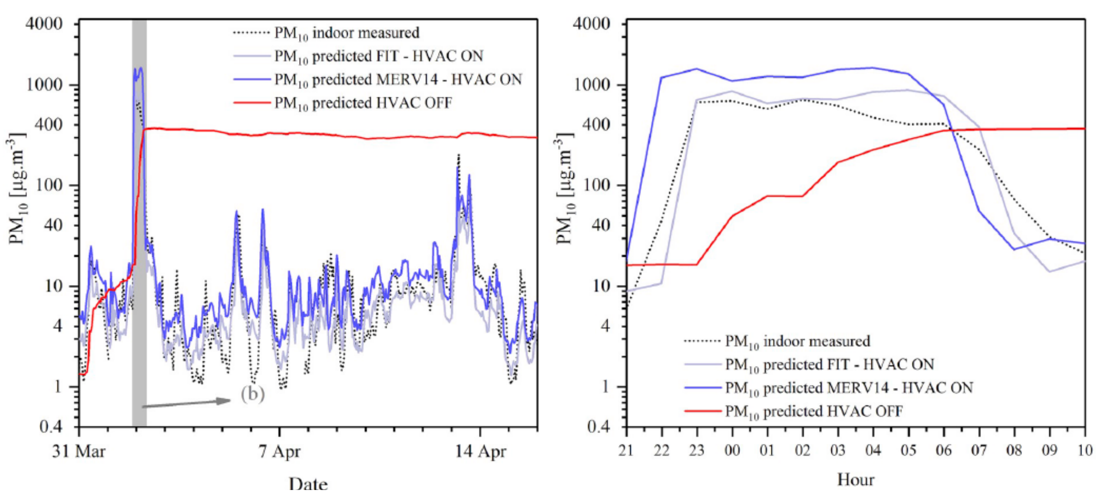


Figure 4-39 I/O concentration ratios as a function of particle size for (a) house with HVAC, and (b) house without HVAC

The simulations by Thornburg et al., also revealed that filter efficiency and duty cycle were the most important contributors to particle removal when an HVAC system was present.

Dust storms are another phenomena analogous to the release of particulates from a nuclear power plant. Dust storms are characterized by enormous amounts of airborne dust and other pollutants that can increase indoor and outdoor concentration levels 50-fold in just minutes with a gradual decrease to baseline levels after several hours or days (Kanatani, 2013). Argyropouls et al., performed measurements and modelling of particulate matter ingress during a severe dust storm event (Argyropoulos, 2020). This study illustrates the utility of HVAC systems with high efficiency filters in reducing indoor concentrations of particulate matter. Figure 4-40 shows trends in daily and hourly indoor measured and predicted PM_{10} concentrations before and after a severe dust storm event (represented by the shaded grey area). Securing ventilation has the predicted result of slowing the rate of air exchange to that only due to natural infiltration, but with no loss mechanism. By contrast, operating the HVAC unit during the dust storm results in a more rapid increase in the indoor concentration, as expected; however, HVAC operation also supports removal of particulates, resulting in a rapid decrease in indoor concentrations after the storm as demonstrated in both the measured and predicted results shown in Figure 4-40(b).

In addition to HVAC system filtration, indoor air cleaning filters have been found to be increasingly more effective especially as supply air filtration efficiency and building air tightness diminishes. Ward et al., concluded that a representative room air cleaner in a typical U.S. house would reduce the indoor concentration of outdoor originated particulate contaminants by 40-60% in the size range of 0.1-2 μm with maximum reductions as high as 90% for HEPA filters (Ward, 2005).



(a) **(b)**

Figure 4-40 Comparison of indoor measured and predicted PM_{10} levels for (a) study period and (b) dust storm period

The study of the sheltering efficiency of mechanically ventilated buildings conducted by Kulmala also revealed a substantial reduction in exposure to outdoor hazardous agents when using mechanical ventilation and high efficiency filters, as shown in Figure 4-41. Kulmala concluded that the main factors affection protection against outdoor Chemical, Biological, Radiological and Nuclear (CBRN) threats are ventilation flow rate, supply air filtration efficiency for the threat agent and infiltration of contaminants. Furthermore, this study concluded that while standard recommendations to go in, stay indoors, close windows and shut ventilation off is effective, it may be more beneficial to run the ventilation continuously to minimize occupant exposure provided that the supply air filter is effective against the threat agent in question (Kulmala, 2016). The results of the PARatus tool are consistent with these findings.

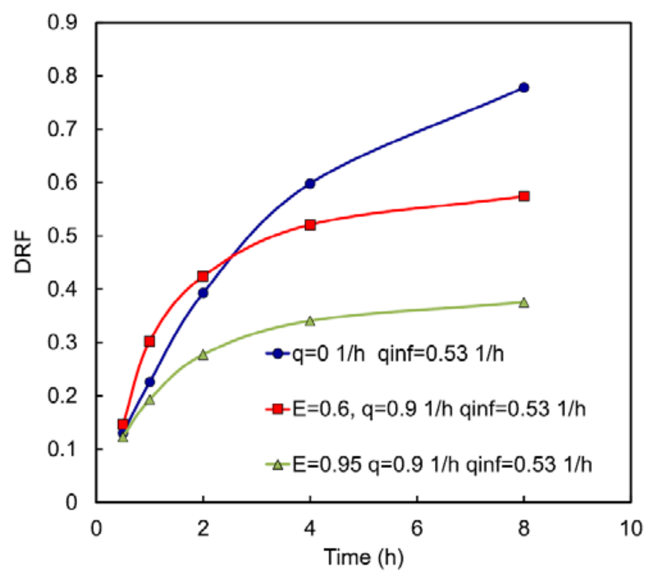


Figure 4-41 Dose reduction factor for different ventilation rates and filter efficiencies

4.8 PARatus

As the EPA PAG Manual notes, the selection of evacuation or sheltering-in-place is far from an exact science (EPA, 2017a). The PARatus tool is meant to serve as an example of how protective action strategies for radiological emergencies can be enhanced by exacting the science. PARatus combines state-of-the art building protection factor models with the results of RASCAL dose projections to provide new insights into factors that are important to effective use of shelters.

The sensitivity studies performed using the PARatus tool were not exhaustive, and the results presented focused mostly on parameters important to effective sheltering-in-place. The PARatus tool can be used to simulate a variety of shelter and evacuation parameters and examine the effect on the projected dose.[20] The usefulness of such simulation tools is that they provide the means for performing exploratory research, in a cost-effective manner. PARatus revealed important insights on the use of shelters that may be worth additional research to fully understand the physical processes involved and the implications for enhancing implementation strategies. In addition, PARatus provides an example of what can be accomplished to enhance protective action decision-making. A decision-aid like PARatus could easily be coupled to dose projection software and modeled with site-specific shelter parameters and evacuation dynamics. The relative effectiveness of evacuation vs. shelter-in-place could be evaluated in real-time, providing decision-makers with additional information to support making protective action decisions.

4.9 Application

There is a clear opportunity to develop enhanced strategies and guidance for implementing effective shelter-in-place. All-hazards emergency planning and preparedness benefits from the cycle of responding to natural and technological hazards that occur more frequently. Fortunately for the public (but unfortunately for research purposes) radiological releases are rare events. As such, radiological emergency planning must make the most of the lessons learned from the few events that have occurred. However, given the commonalities with all-hazards emergency planning, it is expected that a significant body of work is already available from which additional insights can be drawn to help refine protective action strategies for radiological emergency events. Radiological emergency planning can benefit from the insights provided by research in other areas like response to chemical emergencies

[20] The PARatus tool is available from the author upon request. todd.ryan.smith@gmail.com

and dust storms. Another advantage provided to radiological emergency preparedness is the commonality involved in implementing evacuation and sheltering-in-place. The lessons learned in response to other events are likely to be directly applicable to radiological releases. This promotes a common response framework and protective actions that are likely to do more good than harm.

The PARatus tool provided proof that protective action decision-making can be turned into a more exact science. Analytical tools provide the opportunity to examine the parameters important to effective evacuation and sheltering so that detailed practical implementation methods can be devised. In addition, tools can be developed to inform decision-making during an emergency. The previous analyses demonstrates that detailed implementation strategies for the use of sheltering-in-place could have significant advantages in dose savings and overall reduction in health risks. In particular, HVAC systems can be used to control the levels of indoor contaminants and provide the added benefit of reducing the risk of sheltering-in-place under extreme environmental conditions.

The results of this study emphasize the importance of applying a graded approach to emergency preparedness that considers the specific risk of the facility when developing and implementing protective action strategies. As new reactor technologies enter into operation, there will be a need to alter the approach to protective action strategies. The planning considerations for a large light water reactor may not translate directly into the planning needs for a small modular reactor. Prompt protective actions based on plant conditions may not be a planning concern for a facility with passive safety features, smaller core inventory, or an advanced design that extends the time available before a release could ever occur. Protective action strategies will need to be rethought and developed specific to the risk posed by the facility. But changing the approach to radiological emergency preparedness and response will take more than just exacting the science—it will require a shift in our cultural thinking and philosophy toward radiation, as well.

Chapter 5 – Changing the Protection Culture

I must not fear. Fear is the mind-killer. —Frank Herbert, Dune

On Friday, January 8th, 2021, a hazardous material team, and local fire and police, deployed to the Haddon Township High School and quickly secured the building. Students and teachers were evacuated. Reporters soon arrived and spoke to the bewildered group outside to discover the reason for the evacuation.
"A dangerous substance was found," one teacher said, adding that school was dismissed, "so we could all be safe."[21] What dangerous substance was found in the school that prompted such a response?

A plate of grandma's Fiestaware.

The previous chapters provide a basis to improve upon protective action strategies by reconsidering the benefits of sheltering-in-place and weighing the risk of evacuation and relocation against the holistic health risk of those actions. However, for decades evacuation has been identified as the preferred protective action; so even if these new risk insights are acceptable, changing the protection paradigm also requires cultural acceptance. But is a cultural shift achievable? One might assume that the population will always be so afraid of radiation that no one would agree to shelter-in-place over evacuation. But is this view of the public correct? Would the public really demonstrate irrational fear and panic over a rational concern for safety and a reasoned response? Or is the public more accepting of being told what to do during an emergency—even a radiological event—than often given credit? Does the public need a detailed understanding of radiation for protective actions to be effective? Certainly, the students evacuated from the Haddon Township High School

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[21] https://www.courierpostonline.com/story/news/2021/01/08/report-haddon-township-high-school-student-brought-uranium-school-hazardous-materials-south-jersey/6595724002/.

due to a piece of Fiestaware have now received a mixed-message about radiation that counters the science they are taught. Was this evacuation a result of wide-spread fear of radiation on the part of the student population, or did one person make the wrong decision based on their own ignorance? And might this ignorance be the result of decades of poor communication about the risks of radiation? If so, what cultural changes are necessary to support protective action decision-making?

This chapter examines cultural aspects of radiological emergency preparedness to identify what needs to change in order to move forward. The goal is to identify the preparedness efforts that will most likely lead to a successful public response. Since how we communicate about radiation is such a large part of the culture, this chapter focuses primarily on radiological risk communication. While the radiological community and experts on risk communication are well-prepared to respond to an actual event, it will be argued that cultural biases still exist that send a mixed-message. It will be demonstrated that wide-spread public fear of radiation is largely a myth, perpetuated at times by the very same radiological community that so desperately wants to see a change in public attitudes toward radiation. This is evident in risk communication strategies that appear to have been shaped by the Precautionary Principle and LNT-inspired message of “no safe dose.” This precautionary approach to radiological emergency preparedness—an approach that is based in uncertainty—is believed to have resulted in a deep-rooted cultural bias that views radiation as uniquely different from other hazards, such that it requires special considerations when communicating with the public. However, it will be demonstrated that the principles of radiological risk communication are no different than the principles used for all-hazards risk communication, and that they share a common foundation. In addition, it will be shown that modern risk communication strategies have begun to move away from the cultural biases of the past, including fatalistic attitudes toward the public and adherence to messages of “no safe dose”. Even so, it will also be argued that advances in radiological risk communication efforts have not gone far enough to inform both decision-makers and the public on the principles needed to ensure that protective actions do more good than harm.

5.1 Setting the Stage

Risk communication is an essential part of emergency preparedness and response, and radiological risk communication has received the much needed attention it deserves. There is no shortage of tools, lessons learned, and research on effective communication strategies for radiological emergencies, and the process continues to evolve. This chapter includes a brief historical perspective on the evolution and practice of radiological risk communication. By doing so, the stage will be set to ask a number of questions. Is radiological risk communication any different than risk communication for other hazards? Is the radiological risk clearly communicated or do personal biases of the risk communicators create mixed-messages? What message does the public want to hear? Are there gaps in current risk communication strategies? The analyses presented will reveal that there has been, at times, a cultural bias toward a presumed widespread public fear of radiation. This bias shows up in unexpected ways in risk communication tools and in public information on radiation. In order to move forward, there needs to be a change in the cultural mindset of the radiological community, and that needs to start with changing attitudes towards the public.

5.2 Is the Public Really Afraid of Radiation?

The radiological and nuclear communities often make stereotyped statements when it comes to public perception of radiation. Rarely can there be a discussion about radiation or nuclear power without someone asserting the public is afraid of radiation. That this is not a tautology is never challenged. Heads typically nod in agreement while everyone recalls a poor experience explaining radiation to someone less familiar with the subject. But is it fair, or even accurate, to stereotype the public as being afraid of radiation and nuclear power? And by “fear” do we mean irrational fear or rational fear? Is caution a better word? And is it really widespread? Just who is meant when someone says, “the public?” To counter the notion that there is currently widespread fear of nuclear power and radiation within the public, it is worth examining whether public opinion about nuclear power and radiation has changed since the days of atomic bomb testing.

More than three generations have passed since the early days of nuclear bomb testing, and attitudes toward radiation are no longer those reflected by the culture of the 1950s. Today, the youngest generation of Americans have more important concerns besides nuclear weapons. According to the Chapman University Survey of American Fears Wave 5, in a sample of 1,190 adults, nuclear power and radiation are nowhere near the Top 10 concerns in the U.S; these top concerns are shown in Figure 5-1 (Chapman, 2018). So, where does nuclear power and radiation rank? Out of 94 different phenomenon including crime, government, the environment, disasters, personal anxiety, and technology, a nuclear meltdown comes in at number 37, with 36% of the population expressing they are afraid or very afraid of such an event. How does that compare to other fears? Table 5-1 provides a sample of the public views of the threats faced as a society. The Chapman survey data provides a number of interesting observations. First, a nuclear meltdown ranks alongside more common natural disasters. In other words, a large radiological release from a nuclear power plant is perceived as not much different from the level of concern for a hurricane, wildfire, earthquake, and other natural events routinely faced by society. And among technological hazards, nuclear power is far from the list of top concerns.

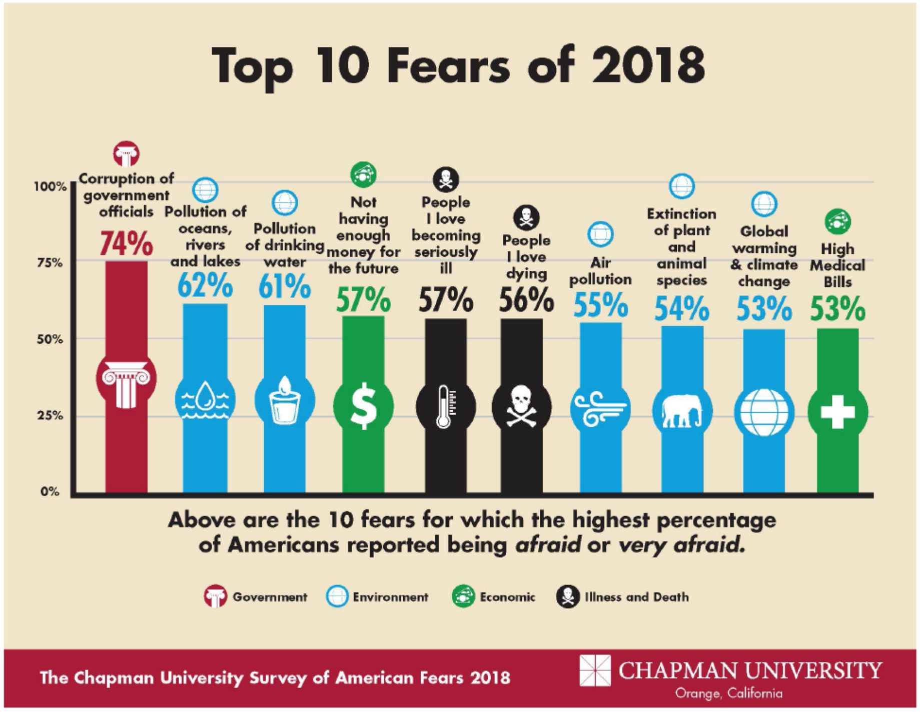

Figure 5-1 Chapman University survey Top 10 American fears of 2018

Table 5-1 Sample of fears by rank and perception of risk

Rank	Fear Addressed in Study	Percent Afraid or Very Afraid
1.	Corrupt government officials	73.6
9.	Global warming and climate change	53.2
11.	Cyber terrorism	52.5
20.	Biological warfare	44.7
22.	Oil spills	44
23.	Terrorist attack	43.8
25.	Nuclear weapons attack	42.9
32.	Pandemic or a major epidemic	38.6
34.	Devastating drought	37.7
37.	Nuclear accident/meltdown	36
39.	Devastating tornado	34.7
43.	Devastating hurricane	32.8
46.	Devastating flood	31.1
47.	Devastating earthquake	30.9
49.	Devastating wildfire	30.7
75.	Technology I don’t understand	17.8
90.	Clowns	7.1

But what about like hazards? Does the public equate nuclear power with nuclear weapons? From the survey, the fear of a nuclear attack ranks 12 spots closer to the top fears, with a 7 point differential among those afraid of such an attack versus those afraid of a nuclear meltdown. This points to a public understanding of the difference between a nuclear weapon and a nuclear reactor. In addition, the fear of technology that is not well understood is low on the list of public fears, with only 17.8 percent afraid of such risks. This data points to a public that is educated enough to place their concerns in context and not inflate the risk by virtue of being unfamiliar with radiation. Is that the picture of public perception held by the radiological community? Is it fair to assume that the public is ignorant of radiation and is, therefore, fearful and overly mistrustful of nuclear power? The data from the 2016 Nuclear Energy Institute (NEI) survey does not support that view. As shown in Figure 5-2, even among those not well-informed at all about nuclear energy, a majority still support its use (NEI, 2016).

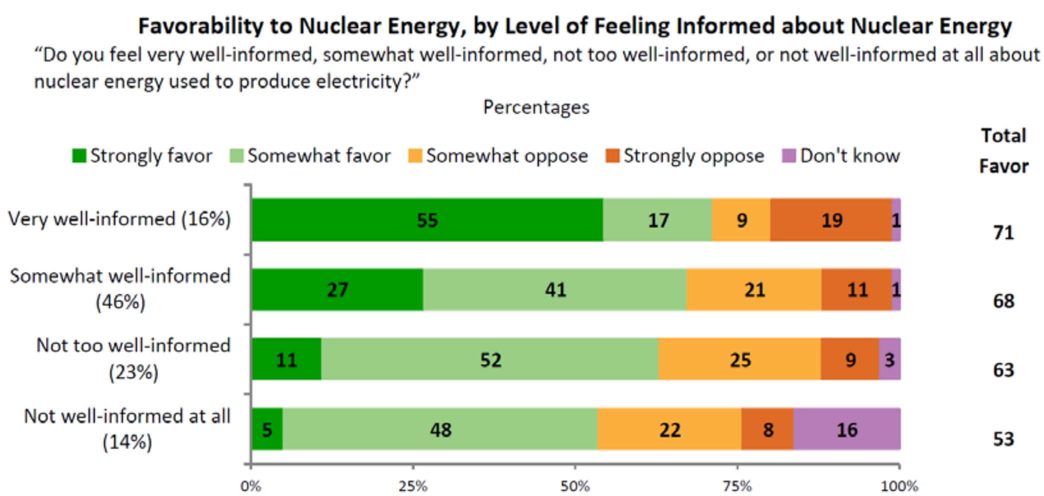

Figure 5-2 Favorability of nuclear energy by level of understanding

And what of overall public support for nuclear power? The same 2016 NEI survey shows support for nuclear energy remains strong with 65 percent of the public favorable to its use, as shown in Figure 5-3 (NEI, 2016). Not only that but the survey also found (NEI, 2016): 84 percent think nuclear should be important in the future;

82 percent agree we should take advantage of all low-carbon energy sources, including nuclear, hydro and renewable energy; 95 percent agree it is important to maintain diverse electricity sources. And while the Chapman survey reveals that the Number 1 public fear is corrupt politicians, from the survey data shown in Figure 5-4 it seems that most people on both sides of the political aisle can agree on the use of nuclear energy (NEI, 2016).

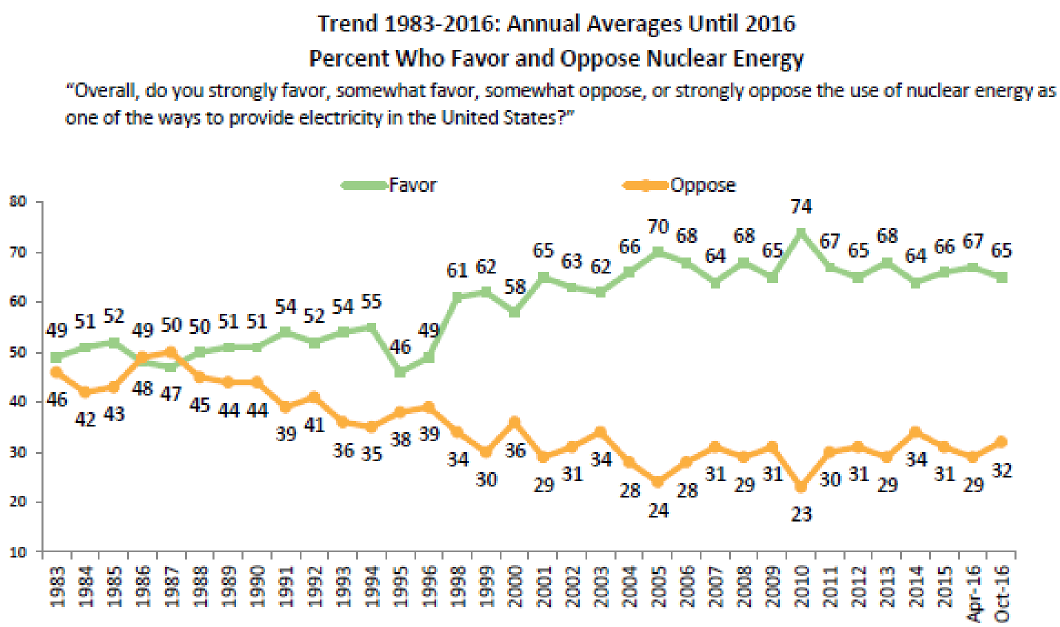

Figure 5-3 Annual trends in public favorability of nuclear energy

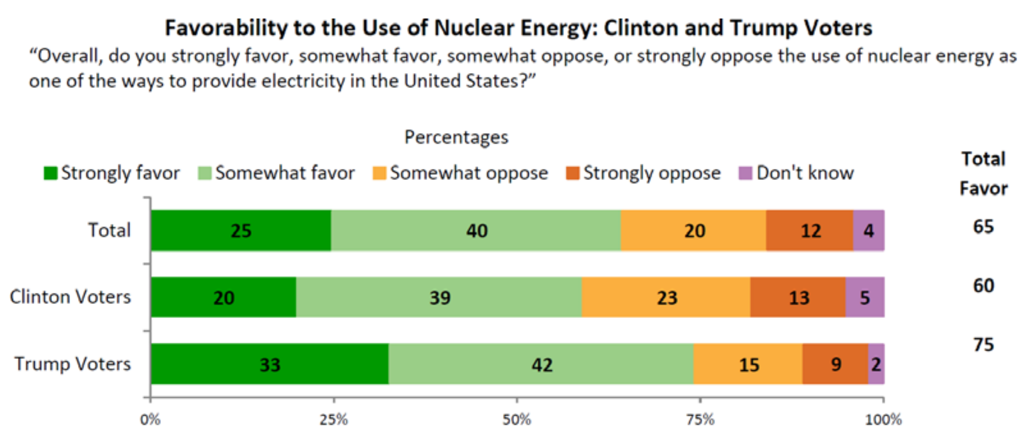

Figure 5-4 Favorability of nuclear energy among political parties

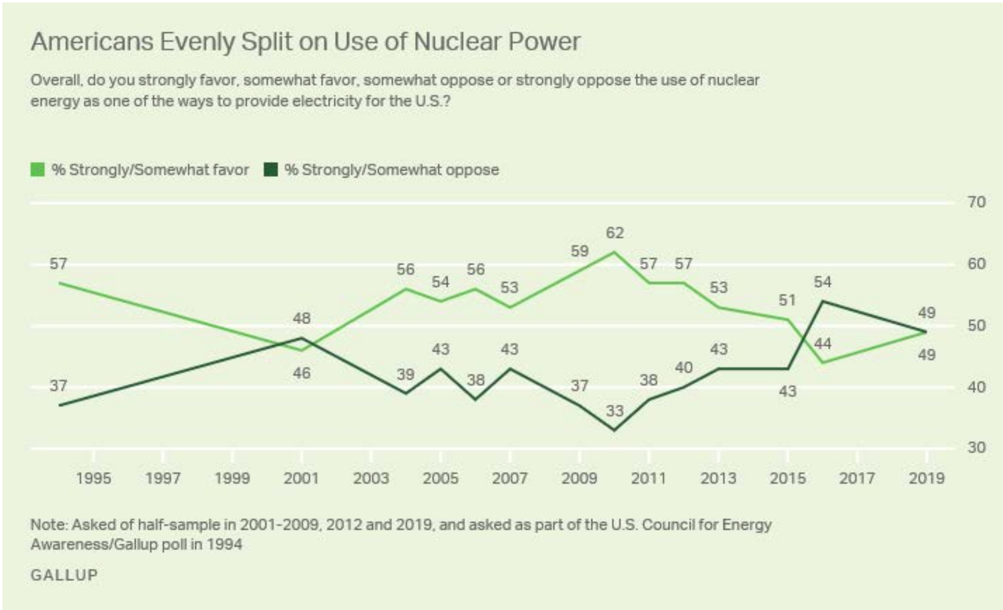

Figure 5-5 Gallup poll opinions on nuclear power over time

In regard to nuclear power, the public was recently fairly split according to a 2019 Gallup pool as shown in Figure 5-5 (Reinhart, 2019). But, even more interesting, is that the trends in opinion shown in this figure reveal that the Fukushima Daiichi accident in 2011, did not appear to have a lasting impression on public support for nuclear power. Unfortunately, news reports on nuclear power are sometimes too quick to put a spin on the poll data or leave out important context. For example, a few years ago an article was published, titled, “Nuclear power is losing popularity in the US. Here’s why” (Plumer, 2016). Any number of reasons for a decline in popularity may come to mind from just reading the headline. Is it fear of radiation? Is it the waste issue? Casual readers may assume so, but the article continues, “For all its problems and setbacks over the years, nuclear power has long been broadly popular in the United States. But there are signs that may be changing.” And what were those signs? According to the article, the decline “…doesn’t seem to be driven by radiation fears or safety concerns.” The reactor meltdown in Fukushima Japan in 2011, barely moved the needle on popular opinion in the U.S. Instead, the decline in popularity is believed to be a function of over-regulation and cost compared to other energy sources (Plumer, 2016).

5.3 Moving Beyond Fear

Traumatic events, by their very nature, elicit a range of emotional responses. The public response to COVID-19 is a perfect example. During the outbreak, researchers in Italy monitored emotions and general sentiments in Italian and English language content on social media. The map in Figure 5-6 shows the emotions derived from a semantic analysis of 140,000 social media posts in a 48 hour time period. Fear is but one of many of the negative, positive, and neutral, feelings expressed. This study also revealed that cultural differences lead to subtle variations in response. In like manner, it should be recognized that a radiological emergency is likely to elicit a wide a range of emotional responses.

Day 12: Expert System and Sociometrica are monitoring the emotions and general sentiment around the COVID-19 pandemic expressed by people in the US and UK across social media.

Figure 5-6 Map of Emotions and Sentiments on Social Media Posts in Response to COVID-19[22]

[22] https://techstartups.com/2020/04/14/negative-emotions-spike-coronavirus-covid-19-spread-continues-according-analysis-italian-based-ai-company/

The previous analyses have shown that by and large the public does not have an unhealthy fear of radiation. Rather, much like with any hazard, in the event of a radiological release, the public is likely to exercise caution and await further instruction on actions to take. Risk communication tools have evolved to address a variety of potential radiological incidents. The messages are ready and the public is prepared to listen, but there is still a problem. The problem is that a cultural mindset exists that can undo all these preparation efforts in a single instant. One wrong message, one wrong decision, and the public will lose trust. This must not be allowed to happen. To prevent this from occurring, the response to a radiological emergency cannot be driven by expectations of widespread fear and panic.

Yet, the predominant cultural expectation of the radiological protection community is precisely that—a hyper-focus on the fear of radiation. It has already been placed on record that such irrational and misinformed fear of radiation leads to disastrous results in responding to a radiological emergency (Conca, 2020).
To combat this, the World Health Organization notes that risk communication is essential and should be carried out by trained specialists (WHO, 2016). But are the specialists themselves prepared to respond with the correct message? Or would the cultural bias of the experts toward expecting widespread fear and panic among the public create that very response? Is it possible that the radiological community could be partly to blame for misconceptions about radiation? And does this bias show up in the ways radiation is communicated such that it promotes feelings of hopelessness rather than empowerment? To answer that question, information provided by a trusted source— the CDC—will be examined next for evidence of a cultural bias toward communicating about radiological hazards.

5.4 Comparison of Public Health Communication Products

The CDC works to protect America from health, safety, and security threats. As part of their mission, the CDC nurtures public health by providing communication resources to the public covering a variety of health hazards. The following images and educational materials were taken from the CDC website for various diseases and conditions. For the listed conditions, which include coronavirus, cancer, diabetes, heart disease, sexually transmitted diseases (STDs), and more, the CDC provides a wealth of information on the health risks and how to seek help and be safe.

Cancer, for example, is one of the leading causes of death in the U.S. and has devastated the lives of millions of Americans. For those seeking information on the CDC website on ways to prevent and fight cancer, they are immediately greeted with images of hope and reassurance, and messages of survival, as shown in Figure 5-7. Different diseases affect different portions of the population, and the CDC appeals to these sub-populations by the use of positive imagery geared toward their target audience. For example, the CDC uses a photo expressing excitement and friendship to relate to teenagers on the Spanish version link for information on sexually transmitted diseases, as shown in Figure 5-8. And the CDC connects with children through fun and informative activities. For example, there is a colorful webpage where kids can learn more about rabies (Figure 5-9), and a brightly-colored, fun activity book for kids on how to be safe after a flood (Figure 5-10).

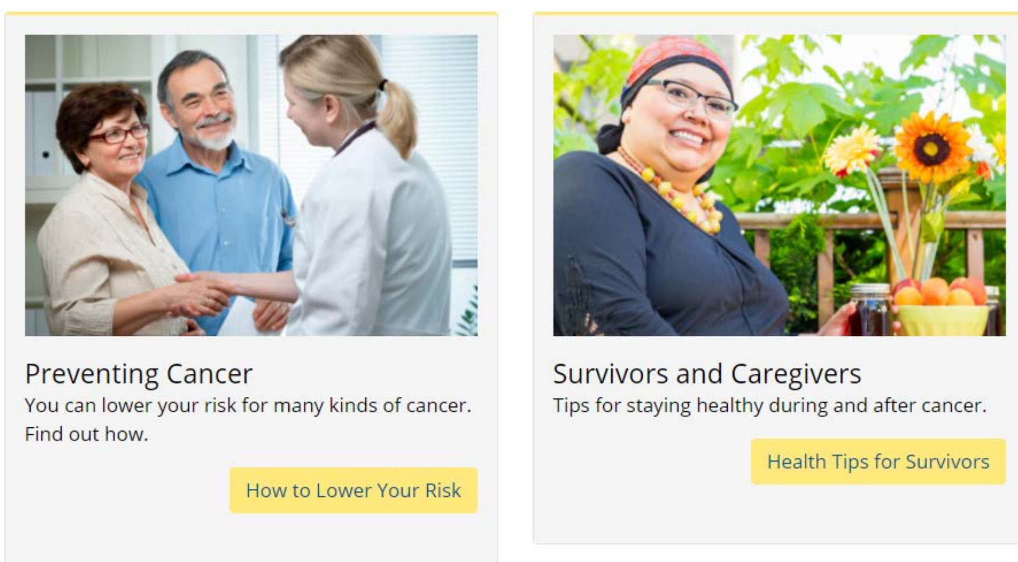

Figure 5-7 Information on preventing and fighting cancer[23]

[23] https://www.cdc.gov/cancer/index.htm

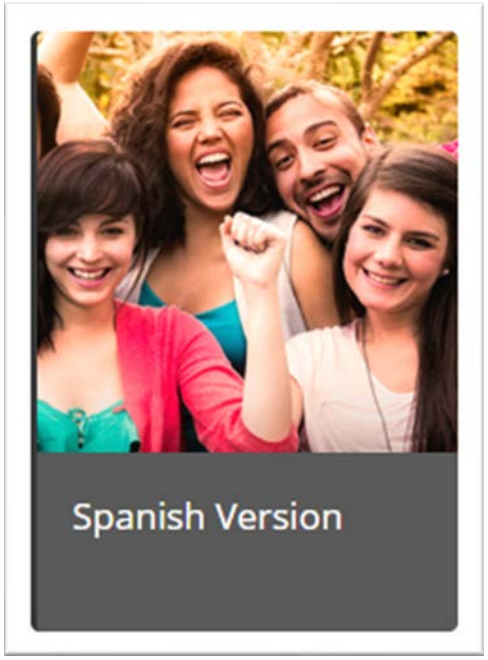

Figure 5-8 Spanish version link on sexually transmitted diseases[24]

Figure 5-9 Webpage on kids and rabies[25]

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[24] https://www.cdc.gov/std/default.htm
[25] https://www.cdc.gov/rabiesandkids/

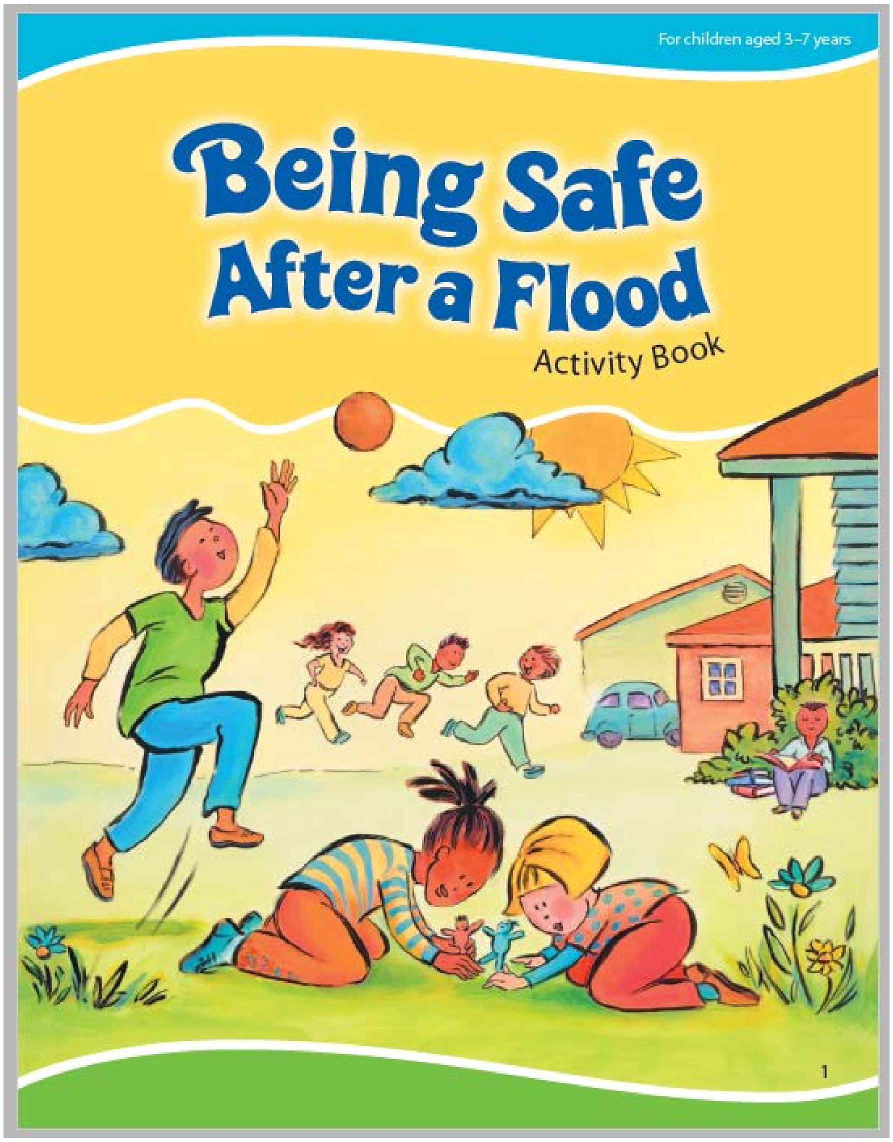

Figure 5-10 Being Safe After a Flood activity book for children[26]

The CDC also understands that caring for children is a concern for parents, so abundant resources with reassuring messages are available to families coping with disaster. Important information is provided and reinforced by positive imagery and messaging such as, protecting your child at school, "is as easy as A-B-C," as demonstrated in Figures 5-11 through 5-14.

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[26] https://www.cdc.gov/childrenindisasters/pdf/being_safe_after_a_flood-activity_book.pdf

Before, During and After an Emergency

Regardless of your child's age, he or she may feel upset or have other strong emotions after an emergency. Some children react right away, while others may show signs of difficulty much later. How children react or common signs of distress can vary according to age. Knowing how to help children cope after an emergency can help them stay healthy in future emergencies.

An emergency can happen anywhere and at any time. It is important for parents to know what steps they can take before, during, and after an emergency to protect their family. Parents ensure that family members are ready and know what to do when emergencies happen.

Figure 5-11 Before, during and after an emergency[27]

Keeping Children Safe

School is back in session. As you stock up on pencils, take first-day pictures, and adjust to new bus schedules, take a few, quick steps that can keep your child safer during an emergency.

From tornadoes to water main breaks, emergencies can occur with little or no warning—even during the school day. As children head back to school, take a few steps to help protect your child from an emergency and to reunite with your child quickly and safely.

Protecting Your Child Is as Easy as A–B–C

Figure 5-12 Keeping children safe—easy as A-B-C[28]

[27] https://www.cdc.gov/childrenindisasters/before-during-after.html
[28] https://www.cdc.gov/childrenindisasters/school-return-after.html

Returning to School After an Emergency or Disaster: Tips to Help Your Students Cope

Español (Spanish)

Teachers have an important role to play in helping children both prepare for and recover after a public health emergency.

Public health emergencies and disasters affect millions of children worldwide each year. These emergencies and disasters include natural events (such as severe weather, earthquakes, fires, floods, and tsunamis) and man-made events (such as acts of terrorism). An emergency or disaster can be destructive to a child's physical environment, as well as affect their mental health. As a teacher, you are committed to keeping schools safe and supporting children and their families. If your students experience an emergency or disaster, there are steps you can take to help your students cope and recover.

Figure 5-13 Returning to school after an emergency[29]

Helping Your Child Cope with a Disaster

Español (Spanish)

Disasters are stressful events that can cause substantial harm to communities and families. After a disaster, children may develop symptoms of anxiety, depression, and post-traumatic stress disorder. Mental health plays an important role in physical health, school performance, behavior, and long-term quality of life. Therefore, it is important to keep children physically and mentally safe during and after a disaster.

Figure 5-14 Helping your child cope with a disaster[30]

[29] https://www.cdc.gov/childrenindisasters/school-return-after.html
[30] https://www.cdc.gov/childrenindisasters/children-disaster-help.html

Across the CDC website, positive images of hope and reassurance and messages about overcoming adversity are repeated over and over again for a multitude of diseases and conditions: ADHD, arthritis, asthma, autism, avian influenza, birth defects, chlamydia, diabetes, Ebola, epilepsy, fetal alcohol spectrum disorder, genital herpes, gonorrhea, hepatitis, HIV/AIDS, kidney disease, obesity, stroke, traumatic brain injury, tuberculosis, and many more.

But then there's radiation…

Radiation Emergencies

Radiation Emergencies and Children

Radiation, sometimes known as electromagnetic waves, is energy that comes from a source and travels through space at the speed of light. Radioactive atoms in the source (called radioactive material) give off radiation in waves or particles. Each of us is exposed daily to radiation from natural sources, including the sun and the earth. Small traces of radiation are present in food and water. Radiation from manmade sources, such as x-ray machines, are released in controlled amounts to minimize harmful effects.

However, in a radiation emergency, such as a nuclear power plant accident, transportation accident, dirty bomb explosion (a mixture of explosives and radioactive powder or pellets), or nuclear blast, you could be exposed to a large amount of radiation that could be harmful to your health and the health of your family.

Why Children are More Vulnerable to Radiation

Although anyone exposed to radiation may experience harmful health effects, children are more likely to get sick from radiation exposure than healthy adults. Children have more cells that are growing and dividing rapidly, their organs and tissues are growing, and they have a longer lifespan ahead of them, giving cancers more time to develop. Children have thinner skin and breathe in more air for their size than adults, so they could absorb more radiation. Children may not know what to do or how to keep themselves safe by limiting their exposure to radiation in an emergency.

It is especially important for children to follow instructions to protect themselves from radiation and to receive medical attention after a radiation emergency as soon as emergency officials say it is safe to do so.
During pregnancy, a developing baby is vulnerable to radiation exposure. Pregnant women should take extra precautions during a radiation emergency. It is possible for nursing mothers to pass radioactive materials to their babies through their breastmilk. They should consider not breastfeeding if other milk sources are available until they can see their healthcare professional.

Figure 5-15 Radiation emergencies and children[31]

[31] https://www.cdc.gov/childrenindisasters/radiation-emergencies.html

The image for radiation emergencies is a forlorn teddy bear, abandoned amidst a pile of rubble and ashes. No imagery of hope. No message of compassion as used for every other public health hazard. Clearly, this image does not inspire or promote trust, nor does the heading, “Why Children are More Vulnerable to Radiation,” inspire confidence. As risk communicators know, the connection to vulnerable populations, like children, only heightens the intensity of the negative imagery (Ropeik, 2011). Although it is important to communicate that radiation can affect people differently depending on age, the reassuring positive imagery and messages of hope are replaced by a single message to parents that their children are vulnerable. Unfortunately, this is not an isolated instance when it comes to communicating about radiological emergencies. Infographics concerning radiation only continue to display a negative bias not exhibited toward other hazards. This is exemplified in the CDC infographics on nuclear accidents and radiation which convey their information using faceless shadows set on backgrounds of dirty brown and grey and echoes of a bygone atomic age as shown in Figures 5-16 and 5-17.

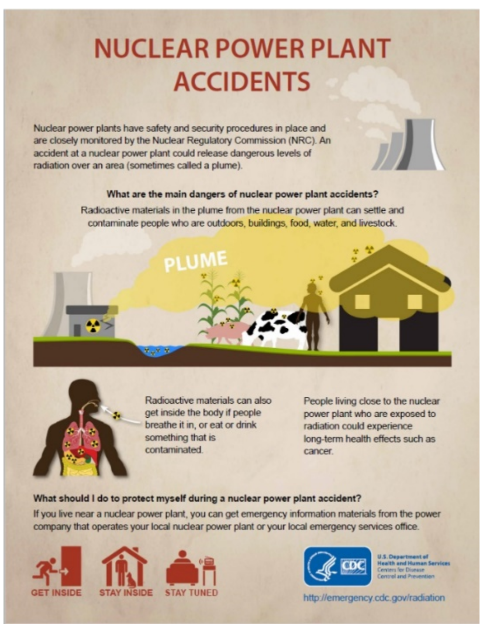

Figure 5-16 Nuclear power plant accidents infographic[32]

[32] https://www.cdc.gov/nceh/radiation/emergencies/resourcelibrary/infographics.htm

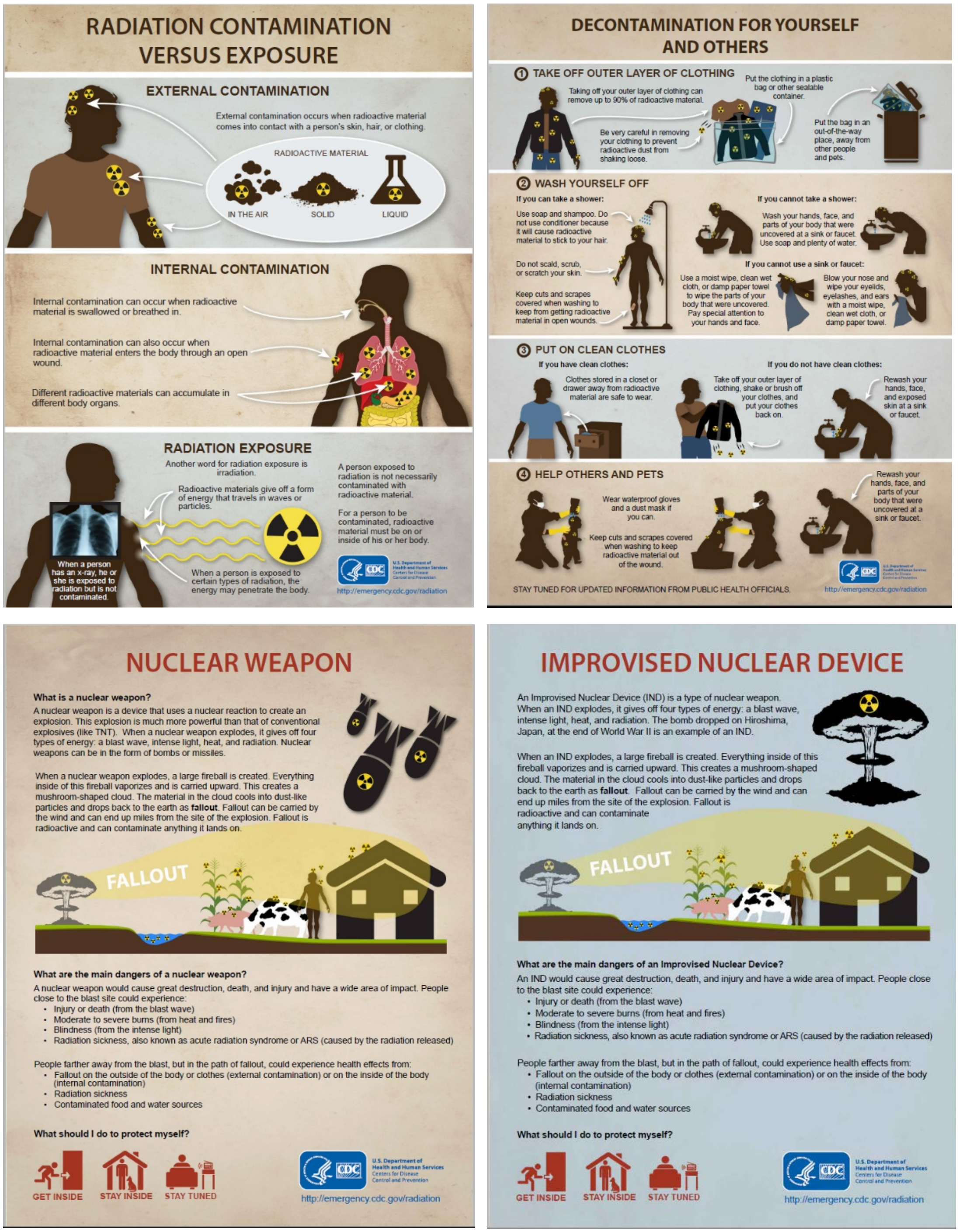

Figure 5-17 Infographics on radiation, decontamination, nuclear weapons and devices[33]

[33] https://www.cdc.gov/nceh/radiation/emergencies/resourcelibrary/infographics.htm

These radiation infographics stand in stark contrast with the CDC's tornado infographic. For as devasting as tornadoes are—bringing sudden destruction to whole communities—the infographic is instead colorful and cartoonish. The preparedness information reads like the pages out of a comic book.

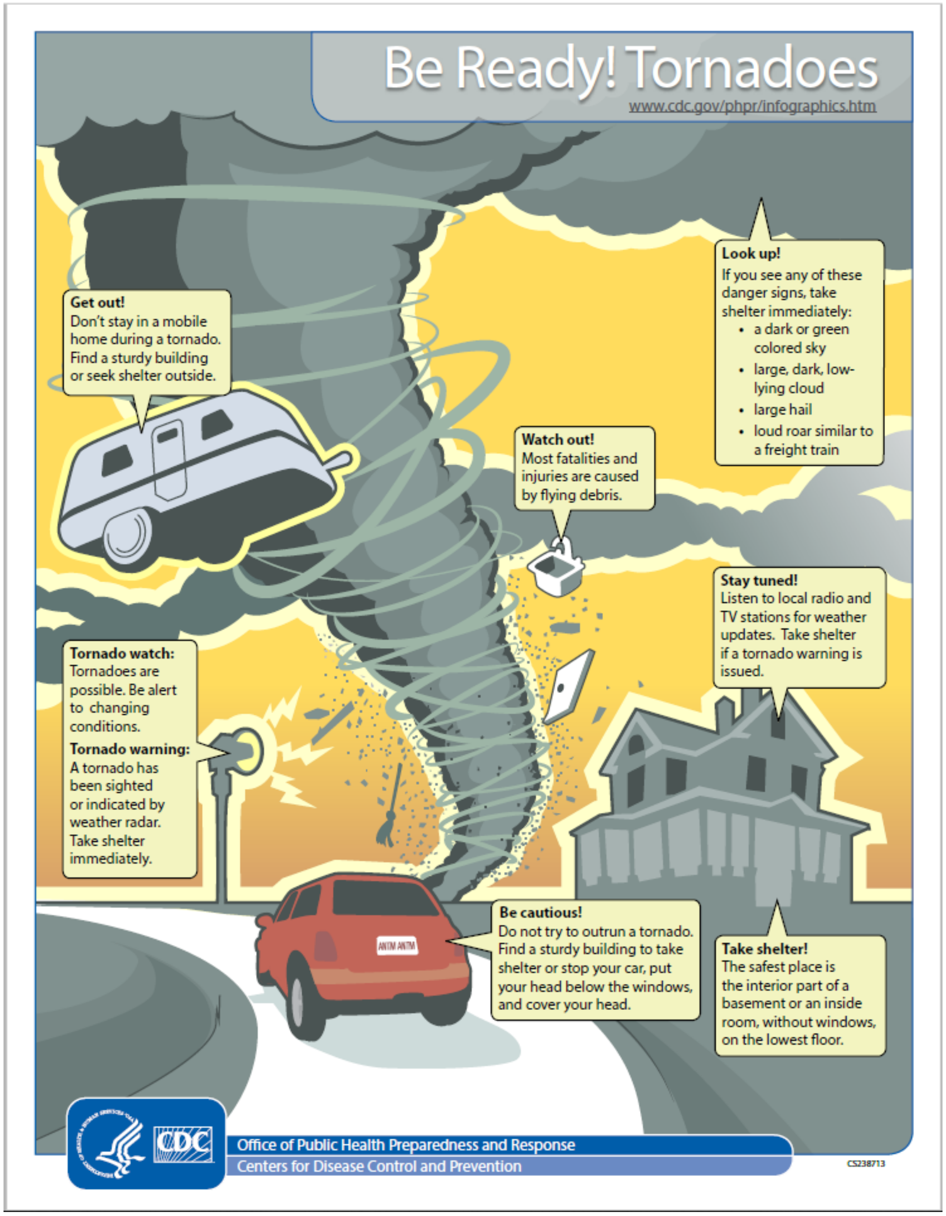

Figure 5-18 Tornado infographic[34]

[34] https://www.cdc.gov/cpr/infographics/br-tornadoes.htm

Are these just random art choices, or is it possible that someone is making conscious decisions on the emotions expressed by these infographics? The infographic for food poisoning certainly seems to support that idea. Food poisoning feels awful. In the CDC infographic (Figure 5-19), everyone in the line of people is smiling, except for the patient in bed who is undoubtedly feeling the effects of food poisoning. But the patient is shown smiling in the bottom part of the page where the emphasis is on people with weakened immune systems. Clearly a conscious decision was made to alter the graphic to create the impression of a smiling patient suffering from food poisoning. So why are nuclear hazards presented differently? Where are the bright colors and smiling faces when discussing radiation?[35]

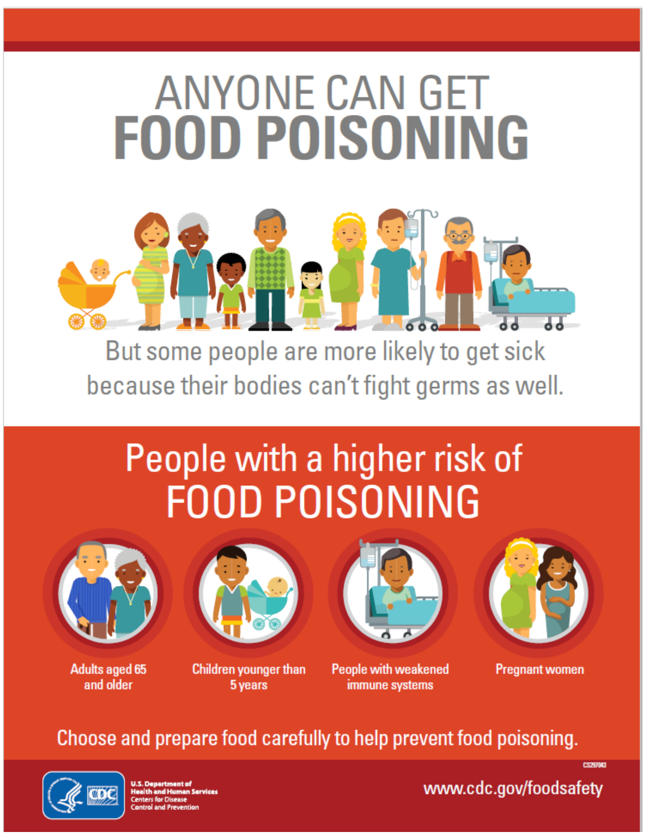

Figure 5-19 Food poisoning infographic[36]

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[35] The author does not recommend this approach, as demonstrated by response to Little Mr. Tritium.

[36] https://www.cdc.gov/foodsafety/symptoms.html

There is at least one good example of a radiation product that conveys important information without apparent bias toward the hazard. The infographic *Where to go in a Radiation Emergency* (Figure 5-20) is reasonable and comparable to the other types of infographics CDC produces. The infographic provides a concise message to the public on the actions to take in a radiation emergency and avoids conveying a message that there is no safe dose. There are no extraneous images of atomic bombs, mushroom clouds, cooling towers, or radiation symbols. More importantly, the infographic uses the words "safe," "safer," and "safest," and provides easy to understand graphics to clearly communicate the actions the public can take to protect themselves.

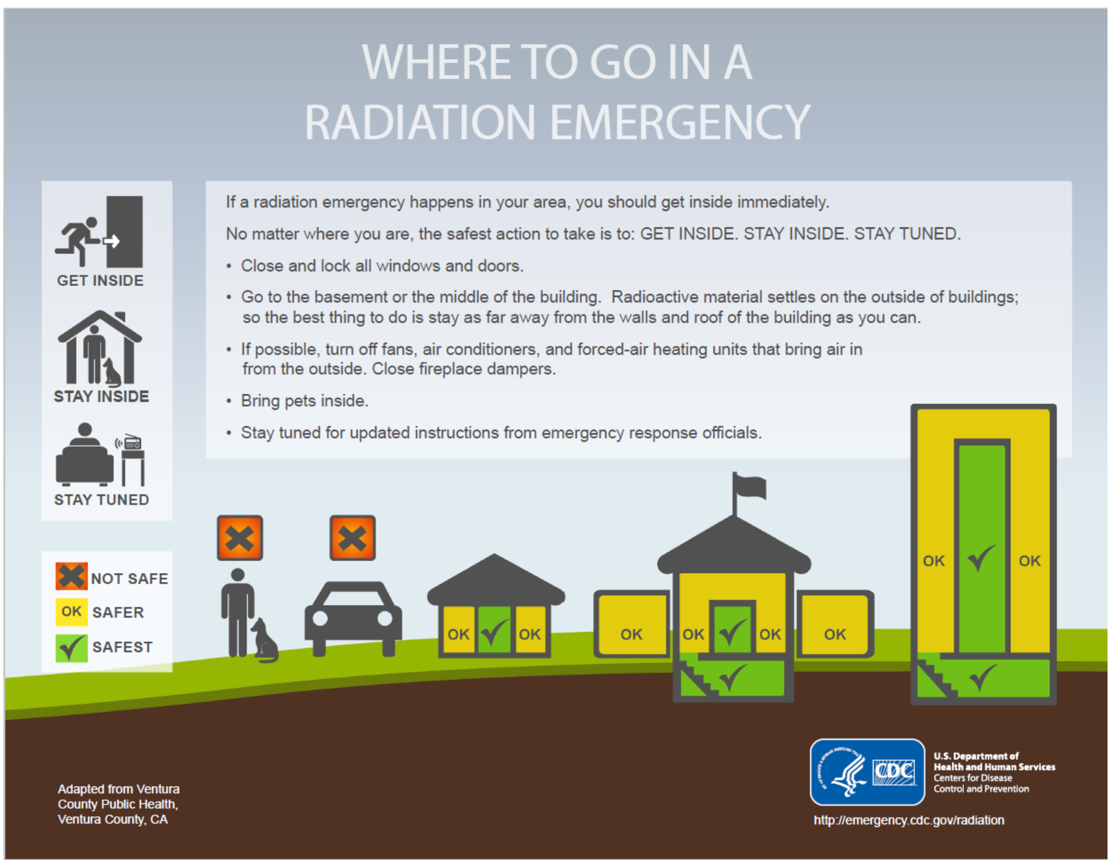

Figure 5-20 Where to go in a radiation emergency[37]

[37] https://emergency.cdc.gov/radiation/pdf/infographic_where_to_go.pdf

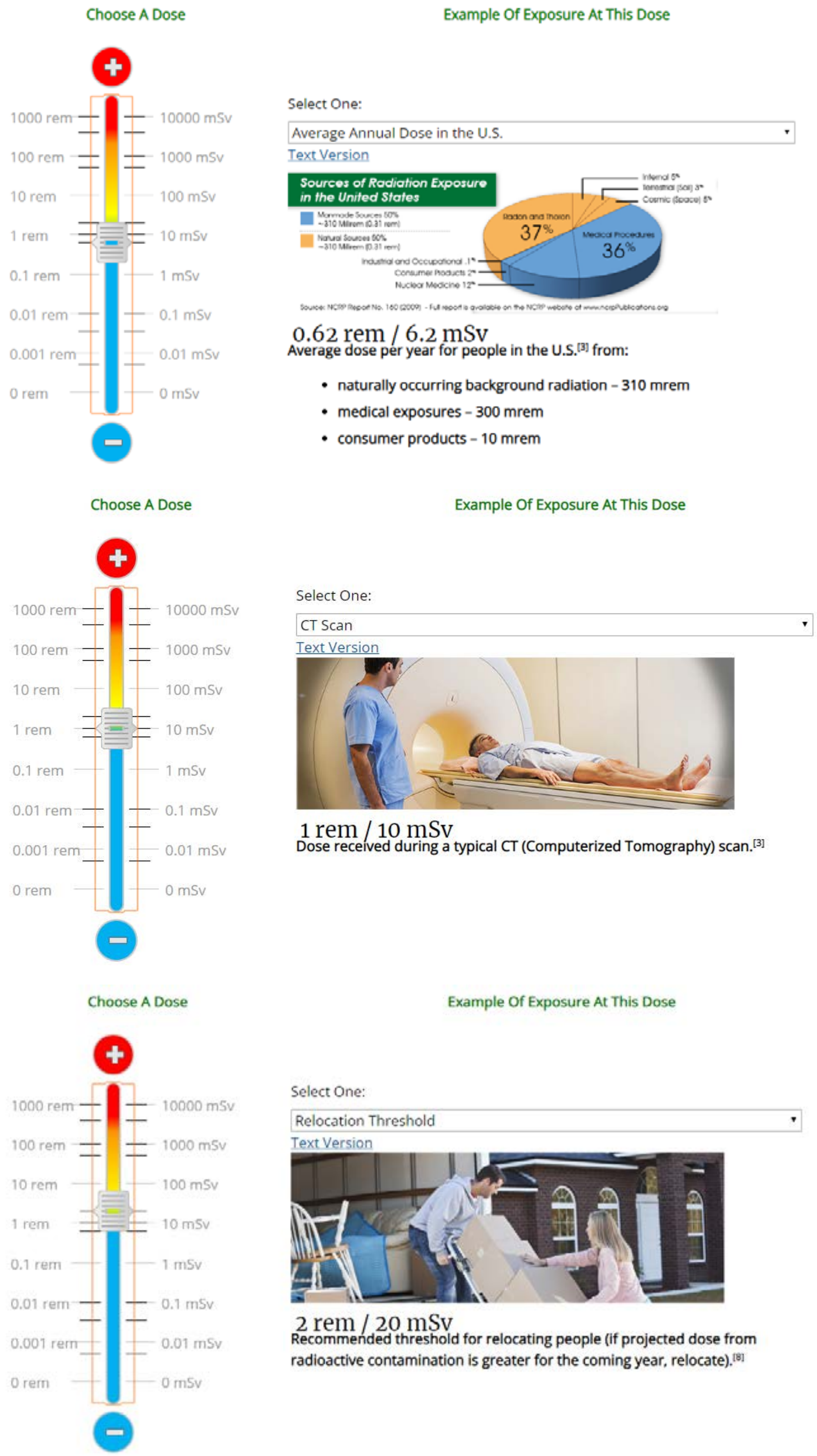

Figure 5-21 Radiation thermometer and associated imagery[38]

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[38] https://www.cdc.gov/nceh/radiation/emergencies/radiationthermometer.htm

But even good communication products can inadvertently provide mixed messages about the hazard of radiation exposure. The CDC has a Radiation Thermometer designed to put common radiation doses in perspective. The CDC designed this thermometer as a tool to help people assess their own risk in a radiation emergency. Some example dose levels and the accompanying messages and imagery are shown in Figure 5-21. The difference in dose between annual background exposure, a computed tomography (CT) scan, and the relocation PAG is just over 1 rem in a range of 0.62 to 2 rem. Unfortunately for the public, there is no context as to why such a small difference in dose makes all the difference between living comfortably at home bathed in constant background radiation, being able to go home after x-ray imaging, or being forced to permanently move from home! The dose levels have barely moved on the thermometer and are two orders of magnitude away from the red levels on the scale, but the message conveyed in the imagery is that a small increase in the amount of dose over 1 year is dangerous enough that it makes all the difference between staying home or starting your life over somewhere else.

5.5 Time for a Change

Given the preponderance of the evidence, it appears that the radiation community may be its own worst enemy when it comes to conveying their message to the public. This is likely driven by a cultural mindset that takes public fear of radiation as a given. Further evidence of this exists in many places. For example, on December 13, 2018, the DOE Office of Nuclear Energy posed a question on their Facebook page, “What do YOU think are the 3 biggest hurdles facing nuclear energy?”[39] Out of 215 comments, many commenters put public perception and fear of radiation at the top of their list; some even stated “public perception” for all three hurdles. However, astute commenters were quick to point out that this fear is driven by adherence to LNT and ALARA practices. Additionally, many commented that it is

[39] https://www.facebook.com/NuclearEnergyGov/posts/363210924254997

the industry's own fear of itself and unwillingness to self-promote that is driving that negative public perception. So again, it is worth questioning if there is such rampant fear and negative perception of nuclear power as asserted by the commenters; or is there a cultural bias that just assumes such barriers exist. By contrast, on April 26, 2021, the Green Party of England and Wales posted a meme on their Facebook page stating, "Nuclear Power Carries Unacceptable Risk."[40] What was the public response to that meme? "Bollocks."

It would appear that rather than the public actually being terrified of radiation and nuclear power, the bigger concern to be addressed is the cultural bias within the radiological community that assumes the existence of widespread public fear of radiation. This cultural belief is never challenged, only accepted as a tautology. Such beliefs are then turned into reality by communicating messages to the public of "no safe dose" accompanied by dark imagery to enhance the feeling of helplessness. Theodore Rockwell, summed up the problem well in his perspective piece in Nuclear News (Realism Project, 2004):

> *The nuclear community agonizes over its inability to communicate its message to the public. We hire public relations experts, pollsters, and communication consultants to polish up our messages of reassurance. But [public relations] expertise cannot overcome a basic problem: Our credibility is continually undermined by ostensibly authoritative statements that no amount of radiation is small enough to be harmless and that a nuclear casualty could kill as many as hundreds of thousands of people. That message we have communicated, and therefore the public and the media are not wholly to blame for the resulting public fear of radiation and all things nuclear. We cannot expect people to believe our assurances of safety so long as we acquiesce in terrifying messages to the contrary.*

Yet despite the attitude from within, across a variety of media outlets, more and more articles are published every day supporting the view that society has less to fear about radiation and nuclear power than once believed. These news reports and opinion pieces on radiation all share the same sentiments—*do not fear the radiation*.

[40] https://www.facebook.com/thegreenparty/photos/a.93577690784/10157825482865785/

Especially in light of the lessons learned from Chernobyl and Fukushima, more and more scientists, medical professionals, risk analysts, and the public at large are fighting back against the unfounded notion that any dose of radiation is unsafe. Furthermore, the LNT hypothesis is being implicated for the role it plays in the messaging leading to radiophobia. The volume of literature is too extensive to review in detail here (Appendix C provides links), but the resounding conclusions are:

- radiation is not as scary as people were led to believe.
- the lessons learned by the public from radiological emergencies is that protective actions may do more harm than radiation.

The self-defeating "public fear of radiation" ideology must come to an end. The result of such thinking is detrimental to radiological emergency preparedness, particularly when biased attitudes toward radiation are allowed to appear in public information tools. Public opinion will always fluctuate, but in time of need the public will generally act as directed and the risk communication messages cannot be contradictory to the desired public response. For risk communication to be effective, the communicators cannot start with a false notion of the public's acceptance of the risk; nor can risk communications contain messages that inflate the risk of radiation. Above all, the message itself should not put the public at more risk of harm.

To ensure protective actions do more good than harm, cultural transformation needs to start in the radiological and nuclear communities. Specifically, transformation is needed in the cultural mindset to eradicate the myths of widespread public fear of radiation and assertions of "no safe dose." Such myths—particularly when perpetuated by those who are viewed as trusted sources—are counterproductive to establishing public trust. Risk communication is critical to successful implementation of protective actions, and risk communication strategies need to provide information that supports risk-informed implementation of protective actions. As such, the state of risk communication is examined next.

5.6 Lessons from Radiological Risk Communication

Communicating radiological risk is not a modern issue. For the past century, radiological risk communication has developed alongside the scientific advances in our understanding of radiation and radiological emergencies. The practice of radiological risk communication has been well-studied and is well-established. Although communicating about radiation is seen as a challenge by some, there are many experts well-versed and prepared to provide support, especially in an emergency. Numerous guides exist that provide the key principles of risk communication and specific radiation-related messages targeted to a wide audience.

But do radiological risk communication strategies support protective action strategies? The radiation protection culture has been dominated for years by the idea that there is no safe dose. Although current guidance in radiological risk communication supports the fundamental principles of radiological protection, it is worthwhile to examine whether such guidance is reflective of public understanding of the risks and to assess how the radiological risk is presented compared to the risk of protective actions. Specifically, does radiological risk communication lend itself to practical risk management decisions by decision-makers and the public? That is, does radiological risk communication support protective actions that will do more good than harm? To answer this question, a review of the past 15 years of studies and guidance in radiological risk communication was performed to examine the evolution of public messaging and the principles behind those messages. The results of this review are provided in the following chronology. A summary of each document is provided followed by a short analysis. Key messages and study findings are emphasized for further discussion.

5.6.1 Radiation-Specific Risk Communication Guidance

A number of radiation-specific risk communication guidelines exist. Over the years, the communication strategies for radiological events has evolved, informed by modern research in risk communication practices. However, even less than 15 years ago, pre-determined messages to the public included the idea that any amount of radiation was harmful. Over time, and across radiation-related events, this was replaced with more accurate messages that convey the current understanding of radiation effects at low dose. In addition, how the public perceives these messages has been studied and incorporated into guidance. A chronological review of key risk communication guidance documents from 2007-2021 is presented in the following. Each document is described as to its development and purpose, and the contents within analyzed to illustrate the evolutionary change in public messaging on radiation hazards.

Communicating Radiation Risks (EPA, 2008)

This document was developed by the EPA as a guide for emergency responders and Federal, state, and local officials for communicating with the public and the media during a radiological event. Communication techniques and advice based on proven risk and crisis communication strategies are provided within. However, this communication guidance appears to be influenced by the LNT hypothesis and message that any amount of ionizing radiation is harmful. Contributing to this, the key messages on radiation risk at low dose are presented out of context to the actual statements about LNT from scientific bodies. As a result, the emphasis of protective actions is based on ALARA principles and minimizing exposure; no balance of the risk is emphasized. Public perception of the risk is characterized throughout the document as dominated by fear and dread. The adherence to an LNT and fear-driven mindset is exemplified in the following excerpts:

3. How much radiation is safe?

- *There is no known safe amount of radiation.*
    - *The current body of scientific knowledge tells us this.*
- *We always assume that less radiation is better.*
- *There are steps you can take to minimize your exposure.*
    - *Your local officials can advise you on what steps to take.*

5. What should we do about low levels of radiation?

- *There may be some risk from low levels of radiation.*
- *It is reasonable to assume that less radiation exposure is better.*
- *To be safe, take all reasonable precautions to reduce exposure.*
  - *It may be difficult to reduce exposure to low-level radiation in our everyday lives.*

13. Am I going to get cancer?

- *There are many causes of cancer, both environmental and genetic.*
- *Radiation is a minor contributor to our overall cancer risk.*
- *The risk of radiation causing cancer increases with the level of radiation exposure.*
- *Sheltering-in-place or evacuation can help minimize cancer risk.*

How the Public Perceives Risk
During an emergency it is important to understand how the audience thinks, what concerns them, and what is important to them. People do not like to be "put" at risk in any situation. While they may engage willingly in "risky behaviors," they reject being forced into risky situations they did not choose. Research shows that "situations involving radioactive materials have a remarkable capacity to produce widespread fear, a profound sense of vulnerability, and a continuing sense of alarm and dread" among people (Becker, 2004). In light of this deep-rooted fear, communications about risk must go beyond simply providing information. Remember:

- *Facts alone cannot overcome strong emotions, and*
- *When confronting fear, who gives the information and how it is perceived overpowers what is being said.*

Interestingly, although this document was produced by the EPA, there is no guidance on communicating the basis of the PAGs and the principle of doing more good than harm. The PAG is defined within, but there is only one reference to the PAG in a section on building on lessons learned. Communicating the risk balance to the decision-maker and the public is not part of the messaging. The guidance also states, "The public must have information quickly about what is happening, what they should do, and what government agencies are doing to help." Although timely communications are important, such statements may convey a false sense of urgency in regard to the timing of protective actions.

Radiological Emergency Preparedness Communications Message Testing Phase 1 Report (CDC, 2009a)

This project sought to improve public-facing messages about protective actions and responses to radiological emergencies. Test messages were developed by the CDC and responses gathered from test audiences. This study provides valuable insights into what the public wants to hear. In particular, public participants wanted to be given a rationale for why they were being instructed to do something. The term *radiation* though not well understood, increased the likelihood of compliance with instructions that might otherwise be ignored, such as "seek shelter in the nearest building." There were no apparent differences in responses from participants with higher education (college degree) and lower education (less than a high school degree), indicating that education level was not a significant factor in response. Although no basic concepts of risk management in the face of competing risks or balancing the risk of protective actions were given to participants, a key finding was that the public wants a rationale for what they are being asked to do. This indicates a desire to assess the risks and take action based on available information.

NUREG/CR-7033, "Guidance on Developing Effective Radiological Risk Communication Messages: Effective Message Mapping and Risk Communication with the Public in Nuclear Plant Emergency Planning Zones" (NRC, 2011c)

This document focuses on development of skills critical to successful radiological risk communication to the public, the media, and other stakeholders. The guidance contains principles, strategies, and tools for producing messages before, during, and after a radiological emergency that are timely, understandable, accurate, consistent, and credible. A series of potential questions and answers (Q&As) that may be asked during an emergency are also provided. The document is based largely on the science of message-mapping. This NUREG is a good tool for how to communicate and what words to use. Protective action decision-making is assumed to belong to state and local decision-makers. As such, many of the messages are stated in terms of the types of protective actions the public will be instructed to take rather than how to communicate to the public the information they need in order to make their own decisions. The primary public consideration is perception of the message, and the guidance acknowledges that this information is important to how people both perceive and act upon the risk. While decision-makers are assumed to be part of the group of stakeholders that would benefit from this document, recommended practices for communicating to the decision-makers themselves and educating them on the risks of both radiation and protective actions are not addressed.

Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant (IAEA, 2013)

This report highlights lessons learned in the area of emergency preparedness and response in light of the Fukushima Daiichi accident. Specific sections on risk communication lessons learned are included. A key conclusion in Section 3 of this report is the need to communicate the radiation hazard in perspective:

> *In support of the implementation of the IAEA safety requirements in the area of emergency preparedness and response, IAEA Safety Guides on the following topics need to be developed: (i) public communication in a nuclear or radiological emergency, including placing the health hazard into perspective; and (ii) transition from an emergency to an existing exposure situation.*

Despite this conclusion which supports the idea that there is a balance to the risks that should be communicated, the specific actions recommended within Section 7 only reinforce previously established ideas about *how* to effectively communicate with the public and not *what* to communicate:

> *Lessons learned: Provision of clear, objective and understandable information to the public in an emergency reduces public concern and contributes to the prevention and mitigation of consequences of an emergency. Public communication arrangements need to be made at the preparedness stage based on the IAEA safety standards.*

Although the IAEA recognized that health hazards must be put into perspective, *what* was communicated was believed to be deficient only in the use of dose quantities and the consequences of the radiological hazard from those dose levels. Overall, no lessons learned were mentioned about balancing the of risk of protective actions and the need to communicate those risks to the public. Although the importance of non-radiological consequences are mentioned, the conclusion drawn in Section 7.3 is that these consequences are the result of an event involving radiation. Such conclusions ignore the evidence that these consequences are a common response to various emergency events and prolonged evacuations and relocations.

> *Experience clearly shows that non-radiological consequences of an emergency and response can extend beyond the radiological consequences. Moreover, even a perceived emergency can cause concern among members of the public and create the need to provide the public with appropriate information. The spokespersons must take into account public perceptions and the specific psychological impacts that nuclear and radiological emergencies can have, and the fact that these impacts can persist long after an emergency ends.*

Although correct in identifying the need for spokespersons to take public perception into account, this conclusion sends the wrong message and reinforces radiophobia, implying that radiological events are uniquely different. It also implies that fear of radiation is the lingering public health concern, rather than the prolonged displacement from home. Such ideas could be contrary to lifting of protective actions that would allow people to return home.

Communicating During and After a Nuclear Power Plant Incident (FEMA, 2013a)

This document provides communication guidance for domestic NPP accidents, including sample text and suggested answers to anticipated public and media questions. This document is the product of an interagency group of communication experts, convened under the Federal Radiological Preparedness Coordinating Committee (FRPCC), assisted by state and local communicators. It provides a background on the roles and responsibilities of all levels of government during an NPP incident. The guidance was created primarily for Federal leaders who will speak to the public but may be used to compliment the capabilities of state, local, tribal officials. Overall, the guidance does a good job at not hyping the radiation risk. The avoidance of language driven by the LNT assumption of "no safe dose" demonstrates an evolution of thought on effective communication over the Federal guidance prior to 2010. Section D "Critical Questions and Answers for National Spokespersons" has good examples of risk communication messages, generally stating more positive facts first. In this Q&A, the radiation hazard is put into reasonable perspective. Messages emphasize the importance of protective actions and communicating the benefits of sheltering-in-place and evacuation. For emergent life-threatening situations unrelated to the radiological event, a clear message is given that emergencies of this nature require immediate action and take precedence over any radiological concerns. Examples include:

> ***1. Is there an immediate danger?***
> *• People are being told to evacuate or stay inside (shelter-in-place) because exposure to the radioactive material outside is potentially dangerous.*
>
> > *o If you were instructed to stay inside, remain inside until you are told otherwise by local authorities.*
> > *o Having walls, brick, concrete, or soil between yourself and the source of radiation can help reduce your radiation dose.*
>
> ***3. Who should evacuate and who should go inside and stay inside?***
> *• As stated by [insert official], people in [area/location] should evacuate and people in [area/location] should go inside and stay inside.*
> *• Officials work with experts to determine the actions that will keep exposure to the public as low as possible.*
> *• Local officials' number one priority is to protect people from exposure to potentially dangerous levels of radiation.*
>
> > *o Depending on specific conditions, radiation levels can be dangerous.*
> > *o The two main protective actions are evacuation (leave the area) and sheltering-in-place (go inside and stay inside).*
> > *o These decisions are based on radiation science and other important factors such as direction of the wind, amount and type of radioactive material released, and how quickly radiation levels decrease.*

4. What should people do if they're told to evacuate?
• If you are told to evacuate, leave the area immediately.
• When the public evacuates, they are moved to safer areas depending on levels of radiation and radioactive material in order to keep exposures as low as possible, and under most conditions evacuation is preferred.

5. What should people do if they're told to shelter-in-place?
• If you are told to shelter-in-place, go inside a building immediately.
• Sheltering-in-place may be ordered in some cases.
o In some situations sheltering-in-place may provide protection that is equal to or even greater than evacuation, such as in cases where weather, traffic, competing events, or short-term releases are factors.

6. What should people do if they are told to stay inside but do not have food, water, or medications?
• Continue to remain inside for as long as you can until you receive additional instructions from authorities.
o Staying inside will help protect you from the radiation and other hazards associated with the incident
o Please remember that leaving your location may expose you to additional radiation.
o Once authorities provide instructions that it is safe to go outside, quickly but safely proceed to designated assembly areas or shelters if you require food, water, or medical attention.
• For food or water concerns:
o Authorities are aware of the limitations in food and water and are making efforts to resolve these issues.
• For needed medication concerns:
o Stay sheltered for as long as possible.
o If the lack of medication(s) creates a life-threatening condition that requires
immediate medical attention, please call 911 or proceed to the nearest fire station, hospital, or medical triage area for assistance.
• For non-life-threatening medical care:
o If you have injuries or an illness that do not require immediate medical attention, please remain in your shelter until you are told it is safe to proceed to your nearest fire station, hospital, or medical triage area for assistance.

Although the radiation risk is not down-played in the messages, the risk is put into context. This is in clear contrast to the message of no safe level of radiation exposure as stated in earlier EPA risk communication guidance (EPA, 2008). A consistent idea expressed is that the level of danger depends on the specific conditions. For example, urgent medical needs are clearly indicated to take precedence over concern for radiation exposure. But while the effectiveness of shelters and evacuation are clearly communicated, the Q&A does not provide information on the risk of taking the protective actions themselves for decision-makers and the public to consider. Regardless, this guidance provides more reasoned responses to questions on personal safety. Of note, this FEMA guidance—based on an interagency effort—is not reluctant to use the words “safe”, “safer”, “safety” as exemplified in the following example message:

> ***50. How much radiation is safe? How much is considered low risk?***
> *• According to radiation safety experts, radiation exposure between 5–10 rem usually results in little to no harmful health effects.*
> > *o Infants, the elderly and pregnant women are more sensitive to radiation exposure than healthy adults.*
>
> *• It takes a large dose of radiation—more than 75 rem—in a short amount of time (usually minutes) to cause immediate health effects like acute radiation sickness.*
> > *o Differences like age, gender and even previous exposure are factors that might influence a body's reaction to radiation exposure.*
>
> *• You can lower your risk of developing health effects by limiting your exposure to radiation.*
> > *o Get inside a building or to a basement to protect yourself.*
> > *o Get clean.*
> > *o Listen to officials and emergency responders for further safety instructions.*

Improvised Nuclear Device Response and Recovery: Communicating in the Immediate Aftermath (FEMA, 2013b)

This document is another Federal interagency effort for how to communicate effectively during the immediate aftermath of an Improvised Nuclear Device (IND) or Radiological Dispersal Device (RDD). Message content was reviewed by state and local responders and tested by public focus groups. The document was also reviewed by the Federal Advisory Team for Environment, Food and Health. The messages of this document are focused on ideas of community resilience and reinforcing attitudes of personal empowerment and action during an emergency, rather than victimization. It uses Q&As in a manner that addresses how the public can best protect themselves and others in a nuclear detonation emergency. There is a distinct community focus. For example, questions are not posed as, *am I safe?*, but rather ask, *are people safe*? The radiation risk, although recognized to be very high in some areas, is not hyped. Feelings of anxiety and stress are described as a normal human response to the incident, not characterized as radiophobia. This document also does not hesitate to use the word "safe" and relates being safe to protective actions such as sheltering-in-place. For example:

> ***7. Are people safe?***
> *• If you are in [LOCATION], you are in danger extremely high levels of radiation.*
> *• You are safest inside a basement or building made of brick or concrete for the first 12-24 hours, while radiation levels outside are most dangerous.*
> *• If you were instructed to stay inside, remain inside until you are told otherwise by authorities.*
> *• Instructions given by officials or emergency responders are for your safety. The instructions will be updated as more information is available.*
>
> ***17. How can the public help?***
> - *Immediately after the explosion, there are three things the public can do to help:*
> - *Let emergency responders help those in need:*
>   - *If you are near the affected area, stay inside unless told otherwise by authorities. This will help protect you from radiation and keep roads clear for emergency vehicles.*
> - *Unless you are critically injured, stay away from hospitals, and fire and police stations. These facilities need to be available for injured victims.*
> - *Keep phone lines clear*
> - *Use text messaging to communicate with friends and family.*
>   - *This will free up phone lines, allowing people in extreme need to call for help and emergency personnel to communicate with each other.*
> - *Provide shelter*
>   - *If you are able to take someone seeking shelter into your home, there are*
>   - *simple safety steps to keep radioactive material out of your home.*
>   - *First, ask your visitor to remove their outer layer of clothing and place it in a plastic bag. Place the bag away from people and pets.*
>   - *If possible, have your visitor shower with soap and warm water to remove any remaining radioactive material.*

        - *If they do not have clean clothes, ask your visitor to shake or brush off their outer layer of clothing and redress. Do not breathe in any dust-like particles.*
- *Do your best to remain as calm as you can and take care of yourself by*
    - *Maintaining healthy eating, sleeping, and exercise routines*
    - *Staying in contact with loved ones whenever possible.*
    - *Seeking accurate information about what is happening.*
    - *Reaching out to helplines, when they're available, if your anxiety becomes overwhelming.*
    - *Provide emotional support to those around you, particularly children.*
        - *Children react to signs of stress in parents and caregivers; try to speak in an even manner and tone.*
        - *If possible, give children practical tasks or activities.*
        - *Understand that children at different developmental levels (e.g. toddlers, school-age children, teenagers) will have different needs and reactions.*
- *Understand that it's common for individuals and families in and around the affected region to experience distress and anxiety about safety, health, and recovery.*
- *These reactions are common and usually decrease over time.*

28. Can I let someone into my home after a nuclear explosion?
• Providing shelter to someone who was outside during the nuclear explosion can save their life without endangering your own.

63. How much radiation is considered low risk?
• According to radiation safety experts, radiation exposure between 5–10 rem usually results in little to no harmful health effects.
o Infants, the elderly and pregnant women are more sensitive to radiation exposure than healthy adults.
• It takes a large dose of radiation—more than 75 rem—in a short amount of time (usually minutes) to cause immediate health effects like acute radiation sickness.
o Differences like age, gender and even previous exposure are factors that might influence a body's reaction to radiation exposure.
• You can lower your risk of developing health effects by limiting your exposure to radiation.
o Get inside a building or to a basement to protect yourself.
o Get clean.
o Listen to officials and emergency responders for further safety instructions.

Protective Action Questions & Answers for Radiological and Nuclear Emergencies: A companion document to the U.S. Environmental Protection Agency Protective Action Guide (PAG) Manual (EPA, 2017b)

This EPA document is intended to help emergency planners prepare public communication messages prior to and during various types of radiological emergencies. In contrast to the 2008 EPA guidance, this document compliments the planning considerations of the EPA PAG Manual. As such, more discussion is provided on the PAGs, the use of PAGs, as well as the benefits of sheltering-in-place, evacuation, and other protective measures. The questions and answers were based on, and are consistent with, other government radiological risk communication products. For example, example question 58 is almost identical to example question 63 from the guidance in *Improvised Nuclear Device Response and Recovery* (FEMA, 2013b), and question 50 from the guidance for *Communicating During and After a Nuclear Power Plant Incident* (FEMA, 2013a). In addition, new messages were considered to address special populations such as pregnant women, children, and individuals with disabilities:

> ***58. How much radiation is safe? How much is considered low risk?***
> *According to radiation safety experts, radiation exposures of 5–10 rem (5,000–10,000 mrem or 50–100 mSv) usually result in no harmful health effects, because radiation below these levels is a minor contributor to our overall cancer risk.*
> *Safety recommendations are designed to keep your dose as low as possible. It takes a large dose of radiation—more than 75 rem (75,000 mrem or 750 mSv)—in a short amount of time (usually minutes to hours) to cause immediate health effects, such as acute radiation sickness.*
> *Infants, the elderly and pregnant women are more sensitive to radiation exposure than healthy adults. Factors like age, gender and even previous exposure also might influence a body's reaction to radiation exposure.*
> *Follow these three steps to limit your exposure to radiation and lower your risk:*
>
> *1.* ***Get inside*** *a building or to a basement to protect yourself.*
> *2.* ***Carefully remove the outer layer of your clothing****, seal it in a plastic bag and get clean (shower or wipe off).*
> *3.* ***Listen*** *to officials and emergency responders for further safety instructions.*

Compared with the EPA's 2008 risk communication guide, the message of "no safe dose" has been expunged. Even more interesting, is that the words "safe," "safer," and "safety," appear almost 100 times throughout this document, as compared to only 25 times in EPA's 2008 guidance. Just the word "safe" is used 3 times more often in current messaging.

In short, this survey of the past 15 years of guidance document development in radiological risk communication reveals an evolving cultural mindset that recognizes the importance of communicating radiation risks in perspective and the need to move away from the LNT-inspired messaging of the past. The positive developments in radiological risk communication would appear to be ready to support the development of messages for a new paradigm in protective action strategies and optimized approaches that may lead to more radiation exposure, but also greater societal benefit overall.

But what is not evident in these risk communication documents is exactly how this evolution in thought came about. Clearly there was a cultural shift away from the mindset of "no safe dose" and precautionary principles. But what factors made it possible to turn these ideas into practical guidance? While certainly advances in our understanding of radiation effects at low dose contributed to the messaging, there is another factor that stands out; that is, guidance documents appear to benefit when multiple agencies, organizations, and levels of government are involved. This suggests that preparedness efforts can be enhanced through collaboration and diversity of thought. This further suggests that a single-minded focus or a singular thought—such as the notion that the public is afraid of radiation—can detract from preparedness efforts. Of course, additional data is needed to test this idea. Fortunately, a number of well-documented government roundtable discussions and focus-group studies centered on radiological risk communication occurred during this same time period. As described in the next section, these studies provide additional insight into ways cultural changes can be effected through diversity in thought and a willingness to be open to public opinion. They also demonstrate that a single-minded approach and preconceived notions should be avoided to prevent stagnation.

5.6.2 Risk Communication Roundtable and Focus-Group Studies

CDC National Prevention Information Network: Public Reaction to the Information Related to Radiologic Terrorist Threats, Draft Final Report, Analytical Sciences, Inc. (CDC, 2003)

This report documents the results of a series of focus group studies sponsored by the CDC to develop methods for dissemination of public messages during chemical or radiological terrorist events. Three focus groups across the nation were presented with "the mall scenario"—an event that starts with the release of an unknown agent causing harm to shoppers at a local mall. The hazardous agent is later revealed to be a dispersed radionuclide. The response of the focus groups to this event was often very general, even upon learning of the unique radiological component to the event. Notably, participants in the scenarios asked reasonable questions about radiation. Although participants mixed up the terms *exposure* and *contamination* the questions asked by the public participants revealed a conceptual understanding of the radiation hazard. Another interesting facet of these focus group studies is that while some misconceptions about radiation existed, the participants were all satisfied with the state of communications received during the mock scenario.

While the three focus groups consisted of participants from different locations across the U.S., there were many similarities found. Discussion revealed extremely low awareness and understanding among participants about keys concepts and terms such as dirty bomb; radiation; the risks from radiation (especially those likely to occur from a dirty bomb); the difference between radiation exposure and contamination; what nuclear meant; and appropriate actions to take if a radiological event occurs. In general, people seemed to over-estimate the risks and likely effects of radiation. However, participants found the CDC information materials they reviewed extremely informative and often reassuring. Questions and concerns of participants raised by the hypothetical dirty bomb incident were often addressed in the prepared information materials to a significant degree. When people were asked to give a thumbs up or thumbs down or a letter grade for how well different information excerpts addressed their concerns or questions, the feedback was generally very positive. Participants also indicated that the information generally was presented clearly and in appropriate tone, language and length. A key takeaway from this focus group study is that effective risk communication is possible even when misconceptions and preconceived notions about radiation exist.

Roundtable on the Psychosocial Challenges Posed by a Radiological Terrorism Incident (CDC, 2005)

This report is a summary of a two-day roundtable discussion to examine psychosocial issues associated with radiological terrorism. Participants included nearly 30 U.S. and international experts from academia, government, professional societies, and the healthcare community. While highlighting the importance of preparing for psychosocial impacts, the fear of radiation was hyped more than the fear and anxiety of a terrorist attack. The report states, that, “a large body of research shows that radiation is among the most dreaded of all hazards.” However, no effort was made to quantify the psychosocial impact of a radiological terrorist attack against a nonradiological terrorist attack. As a result, participants assumed the fear of radiation would amplify the consequences of a terrorist attack:

> *Recommendation 1: Roundtable participants generally agreed that the psychosocial impacts on individuals and communities would be enormous in a large-scale radiological terrorist attack, and that these impacts can outweigh even the physical consequences of an incident. Hence the need, they said, to better incorporate psychosocial issues into healthcare planning.*

Despite this, the recommendations made by this diverse group of experts at least spoke to the need to balance the radiological risk with the psychosocial risks. The belief expressed in the report is that building resilient communities will reduce the psychosocial impact:

> *Recommendation 6: Recognize the importance of effective communication and information strategies in the prevention of, and response to, the psychosocial impacts of a large-scale radiological terrorism event.*

This recommendation is in-line with general principles of risk communication. Of note, the roundtable panel did not identify any communication practice that was not already a key principle in risk communication. The only recommendation was to tailor messages to the impacts of a radiological terrorism event. However, the group also asked questions about what could be done to transmit information in a way that enables people to take appropriate self-protective actions and increases the trust and credibility of agencies and officials responsible for public communication. Whether and how the public would understand those messages is demonstrated in these next focus group studies.

Health Effects Message Testing: Detonation of Improvised Nuclear Device (CDC, 2012)

In 2009-2010, the Nuclear Detonation Response Communications Working Group, a Federal interagency group of communications and radiation technical experts, developed key messages for affected communities, as well as the rest of the nation, to be used during the immediate aftermath of an IND detonation. To help ensure the quality of those messages, CDC, in partnership with the Oak Ridge Institute for Science and Education (ORISE) and FEMA, set out to test selected messages specifically related to radiation exposure and health effects with the public.

Of note, from this message testing study, the perceived key messages across all demographics supports the idea that people will accept recommendations to shelter-in-place. As an example of one of the tested messages:

> ***Perceived Main Message(s):***
> *Participants thought the main message was to get inside a strong building to shelter from radiation. Participants felt another key message was that low exposures of radiation may result in minimal or no health effects.*
>
> - *It's telling you to get inside of a strong building or basement to provide shielding.*
>   - *If there was any good message, it was one that you're best off being inside and I really don't remember exactly, but let's say go in a cellar or someplace that's secure.*
>   - *Exposure to the radiation can be harmful.*
>   - *I guess that not all radiation is bad, depending on the dose.*

Perceived Strengths:
The second half of Message 55 ("getting inside a strong building," "listening to state and local officials," and "advice during an emergency is meant to limit exposure") was the most valuable information to participants. The information provided actions that participants could take to protect themselves and limit radiation exposure.

- *The three bullet points at the bottom are probably the most important part.*
    - *Get inside a strong building. Basically, what I have control over, what it is I can do.*
    - *I liked that it says "any advice given during an emergency is meant to limit exposure." It makes you feel like they are trying to protect you as much as they can, so listen to what they are saying.*

Perceived Weaknesses:
Although participants understood the main messages, they expressed that the information they would want to hear during an emergency came too late in the message. The first half of the message was considered irrelevant information to participants during an emergency situation and many suggested removing the first two bullet points.

- *The main message came way too late. It should have been the first statement instead of the third or fourth.*
    - *The first part of it reminds me of just going back to very informational, and the second part reminds me more of what you would do for an emergency.*
    - *I marked out the first two sections. Just give me the rest down at the bottom.*
    - *Just give them the information to keep themselves safe, what to do until further notice.*

The study was premised on the idea that effective and timely communication will play a vital role during an IND event; as such, communication must address the public's concerns using simple and concise messages. The working group concluded that the findings from this study, combined with findings from previous message testing research, could be used to revise the current messages for more effective communication with the public.

The results of these roundtable and focus group studies make it clear that a high degree of readiness in risk communication has already been established and that effective risk communication with the public is achievable. As these focus group studies demonstrate, effective radiological risk communication strategies do exist. Additionally, the public does not need to be well-informed on radiation science in order to understand the message. During the emergency phase, most people simply want to know what actions to take to keep themselves safe.

One key to the success of these risk communication efforts seems to be attributable to a high degree of collaboration across various disciplines and agencies. This was also seen in the development of risk communication guidance, in which interagency guidance provided a solid framework for future efforts. However, the advantage a diverse group brings to the table does not appear to be just diversity of thought for diversity's sake; rather, as the name implies, the success of risk communication appears to depend on the ability to understand both communication and the risk. This next roundtable discussion provides evidence that without diversity in knowledge, skills, and experience, even the experts can get stuck in their cultural biases.

Communication Strategies for Addressing Radiation Emergencies and Other Public Health Crises: Summary of the January 28-29, 2009 Roundtable (CDC, 2009b)

In 2009, the CDC held an updated roundtable discussion on terrorist events involving radioactive material, considering a broad range of events from INDs, RDDs, and radiological exposure devices (REDs). This roundtable event allowed communicators from a few Federal agencies to share information and strategies and challenges for effective risk communication in a radiation emergency. In total, there were 19 participants representing only 5 Federal agencies: CDC, DHS, EPA, USDA, and NIH. Additionally, participants were primarily public affairs personnel and communications specialists. The panel was lacking in representation from experts in health physicists, nuclear power, and emergency preparedness and response. The impact was noticeable. The roundtable was not successful in advancing the practice of risk communication. The only outcome of the 2-day event was an agreement to continue interagency coordination and dialogue. But even the dialogue that did occur was not particularly helpful as participants raised questions seemingly without answer, leaving the impression that gaps existed in the current planning. Some of the "big picture" questions asked by participants included:

- *Can we get radiation emergency subject matter experts to agree on a unified set of messages?*
- *What can and cannot be addressed using an all-hazards approach to preparedness and response?*

These questions could readily have been answered if the subject matter experts in these areas had been involved. But without external expertise and guidance, the questions that stood out the most among the communication experts were only the ones that they themselves could not answer. Unfortunately, when presented as an open question, it creates the sense that preparedness is lacking.

The absence of input from qualified emergency planners and experts on radiation continues to manifest throughout the report. For example, the communication specialists raised concerns over the ability to implement practiced and commonplace all-hazards protective actions like shelter-in-place. Even the term "shelter-in-place" was questioned—this is despite the fact that previous and follow-on risk communication studies led by the CDC demonstrated an adequate public understanding of this term (CDC, 2003; CDC, 2009a, CDC, 2012). These communication "issues" were clearly driven by the participant's biases and pre-conceived notions about radiation:

- *How do we address the need for pre-event education without scaring the public and without damaging the reputations of Federal agencies?*
- *It is challenging to communicate scientific information to the public. For example, it is difficult to explain to the public the difference between medical exposure and nonmedical exposure to radiation.*

These comments reflect the concerns of public affairs staff without the practiced insights that could have been provided by subject matter experts on radiological emergency preparedness and response, and radiation and medical health physics. This group-think was reinforced in the roundtable discussion as participants were led through two practice scenarios involving response to dispersed radionuclides (one of which was the "mall scenario"). These scenarios are specifically designed to emphasize uncertainty and fear and they are challenging even to practiced emergency planners[41]; and running a scenario without the participation of qualified emergency responders only heightens the feeling of uncertainty. Consequently, the example issues identified are only a reflection of the participants own unfamiliarity with these potential events, the actual risks involved, and the significant level of emergency preparedness that exists in the U.S. The *Radiation-Specific Communications Challenges* identified by the group are particularly egregious in that they are issues that had already been addressed in radiological emergency preparedness efforts. Furthermore, many of these "challenges" contradict well-established principles in emergency preparedness and response and cast doubt on the ability of trained responders to effectively manage an emergency:

Radiation-Specific Communication Challenges

- *Fatalism can affect a person's response to radiation-specific messages. When some people hear the term "radiation," they assume they are going to die. They don't believe that effective, protective steps can be taken. This can reduce the likelihood that protective actions will be undertaken.*
- *The all-hazards approach is problematic to some people. People can rehearse for natural disasters, because they are more familiar with them, but people cannot rehearse for terrorism involving radiation.*
- *There are too many "what ifs" with radiation emergencies.*
- *It is difficult to determine what to advise people to do if no specifics are known about the incident (explosion). It could be radiological, biological, chemical, etc.*
- *Communicating about preparedness for radiation emergencies is challenging, because preparedness is not a one-time action. It requires maintenance. Therefore, a "stop, drop, and roll" communication strategy is not practical.*
- *Collaboration across the Federal agencies is also challenging. The following question was posed by a participant in the group: "If we collaborate as a team to combine what we have today, could we*

[41] The author has participated in this mock scenario as part of the Harvard University course on "Radiological Risk Communication."

> *deliver in 90 days a public message with all of our brands/seals to inform the public how to stay alive in a radiation emergency (e.g., a series of protective actions)?" Responses to this question include: "Government doesn't really work that way… It has to be so quick in an event…" In terms of tactical aspects, local-level authorities would be the ones to release a statement of what to do (not the Federal Government).*

This report is in stark contrast to the outcomes of the 2003 focus group on public messaging which benefited from public input, and the 2005 roundtable discussion with experts from a variety of disciplines and groups. When left to themselves, the communications specialists all assumed a limited understanding by the public would lead to a fatalistic response to a radiological release even though prior studies suggested quite the opposite. In fact, a prior study led by the CDC already concluded that effective risk communication is possible even when misconceptions and preconceived notions about radiation exist (CDC, 2003). Ironically, it was the roundtable participants that clearly had a fatalistic attitude toward radiation.

Ultimately, this roundtable would have benefitted by input from experts outside of the field of communication and public affairs; a further consequence of the lack of expert opinion is illustrated by the fact that there are many areas described within the report where consensus was not reached, even among this small group of like-minded communication specialists. This is quite the opposite result from roundtables involving participants from across disciplines, which again suggests that multi-disciplinary approaches are one way to confront cultural biases. The benefit of this report is that it serves to point out that the biases of the specialists need to be carefully examined. That the outcome of this roundtable was influenced by the bias of the participants is further evident when compared to an almost identical roundtable discussion that took place just one year earlier.

Report on the CDC-CRCPD Roundtable on Communication and Teamwork: Keys to Successful Radiological Response (CRCPD, 2008)

The CDC and CRCPD co-sponsored this roundtable discussion to bring together experts in the field of health physics, hospital preparedness, epidemiology, public health, risk communication, psychology, and emergency medicine to address concerns on the need for strengthening communications and improving working relationships for radiological events. In this roundtable discussion, the mall scenario was used, but this time with a diverse group. Unsurprisingly, the conclusions reached were not the same as the 2009 CDC roundtable of communication specialists, and as a testament their combined expertise, this group came to a very different understanding of the perceived gaps in radiological emergency preparedness. Without the hyper-focus on communication and fatalistic mentality, more reasoned responses to the planning needs and identification of actual gaps in planning came out of this roundtable discussion. Once again, this same type of synergy was seen in development of risk communication guidance—when a diversity of agencies are involved, the final product is generally more balanced and practical.

Given the difference in roundtable outcomes, it is worth considering other possible reasons why different groups presented with the same scenario could have arrived at such different conclusions. Was it really bias? Or are there factors about radiological risk communication the communication specialists were aware of that the more diverse group was not? Is radiation such a unique hazard that it requires altogether a different approach to risk communication? To answer that question, an examination of all-hazards risk communication guidance is performed next to assess the degree to which radiation presents unique barriers to communication.

5.7 All-Hazards Risk Communications Guidance

Analysis of Risk Communication Strategies and Approaches with At-Risk Populations to Enhance Emergency Preparedness, Response, and Recovery (HHS, 2008)

This report is the product of a one-year study to assess literature on emergency preparedness risk communication and public health messaging strategies, with emphasis on reaching vulnerable populations. The study demonstrates that barriers to communication are not unique to radiological events. When examined across a range of emergency types, common barriers to communication emerged including trust, emotional interference (e.g., fear, anxiety), inconsistent messaging, and preconceived assumptions. Barriers to trust was the issue most commonly addressed in studies identified in the literature review, followed by inadequate communication resources to disseminate. A key recommendation of this report is:

> ***Present clear facts with actionable plans.*** *Consistent with the risk communication literature (Lundgren, 1994; Mileti, Fitzpatrick, and Farhar, 1992; Renn and Levine, 1991; Sandman, 2003), a strong theme from the site visits was the importance for messages to deliver balanced facts that incorporate the most timely and accurate information. The facts about the risks should be accompanied by information about what individuals can do to protect themselves. Specifically, risk messages should allow recipients to access, confirm, and take direct action (Mileti and Sorensen, 1990). Further, these actions need to be presented in terms that populations at-risk can embrace. As an example, it is insufficient to recommend evacuation without qualifying how someone in a wheelchair might comply; they might need to be advised to ask for help. Therefore, training for spokespersons delivering risk communication messages should emphasize these principles. However, to enhance reach to at-risk populations, it will be important to broaden the number and types of professionals available and trained in risk communication beyond the health department PIO. Additionally, use of message mapping (Covello, 2008) is a useful tool to help address mental noise and focus practitioners on creation of clear, jargon-free messages.*

The study also concluded that a wide range of risk communication resources are available. These resources, although varying in superficial ways, were reported to consistently highlight the importance of clarity of presentation, careful vetting of information, and the ability to act on the information provided. Of note, many of the researchers cited in this report are the same researchers and studies cited in EPA, NRC, and CDC guidance. In fact, the NRC guidance in NUREG/CR-7033 is based on the message mapping strategy of Covello described above (NRC, 2011c). This study demonstrates that the framework of modern radiological risk communication shares its foundations with all-hazards risk communication. The recommendations of this study also support the need to present the radiological risk in a clear balanced manner, accompanied by information about what individuals can do to protect themselves, particularly for the at-risk population. Messages of "no safe dose" would be particularly damaging to populations that may have difficulty evacuating or are unable to obtain access to adequate shelters.

Risk Communication Strategies for the Very Worst of Cases (Johns Hopkins, 2019)

This study was a multiphase research project to inform development of a strategic approach for communicating about global catastrophic biological risks (GCBRs). Information was gathered from 11 countries and assessed by experts in diverse fields including the life sciences, the history of plagues and pandemics, public health preparedness and disaster medicine, security policy and new technologies, and existential risks. Researchers analyzed globally catastrophic events to inform how to prepare for GCBRs. These events were presented as case-studies to reinforce basic concepts and convey messages found throughout other risk communication guidance. Fatalistic views of the GCBR hazard were not exhibited in any of the advice gathered from the GCBR subject matter experts around the globe. The recommendations by the experts included:

- *Present GCBRs as a challenge where solutions are possible, enhancing a sense of self-efficacy.*
- *Diversify, strengthen, and share the scientific evidence for GCBRs and their mitigation.*
- *Relate GCBRs to the current context and concerns of those you seek to engage and make the risk as tangible as possible.*

Within these recommendations, the ideas of diversification, self-protection, and evidence-based communication are just as true for GCBRs as they are for radiological hazards. This suggests that communicating radiation risks is not uniquely different from other types of hazard.

While there is no specific discussion on communicating how to balance the risk of protective actions against the risk of the hazard, the point is made that, "people require confidence in their ability to exercise control in a threatening situation. GCBR issues advocates should work to outline specific risk reduction approaches and a concrete path for developing an overall plan of action." Notably, these ideas have already been developed for radiological emergencies, particularly with messages of simple decontamination measures and protective actions people can take themselves that do not require special equipment or training.

However, there is one crucial observation made in this report that is lacking a parallel in radiological risk communication. The point is made that the decision-maker is vitally important to the emergency response; particularly so when it comes to public trust and willingness to take action, as reflected in the following participant comments:

> *"Our elected officials…don't really talk about these issues with any degree of urgency because they don't understand them, or they fear them. Improving or increasing the knowledge of key leaders and decision makers will help.*
>
> *"For [low probability, high risk] scenarios, any policymaker is going to throw up their hands and work on something else…because it's in the way-too-hard category.*
>
> *"One has to be careful of scaring the hell out of people…You also have to show that there are solutions. Otherwise people go, "oh, my God, it's too big for me to grasp. I'm giving up. I can't even think about it."*

The previous all-hazard risk communication study emphasized the importance of trust (HHS, 2008). This study reinforces that public trust is important as it builds confidence to act, but also emphasizes how quickly that trust can be lost. Of note, just like the group of communicators from the 2008 CDC roundtable, the idea of scaring the public is conveyed as a real possibility. The difference in this case is that the problem is not claimed to be a unique response to GCBRs; additionally, a solution to the problem is presented. The solution rests in understanding that the decision-maker is critical to crisis response. The importance of the decision-maker and how they perceive and communicate with the public is further emphasized in this next all-hazards manual for risk communications.

Crisis and Emergency Risk Communication (HHS, 2014)

This manual introduces principles and practical tools of crisis and emergency risk communications. It is an amalgamation of risk communication, issue management, crisis communication, and disaster communication, informed by theory and practice. The manual is comprehensive and consistent with other manuals of its type. This manual provides another good example of how useful guidance can be developed when experts in multiple areas work together, rather than relying on a few experts in a single area.

Chapter 2 on "Psychology of a Crisis" provides evidence that the psychological response to a radiological event will be no different than what is observed for all hazards. The barriers to effective communication are the same as repeated elsewhere: uncertainty and fear, foremost. Such responses are assumed to be common among all events and are not unique to a particular crisis situation. Similarly, the chapter on "Behaviors in a Crisis" point out to watch for people seeking special treatment and for signs of stigmatization. Positive outcomes are associated with empowerment, risk management, new resources and skills, renewed sense of community, and renewal. The manual also emphasizes the commonality of the feelings of uncertainty that exist during a disaster and the importance of the decision-maker in making efficient and effective decisions:

> *Crises by definition create very high levels of uncertainty…. During crisis situations, decision makers are often unable to collect and process information in a timely manner. They rely on established routines for situations that are, by definition, not routine.*

This document recognizes the critical role decision-makers play in crisis response. As such, the information needs of the decision-maker are emphasized just as much as the information needs of the community. The manual also recognizes there is a natural human response to a crisis event, which often includes feelings of fear and anxiety but seldom results in irrational behaviors. As such, it is asserted that the public can tolerate considerable risk even in the face of uncertainty:

> *Give decision-makers and others with influence in the community open access to complete scientific information.*
>
> *In a crisis, people in your community may feel fear, anxiety, confusion, and intense dread. As communicators, our job is not to make these feelings go away.*
>
> *Contrary to what you may see in the movies, people seldom act completely irrationally during a crisis. During an emergency, people absorb and act on information differently from nonemergency situations. This is due, in part, to the fight-or-flight mechanism.*
>
> *Remember that people can tolerate considerable risk, especially voluntary risk.*
>
> *The natural tendency to recover and rebuild are very common responses to crises. Encouraging those inherent traits will help people cope with uncertainty, fear, and despair.*

A key observation is that when faced with a crisis, although people will experience various levels of fear and anxiety, people will also rely on established routine. This suggests that developing good habits will aid in response.

As another testament to the common framework for risk communication that exists among all hazards, the manual also highlights the EPA's Seven Cardinal Rules of Risk Communication, which are similarly echoed in the principles found in radiological risk communication guides. For example, all of the following guidelines are used in radiological risk communication strategies:

7. Plan carefully and evaluate performance.
Different goals, audiences, and media require different risk communication strategies. Risk communication will be successful only if carefully planned and evaluated.
Guidelines:

- *Begin with clear, explicit objectives.*
- *Provide information to the public.*
- *Offer reassurance that something is being done.*
- *Encourage protective action and behavior change.*
- *Stimulate emergency response.*
- *Involve partners, businesses, and colleagues in dialogue and joint problem solving.*
- *Assess technical information about risks. Know its strengths and weaknesses.*
- *Pretest messages.*
- *Identify important organizations and subgroups within the audience.*
- *Aim communications at specific groups and subgroups in the audience.*
- *Recruit spokespersons with effective presentation and human interaction skills.*
- *Train staff, including technical staff, in communication skills.*
- *Evaluate efforts and learn from mistakes.*

As this manual demonstrates, no matter the hazard, crisis, or emergency, our natural human response to events that disrupt our daily lives makes it possible anticipate that response and to employ a common and consistent approach to developing effective risk communication tools and guidance.

5.8 Conclusions on Risk Communication

Fundamentally, the principles of risk communication are the same regardless of the hazard. While it is essential to communicate clear messages regarding the unique risk of radiation exposure, the elements of effective risk communication are common to all types of emergencies and preparing to respond to a radiological risk does not require a unique set of principles. This is partly because the fundamental human response to crisis events is driven by more than just the unique characteristics of the hazard or event. Our fight-or-flight response is part of our evolutionary history. And because technological hazards are relatively new on the evolutionary scene, we are still adapting our response to such events. A good explanation on our human fear response and why some threats feel scarier than others is provided in David Ropeik's books, *How Risky Is It Really? Why Our Fears Don't Always Match the Facts* and *RISK: A Practical Guide for Deciding What's Really Safe and What's Really Dangerous in the World Around You*. How these cognitive processes relate to the perception of radiation risks in particular is put into perspective in the aptly titled, *Radiation Risks in Perspective,* by Kenneth L. Mossman, and the books, *Radiation and Reason* and *Nuclear is for Life,* by Wade Allison, among others.

Fortunately, our experience with large scale radiological emergencies is still limited. But the relative infrequency of accidents and the lack of familiarity with large-scale radiological events is not a reason to assume a precautionary approach to radiological emergency preparedness is needed. If the central message of radiological risk communication were "no safe dose" this would inevitably suppress our evolutionary instinct to fight and weaken our response. In addition, the wrong message can lead to feelings of victimization and stigmatization. Such misguided measures would be detrimental to current emergency planning efforts to build resilient communities and contrary to every principle of effective risk communication. This makes it all the more important to ensure radiological emergency planning and response is not viewed as somehow special and treated different from other hazards, when in fact there is a common framework for response. This is a cultural mindset that needs to change.

Since the inception of radiological emergency planning, the commonalities with all-hazards planning has been recognized and emphasized (NRC, 1978). Although radiation requires specialized equipment for detection and accident assessment, radiological incidents do not require special planning considerations for implementation of protective actions in excess of the requirements of other hazards. This is true of radiological risk communication as well. Radiological risk communication does not require a unique set of principles but shares its foundation among all-hazards risk communication. This is fortunate for radiological emergency preparedness efforts because the lessons learned from responses to more frequent emergency events can be applied to radiological emergency planning. In fact, the review of all-hazards risk communication strategies and studies presented within revealed two areas where radiological risk communication could be enhanced:

1. The balance of the risk, weighing the risk of the hazard against the risk of protective actions, should be communicated to the public before the event, and during the event to inform public decisions to act.
2. Decisionmakers should be trained on the risks of the hazard and the protective actions in order to inform protective action decisions that balance the risk.

Incorporating these recommendations into emergency planning would likely help ensure that protective actions do more good than harm. Additional conclusions and insights from this review of risk communication include:

- Radiological risk communication guidance is based on well-established principles of risk communication.
- The principles of radiological risk communication are no different than the principles of risk communication used for any hazard.
- The human psychological response appears to be consistent across many hazards and disruptive events.
- All-hazards risk communication emphasizes the importance of the decision-maker and the resilience of the public in the face of adversity.
- Risk communication guides serve as useful tools for preparing information on radiological hazards to a broad audience during an emergency; however, the guidance is currently lacking in specific communication needs of decision-makers.
- Risk communication studies and guidance often reveal the bias of the groups involved. Interagency and collaborative reports tend to suppress one-sided views and provide balanced guidance.
- Radiological risk communication guidance is varied in the degree to which it presents the radiological hazard as a risk but does show an evolution of thought against hyping the radiation risk at low dose.
- Good public information tools avoid messages of “no safe dose” and instead emphasize the safety benefit of protective actions.

Chapter 6 – Conclusion

The theory of the Tipping Point requires, however, that we reframe the way we think about the world. —Malcolm Gladwell, The Tipping Point

Malcolm Gladwell concludes *The Tipping Point* with the observation that the world often does not accord with our intuition. What must underlie successful change is a bedrock belief that change is possible. The book concludes with the statement,

> *In the end, Tipping Points are a reaffirmation of the potential for change and the power of intelligent action.*

Radiological emergency preparedness is at a tipping point. Conditions are right for change. All that is needed is nudge in the right direction. The past was fraught with notions of uncertainty and fears of “no safe dose” upheld by belief in a conservative protection model. The future holds the promise of a more exact science, an improved understanding of the risks and better ways to manage those risks. But what comes after the tipping point? How do we move forward? It involves *deliberation*.

Elaine Scarry offers a glimpse of this future in her book *Thinking in an Emergency* in which she eloquently states,

> *Rather than emergency bringing about the end of thinking, thinking should bring about the end of emergency.*

According to Scarry, the implicit claim of emergency is that all procedures and all thinking must cease because the emergency requires that 1) an action must be taken, and 2) the action must be taken relatively quickly. Such actions are usually taken as a course of habit. But according to Scarry, “the question is not whether habit will surface in an emergency (it surely will) but instead which habit will emerge, and whether it will be serviceable or unserviceable.”

Scarry illustrates her point with the example of the Swiss shelter system. The shelter system in Switzerland was part of a national civil defense project to provide a shelter for every person in the event of a nuclear war. The project included construction of 290 shelters throughout the country, providing 7,416,000 cubic feet of storage. The shelter system restored to the Swiss the power to affect their own destiny in the atomic age. And it was brought about by a deliberative process that involved the whole community.

Thinking in an Emergency explores the question: do emergency and habit go together? The answer is yes, they do go together. Habit yokes thought and action together. The key is to develop good habits based on serviceable action. How then can good habits be developed? One way is through good governance. Scarry creates the link between habit and governance and deliberation and governance. She observes that deliberation and governance are inextricably linked with a bond almost as strong as between habit and governance. As a word of warning, Scarry notes that ideas govern the state because they govern our individual actions,

> *In truth the ideas and images in men's minds are the invisible powers that constantly govern them, and to these they all universally pay a ready submission.*

It follows that as good ideas make possible good governance, so bad ideas can take possession of the mind as if they had a legal right to be alone considered there, leading to bad governance. And here revealed is the danger of a singular focus on the LNT model for radiological protection. Although only a hypothesis, and despite recognition of the uncertainties and lack of predictive power at low dose, LNT formed the basis for governance. As a result, LNT took possession of some minds as the only way to ensure the health and safety of the public. Deliberation gave way to habit, and habit—without the benefit of deliberation—results in overreaction to the perceived threat of radiation. Unbeknown to many is that such overreactions can ultimately do more harm than radiation. Therefore, it is time to deliberate and develop new habits.

Scarry notes that Charles Peirce provided a strikingly similar account of deliberation, describing the act of thinking as motivated "by the irritation of doubt," an uncomfortable state which is only "appeased" once the act of thinking finds an appropriate object of belief, which in turn leads to "the establishment in our nature of a rule of action, or, say for short, a *habit*." Habits developed to manage everyday life are even more crucial in time of emergency. "Now, the identity of a habit," Peirce writes, "depends on how it might lead us to act, not merely under such circumstances as are likely to arise, but under such as might possibly occur, no matter how improbably they may be." Radiological emergencies will remain improbable events. This is not to say impossible, but merely of such low probability that most people will likely never find themselves involved in a response to an uncontrolled radiological release. Because of the low probability of these events, deliberation is needed ahead of time to consider the types of habits that will best serve the public when needed.

The Chernobyl and Fukushima Daiichi accidents are examples of why further deliberation is needed. In the aftermath of these accidents, it became evident that psychosocial issues were the dominant health concern. The World Health Organization states (WHO, 2020),

> *The health impact of radiological and nuclear emergencies can last for decades. Lessons learned from past radiological and nuclear accidents have demonstrated that the mental health and psychosocial consequences can outweigh the direct physical health impacts of radiation exposure. International radiation emergency preparedness and response standards outline provisions for mitigating these effects. Yet, practical guidance for addressing the mental health and psychosocial aspects of radiation emergencies remains scarce.*

The WHO further asserts that in the event of a nuclear accident, these effects arise from exposure to the stress from three major factors (WHO, 2020): (1) the unknown nature of radiation and uncertainty related to the extent risk for people's health; (2) implementation of the protective actions taken (such as evacuation, temporary relocation, resettlement), resulting in drastic socioeconomic consequences and changes for the affected communities, and the problem of returning to normal life following the disaster; and (3) stigmatization of affected people, mostly evacuees and residents of the affected settlements. In response, the WHO issued a framework for mental health and psychosocial support specific to radiological and nuclear emergencies to bring together existing knowledge at the intersection of mental health and radiation protection. While this is a step forward, it also makes sense to address these health effects by mitigating the stress factors believed to be the source of the problem.

This thesis offers a deliberative approach to mitigate these stress factors. Specifically, this thesis examined the *philosophy*, *science*, and *practice* of radiological emergency preparedness as related to taking protective actions. The deliberative process should further be used to consider the types of habits that will best serve the public in an emergency, then to develop those habits through good governance and practice. Emergency procedures are laden with deliberation. Our fate is not left to chance and unknowns. And through deliberation, we can choose to accept the risk and find the best ways to manage those risks. From this deliberation comes good governance in the form of good regulations and guidance. And good guidance, when practiced, becomes good habit.

Philosophy

The first major stressor the WHO identifies is, “the unknown nature of radiation and uncertainty related to the extent risk for people’s health.” But radiation is not an unknown. And the effects are not uncertain. As such, we need to be deliberative in our choice of words when discussing radiation. Often times, scientific-sounding statements get thrown around as if they have practical meaning and application when they do not. One such phrase that gets misused in the radiological community is that *absence of evidence is not evidence of absence*. Casual use of this phrase can be taken out of context and misapplied. For example, in his book, *Radiation Risks in Perspective*, Kenneth Mossman illuminates the fundamental problems in public perception, reaction, and policy when faced with the possible health risks of radiation. Mossman states,

> *For very small risks it is practically impossible to distinguish between zero probability and probabilities that are too small to be measured reliably. But absence of evidence of risk is not evidence of absence of risk!*

An incorrect interpretation of this statement is that an inability to reliably measure something because it is a very small quantity, is an absence of evidence. An incorrect inference from this statement is that there is large uncertainty in what we know about the effects of radiation at low dose. This is not what this statement means. The "absence of evidence" means that if no effort has been made to even look for the evidence to begin with, then one cannot conclude *a priori* the absence of something. This cannot be said about the health effects of radiation at low dose. We know the evidence we are looking for, we have sufficient tools and methods to find it, and we have been looking for a very long time. Mossman goes on to state, "We know more about the health effects of ionizing radiation than most other carcinogenic agents." This is not absence of evidence. Quite the opposite, there is abundant evidence that the risk is either non-existent or so small as to be unmeasurable. Either way, the result is the same—the radiological risk is very small and the effects are understood; the *uncertainty* is very low that it could be otherwise. This is the message that needs to be heard. As demonstrated in Chapter 5, radiological risk communication has evolved from messages of "no safe dose" to providing direct answers to the question of, "Am I safe?" This messaging was the result of deliberation among a diverse group of experts. But good risk communication practices need to be turned into good habit, and Chapter 5 also highlighted that good habits are not yet fully developed. Here are two example habits for communicating about radiation:

> Habit 1: Radiation is invisible, and its effects are uncertain.
>
> Habit 2: Radiation is detectable, predictable, protectable.

Habit 1 emphasizes uncertainty and a quality about radiation that only heightens the uncertainty (while being slightly misleading in that visible light is radiation, although non-ionizing). Habit 1 conveys the message that radiation is undetectable and scary, with unpredictable consequences. Habit 2 is concise, informative, and positive. The second habit conveys everything we have known about radiation for more than 100 years in a concise message. We know how to detect radiation and can do so at will through a variety of ways. We know the radiological source terms in a potential release—what radionuclides to expect, how they will decay, what radiations they release, and we can predict where radionuclides will go in the environment. We know how radiation interacts with matter, the resultant health effects, and the amount of radiation dose it takes to produce those effects. And we know how to protect ourselves using simple methods. In a radiological emergency, evacuation and sheltering-in-place are commonplace actions for implementing the time-tested radiological protection principles of time, distance, and shielding. This is a protection philosophy based on certainty, rather than uncertainty.

Science

The second major stressor identified by the WHO is, "implementation of the protective actions taken (such as evacuation, temporary relocation, resettlement), resulting in drastic socioeconomic consequences and changes for the affected communities…" As the deliberative process was shown to improve radiological risk communication, deliberation can also be used to enhance protective action strategies. Protective action strategies that balance the risk can be turned into good governance and then developed into good habit. Here are example habits that could be developed to respond to a radiological emergency:

Habit 1: Go inside, stay inside, tune in.

Habit 2: Precautionary evacuations of special populations at an Alert declaration, even if no radiological release is expected to occur.

Habit 1 is decisive, easily implemented, and supports future deliberate action, thereby empowering. Habit 2 is reactionary, resource intensive, and is not easily undone, thereby prohibitive. Habit 1 is already applied in response to a variety of hazards and builds upon established public trust. Habit 2 is specific to a radiological emergency and creates uncertainty.

As demonstrated in this thesis, deliberation can be used to exact the science of protective action strategies. While the protective actions themselves remain unchanged, how we implement these actions can be improved by considering, at a minimum: (1) the inherent long-term risks of evacuation and relocation, (2) the effectiveness of shelters, and (3) the specific risk posed by the facility. Although radiological emergencies are rare, implementation strategies can be tested through simulation tools firmly based in science. Practical experience can be leveraged from the use of these actions in response to other hazards. New tools can be developed to aid decision-makers balance the risks and make decisions that provide adequate protection of the public from radiation while minimizing the socioeconomic and health consequences of those actions. The PARatus tool was developed to demonstrate the practicality and usefulness of such efforts. The insights developed in this study would support the following changes to protective action strategies:

- Sheltering-in-place is a viable initial protective action when dose projections are at PAG levels.
  - Sheltering provides adequate protection, particularly for SMRs or advanced reactors with smaller source terms.
  - Sheltering adds time to gather ground-truth data to decide if further action is warranted.
  - Implementation strategies can be enhanced to provide detailed considerations for use of HVAC systems.
- Prompt evacuation could be limited to areas close-in to the point of release when based on plant conditions, or in areas where dose projections are above PAG levels.
  - Similar to a staged evacuation strategy without automatic evacuation of the downwind zones, a limited prompt evacuation close-in would provide time to assess the need for further evacuations.
  - For a large light water reactor, evacuation within a radial distance of approximately 2 miles from the release point would likely provide adequate protection.

- For small modular and advanced reactors, the initial evacuation distance may be less than 2 miles, or sheltering-in-place may be the preferred initial action even close-in.
- In all cases, an initial evacuation of the area within 2 miles would minimize the number of displaced individuals.

Practice

The third major stressor identified by the WHO is, “stigmatization of affected people, mostly evacuees and residents of the affected settlements.” Here again, deliberation is needed to respond to the concern and the potential aversion to populations displaced after an accidental radiological release. The fundamental question people will want to know is, when is it safe to return home? This is a challenging question to answer based only on the PAGs. The PAG Manual states, “Conditions may develop in which some groups who have been evacuated in an emergency may be allowed to return based on the relocation PAGs, while others may be converted to relocation status.” But the PAG Manual also states, “PAGs do not establish an acceptable level of risk for normal, non-emergency conditions, nor do they represent the boundary between safe and unsafe conditions.” Then again, the PAG Manual goes on to state, “The PAG[s] have been developed on the basis of considerations of acceptable risk...” (EPA, 1992a). This is all rather confusing. Is the risk acceptable or not? Is exposure above or below the PAG levels safe or not? How do we develop good habits without clear expectations of the desired response? Here are some possible habits that could emerge:

Habit 1: Return of evacuees to homes within contaminated areas as soon as practicable (within 1 week).

Habit 2: Prolonged displacement with no clear expectation for when evacuees can return home.

Habit 1 is based on accepting and managing the risks. Habit 2 is based on uncertainty, indecision, and aversion to risk. And this aversion leads to stigmatization.

Protective action strategies for radiological emergencies should be transformed to build resilient communities. A population empowered to manage the risks they face will also be able to face the pressures from outside, including stigmatization by those averse to radiation. Fundamentally, this comes down to what level of risk society will accept. Below 10 rem, the radiological risks are certainly tolerable. As such, protection efforts should focus more on risk management rather than risk avoidance. According to the EPA, a dose of 5 rem to each member of a population group of 100,000 persons carries an estimated lifetime risk of about 150 fatal cancers, which compares to the lifetime risk of drowning for the same population (EPA, 1992a). But a lifetime risk of drowning does not require one to move away from the beach or never go swimming again. Why? Because we manage those risks with safety devices, lifeguards, notices of strong tides, and a variety of other methods. Conversely, prolonged displacement of a population on account of low levels of radiation is not risk management, it’s risk aversion.

The opposite of aversion is acceptance. And acceptable risk is the answer to the question, *what is safe*? In fact, as described in the PAG Manual, “Safety is the degree to which risks are judged acceptable” (EPA, 1992a). Perception of the risk will vary from person to person. However, in an emergency, the public will look to trusted authorities for information and recommended actions. As such the decision-maker is crucial to the effectiveness of the emergency plan. The beliefs of the decision-maker cannot run counter to the deliberation put into developing the plan. And so, a cultural transformation is needed to modify beliefs so that natural actions achieve the desired results.

Transformation of protective action strategies for radiological emergencies is possible. Through deliberation, good governance, and habit, we can change our *philosophy*, exact our *science*, and improve our state-of-*practice*. When the risks are known and the science is exact, the uncertainty is low. Preparedness and certainty can replace precaution. And when the risks are balanced, protective actions can do more good than harm.

Considerations for future work:

1. Reperform shelter analyses in PARatus with realistic weather conditions.

2. Conduct basic and applied research to characterize the penetration factor for radiological releases.

3. Optimize implementation strategies for HVAC system use during a radiological release. Conduct research as needed and gather insights from other fields of study that quantify the benefit of HVAC filtration.

4. Estimate the contribution to internal and external dose from particle deposition indoors. Characterize indoor deposition patterns.

5. Couple state-of-the-art shelter and evacuation models into state-of-the-art consequence analysis codes.

6. Perform protective action strategy studies using advanced reactor and small modular reactor accident timing sequences and source terms.

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Appendix A After Action Report Data

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
Arkansas Nuclear One	2016	Alert	0746				
		SAE	0850				
		GE	1038	Evacuate 2-mile radius, 2-5 miles downwind. Remainder of EPZ remain indoors.	Evacuate (Subzones G, H, K, N, O, P, Q, R, U), Shelter (Subzones I, J, L, M, S, T), KI for Emergency Workers & Institutionalized	GE	1045
		SR	1038		Livestock impound and quarantine	GE	1230
Braidwood Station	2016	Alert	0834				
		SAE	0947				
		GE	1055		Evacuate K-6, W-1,3,9, G-7, 10, 11, 14, 15	GE	1124
		SR	1055		KI	GE	1121
Browns Ferry Nuclear Plant	2017	Alert	0832		PAD: EHO-3 Evacuate A2, G2, A5, G5, H10, K10	SAE	1027
		SAE	0940		Stay Tuned messages	GE	1121
		GE	1103		PAD: EHO-4 Evacuate B2, F2	GE	1119
		SR	1103		PAD: EHO-5 SIP B5, E5, F5, A10, B10, C10, D10, E10, F10, G10, I10, J10	GE	1128
Browns Ferry Nuclear Plant	2016	Alert	0829				
		SAE	0925				
		GE	1038	Evacuate 2-mile radius, 2-5 miles downwind. Zones A2, B2, F2, G2, E5, F5, G5; SIP 10 miles downwind zones E10, F10, G10.	EHO-4 Evacuate A2, B2, F2, E5, F5, G2, G5; KI same zones	GE	1125
		SR	1144		EHO-5 Evacuate E10, F10, G10	GE	1155
Brunswick Steam Electric Plant	2016	Alert	0809				
		SAE	1049				
		GE	1153	Evacuate: Zones A, B, J; Shelter: Zones K, L, M	Evacuate Zones: A, B, J, K, L, M Go inside stay inside: N	GE	1229
		SR	1153		KI emergency workers	GE	1232
Byron Station	2017	Alert	0810				
		SAE	0920		Public advisory	SAE	1006
		GE	1030	Evacuate sub-areas 19, 23, 25	Evacuate sub-area 1	GE	1050
		SR	1042				

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
Byron Station	2014	Alert	0809				
		SAE	0909		Public advisory	SAE	1016
		GE	1037	Evacuate sub-areas 19, 20, 23, 25	Evacuate sub-areas 19, 20, 23, 25	GE	1057
		SR	1037		Evacuate sub-areas 17, 19, 20, 23, 25	GE	1147
Calvert Cliffs Nuclear Power Plant	2017	Alert	0811				
		SAE	1019				
		GE	1142		Evacuate zones 1, 2, 4, 5; Shelter zones 3, 6, 7. Agriculture 50 miles, restrict air space 10 miles 360	GE	1210
		SR	~1000		KI for EWs and general public zones 1, 2, 4, 5	GE	1210
Catawba Nuclear Station	2018	Alert	0853		Evacuate A0, B1, C1	SAE	1119
		SAE	1045		Evacuate A0, B1, B2, C1, C2, SIP A3	GE	1344
		GE	1248		Evacuate A1	GE	1513
		SR	1039		KI for general public in evacuation zones and some EWs (1515)	GE	1522
Clinton	2017	Alert	0820				
		SAE	1000				
		GE	1108	Evacuate sub-area 1	Evacuate sub-area 1	GE	1124
		SR	1108				
Columbia	2016	Alert	0820				
		SAE	0943				
		GE	1024		Evacuate 0-2 mile CGS and zones 2 & 3, SIP 2-10 mile (zones 1 & 4)	GE	1037
		SR	0943		KI for EWs	GE	1102
Comanche Peak Steam Electric Station	2017	Alert	0820				
		SAE	0950		Evacuate 2A	SAE	1009
		GE	1026	Evacuate 2A, 4A, 1A, 1B, 4B, 2B, 2D, 2E; SIP 1C, 2G, 1D	Evacuate 2A, 4A, 1A, 1B, 4B, 2B, 2D, 2E; SIP 1C, 2G, 1D	GE	1036
		SR	1026	Evacuate 2A, 4A, 1A, 1B, 4B, 2B, 2D, 2E, 1C, 2G, 1D	Evacuate 2A, 4A, 1A, 1B, 4B, 2B, 2D, 2E, 1C, 2G, 1D	GE	1105
					KI for EWs	GE	1200
Cooper Nuclear Station	2018	Alert	0753		Missouri Actions		
		SAE	0927		Shelter sub-area 1	SAE	0942
		GE	0945		Evacuate sub-area 1	GE	1001
		SR	1130		KI for EWs	GE	1004
					Nebraska Actions		
					SIP 11, 12, 13e, 13w, and 14	GE	1001
					KI for EWs	GE	1019

Compilation of After Action Report Data							
Site	Year	ECL	Time	PAR	PAD	ECL	Time
Davis-Besse Nuclear	2017	Alert	0809				
		SAE	1028		Information message, monitor EAS within 10-mile EPZ	SAE	1053
		GE	1213	Evacuate 1, 2, 10, 12	Evacuate 1, 2, 10, 12	GE	1238
		SR	1028 and 1211		KI to public, institutionalized persons, EWs, 1, 2, 10, 12	GE	1236
Diablo Canyon Nuclear Power Plant	2018	Alert					
		SAE					
		GE	1047	Evacuate PAZ 1, 2, and ocean out to 5 nautical miles	Evacuate PAZ 1, 2, and ocean out to 5 nautical miles	GE	1047
		SR	1126		PAD: Evacuate PAZ 3, 4, 5	GE	1126
Dresden Nuclear Power Station	2017	Alert	0815				
		SAE	0935				
		GE	1033	Evacuate sub-areas 1, 3, 4	Evacuate sub-areas 1, 3, 4, 6	GE	1104
		SR	1101		KI for EWs and immobile population	GE	1049
Edwin I. Hatch Nuclear Plant	2017	Alert	0820				
		SAE	1019				
		GE	1145	Evacuate A, B-5	Evacuate A, B-5, others stay tuned	GE	1220
		SR	1102				
Fermi	2016	Alert	0837				
		SAE	1002				
		GE	1142		Evacuate PAAs 1, 2, 4	GE	1149
		SR	1145		Evacuate PAAs 1, 2, 4, 6, 7	GE	1208
					KI	GE	1150
Fort Calhoun Station	2017	Alert	0942		Iowa Actions		
		SAE	1050				
		GE	1141	2 mile radius and 5 miles downwind	Evacuate subareas 10, 11	GE	1217
		SR	0802				
					Nebraska Actions		
					Close river	GE	1149
					SIP 0-2 miles from plant, sub-area 1 and schools	GE	1159
Grand Gulf Nuclear Station	2017	Alert	N/A				
		SAE	0824				
		GE	1016		Evacuate Areas: 1, 5a, 5b, 6 all others monitor and prepare; KI to EWs	GE	1048
		SR	1016		Evacuate Areas: 1, 2a, 2b, 3a, 4a, 5a, 5b, 6, 7; SIP all remaining	GE	1148

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
H.B. Robinson Steam Electric Plant	2017	Alert	0745				
		SAE	1054				
		GE	1319		Evacuate Zones: A-0, D-1, D-2, E-1, E-2; SIP none	GE	1356
		SR	1031		KI for public and EWs in evacuation zone	GE	1346
Joseph M. Farley Nuclear Plant	2012	Alert	0826				
		SAE	0934				
		GE	1045	PAR 2 (0-2 miles and 5 miles downwind)	Evacuate Zones: Alabama A, E-5, F-5; Georgia A, I-5	GE	1100
		SR	1041				
LaSalle County Station	2016	Alert	0824				
		SAE	0925				
		GE	1011	Evacuate sub-area 1, 3	Evacuate sub-area 1, 3	GE	1026
		SR	0925		KI to EWs and immobile populations - No KI required as release limits below levels	GE	1015
Limerick Generating Station	2017	Alert	1715				
		SAE	1817				
		GE	1931		Evacuate 10 mile EPZ, SIP special populations and ingest KI	GE	2008
		SR	ongoing		KI for EWs, general public, persons with disabilities or functional needs	GE	2019
Millstone Power Station	2012	Alert	0817				
		SAE	1015				
		GE	1116	Evacuate A/B/C; SIP all others; KI not recommended	1st PAD (Unknown)	GE	1214
		SR	1026		2nd PAD (Unknown)	GE	1228
					3rd PAD (Unknown) and KI administration	GE	1213
Monticello Nuclear Generating Plant	2017	Alert	0848				
		SAE	1008		Public Advisory	Alert	0933
		GE	1125	Evacuate 2 mile 360 and 5 miles downwind sectors P, Q & R; affected subareas 2, 5N, 5W	Evacuate sub-areas 2, 5N, and 5W	GE	1155
		SR	1125		KI General Population	GE	1200

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
North Anna Power Station	2018	Alert	0822				
		SAE	0949				
		GE	1051		1st PAD: Evacuate sectors A, B, C; PAZs 4, 6, 8, 9, 10, 11, 12, 13, 14, up to 5 miles	GE	1113
		SR	1051		2nd PAD: Evacuate sectors A, B, C; PAZs 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 25, 0-5 miles 360 degrees, up to 10 miles downwind	GE	1148
					3rd PAD: Evacuate 10 miles 360 degrees, KI for all (EWs and public)	GE	1304
Oconee Nuclear Station	2016	Alert	0817				
		SAE	0916		1st PAD: Evacuate A0, C1, D1; SIP D2, hunting/fishing ban; issue KI to EWs and institutionalized only; animals on stored feed/water	SAE	1022
		GE	1121	Evacuate A0, C1, D1	SIP add C2; evacuate hospitals (D2)	GE	1152
		SR	0919	Evacuate add B1 due to wind shift	Evacuate add B1, B2, C2, D2	GE	1252
					Do not ingest KI	GE	1254
Palisades Nuclear Plant	2014	Alert	N/A				
		SAE	0812				
		GE	1144	Evacuate PAAs 1 and 2	Evacuate all non-essential personnel in PAAs 1, 2, 3	GE	1205
		SR	N/A		KI administration	GE	1205
Peach Bottom Atomic Power Station	2016	Alert	1614				
		SAE	1730		KI for EWs	SAE	1814
		GE	1819	Unknown. Presumably evacuate 2 miles, 5 miles downwind. At 1915 an updated PAR adds south sector out to 5 miles for windshift	Evacuate 0-10 mile	GE	1846
		SR	N/A (1807-see note)				
Perry Nuclear Plant	2012	Alert	0824				
		SAE	1001		Public advisory	GE	1248
		GE	1225	Evacuate subareas 1, 3, and Lake Erie	Evacuate subareas 1, 3, and Lake Erie	GE	1255
		SR	1235		KI for EWs, Institutionalized, and General Public	GE	1248

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
Pilgrim	2016	Alert	0851				
		SAE	1027		KI for EWs and general public	SAE	1055
		GE	1131	2 mile, 5 mi downwind; Evacuate subareas 1, 2, 3, 12 and SIP 4, 5, 6, 7, 8, 9, 10.	PAD Unknown	GE	1153
		SR	1043-1231				
Pilgrim	2015	Alert	0825				
		SAE	0944				
		GE	1116	Evacuate 2 mile rings and 5 miles downwind; SIP all remaining (evacuate 1, 2, 12; SIP 3, 4, 5, 6, 7, 8, 9, 10, 11)	Evacuate 1,2, 4, 5, 12; SIP 3, 6-11	GE	1131
		SR	1122	KI for public and EWs in zones 1, 2, 5, and 12	KI for EWs, Field Monitoring Teams, General Public (1, 2, 4, 5, 12), Institutionalized Individuals	GE	1131
Point Beach Nuclear Plant	2017	Alert	0859				
		SAE	1105				
		GE	1159	Evacuate 0-5 miles and 10 miles downwind	PAD Unknown	GE	1222
		SR	1214		KI Administration	GE	1222
					PAD	GE	1345
Point Beach Nuclear Plant	2012	Alert	0841				
		SAE	1010				
		GE	1107	Evacuate Subarea 5	Evacuate Subarea 5	GE	1114
		SR	1010-1045/ 2nd 1226	Evacuate Subarea 5, 10SW, 10N	Evacuate Subarea 5, 10SW, 10N	GE	1252
					KI for EWs and immobile population	GE	1123
Prairie Island Nuclear Generating Plant	2016	Alert	0856		Public Advisory	Alert	0956
		SAE	0957				
		GE	1140	Evacuate subarea 2, 5N, 5W	Evacuate subarea 2, 5N, 5W	GE	1159
		SR	0957		KI for General Public	GE	1216
Quad Cities Nuclear Power Station	2016	Alert	0809				
		SAE	0937				
		GE	1029	PAR IL: Evacuate subareas 1, 2; IA; Evacuate subareas 1, 2, 5	PAR IL: Evacuate subareas 1, 2; IA; Evacuate subareas 1, 2, 5	GE	1052
		SR	0937				

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
Riverbend	2018	Alert	0834				
		SAE	1106				
		GE	1212		Evacuate scenario 20	GE	1240
		SR	1212		KI Administration	GE	1310
Riverbend	2016	Alert	0821				
		SAE	0941				
		GE	1100		Par scenario #5: Evacuate PAS 1, 4, 9; All others monitor and prepare	GE	1134
		SR	1114		KI for EWs	GE	1231
R.E. Ginna Nuclear Power Plant	2015	Alert	0901				
		SAE	1036				
		GE	1137	Evacuate W (1,2, and W-Lake), M (1, and M-Lake); implement KI plan			
		SR	1149				
Salem and Hope Creek Nuclear Generating Stations	2018	Alert	1617				
		SAE	1813				
		GE	2005		Evacuate ERPA A and 0-5 mile; monitor and prepare ERPA B, C	GE	2102
		SR	1813-2030		KI EWs and general public	GE	2049
Seabrook Station	2016	Alert	0752				
		SAE	0925		1st A&N Decision: (Unknown)	SAE	0946
		GE	1100		2nd A&N Decision: (Unknown)	GE	1130
		SR	1053		KI for EWs and general public	GE	1130
Sequoyah Nuclear Plant	2016	Alert	0829		1st PA: Stay Tuned EAS	Alert	0856
		SAE	0952		2nd PA: Monitor and Prepare	SAE	1019
		GE	1024	Evacuate: 2 miles (A-1, B-1, C-1, D-1) and SIP 5 miles downwind (A-3, D-2); consider KI	3rd PA: Evacuate: A1, B1, C1, D1; SIP A2, A3, D2; Go inside and stay inside A4, A5, A6, D3, D4, D5, D6	GE	1057
		SR	1050	Scenario states additional PAR would be added at 1315 if exercise ongoing. This PAR adds evacuate 5 miles downwind in Zones A-2, A-3, D-2. (Not clear if this is ORO or licensee PAR)	No KI for EWs for public.		

Compilation of After Action Report Data							
Site	**Year**	**ECL**	**Time**	**PAR**	**PAD**	**ECL**	**Time**
Sharon Harris	2017	Alert	0817				
		SAE	0922		1st PAD: Public Warning	SAE	0937
		GE	1109	Evacuate A, B, L; SIP C, D, E, F, G, H, I, J, K, M, N	2nd PAD: Evacuate Zones A, B, L, M, N; SIP Zones C, D, E, F, G, H, I, J, K	GE	1130
		SR	1107	At 1200, PAR to issue KI	3rd PAD: Ingest KI in evacuated zones	GE	1225
					KI for EWs	GE	1228
South Texas Project	2012	Alert	0718				
		SAE	0945				
		GE	1109	Evacuate Zones 1, 2; SIP 6, 11. Affected downwind sectors are R, A, B, C.	1st PAD: (Unknown)	GE	1150
		SR	1100	Evacuate Zones 1, 2, 6, 11; SIP 3, 5, 7, 10	2nd PAD: (Unknown)	GE	1230
					KI administration	GE	1348
St. Lucie Plant	2016	Alert	0745				
		SAE	0847		1st PAD: Stay tuned and sirens	SAE	0940
		GE	1032	2 miles, 5 miles downwind (Sectors P, Q, R)	2nd PAD: Evacuate Zones 1, 2, 8; SIP Zones 3, 4, 5, 6, 7	GE	1105
		SR	0845				
Susquehanna Steam Electric Station	2016	Alert	1813				
		SAE	1944		Evacuate 10 miles 360 degrees	GE	2114
		GE	2045		KI for EWs and public	GE	2115
		SR	1813				
Three Mile Island Nuclear Station	2017	Alert	1655				
		SAE	1818				
		GE	1909		Evacuate 0-10 miles, 360 degrees; SIP Hershey Medical Center, Dauphin County Prison, 3 downwind nursing homes	GE	1949
		SR	1624		KI for EWs and public	GE	1949
Turkey Point Nuclear Generating	2017	Alert	0819				
		SAE	0923		1st PAD: Stay Tuned	SAE	1005
		GE	1023	Evacuate 0-2 mile, 5 mile downwind; All 2-mile sectors and Q, R, A; SIP all remaining 2-5 mile downwind sectors	2nd PAD: Evacuate 2, 4; SIP 3, 5, 6, 7, 8, 9)	GE	1103
		SR	1010		KI for EWs; Shelter animals 0-10 miles, Marine restrictions 0-10 mile	GE	1103

Compilation of After Action Report Data

Site	Year	ECL	Time	PAR	PAD	ECL	Time
Vermont Yankee	2013	Alert	0857				
		SAE	1049		1st PAD: (Unknown)	SAE	1108
		GE	1157	Evacuate Brattleboro, Guilford, Vernon, Hinsdale.	2nd PAD: For NH: Evacuate Vernon, Hinsdale, SIP all others	GE	1206
		SR	1157		KI Administration	GE	1201
V.C. Summer Nuclear Station	2017	Alert	0820				
		SAE	1019		KI for EWs	SAE	1046
		GE	1212	Evacuate Zones A0, A1, B1, C1; SIP Zones A2, B2; consider KI	Evacuate Zones A0, A1, B1, C1; SIP Zones A2, B2	GE	1243
		SR	1248		Evacuate Zones: add A2, B2	GE	1415
					KI for general public	GE	1415
Vogtle Electric Generating Plant	2018	Alert	0819				
		SAE	0952				
		GE	1105		Evacuate: A, C-5, D-5, E-5; SIP D-10, E-10, F-10	GE	1132
		SR	1100-1300				
Waterford Steam Electric Station	2017	Alert	0809				
		SAE	0948				
		GE	1037	Evacuate A1, B1, C1, D1 (0-2 mile) and A2, C2 (2-5 mile downwind); all others monitor and prepare	Evacuate PRAs: A1, B1, C1, D1, A2, C2	GE	1130
		SR	1050		Expanded Evacuation PRAs: A3, A4	GE	1137
					Expanded Evacuation PRAs: B2, D2	GE	1221
					KI Administration	GE	1221
Wolf Creek Generating Station	2017	Alert	N/A				
		SAE	0819				
		GE	1032		Evacuate CTR, S1, S2, SW1, SW2	GE	1050
		SR			KI Approved	GE	1216

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Arkansas Nuclear One	2016	Alert & Call in School Bus Drivers/ Activate Reception Centers	Alert	0802/ 0822		
		Evacuate Schools	SAE	0927		
Beaver Valley Power Station	2018	Water and Rail 10 mile 360	SAE	1853		Plume exposure pathway exercise
		Shelter Livestock place on stored feed	SAE	1853		
		Water and Rail 10 mile 360	SAE	1853		
Braidwood Station	2016	Livestock advisory	GE	1055		
		Evacuate Schools & Special Populations	GE	1059		
		State Parks & Hunting Areas	GE	1108		
		Air, Water, Rail	GE	1114, 1107, 0958		
Browns Ferry Nuclear Plant	2017	EHO-1 Public Warning and EHO-2 Restricted Access	SAE	0953		
						Schools were out of session; Relocation of special populations and certain industries in the 10-mile EPZ decision by one County
Browns Ferry Nuclear Plant	2016	EHO-1 Public Warning and EHO-2 Restricted Access	SAE	1010		
Brunswick Steam Electric Plant	2016	Waterway Warning, special populations, schools (summer activities) evacuated A, B, J, M	Alert	1040		Winds out of south-southeast and steady, 3-5 mph, from 238 degrees; high of 79 F
Byron Station	2017	evacuate state parks and hunting areas	GE	1102		Wind direction from 290 degrees, 22 mph, Stability Class C
		livestock advisory	GE	1103		
		air, water, rail traffic restrictions	GE	1050		Dose Projections (2 hour release): TEDE: SB (143 mrem), 2 miles (955 mrem), 5 miles (2.41 mrem), 10 miles (1.20 mrem)
		evacuate schools and special populations	GE	1050		
Byron Station	2014					Wind direction from 358 degrees, 6 mph, Stability Class D
		air, water, rail traffic suspended	GE	1055		Dose Projections: TEDE: SB (1.13 rem), 2 miles (109 mrem), 5 miles (50 mrem), 10 miles (29.9 mrem)
Calvert Cliffs Nuclear Power Plant	2017	Agriculture: farm animals on stored feed and covered water 10 miles from plant. Schools in risk counties relocated to host school. Water restrictions. Close all parks and recreation areas.	SAE	1050		

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Catawba Nuclear Station	2018	lake clearing ban hunting and fishing	SAE	1015	Y (1423)	Wind shift did not affect PAD
Clinton	2017	Evacuate state parks	GE	1140		
		Livestock advisory, sheltered and placed on stored feed and water within the 10-mile EPZ	SAE	1025		Winds from 190 degrees, 14 mph, Stability class D, 58 F
		Water restrictions within 5/10 miles of CPS.	GE	1140		Dose Projections: TEDE: SB (25.8 mrem), 2 miles (4.44 mrem), 5 miles (1.14 mrem), 10 miles (0.4 mrem)
Columbia	2016	Evacuate rivers, parks, recreational areas, hunting areas and relocate schools	SAE	0958		
		Agriculture advisory	GE	1204		
Comanche Peak Steam Electric Station	2017	Evacuate Schools - Hood and Somervell Counties	GE	1046		Winds from 220 degrees, 15 mph, stability class E, 86 F
Cooper Nuclear Station	2018	Close parks	Alert	0818		
		Close parks, place animals on stored food	SAE	0942		Severe thunderstorms in area for next 4-12 hours. Winds from 355 degrees
		restrict boating traffic, close parks	Alert	0850	Y (1207)	Wind shift from 355 to 42 degrees
		Relocate school children	SAE	1051		Winds from the east-northeast at 6 mph, Stability class D.
		restrict air and rail traffic	SAE	1110		Projected offsite release at time of GE was < PAG. Dose exceeds PAG at 1250, no changes needed to PAR.
		livestock advisory	SAE	1056		
Dresden Nuclear Power Station	2017	Livestock advisory within 10-mile EPZ: shelter and stored feed	SAE	1020		Wind from 130 degrees, 12 mph
		Evacuate school and special populations	GE	1104		Evacuation of sub-area 6 was via controller inject into the PAR.
						Dose Projections: TEDE: SB (648 mrem), 2 miles (288 mrem), 5 miles (145 mrem), 10 miles (102 mrem)
Edwin I. Hatch Nuclear Plant	2017	Busses to schools, relocate schools	Alert	0912		
Fermi	2016	Shelter animals	Alert	0957		
		KI to special populations	SAE	1012		
		Ag Advisory	GE	1208		
		Air, water, rail	GE	1218		Not clear who received instructions to take KI at 1150

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Fort Calhoun Station	2017	Relocate schools, close state parks	SAE	1105		Wind from 223 degrees, 6.6 mph, stability class D, 58 F
		Dairy animals on stored feed/water/shelter	SAE	1110		Approximately 174 residents in sub-areas.
						Dose Projection 1.18 Rem TEDE at SB
		Dairy animals on stored feed/water/shelter	SAE	1100		
						Approximately 668 residents, 11 transients, 1080 non-resident employees or 1759 affected by SIP
Grand Gulf Nuclear Station	2017	Transfer of nursing homes, hospital patients, special needs populations, inmates, schools. Shelters and reception centers staffed and opened	SAE	0916		Winds variable from the northeast
						Direction to "monitor and prepare" was later corrected to SIP
H.B. Robinson Steam Electric Plant	2017	Hunting and fishing ban, clear lakes, livestock on stored feed	SAE	1125		
Joseph M. Farley Nuclear Plant	2012	Georgia agricultural advisory	SAE	1016		
		Emergency Health Orders - public warning and restricted access; schools relocated	SAE	0952	Y (1100)	
LaSalle County Station	2016	Evacuate state parks and hunting areas	SAE	0940		Wind from 080 degrees, 6.4 mph, stability class D
		Livestock advisory	SAE	1000		
		Air, water, rail restrictions 5/10 miles	SAE	1000		Dose Projections: TEDE: SB (17.5 mrem), 2 miles (5.18 mrem), 5 miles (3.54 mrem), 10 miles (1.72 mrem)
		Evacuate schools and special populations (LaSalle County only)	GE	1057		
Limerick Generating Station	2017	Air restrictions 3 miles, 3K feet, boating and fishing restriction, water/rail restriction to 10 miles, livestock sheltered and stored feed	SAE	1859		
		Air restrictions 10 miles, 10K feet	SAE	1859		
						Wind from 270 degrees, 6 mph, stability class E. Forecast wind shift to southwest
Millstone Power Station	2012					Winds from 140 degrees, 3 mph, sunny day
		Precautionary actions dismiss schools	SAE	1058	Y(1000)	Winds now from 166 degrees
		Evacuation of Special Needs Populations	SAE	1051		

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Monticello Nuclear Generating Plant	2017	Livestock advisory	SAE	1044		
		Evacuate schools and special populations; evacuate state parks/hunting areas; air, rail, water restrictions	SAE	1047		
		KI for EWs and immobile populations	SAE	1036		
North Anna Power Station	2018	Shelter animals and place on stored feed/covered water	SAE	1042		Winds from 202 degrees, 4 to 5 mph
		Clear Lake Anna	SAE	1048		
Oconee Nuclear Station	2016					Winds from 010 degrees, 6 mph, stability class F
		Early dismissal of schools (Pickens); relocation of schools (Oconee)	SAE	0925	Y (1205)	Wind shifts and PAR adds evacuate B1
Palisades Nuclear Plant	2014	Evacuate schools	SAE	0922		Stable weather conditions
		Agricultural advisory for PAAs 1-5; shelter animals and place on stored feed/water	SAE	0950		There was no release. Hostile action at the plant. Individuals were placed on the road to evacuate into an unknown threat environment.
Peach Bottom Atomic Power Station	2016	School activities cancelled; parks closed	SAE	1756	Y (1700)	Winds from 085 degrees
		Animals on stored feed/water; rail, feed & water 10 mi; air restriction 5 mi, 5000 ft	SAE	1800	Y (1810)	Winds from 065 degrees
		Air restriction 10 mile, 10000 ft	SAE	1850	Y (1915)	Winds from 030 degrees
						Release was simulated only for offsite
Perry Nuclear Plant	2012	Livestock advisory	SAE	1017		
		Close parks; restrict boating	SAE	1025		
		Relocate school children	SAE	1028		
Pilgrim	2016	Restrict water traffic	Alert	0935		Winds form NE (045 degrees) at 8-10 mph, 45 F.
		School transfers	Alert	0944		
		Close parks	Alert	0954		
		Shelter livestock, stored feed & water	SAE	1027		
Pilgrim	2015	Close parks; School transfer; Shelter livestock/stored feed	SAE	0956		
						Winds from 315 degrees.
					Y (0900)	Winds from 355 degrees, 8 mph; Note that dose projections at 1135 predicted PAGs exceeded only to a distance of 1.5 miles from the plant. At 1226, predicted releases were updated (assuming a filtered release) with no PAGs exceeded offsite. ORO and licensee projections matched.

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Point Beach Nuclear Plant	2017	Evacuate State parks; fishing and hunting restrictions; livestock advisory	SAE	1145		Winds from 055 degrees, 4 mph, partly cloudy, 60 F, steady winds
		air restrictions	GE	1300		
		water restrictions	GE	1216		No 0-2 mile region at Peach Bottom
		rail traffic restrictions	Alert	1028		PAGs expected to be exceeded at 5 miles, but not at 10 miles
		evacuate schools and special populations	SAE	1145		
Point Beach Nuclear Plant	2012					Winds from 055 degrees, 4 mph, partly cloudy, 60 F, steady winds
		Livestock advisory, shelter and place on stored feed within 10 mile EPZ	SAE	1029		
		Evacuation of schools and special populations within 10 mile EPZ	SAE	1029		No 0-2 mile region at Peach Bottom
		Ban hunting and fishing in state parks within 10 mile EPZ	GE	1137		PAGs expected to be exceeded at 5 miles, but not at 10 miles
Prairie Island Nuclear Generating Plant	2016	Livestock advisory within 10-mile EPZ	SAE	1040		Winds from 146 degrees, 9-12 mph, stability class E, 70 F. Thunderstorms.
		Evacuate schools and special populations	SAE	1030		
		KI for EWs and immobile populations	SAE	1035		
		Evacuate State parks and hunting areas	SAE	1038		
Quad Cities Nuclear Power Station	2016	Livestock advisory	SAE	1018		Winds from 221 degrees, 7 mph, stability class D
		Air, rail, water restrictions	GE	1031		
		Evacuate schools	SAE	1008		
Riverbend	2018	Early Precautionary Actions	Alert	0926		
						Monitored release. Highest level at 1250, leak isolation results in background release rates by 1330
Riverbend	2016	No schools in session, but schools called	SAE	1000		
Salem and Hope Creek Nuclear Generating Stations	2018	After school activities cancelled; monitor and prepare all ERPAs	SAE	1859		Initial winds toward Delaware, later (after the GE) shift toward New Jersey side.
		Livestock on stored feed and water	SAE	1859		
		River alerting and clearing	SAE	1859		
Seabrook Station	2016	Schools	Alert	0911		
		Close parks; Restrict water, rail, air traffic	SAE	0946		
		Shelter animals, place on stored feed and water	SAE	0946		

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Sequoyah Nuclear Plant	2016	Pre-position school buses; prepare schools; waterway clearance	Alert	0852		
						The licensee dose projection indicates EPA PAGs for Adult Thyroid CDE will not be exceeded at the 0.62 mile site boundary.
					Y (1215)	Wind shift; adds A-2 to shelter PAR
Sharon Harris	2017	Early release of schools; waterway clearing; prepare to evacuate special needs population	SAE	0934		Wind direction from 135 degrees, 2 mph, stability class D, steady.
						Dose projections indicated TEDE exceeded out to 0.7 miles off-site, thyroid exceeded at 2 miles off-site.
South Texas Project	2012					Wind from 152 degrees, 9 mph, 75 F.
						PAR based on wind speed 7.76 mph, 186 degrees, 4 hour release of gap inventory, 2.5E+09 microcuries/sec
						Later dose projection, 10.25 mph, 177 degrees using field data indicates Iodine higher than expected.
St. Lucie Plant	2016	Evacuate school and special populations; call-down within the 10 mile EPZ	SAE	0902		Dose projections indicate no PAR upgrade needed.
Susquehanna Steam Electric Station	2016	Livestock on stored feed/water; river and lake restrictions; FAA 3 miles 3000 ft.	SAE	2027		
		Expand air restriction 10 mile, 10,000 ft.	GE	2105		
Three Mile Island Nuclear Station	2017	Livestock on stored feed and water; 10 mile water and rail restriction	SAE	1851		Wind from 305 degrees, 8 mph, stability class C. Varies from 305 to 315.
		Close parks and recs	GE	1932		
		Air restriction 5 miles, 5000 ft	GE	1946		
Turkey Point Nuclear Generating	2017	Relocate schools, special populations in 2, 3, 4, 5, 6, 7, 8 (Q, R, A). No marine restrictions	GE	1032		Winds from 150 degrees, 10 mph, 78 F, stability class F.
						ORO dose projections were about 5 times higher than utility due to unfamiliarity with forms and RASCAL. Utility showed no PAGs exceeded beyond 2 miles. ORO had various projections from 7 to 15 miles. However, this does not appear to have affected the PAD.

Compilation of After Action Report Data						
Site	**Year**	**Precautionary Measures**	**ECL**	**Time**	**Wind Shift?**	**Notes**
Vermont Yankee	2013	Close parks, school transfer, shelter livestock	Alert	1015		
V.C. Summer Nuclear Station	2017	Ban hunting and fishing; place livestock on stored feed and water; school evacuation; waterway clearance, stay tuned	SAE	1057		Wind from 150 degrees at 10 mph, stability class D.
Vogtle Electric Generating Plant	2018	Notification to FAA, USCG, Norfolk Southern to clear airspace; close river and rail; Animals on stored feed and water; early dismissal of schools	Alert	0926		Prevailing winds towards Georgia.
Waterford Steam Electric Station	2017	Precautionary actions in St. John's Parish	SAE	1023		At 0800 winds from 180 degrees, 7-11 mph, stability class D, 60 F
Wolf Creek Generating Station	2017	Close and evacuate Coffey County Lake, John Redmond Reservoir	SAE	0852		Winds from 020 degrees, 5 mph, 73 F, stability class A.
		Relocate EW Decon/Road Equipment	SAE	0930		Approximately 3,249 in evacuation zone.

Appendix B RASCAL Source Term Data

BWR Case Summary

Event Type Nuclear Power Plant

Case description
None

Location

Name:	Peach Bottom - Unit 2
City, county, state:	Peach Bottom, Lancaster, PA
Lat / Long / Elev:	39.7589° N, 76.2692° W, 36 m
Time zone:	Eastern
Population (2010):	465 / 8,753 / 44,595 (2 / 5 / 10 mi)

Reactor Parameters

Reactor power:	3951 MWt
Average burnup:	30000 MWd / MTU
Containment type:	BWR Mark I
Containment volume:	3.04E+05 ft^3
Design pressure:	56 lb/in^2
Design leak rate:	0.50 %/d
Coolant mass:	1.73E+05 kg
Assemblies in core:	764

Source Term

Type:	Long Term Station Blackout (SOARCA)
Shutdown:	2019/12/26 00:00
Release from core starts:	2019/12/26 06:00
Core damage estimated by:	Core recovered status
Core recovered:	2019/12/26 18:00
Inventory:	Default

Release Pathway

Type:	BWR - Release Through Dry Well via direct, unfiltered pathway
Release height:	10. m

Release events

2019/12/26 06:00	Leak rate (% vol) Design
2019/12/26 06:00	Sprays Off

Meteorology

Type:	Actual Observations
Dataset name:	PEAC 2020-01-15 1153
Dataset desc:	Obs/fcsts for Peach Bottom - Unit 2

Summary of data at release point:

	Type	Dir deg	Speed mph	Stab class	Precip	Temp °F
2019/12/26 06:00	Obs	090	4.0	D	?	70

Dataset options: Est. missing stability using: Wind speed, time of day, etc.
Modify winds for topography: Yes

Calculations

Case title:	PWR LTSBO
End of calculations:	2019/12/30 06:00 Start of release to atmosphere + 96 h
Distance of calculation:	Close-in + to 10 miles
Close-in distances:	0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0 miles
Analyst name:	Todd Smith
Inhal. dose coefficients:	ICRP 60/72

BWR Source Term

Summary of activity released to atmosphere

	Ci	% of total
Noble gas	3.6E+06	91.4
Iodines	1.8E+05	4.7
Other	1.5E+05	3.9
Total	3.9E+06	100.0

Noble gas / I-131 ratio = 84:1

Approximate activity balance at end of simulation

Core	2.7E+09 Ci
Containment	1.3E+08 Ci
RCS	0.0E+00 Ci
Environment	3.9E+06 Ci

List of all radionuclides released with total activity

Nuclide	Ci	Nuclide	Ci	Nuclide	Ci
Ba-139	1.9E+01	Mo-99	1.8E+04	Te-127m	6.6E+02
Ba-140	2.4E+03	Rb-86	8.4E+01	Te-129	1.9E+03
Cs-134	5.9E+03	Rb-88	1.0E+04	Te-129m	2.8E+03
Cs-136	2.3E+03	Rh-103m	3.9E+03	Te-131	1.5E+03
Cs-137*	4.1E+03	Rh-105	2.1E+03	Te-131m	6.5E+03
Cs-138	2.6E+00	Ru-103	3.9E+03	Te-132	5.5E+04
I-131	4.3E+04	Ru-105	4.3E+02	Xe-131m	2.5E+04
I-132	5.7E+04	Ru-106*	1.1E+03	Xe-133	3.2E+06
I-133	5.8E+04	Sb-127	3.9E+03	Xe-133m	7.0E+04
I-134	1.3E+02	Sb-129	2.6E+03	Xe-135	2.6E+05
I-135	2.6E+04	Sr-89	1.3E+03	Xe-135m	5.8E+03
Kr-83m	5.7E+02	Sr-90	9.8E+01	Xe-138	1.0E-04
Kr-85	1.7E+04	Sr-91	5.3E+02	Y-90	1.0E+01
Kr-85m	1.2E+04	Sr-92	9.1E+01	Y-91	2.7E+00
Kr-87	5.4E+02	Tc-99m	1.7E+04	Y-91m	2.1E+02
Kr-88	1.2E+04	Te-127	4.5E+03	Y-92	3.4E+01
La-140	3.5E+02				

Notes:

• Nuclides with * in name include implicit daughters.

Nuclides important to dose - top 10 by pathway with cumulative contribution

	Cloudshine		Inhalation		Groundshine	
1	Xe-133	0.40	I-131	0.48	I-132	0.35
2	I-132	0.74	Cs-137*	0.64	Cs-134	0.50
3	I-131	0.80	Cs-134	0.76	Te-132	0.60
4	Cs-134	0.85	Ru-106*	0.84	I-131	0.67
5	Te-132	0.88	Te-132	0.89	Cs-136	0.74
6	Cs-136	0.90	Te-129m	0.91	La-140	0.81
7	La-140	0.93	Sr-90	0.93	Cs-137*	0.85
8	Cs-137*	0.94	Ba-140	0.94	Ru-103	0.88
9	I-133	0.95	Ru-103	0.95	Sb-127	0.91
10	Ru-103	0.96	Sr-89	0.96	Mo-99	0.93

BWR Maximum Dose Values (rem) - Close-In

Dist from release miles (kilometers)	0.1 (0.16)	0.2 (0.32)	0.3 (0.48)	0.5 (0.8)	0.7 (1.13)	1. (1.61)	1.5 (2.41)	2. (3.22)
Total ED	2.7E+02	8.7E+01	4.7E+01	2.1E+01	1.3E+01	7.1E+00	4.1E+00	3.2E+00
Thyroid CED	2.6E+03	8.1E+02	4.3E+02	2.0E+02	1.2E+02	6.5E+01	3.8E+01	2.9E+01
Child Thyroid CED	4.9E+03	1.5E+03	8.2E+02	3.7E+02	2.2E+02	1.2E+02	7.2E+01	5.6E+01
Inhalation CED	2.0E+02	6.4E+01	3.4E+01	1.6E+01	9.3E+00	5.2E+00	3.0E+00	2.3E+00
Cloudshine	2.0E+00	9.9E-01	6.6E-01	3.6E-01	2.3E-01	1.4E-01	9.5E-02	8.1E-02
4-day Groundshine	6.9E+01	2.2E+01	1.2E+01	5.3E+00	3.2E+00	1.8E+00	1.0E+00	7.9E-01
Inter Phase 1st Yr	5.3E+02	1.7E+02	8.9E+01	4.0E+01	2.4E+01	1.3E+01	7.8E+00	6.1E+00
Inter Phase 2nd Yr	2.9E+02	9.0E+01	4.8E+01	2.2E+01	1.3E+01	7.3E+00	4.3E+00	3.3E+00

BWR Maximum Dose Values (rem) - To 10 mi

Dist from release miles (kilometers)	3 (4.8)	4 (6.4)	5 (8.0)	7 (11.3)	10 (16.1)
Total ED	2.5E+00	2.1E+00	1.7E+00	1.3E+00	7.7E-01
Thyroid CED	2.2E+01	1.8E+01	1.5E+01	1.1E+01	7.0E+00
Child Thyroid CED	4.7E+01	3.9E+01	3.2E+01	2.4E+01	1.5E+01
Inhalation CED	1.8E+00	1.5E+00	1.2E+00	9.0E-01	5.6E-01
Cloudshine	6.5E-02	5.4E-02	4.4E-02	3.2E-02	2.0E-02
4-day Groundshine	6.6E-01	5.6E-01	4.5E-01	3.4E-01	2.0E-01
Inter Phase 1st Yr	5.0E+00	4.2E+00	3.4E+00	2.6E+00	1.5E+00
Inter Phase 2nd Yr	2.7E+00	2.3E+00	1.8E+00	1.4E+00	8.2E-01

Notes:
- Inhalation dose coefficients used: ICRP 60/72
- Doses exceeding 2013 EPA Interim PAGs are underlined.
- Early-Phase PAGs: TED - 1 rem
- Thyroid CED - adult thyroid dose from exposure to all radionuclides - as related to 1992 EPA PAGs (no interim PAG - not underlined)
- Child Thyroid CED - 1y old result (most limiting) from exposure to radio-iodines only - for KI administration considerations
- Intermediate-Phase EPA PAGs: 1st year - 2 rem, 2nd year - 0.5 rem
- *** indicates values less than 1 mrem
- To view all values - use Detailed Results | Numeric Table
- Total ED = Inhalation CED + Cloudshine + 4-Day Groundshine

PWR Case Summary

Event Type	Nuclear Power Plant

Case description

None

Location

Name:	Surry - Unit 1
City, county, state:	Gravel Neck, Surry, VA
Lat / Long / Elev:	37.1656° N, 76.6983° W, 8 m
Time zone:	Eastern
Population (2010):	37 / 3,885 / 130,424 (2 / 5 / 10 mi)

Reactor Parameters

Reactor power:	2587 MWt
Average burnup:	30000 MWd / MTU
Containment type:	PWR Subatmospheric
Containment volume:	1.80E+06 ft^3
Design pressure:	45 lb/in^2
Design leak rate:	0.10 %/d
Coolant mass:	1.87E+05 kg
Assemblies in core:	157
Steam generator type:	U-Tube
SG water mass:	42184 kg

Source Term

Type:	LOCA (NUREG-1465)
Shutdown:	2020/05/28 00:00
Core uncovered:	2020/05/28 13:00
Core damage estimated by:	Core recovered status
Core recovered:	2020/05/29 01:00
Inventory:	Default

Release Pathway

Type:	Bypass of Containment via direct, unfiltered pathway
Release height:	10. m

Release events

2020/05/28 13:00	Bypass flow rate 150 gal/min
2020/05/28 13:00	Filters On

Meteorology

Type:	Actual Observations
Dataset name:	SRRY 2020-05-28 1558
Dataset desc:	Obs/fcsts for Surry - Unit 1

Summary of data at release point:

	Type	Dir deg	Speed mph	Stab class	Precip	Temp °F
2020/05/28 13:00	Obs	270	4.0	C	None	72

Dataset options:	Est. missing stability using: Wind speed, time of day, etc. Modify winds for topography: Yes

Calculations

Case title:	Surry LOCA
End of calculations:	2020/06/01 13:00
	Start of release to atmosphere + 96 h
Distance of calculation:	Close-in + to 10 miles
Close-in distances:	0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0 miles
Analyst name:	Todd Smith
Inhal. dose coefficients:	ICRP 60/72

PWR Source Term

Summary of activity released to atmosphere

	Ci	% of total
Noble gas	2.3E+08	99.6
Iodines	6.5E+05	0.3
Other	3.6E+05	0.2
Total	2.3E+08	100.0

Noble gas / I-131 ratio = 1179:1

Approximate activity balance at end of simulation

Core	1.8E+09 Ci
Containment	0.0E+00 Ci
RCS	3.4E+00 Ci
Steam generator	0.0E+00 Ci
Environment	2.3E+08 Ci

List of all radionuclides released with total activity

Nuclide	Ci	Nuclide	Ci	Nuclide	Ci
Am-241	6.9E-04	Mo-99	2.1E+03	Sr-91	8.8E+03
Ba-139	8.0E+00	Nb-95	2.4E+03	Sr-92	3.5E+02
Ba-140	5.6E+04	Nb-95m	2.5E+00	Tc-99m	2.0E+03
Ce-141	2.5E+03	Nb-97	5.6E+01	Te-127	7.9E+03
Ce-143	1.5E+03	Nd-147	8.9E+02	Te-127m	1.3E+03
Ce-144*	2.0E+03	Np-239	2.5E+04	Te-129	3.4E+03
Cm-242	6.0E+01	Pm-147	5.8E-01	Te-129m	5.2E+03
Cs-134	2.8E+04	Pr-143	2.1E+03	Te-131	2.4E+03
Cs-136	1.1E+04	Pr-144	2.0E+03	Te-131m	1.1E+04
Cs-137*	2.0E+04	Pu-238	1.2E-03	Te-132	1.0E+05
Cs-138	3.8E-04	Pu-239	1.9E-03	Xe-131m	9.1E+05
I-131	1.9E+05	Pu-241	1.9E+02	Xe-133	1.3E+08
I-132	1.9E+05	Rb-86	4.0E+02	Xe-133m	3.7E+06
I-133	2.2E+05	Rb-88	4.1E+02	Xe-135	5.6E+07
I-134	1.1E+00	Rh-103m	2.2E+03	Xe-135m	3.5E+07
I-135	5.4E+04	Rh-105	1.1E+03	Xe-138	1.4E-10
Kr-83m	3.7E+04	Ru-103	2.2E+03	Y-90	2.5E+02
Kr-85	5.6E+05	Ru-105	8.7E+01	Y-91	1.7E+03
Kr-85m	1.8E+06	Ru-106*	6.2E+02	Y-91m	4.1E+03
Kr-87	1.4E+04	Sb-127	6.5E+03	Y-92	2.9E+02
Kr-88	1.4E+06	Sb-129	1.3E+03	Y-93	3.4E+02
La-140	7.0E+03	Sr-89	3.0E+04	Zr-95	2.4E+03
La-141	7.9E+01	Sr-90	2.3E+03	Zr-97*	9.9E+02
La-142	6.5E-01				

Notes:
- Nuclides with * in name include implicit daughters.

Nuclides important to dose - top 10 by pathway with cumulative contribution

	Cloudshine		Inhalation		Groundshine	
1	Xe-133	0.85	I-131	0.38	La-140	0.36
2	I-132	0.89	Cs-137*	0.52	Cs-134	0.53
3	La-140	0.92	Cs-134	0.62	I-132	0.67
4	I-131	0.94	Pu-241	0.70	Cs-136	0.74
5	Cs-134	0.96	Sr-90	0.76	I-131	0.81
6	Xe-133m	0.97	Cm-242	0.82	Cs-137*	0.86
7	Cs-136	0.98	Ba-140	0.87	Te-132	0.90
8	Cs-137*	0.98	Sr-89	0.91	Ba-140	0.93
9	Xe-135	0.98	Ce-144*	0.93	I-133	0.94
10	Te-132	0.99	Te-132	0.95	Sb-127	0.95

PWR Maximum Dose Values (rem) - Close-In

Dist from release miles (kilometers)	0.1 (0.16)	0.2 (0.32)	0.3 (0.48)	0.5 (0.8)	0.7 (1.13)	1. (1.61)	1.5 (2.41)	2. (3.22)
Total ED	1.1E+03	3.6E+02	1.9E+02	8.4E+01	4.7E+01	2.5E+01	1.1E+01	6.4E+00
Thyroid CED	8.3E+03	2.5E+03	1.3E+03	5.4E+02	3.1E+02	1.6E+02	7.9E+01	4.7E+01
Child Thyroid CED	1.6E+04	5.0E+03	2.5E+03	1.1E+03	6.1E+02	3.2E+02	1.6E+02	9.3E+01
Inhalation CED	8.1E+02	2.5E+02	1.3E+02	5.3E+01	3.0E+01	1.6E+01	7.8E+00	4.6E+00
Cloudshine	1.4E+02	6.4E+01	4.1E+01	1.9E+01	1.0E+01	5.4E+00	1.4E+00	7.6E-01
4-day Groundshine	1.8E+02	5.5E+01	2.8E+01	1.2E+01	6.7E+00	3.5E+00	1.7E+00	1.0E+00
Inter Phase 1st Yr	2.2E+03	6.7E+02	3.4E+02	1.5E+02	8.2E+01	4.4E+01	2.1E+01	1.3E+01
Inter Phase 2nd Yr	1.2E+03	3.5E+02	1.8E+02	7.6E+01	4.3E+01	2.3E+01	1.1E+01	6.6E+00

PWR Maximum Dose Values (rem) - To 10 mi

Dist from release miles (kilometers)	3 (4.8)	4 (6.4)	5 (8.0)	7 (11.3)	10 (16.1)
Total ED	4.1E+00	3.2E+00	2.5E+00	1.9E+00	1.3E+00
Thyroid CED	2.8E+01	2.2E+01	1.6E+01	1.2E+01	8.6E+00
Child Thyroid CED	5.8E+01	4.5E+01	3.3E+01	2.5E+01	1.8E+01
Inhalation CED	2.7E+00	2.1E+00	1.6E+00	1.2E+00	8.5E-01
Cloudshine	1.1E+00	7.6E-01	5.4E-01	3.7E-01	2.6E-01
4-day Groundshine	2.7E-01	3.6E-01	3.8E-01	3.2E-01	2.3E-01
Inter Phase 1st Yr	3.5E+00	4.4E+00	4.6E+00	3.8E+00	2.8E+00
Inter Phase 2nd Yr	1.8E+00	2.3E+00	2.4E+00	2.0E+00	1.4E+00

Notes:
- Inhalation dose coefficients used: ICRP 60/72
- Doses exceeding 2013 EPA Interim PAGs are underlined.
- Early-Phase PAGs: TED - 1 rem
- Thyroid CED - adult thyroid dose from exposure to all radionuclides - as related to 1992 EPA PAGs (no interim PAG - not underlined)
- Child Thyroid CED - 1y old result (most limiting) from exposure to radio-iodines only - for KI administration considerations
- Intermediate-Phase EPA PAGs: 1st year - 2 rem, 2nd year - 0.5 rem
- *** indicates values less than 1 mrem
- To view all values - use Detailed Results | Numeric Table
- Total ED = Inhalation CED + Cloudshine + 4-Day Groundshine

SMR Case Summary

Event Type	Nuclear Power Plant

Case description
None

Location

Name:	Surry - Unit 1
City, county, state:	Gravel Neck, Surry, VA
Lat / Long / Elev:	37.1656° N, 76.6983° W, 8 m
Time zone:	Eastern
Population (2010):	37 / 3,885 / 130,424 (2 / 5 / 10 mi)

Reactor Parameters

Reactor power:	250 MWt
Average burnup:	30000 MWd / MTU
Containment type:	PWR Subatmospheric
Containment volume:	1.80E+06 ft^3
Design pressure:	45 lb/in^2
Design leak rate:	0.10 %/d
Coolant mass:	1.87E+05 kg
Assemblies in core:	157
Steam generator type:	U-Tube
SG water mass:	0 kg

Source Term

Type:	LOCA (NUREG-1465)
Shutdown:	2020/05/28 00:00
Core uncovered:	2020/05/30 13:00
Core damage estimated by:	Core recovered status
Core recovered:	2020/05/31 01:00
Inventory:	Default

Release Pathway

Type:	Bypass of Containment via direct, unfiltered pathway
Release height:	10. m

Release events

2020/05/30 13:00	Bypass flow rate 50 gal/min
2020/05/30 13:00	Filters On

Meteorology

Type:	Actual Observations
Dataset name:	SRRY 2020-11-08 1014
Dataset desc:	Obs/fcsts for Surry - Unit 1

Summary of data at release point:

	Type	Dir deg	Speed mph	Stab class	Precip	Temp °F
2020/05/31 13:00	Obs	270	4.0	D	None	72

Dataset options: Est. missing stability using: Wind speed, time of day, etc.
Modify winds for topography: Yes

Calculations

Case title:	SMR LOCA
End of calculations:	2020/06/03 13:00 Start of release to atmosphere + 96 h
Distance of calculation:	Close-in + to 25 miles
Close-in distances:	0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 miles
Analyst name:	Todd Smith
Inhal. dose coefficients:	ICRP 60/72

SMR Source Term

Summary of activity released to atmosphere

	Ci	% of total
Noble gas	1.0E+07	99.5
Iodines	2.7E+04	0.3
Other	2.6E+04	0.3
Total	1.0E+07	100.0

Noble gas / I-131 ratio = 668:1

Approximate activity balance at end of simulation

Core	1.4E+08 Ci
Containment	0.0E+00 Ci
RCS	3.1E+04 Ci
Steam generator	0.0E+00 Ci
Environment	1.0E+07 Ci

List of all radionuclides released with total activity

Nuclide	Ci	Nuclide	Ci	Nuclide	Ci
Am-241	2.5E-04	Nb-95m	7.4E-01	Sr-92	7.3E-05
Ba-140	4.8E+03	Nb-97	5.6E-01	Tc-99m	1.0E+02
Ce-141	2.3E+02	Nd-147	7.4E+01	Te-127	5.6E+02
Ce-143	4.3E+01	Np-239	1.2E+03	Te-127m	1.2E+02
Ce-144*	1.9E+02	Pm-147	2.0E-01	Te-129	3.1E+02
Cm-242	5.7E+00	Pr-143	1.9E+02	Te-129m	4.8E+02
Cs-134	2.7E+03	Pr-144	1.9E+02	Te-131	6.2E+01
Cs-136	9.4E+02	Pu-238	4.3E-04	Te-131m	2.8E+02
Cs-137*	1.9E+03	Pu-239	5.2E-04	Te-132	5.8E+03
I-131	1.5E+04	Pu-241	1.8E+01	Xe-131m	7.8E+04
I-132	8.3E+03	Rb-86	3.5E+01	Xe-133	9.7E+06
I-133	3.2E+03	Rb-88	1.1E-04	Xe-133m	1.9E+05
I-135	1.9E+01	Rh-103m	2.0E+02	Xe-135	2.5E+05
Kr-83m	4.5E-05	Rh-105	3.6E+01	Xe-135m	3.2E+04
Kr-85	5.4E+04	Ru-103	2.0E+02	Y-90	4.2E+01
Kr-85m	1.0E+02	Ru-105	2.4E-03	Y-91	1.6E+02
Kr-87	5.9E-09	Ru-106*	6.0E+01	Y-91m	8.7E+00
Kr-88	1.0E+00	Sb-127	4.0E+02	Y-92	7.6E-04
La-140	1.2E+03	Sb-129	2.9E-02	Y-93	7.9E-01
La-141	8.1E-04	Sr-89	2.8E+03	Zr-95	2.2E+02
Mo-99	1.1E+02	Sr-90	2.2E+02	Zr-97*	9.7E+00
Nb-95	2.3E+02	Sr-91	1.6E+01		

Notes:

• Nuclides with * in name include implicit daughters.

Nuclides important to dose - top 10 by pathway with cumulative contribution

	Cloudshine		Inhalation		Groundshine	
1	Xe-133	0.85	I-131	0.35	La-140	0.37
2	La-140	0.89	Cs-137*	0.50	Cs-134	0.57
3	I-132	0.92	Cs-134	0.61	I-132	0.68
4	I-131	0.94	Pu-241	0.69	Cs-136	0.75
5	Cs-134	0.96	Sr-90	0.76	I-131	0.83
6	Cs-136	0.97	Cm-242	0.83	Cs-137*	0.88
7	Xe-133m	0.98	Ba-140	0.88	Ba-140	0.91
8	Cs-137*	0.98	Sr-89	0.92	Te-132	0.94
9	Ba-140	0.99	Ce-144*	0.94	Sr-89	0.95
10	Te-132	0.99	Te-132	0.95	Nb-95	0.96

SMR Maximum Dose Values (rem) - Close-In

Dist from release miles (kilometers)	0.25 (0.4)	0.5 (0.8)	1. (1.61)	1.5 (2.41)	2. (3.22)	3. (4.83)	4. (6.44)	5. (8.05)
Total ED	2.2E+01	7.6E+00	2.5E+00	1.4E+00	1.1E+00	8.9E-01	7.6E-01	6.4E-01
Thyroid CED	1.6E+02	5.4E+01	1.8E+01	1.0E+01	7.8E+00	6.2E+00	5.3E+00	4.5E+00
Child Thyroid CED	3.0E+02	1.0E+02	3.5E+01	1.9E+01	1.5E+01	1.2E+01	1.0E+01	8.6E+00
Inhalation CED	1.8E+01	6.3E+00	2.1E+00	1.2E+00	9.0E-01	7.2E-01	6.2E-01	5.2E-01
Cloudshine	7.6E-01	3.4E-01	1.2E-01	7.9E-02	2.6E-02	5.4E-02	4.6E-02	3.8E-02
4-day Groundshine	2.8E+00	9.6E-01	3.2E-01	1.8E-01	1.4E-01	1.1E-01	9.3E-02	7.9E-02
Inter Phase 1st Yr	5.4E+01	1.9E+01	6.2E+00	3.5E+00	2.7E+00	2.1E+00	1.8E+00	1.6E+00
Inter Phase 2nd Yr	2.9E+01	1.0E+01	3.3E+00	1.9E+00	1.4E+00	1.2E+00	9.8E-01	8.4E-01

SMR Maximum Dose Values (rem) - To 25 mi

Dist from release miles (kilometers)	7 (11.3)	10 (16.1)	15 (24.1)	20 (32.2)	25 (40.2)
Total ED	6.4E-01	3.8E-01	1.9E-01	9.8E-02	7.7E-02
Thyroid CED	4.5E+00	2.6E+00	1.3E+00	7.3E-01	5.8E-01
Child Thyroid CED	8.9E+00	5.2E+00	2.6E+00	1.5E+00	1.2E+00
Inhalation CED	5.2E-01	3.0E-01	1.5E-01	8.5E-02	6.7E-02
Cloudshine	4.1E-02	2.5E-02	1.3E-02	7.4E-03	5.8E-03
4-day Groundshine	8.4E-02	5.1E-02	2.1E-02	5.5E-03	3.3E-03
Inter Phase 1st Yr	1.6E+00	1.0E+00	4.3E-01	1.2E-01	7.4E-02
Inter Phase 2nd Yr	8.8E-01	5.4E-01	2.3E-01	6.4E-02	4.0E-02

Notes:
- Inhalation dose coefficients used: ICRP 60/72
- Doses exceeding 2013 EPA Interim PAGs are underlined.
- Early-Phase PAGs: TED - 1 rem
- Thyroid CED - adult thyroid dose from exposure to all radionuclides - as related to 1992 EPA PAGs (no interim PAG - not underlined)
- Child Thyroid CED - 1y old result (most limiting) from exposure to radio-iodines only - for KI administration considerations
- Intermediate-Phase EPA PAGs: 1st year - 2 rem, 2nd year - 0.5 rem
- *** indicates values less than 1 mrem
- To view all values - use Detailed Results | Numeric Table
- Total ED = Inhalation CED + Cloudshine + 4-Day Groundshine

Appendix C Additional Literature

1. Statistics on Fears

https://blogs.chapman.edu/wilkinson/2018/10/16/americas-top-fears-2018/

https://blogs.chapman.edu/wilkinson/2017/10/11/americas-top-fears-2017/

https://blogs.chapman.edu/wilkinson/2016/10/11/americas-top-fears-2016/

https://blogs.chapman.edu/wilkinson/2015/10/13/americas-top-fears-2015/

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