An Interdisciplinary Decision Framework for Risk-Based Nuclear Power Plant Emergency Planning and Protective-Action Strategy Selection

Submitted in partial fulfillment of the requirements for

the degree of

Doctor of Philosophy

in the

Department of Engineering and Public Policy

Adam M. Stein

B.S., Mechanical Engineering, University of Pittsburgh
C.E., Nuclear Engineering, University of Pittsburgh
M.B.A., Business Operations, Indiana University of Pennsylvania
M.S., Engineering and Public Policy, Carnegie Mellon University

Carnegie Mellon University
Pittsburgh, PA

May, 2021

Acknowledgments

Funding support for this work was generously provided by the Emerson and Elizabeth Pugh Fellowship for New and Innovative Research and the Department of Engineering and Public Policy at Carnegie Mellon University. Completing this dissertation would not have been possible without that support.

I would like to express my deepest appreciation to my committee members for their mentorship, guidance, support, and encouragement over the course of this journey. I greatly appreciate the guidance and opportunities that my committee chair and advisor Dr. Paul Fischbeck has provided. Paul's continual questioning of the assumptions used in the existing literature shaped the direction of a large portion of this work. Dr. H. Scott Matthews has given me guidance and assistance even prior to joining EPP. Without his help, this journey would never have begun. Dr. Jared Cohon introduced me to multi-criteria decision methods and worked with me extensively to define new metrics for time-sensitive decision-making. His warm tone for feedback is always appreciated. Dr. Elizabeth Casman's course, and many associated long discussions, helped me to expand my view of risk to include health related factors. Dr. Sola Talabi has become a valued colleague on this and many other projects.

In addition to my committee, I would like to thank Dr. Deanna Matthews, Dr. Nicholas Muller, Dr. Paul Fischbeck, Dr. Jay Whitacre, and Dr. Jay Apt who have invited me to guest lecture or assist with their courses. Ken Redus for his willingness to discuss experiment design, which evolved into one of the chapters of this work. Dr. John Lipinski for his support at IUP and recommendation to CMU. Dr. Alex Davis, Dr.

Granger Morgan, Dr. Baruch Fischhoff, and Dr. Doug Sicker who have provided feedback and suggestions. Dr. Inês Azevedo, for asking very insightful questions coupled with a heavy dose of confidence following my qualifier presentation. The EPP staff who keep everything running for all of us, Vicki Finney, Debbie Kuntz, Adam Loucks, Kim Martin, and Peter Luetkehans. And, of course, to all of the friends and colleagues I have made in Engineering & Public Policy, the Graduate Student Assembly, and at Carnegie Mellon.

Finally, and most importantly, to my family, who have been my constant support, escape, distraction, and source of never-ending change. My amazing wife, Cassandra, who first suggested this journey and supported me the entire time. To my three wonderful children who were all born during my time at CMU. You have listened to me talk about this dissertation since before you were born.

Abstract

Emergency planning is a required component of licensing for nuclear power plants. A rare opportunity to redefine emergency preparedness has been created by the ongoing work at the Nuclear Regulatory Commission to develop the capability to address small modular reactors and other new technologies and to transition to a risk-informed performance-based regulatory structure.

This dissertation develops a new framework for emergency preparedness that can address the characteristics of new reactor technologies while also addressing the limitations of current methods. A review of the literature, current regulations, and methods identifies gaps and limitations. Statistically valid methods are defined to enable new analysis of uncertainty and use cases in limited regulatory validated computer codes. A new interdisciplinary framework for emergency planning is developed to reduce the barriers present in current methods, then a risk-based model that integrates protective action and hazard dispersion models is defined. This integrated model considers the risk caused by multiple hazards, including radiological and transportation hazards. The interdisciplinary and integrated structure of the model provides the opportunity for new measures of effectiveness that provide additional insights beyond existing metrics.

The integrated model is used to evaluate emergency response at the Peach Bottom Atomic Power Station as a case study. The key findings of this case study provide insight into effects previously not discussed in nuclear power emergency planning studies. The ability to compare protective actions across multiple metrics allows for risk and consequences-based evaluation and provides more information for decision-makers.

When combined dose and non-dose risks are considered, many historically common protective action strategies become inadvisable by creating more combined risk than taking no action. Even small amounts of time between initiating a protective action and the release of radiation can potentially result in a substantial reduction of consequences. The behavior of the population has a large impact on consequences but is not sufficiently captured in prior studies.

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Chapter 1: Introduction

Emergency preparedness is one of the seven cornerstones of safety in reactor oversight [1]. Emergency preparedness and planning for nuclear power facilities is required and defined at the U.S. Federal level by laws, regulations, guidance, and over forty years of precedence. Over the last decade, there have been broad proposed or enacted changes to these requirements, predominantly to meet the different needs and characteristics of advanced nuclear reactors. Existing licensing pathways, under 10 CFR Part 50 or Part 52, are being updated through rulemaking. The Nuclear Energy Innovation and Modernization Act (NEIMA) directs the NRC to create a technology-inclusive regulatory framework for advanced reactors [2]. A technology-inclusive licensing pathway (i.e., 10 CFR Part 53) is one outcome of NEIMA.

To accomplish the necessary modernization, the Nuclear Regulatory Commission has shifted from a prescriptive, deterministic regulatory approach to a technology-neutral, risk-informed, and performance-based approach. This allows for adaptation but requires revision of over forty years of guidance and regulation. The following chapters provide some of the context, insight, and solutions necessary to shift from prescriptive guidance designed for large light water reactors to risk-informed performance-based models.

Chapter 2 provides a detailed review of emergency planning requirements. A focus is placed on evacuation time estimate studies due to the regulatory requirement for this type of study. Evacuation time estimates are intended to provide a modicum of information for emergency planning and decision-making. The focus in regulation and guidance on evacuation time is a relic from when risk-based studies were not tractable. Existing evacuation time guidance and the models used for evacuation time studies have been refined to meet the outdated requirements. These models have become very complex and accurate but cannot be used in conjunction with risk models. This chapter identifies areas for evacuation time estimate studies to be enhanced and provides an initial concept for an integrated risk-based evacuation model.

To consider uncertainty with some functionally limited and legacy computer models, new approaches for computer experiment design are needed. These approaches need to be compatible with legacy and limited computer codes that are validated and cannot be directly altered. The code must be used “as-is” but for a new use case. This situation described the majority of the Nuclear Regulatory Commission computer code for evaluating emergency planning and response. Chapter 3 discussed methods to use these existing computer codes that are the only available and validated tools but are often outdated and limited in function.

The limitations in emergency planning modeling identified in Chapter 2 made evident the discipline-specific approaches and barriers. An interdisciplinary approach is needed to model the interaction of engineering, behavior, and policy factors. Chapter 4 defines an interdisciplinary framework for emergency planning and decision-making and provides performance-based metrics. This framework can be used by emergency planners, researchers, and decision-makers as a basis to build new models and understand the interdisciplinary system that defines emergency response.

Chapter 5 builds on the framework developed in Chapter 4 and defines a risk and consequence model that can be used to evaluate emergency planning. This model integrates a hazard dispersion model (i.e., where the radiation hazard is) with a protective action model (i.e., where the population is). This integration is critical to understand the risk and consequences during an emergency. However, this capability does not exist in other models.

Chapter 6 applies the integrated model to the well-studied Peach Bottom Atomic Power Station as a case study. This study provides risk-based insight that is not possible with evacuation time estimate studies. Multiple protective action strategies are evaluated across ranges of uncertain conditions, using a total of 276,950 model simulations. Factors that are impactful to emergency response or decision-making are identified and quantified.

Chapter 2: Refinement of Evacuation Time Estimate (ETE) Calculation and Modeling Methodologies[1]

Abstract

This chapter presents a method and modeling approach intended to potentially provide additional insights for scenarios involving a nuclear accident emergency planning and evacuation. An evaluation of the current practices, regulations, and literature associated with the post-accident Evacuation Time Estimate (ETE) is provided. Enhancements to potentially improve the estimates associated with the methods and models used to estimate post-nuclear accident evacuation times are provided.

A model to integrate an ETE model with a radiological hazard dispersion model for risk and consequence analysis is developed as part of this study. The proposed integrated consequence model allows for analyses that were previously not possible with current tools. This integrated model allows for health and transportation risk to be estimated along with the ETE for a given scenario. Specifically, the proposed method described in this report is intended to enhance the identification of risks to the

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[1] Portions of this chapter published in
S. Talabi, Adam Stein, Paul Fischbeck, Advanced Nuclear Technology: Refinement of Evacuation Time Estimate (ETE) Calculation and Modeling Methodologies, Electric Power Research Institute, Palo Alto, CA, 2019., and

Adam Stein, Paul Fischbeck, Sola Talabi, and Cristian Marciulescu, "Nuclear Power Plant Evacuation: Gaps, Strategies, and Activity Scheduling," in *Transactions of the American Nuclear Society*, Virtual Conference, June 8–11, vol. 122, pp. 515–518, doi: 10.13182/T122-32638.

evacuating public and enhance the mitigation of the risks. The goal is for the proposed method to provide means for an objective evaluation and selection of protective action strategies.

Acronyms and Abbreviations

ANS	Alert and Notification Systems
CEP	Critical Evacuation Phases
CFR	Code of Federal Regulations
DOT	Department of Transportation
DUA	Duration Uncertainty Analysis
EAL	Emergency Action Level
EAS	Emergency Alert System
EP	Emergency Plan
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
ER	Emergency Response
ERPA	Emergency Response Planning Areas
ETE	Evacuation Time Estimate
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GE	General Emergency
GERR	General Evacuation Risk Register
IAEA	International Atomic Energy Agency
IPAWS	Integrated Public Alert and Warning System
MACCS2	MELCOR Accident Consequence Code System, Version 2
MOE	Measure of Effectiveness
NOAA	National Oceanic and Atmospheric Administration
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NWS	National Weather Service
ORO	Offsite Response Organization
PAD	Protective Action Decision
PAG	Protective Action Guide
PAI	Protective Action Initiation
PAR	Protective Action Recommendation
PDM	Precedence Diagram Method
PRA	Probabilistic Risk Assessment
RASCAL	Radiological Assessment System for Consequence Analysis
SAE	Site Area Emergency

SERR	Site-Specific Evacuation Risk Register
SIP	Shelter in Place
SMR	Small Modular Reactor
SOARCA	State-of-the-Art Reactor Consequence Analyses
WEA	Wireless Emergency Alert

1 Introduction

This chapter presents a method and modeling approach to provide additional insights for scenarios involving nuclear accident emergency planning and protective actions. Current practices associated with post-accident Evacuation Time Estimate (ETE) calculations as documented in the NRC's emergency planning standards of Title 10 of the Code of Federal Regulations 10CFR 50.47(b) [3] and the State-of-the-Art Reactor Consequence Analyses (SOARCA) project [4]–[7] are reviewed, and enhancements are proposed. The role of advanced communication in enabling protective actions and how it can impact ETE is discussed throughout the chapter.

Specifically, this paper covers the following issues:

1. Review the methodology, tools, and utilization of current ETE practices in consequence analyses and protective action decision-making
2. Identify areas where current ETE practices can be enhanced to achieve greater accuracy and fidelity
3. Propose technical solutions for the identified enhancements and qualitatively consider potential changes associated with the implementation of the proposed technical approaches.
4. Propose a consequence model for evaluating a risk metric of protective action effectiveness.

It is important to note that while this chapter provides a method and modeling approach for improving emergency planning, it does not provide the technical basis for risk-model parameter selection, perform the proposed analysis needed to justify changes to the emergency planning zone (EPZ) surrounding the nuclear power plant, or provide a definitive evaluation of evacuation strategies.

The chapter is organized as follows:

- Literature review of current regulations, requirements, and guidance
- Assessment of current ETE practices
- Opportunities for enhancement of ETE studies
- Development of an ETE method that incorporates uncertainty using a duration uncertainty analysis method
- Propose an integrated consequence model
- Conclusions

2 Literature Review Summary

Emergency preparedness is one of the seven cornerstones[2] of safety in nuclear reactor oversight [1]. Emergency preparedness and planning for nuclear power facilities are required and defined at the U.S. Federal level by laws, regulations, guidance, and over forty years of precedence. Over the last decade, there have been broad changes to these requirements, predominantly due to advanced nuclear reactors that have different characteristics from typical large light water reactors (LLWRs). Existing licensing pathways, under 10 CFR Part 50 or Part 52, are being updated through rulemaking [8], [9]. The Nuclear Energy Innovation and Modernization Act (NEIMA) directs the Nuclear Regulatory Commission (NRC) to create a technology-inclusive regulatory

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[2] The seven cornerstones of the reactor oversight process are: initiating events, mitigating systems, barrier integrity, emergency preparedness, occupational radiation safety, public radiation safety, and security

framework for advanced reactors [2]. A technology inclusive licensing pathway (i.e., rulemaking for 10 CFR Part 53) is one outcome of NEIMA [2], [10, p. 53], [11]. Included in these new frameworks are changes to emergency-preparedness requirements.

Emergency preparedness for nuclear power plants is required to comply with complex and often prescriptive regulations. The section provides a review of the current NRC regulations associated with emergency planning, communication, evacuation time estimates, and international standards.

2.1 Regulatory Standards Associated with Emergency Planning and Preparedness

Nuclear power plant (NPP) licensees in the U.S. are required to assess the post-accident ETE, given the possibility of an NPP accident. This requirement is provided in 10 CFR 50.47, "*Emergency Plans,*" and Appendix E, "*Emergency Planning and Preparedness for Production and Utilization Facilities*," [12]. The NRC revised its regulations in Part 50 of Title 10 of the Code of Federal Regulations (CFR) to incorporate additional EP requirements, including 16 planning standards for onsite and offsite emergency plans as required by Public Law 96-295. The Federal Emergency Management Administration (FEMA) maintains the same 16 planning standards in its regulations in Part 350 of Title 44 of the CFR.

The NRC and FEMA provide acceptance criteria for emergency planning in a jointly maintained document NUREG-0654/FEMA-REP-1 [13]. Revision 2 of this guidance was completed in 2019 and integrated 35 years of lessons learned within the

Radiological Emergency Preparedness (REP) Program and consolidates and clarifies previous NRC guidance [13], USNRC, 2019]. Guidance for offsite response organizations (ORO)s is provided by FEMA in the REP Program Manual FEMA P-1028 [14]. This update incorporates the REP Program guidance into the National Preparedness System[3]. While the NRC does not require backfitting of this updated guidance to existing licenses, FEMA expects all OROs to adopt and transition to the updated version, and the NRC will use this version for new license applications. This makes the emergency planning criteria uniform for OROs but split between existing or new reactor licensees.

A LLWR typically has an EPZ defined by a 10-mile radius [16]. Rulemaking related to EPZ sizing for small modular reactors (SMR)s and other new technologies (ONTs) is in process, with a final rule expected in June 2021 [8], [9]. The primary goal is to provide alternative emergency preparedness requirements for small modular reactors SMRs and ONTs, including non-light water reactors. One major component of this proposed rule is an EPZ that is scalable to meet a risk-informed performance-based requirement. The requirement is the same dose threshold currently in place for LLWRs, which make up the vast majority of existing reactors. A major divergence from prior EP is the potential for an EPZ that does not extend beyond the NPP site boundary. In this case, off-site EP would not be required for licensing by the NRC. FEMA provided comment to the proposed rule indicating opposition to any approach that excluded off-

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[3] National Preparedness System contemporary EP guidance includes, but is not limited to, the National Preparedness Goal and System Description; the National Planning Frameworks; Comprehensive Preparedness Guide (CPG) 101, “Developing and Maintaining Emergency Operations Plans”; CPG 201, “Threat and Hazard Identification and Risk Assessment (THIRA) and Stakeholder Preparedness Review (SPR) Guide”; the core capabilities; the National Incident Management System (NIMS) and Incident Command System (ICS); the Homeland Security Exercise and Evaluation Program (HSEEP); and the Integrated Planning System. [15]

site EP. In anticipation of the final rule, Oklo[4] submitted a license application for a non-LWR advanced micro-reactor (approximately 4 MW thermal) that defines the reactor building as the EP boundary, which is significantly smaller than the site boundary [17]. The EPZ for SMRs and ONTs is scheduled for final rulemaking by the end of 2021.

2.2 Regulatory Requirements for Performing Evacuation Time Estimate

ETE is an estimate of the time it would take to evacuate the population contained inside the EPZ surrounding an NPP. Nuclear power plant (NPP) licensees in the U.S. are required to assess the post-accident ETE, given the possibility of an NPP accident. This requirement is provided in Appendix E, "*Emergency Planning and Preparedness for Production and Utilization Facilities*," to 10 CFR 50.47, "*Emergency Plans*" [18].

The ETE is site-specific and considers factors that could pose impediments to emergency planning. ETE studies are used for preplanning, the establishment of protective actions, and decision-making in the event of an emergency. Guidance on required contents and ETE methodology has evolved over time [16], [19], [20]. Current guidance and recommendations for the performance of the ETE are found in NUREG/CR-7002, "Criteria for Development of Evacuation Time Estimate Studies" [16].

The NRC emphasizes that the value of the ETE is in the insights gained by the use of the ETE as an objective function and that no specific evacuation time is required. NUREG 0654/FEMA-REP-1 Rev. 2 states, "*It is important to note that the value of the ETE analysis is in the methodology required to perform the analysis rather than in the*

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[4] Oklo Inc, is a nuclear reactor developer based in Sunnyvale, California that focuses on advanced micro reactor designs with metallic fuel

calculated ETE times." [15] This NRC objective is in alignment with this chapter's objective: to evolve methods to reflect the best available information and insights for use in performing and utilizing ETE studies.

It is important to note that while a specific ETE is not a performance-based target for licensing purposes, the ETE value is used in other NRC requirements and guidance for the selection of protective action. ETE values are used to make protective action decisions (e.g., shelter in place, evacuate) in [21]–[23]. The requirement to perform a detailed ETE analysis, but not a consequence analysis that would directly inform a protective action decision (i.e., which protective action has the lowest risk?), makes ETE the readily available metric to a decision-maker[5] in the event of an emergency. This near-exclusive reliance on ETEs for emergency decision making makes the narrowly defined transportation engineering approach for ETE determination, which treats the insights from the ETE study as paramount, is not necessarily in line with risk-based emergency response decision-making. This is addressed further in Chapter 3.

2.3 Regulatory Requirements for Emergency Communication

Emergency communication is a critical factor for emergency response and initiates an evacuation. Section IV.D of Appendix E to 10 CFR Part 50 and 10 CFR 50.47(b)(5) requires NPP licensees in the U.S. to provide means of early notification within the plume exposure pathway in the EPZ [12]. NRC staff proposed the introduction of advanced Alert and Notification Systems (ANS) to provide an additional defense-in-depth layer of protection. While NRC acknowledges that the existing ANS (typically

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[5] NPP emergency managers are required to recommend a protective action to the off-site emergency organizations. A specific decision-maker is not defined by regulation and varies by site, but is usually an emergency manager at the state emergency operations centers.

sirens) along with other defense-in-depth strategies are adequate, it also recognizes some limitations with the current system. These include the potential for loss of off-site power, which may affect the ANS. Other considerations include system reliability because of multiple failures that have been recorded at some sites [24]. Advanced communication systems that rely less on physical infrastructure and electricity may be affected less by natural disasters and, therefore, may be advantageous. Some of these include communication technologies such as cell phones and wireless internet-connected devices. Other possibilities are the use of unmanned aircraft (drones) fitted with sirens. While various nuclear industry stakeholders have investigated the use of these technologies, little evidence was found in the literature review that the benefits and costs of such systems have been quantified and analyzed.

The NRC acknowledges that a major challenge to adopting a scalable EPZ for SMRs is accounting for uncertainties in the state of knowledge of SMR designs [25]. In response, the Nuclear Energy Institute (NEI) developed a methodology to support the establishment of a scalable SMR-specific EPZ that includes *"…enhanced plant capabilities to account for uncertainties, including an operationally-focused mitigation capability and other features emphasizing traditional engineering insights"* as a mitigation strategy. The deployment of advanced ANS supports NEI's defined mitigation strategy by adding enhanced capabilities and layers to defense-in-depth to account for the uncertainty associated with communication in the event of an emergency.

Deployment of advanced ANS to enhance communication in an emergency is of particular importance to SMR sites due to the potential for SMR deployment in more densely populated locations than current large reactors. This is generally in line with the requirements for NPP communication system resiliency. Specifically, the Energy Policy Act of 2005 mandated that any licensed nuclear power plants located where there is a permanent population over 15,000,000 within a 50-mile radius of the power plant must have backup power available for the emergency notification system of the power plant, including the emergency siren warning system [26].

2.4 International Standards

The International Atomic Energy Agency (IAEA) provides guidelines for emergency planning, which include general and operational intervention levels based on the impact assessment of prior nuclear accidents. The IAEA recommends the use of these guidelines by its member states [27] and [28]. Following the Fukushima Daiichi NPP accident in 2011, the IAEA revised its guidance for EPZs and re-established operational concepts, which included establishing specific targeted times for emergency responses after the occurrence of an accident [29]. These standards are generally the same as the NRC, with the exception of the size and structure of an EPZ. Relevant IAEA standards include the following documents:

- Preparedness and Response for a Nuclear or Radiological Emergency. IAEA safety standards series No. GSR- Part 7. 2015.
- Arrangements for Preparedness for a Nuclear or Radiological Emergency. IAEA safety standards series No. GS-G-2.1. 2007;89-99.
- Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor. EPR-NPP Public Protective Actions. 2013;102-114.

- Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency. EPR-METHOD. 2003;2-14.

3 Assessment of Current ETE Practices

The assessment of standard ETE practices includes items that could be implemented and modeled in ETEs and have the potential to improve the understanding, assessment, and mitigation of risks to various evacuating cohorts. The assessment is performed based on a review of the documents identified in the literature review (Section 0) and regulatory references (Section 9).

3.1 Evacuation Time Estimate Studies

Emergency planning is required to include ETE studies, which are used for preplanning, the establishment of protective actions, and decision-making for an event that requires evacuation. The ETE studies employ detailed traffic modeling codes to develop ETE times and insights for a variety of conditions. The NRC has commissioned several studies to update ETE study guidance and format recommendations. The current guidance from the NRC for developing an ETE is defined in NUREG/CR-7002 "Criteria for Development of Evacuation Time Estimate Studies" [16]. The NRC published a study as a basis for future updates to ETE guidance in 2020 [20].

Existing NPP licensees in the U.S. are required to prepare an ETE study during the licensing process. The study must be updated within 365 days of the most recent decennial census or when a change occurs that results in an ETE time increase of 25% or 30 minutes [16]. Licensees may choose to employ alternative methods for performing

ETE analysis than what is detailed in the guidance, provided that they justify how the site-specific ETE study methods and report meets regulatory requirements and acceptance criteria [16].

3.2 Parameters for ETE Analysis

Important parameters for ETEs have been identified from the literature review and are collected in Table 1. Some parameters relevant to emergency planning and protective actions are out of scope for ETE studies. Parameters related to subsequent dose consequence analysis have been omitted from this section as they are not part of existing ETE guidance. Consequences were assessed in SOARCA and are assessed in the integrated methodology proposed in Section 6 of this chapter. Current ETE guidance and SOARCA studies consider ETE to occur after the alert and warning have been received by the population and evacuation begins. Parameters related to communication time and protective action initiation (PAI) time are therefore not included in this section. Discussion of these parameters can be found in Section 6.

Table 1: Typical parameters that are considered in ETE analysis

Parameter	Description
Population	Accurate information for the population present in the EPZ. Population is often divided into multiple cohorts based on time of day, location, age, common activities, etc.
Shadow evacuation	A portion of the population that evacuates before being told to do so. Some literature describes this as 'spontaneous evacuation'
Background traffic	Traffic that normally exists on EPZ roadways for a given day and time. Some literature describes this as 'pass-through traffic', which further implies the traffic destination is not in the EPZ, but simply reduces available capacity.
Public compliance	The portion of the population that comply with a protective action order. A portion of the public is expected not to comply with an order to evacuate.
Emergency Response Planning Areas	Areas around an NPP that may be evacuated as a cohort during an emergency. Zones may be based on distance from the NPP, geographic barriers, governmental barriers, or other factors.
Evacuation strategy	The strategy that is used to determine when and how to move specific cohorts or geographic areas of a population.
Road capacity	The vehicle travel rate that the existing roadway network can provide during an evacuation. The road capacity can be adjusted in some cases through interventions (e.g., making roadways one direction).
Demand estimation	The total number of people and vehicles to be evacuated for each cohort.
Loading curve	The rate at which vehicles enter the roadway network
Vehicle estimation	The number of vehicles available to the population. Vehicle use and access are determined for cohorts.
Bus estimation	Buses have been identified as the most likely form of transportation for some cohorts, particularly schools. The availability of buses and drivers, number of trips required for each bus, time to make each trip are considered.
Trip generation time	Includes determining the sequence, duration, and time distribution of activities performed prior to evacuation. Telephone surveys of EPZ residents are commonly used to obtain some of this information. Trip generation times are used to determine loading curves.
Speed	Travel rate of vehicles on roadways. Often modeled as a function of other parameters, such as capacity, demand, and weather conditions.
Season	The time of the year (e.g., Summer, Winter) influences population characteristics such as the school cohort.
Day	The day of the week (e.g., midweek, weekend) influences population characteristics (e.g., workers, school attendance) and background traffic.
Time of day	Generally limited to day, night, and special events. Used in trip generation time calculations.
Weather	Weather conditions (e.g., normal, adverse) are considered for their impact on other parameters such as evacuation speed.
Emergency assets	Assets that are necessary or beneficial to the evacuation process. These may include ambulances, barricades for directing traffic flow, equipment needed for or special needs population, or other similar resources. Limited availability of assets may affect ETE.
Traffic hazards	Potential impediments to traffic flow. These may include flow-constrained intersections, low-lying areas that may flood, bridges, or other similar hazards.

Reception and Congregate Care Centers	Locations that may be used to collect and care for evacuees. ETE may be affected by directing traffic to specific locations, and the time it takes to care for evacuees. Two-way traffic may also be necessary near these facilities to allow buses or ambulances to re-enter the EPZ for additional trips.

Guidance in NUREG/CR-7002 stresses the use of existing ORO emergency plans and methodology when developing an ETE. Incorporating existing emergency plans ensures the results are representative of the expected response by authorities. The effect of authority actions on evacuation times can be significant through traffic control, evacuation route choice, and other factors.

Emergency Resource Planning Areas (ERPA) are local districts, usually based on political boundaries, which operate as sub-regions for local emergency plans and protective actions. A fictitious example of EPRAs is depicted in Figure 1. It is important to note that ERPAs do not coincide with the 16 radial sectors, and some extend beyond 10 miles.

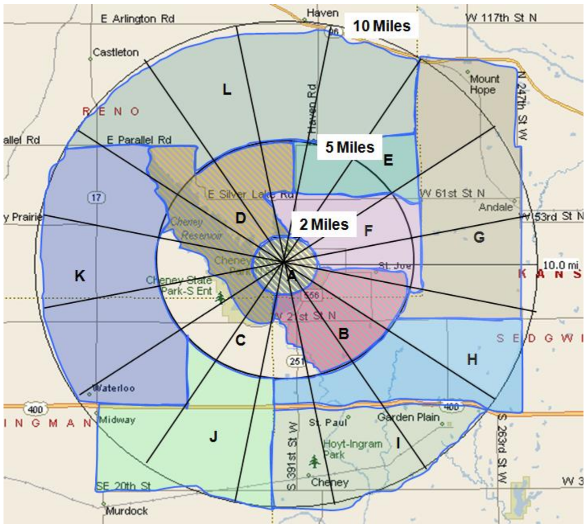

Figure 1: Simulated Emergency Resource Planning Areas (ERPA) around a fictitious nuclear power plant. Reproduced from [20]

General assumptions provided by the NRC for a site-specific ETE analysis are listed in Table 2. Adjustments to the general assumptions, or inclusion of additional site-specific assumptions, may be made for a site-specific ETE study if justified.

Table 2: NRC General Assumptions for use in an ETE study. Reproduced from [16]

General Assumptions for ETE studies
1. The ETE is measured from the time that instructions were first made available to the public within the EPZ (e.g., initial emergency alert system (EAS) broadcast).
2. Mobilization of the public begins after initial notification.
3. Schools and special facilities receive an initial notification at the same time as the rest of the EPZ.
4. Evacuation time ends when the last vehicle has exited the EPZ.
5. Most vehicles at each residence will be used in the evacuation.
6. Background traffic is on the roadway when the initial notification occurs.
7. A 50 percent capacity is appropriate for buses used in the evacuation of the population dependent upon public transportation.
8. Buses used to evacuate schools and special facilities are loaded to capacity.
9. Shadow evacuation of 20 percent of the public occurs to a distance of 15 miles from the NPP.

Population cohorts are divided into the following five categories: permanent resident, transient, transportation-dependent, special facility, and school. The guidance specifies that the permanent resident and transient population should be determined based on the most recent census and field studies. Transient (visiting) populations include workers, vacationers, shoppers, or other similar members of the public that do not reside permanently in the EPZ. Transportation-dependent populations consist of individuals that cannot evacuate their homes without assistance, including elderly people, children that may be home alone, multi-person households with one vehicle, or similar. Special facility populations include those in nursing homes, jails, hospitals, or similar facilities. The guidance specifies that school populations should be determined along with transportation resources available. ETEs should be developed for each cohort separately.

In general, part of the population takes an excessively long time to evacuate, often due to transportation limitations or non-compliance with orders to evacuate [30]. Due to this fact, the NRC specifies that ETE reports should estimate evacuation of 90% of the permanent resident and transient cohort population and separately an ETE that includes the remaining 10% “tail” [22]. The transportation-dependent, special facility, and school cohorts are modeled based on a 100% evacuation.

Shadow evacuation is the portion of the public that is outside of the defined evacuation zone that evacuates spontaneously, adds vehicles to the roadways. The NRC specifies a shadow evacuation consists of 20% of the population from areas outside an officially declared evacuation zone [16]. The SOARCA studies only model shadow evacuation in the area between 10 to 15 miles from the NPP [4]. The purpose of considering a shadow evacuation in the study is to conservatively account for traffic loading that may increase ETE [22]. Background traffic is expected to be on the road network before the ETE time starts. Hence, background traffic is modeled at levels consistent with normal traffic levels and road capacity.

In some cases, multiple trips will need to be completed to evacuate portions of the public, especially for the transportation dependent, school, and special facility populations. Committed resources should be determined and quantified to gauge the effect on ETE. Some examples of committed resources include police to control traffic, the number of buses to evacuate schools, and ambulances.

3.3 ETE Scenarios

Specific scenarios are required by the NRC to be included in an ETE analysis for traffic modeling, as shown in Table 3. These scenarios represent a range of populations and weather conditions that can impact the flow of traffic and ETEs [16]. In Table 3, season, day, and time all correspond to fluctuations in population for each cohort. Residents would be less likely to be home during the day, but transient or school populations are more likely to be larger due to employees entering the area and schools being in session. In ETE analyses, adverse weather is considered as a capacity reduction factor for evacuation scenarios. The deterministic, defined weather scenarios do not attempt to capture weather probability or variability. Instead, the guidance is to generate ETEs for each possible wind direction with each weather type (normal, adverse), time of day, and season to build a table of potential ETE outcomes.

Table 3: Evacuation Scenarios reproduced from NUREG/CR-7002 [16]

Scenario	Season	Day	Time	Weather
1	Summer	Midweek	Daytime	Normal
2	Summer	Midweek	Daytime	Adverse
3	Summer	Weekend	Daytime	Normal
4	Summer	Midweek and Weekend	Evening	Normal
5	Winter	Midweek	Daytime	Normal
6	Winter	Midweek	Daytime	Adverse
7	Winter	Weekend	Daytime	Normal
8	Winter	Midweek and Weekend	Evening	Normal
9	Special Events			Normal
10	Roadway Impact	Midweek	Daytime	Normal

While there are multiple variables and sub-models in ETE assessments, only the traffic models have advanced substantially enough to be reflected in recent updates to ETE guidance. Microscopic, mesoscopic, and macroscopic traffic models may be appropriate for use. Guidance in NUREG/CR-7002 [16] specifies the performance criteria of traffic simulations using software that has been approved for transportation or evacuation modeling and references reports that outline several such software tools, created by the U.S. Department of Transportation (DOT) [31] and Federal Highway Administration (FHWA) [32]. Since the original publication of NUREG/CR-7002, more recent guidance on traffic modeling from the DOT and FHWA on traffic modeling has become available [33], [34].

Detailed traffic models do not consider the sensitivity of multiple parameters, including the number of vehicles, road network capacity, and loading curves. Some NPPs have chosen to perform more detailed ETE studies at the microscopic model level with a wide range of scenarios and extreme events, while others use broader macroscopic or mesoscopic models.

3.3.1 Modeling of Protective Action Strategies

Several evacuation strategies are available for consideration. Radial evacuation, or straight out from the NPP, is considered the easiest to implement and an important option. If successfully executed, staged evacuations, where concentric rings around the site are evacuated sequentially from the center to farthest, may provide a greater reduction of consequences in the event of an emergency. Licensees may also consider staged keyhole evacuations, which focus on the area closest to the NPP and downwind area. During ETE analysis, each ERPA that partially intersects the downwind evacuation keyhole[6] must be evacuated. Evacuation schemes that move the population laterally away from the direction of the radiological plume are also possible [22]. NUREG/CR-7002 currently specifies ETEs for radial and staged evacuation and provides guidance for the assessment of other evacuation types [16].

The guidance [16] requires that 90% and 100% ETEs should be developed for each of the following:

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[6] A ‘keyhole’ evacuation consists of the 2-mile radius around an NPP and the downwind sectors forming a configuration that resembles a keyhole

- Complete EPZ.
- 0-2 mile zone
- 2-5 mile zone for a staged evacuation
- 0-5 mile zone
- Affected ERPAs necessary to support site-specific PAR logic (i.e., keyhole based on 16 wind directions)

To complete the above scenarios for 16 wind directions (Figure 1) and the ten weather and population scenarios (Table 3) for 90% and 100% evacuation requires 400 ETEs to be determined. This excludes any site-specific evacuation strategy based on PAR logic and does not include any consideration of consequence analysis.

3.3.2 Modeling of Weather Inputs

NUREG/CR-7002 [16] does not specify that historical weather data must be used in the development of an ETE, as it is not an integrated analysis that considers atmospheric dispersion. Instead, NUREG/CR-7002 takes a deterministic approach and provides data (reproduced in *Table 4*) of roadway capacity and speed reduction factors to apply to estimated scenarios for traffic travel times. A separate table of required weather/time/population combinations is also provided in the guidance.

Table 4: Weather Capacity Factors from NUREG/CR-7002 [16]

Weather Condition	Roadway Capacity	Speed
Normal	100%	100%
Adverse – Heavy Rain	90%	85%
Adverse – Heavy Snow/Ice	85%	65%
Adverse – Fog	75%	85%

3.4 Review of SOARCA Study

The SOARCA project calculated the potential effect of a severe accident on an operating nuclear reactor and the possible resulting consequences to the public. The SOARCA project has evaluated three reactor sites (Peach Bottom in Pennsylvania, Surry in Virginia, and Sequoyah in Tennessee), a separate uncertainty study, and a review report on the benefits of the SOARCA program [4]–[7], [35]–[37]. For the ETE portion, SOARCA cites and follows most of the recommendations of NUREG/CR-7002 [16]. However, there are some existing differences between the SOARCA and the NUREG/CR-7002 recommendations, predominantly due to the limitations of the software used in the SOARCA assessment.

SOARCA analyzed specific NPP accident scenarios and offsite consequences using the WinMACCS2 user interface, SECPOP, MELCOR, and MACCS2 computer codes [4], [38]. SECPOP is used to estimate the population in map cells around the NPP defined by a polar grid. MELCOR calculates accident progression using plant design information and theoretical models for accident phenomena. MACCS2 calculates the offsite dose consequences of an airborne release of radioactive material using site-specific information and radiological release data [36].

3.4.1 Time Estimation

Although MACCS2 and WinMACCS can model the evacuation of persons in multiple cohorts, the modeling is simplistic in nature when compared available to detailed traffic simulation codes. MACCS2 is unable to accept distributions of time for the loading of the road network or travel times as produced by ETE studies. This is an acknowledged limitation in the SOARCA analysis[7]. Instead, both MACCS2 and WinMACCS2 require discrete and sequential events to be used in place of evacuation time distributions, resulting in the entire cohort being modeled to act in unison (e.g., entering the road network at the same time) [38]. Similarly, evacuation activity modeling is simplistic in nature compared to Decision Uncertainty Analysis (DUA) codes or approaches. Uncertainty analyses can be performed across several model realizations using ranges of variable values, but this cannot recreate the integrated effects that would be missed through the progression of the evacuation.

3.4.2 SOARCA Speed Assumptions

SOARCA uses an averaged travel speed based on the 90% cohort evacuation time in the site-specific ETE studies [4]. This results in a discrete start time for the entire population of each cohort and a discrete and constant piecewise travel speed during the evacuation[8]. The average evacuation speed (mph) is rounded to the nearest whole number. This is done to acknowledge the imprecise nature of a speed that was averaged.

The speed is based on the assumption of congestion and scaling to the site-specific ETE, with the SOARCA model providing a speed before congestion starts applied to the duration of the beginning phase, and a speed after congestion starts applied to the duration of the middle phase for the 10-mile (16.09 km) EPZ. In all SOARCA studies, the beginning evacuation speed has an assumed value of 5 mph for the general public [4], [5], [7]. This speed is applied uniformly for the first 15 minutes of the evacuation

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[7] The SOARCA report acknowledges that using discrete assumptions is a simplification, stating *"…evacuations include mobilizing and evacuating the public over a period of time, which is best modeled as a distribution of data. WinMACCS2 requires this distribution of data be converted into discrete events."*

[8] Averaged ETE speeds were varied for some model realizations to simulate alternate conditions, based on the site-specific ETE study. Alternate conditions are described in the site ETE study and may include inclement weather, large population events, or other conditions that affect ETE due to congestion or travel speed limits.

covering 1.25 miles in the process, noting from earlier that all evacuees enter the roadway at the same instant in the SOARCA studies. The speed of the following period is calculated to provide an average speed that uses the distance (8.75 miles (14.08 km) in all studies) and remaining site-specific ETE time. Beyond the 10-mile EPZ, the SOARCA studies assume minimal congestion and assign a uniform speed of 20mph.

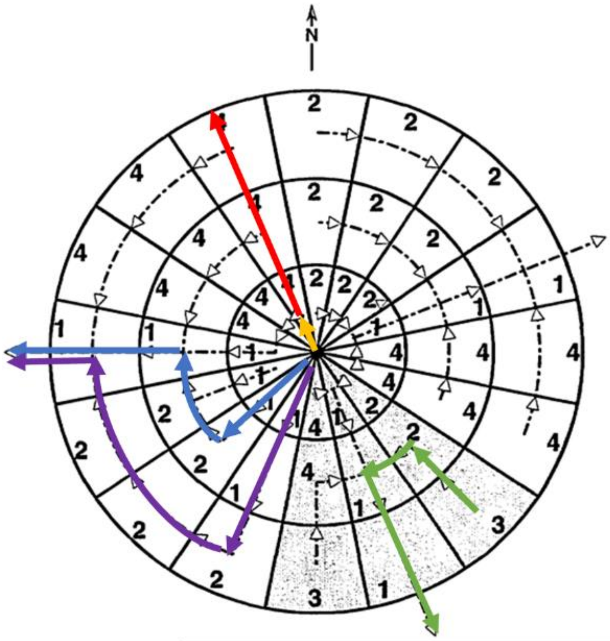

Figure 2: Polar grid map and representative routes using the MACCS2 'network' feature. Speed setting numbers are shown in each cell, modified from NUREG/CR-6613.

The routes shown in Figure 2 below include the distance used for the beginning period in SOARCA (orange), the distance used to calculate evacuation speed for the middle period in SOARCA (red), and possible MACCS2 network routes (blue, green, and purple).

Further speed adjustments can be made in WinMACCS2 using a speed multiplier that augments speeds between polar grid cells based on assumed areas of congestion. These areas were generally described as urban or rural grid cells. Speed multipliers of

1.0 (same as averaged ETE speed), greater or less than 1.0 (increased or reduced speed respectively) were used depending on rural or urban roadways. The speed settings shown in Figure 2 represent a speed multiplier but do not indicate the value of the speed multiplier. For example, setting 2 in the figure could represent a speed multiplier of 0.8.

The result is an evacuation time that differs from what the average speed for a 90% ETE would imply. A variable evacuation speed provided by the speed multiplier function is more realistic than a fixed speed. However, the speed, portion of the population, and location of population evacuation may differ substantially from the results provided by more detailed traffic modeling codes.

3.4.3 SOARCA Roadway Assumptions

A radial evacuation strategy following a simplified network (see Section 4.8) is used for the initial SOARCA studies [4], [5]. Since actual roadways are not strictly radial from the nuclear power plant, SOARCA estimates that there is an additional 30 to 50 percent increase in the travel distance in order to exit the 10-mile EPZ. The distances used for speed and duration calculations are stated as a portion of the 10-mile radius; therefore, it is unclear how this 30 to 50 percent difference is applied in SOARCA. While this assumption might be conservative in some cases, it will not be in some other cases, as the effect of emergency conditions may lead to longer delays than would be realized by a simple increase in distance. For example, the probability of accidents due to roadway elements such as intersections, bottlenecks, train track crossings, etc., may be higher during emergency situations.

The occurrence of vehicle crashes or physical barriers to traffic flow (e.g., downed trees, damaged bridges) can create a hindrance for cohorts exiting the EPZ. Sensitivity related to roadway barriers following an earthquake was considered as part of SOARCA in both the Peach Bottom and Sequoyah studies [4], [7]. The Peach Bottom SOARCA study did not expect ETEs to be affected by infrastructure impacts due to an earthquake, while the more recent Sequoyah study estimated that the ETE would approximately double [4], [7]. The Sequoyah SOARCA study also considered the time it would take the public to determine that the route they are traveling on is blocked and find an alternate rural route that may or may not lead to an unblocked exit from the EPZ.

3.4.4 Modeling Different Types of Evacuation Strategy

The NRC guidance for ETE studies, covered in this Section, states that staged evacuations should be considered. The original SOARCA study did not consider staged evacuation in its consequence assessment due to modeling software limitations. At the time, MACCS2 was only capable of modeling evacuations for two methods: radial and network. For the radial method, the evacuation is a straight path out of the EPZ. The network evacuation type in MACCS2 allows for speed scaling factors to be applied between grid cells and a single direction of traffic flow to be defined. This single direction of flow from one cell to the next is a limitation that cannot account for multiple directions of travel out of a cell, such as a highway that crosses the cell and allows travel in two directions. Options for Staged, Lateral, Staged Lateral, or other evacuation types were not available in MACCS2 at the time of all SOARCA studies [38].

A review of site emergency plans and ETE studies indicated that a “staged keyhole” evacuation strategy is a common protective action strategy option [7]. The ability to model a “staged keyhole” was not available for the 2011 Peach Bottom and Surry SOARCA reports [4], [5] but has been added to WinMACCS2 for use in the most recent

2018 Sequoyah SOARCA report [7]. This allows a wedge-shaped portion of the EPZ that is downwind of the NPP to be evacuated independently of the remaining EPZ and can also be applied to specific cohorts.

3.4.5 Modeling Variability in Cohort Size and Behavior

SOARCA acknowledges additional limitations to evacuation design capabilities due to software limitations. Cohort populations are considered uniformly distributed in the 10-mile EPZ, which SOARCA acknowledges may not be representative [4]. A feature to locate special populations in specific cells (SUMPOP) was added after the initial SOARCA studies [38].

When an evacuation begins, the entire cohort is assumed to enter the roadway immediately, which is also acknowledged to be unrealistic [6]. Cohorts in SOARCA are comprised of the five population types (resident & transient, transportation dependent, school, and special facility), but not divided into ERPA locations. This precludes modeling an evacuation by cohort and ERPA [16].

3.4.6 Modeling of Weather Inputs

In the SOARCA studies, a more representative weather input was used versus the existing guidance for ETE studies. The SOARCA model utilized one year of historical hourly weather data and generated bins of representative seasonal weather, which were used to model atmospheric dispersion and travel during adverse conditions.

3.4.7 SOARCA Evacuation Phases

Critical Evacuation Phases (CEP) are evacuation-related phases that are defined in discrete consecutive intervals. These phases do not fully represent all expected responses to the accident, but rather the limiting scenarios for estimation of overall evacuation time.

Delay-to-shelter represents the duration from the start of the accident until the cohorts begin sheltering in place. The SOARCA MACCS2 model assumes all evacuating cohorts shelter while preparing to evacuate. It is recognized that full compliance with an order to shelter should not be expected, just as with an order to evacuate. Shadow evacuation is one example of when the population evacuates despite the protective action orders. There are many potential causes for this non-compliance, which may include trust in the message, not receiving the message, or choosing to ignore the warning in favor of another activity such as reuniting with family [30], [40]. The non-sheltering portion of the population is a sub-set of the evacuating population cohorts because they do evacuate but do not initially shelter-in-place (SIP). This sub-set is different from the population that does not comply with an order to evacuate, which is modeled as continuing normal activity. This population may also evacuate at a different rate, which will affect the ETE.

The delay-to-evacuation phase represents a 1-hour duration of the sheltering period from the time a cohort enters a shelter until the point at which it begins to evacuate. In the Surry and Peach Bottom SOARCA studies, the only activity is preparing to evacuate. This modeling approach assumes non-emergency conditions and behaviors where the entire cohort responds in the same way. Uncertainty was considered in the subsequent Sequoyah SOARCA study and was found to contribute to overall consequences [7], [37]. This was accomplished by applying a triangle distribution to evacuation delay and evacuation speed for each cohort. While the approach of using triangular distributions in the Sequoyah SOARCA study is effective at modeling the existence of uncertainty in this phase, the approach was further improved by breaking the evacuation cohorts into three segments: early, middle, and late portions.

The first evacuation phase begins for each cohort when the first individual leaves the shelter and starts to evacuate the region and ends after a modeler-defined duration. All members of evacuating cohorts are assumed to evacuate during this period. In reality, some evacuees who chose not to shelter, or sheltered less than the delay-to-shelter time, may already have evacuated, while other evacuees may continue to shelter for some portion of this period.

The SOARCA study assumes that the first evacuation phase starts with no congestion, but that congestion quickly develops as the majority of vehicles enter the roadway. The assumption of no congestion to start this phase is based on the prior assumption that all evacuees shelter during the delay-to-evacuate phase and that the roadways would not be congested with the non-sheltering public. Congestion is not explicitly estimated based on a system model, which would estimate restriction to the traffic flow based on a demand and capacity model. Rather, it is based on observations from ETE studies. For the general public, congestion is assumed to occur 15 minutes after instantaneous loading into the roadway, and the speed is assumed to be 5 miles per hour in this phase. The distance traveled during this period is 1.25 miles based on the assumed duration and speed. Considering there is a one-hour sheltering period prior to evacuating, congestion occurs, and evacuation speed changes 75 minutes after notification.[9]

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[9] These values were assumed in the SOARCA study, without further justification for the assumed values.

The duration-of-the-middle phase is a user-defined parameter assigned to the period immediately after the first phase ends and continues until the cohort reaches the 10-mile EPZ. The SOARCA study assumes that the entire evacuating cohort is on the roadways and that there is congestion. The speed for this phase is calculated from the remaining site-specific evacuation time (after considering prior time phases), along with the remaining radial distance to travel (assuming that the first 1.25 miles of the 10-mile EPZ radius are traveled during the first evacuation phase), and then rounded. This is a simplistic approach to meet the 90% ETE from the site-specific ETE study. For example, the Peach Bottom SOARCA study estimates the average speed for the general public cohort during this phase to be 3-mph [4].

In general, the approach used in SOARCA may result in the population exiting the EPZ at the same time as the ETE study scenario it was based on, but it will not do so with the same spatiotemporal profile, which can be important for understanding consequences. For example, an average speed will move the population sooner and farther than would a slow ramp loading function. Also, all members of evacuating cohorts are assumed to evacuate during this period. In reality, some evacuees who chose not to shelter or sheltered less than the assumed time may already have evacuated, while some evacuees may continue to shelter for a larger portion of this period.

The late phase starts at the time at which the cohorts reach the boundary of the 10-mile EPZ and continues as they travel radially through the 10 to 20-mile region. A constant speed of 20 mph is assumed. The late phase thus assumes independent distance, time, and speed. These variables are all physically related; however, the model does not reflect the physical relationships and lacks the flexibility to approximate reality in this regard. Hence, the 20-mph speed may be inconsistent with the expected number of people who can physically be moved out of the EPZ in the specified time.

3.5 Implications of Advanced Communication Relative to 10 CFR 50.47

NRC SECY-11-0152 discusses a scalable EPZ based on the SMR accident source term and associated dose characteristics. This SECY states that an acceptable methodology may include (1) the use of a suitable design-specific Probabilistic Risk Analysis (PRA); and (2) accounting for uncertainties. NEI's proposed methodology for establishing the technical basis uses a risk-informed approach that includes the following two complementary efforts to address the SECY considerations:

- Use of PRA is required for new plant designs, which includes determining offsite doses
- Enhanced plant capabilities to account for uncertainties, using a four-step method

One NEI report proposes that Small Modular Reactor (SMR) and advanced reactor emergency preparedness may be better by refined consequence analysis [25]. This chapter provides a strategy for addressing uncertainties, which includes developing a generic SMR EP guidance for addressing the 16 planning standards described in 10 CFR 50.47(b), and the associated requirements in 10 CFR Part 50, Appendix E. Consistent with NEI's approach, this section identifies potential implications of advanced communication systems on advanced and existing nuclear power plant emergency preparedness as summarized in Table 5.

Table 5: Planning standards from 10 CFR 50 [12] with Implications for SMR and Advanced Reactors

Section	Regulatory Planning Standard from 10 CFR 50	Potential Impacts of SMRs and/or Advanced Communication on the traditional approach to meeting this standard
10 CFR 50.47(b)(1)	Primary responsibilities for emergency response by the nuclear facility licensee and by State and local organizations within the Emergency Planning Zones have been assigned, the emergency responsibilities of the various supporting organizations have been specifically established, and each principal response organization has staff to respond and to augment its initial response on a continuous basis.	Fewer ERPA jurisdictions due to smaller EPZ.
10 CFR 50.47(b)(2)	On-shift facility licensee responsibilities for emergency response are unambiguously defined, adequate staffing to provide initial facility accident response in key functional areas is maintained at all times, timely augmentation of response capabilities is available, and the interfaces among various onsite response activities and offsite support and response activities are specified.	Fewer on-shift staff dues to a potentially reduced staffing requirement
10 CFR 50.47(b)(3)	Arrangements for requesting and effectively using assistance resources have been made, arrangements to accommodate State and local staff at the licensee's Emergency Operations Facility have been made, and other organizations capable of augmenting the planned response have been identified.	Arrangements may not be required if EPZ is limited to NPP site boundary
10 CFR 50.47(b)(4)	A standard emergency classification and action level scheme, the bases of which include facility system and effluent parameters, is in use by the nuclear facility licensee, and State and local response plans call for reliance on information provided by facility licensees for determinations of minimum initial offsite response measures.	State and local response plans may not be required if EPZ is limited to NPP site boundary
10 CFR 50.47(b)(5)	Procedures have been established for notification, by the licensee, of State and local response organizations and for notification of emergency personnel by all organizations; the content of initial and follow-up messages to response organizations and the public has been established; and means to provide early notification and clear instruction to the populace within the plume exposure pathway Emergency Planning Zone have been established.	Fewer agencies and ERPA jurisdictions due to potentially smaller EPZ. Advanced communication systems, including IPAWS and ANS, may provide more improved communication.

Section	Regulatory Planning Standard from 10 CFR 50	Potential Impacts of SMRs and/or Advanced Communication on the traditional approach to meeting this standard
10 CFR 50.47(b)(6)	Provisions exist for prompt communications among principal response organizations to emergency personnel and to the public.	No impact
10 CFR 50.47(b)(7)	Information is made available to the public on a periodic basis on how they will be notified and what their initial actions should be in an emergency (e.g., listening to a local broadcast station and remaining indoors), the principal points of contact with the news media for dissemination of information during an emergency (including the physical location or locations) are established in advance, and procedures for coordinated dissemination of information to the public are established.	Public information and training may not be required if EPZ is limited to NPP site boundary.
10 CFR 50.47(b)(8)	Adequate emergency facilities and equipment to support the emergency response are provided and maintained.	Reduced emergency facilities commensurate with reduced risk or a reduced size EPZ.
10 CFR 50.47(b)(9)	Adequate methods, systems, and equipment for assessing and monitoring actual or potential offsite consequences of a radiological emergency condition are in use.	No impact
10 CFR 50.47(b)(10)	A range of protective actions has been developed for the plume exposure pathway EPZ for emergency workers and the public. In developing this range of actions, consideration has been given to evacuation, sheltering, and, as a supplement to these, the prophylactic use of potassium iodide (KI), as appropriate. Evacuation time estimates have been developed by applicants and licensees. Licensees shall update the evacuation time estimates on a periodic basis. Guidelines for the choice of protective actions during an emergency, consistent with Federal guidance, are developed and in place, and protective actions for the ingestion exposure pathway EPZ appropriate to the locale have been developed.	Communication strategies, systems, and message content may need to be adjusted to match more targeted or refined protective actions. Periodic required ETE updates may be conducted to account for more advanced communication, increased understanding of societal behavior, and revised modeling approaches.
10 CFR 50.47(b)(11)	Means for controlling radiological exposures, in an emergency, are established for emergency workers. The means for controlling radiological exposures shall include exposure guidelines consistent with EPA Emergency Worker and Lifesaving Activity Protective Action Guides.	No impact

Section	Regulatory Planning Standard from 10 CFR 50	Potential Impacts of SMRs and/or Advanced Communication on the traditional approach to meeting this standard
10 CFR 50.47(b)(12)	Arrangements are made for medical services for contaminated injured individuals.	No impact
10 CFR 50.47(b)(13)	General plans for recovery and reentry are developed.	No impact
10 CFR 50.47(b)(14)	Periodic exercises are (will be) conducted to evaluate major portions of emergency response capabilities, periodic drills are (will be) conducted to develop and maintain key skills, and deficiencies identified as a result of exercises or drills are (will be) corrected.	Changes to evacuation strategies and changes to communication tools and messages should be included in these exercises.
10 CFR 50.47(b)(15)	Radiological emergency response training is provided to those who may be called on to assist in an emergency.	No impact
10 CFR 50.47(b)(16)	Responsibilities for plan development and review and for distribution of emergency plans are established, and planners are properly trained.	No impact

Further research is needed to quantify the importance and effect of several potential impacts listed in Table 5. Some of the impacts listed may not be relevant for future licensees after the in-development 10 CRF 53 standard is finalized [11, p. 53].

3.6 Relevant Observations from an International Case Study

To gain a deeper understanding of international practices, in addition to reviewing the IAEA standards, a case study of the Kori site in the Republic of Korea was reviewed [41]. The Kori study underscored the potential that some events and sequences might deviate from model assumptions. The study was performed by Korea Hydro and Nuclear Power (KHNP) to comply with the Korean Nuclear Regulatory Authority mandated lessons-learned review of the Fukushima Daiichi nuclear plant accident. The study was completed, and various measures were recommended for implementation to align with the IAEA recommendations. The recommendations for implementation by KHNP included the classification of the EPZ into precautionary action zones and urgent protective action planning zones. Following the study, the Korean nuclear regulatory authorities also updated the relevant legislative acts that governed nuclear emergency planning to reflect the updated IAEA guidance and to specify that nuclear operators establish more detailed calculations of the ETE from the revised EPZ.

To perform a more detailed ETE analysis some additional factors were considered based on best practices, including regional characteristics such as climate, condition of roads, vehicle availability, mobilization, disruptions to traffic flow such as postulated accidents, and socio-behavioral traits of the evacuating public. The analysis was performed with a traffic simulation tool, and with the additional insights gained from this, more effective protection guidance was developed for each evacuating cohort. Specifically, the methodology included:

1. Use of a static assignment module of the VISSIM traffic simulation program.[10]
2. Vehicles are assigned to neighborhoods within the EPZ along designated evacuation routes.
3. The evacuation time included the preparation time after notification of the accident and the time to move out of the EPZ.
4. Socio-behavioral elements of the population in and outside the EPZ were determined based on questionnaires, which provided the following input to the analysis:

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[10] "**V**erkehr **I**n **S**tädten - **SIM**ulationsmodell" (German for "Traffic in cities - simulation model")

5. Preparation time based on cohort behavior
6. Evacuation patterns
7. The VISSIM program's dynamic assignment module was used to simulate traffic patterns based on emergency conditions, neighborhood characteristics, and specific considerations for special facilities such as schools.

3.6.1 Use of Region-Specific Socio-Behavioral Traits

The Kori study incorporated socio-behavioral traits that were specific to the population in the vicinity of the NPP, which were estimated by conducting surveys of the residents in the vicinity of the plant. The content of the Kori study survey goes beyond what is normally captured in the NRC-related ETE study trip generation time surveys.

The relevant cohort traits that affect ETE were used to estimate the time to prepare for evacuation and the time to evacuate. The benefit of location-specific traits is that the behaviors of people in emergency situations may be different, depending on demographics and environment. For example, people in densely populated urban areas may have fewer belongings and smaller households than people who live in rural areas; therefore, the time to prepare for an evacuation may be significantly different.

3.6.2 Assumptions for Evacuation of Vulnerable Cohorts

The Kori study recommended that vulnerable cohorts who may have difficulty evacuating on their own should be prioritized and should be the first to be evacuated. However, there are two potential issues with this approach: 1) it assumes that dose reduction is best achieved through evacuation, and 2) dose exposure is the limiting health consideration. For item 1, SIP may be a better strategy depending on the environmental conditions and plume trajectory. For item 2, for patients in a hospital who may be critically ill, removal from the hospital premises may pose a higher and more immediate health risk than the potential exposure to a radiological dose. This scenario was observed during the Fukushima accident, where the unplanned evacuation resulted in higher mortality rates [42]. Studies recommend that hospital evacuations should be carefully considered, and preplanning activities should consider tradeoffs that factor overall health and well-being, and not simply an assumption of dose reduction by evacuation [42].

For the US, typical Emergency Plans (EP) may have a range of protective actions, depending on specific situations. In many site-specific ETE studies, vulnerable cohorts are among the last to complete evacuation because it takes more resources to evacuate them. Vulnerable cohorts might also be evacuated early when a Site Area Emergency (SAE) is declared, which is not normally considered in site-specific ETE studies.

3.6.3 Evacuation Staging to Control Shadow Evacuation

The survey from the Kori study also established that a shadow evacuation of more than 40% could be expected around the Kori NPP EPZ. This level of shadow evacuation is much higher than the NRC assumption of 20%. Due to the expectation of high shadow evacuation, the Kori study recommends that all future studies should include a 100% shadow evacuation scenario (similar to current Japanese practice). To prepare for this level, extensive staged evacuation planning is recommended for each street in the urgent protective action zone.[11]

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[11] Note that for Korean nuclear sites, the EPZ is divided into the precautionary and urgent protective action zones, which have 5km and 20km radii respectively.

4 Opportunities for Enhancing the Analytical Capabilities of ETE Models

In this section, opportunities to improve ETE accuracy and reduce uncertainties are described. These opportunities were identified through consideration of current industry practices, assuming the industry has implemented the guidance described in NUREG/CR-7002, as written, and the SOARCA analyses, as previously described.

4.1 Emergency Response Timeline

An Emergency Response Timeline represents the time from relevant condition identification to notification of the public. The activities involved are generally consecutive and completed in the same order and include Protective Action Recommendations (PAR) which are provided to the principal offsite response organization (ORO) according to the approved Emergency Plan. In many cases, the principal ORO, normally the state nuclear safety agency, confirms the PAR and makes a Protective Action Decision (PAD) on how and what to communicate to the public. Uncertainty exists related to the duration of each activity, completion order, and errors that affect response times.

Emergency procedures are generally well practiced and understood by licensees and OROs. Exercises and drills are required to evaluate the response by these organizations. For a ‘table top’ drill, the emergency response timeline and activities up to notifying the OROs and the public may be simulated and documented. Actual notification of the public during a drill is not common but is occasionally done for testing and education purposes.

ETE studies define that the evacuation time begins after the public receives the notification to evacuate. Therefore, the time periods associated with the earlier portions of the emergency response timeline and their inherent uncertainties are not included in ETEs [16]. The NRC provides time thresholds that an NPP must be able to meet, which have been used to develop a timeline in SOACA and other studies. The NPP is expected to notify OROs within 15 minutes of declaring an emergency action level (EAL)[12] exceedance and include a PAR [30]. The NRC requires that communication systems have the capability to alert and provide an instructional message to essentially 100% of the public within 15 minutes of identifying that an emergency action level has been exceeded [12]. Backup notification methods are required to assure essentially 100% notification of the population in the EPZ that may not have received the initial notification within 45 minutes [43]. A review of emergency drill results indicates that the time to notify the ORO and time to notify the public is a range of values and occasionally exceeds the limit of 15 minutes. In the SOARCA studies, a simple deterministic assumption of a 30-minute delay was used for the period prior to evacuation beginning. This 30-minute duration is simply derived by combining the two maximum 15-minute limits. To enhance the accuracy of ETE studies, uncertainties related to the time necessary for decision-making and communication should be considered.

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[12] Emergency action levels are pre-determined, site-specific, observable triggers for placing the plant in an emergency classification level. The four NRC emergency classification levels (ECL) include unusual event, alert, site-area emergency, and general emergency, where general emergency is the highest of [15].

4.2 Early Protective Actions

Early protective actions include protective actions taken during the time between accident identification and notification of a general emergency (GE) to the public. Early protective actions are generally issued as precautionary measures before a GE. ETE studies assume evacuation begins at the initial notification to the public. Early protective actions, such as evacuating schools at a Site Area Emergency (SAE), are not considered in the ETEs, even though industry guidance notes that most states have plans in place which would implement early protective actions for schools if time allows [16]. To make ETEs more realistic and provide more insight, early protective actions should be included in ETE calculation.

4.3 Concurrent Task Modeling

ETEs are assumed to begin when the notification is communicated to the public and do not include the timing or sequence of events leading up to that notification. Distributions of timings associated with the various steps in this sequence of events leading up to the issuance of the notification to the public are not considered in most simulation tools used for ETE calculation. Deterministic assumptions about timing, such as 15 minutes to issue a PAR, are used in modeling. These assumed durations are based on NRC criteria and practiced and evaluated in emergency planning drills. As discussed in Section 4.1, after the PAR from the site, the principal ORO must issue a PAD and complete the notification to the public. To enhance ETE analysis, concurrent tasks should be considered in the protective action process. One method to include concurrent tasks in ETE studies is described in Section 5.

4.4 Representation of Uncertainties in the Evacuation Process

The NRC has completed several studies on consequence reduction relative to evacuation [19], [23], [44]–[46]. NUREG/CR-7002 only specifies consideration of staged evacuation as a best practice to reduce consequence relative to ETE studies [16]. Current ETE criteria do not specify that an integrated dose consequence analysis should be considered with related ETE traffic studies. Integrated consideration of ETE models paired with dose consequence models may provide additional insights. For example, it is reasonable to conclude that while rain increases ETE time, it will also reduce radiation exposure during travel as radionuclides are removed from the atmosphere by the rain.

Current ETE guidance does not specify the explicit treatment of uncertainty. For some cases presumably considered to be important, the current guidance prescribes specific analyses (Section 3.3) that must be completed with specific assumptions (i.e., do not include early protective actions for schools even if plans to execute early PARs for these facilities are in place) [16]. The specific prescribed analyses may miss potentially significant scenarios. Performance of sensitivity studies beyond what is stated in the guidance are not explicitly precluded and may provide additional insights, which is consistent with the NRC stated goal for requiring the performance of an ETE [15]. To enhance ETE analysis, sensitivity studies should be used to understand the potential for a discontinuous or large variation in outcomes outside of the prescribed ETE scenarios.

4.5 Representation of Public Compliance Variability

For the ETE development, public compliance is only modeled through the implementation of a 20% ‘shadow evacuation’. Shadow evacuation is where a portion of the public outside the ordered protective action zone spontaneously evacuate based on perceived danger, thereby adding traffic and congestion to the roadways [20]. The ETE guidance specifies that shadow evacuation should be modeled to 5 miles beyond the EPZ, which generally ends near 10 miles (i.e., the 10 – 15 mile range). The potential for a portion of the public within the EPZ not to comply with an evacuation order, thereby reducing traffic and potentially decreasing evacuation time, is conservatively ignored.

The SOARCA study assumed the public would comply with instructions, other than the standard 0.5% non-compliance assumptions and 20% shadow evacuation. However, SOARCA differs from current guidance by modeling shadow evacuation to a 20-mile radius instead of the 15-mile radius.

The literature indicates a wide range of public compliance, both shadow evacuation and compliance with an order to evacuate, through a study of historical events and public surveys [23], [30], [30], [44], [47]. The Government Accountability Office raised concern that public response is not adequately considered in EP [48]. In the NEIMA legislation of 2019, U.S. Congress required some aspects of public response, including shadow evacuation, to be analyzed in more detail [2]. Recent studies to address that requirement indicate high levels of shadow evacuation are unlikely to cause significant delays [20], [49]. While large amounts of shadow evacuation may not significantly impact overall evacuation time, the effect of risk to the population has not been studied. No evaluations of the impact on evacuation time or risk due to the level of compliance with an order to evacuate were discovered in the literature. A model that is capable of evaluating risk is necessary to understand the impact of public response and enhance decision making.

4.6 Communication During In-Process Evacuation

The guidance specifies that the ETE begins after the dissemination of the initial order to evacuate is complete [16]. No distribution is used to consider the population receiving the warning over a period of time; it is assumed to happen instantaneously. Communication may be necessary or desired after the initial notification to the public. Communication during the evacuation process could be used to cancel the initial warning, expand a keyhole evacuation area, alert the public to a new emergency, initiate another stage of a staged evacuation, or several other potential reasons.

It would be useful to the emergency management agency to understand the potential benefit or detriment of in-process communication. The majority of models listed in the guidance do not have the capability to alter the evacuation in the middle of a simulation to represent a change caused by new information. This enhanced capability would make evacuation models more realistic and allow for sensitivity studies.

4.7 Customization of Communication to Specific Areas or Populations

In general, protective action recommendations are provided to the principal ORO by NPP licensees according to the approved EP. In many cases, the principal ORO, normally the state nuclear safety agency, confirms the recommendation and makes a protective action decision on how and what to communicate. Some states (such as Pennsylvania) currently have restricting policies that specify a specific protective action (i.e., full 360-degree EPZ evacuation) given a declaration of a GE [50].

Common forms of communication to the public include sirens in the EPZ, IPAWS communications tools such as the Emergency Alert System (EAS), National Oceanic and

Atmospheric Administration (NOAA) weather radio alerts, or the Wireless Emergency Alert (WEA) system for cellular phones. NPP licensees do not have direct access to systems such as IPAWS and WEA.

In general, an initial communication will be concluded with guidance directing the public to "*…monitor television and emergency communication channels for further instructions.*" [51] Instructions are provided to the entire population as opposed to targeting different communications to different locations and/or cohorts. Multiple communication pathways are generally used to attempt to reach the entire population promptly [52].

In the Peach Bottom SOARCA study, special populations (e.g., schools) were assumed to begin evacuation at the activation of sirens when an SAE is declared. Communication was made to the general public to evacuate at the declaration of a GE. It was assumed that the entire general public received the evacuation alert and warning at the same time. Once communication was made to evacuate, it is assumed that the entire evacuating population begins activities to prepare to evacuate. Applicable local or state policies may necessitate changes to reduce risk or ETE by utilizing advanced notification and communication systems to implement alternative evacuation strategies. An enhanced tool to compare the risks associated with geo-targeted warnings and alternate strategies (Section 6) is needed to evaluate these policies.

4.8 Accuracy of Traffic Models

NUREG/CR-7002 guidance specifies the use of traffic models from an approved list or that have been demonstrated for use with evacuations. The expectation for this guidance is that current best practices in traffic modeling methods and tools are used

[32], [53]. A more recent study reviewed current ETE practices and focused extensively on traffic models as a means to improve ETE studies [20].

For the SOARCA studies, an independent traffic model for ETE purposes was not developed. Rather, existing site-specific ETE results (based on previous site-specific traffic models) were used to develop simplified evacuation inputs (e.g., average vehicle speed) for the dose-consequence modeling code. Rather simple traffic modeling was utilized due to MACCS2 code limitations. MACCS2 does not reflect actual traffic patterns and the effects of such patterns on the ETE. For example, the majority of traffic (except cohorts that were mobilized early) enters the roadway at the same time, and average speeds are used from industry ETE studies for the representative site in a given SOARCA study. This modeling approach may impact the results and insights by making simplifying assumptions (e.g., all traffic enters at the same time, creating a progression of traffic at a uniform speed out of the EPZ).

MACCS2 has a road network evacuation feature (illustrated in Figure 2) that allows for evacuation modeling beyond simple radial evacuation strategies, where the entire population exits straight away from the NPP. However, this model does not use a detailed road network to perform calculations and creates unreconciled inconsistencies in the direction and speed of the evacuees in the model [54]. The network travel feature in MACCS2 cannot determine congestion between cells (which is time-dependent) and can only apply previously mentioned speed factors. The travel distance may be much longer through each cell, where a direction change occurs (creating a near right angle travel path) or where a path travels around the ring when the road may only hit a corner of the cell. The model also cannot move a portion of the traffic in two directions out of one cell. This would be likely for a cell that feeds onto a major roadway that runs perpendicular to a radial evacuation and could be taken in two directions out of the EPZ. One method to remove this limitation is to develop a means to import spatiotemporal data from ETE traffic analysis into a consequence model like MACCS2 or the model developed in Section 6.

4.9 Effect of Artificial Geographical Barriers on Consequence Models

Artificial barriers, such as state, county, and ERPA boundaries, are used for emergency planning and response. ETE and evacuation models are generally based around existing local emergency plans and ERPAs. The location of evacuation shelters, congregation areas, and evacuation routes, and by extension ERPAs, can be an important consideration in ETE analysis [16]. While in line with the guidance of using existing local emergency plans and methods that are often written and implemented by local governments, artificial barriers may introduce new limitations. These limitations may reduce the effectiveness of certain evacuation types.

Current NRC guidance indicates an entire ERPA is expected to be given an order to evacuate at the same time, even if only a portion of the ERPA is in the evacuation area [16]. Using the ERPAs in Figure 1 (Section 3.2) as an example, if the downwind sector is NNW (11 o'clock position just to the left of top center), then ERPAs A, D, L, and even F should be evacuated.

Some ERPAs extend from the center of the EPZ to beyond the 5-mile radius, eliminating the potential to use a 0-2 and 2-5 mile staged evacuation [16]. Evacuation planning based on artificial boundaries can lead to increased risk by evacuating a larger population than needed or where an evacuation route may cross a plume path. Training to evacuate on a specific route or to a county-specific shelter may increase consequences in these situations.

4.10 Spatiotemporal Assumptions

The spatiotemporal location of the population has an impact on various factors in the ETE, including roadway loading, congestion, likelihood, and location of vehicle crashes, and effects of infrastructure failure. The spatiotemporal location of the population is also important for consequence analysis, as the received dose is a function of the exposure of an individual to the hazard over time. Site-specific ETE studies provide varying levels of spatiotemporal insight.

Time of travel is a function of speed and the necessary distance to travel. An ETE model can be designed to calculate the time of travel based on distance, demand, and capacity of the roadway network. NRC guidance allows NPP licensees to comply with ETE requirements by way of any reasonably supported method. One example is the acceptance of a range of traffic model types (micro, macro, etc.) and broad guidance on models that may be acceptable. Variations in methods, models, resolution, and quality of local information can lead to a wide variety of spatiotemporal modeling.

SOARCA assumes that at a specified time, the evacuating cohorts would be at a specified location, traveling at a specified speed. The rationale provided relates to the outcome: moving cohorts out of the EPZ within the target ETE. This is a simplification of a more advanced traffic model found in the site-specific ETE study, which may result in different spatiotemporal locations of the population while evacuation is in progress. ETE studies can be enhanced by providing spatiotemporal traffic data for a better understanding of traffic flow and for use in consequence analysis.

4.11 Real-Time Information

Real-time information is needed to make informed decisions that could most reduce the risk for the complying public. This includes informing people when to leave based on risk timing and traffic loading. To achieve this level of sophistication, near real-time, event-specific information would be needed.

The availability of real-time evacuation information varies from site to site depending on ORO access to input sources such as traffic cameras, roadway sensors, and radionuclide monitors[13]. It is also expected that ORO's will receive some real-time information from the public through 911. This information may provide significant insight into unanticipated events such as roadway obstructions, traffic crashes, or medical emergencies that are a result of the evacuation. OROs may also gain insight through trained 'spotters' that are part of the general public and by monitoring social media for information from the public that may not be directly provided to the ORO[14]. The benefit of real-time information depends on the ability to receive the message, comply and act. Hence, it may only be an incremental and relative benefit as compared to not having real-time information.

The NRC provides guidance for addressing critical points to be considered for ETE traffic modeling (Section 3.2) [16]. This guidance helps to provide insight into ETE challenges (e.g., a blocked road) and plan accordingly. However, it does not address the real-time information necessary to identify if that need exists during an event. Licensees are responsible for making timely PARs and for providing the PARs to OROs to allow

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[13] This may include drones, GPS tracking, vehicle-to-vehicle communications, and other emerging technologies

[14] Utilizing 'spotters' and unverified public reports (i.e., social media) is a well-established practice to receive real-time emergency information. One example is the National Weather Service Skywarn program.

them to make timely and well-informed PADs. ETE studies can be enhanced by adding the capability to model obstacles and interventions to mitigate the obstacle at some point in time during the evacuation.

5 An Evacuation Time Estimate Method Incorporating Duration Uncertainty Analysis

The current ETE methods are used to produce simplified, discrete values. A major recommendation of this chapter is that uncertainty must be included in the analysis. One approach is to use Duration Uncertainty Analysis (DUA). The DUA method can use the inputs from the site-specific ETE and traffic models, but it improves the ETE inputs to the dose-consequence modeling tools. This will be performed by creating a stochastic logic-tied schedule instead of a discrete or bounding schedule, as is the current practice. The evaluation is performed by an analysis method that integrates a DUA tool[15, 16] with a dose consequence analysis code, such as MACCS2 or the Radiological Assessment System for Consequence Analysis (RASCAL) code. RASCAL was chosen for this study because it is specifically designed to be used in the independent assessment of dose projections during the response to radiological emergencies. RASCAL is used by emergency response personnel to conduct nearly real-time evaluations of dose projections for emergencies, training, and drills [55].

The DUA simulates the overall evacuation time through a logic-tied schedule, which includes activities with variable durations. Duration variability is the effect of inherent

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[15] DUA is also referred to as Schedule Risk Analysis (Hulett, 2000).

[16] DUA scheduling software examples include Primavera Risk Analysis by Oracle or Project by Microsoft

activity variability plus the potential for threat or opportunity occurrences that may increase or decrease the time of each activity and which may be more significant during emergency conditions. A threat event may be inclement weather, while opportunities may include the use of enhanced communication capabilities such as the Wireless Emergency Alert system [56].

5.1 Overview of DUA Process

In DUA, a stochastic model of logic-tied schedule activities is built, which includes uncertainties of the duration of each of the evacuation activities. A threat and opportunity register is also built, which is a repository of all potential threat events that may increase or opportunities that may reduce the overall ETE[17]. The threats and opportunities each have an assigned probability of occurrence, a range of impacts, and an assigned distribution.

During the DUA, durations and distributions for all events in the threat and opportunity register are sampled with a Monte Carlo method. This process is repeated numerous times (user-defined but usually thousands), with each iteration providing an ETE outcome. At the end of the simulation, there is a frequency distribution of ETE outcomes, with which summary statistics can be assessed. This frequency distribution can be used to create a cumulative distribution, which shows the probability of completing the evacuation over a targeted period. (e.g., there is a 75% chance that the population will be outside the EPZ in 80 minutes)

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[17] Note that the term "threat", which is often used to denote unfavorable uncertainties in the project risk management, is used in this context, to avoid confusion with nuclear plant and "safety" and "risk."

5.2 Development of the Evacuation Activity Schedule

The evacuation activity schedule is developed with a Precedence Diagram Method (PDM) [57], as documented in Figure 3, which describes the evacuation activities by constructing a schedule network diagram. The PDM uses nodes to represent activities, which are linked by arrows that show relationships and dependencies. Unlike other system progression techniques[18] that require activities to end before the next one starts, PDM provides the capability to consider other types of relationships between activities. The PDM describes all the activities with durations that cumulatively make up the overall evacuation duration. This is similar in many ways to the standard use of fault trees in nuclear system PRA to identify pathways to system-level failures through event-level failures. The similarity is beneficial because it reduces the challenge of incorporating a new method in the ETE process. The steps to define the activities include:

1. Identify activities
2. Identify overlapping activities
3. Identify sequential activities
4. Identify the critical path
5. Identify critical to success activities
6. Develop logic to represent activity durations, including considerations of uncertainty

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[18] Many scheduling techniques exist such as PERT or CPM. See [57]

The temporal occurrence and duration of each activity are defined by a schedule logic that describes the amount of time the activity takes and how it is reflected in the overall schedule. Figure 3 illustrates the PDM with distributions that represent the duration uncertainty based on inherent activity variability with specific threats and opportunities that may influence the duration. For the purposes of this illustration, all but one of these distributions are symmetric, but this is not necessarily the case in practice. Different forms of distributions can be assigned to various events, threats, and opportunities, as appropriate.

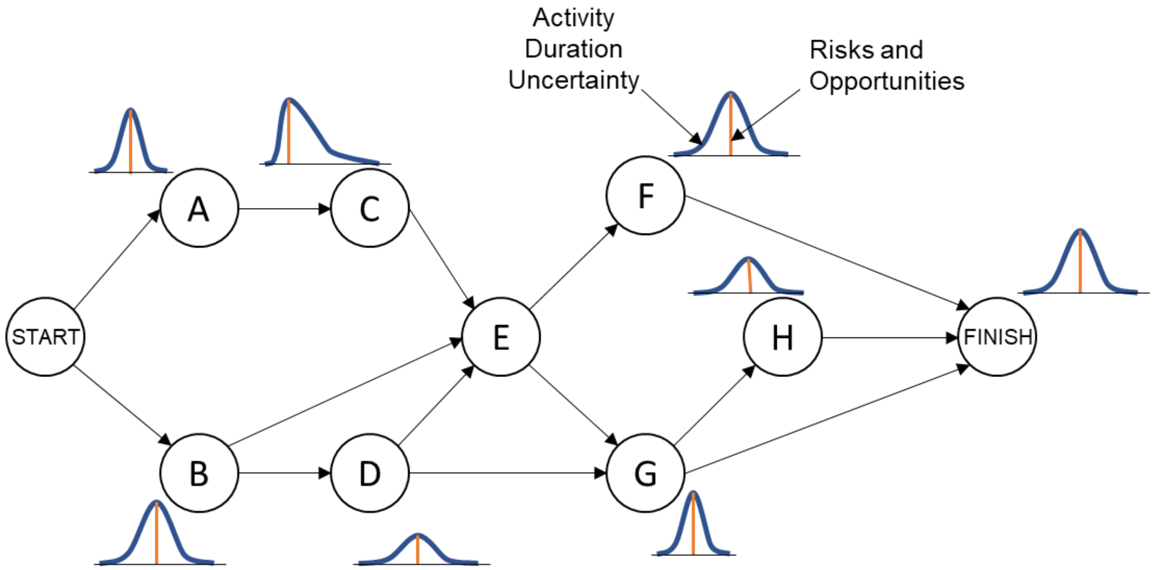

Figure 3: Example of the Precedence Diagram Method (PDM)

5.3 Description of Applicable Model Assumptions

The DUA method can be used for multiple parameters integral to ETE calculations. The following sections cover three such parameters. In addition to these parameters, state variables (e.g., daytime, nighttime) that can change the activities and structure of the precedence diagram can also be considered.

5.3.1 Protective Action Initiation

Protective Action Initiation represents the actions that are taken by an individual when informed of the emergency and instructed to evacuate. Individual differences in behaviors lead to differences in roadway loading times. Behaviors may include compliance, preliminary actions such as packing belongings, securing property, assisting others, seeking out family and friends, and making arrangements for transportation. Protective action initiation must be completed for each evacuee prior to evacuation and thus can be reflected as a delay to roadway loading. To implement this capability, a technical basis for the values used and associated distributions for the following would be required:

- Cohort Matrix: A separate assessment of roadway loading functions by cohort-type
- Threat and Opportunity Register: This allows for a cohort-specific assessment of the time it will take to load the roadway based on items that may affect each cohort

5.3.2 Effect of Communications

The DUA model allows for the evaluation of evacuation time impacts based on actual notification, including the use of advanced or multiple communications methods. Accounting for the effect of communication may be achieved by modeling the spatial distribution of the population, using the time it takes to be notified, based on communication devices available. This metric may be developed by a combination of the number of people who own a particular type of device and their likelihood of receiving information from the device and then taking action. With regards to the DUA, the effect of communication may be assessed by categorizing the evacuating public into multiple groups based on modes of communication, levels of information provided, and cohort response to the information.

5.3.3 Roadway Loading

The standard practice for modeling roadway loading of the evacuating population is to use an S-curve shown in Figure 4. This curve is based on empirical data and experience from evacuations related to natural disasters. It is unclear if an evacuation near an NPP, with the extensive planning, education, training, and support systems in place, will follow a similar curve.

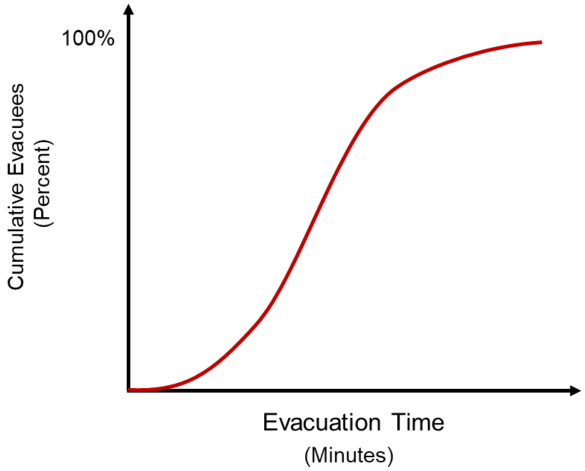

Figure 4:Typical S-curve Representing Evacuation Response

The proposed DUA approach, while more complex, provides a theoretical model to replace this empirical model based on limited and tangentially relevant data from unplanned and tested regional evacuations. This approach allows for the use of site-specific data, including survey responses on expected behavior, emergency exercise results, and traffic emergency services response times.

5.4 Description of Quantitative Schedule Uncertainties

Schedule activity durations are inherently probabilistic due to the nature of modeling a cohort of individuals who are making independent decisions and taking independent actions. There are two major aspects required to quantify schedule uncertainties: activity uncertainty and threat/opportunity occurrence.

Activity uncertainty is the variability in the time it takes to perform a planned activity. For activities that have been performed multiple times in the past, the available historical data can be used to estimate the variability in the schedule duration. The probability distribution that describes the likelihood of a threat or opportunity occurrence may be represented by a frequency histogram of the historical occurrences. The three-point estimate method is typically employed to represent the variability in a DUA model.[19]

Threats and opportunity occurrence, which may affect the duration of planned activities due to the occurrence of probabilistic events, should also be factored into the variability of activity duration. Examples of threats associated with traffic patterns include construction, roadway deficiencies, and traffic crashes, while opportunities may include the use of navigation tools that find shorter routes. The threat and opportunity register is used to identify and quantify applicable threats and opportunities as well as technically appropriate probability distributions for each item in the register.

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[19] The three-point estimate method involves description of a variable parameter by a distribution of values based on an optimistic, pessimistic, and most likely estimate [NASA, 2015].

Schedule durations are described probabilistically or in terms of percentile confidence levels to represent the uncertainties associated with activities, providing a more objective and realistic representation of the expected overall duration.

5.5 Overview of the Monte Carlo Method

The Monte Carlo method is a stochastic estimation process that uses a simulation based on random numbers or inputs to arrive at solutions to problems that are difficult or impossible to solve deterministically [58]. These types of problems are typically mathematically unbounded or too complex to solve analytically. The Monte Carlo method resolves the problem by using a technique that approximates the probability of certain outcomes by running multiple iterations using random sampling variable values based on their established distributions. These distributions are developed based on the best available activity durations distributions as well as the threats and opportunities impacting each variable.

Activities are described stochastically as a range of possible values. A Monte Carlo simulation includes multiple iterations, of which each iteration represents a possible outcome. The result is a distribution of possible outcomes based on the probabilistic inputs.

5.6 Develop Informed Mitigation Strategies

DUA outputs may be used to develop quantitatively informed mitigation actions and strategies. This is accomplished by identifying the ability of a given intervention to impact performance along with a probabilistic confidence interval.

To support performance-based regulations and account for the inherent uncertainty in the evacuation duration estimation, it is important to understand the relationship between the uncertainties and the accommodations made for the uncertainties. For probabilistically described duration uncertainties associated with ETE, there is percentile probability associated with the schedule duration. Hence, a targeted or prescribed evacuation time can be compared against the predicted probabilistic continuum of potential durations. This allows a confidence level to be assessed for evacuation effectiveness of various cohorts. This is notionally illustrated in Figure 5 below, which represents the cumulative distribution of evacuation time duration for an activity that is targeted to be less than 14 hours for two different scenarios, with and without intervention.

Figure 5: Schedule Uncertainty Represented with a Cumulative Distribution Function

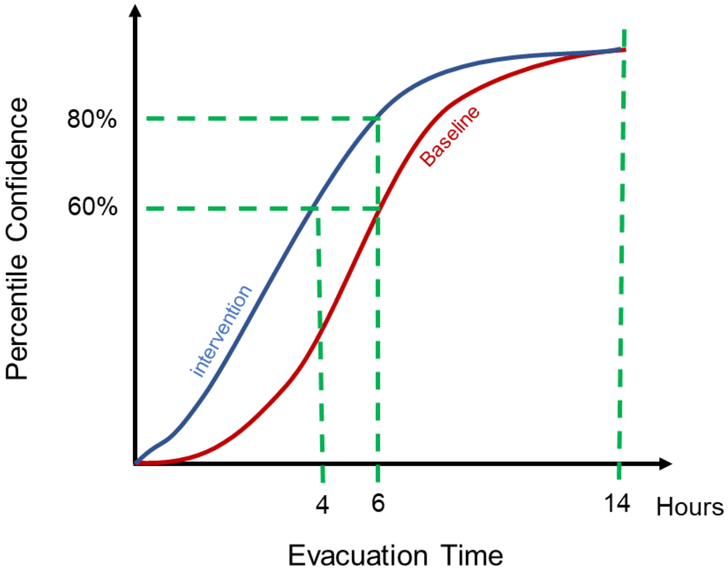


Figure 5 shows that for the pre-intervention beyond the basic evacuation plan scenario, there is a 60% chance that the evacuation will be completed in 6 hours or less.

The post-intervention scenario shows the effect of additional mitigation actions and interventions, such as advanced communications. Based on this graphic, the intervention results in an increase from 60% to 80% chance that evacuation will be completed in under 6 hours or that there is a 60% chance that the evacuation will be completed in 4 hours or less. A stochastic ETE model that provides results in this manner allows strategies to be quantitatively evaluated in terms of the ability to reduce the ETE or increase the likelihood of a particular ETE. The following sections describe how these strategies can be investigated and developed.

5.6.1 Determine the Criticality Indices

For every iteration of the Monte Carlo analysis, a critical path is determined based on the schedule logic and the stochastic sampling. A criticality index score expresses the percent of iterations that a particular task was on the schedule critical path for a set of repeated Monte Carlo iterations. Tasks with a high criticality index are more likely to impact the ETE as they are more likely to be on the critical path. For example, a task that was completed for 50% of the iterations and was critical in 50% of those iterations would have a criticality index of 25%. As shown in Figure 3, multiple pathways exist, and not all activities must be completed on each pathway. ETE mitigation strategies based on the criticality index may include allocating additional resources to activities that have a higher criticality index.

5.6.2 Determine the Duration Sensitivity

The duration sensitivity is a correlation between the duration of a task and the duration of the evacuation. This correlation represents the influence that a value for a specific activity has upon the total duration for all activities. When combined with the criticality index, the duration sensitivity can help identify the most critical tasks to target for mitigation. Activities that have a short duration could have high criticality index values but low duration sensitivity. ETE mitigation strategies based on the duration sensitivity analysis may include prioritization of resources based on index activities that have the highest sensitivity and effect on the overall duration.

6 Integrated Consequence Model

Differentiating between a calculation of the various factors that can contribute to risk individually and an integrated risk calculation is important for understanding the limitations of current evacuation planning approaches. In a typical ETE study, the focus is solely on characterizing the total time needed to complete the evacuation process without considering the geographic dispersion of radioactive material. The typical approach to ETE studies may miss important insights and lead to inferior strategies; for example, local evacuation routes may be designed to reduce evacuation time or avoid congestion but without considering public health impacts such as dose or evacuation-related injuries or fatalities. Public health consequences are not explicitly included in current ETE assessment practices.

To explore the effects of ETE modeling method enhancements proposed in this chapter, a risk and consequence model was developed. It is desirable to consider the risk and consequences because evacuation time is a proxy for risk, and ETE reduction may not necessarily result in risk or consequence reduction. For example, a SIP scenario often reduces dose but increases the evacuation times by restricting PAI activities. Using the integrated model, protective action strategies can be directly compared using risk and consequences as metrics for effectiveness rather than the total time to evacuate.

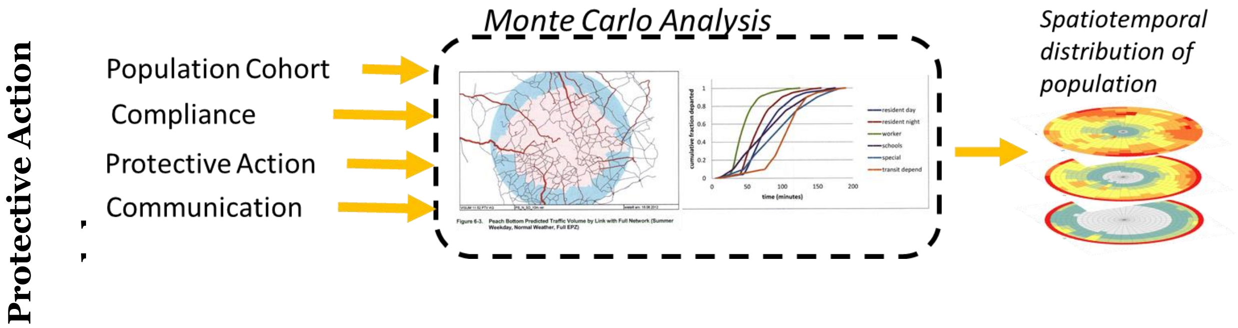
The current evacuation time estimate methods predominantly use deterministic assumptions, which by their nature are static and limited in their ability to provide the insights that may be available in a stochastic model [59]. To complete a stochastic integrated analysis, it is necessary to understand the impact of the deterministic assumptions. Recent studies that are based on the risk-informed approach attempt to create distributions to replace some of the deterministic assumptions [59]. Research needs to continue in this area to improve integrated analysis.

Overall risk impacts can be better considered through the integration of the location of the population and radiation to determine evacuation (evacuations risks are discussed in Section 6.4.4). This integrated analysis functions by joining a radionuclide exposure module and a protective action module using a common time step, as illustrated in Figure 6 below. Licensees can apply this integrated consequence model during ETE development to gain deeper insight into opportunities for time and/or consequence reduction while complying with current guidance.

The integrated model is built on current best practices for ETE studies and protective actions but creates a flexible framework that can go beyond current guidance. This allows for potentially deeper insights into an emergency response by addressing some limitations in existing methods and tools. A more inclusive scope of the potential protective actions and public response is used to allow for the quantification of factors that are not included in current ETE guidance, such as considering early protective actions or alternative evacuation strategies. Notably, deterministic assumptions were relaxed by incorporating the capability to use probability distributions for key variables. A modular design allows for a flexible operation that can be utilized for detailed analysis (similar to SOARCA) or prompt analysis (emergency situations) by providing computation times that meet NRC guidance for PARs. The design and function of the integrated model are described in Chapter 5.

6.1.1 *Model Inputs and Outputs*

The integrated model is used to assess the consequences experienced in the event of a particular accident sequence under a given set of circumstances. The model is comprised of three main modules: a Protective Action module (where the people are), a Hazard Dispersion module (where the radiological hazard is), and a Consequence module (risk and effects to the people). These modules take in several types of information, including data (e.g., weather, population), scenario choices (e.g., radial evacuation type), and probability/frequency distributions or deterministic assumptions (e.g., for compliance) as illustrated in Figure 6 below. With each model iteration, the spatiotemporal progression of the hazard dispersion and public response is calculated. Consequences are calculated in each map cell for each timestep using the spatiotemporal progression output of the other modules.



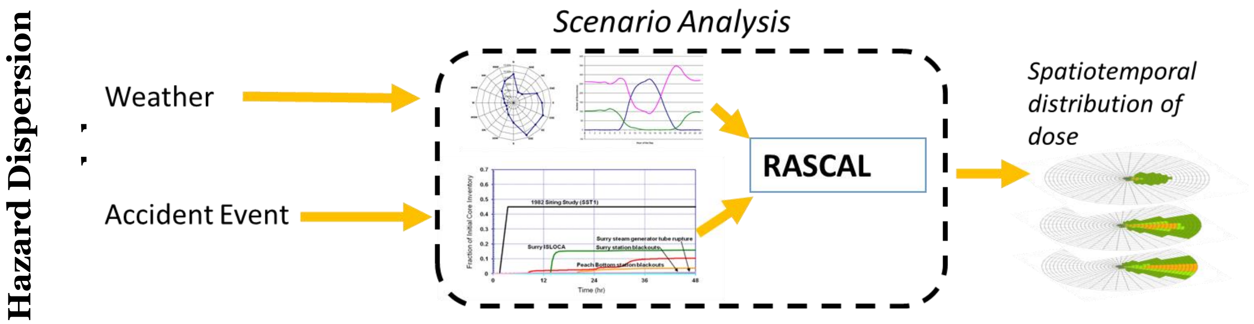


Figure 6: Representation of most inputs and outputs for the Protective Action (top) and Hazard Dispersion (bottom) modules.

6.1.2 Integration of the DUA and Consequence Models

Integration of the DUA model (see Section 5), with the protective action, hazard dispersion, and consequence modules allows for deeper insights into overall consequences. The integrated model can be used in a Monte Carlo manner to characterize the sensitivity and contribution of activity-based variables. The integrated model can also be used in a scenario-based manner that allows for prompt computations of estimated consequences while still considering activity duration values that are considered most likely by the DUA model. This chapter provides a method and framework to compare factors and quantify the benefits in future studies.

7 Conclusions

This chapter identifies existing practices for evacuation time estimation and provides recommendations for enhancement by using modern computing resources. As previously stated, a major objective of ETE analysis is the ability to provide deeper insights that may help reduce the risks associated with the evacuation process. A major finding is that current methods have very limited ability to achieve this objective because risks experienced during a protective action cannot be directly modeled, leaving only proxies for risk (e.g., evacuation time) to be used. The consequence models in existing codes (e.g., MACCS2 or RASCAL) do not include a dynamic ETE model that would allow for simulations and scenario analysis that could provide deeper insights. Current models also lack the ability to evaluate the impact of emergency technologies such as advanced communications technology like cell phones, systems such as WEA, or social media that can improve emergency communication and potentially reduce health impacts in the event of an NPP accident.

7.1 Recommendations for Communication and Public Response

A review of literature, modeling practices, and regulations included in Section 3.5 identified several opportunities to better inform EP decision-making associated with ETE and advanced communications [12]. Three of the key recommendations are:

- Assess options for improvement of communications and public response based on the existence and prevalence of systems such as cell phones and social media
- Assess the equivalency and relative effectiveness of advanced communication systems against existing prescribed systems such as sirens.
- Evaluate potential to provide protective action instructions, potentially geo-targeted instructions, to the evacuating public based on actual conditions such as dose risk and roadway conditions

7.2 Recommendations for Enhancements to ETE studies

ETE studies are used in emergency planning and protective action decision making. Current protective action guidance uses evacuation time as a proxy for risk and provides evacuation time thresholds for protective action decisions (e.g., If the 90-percent ETE for this area is 2 hours or less, immediately evacuate) [22]. A recent technical basis for updated ETE studies requires more detailed traffic models but still only results in point estimate evacuation times with no ability to integrate with a consequence model.

As outlined in Section 3.4, a detailed review of recent applications of MACCS2 capabilities (e.g., NRC SOARCA project) identified several limitations of the existing codes and guidance concerning the ability to obtain more detailed insights for ETE and EP purposes. Opportunities for ETE enhancement are provided in Section 4. The development of alternative modeling approaches, such as the integrated consequence model presented in Section 6, is another method to address some of the identified limitations. The key recommendations are summarized:

- Use a risk-based model for protective action strategy selection instead of proxies for risk such as evacuation time. Incorporate the ability to analyze multiple evacuation strategies, such as Keyhole and staged evacuations. Model planned activities such as early protective actions (e.g., school evacuations).
- Consider the effects of uncertainty in ETE analysis, including the ability to model public response and compliance

- Include the ability to model cohort-specific time estimates and speeds for each phase and location. This is needed for more accurate consequence analysis.
- Use dynamic concurrent timelines and spatiotemporal analysis instead of concurrent timelines and point estimate ETEs

Due to significant advances in models and computation resources, evacuation time is no longer needed as a simplified proxy for risk. This chapter introduces a risk-based method to quantify the effects of interventions that may affect the protective action effectiveness and the resulting risk impacts to the affected population. The proposed integrated consequence model allows for analyses that were previously not possible with current tools. The design and function of the integrated model are described in Chapter 5.

8 Appendix – Chapter 2

9 Regulatory References

The following list of documents was used in the literature review work performed in this chapter.

1. Title 10 to the Code of Federal Regulations (10 CFR) Sections 50, 52
2. NUREG-0654 Rev 1 (1980) – Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants
3. NUREG-2239 (1982) - Technical Guidance for Siting Criteria Development (Siting Study)
4. NUREG-0654 Supplement 1 (1988) - Criteria for Utility Offsite Planning and Preparedness
5. NUREG-0654 Supplement 2 (1996) - Criteria for Emergency Planning in an Early Site Permit Application
6. NUREG-0654 Supplement 3 (1996) - Criteria for Protective Action Recommendations for Severe Accidents
7. NUREG-0302 (2004) Effective Risk Communication: The Nuclear Regulatory Commission's Guidelines for External Risk Communication
8. Regulatory Guide 1.101 (2005) Emergency Response Planning and Preparedness for Nuclear Power Reactors
9. NUREG – 6863 (2005) - Development of Evacuation Time Estimate Studies for Nuclear Power Plants

10. NUREG – 6864 (2005) - Identification and Analysis of Factors Affecting Emergency Evacuations
11. NRC Regulatory Issue Summary 2005-08 (2005) Endorsement of Nuclear Energy Institute (NEI) Guidance “Range of Protective Actions for Nuclear Power Plant Incidents
12. NUREG-6953 Vol 1 (2007) –Review of NUREG-0654 Supplement 3, Criteria for Protective Action Recommendations for Severe Accidents (Technical Analysis of Alternative Protective Actions)
13. NUREG-6953 Vol 2 (2007) –Review of NUREG-0654 Supplement 3, Criteria for Protective Action Recommendations for Severe Accidents (Focus Groups and Survey)
14. NUREG-6953 Vol 3 (2007) –Review of NUREG-0654 Supplement 3, Criteria for Protective Action Recommendations for Severe Accidents (Technical Basis for Protective Action Recommendations)
15. SECY-06-200 (2007) Results of the Review of Emergency Preparedness Regulations and Guidance
16. NUREG-6981 (2008) – Assessment of Emergency Response Planning and Implementation for Large Scale Evacuations
17. NUREG-0654 Supplement 3 Rev 1 (2011) - Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants: Guidance for Protective Action Strategies
18. NUREG-0654 Supplement 4 Rev 1 (2011) - Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in

Support of Nuclear Power Plants: Criteria for National Preparedness Initiative Integration, Exercise Enhancement, and Backup Alert and Notification Systems

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21. NUREG-7033 (2011) - Guidance on Developing Effective Radiological Risk Communication Messages
22. SECY-11-0152 (2011) Development of an Emergency Planning and Preparedness Framework for Small Modular Reactors
23. SECY-15-0077 (2011) Options for Emergency Preparedness for Small Modular Reactors and Other New Technologies
24. NUREG-1935 (2012) State-of-the-Art Reactor Consequence Analyses (SOARCA) Report: Part 1&2
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27. NUREG-7110 (2013) State-of-the-Art Reactor Consequence Analyses (SOARCA): Integrated Analysis Volume 1&2
28. Periodic Review of Regulatory Guide 1.101 (2013)
29. Nuclear Energy Institute (NEI). (2007). Guidance Range of Protective Actions for Nuclear Power Plant Incidents, 2007

30. Nuclear Energy Institute (NEI). (2013). Proposed Methodology and Criteria for Establishing the Technical Basis for Small Modular Reactor Emergency Planning Zone, 2013
31. U.S. Nuclear Regulatory Commission (USNRC). (2013). Evacuation Time Estimate Update, Adams Portal ML13193A348, 2013
32. Sandia National Laboratory - SAND2013-3683 - Evaluation of the Applicability of Existing Nuclear Power Plant Regulatory Requirements in the U.S.to Advanced Small Modular Reactors
33. Regulatory Guide 4.7 Rev 3 (2014) - General Site Suitability Criteria for Nuclear Power Stations
34. NUREG-0654/FEMA-REP-1 Rev 2 (2015) – Pre-decisional Draft, Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants (Planned release in 2017 delayed)
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37. Idaho National Laboratory - INL/EXT-14-33137 – Opportunities in SMR Emergency Planning
38. NUREG-2206 (2018) - Technical Basis for the Containment Protection and Release Reduction Rulemaking Boiling Water Reactors
39. NUREG/CR-7245 (2018) State-of-the-Art Reactor Consequence Analysis Project: Sequoyah Integrated Deterministic and Uncertainty Analyses
40. NUREG/CR-7269 (2020) Enhancing Guidance for Evacuation Time Estimate Studies

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Chapter 3: Making the Most of a Model: Interrogation Methods for Computer Codes[20]

Abstract

Computer code models have become the default tool for analysis in many areas of research and industry. The research for evaluating these models has been primarily focused on theoretical simulation methods and overlooks the application of these methods. Many existing and highly valued computer codes and models do not allow for simulation, uncertainty quantification, or other modern computing capabilities. These limited computer codes are generally comprised of two categories: those with restricted operation by design and older legacy codes. Updating these software codes is not an option in many situations due to time constraints, cost, loss of skills needed to upgrade aging programming languages, lack of access to source code, and other constraints. This paper compiles and evaluates methods to interrogate computer codes systematically, including reduced iteration design of experiments (DoE) methods. While several of these methods are routinely used in other fields, they have not been applied to explore computer code models. This paper discusses the challenges present when evaluating computer codes and offers a decision framework for selecting interrogation methods. An example case study application of a definitive screening design (DSD) to aerosol

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[20] Published as Adam Stein, Kenneth Redus, and Paul Fischbeck, “Making the Most of a Model: Interrogation Methods for Computer Codes,” engrXiv, Nov. 2020, doi: 10.31224/osf.io/npqs2.

transport modeling using the Atmospheric Relative Concentrations in Building Wakes (ARCON96) computer code is provided to illustrate the use of the decision framework and application of DoE fractional factorial designs to computer codes.

Acronyms and Abbreviations

ARCON96	Atmospheric Relative Concentrations in Building Wakes
DoE	Design of Experiments
DSD	Definitive Screening Design
ME	Main Effects
OFAT	One Factor At a Time
χ/Q	Atmospheric Relative Concentration (Chi/Q)

1 Introduction

Computer code models have become the default tool for analysis in many areas of research and industry. Understanding how to explore these models effectively is useful to researchers and code operators alike. Computer code models are commonly used to calculate one result without mechanisms to consider uncertainty or sensitivity, leading to inefficient and incomplete analyses. Further, the application of theoretical statistical methods for evaluating these computer codes and models has been limited. In this paper, a computer code is defined as a computer program or software that contains a model representation of a system. A computer code model, or computer model, is the portion of the code that calculates a response output from inputs. The distinction seems obvious but is inconsistently defined in a large portion of the literature.

Proper experiment design is needed to ensure the model input factors are varied in a way that fully interrogates the model. Multiple iterations, or 'runs,' are needed for sampling, uncertainty quantification, and reliability analyses. Simulation and similar methods have been the focus of research for this purpose [60]–[62]. These methods are generally applied to complex computer models that have been designed to be compatible with simulation. However, simulation is not compatible with the design and operation of many computer codes and models. Therefore, other analysis methods must be considered to interrogate these computer codes. To address this gap, this paper provides a framework for the selection of an analysis method that explicitly delineates the challenges that must be considered. An example case study is presented.

Many computer codes were designed to complete a function, and only that function, as efficiently as possible. Older legacy codes were written when the computational cost was at a higher premium, using less advanced programming languages, necessitating simple design. Despite a significant reduction in computational costs and the development of more advanced computer languages, many modern codes are still written with limited functionality. This is done to make it less costly to develop, easier to maintain, or simpler to validate. While these limitations were designed into the code for resource or functional efficiency, they also create challenges for evaluation. A large body of literature exists on operating computer code models [61]–[64], but little has been published on effective and appropriate methods to operate limited or legacy computer codes systematically. We present methods that could be applied to interrogate these common and valuable computer codes, along with a decision framework to select a method that will function with a specific computer code.

One largely unexplored approach that could be used to interrogate computer code models is the design of experiments (DoE). These methods have long been used to characterize physical models and are prevalent in many fields, including scientific studies and industrial quality control. Instead of prescribing parameters and running physical experiments, the process of getting data from most computer models more closely resembles *interrogation*. In this context, interrogation can be thought of as asking code-specific questions. In this paper, we propose the application of factorial experiment designs to interrogate an existing model or code where other methods are not well suited.

This paper is organized into four main sections. First, the challenge of utilizing codes that are not designed for multiple simulation use is described. Second, applicable methods and tools are collected and discussed. Third, the application of experimental design to interrogate an existing computer code model is presented. Finally, a case study applying a definitive screening design (DSD) method to the aerosol transport modeling code ARCON96[21] is provided.

2 Current Challenges

There are many challenges to interrogating an existing code. These challenges are often overlooked in the literature and left to the operator to solve. Challenges vary widely based on the characteristics of the code being used, the model contained in the code, and the use case. Seven challenges are discussed in this section, and solutions are presented where possible.

2.1 System Design and Opacity

Experiment design is used to structure experimental observations of a system. The observations are often used to make an experimentally determined empirical model. These models are often called extrinsic because they are defined from the external behavior of the system and not the internal function. A mechanistic model is not based on observations, but instead employ an understanding of the underlying phenomena that define the function of the model.

Model opacity refers to the level of knowledge that is available about the model contained in the computer code, as described in Figure 7. An extrinsic model, a mechanistic model, or a combination of the two, might be contained in an "opaque box"

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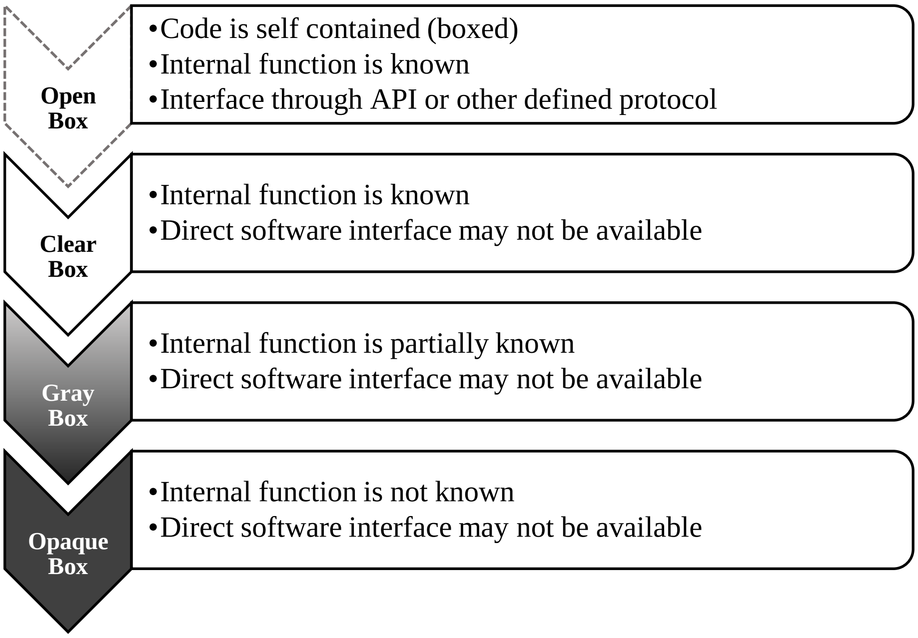
[21] Atmospheric Relative Concentrations in Building Wakes (ARCON96) code is a US Nuclear Regulatory Commission (NRC) code typically used to calculate relative atmospheric concentrations at control room air intakes relative to plumes from hypothetical nuclear power plants accidental releases. As of this writing ARCON96 can be found at https://ramp.nrc-gateway.gov/content/arcon-overview

system[22]. Gray or clear box systems are where some or all of the internal function of the system is known, respectively. Open-box codes provide access to the code and model directly and usually also provide a way to interface with the code. A spreadsheet-based model is a good example of open-box. If the spreadsheet is later locked, it would appear as an opaque box to a new operator.



- Code is self contained (boxed)
- Internal function is known
- Interface through API or other defined protocol

- Internal function is known
- Direct software interface may not be available

- Internal function is partially known
- Direct software interface may not be available

- Internal function is not known
- Direct software interface may not be available

Figure 7: Hierarchy of code system knowledge and connectivity

Connectivity is the ability to interact with the model, such as a direct interface or a communication protocol. It does not affect the function of the model directly but does limit the methods that can be used to interact with the code. The level of opacity is important for selecting the analysis strategy that is best suited to the use case.

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[22] Sometimes referred to as 'black box' and 'white box' systems

2.2 Statistically Valid Results and Uncertainty

Computer models are often representations of a real-world system. Even with calibration, verification, and validation, a computer code rarely models a physical system perfectly because the input data to the system is necessarily a sample of the full data set. The data set used to design, test, and train the model is usually not included with the model. Further, only the most accurately documented models include variance and uncertainty quantification along with methods and formulas.

Opaque and gray box systems make it impossible to know the ability of the model to describe the original system because the internal function and data that were used to define that structure are unknown. When using and interrogating computer code models, it is important to understand that you are subject to the assumptions, conventions, bias, and uncertainty of the computer model.

Model inputs are another source of uncertainty entering the system. When interrogating a model, it is common to use a range of input values regardless of the interrogation technique. The input values should be selected carefully to ensure they are feasible values and are based on reasonable and logical assumptions. Selecting values that are too broad (i.e., beyond the range of the model) or too narrow can result in invalid responses. Not all codes have safeguards built in to avoid out-of-range inputs, so it is prudent to be cautious.

2.3 Operational Design

The operational design of code operation must be considered when selecting statistical experimental design methods. The operational characteristics and both the ability and method of the operator to interface with the code are often overlooked. Codes that have a built-in simulation tool or are easy to integrate with a separate simulation tool have the lowest barrier to operator use. Uncertainty can be explored through extensive interrogation with methods discussed in Section 3.2. A single run code, one that is designed to provide a response in one operation, poses limitations. These codes are not easy to use in a batch or simulation manner. The operator interface design may require direct interaction that completely prevents the use of a separate simulation tool.

Many runs are needed even for the smallest experimental design. Single run codes require additional operator time to set up and run each iteration. Operator expertise can reduce the time needed for each run but is unlikely to match the time savings of a simulation tool. The barriers to simulation usually result in 'normal' operation as described in Section 3.1. However, these codes are typically good candidates for DoE methods, discussed in Section 3.4.

There are exceptions, such as finite element analysis models, that take extensive computational time to run and, therefore, might only be run once. In this case, it is important to quantify and reduce uncertainty as much as possible in the experiment design prior to simulation.

2.4 Code Alteration

Some codes are not designed in a way that allows multiple runs (e.g., ARCON96 discussed in Section 5). It may not be possible to upgrade codes to operate for multiple iterations for a variety of reasons. For instance, the source code could be lost, necessary programming skills are lost, insufficient time or budget is available, and other possible reasons. Third-party codes often cannot be altered.

Simulation tools can be very powerful, but they are only useful when the code can be operated for multiple iterations and is compatible with the simulation tool. Many existing codes were not intended to be run remotely (i.e., by another code) and do not provide API or file access that simulation codes can leverage.

If the code is validated for function (i.e., has been certified in some way and the code functions and provides the expected responses), then altering the code would likely void that validation. If the validation is important to the experiment, to certify that the code is performing the function it was intended to perform, then altering the code is not an option.

2.5 Constrained Design Regions

Constrained design regions exist when factors are limited in combinations or ranges. They can exist for categorical or continuous factors. Mixtures are a typical example where a formulation contains proportions of ingredients up to 100%, but some may only be possible in a limited range. Physical systems such as pressure vessels that can operate in a limited range of temperature and pressure combinations provide another example.

Care must be taken only to interrogate the model with feasible factor parameters. Two general methods exist to accomplish this need. Input factor scenarios can be carefully selected to avoid constrained design regions or techniques can be used to adapt analysis methods to address a constrained design region. Techniques vary by the analysis method used and should be considered prior to interrogation if a constrained design region exists.

2.6 New Use Cases

New use cases provide an opportunity to extend the value of an existing code without creating a new computer code. In some situations, the existing code is applicable but cannot be used as-is, and a new operational method must be developed. Even if a modeler with the necessary experience is available, it may take significant time to design an operational method. One example of a new use case will be illustrated in the case study in Section 5 of this paper.

2.7 Replacement Value

The value of overcoming these challenges should be weighed against the option of replacing the existing computer code model with a more capable computer code. Computer codes require significant time and resources to develop. However, there are often co-benefits associated with developing a new computer code that makes the investment worthwhile, including simplified maintenance, the ability to add features, and uncertainty/sensitivity analysis capabilities. It may not be justifiable to develop a new code, such as when the existing code is used infrequently, there is a short deadline for a project, or no development funding exists. Replacement of gray and opaque box computer code models may not be possible due to insufficient understanding of the underlying foundation. When code verification and validation are necessary, there will be additional development time and cost.

3 Methods and Tools

The selection of an interrogation method must consider the characteristics of the computer code and specific challenges, such as those discussed in Section 2. To explore an existing model or code, there are five main options.

1. Normal operation
2. Scenario analysis
3. Simulation tools
4. Design of Experiments (DoE)
5. Reduced-form models

The development of an analysis plan requires an understanding of the computer model, characteristics, and limitations of analysis design options, and the resources available. The goal of the analysis plan should be clearly understood prior to selecting a method that will achieve that goal. This is especially a concern when multiple methods are sufficient to analyze the computer code but may not result in the desired goal. Goals commonly include determining model response in a specified range of inputs but can also be to understand the processes and functions of the computer code model. The decision tool in Figure 8 is provided to guide the selection process. Further discussion of the analysis options is provided in the subsequent sections.

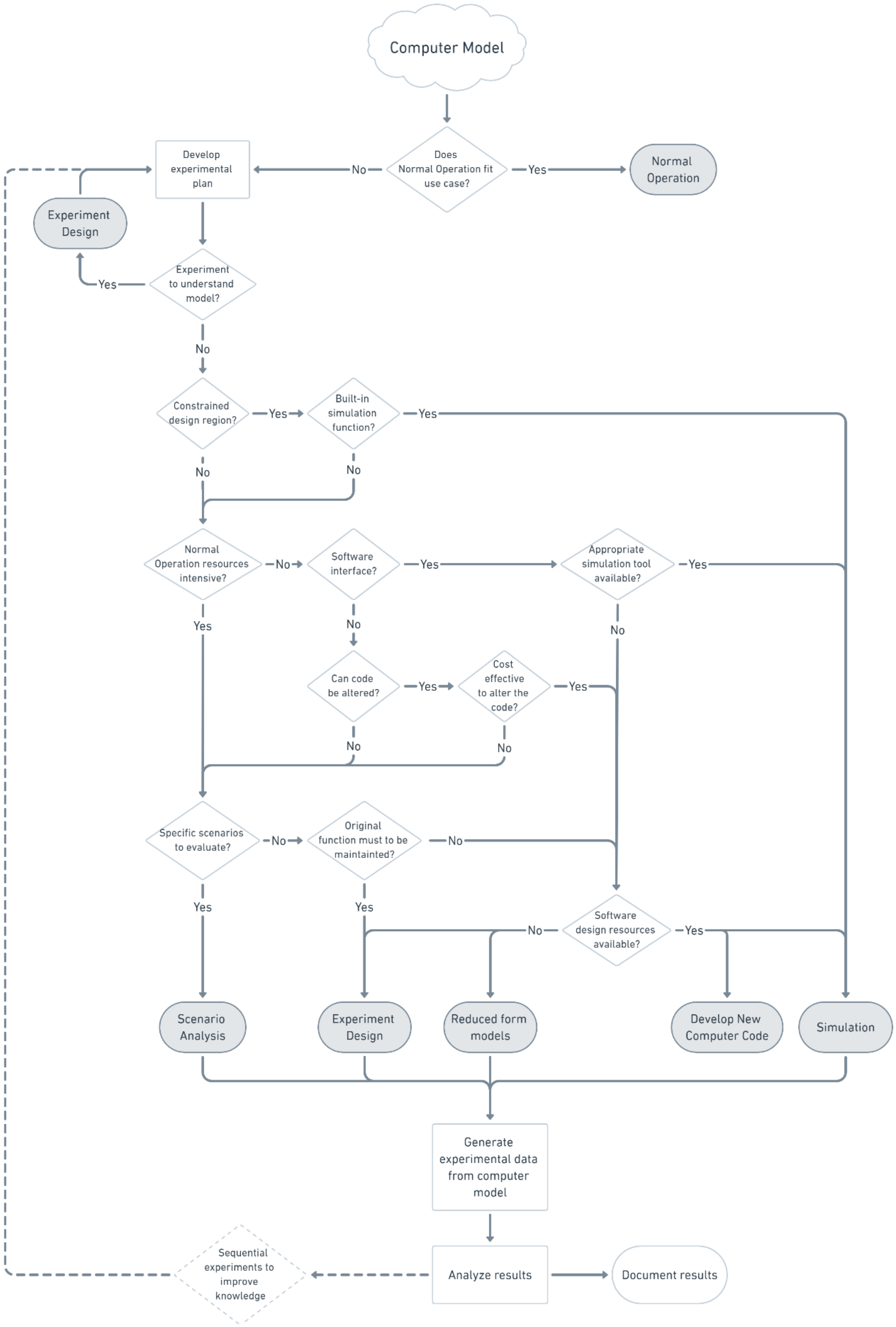

Figure 8: A decision framework for selection of computer code analysis strategies

The following options assume a few points: The modeler has the skills necessary to operate the model. The methods described herein are to enable augmented use of the existing model. Factor levels can be set independently of the level of any other factor. Models can be deterministic or stochastic, but the input factors can be manipulated in a controlled way. It is assumed that the computer model being interrogated is a valid model or it would not be considered for further use.

3.1 Normal Operation

Normal operation is the usual practice but often limits model operation to an original use case. While the normal operation is common, in many cases it does not involve statistically exploring the code. Many operators simply use best assumption input values and run the code one time, avoiding any sensitivity or uncertainty analysis. This is especially true when uncertainty tools are not built into the model.

Using the model in normal operation avoids the need to invest in learning the new skills required for the other options. Under normal operation cases, the input factors should be well known. Fully exploring the model in normal operation requires a brute force approach to complete many runs, which is inefficient and often not feasible. If normal operation is selected as the appropriate strategy for the experiment, the analysis plan should include a detailed workflow checklist, quality assurance, and data management plan. The purpose is to reduce errors that will be difficult to detect later and to potentially reduce the time needed by streamlining the process.

3.2 Scenario Analysis

Scenario analysis is often called 'what-if' analysis and calculates a model response to understand one possible situation or scenario. This approach is used to make the analysis more tractable when the model is too complex for full interrogation of the design region, or when an understanding of specific scenarios is needed, and the remainder of the design region is not of interest. For example, in risk analysis, this approach is commonly used when there are expected modes of failure in a system that can be used as the basis for scenarios. The number of runs needed is defined by the number of scenarios the operator chooses to explore.

Scenario analysis is similar to normal operation in many ways. The code is usually operated in the normal manner and inputs are varied. The analysis plan for a scenario analysis generally includes sets of inputs selected determined to be the best estimates of specific scenarios. Sensitivity analysis is occasionally employed and usually uses an OFAT method. Many DoE methods are also capable of scenario sensitivity analysis if the input boundary values are properly defined. Several of these DoE methods have the advantage of being able to detect factor interaction and higher-order effects.

3.3 Simulation

Simulation[23] allows for semi-automated iteration and interrogation of a computer code model across the defined range of inputs. A simulation tool can be used to iterate a model for hundreds or thousands of runs if needed. These tools often provide a more

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[23] Simulation is commonly referred to as batch processing in industry applications. Batch processing may also refer to a mixture of simulation and scenario analysis

extensive suite of modeling tools for uncertainty quantification. Consequently, it is desirable to fill the experimental region with points as efficiently as possible (i.e., space-filling designs) so that each run provides additional information and captures variability between input factors and the model response. This is a desirable feature if the experimenter does not know the form of the model that is required and believes that interesting phenomena are likely to be found in different regions of the experimental space.

From an experimental design perspective, space-filling designs are often appropriate for deterministic computer models because interrogation points are spread systematically throughout the region of experimentation [61]. Space-filling designs generally do not contain any replicate runs. For a deterministic computer model, this is desirable because a single run of the computer model at an interrogation point provides all of the information about the response at that point. Methods for space-filling designs include Latin Hypercube design [58], [65], spherical packing maximin design [63], Bayesian probabilistic sensitivity [66], and Gaussian process [62].

Simulation can also be a useful interrogation strategy for codes that contain stochastic models which do not return the same response with each run. A Monte Carlo simulation is a common design choice for interrogating stochastic models. In a Monte Carlo model, pseudo-random values are used for interrogation points instead of a structured space-filling design. Replicate runs can be useful in a stochastic model where a different response can occur with the same inputs. Monte Carlo models do not usually limit replicate runs, but the occurrence of replication is usually by chance. Some tools provide options to intentionally replicate runs.

Simulation tools can be used in some cases to interface directly with existing models. Some can be used to 'control' existing codes by direct control of input text files or calling commands. When this option is available, it can be a powerful way to interrogate a model. Significant effort is usually required to set up a simulation tool to interface with a code, even if that code is open-box. If the computer code is a closed system, it may not be possible to use a simulation tool. The time required to develop the interface, expertise with both the computer code being interrogated and the simulation tool, and limitations to the computer code model platforms that specialized simulation tools can interface should be considered. If a suitable tool is available, the investment may be a net benefit compared to alternative methods. While there are some open simulation tools, the majority are complex commercial products.

3.4 Design of Experiments

The design of Experiments (DoE) methods are used to interrogate a system or model in a systematic and statistically valid way. Many examples exist in the literature including full factorial [67], fractional factorial [68], split-plot [69], Plackett-Burman [70], Box-Behnken [71], optimal designs (D-criterion) [72], definitive screening design (DSD) [73], [74], augmented DSD [75]. Experiment designs can be selected to meet the needs or characteristics of the model. These characteristics may include factor interactions, nonlinearity, and constrained design regions. Tools exist to assist in experiment design using a range of methods.

Separation of control and noise factors is usually an important consideration in experimental design to enable reduction of variance. This is especially important for quality control in manufacturing. To address this, techniques such as randomization, blocking, and replication are often employed. Defined computer codes using deterministic models are expected to provide consistently the same results for a set vector of inputs without noise. Therefore, the extra consideration and techniques used to isolate and characterize the effect of systemic variance or noise are unnecessary with deterministic computer codes. Epistemic variance may still exist if the model contains stochastic factors.

The one factor at a time (OFAT) method involves the selection of a baseline for each factor and then successively varying each factor over its range with the other factors held constant at the baseline level. OFAT is analogous to sensitivity analysis used in many other fields and is very common for modelers to perform when testing model output. Factorial designs can provide more information or evaluate more factors with less or equal computational cost than OFAT experiments, making them more efficient [60]. Factorial designs are able to detect interaction effects, where changing the level of one factor changes the output effect caused by a second factor, something OFAT cannot detect [60].

Experimental design methods often offer a significant reduction in the number of runs needed compared to other approaches. It is attractive to limit the number of runs needed when each run is expensive in terms of resources; cost, time, and limited opportunities to test. In the case of computer code models, the expense is usually in run setup or computation time. DSDs are inexpensive to implement, requiring only a minimum of $2m+1$ runs where m represents the number of factors [73]. Reducing workload and expense is beneficial even when the model that is being interrogated is readily available and open.

Screening designs are a family of experiment design methods that are used to identify the main effects (ME) of a system. A testing framework is used to ensure the set of possible factor combinations is explored in a sophisticated manner. Levels for each factor, often two or three levels per factor depending on the design, are selected for analysis. A particular design may be more appropriately matched to the application needed or desired results.

3.5 Reduced-Form Model

Reduced-form models have also been referred to as surrogate models [76] or metamodels [60]. Reduced-form models are used when the existing model is too resource-intensive to operate in a simulation manner, and DoE methods will not provide a sufficient understanding of the model response. Despite a body of literature on other applications, reduced-form models of computer codes have significant limitations for limited and legacy computer codes and should be considered as a last resort. This is especially true for validated codes that cannot be readily replaced by a surrogate model.

A reduced-form model involves making a new but simpler metamodel that attempts to provide the same results. To create a reduced-form model, an input dataset paired with output response is needed. Another analysis is used to generate computer model responses and a metamodel is developed from the model response. Factor combinations in the input dataset should be carefully selected to ensure the reduced-form model covers the needed design region of the original model. Methods such as fractional factorial design can be used, but OFAT is often used because the modeler does not have experience with DoE methods.

It is assumed that the computer code being interrogated is a valid model, or it would not be considered for further use. Despite this assumption, the computer model is still a representation of the actual system and therefore does not perfectly describe the actual system. Extrapolating a reduced form model from the original computer code model further removes the response from the actual system. Without a complete understanding of the inner working of the code (i.e., opaque box), it is difficult to build a reduced-form model that is representative of the computer code model. If the model is well understood, and a reduced-form model is only being considered to allow for simulation operation, it may be a better choice to build a new computer model.

Reduced-form models generally require follow-up experiments or validation using existing data. The reduced form model is ideally trained from the same data that the original model was trained on. However, it is not common for the initial training data to be provided with the original model. Depending on the complexity of the model, many runs (1,000-100,000) may be needed to train and test the reduced-form model sufficiently. The need for this many runs of the computer code is self-defeating if the goal is to create a less resource-intensive model for simulation. To verify and validate the reduced form model, a new test data set is required. Without this step, the variance between the computer code model and the reduced-form model can be determined, but there is no way to know how well the reduced-form model describes the original system.

4 Application of Factorial Designs

The state of knowledge can be advanced through a sequence of staged experiments: screening, effect estimation, optimization, and mechanistic model. Factorial designs are well suited to screening and effect estimation, and some are useful for optimization. Creating a new mechanistic model is beyond the capabilities of a factorial experiment that is being applied to a surrogate model (i.e., computer code model instead of a physical system). Building a mechanistic model requires a deep understanding of the system operation and phenomena along with data to test and validate, similar to a reduced-form model.

Factorial designs are usually employed in a design of experiments program aimed at collecting new data. Their most common use is in the earliest stages of experimentation when a large number of potentially important factors may affect a response of interest, and when the goal is to identify the generally fewer highly influential factors. Screening designs allow for a significant reduction in the number of runs needed compared to a simulation approach. Reducing the number of runs may offer a significant saving in time and cost.

Factorial designs are useful for interrogating legacy or complex computer codes in multiple ways. They allow the codes to be used in a 'non-intrusive' manner, not affecting the code or the results directly. This is especially important for codes that either cannot be modified, cannot be used with third-party simulation tools, or are opaque-box third-party codes that are not allowed to be changed.

As the number of factors m (input factors) increases, the number of runs required increases to the point that can make full factorial designs impractical and inefficient. The sparsity principle states that most of the variability in a system or process output is due to a small number of inputs. Effect sparsity indicates that the number of active effects compared with active factors is relatively small. For example, for a problem with seven factors (input factors) each at two possible values, a full 2^7 design requires 128 runs, but the sparsity of effects means only a subset of the 7 factors and 21 two-way interactions (7 choose 2 combinations) are likely significant. As such, only a fraction of the complete 128 runs is required to obtain estimates on significant effects. Following this logic, reduced run designs have been developed to be more efficient in terms of design size.

The heredity principle is commonly used when considering model selection. Strong heredity implies that if a model includes a two-factor interaction, then its constituent main effects are included in the model. Weak heredity implies that constituent main effects are not included in the model. Robustness to assumptions of model heredity and sparsity is not uniform across all factorial designs [77].

Several advantages are associated with DSD compared to most factorial designs [73]. The main effects are completely independent of two-factor interactions. Two-factor interactions may be correlated but are not completely confounded by other two-factor interactions. Nonlinearity can be detected, and the responsible factors can be identified. Unlike most designs, quadratic effects are estimable, and the responsible factors can be identified. Augmented DSD can be used to include categorical factors [75]. If a classical response surface design is used with a subset of model factors, usually to reduce the number of runs needed, there is a risk of missing other important factors. Conversely, if a screening experiment is used to avoid missing important factors, interactions and quadratic effects will be missed. The DSD approach can be used for simultaneous screening and response surface exploration using quantitative factors with three levels.

Using one of these designs with six or more three-level factors allows fitting the full quadratic model involving any subset of three three-level factors.

After a screening design is selected, factors need to be identified, and feasible and reasonable levels need to be selected. Screening designs often use two levels for each factor, a high (+) and low (-) value. The "+" and "-" representation is a DoE shorthand notation, and its key benefit is illustrating many combinations of many levels of many factors. Some screening designs use three or more levels for each factor to allow for the estimation of factor interactions and quadratic effects. Once the screen and levels are selected, the factors should be entered into the code and run as specified by the screening design, as depicted in Table 6. In this example, eleven factors are identified. Twelve runs of the code are performed where each run sets the factor value at its high (+) or low (-) value. For example, the first run of the code sets factors A, C, G, H, I, and K at the "high" values of the factor, and it sets factors B, D, E, F, and J at the "low" values of the factor. Contrast this to the 12th run of the code in which all values for factors A, B, C … K is set at the "low" value of each factor.

Level selections should be guided by the specific experimental design. Normally three levels for a factor are selected as the lower bound, midpoint, and upper bound. When there is more insight into the model operation (clear or gray box) alternate levels might produce more useful results. When a factor has a default or normal value that is close to the center it can be beneficial to use that value instead in a low, normal, high configuration. For example, if the voltage in a system has a lower bound of 10V and a high bound of 14V, the center would be 12V. If the system usually operates at 12.6V, which is greater than the midpoint of the range, it can be beneficial to use 12.6V in the analysis. Doing so allows the response to be directly usable by the operator as a 'normal' condition without additional analysis. However, some factorial designs require the use of a center value for statistical validity.

Table 6: An example 12-run Plackett-Burman Design for 11 factors. Input factors are alternated low (-) or high (+) systematically.

		Factors (*m*)										
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Run	**1**	+	-	+	-	-	-	+	+	+	-	+
	2	+	+	-	+	-	-	-	+	+	+	-
	3	-	+	+	-	+	-	-	-	+	+	+
	4	+	-	+	+	-	+	-	-	-	+	+
	5	+	+	-	+	+	-	+	-	-	-	+
	6	+	+	+	-	+	+	-	+	-	-	-
	7	-	+	+	+	-	+	+	-	+	-	-
	8	-	-	+	+	+	-	+	+	-	+	-
	9	-	-	-	+	+	+	-	+	+	-	+
	10	+	-	-	-	+	+	+	-	+	+	-
	11	-	+	-	-	-	+	+	+	-	+	+
	12	-	-	-	-	-	-	-	-	-	-	-

Of keen interest in using DoE on computer models is to select a design that incorporates as many key factors as possible. Although high statistical power is always required when stating that a factor indeed has a statistically significant effect on the response, Santos et al. noted that statistical power does not prove a coefficient for a factor is properly estimated by the model generated by DoE [78]. Therefore, it is more important to select a design to match the factor than to have high statistical power. When using a DSD, if additional statistical power is desired beyond the minimum number of runs, additional dummy factors can be added, and then extra columns removed.

Blocking is a DoE technique used to control for variability from known and controllable factors [60]. Batches of raw material that may control some variation are an example of a controllable factor. Blocking is not necessary with a computer code model that is not stochastic and, therefore, is expected to provide reproducible consistent results.

Results can be used to explore intermediate values that were not used in the factor parameters. Experimental plans must be modified if a previously unknown but highly influential factor is discovered, the chosen range for one or more factors is infeasible, or factors cannot be varied independently. A screening experiment may not be able to lead directly to the desired state of knowledge. In these situations, the sequential experimentation strategy is sometimes abandoned in favor of a single design or set of experiments. The case study in Section 5 provides an example of this situation.

5 Case Study: ARCON96

ARCON96 is a computer code used to calculate relative atmospheric concentrations (χ/Q)[24] in building wakes [79]. The primary use of ARCON96 is in support of control room habitability calculations for nuclear power plants. The code is designed to input site parameters along with a year of continuous weather data for that same site. ARCON96 uses the weather data to calculate probabilistic χ/Q atmospheric concentration values for that site and situation. A complex evidence-based model is behind that calculation. Documentation is available on the basic operation and inputs

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[24] The χ/Q is defined to be the relative atmospheric concentration at a receptor location per unit release rate of the material at a release location upwind of the receptor. For material given in terms of Ci, for example, the χ/Q has units of Ci/m^3 per Ci/s. This is normally condensed to s/m^3 with the units associated with the material (Ci, g, mg, etc.) canceling and, therefore, being completely arbitrary.

without underlying model flow diagrams, data, or a full set of equations making this a gray box code.

The case study analysis plan and code characteristics exemplify many of the challenges discussed in this paper. ARCON96 is a legacy code with operational capabilities that were limited by design. The internal operation of the code and model is known to some extent, which makes this a gray box code (Section 2.1). The documentation indicates that the model does a statistical analysis of input factors based on physical experiment data. Quantification of the uncertainty and variance between the physical data and the model is not provided (Section 2.2). The code operation is limited in function and ability to interface with other codes (Section 2.3). Code alteration is not possible due to the code not being available (Section 2.4). Further, the code is validated and widely used for nuclear facility regulation and licensing. Alteration of the code would require re-validation. A constrained design region may exist (Section 2.5). Finally, a new use case for ARCON96 is presented to address the changing needs of nuclear facility licensing without the need to alter the code or develop a new computer code (Section 2.6). Following the analysis method selection framework (Figure 8), an experimental design was selected for this case study, specifically a DSD design.

5.1 Different Use Case

The purpose of this case study is to use the already validated and unmodified code for an alternative use case: calculating χ/Q values for many locations relative to the dispersion source. The χ/Q values are a necessary component for defining the Low Population Zone and Exclusion Area Boundary for nuclear power plant siting. Typically, this process is completed with a different computer code called PAVAN. However, limitations in PAVAN do not allow for calculation near building wakes or near-field (very close) to the dispersion source. The ARCON96 code is designed to operate with these constraints but not to consider a range of distances between the source and receptor. Therefore, an experiment must be designed to interrogate the ARCON96 model in a way that provides the needed response for this alternative use case. Analysis of the full design region and internal operation of ARCON96 is beyond the analysis plan for the presented use case is left for future work.

The model contained in ARCON96 is designed to use empirical and representative weather data to calculate probabilistic χ/Q values for a point-to-point dispersion (e.g., source to control room intake). The model inside ARCON96 can be leveraged to compute χ/Q values for a range of distances, weather patterns, and other site characteristics.

5.2 Operation

ARCON96 is designed for single-run operation. Input factors are considered fixed rather than random effects. Stochastic inputs are not used, and outputs are deterministic and repeatable based on the inputs. ARCON96 was developed in 1996 and did not reflect contemporary software engineering. A user interface exists but is not operable with a modern 64-bit operating system; therefore, operation is performed through the command line. Input consists of complex text files with a very specific format, and therefore error-prone and labor-intensive. Direct text file manipulation for inputs and output makes it easy to overlook a small detail and overwrite prior runs. This is not a large concern for the normal use case of one run, but the risk of error and effort is much higher if a large number of runs are needed. Experience from this case study suggests an experienced operator could create approximately one input file every 5-7 minutes. Once set up, ARCON96 completes an iteration of the code in less than a minute. An additional three minutes is needed to manually copy results from the output files and place them into an appropriate analysis tool for a total of approximately 9-11 minutes per run.

Creating a reduced-form model (i.e., replacing the code with a representative model) that approximates ARCON96 would be a major undertaking. The ARCON96 code is managed under strict regulatory guidelines and is not available for augmentation. The potential is further limited by the lack of access to the full experimental data sets used to build the original model. In this circumstance, the largest barrier to augmenting or replacing the existing model is regulatory acceptability. ARCON96 is a validated code that has been accepted for regulatory use. Using the code in an unaltered state allows the operator to avoid the significant delay and, depending on the situation, a significant cost for validation of a new model. DoE methods enable the use of ARCON96 in an unaltered state while significantly reducing the number of runs and, therefore, the time and cost needed.

5.3 Experiment Design

This case study utilizes DSD to interrogate the ARCON96 code. Factor parameters shown in Table 7 are defined to match the previously described use case and described in detail in the Appendix and [80]. Simplifying assumptions are used in some cases to give bounding values, such as defining the weather files so that the wind always blows at the receptor. A constrained design region has been avoided through an understanding of the use case and proper and feasible parameter selection.

Table 7: ARCON96 factor identification for DSD model

FACTOR ID	Variable	Type
A	Pasquill Stability Class	Mixed
B	Wind Speed (mph)	Continuous
C	Building Area (m2)	Continuous
D	Distance to Receptor (m)	Continuous
E	Receptor Height (m)	Continuous
F	Terrain Elevation Difference (m)	Continuous
G	Surface Roughness	Continuous
H	Initial σy, σz	Continuous

The normal operation of ARCON96 uses weather data (stability class, wind speed, wind direction) for a specific site. This data includes a natural variation that inhibits the ability of the experiment design to find the impact on system response from these factors. If significant factor interactions are present, the weather variation may skew their estimated effects as well. To avoid that conflict, these factors are controlled as inputs. Although a full year of a single stability class, wind speed, and wind direction aimed directly at a receptor is unrealistic, it allows for control of the model to the extent needed for the experimental design. The response is expected to result in conservative values (higher) for all runs.

Table 8: Experiment design and results for ARCON96 model interrogation study

		Factor								**Response (s/m^3)**		
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**χ/Q 0-2 hours**	**χ/Q 2-8 hours**	**χ/Q 8-24 hours**
Run	**1**	0	-	+	+	-	+	+	+	8.28E-05	8.28E-05	5.28E-05
	2	0	+	-	-	+	-	-	-	5.22E-03	5.22E-03	3.33E-03
	3	-	0	-	+	+	+	+	-	2.50E-05	2.50E-05	1.60E-05
	4	+	0	+	-	-	-	-	+	1.09E-02	1.09E-02	5.87E-03
	5	-	-	0	+	+	-	-	+	4.35E-05	4.35E-05	2.77E-05
	6	+	+	0	-	-	+	+	-	7.55E-03	7.55E-03	4.06E-03
	7	+	-	+	0	+	+	-	-	3.96E-04	3.96E-04	2.13E-04
	8	-	+	-	0	-	-	+	+	6.89E-05	6.89E-05	4.39E-05
	9	-	-	+	-	0	-	+	-	7.55E-03	7.55E-03	4.82E-03
	10	+	+	-	+	0	+	-	+	5.73E-05	5.73E-05	3.65E-05
	11	+	-	-	-	+	0	+	+	9.96E-03	9.96E-03	5.35E-03
	12	-	+	+	+	-	0	-	-	1.20E-05	1.20E-05	7.64E-06
	13	-	+	+	-	+	+	0	+	1.31E-03	1.31E-03	8.37E-04
	14	+	-	-	+	-	-	0	-	9.96E-05	9.96E-05	6.35E-05
	15	+	+	+	+	+	-	+	0	4.77E-05	4.77E-05	3.04E-05
	16	-	-	-	-	-	+	-	0	5.73E-03	5.73E-03	3.08E-03
	17	0	0	0	0	0	0	0	0	4.77E-04	4.77E-04	3.04E-04

DSD uses three levels, usually low, middle, and high values, to provide estimates of main effects as well as two-factor interactions and quadratic effects while remaining unbiased by second-order effects. Only (*2m+1*) runs are required (where m is the number of factors) and confounding of any pair of second-order effects is avoided. Designs having six factors or more allow for the estimation of the full quadratic model in any three factors. The resulting design includes eight factors with three levels each. A full factorial design would require 3(8)+1=6,561 runs. If more than three levels are needed per factor, the number of runs needed increases rapidly. The DSD for eight factors described in

Table 8 reduces the needed runs to 17 (*2 x 8 +1*).

Extrapolating the estimated time to complete a run in the prior section, a full factorial design would take a prohibitive 985-1200 hours, and a DSD would roughly take 2.5 hours. This assumes an experienced operator and no errors. When a large number of runs are required (e.g., full factorial), setting up a separate simulation tool may be cost-effective to automate the process and reduce labor time. The structure of input and output text files is compatible with some simulation tools. However, the relatively low time needed for the DSD indicates a setup of a simulation tool for this specific use case is not resource-efficient; it would take longer to set up the simulation than would be saved by eliminating the operator.

Blocking techniques are possible with a DSD but are not needed for this experiment. The ARCON96 model provides deterministic and repeatable results without the kind of variation where a blocking technique would be required.

5.4 Results

System response is provided for three separate time intervals shown in

Table 8. Values for 0-2 hours and 2-8 hours are identical. This indicates that the experimental system response is invariable for these time periods across a wide range of factors. It should not be assumed, however, that the model itself is invariable without an explicit understanding of the model (i.e., clear or open box). The response may be very different if one of the factors that is fixed for this use case is altered.

A forward stepwise regression approach is recommended for the analysis of DSD experiment responses [73]. Results of the stepwise regression for the 8-24 hour time period were calculated using the R programming language and the Design and Analysis of Experiments with R (daewr) package [81], and are shown in Table 9.

Table 9: Stepwise regression results for the experimental model for the 8-24 hour time period based on runs 1-17

Factor	**Estimate**	**Std. Error**	**t statistic**	**P_r (>|t|)**
(Intercept)	3.18E-04	5.31E-05	5.99	3.91E-03
A	4.85E-04	1.66E-05	29.26	8.12E-06
E	-2.41E-04	1.66E-05	-14.54	1.30E-04
A:E	1.67E-04	2.70E-05	6.175	3.49E-03
B	-3.76E-04	1.66E-05	-22.67	2.24E-05
G	1.29E-04	1.66E-05	7.791	1.46E-03
B:G	-1.37E-04	2.12E-05	-6.49	2.91E-03
D	-1.94E-03	1.66E-05	-116.82	3.22E-08
D:G	-3.97E-04	2.08E-05	-19.11	4.42E-05
B^2	-1.56E-03	5.35E-05	-29.143	8.25E-06
G^2	1.33E-03	4.71E-05	28.26	9.33E-06
D^2	1.85E-03	5.85E-05	31.64	5.95E-06
F	-4.21E-04	1.66E-05	-25.38	1.43E-05
Residual standard error: 6.203e-05 on 4 degrees of freedom				
Multiple R-squared: 0.9998			Adjusted R-squared: 0.9992	
F-statistic: 1681 on 12 and 4 DF			p-value: 8.25e-07	

Suppose a simple OFAT sensitivity analysis was used to evaluate the model in a normal operation manner. The results would have suggested the χ/Q could be minimized by increasing receptor height (factor E). However, this method would not have discovered the positive interaction effects with stability class (factor A).

Similarly, distance to the receptor (factor D) is an order of magnitude larger in absolute terms, exhibits a second-order response, and interacts with several other factors. The alternative use case presented here is to determine the χ/Q values for a range of distances. ARCON96 is designed to evaluate χ/Q values for a single-factor configuration. The finding of factor interaction and non-linear higher-order effects is important to the alternative use case. This example clearly illustrates how a simple

OFAT approach would not have provided sufficient insight into the model response caused by the interaction of factors and higher-order effects.

5.5 Additional Runs to Address Challenges

Additional runs can be used to explore the model response further. The stability classes input is categorical and represent binned ranges of temperature differentials and are identified "A" through "G". However, the numeric values that define the stability classes are used in the ARCON96 model. Therefore, the regression in *Table* 9 is valid but not useful for modeling, as a categorical value cannot be used to forecast a result from a regression model. A surrogate numerical value (e.g., 1-7) to replace the categorical classes cannot be used because it may not match the underlying values in the opaque box model. Therefore, the best that can be achieved is to verify the results using additional runs as shown in Table 10 (runs 18 & 19) that isolate stability class (factor A).

The additional response values (run 18 & 19) were used to confirm the results in Table 9, indicating that stability class G (i.e., extremely stable) atmospheric conditions result in higher concentrations at the receptor. That result is in line with intuition. If the air is stable, it is less likely that particles will be scattered and more likely that they will flow directly forward to the receptor. Now that the result is verified, it can be used to bound the max and min combinations, which satisfies the needs of this use case.

Table 10: Additional runs 18 & 19 to check direction and magnitude of response due to stability class (factor A). Runs 20 & 21 were used as upper and lower bounds for the model response.

		Factor								**Response (s/m^3)**		
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**χ/Q 0-2 hours**	**χ/Q 2-8 hours**	**χ/Q 8-24 hours**
Runs	**18**	-	0	0	0	0	0	0	0	1.58E-04	1.58E-04	1.01E-04
	19	+	0	0	0	0	0	0	0	8.28E-04	8.28E-04	5.28E-04
	20	+	-	-	-	-	-	+	-	1.20E-02	1.20E-02	7.64E-03
	21	-	+	+	+	+	+	-	+	1.20E-05	1.20E-05	6.44E-06

Upper and lower estimate scenarios (run 20 & 21) were based on the sign of each factor in Table 9. The runs result in higher and lower responses as expected. It is important to note that the responses were very similar to runs 4 & 12, respectively, which have very different scenario designs. This finding adds further support to the complexity of the system that has already been shown through the stepwise regression analysis.

At this point, there is sufficient understanding of the model for operators that have weather data for a specific site or only need very conservative results. If a regression model is needed as a tool to estimate the response, then multiple experiments are needed.

5.6 Estimation Experiment Sets

Completing additional experiments is dependent on operator needs and outside the scope of this paper. Instead of providing direct results, a roadmap is presented for future use.

If specific site weather data is available for the time of analysis, only one additional experiment is needed. If real data is not available, it may be possible to create representative data files based on nearby weather stations or regional averages. The weather file removes two factors from the input. The resulting 6-factor DSD design (Table 12) will provide a predictive model using thirteen runs. Knowledge of the site surface roughness and building area can further limit the number of factors to four, requiring only nine runs.

Table 12: DSD design for 6 factors

		Factor					
		A	**B**	**C**	**D**	**E**	**F**
Run	**1**	0	+	-	-	-	-
	2	0	-	+	+	+	+
	3	+	0	-	+	+	-
	4	-	0	+	-	-	+
	5	-	-	0	+	-	-
	6	+	+	0	-	+	+
	7	-	+	+	0	+	-
	8	+	-	-	0	-	+
	9	+	-	+	-	0	-
	10	-	+	-	+	0	+
	11	+	+	+	+	-	0
	12	-	-	-	-	+	0
	13	0	0	0	0	0	0

Table 11: DSD Design for 7 factors.

		Factor						
		A	**B**	**C**	**D**	**E**	**F**	**G**
Run	**1**	0	+	-	+	-	+	-
	2	0	-	+	-	+	-	+
	3	-	0	+	-	+	+	-
	4	+	0	-	+	-	-	+
	5	+	-	0	+	+	+	+
	6	-	+	0	-	-	-	-
	7	+	-	-	0	+	-	-
	8	-	+	+	0	-	+	+
	9	-	-	+	+	0	-	-
	10	+	+	-	-	0	+	+
	11	-	+	-	+	+	0	+
	12	+	-	+	-	-	0	-
	13	+	+	+	+	+	-	0
	14	-	-	-	-	-	+	0
	15	0	0	0	0	0	0	0

If the weather data approach is not possible then a different approach is needed to avoid the obstacle presented by the stability class factor. In the case where only conservative results are needed, then stability class can be fixed as 'G' in all input files and a 7-factor DSD (Table 11) can be used.

Multiple experiments can be used to create models for each stability class, if needed, at the cost of 15 runs per stability class. Time to complete multiple experiments may be reduced in the case of ARCON96 because the text input files could be copied and reused with only the stability class and output file name requiring alteration. Once these models are created and runs completed, they will not need to be re-run unless factor levels fall outside of the range used in the DSD.

5.7 Discussion

Using the ARCON96 model for an alternative use case is possible but requires careful planning. The DSD approach provides reliable results using a significantly reduced number of runs. Additional runs can be used either for confirmation or a deeper understanding of the model.

The DSD analysis provides insight into the complex inner working of the ARCON96 model that is not provided in the documentation and is not apparent during model use. When ARCON96 is used for the originally designed use-case the majority of factors are fixed in value and therefore limit concerns that results are not representative of the true response. The major exception is weather data (e.g., stability class, wind speed, wind direction) that vary throughout the year. This data is usually provided directly to the model, which removes these factors as user inputs altogether.

Techniques can be used to address categorical factors with a continuous response, as is the case with stability class. However, the presented technique limits the use of stepwise regression results. Now that the ARCON96 is better understood, the stability class factor can either be fixed to represent a conservative scenario or replaced with real weather data relevant to the site. The former can provide a stepwise regression model that can be used for prediction, and the latter provides a more realistic response for a single location.

6 Conclusions

Interrogation of computer codes is a complex process, and multiple methods exist. Defaulting to normal operation or one factor at a time analysis can provide an insufficient understanding of the model. Selections of a method are based on operational characteristics, resources, time, and the required outcome. A decision framework was developed to guide analysis method selection based on code characteristics and challenges which may be present.

The application of experimental designs to computer code interrogation provides several benefits. DoE can be used effectively to replace normal operation and provide enhanced results. A more complete understanding of the model response can be achieved with a systematic design. Typically, experimental designs are used to limit the number of experiment runs required to interrogate a model and estimate main effects, factor interaction, and higher-order effects. This approach is useful for legacy or complex codes, particularly ones that are not upgradeable for a variety of reasons. In some situations, the code can be extended to new use cases without changing the code. This is also important for validated codes that cannot be altered.

A novel application of experimental design to interrogate an existing model or computer code was presented in the form of a case study using the code ARCON96. This code was designed more than twenty years ago. When the experimental design is carefully planned, it enables the use of an existing code for alternative use cases. While the operation of the code has several limitations, the underlying complex model is still valuable. Many of these limitations were addressed and overcome through experimental design techniques while maintaining the integrity of code validation.

7 Appendix – Chapter 3

This Appendix is published as a dataset:

Adam Stein, "Dataset - Interrogation of ARCON96 using a Definitive Screening Design," vol. 1, Oct. 2020, doi: 10.17632/4fcstkrrxm.1.

Abstract

This dataset supports the research article "Making the Most of a Model: Interrogation Methods for Computer Codes" [82]. This dataset contains output data in terms of X/Q and files for the operation of the Atmospheric Relative Concentrations in Building Wakes (ARCON96) computer code. The ARCON96 code is a US Nuclear Regulatory Commission (NRC) code that has been verified and validated to calculate relative atmospheric concentrations. The intended application of ARCON96 is calculating atmospheric concentrations at control room air intakes relative to plumes from hypothetical nuclear power plants accidental releases [79].

The dataset is the result of an experiment designed to interrogate the ARCON96 computer code. This experiment was designed to understand how factor parameters interact and affect atmospheric relative concentrations. The experiment used an eight factor Definitive Screening Design [73] to explore the feasible region. Seventeen code runs were completed for the experiment, followed by four additional runs to further explore regions of interest. The data are not representative of a single facility or site location, which would have specific factor parameters.

There are several reuse opportunities. First, the data can be used to understand the underlying model function of ARCON96 or as a verification and validation dataset to

test ARCON96 function. The next version of the code, ARCON 2.0, is expected to provide identical output values with a new user interface. This dataset can be used to verify the ARCON 2.0 output. Second, the data can be used as a surrogate for empirical values to understand the interaction of factors that drive atmospheric relative concentration. The dataset can be used as a basis for expansion to a larger dataset for the previously mentioned use case, saving significant time. Third, the outputs can be used directly for initial site planning and design related to nuclear power facilities.

Keywords

legacy code, design of experiment, uncertainty quantification, computer experiment, definitive screening design, atmospheric concentration, ARCON2

Specifications Table

Subject	**Mathematical Modelling**
Specific subject area	Computer code interrogation using experimental design techniques
Type of data	Raw Table
How data were acquired	Data generated by the ARCON96 computer code
Data format	Raw output files
Parameters for data collection	Output files are generated at completion of the code operation. Selection of model run parameters was made prior to code operation. Therefore, all output files contain unique and necessary data and were collected.
Description of data collection	Data was collected in the form of output files which are generated during operation of the computer code model. These files were retained after code operation and saved to another location.
Data source location	No specific location
Data accessibility	Repository name: Mendeley Data Data identification number: 10.17632/4fcstkrrxm.1 Direct URL to data: http://dx.doi.org/10.17632/4fcstkrrxm.1
Related research article	A. Stein, K. Redus, P. Fischbeck, Making the Most of a Model: Interrogation Methods for Computer Codes, CSDA. In Press.

Value of the Data

- The data is an outcome of a statistical experimental designed to screen input factors to ARCON96. The data characterizes the effect of individual factors and interaction of multiple factors on atmospheric relative concentration phenomena through structured experiment design.
- This data can be exploited by researchers understand the factor level effects on atmospheric concentration close to the release source (i.e. in the near-field). Further, this dataset can be used by those who wish to understand application experiment design to computer codes.

- The outputs can be used directly for initial site planning and design related to nuclear power facilities. This dataset can also used as a basis for expansion to a larger dataset, saving significant time.
- This data can be used to test ARCON96 function and further analysed to understand the underlying model function of ARCON96. The next version of the code, ARCON2.0, is expected to provide identical output values with a new user interface. This dataset can be used to verify the ARCON2.0 output.
- Input parameters were selected based on low, middle, and high values and combined using a definitive screening design. These values explore the design region of the model and provide a broader understanding compared to normal operation of the ARCON96 code. This approach or a similar approach is needed to use ARCON96 to define Exclusion Area Boundaries or Low Population Zone boundary distances for Small Modular Reactor (SMR) or micro-reactor nuclear facility siting requirements.

Data Description

The output of ARCON96 is 95th-percentile values of X/Q over specified periods of time [79]. The X/Q measurement is defined as the relative atmospheric concentration at a receptor location per unit release rate of the material at a release location upwind of the receptor. For material given in terms of kg, for example, the X/Q has units of kg/m^3 per kg/s. This is normally condensed to s/m^3 with the units associated with the material (Ci, g, kg, etc.) cancelling and, therefore, being completely arbitrary. Calculated X/Q values for standard averaging intervals and associated raw data files for each model run are collected in Table 13.

Input files required for code operation and replication are provided in the ARCON96_inputs folder. These include run specification files (.RSF) and weather data files (.MET). The weather files are custom designed to represent constant weather conditions for 8760 hours (one year). These files correspond to factors A, B, and K. The remaining factors are controlled by the RSF file. Factor combinations are translated from level notation (i.e. +, 0, -) to values listed in Table 15 in the "ARCON96_input_summary" file.

Output files generated by ARCON96 are provided in the ARCON96_outputs folder. These files include an output log (.LOG) and cumulative frequency distributions (.CFD) files. The LOG files provide a summary of the model run and critical X/Q values. The CFD files provide time series data of X/Q for the model period.

Table 13: X/Q data per time period and associated data files.

			X/Q per time period (s/m^3)				**File**		
			0 to 2 hours	**2 to 8 hours**	**8 to 24 hours**	**1 to 4 days**	**Input** Run Specification File	**Output** Results Log	**Output** Cumulative Frequency Distributions
Run	**Initial DSD Experiment**	**1**	8.28E-05	8.28E-05	5.28E-05	5.54E-05	DSD01.RSF	DSD01.LOG	DSD01.CDF
		2	5.22E-03	5.22E-03	3.33E-03	3.07E-03	DSD02.RSF	DSD02.LOG	DSD02.CDF
		3	2.50E-05	2.50E-05	1.60E-05	1.67E-05	DSD03.RSF	DSD03.LOG	DSD03.CDF
		4	1.09E-02	1.09E-02	5.87E-03	6.67E-03	DSD04.RSF	DSD04.LOG	DSD04.CDF
		5	4.35E-05	4.35E-05	2.77E-05	2.91E-05	DSD05.RSF	DSD05.LOG	DSD05.CDF
		6	7.55E-03	7.55E-03	4.06E-03	4.61E-03	DSD06.RSF	DSD06.LOG	DSD06.CDF
		7	3.96E-04	3.96E-04	2.13E-04	2.42E-04	DSD07.RSF	DSD07.LOG	DSD07.CDF
		8	6.89E-05	6.89E-05	4.39E-05	4.61E-05	DSD08.RSF	DSD08.LOG	DSD08.CDF
		9	7.55E-03	7.55E-03	4.82E-03	5.06E-03	DSD09.RSF	DSD09.LOG	DSD09.CDF
		10	5.73E-05	5.73E-05	3.65E-05	3.84E-05	DSD10.RSF	DSD10.LOG	DSD10.CDF
		11	9.96E-03	9.96E-03	5.35E-03	6.08E-03	DSD11.RSF	DSD11.LOG	DSD11.CDF
		12	1.20E-05	1.20E-05	7.64E-06	7.04E-06	DSD12.RSF	DSD12.LOG	DSD12.CDF
		13	1.31E-03	1.31E-03	8.37E-04	7.72E-04	DSD13.RSF	DSD13.LOG	DSD13.CDF
		14	9.96E-05	9.96E-05	6.35E-05	5.86E-05	DSD14.RSF	DSD14.LOG	DSD14.CDF
		15	4.77E-05	4.77E-05	3.04E-05	2.80E-05	DSD15.RSF	DSD15.LOG	DSD15.CDF
		16	5.73E-03	5.73E-03	3.08E-03	3.50E-03	DSD16.RSF	DSD16.LOG	DSD16.CDF
		17	4.77E-04	4.77E-04	3.04E-04	3.19E-04	DSD17.RSF	DSD17.LOG	DSD17.CDF
	Added	**18**	8.28E-04	8.28E-04	5.28E-04	4.87E-04	DSD18.RSF	DSD18.LOG	DSD18.CDF
		19	1.58E-04	1.58E-04	1.01E-04	9.28E-05	DSD19.RSF	DSD19.LOG	DSD19.CDF
		20	1.20E-02	1.20E-02	7.64E-03	8.01E-03	DSD20.RSF	DSD20.LOG	DSD20.CDF
		21	1.20E-05	1.20E-05	6.44E-06	7.31E-06	DSD21.RSF	DSD21.LOG	DSD21.CDF

Experimental Design, Materials and Methods

This experiment is designed to understand how factor parameters interact and affect atmospheric relative concentrations (X/Q) through interrogation of the ARCON96 computer code. These factors are defined in **Error! Reference source not found.** and associated with the level values used in this experiment in Table 15.

Table 14: ARCON96 input factor descriptions

Pasquill Stability Class	A classification of atmospheric stability, or the amount of turbulent mixing in the atmosphere and its effect on effluent dispersion. Classes are A through G but are translated for the ARCON96 code to values 1-7, with A corresponding to 1. A stability class of 1 represents extremely unstable conditions, and a stability class of 7 represents extremely stable conditions
Release Height (m)	Elevation where the release of source material occurs
Flow Rate (m3/s)	The flow rate of material being released out of a vent
Vent Radius (m)	The radius of the opening through which the material is being release
Distance to Receptor (m)	Distance between the release point and the receptor location where relative atmospheric concentration is calculated
Receptor Height (m)	Height from ground level to the receptor
Surface Roughness (m)	The value is a function of the ground cover and topography. It is typically called the surface roughness length. The default value is set to 0.1 m.
Diffusion Constants σy, σz	The first is for lateral diffusion, and the second is for vertical diffusion. These values may be used to simulate an area source. Two values are required. The default values are zero. The minimum value for the initial lateral diffusion coefficient is zero, and the maximum is 100.0 m. The minimum and maximum values for the initial vertical diffusion coefficient are 0 and 50 m.
Building Area (m2)	A building cross sectional area was selected to approximate building sizes that have been depicted for advanced reactors.
Direction to source (degrees)	Direction to source is assumed to be directly aimed at the receptor.
Terrain Elevation Difference (m)	Elevation difference between the source point and the receptor
Minimum Wind Speed (m/s)	The lowest wind speed for the model to evaluate.
Release Type	A ground release is assumed. Most advanced nuclear power plants have presented designs that are underground with no vent stack. Therefore, a 60m release is not expected.

Effluent Vertical Velocity	If the vertical velocity is less than the wind speed, the release is treated as a ground level release. The assumption of an advanced nuclear power plant reduces the possibility of a high-pressure release that would cause a vertical velocity that is greater than wind speed. Many advanced reactors are designed to operate at ambient temperature.
Height of Lower Wind Instrument (m)	The lower wind instrument is assumed to be mounted on a tower at 10m. This assumption is in alignment with NRC Regulatory Guide 1.23
Height of Upper Wind Instrument (m)	The upper wind instrument is assumed to be mounted on a tower at 30m. This assumption is in alignment with NRC Regulatory Guide 1.23 which states "A measurement height other than 60 meters (197 feet) may be appropriate for those plants where the most probable atmospheric release height is other than 60 meters (197 feet)." Most advanced nuclear power plants have presented designs that are underground with no vent stack. Therefore, a 60m release is not expected.
Averaging Sector Wind Constant (number of Std. Dev)	The default value is set to 4.0 sigma y units.
Nominal Averaging Period Length (hours)	Time periods which are used for calculating average concentrations.
Minimum Averaging Period Length (hours)	Minimum time periods for averaging. This is used to ensure the code does not shorten the time periods beyond reasonable ranges during calculation.

Factor value selection (Table 15) is based on an understanding of the model as described in the ARCON96 handbook [79] and values for the experiment use case. These parameters are selected to approximate factor values for a hypothetical nuclear power facility. A ground level release is assumed to approximate an accidental release for a below-grade advanced reactor which operates near atmospheric pressure.

The weather inputs are designed to maintain a constant wind direction from 270 degrees and the run specification file sets the receptor location (i.e. testing location) at 270 degrees from the source. This combination simulates the wind blowing directly from the source to the receptor. This allows the experiment to remove unnecessary variation caused by shifting weather to enable better understanding of the other factors. This assumption is unrealistic for an actual site, but it is within reason for the ARCON96 code which calculates the conservative 95th-percentile X/Q value.

Table 15: Input factors and levels for the ARCON96 experiment design.

			Levels		
FACTOR ID	**Variable**	**Type**	**Low (-)**	**Mid (0)**	**High (+)**
A	Pasquill Stability Class	Mixed	A	D	G
B	Wind Speed (mph)	Continuous	1	5	10
C	Building Area (m^2)	Continuous	800	2000	4000
D	Distance to Receptor (m)	Continuous	15	100	250
E	Receptor Height (m)	Continuous	0	5	10
F	Terrain Elevation Difference (m)	Continuous	0	5	10
G	Surface Roughness	Continuous	0.1	2.5	5
H	Initial σ_y, σ_z	Continuous	0,0	1.0, 0.5	2.3,1.4
I	Release Type	Fixed	Ground		
J	Minimum Wind Speed (m/s)	Fixed	0.5		
K	Direction to source (degrees)	Fixed	270, 90		
L	Height of Lower Wind Instrument (m)	Fixed	10.0		
M	Height of Upper Wind Instrument (m)	Fixed	30.0		
N	Averaging Sector Wind Constant (number of Std. Dev)	Fixed	4.00		
	Nominal Averaging Period Length	Fixed	1 2 4 8 12 24 96 168 360		
	Minimum Averaging Period Length	Fixed	1 2 4 8 11 22 87 152 324		
	Effluent Vertical Velocity	Not applicable	0		
	Stack or Vent Flow Rate (m^3/s)	Not applicable	0		
	Stack or Vent Radius (m)	Not applicable	0		
	Release Height (m)	Not applicable	0		

The experiment used an eight-factor Definitive Screening Design (DSD) [73] to explore the feasible region. Seventeen code runs were completed for the DSD experiment, followed by four additional runs to further explore regions of interest. The combinations used for the model runs are shown in Table 16. The "+" , "0", or "-" representation is a shorthand notation used to illustrate combinations of many levels of variables.

Table 16: Experiment design for input factor level combination and associated data files.

Run		**Input Factor**								**File**		
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Input Run Specification File**	**Output Results Log**	**Output Cumulative Frequency Distributions**
Initial DSD Experiment	**1**	0	-	+	+	-	+	+	+	DSD01.RSF	DSD01.LOG	DSD01.CDF
	2	0	+	-	-	+	-	-	-	DSD02.RSF	DSD02.LOG	DSD02.CDF
	3	-	0	-	+	+	+	+	-	DSD03.RSF	DSD03.LOG	DSD03.CDF
	4	+	0	+	-	-	-	-	+	DSD04.RSF	DSD04.LOG	DSD04.CDF
	5	-	-	0	+	+	-	-	+	DSD05.RSF	DSD05.LOG	DSD05.CDF
	6	+	+	0	-	-	+	+	-	DSD06.RSF	DSD06.LOG	DSD06.CDF
	7	+	-	+	0	+	+	-	-	DSD07.RSF	DSD07.LOG	DSD07.CDF
	8	-	+	-	0	-	-	+	+	DSD08.RSF	DSD08.LOG	DSD08.CDF
	9	-	-	+	-	0	-	+	-	DSD09.RSF	DSD09.LOG	DSD09.CDF
	10	+	+	-	+	0	+	-	+	DSD10.RSF	DSD10.LOG	DSD10.CDF
	11	+	-	-	-	+	0	+	+	DSD11.RSF	DSD11.LOG	DSD11.CDF
	12	-	+	+	+	-	0	-	-	DSD12.RSF	DSD12.LOG	DSD12.CDF
	13	-	+	+	-	+	+	0	+	DSD13.RSF	DSD13.LOG	DSD13.CDF
	14	+	-	-	+	-	-	0	-	DSD14.RSF	DSD14.LOG	DSD14.CDF
	15	+	+	+	+	+	-	+	0	DSD15.RSF	DSD15.LOG	DSD15.CDF
	16	-	-	-	-	-	+	-	0	DSD16.RSF	DSD16.LOG	DSD16.CDF
	17	0	0	0	0	0	0	0	0	DSD17.RSF	DSD17.LOG	DSD17.CDF
Added	**18**	-	0	0	0	0	0	0	0	DSD18.RSF	DSD18.LOG	DSD18.CDF
	19	+	0	0	0	0	0	0	0	DSD19.RSF	DSD19.LOG	DSD19.CDF
	20	+	-	-	-	-	-	+	-	DSD20.RSF	DSD20.LOG	DSD20.CDF
	21	-	+	+	+	+	+	-	+	DSD21.RSF	DSD21.LOG	DSD21.CDF

Weather data files were generated to match the combinations specified by the DSD design using a custom code. A runs specification file (*.RSF) defines the factor levels, weather file, and output log files (*.LOG) for one ARCON96 model run. Run specification files were created to match the factor levels specified for each run and call the appropriate weather file. Cumulative Frequency Distributions provide summary information on the distribution of X/Q values over time.

To replicate these results, place all input files in the ARCON96 installation folder. Code runs are completed one at a time. Using the Command Prompt, navigate to the ARCON96 directory, then execute the code for each RSF file. An example execution command is "ARCON96F.EXE DSD01.RSF" which corresponds to the first run specification file of this experiment. Complete this process for each run specification file. Output files are automatically placed into the same folder as the run specification file.

Chapter 4: A Decision Framework for Interdisciplinary Multi-Criteria Risk-Based Emergency Planning and Protective Action

Abstract

Emergency planning and response are necessary to reduce the consequences of a disaster. Emergency planning is often studied within siloed discipline-specific boundaries. This approach leads to discontinuous planning. Despite the common object of study, previous works integrating these siloes of research are relatively sparse and fail to combine every area of research discussed in this chapter. However, an interdisciplinary solution is complicated because many factors not directly transferable across boundaries, and existing models are not designed to accept all factors. Most studies fail to recognize that transportation systems, human behavior, socio-economics, communication, and risk are intertwined.

Interaction between variables contained in separate research areas may not be considered or even discovered. Tradeoffs between inconsistently defined outcome metrics, competing objectives, and objectives that require normative judgments are not well evaluated in current methods. Uncertainty is not consistently defined in disciplinary research or propagated forward through other studies. Emergency plans can be less than ideal due to deterministic assumptions. These assumptions are used as constraints to make the analysis more tractable but also limit deeper understanding.

This chapter examines the challenges presented by the current methods and explains the need for an integrated and interdisciplinary emergency planning decision framework. An outline for a more comprehensive model that focuses on the primary goal of reducing risk and consequences in the event of an emergency is presented and applied to nuclear power plant emergency planning. A method for determining the robustness of a protective action strategy to uncertainty is defined, and a method of multicriteria decision-making between protective action strategies using this robustness metric is proposed.

Acronyms and Abbreviations

EP	Emergency Plan
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
ETE	Evacuation Time Estimate
FEMA	Federal Emergency Management Agency
GIS	Geographic Information Systems
GPS	Geo-positioning System
MOE	Measure of Effectiveness
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
ORO	Off-site Response Organization
PAI	Protective Action Initiation
PAG	Protective Action Guide
PAR	Protective Action Recommendation
PAS	Protective Action Strategy
PRA	Probabilistic Risk Assessment
RASCAL	Radiological Assessment System for Consequence Analysis
SIP	Shelter in Place
SOARCA	State-of-the-Art Reactor Consequence Analyses
WEA	Wireless Emergency Alert

1 Introduction

Emergency preparedness is intended to anticipate risks, determine mitigating or avoiding counteractions, and then establish the processes, resources, and training necessary to carry out the emergency response plan. By nature, this is an exercise in projection and prediction to narrow the risks that are addressed by the emergency plan from infinite to finite and manageable. This study is intended to show the need for interdisciplinary evacuation models and provide a base framework. This paper is not intended to provide a detailed model as that will be part of the future research agenda for the field.

This paper focuses on the emergency and protective action planning needed for accidents involving nuclear power plants (NPP), but many findings can be extrapolated to other hazards. Emergency preparedness and response have been studied in the context of environmental events (e.g., hurricanes [83]–[86], floods [87], wildfires [88], and earthquakes) and engineered systems (e.g., dam failures, industrial accidents involving chemical plants [89], [90], hazardous material transport [91], and nuclear power plants [92]). Some risks provide multiple-day lead times before evacuation is warranted, while others only seconds [93]. Because of the wide range of events and risks, general, overarching rules and lessons are difficult to extract. Regardless of the source of the risk, all plans need to temporally model the fate and transport of the risk and the movement and exposure of populations in response to perceptions of the risk. Some of these models are well understood and based on extensive historical data, while others are highly uncertain and characterized by rarely experienced, event-specific variables that are unknowable prior to the event.

Emergency plans (EP) for NPPs should include not only the health risks associated with exposure to radioactive material but also the transportation risks of the actual evacuation. To do so requires engineering models of the radioactive material release profiles, environmental models of weather, behavioral models of the population as they react to available information and directions, transportation models of vehicle flows and congestion, and exposure models capturing the exposure health risks. Constructing all these models, accounting for their inherent uncertainties, and integrating them in a decision-relevant framework that allows for an evaluation and comparison of different plans is difficult and has only been discussed in very general terms. To simplify the task, planners to date have ignored pervasive uncertainties, replaced entire behavioral models with single deterministic parameters, and selected performance metrics (e.g., minimizing evacuation time) that are computationally tractable but do not capture the relevant concerns (e.g., minimizing risk).

Several contributions toward that agenda are made in this paper and are organized as follows: Section 2 summarizes the current approaches and their limitations, Section 3 covers the importance and provides the components of an interdisciplinary approach, Section 4 introduces the characteristics of a new robust decision framework for selecting evacuation strategies and the difficulty of combining different types of risks (vehicle accident risk with hazard exposure risk) with large uncertainties, and Section 5 lays out future work.

2 Current Methods

Emergency preparedness is a critical component of managing risk to a population. While this paper focuses on emergency planning related to NPPs, most of this information can easily be applied to other risk sources.

Evacuation from an NPP is unique due to the significant planning, training, and regulation involved. The Nuclear Regulatory Commission (NRC) requires an emergency plan for all NPPs. These requirements are described in NUREG-0654/FEMA-REP-1 [15]. Supplements have been added to the criteria over time [22], [43], [94], [95], but the release of revision 2 in 2019 was the first update to the main document in 39 years. Guidance for radiation protection criteria for emergency response is provided in the Federal Emergency Management Agency (FEMA) Protective action guidance (PAG) Manual [96].

One of the requirements for EP is an estimation of the time required to evacuate the emergency planning zone (EPZ). Guidance for the creation and content of an evacuation time estimate (ETE) study is provided in NUREG/CR-7002 [97] with a recently released technical basis for future updates to the guidance in NUREG/CR-7269 [20]. The primary focus of this guidance is transportation modeling. The behavior of the evacuees is considered in ETE studies using deterministic assumptions and significantly dependent on the capabilities of the transportation model that is used for the ETE study. No single model is prescribed for ETE studies, but references are provided in the guidance above to some accepted models.

Evacuation from nuclear facilities has been studied several times [98]. Most of these studies were conducted shortly after the Three Mile Island accident in 1979. There have been some efforts to fit more recent methods or theories to NPP evacuation [99]–[101]. Advances in communication channels and methods, evacuation strategies, and technologies have left many of these studies not directly applicable. Advanced nuclear reactors will utilize new technologies, come in generally smaller sizes, and have different risk profiles than most existing NPP. Many of the new nuclear technologies will have a smaller physical footprint and reduced risk associated with their use of passive safety systems, smaller reactors with less fuel, and accident tolerant fuels.

Regulation changes are in process to replace the standard 10-mile EPZ with a zone that is scalable to the risk posed by advanced reactors [9]. These reactors may also be sited closer to population centers because of their reduced risk profile [102]. The risk-informed performance-based perspective of NRC requirements further supports the need for risk and performance-based integrated models for evacuation studies. ETE studies must be updated after the next decennial census is released [103], which provides an opportunity to update the methodology used.

3 Interdisciplinary Approach

All emergency planning considers factors that cross disciplines. Predominantly, understanding of effects is siloed, and simplified best practices or proxies are used to cross-discipline barriers. Interdisciplinary[25] research can increase understanding and improve decisions by considering the intersection of effects. The intersections of disciplines in Figure 9 are not well studied in the literature. While some are more

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[25] Also referred to as multidisciplinary, convergence areas, or broad scope research

explored, others are largely untouched, and a comprehensive model has not been developed.

The need for interdisciplinary emergency planning has been recognized and encouraged in several fields, including building fires [104] and transportation models [98], [105]. Nevertheless, transportation engineers and social scientists, despite extensive research in their areas, have rarely crossed disciplinary boundaries [106]. Some studies criticize traffic simulation models and studies for not effectively considering the extensive literature in behavioral sciences [107]. While progress is being made to combine these two fields, risk analysis has seldomly been included in models and methods.

There are two main reasons for siloed research in NPP-related EP. First, regulatory guidance uses topic-specific sections assembled like building blocks. If the guidance is siloed in topic-specific analysis, the research will likewise be focused on meeting the limited scope of the guidance. This is easily demonstrated by considering the separation of the communication plan from the ETE study. It is well understood that communication during an emergency influences behavior [108]–[110]. However, the communication plan is not used to inform the deterministic behavioral assumptions used in the ETE study. Instead, they exist as separate building blocks that do not relate to each other, let alone integrate into a cohesive decision framework. This can create conflicting objectives and tradeoffs that are not well understood or completely undiscovered.

The second major cause of research siloes is the many challenges to interdisciplinary research in general. Terminology varies between research areas in both jargon and specific definitions. Funding agencies tend to prefer more narrowly focused research agendas. When interdisciplinary groups are formed, it is often for a single project which has limited impact on removing the barriers in the long term.

Major questions have been largely unaddressed in the emergency response literature. Some of these questions have quantitative solutions which have not been explored or framed in a decision context. Others are normative and require value judgments. These include: How can consequences be minimized? What losses are acceptable when consequences are inevitable? How can the proper metrics, risk, and consequences, be the focus instead of the dominant measures of effectiveness (MOE) and metrics (e.g., clearance times, compliance, property damage)? What categories of losses have priority, who decides how to rank them, and what method should be used? What tradeoffs are acceptable when there are conflicting consequences? Which factors cross discipline boundaries or intersect with other factors?

To address these questions, we are proposing the next step in the evolution of evacuation planning and decision making: an integrated, interdisciplinary, and decision-focused framework. The scope and primary components of that framework are illustrated in Figure 9.

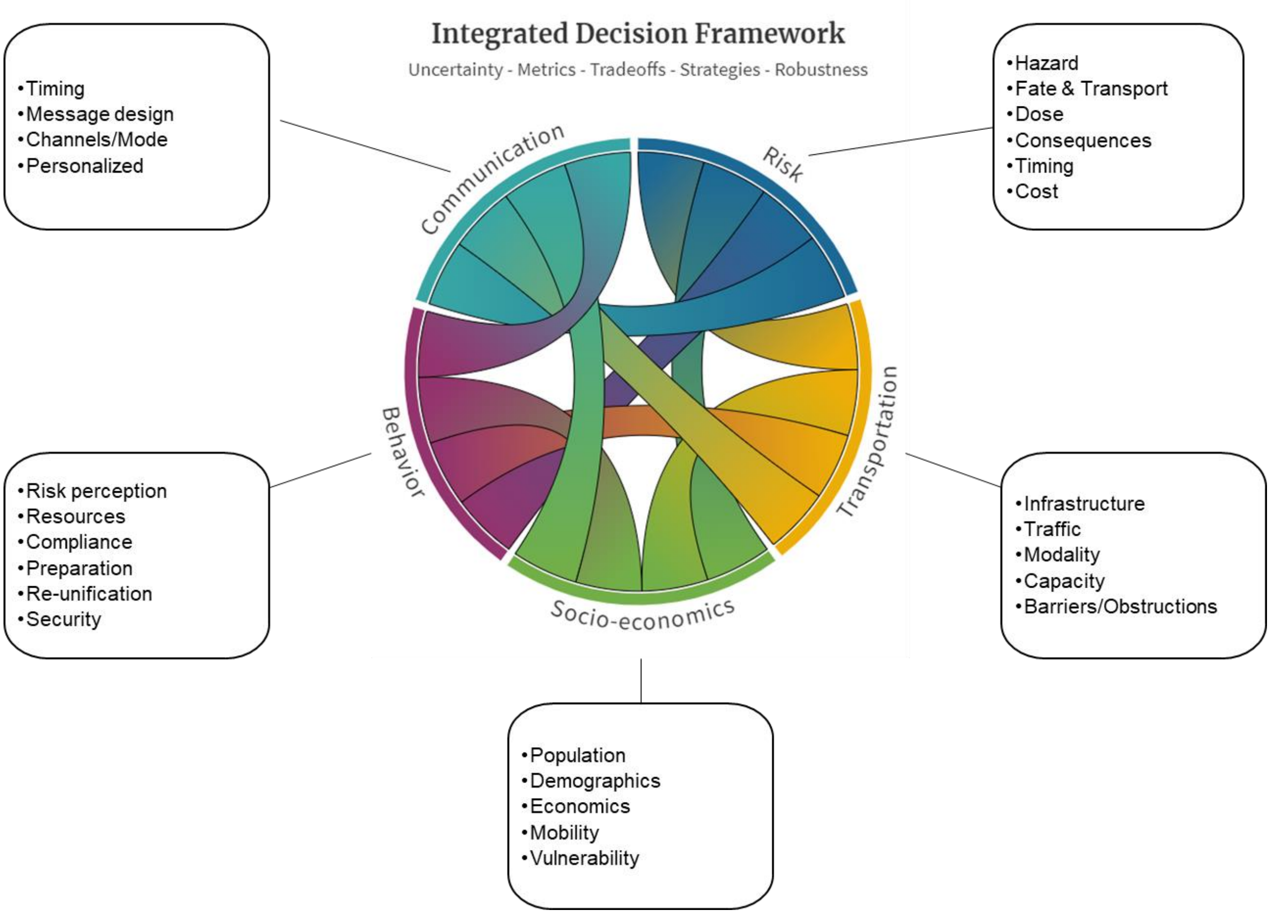

Figure 9: Interdisciplinary scope of an integrated protective action decision model

Incorporation of social science research with transportation modeling allows for exploration of effects and comparison to historical evacuation data. Theories related to individual decision-making along with traffic models have enabled a better understanding of what happens under certain evacuation conditions. Primarily, this has been used to update a priori leave or stay compliance decisions, demand estimation, and trip generation time estimates. However, little has been done to go to the next steps and quantify the risk and consequences of the hazard and evacuation with more detailed interdisciplinary models and then suggest and analyze interventions that might avoid the risk. Many studies on evacuation state the goal is simply to evacuate the population in the shortest time possible [111].

3.1 The Decision Maker

There are multiple decision-makers in any emergency response: emergency managers, first responders, individuals in the population, elected officials, and more. The primary decision maker for selecting a protective action strategy is the emergency manager in charge. When using the FEMA National Incident Management System, the Incident Commander has this authority [112].

For NPP, in the event of an emergency, the licensee must determine a Protective Action Recommendations (PAR) and provided it to the principal ORO according to the approved Emergency Plan [15]. The principal ORO confirms the PAR and makes a Protective Action Decision (PAD) on how and what to communicate to the public. In many cases, the principal ORO is the state nuclear safety agency. The specific ORO and individual in that organization that is the decision-maker vary from site to site. Unless otherwise indicated, the principal ORO is considered the decision-maker for the remainder of this chapter.

Individuals are important decision-makers in an emergency. In a well-organized emergency response, the role of the individual is not to determine a protective action but to comply with the prescribed protective action. However, they comprise the vast majority of decision-makers, and no two have the exact same objectives. In a poorly organized emergency or when communication is insufficient, individuals must make their own choices.[26] This can make individual decisions and actions one of the largest

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[26] Examples of this are Hurricane Katrina and the winter blackout of Texas in 2021

sources of uncertainty which is not sufficiently accounted for in current models. This behavioral uncertainty is discussed throughout the remainder of this chapter.

3.2 Timeline

When factors interact, it is often over a period of time. Emergency response progresses through several stages. These stages of accident progression are often depicted as a timeline similar to Figure 10, with adjustments to match the theory being presented. In general, the stages consist of detection of a hazard, protective action decision making by emergency managers, providing warning information to the public, public response to the warning by preparing, and finally, the public performing the protective action. Some models use these consecutive discrete stages to simplify the analysis or due to model limitation [6]. While this representation is effective at showing the simplified stages of choice and action, it is ineffective at depicting the uncertainty or varied range of time and behavior.

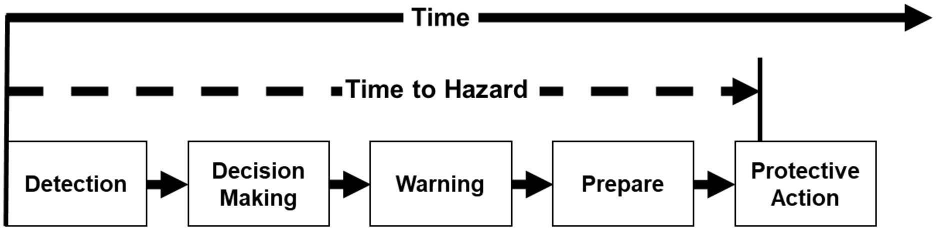

Figure 10: Accident timeline with segmented 1-dimension and discrete hazard event

The cumulative timeline plot in Figure 11 shows that stages evolve and overlap in time instead of discrete instances. What is still not communicated is uncertainty, spatial location, or individual evacuee choice. An individual may be located just before the plateau of the warning curve and still be one of the first to complete the protective action if they need very little preparation time. A visitor to an area that has nothing to prepare is a good example. The opposite can also be true; one of the first to receive a warning could take a very long time to prepare and be one of the last to complete the protective action. This case is the basis for using a 90% evacuation as the threshold for ETEs because the last 10% take a disproportionate time to evacuate [99].

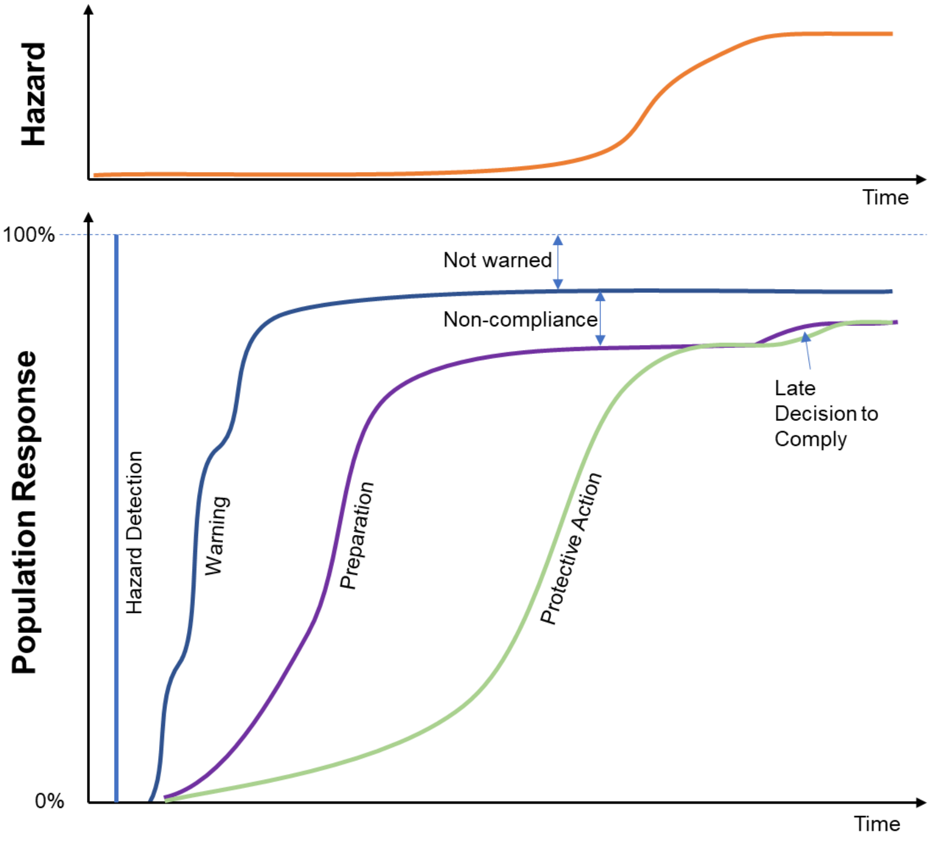

Figure 11: Example accident timeline with 2-dimensions (response, time) and separate but concurrent hazard progression. Uncertainty and spatial variations cannot be shown with this method.

Integration of risk and the population location through time is needed to understand the interaction and dose resulting from a protective action. Deterministic models similar to the one depicted in Figure 10 do not provide a sufficient level of detail to make an informed decision. The fact that many recent studies use ever more complex microscopic transportation models with a deterministic, all or none dose model underscores the need for a truly interdisciplinary approach.

The majority of models in the literature, and in use by industry, use this type of discrete model [101], [113], [114]. MACCS2 is a notable model that uses discrete stages for transportation simulation due to model limitations but has a detailed spatiotemporal dose model (see Chapter 2). MACCS2 is the off-site consequence analysis model used for the NRC's State-of-the-Art Offsite Consequence Analysis project [38]. The models in the literature that consider temporal changes (Figure 11) only consider a portion of the parameters and usually exclude risk altogether [49], [88], [99], [100], [111], [115].

3.3 Transportation

Transportation models have already been engineered to the point where individual vehicles interact with traffic controls and other vehicles on second timescale precision. There are multiple transportation models that have been approved for evacuation modeling. These models are discussed in Chapter 2 and can be found in [31]–[33], [98], [106]. The greatest benefits of future work will not come from more precise transportation models; they will come from improved accuracy resulting from interdisciplinary research, which discovers and incorporates unobserved effects and interactions.

To enable this effort, evacuation transportation models need to add capabilities to simulate advances in emergency management technologies for communications, real-time situational awareness, traffic management strategies, and public behavior. These new capabilities draw from expertise outside of transportation engineering. However, the complexity and maturity of transportation models provide a valuable basis to build upon.

Perhaps most important for building an interdisciplinary model that uses risk as a MOE is the ability to integrate with hazard fate and transport models. The current lack of ability to integrate forces integrated risk models, such as the model proposed in Chapter 2 and the NRC MACCS2 model [116], to build new transportation models instead of using a well-developed model.

Terminology can have inconsistent definitions across the transportation literature. For example, 'clearance times' is often defined as 'the time required for the population to leave the area of risk' but may also be defined similarly to 'the time to leave the designated evacuation zone.' These definitions often describe the same areas and therefore are congruent. However, that is not always true. Most NPPs plan to use a keyhole evacuation strategy, but some NPPs plan a full evacuation of the EPZ. A full evacuation of the EPZ creates an 'evacuation zone' that is much larger than the 'area of risk' keyhole. Consistency of definitions would reduce barriers to interdisciplinary research.

3.4 Socio-Economics

While barriers to mobility are often considered in evacuation studies, the broader topic of social vulnerability is not sufficiently considered. Social vulnerability refers to the socioeconomic and demographic factors that affect the resilience of communities. Studies have shown that in disaster events, the socially vulnerable are more likely to be adversely affected [117]. Multiple social vulnerability indexes (SVI) have been developed, but they do not directly apply to emergency response planning [117], [118].

One attempt to integrate social vulnerability as a metric in emergency planning only considered maximum doses in specific geographic zones for a single accident, ignoring temporal considerations [119]. The paper did not consider if protective actions or other evacuation resources might be impacted by social vulnerability or how a social vulnerability index might be useful to a decision-maker. In isolation, an SVI could be misleading to the decision-maker because it is a static point estimate. Similar to census population data, the SVI would not reflect spatiotemporal changes during an evacuation as the population moves. This type of interaction exemplifies the need for an interdisciplinary approach that dynamically considers a range of factors instead of using siloed reports and metrics such as a static SVI.

3.5 Behavior

The role of population behavior and choice is well studied. However, this body of research is considered in emergency planning to varying degrees. To develop an interdisciplinary model as proposed in this chapter, there is a need to develop methods and best practices for incorporating behavior and the social sciences [29], [93], [105], [114], [120]. Some of the primary behavioral factors addressed in the literature are shadow evacuation [49], compliance [121], mobilization time [100], stay/leave choice [93], [114], and alternative choice on actions (e.g., going home first, picking up children) [122].

Emergency response progresses through several stages that can overlap in time, as Figure 1 shows. What is not communicated in this figure is uncertainty, spatial location, or individual choice or chance. It is important for emergency planners and managers to have situational awareness of how the response is progressing.

3.6 Communication

Communication impacts public response but is largely ignored by transportation models, even those that consider social sciences. Communication is critical to the timely and effective implementation of protective action [52]. The rapid communication of an alert with a warning, which reaches a broad portion of the population through many channels, does improve emergency response [108]. Communication should be included in evacuation models to enable a better understanding of the timing, behavioral effects, and the ability to implement complex protective action strategies. Some models include warning time as part of protective action initiation (PAI), but most do not model explicit evacuation strategies or public response based on communication.

Emerging communication technology, such as hazard notification apps, GPS tracking, cell phone location data, phone call data, and social media tracking, creates an expanding source of information. These rapid changes in technology necessitate a renewed look at how it affects emergency response [108]. This includes how communication is and can be used to improve emergency management.

3.6.1 Alert and Warning

Alerts are used to indicate that something significant has happened or may happen. Warnings messages provide more detailed information indicating what protective action should be taken. Alert and warnings can occur concurrently (e.g., a wireless emergency alert (WEA) message) or spread over time (e.g., a siren followed by a TV broadcast).

The NRC requires that alert and warning must be possible to the entire EPZ and reach essentially 100% of the population within 5 miles under 15 minutes and the entire population within 45 minutes [43]. Communication is not generally a smooth curve. Individual channels progressively reach larger portions of the population, as depicted in Figure 11. Warning channels can be added rapidly but with some delay between automated systems such as WEA and operator-dependent TV broadcasts.

Customized warning messages and information that are directed to specific locations allow for an even deeper level of impact and opportunities for evacuation strategies that are more effective at avoiding consequences. Communication with content that is tailored to the receiver, which may include geographically-based warnings, is one component of the emergency communication research agenda [108]. Recent updates to the WEA system can enable geo-targeted warning messages and protective actions [123]. Geo-targeted warning messages can provide more useful information and protective action recommendations that include rich content [108].

3.6.2 Networks

Interpersonal and technological communication networks exist beyond the controlled alert and warning channels [54], [108]. For example, it is expected that families will communicate to reunite if possible before evacuation [30]. It is also expected that indirect communication, through social media or seeing others evacuate, will influence the behavior of others [108].

Vehicle-to-vehicle and vehicle-to-infrastructure communication is an emerging field that will enable real-time situational awareness. Advanced traffic communication has the potential to reduce congestion and guiding evacuees to resources such as fuel or lodging [124]. There is potential to leverage this technology for emergency warning and response coordination in the future.

3.6.3 Social Media

The role of social media and other interpersonal communication is not well defined in EP but is a growing area of research. There are benefits and challenges to including social media in emergency plans. The technology, public adoption, research, and best practices are still being developed. However, the population is increasingly turning to social media for information. Some recent progress has been made on evaluating the current state of social media-based emergency communication literature and provides a roadmap to connecting with interdisciplinary models [125].

Some countries and industries leverage social media significantly to take advantage of the additional channels of communication. Adding communication channels increases the chance that a warning will reach the entire population quickly [108]. Others are hesitant because social media relinquishes some control of message content, spread, and timing. However, people are more willing to take appropriate actions related to a warning that they may have helped to disseminate [108]. In an emergency, timing is critical, and confusion caused by an outdated message still spreading on social media long after the recommendation has changed could cost lives. While most social media platforms employ a way to notify the user, not all of them are able to alert the users in a time-sensitive manner or provide detailed protective action information. Shadow evacuation may increase if the message is shared beyond the defined protective action area.

3.7 Risk and Consequence

The definition of risk is one of the critical terms that vary between and even inside disciplines and industries. A small selection can be found in [126]–[130]. Given the emphasis placed in this framework on risk as a MOE and the potential for different views of risk to change decisions, it is important to provide a working knowledge of some definitions of risk and, more importantly, the definition used in this framework.

For NPP emergencies, three main government organizations are involved with regulation and guidance: the NRC, FEMA, and the EPA. Each of these organizations has a slightly different definition of risk. FEMA adopts the Department of Homeland Security's definition where risk is the product of probability and consequences of an event [131], [132]. The EPA uses several definitions of risk. The broad basis definition used for human health risks is the product of hazard dose-response and exposure to the hazard [133]. The NRC defines risk as to the probability and consequences of an event, as expressed by the "risk triplet" that is the answer to the following three questions: (a) What can go wrong? (b) How likely is it? (c) What are the consequences if it occurs? [134]. The risk triplet highlights the importance of qualitative outputs from a risk assessment, most importantly the descriptions of accident sequences (the answer to the question "What can go wrong?"). It also differentiates high-probability, low-consequence events from low-probability, high-consequence events [135].

The value of formal NPP emergency preparedness programs can be estimated using consequence reduction as a MOE [92]. Several MOEs are currently being used as a proxy for risk reduction without actually calculating risk or consequences. The most common of these metrics is minimizing evacuation time [121], [136], but others have been considered, including distance to shelters [111], and distance to hazard [89].

The NRC State-of-the-Art Reactor Consequence Analysis (SOARCA) advances understanding of accident progression but is not usable as a decision framework due to limited simulation of protective action strategies and behavior uncertainty. The SOARCA set of studies were designed to provide a more realistic understanding of accident progression and off-site consequences of light-water NPP accidents inside a typical 10-mile EPZ [4]–[6], [137], [138]. The existing site-specific emergency plan was used as the basis for modeling in the SOARCA studies. While an advanced accident and radionuclide fate and transport model is used, it is integrated with a simple vehicle transportation model that uses a static ETE study as an input. The ETE study output was simplified to an average speed that eliminated any nuance that was included in that analysis.

Several risks are present during an evacuation. Integration of hazard risk and evacuation transportation risk has been studied for hurricanes [83], chemical plants [89], [139], wildfire risk [140], and hazardous material routing [91] using simplified models. More sophisticated interdisciplinary models for quantifying fatalities as a consequence of evacuation have been proposed but are not well developed in the literature [141]. A better understanding of how to reduce exposure during an evacuation is still needed, as was evident during the Fukushima accident. The exposure and transportation risk could have been reduced further through better communication and evacuation execution [142].

Comparison of different risk sources and outcomes is non-trivial. For example, comparing morbidity and mortality is not straightforward. Similarly, the chance of immediate mortality due to a transportation accident is not the same as the chance of mortality at some point in the future from radiation exposure. Threshold-based risk guidance, as provided in the PAG manual, can simplify the planning process but fail to consider uncertainty and confounding interactions. When the risks are sufficiently close in magnitude that tradeoffs between risks depend on decisions and uncertainty, it becomes imperative to understand the drivers of these tradeoffs.

3.7.1 Radiation Risk

The risk of a nuclear power plant accident is determined through a probabilistic risk assessment (PRA). This is a complicated process that considers the statistical probability of an accident, damage to the reactor core during the accident, and potential for release to the environment[135]. To determine if safety goals are met, the NRC uses two surrogate risk measures: core damage frequency (CDF) and large early release frequency (LERF) [135]. As such, a large early release (LER)[27] accident scenario is part of emergency planning and preparedness in addition to design basis accident (DBA) scenarios used for licensing and siting purposes. However, when an accident is ongoing and a hazardous release is imminent[28], probabilistic calculations of CDF or LERF no longer have practical value, and the risk triplet is no longer used. Instead, risk assessment focuses solely on consequences in terms of early and latent fatalities [134].

Risk is not considered when selecting protective action recommendation (PAR)s in most evacuation models for natural disasters. A few examples do exist where risk is the MOE. A risk-informed protective action decision tool for chemical accidents is presented in [143]. This tool is limited to simple protective actions and population behavior. Distance to hazard is used as a proxy for network path risk in [144]. A multicriteria decision method for medium and long-term radiological emergency

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[27] Sometimes referred to as a Rapidly Progressing Severe Accident

[28] Defined by the NRC as Level 3 Probabilistic Risk Assessment. Probabilistic Risk Assessment levels include all lower levels. For reference, Level 1 consists of computation of core damage frequency and Level 2 is computation of radioactive material release frequency [134]

management can be found in [145]. This method does not apply to emergency phase (immediate) protective actions that are covered in this work. Sophisticated but discrete fate and transport models, such as RASCAL, are available for risk modeling and decision making for NPP accidents. These models are not currently integrated into an interdisciplinary decision framework.

Radiological accidents do not provide visual indicators of the risk, such as smoke does with wildfires. Depending on the location of the plume relative to the population, evacuation routes, and shelters, a time or distance minimizing strategy could result in evacuees traveling through the plume to exit the opposite side of the EPZ. Thus, a focus on minimizing time or travel distance can inadvertently increase risk. Evacuation strategies with similar ETEs can have very different risks [146].

Radiological consequences are the subject of significant debate. NRC staff provided a review of off-site health consequence models for use in the SOARCA project [147]. Depending on the model used, consequence estimation could vary widely, especially at low doses. The SOARCA studies evaluated multiple radiation dose consequence models and found differences in consequences would exist at low dose levels [4].

3.7.2 Evacuation Imposed Risk

Transportation risk during an evacuation is not commonly included in evacuation transportation studies which generally focus on evacuation time. FEMA states the transportation risk (i.e., fatalities and injuries from traffic accidents) during evacuations is expected to be similar to average transportation risk [96], [148]. NRC studies of large evacuations found only one transportation-related fatality [46], [110]. Following the completion of these NRC studies, 106 fatalities were attributed to evacuation caused by

Hurricane Rita and over 1,000 fatalities due to evacuations following the Great East Japan Earthquake and following the Fukushima Daiichi Nuclear Power Plant accident [96].

The FEMA PAG manual equates the transportation risk of an individual over an assumed 100-mile round trip (evacuation and return) to a radiation dose of 0.03 rem [96]. This is used as a minimum threshold for when an evacuation is warranted. The EPA uses a single study on transportation risk from 1974 as a basis for 9×10^{-8} deaths per person-mile risk in the PAG manual [148]. This person-mile risk is then converted to a risk of 9×10^{-6} fatalities per evacuating person for the assumed 100-mile round trip. This risk is then divided by the assumed risk of fatal cancer from the radiation[29] of 3×10^{-4} per person-rem dose, resulting in 0.03 rem [151]. The study equates evacuation risk as equivalent to normal transportation risk, but the fatality rate per 100 million vehicle miles of 1974 is three times greater than in 2017 (3.35 and 1.16 respectively) [152]. Other studies exist but have not been updated recently [153], [154]. It could be argued that the PAG threshold should be reduced to reflect the reduction in transportation risk.

Two lines of inquiry need to be resolved before such a change to the PAG could be justified. First, further research needs to be completed on the transportation risk during an evacuation. Second, evacuation also causes health and safety risks after the initial transportation due to stress, anxiety, and other psychological effects [155]. These effects are not currently considered in PAG transportation risk values. It should be evaluated,

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[29] This assumed risk of fatal cancer from radiation is not settled science [149]. The Interagency Steering Committee on Radiation Standards (ISCORS) provides guidance 3×10^{-4} per person-rem dose [150]. It is dependent on a linear dose response, which is the position on the NRC but not several other organizations [147].

and justification provided if these risks should be included in the evacuation risk threshold used in the PAG manual.

4 Toward a better model

Improvements are needed to make robust decisions that focus on consequence reduction as the primary MOE. These improvements predominantly relate to the conceptual approach used to define the model and the challenges associated with creating a cohesive framework for interdisciplinary models to interact.

4.1 Utilize a Decision-Maker Point of View

To ensure that suggested protective actions or strategies are plausible, it is necessary to take the viewpoint of the decision-maker coordinating the emergency response. The existing approach uses discipline-specific studies, and the MOE cannot consider how these various components interact. These interactions emerge during the implementation of the various components of a protective action strategy, whether planned for or not.

The decision-maker does not have a direct influence on the evacuation outcome. A limited set of tools are available, and they have varying levels of direct influence on the situation (Figure 12). The decision-maker can only select a strategy and influence public behavior using indirect communication (e.g., PARs, location-based information) or physical barriers (e.g., contraflows, traffic signals). Decision-makers need to understand which protective actions and strategies are achievable and most effective under these constraints.

Protective action strategies are communicated to the population through multiple channels. The public then makes individual behavior decisions throughout the evacuation process with imperfect information [93], [121], [156]. Public response is the aggregation of discrete choices to stay or leave and when. These choices are as varying as the individuals making them.

Transportation models are stochastic processes that need to take in these prior choices and constrain them with spatial limitations. Many transportation methods and models make problematic assumptions about the decision maker's ability to direct traffic flow in a specific way to optimize evacuation time, distance, and even specific intersection decisions for individual vehicles.

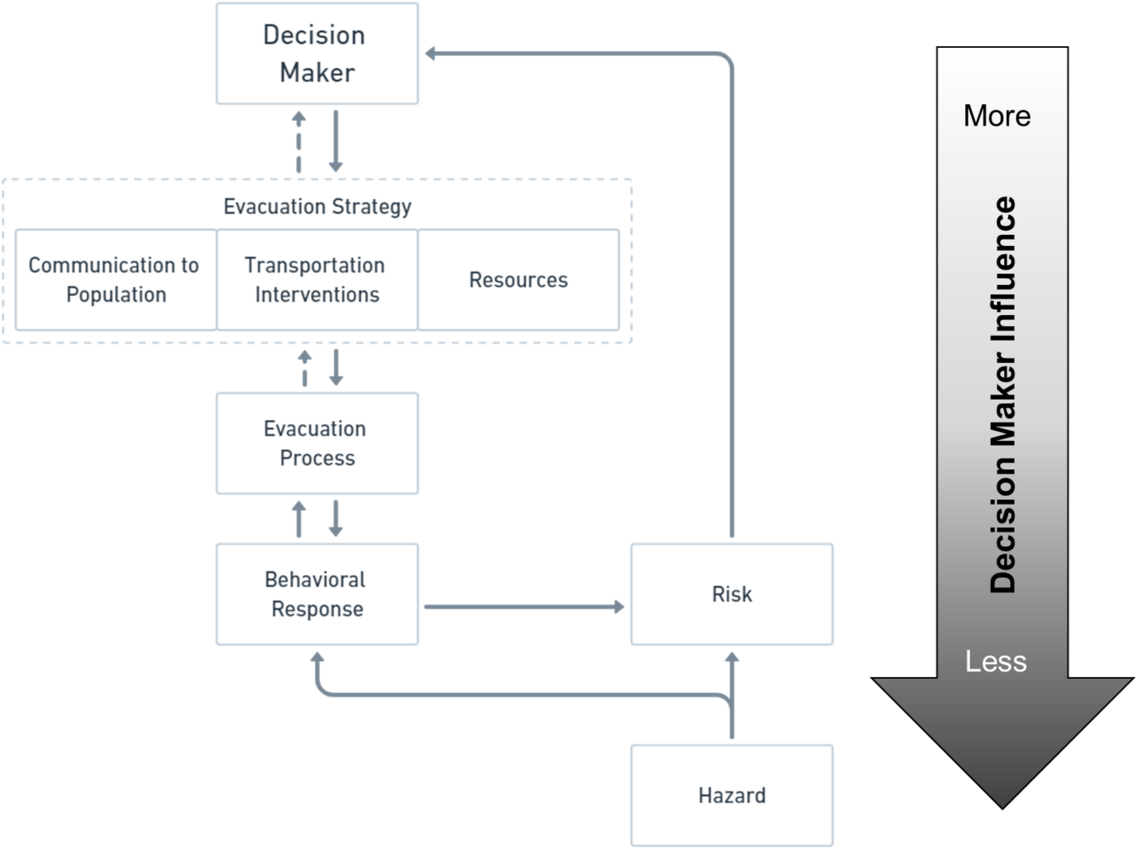

Figure 12: Emergency management decision-maker influence gradient diagram

The risk to the population, in the form of a one rem PAG threshold, is used to determine if a protective action is needed [96]. A radiation hazard dispersion model or real-time radiation measurements are used to define the zone that requires a protective action [55], [96]. ETE times are estimated for a range of potential zones as part of NRC-mandated ETE studies (see Chapter 2 for extensive discussion) [97]. ETE studies provide point estimates of the time required to evacuate a population from a specific zone under specific conditions and assumptions. The ETE study must be compared to the at-risk zone that requires a protective action to determine if an ETE is available for that area. A decision-maker can then compare the data points from defining the at-risk zone, ETE to evacuate that zone, and general guidance in [22], to make a protective action decision.

Decisions are made against the clock. The feasible set of protective actions becomes more constrained with time, limiting options available to decision-makers. That is particularly true with rapidly progressing events. Conversely, uncertainty may be reduced over time as more information is accumulated, improving confidence in the remaining feasible protective actions. The PAR options available can be reduced when feasibility (solutions that are logistically possible) and influence (solutions that PAR can help to achieve) are considered.

The evacuation decision deadline is the time at which it is no longer safe to initiate an evacuation [106]. At some point, it is too late to start an evacuation; the window has been missed. The prescriptive PAR guidance is derived from the concept of evacuation decision deadline. This assumes that if an evacuation is still underway when the hazard arrives, it results in higher consequences to the evacuees. Weather plays a major role in the direction and timing of hazard dispersion and therefore planning for protective action decisions.

Being trapped under a chemical plume might be survivable when using a shelter-in-place (SIP) strategy in a building, but it could be fatal in a vehicle because of the much higher air changeover rate [143]. However, SIP does not provide full shielding from the hazard, and the population could remain under the plume for a long period and, thus, accumulating a dose [106]. Therefore, there must be some dose value greater than zero at which evacuation is still preferred to SIP. A dynamic model of the interaction between hazard and protective action is needed to understand when SIP is no longer more protective than evacuation.

4.2 Spatiotemporal Model

Response curves such as those in Figure 11 provide the status of the evacuation across the entire evacuation area. This simplification does not provide any insight into the spatial distribution of the population or hazard. It should not be assumed that the population, road networks, or hazards are uniformly distributed. The pitfalls of this approach can be easily illustrated with an example. Consider if the hazard curve in Figure 11 were to roughly mimic or precede the protective action curve, assuming the protective action modeled in this case is an evacuation. That would imply that the risk would reach the population prior to their ability to evacuate. The emergency manager may then choose a more rapid protective action such as SIP. Using the same example, consider if the population in the downwind keyhole[30] of the EPZ has already evacuated prior to the hazard. From the information in Figure 11, the emergency manager would not know the population is out of the risk zone (e.g., the downwind area), only that they have not completed the prescribed protective action (e.g., evacuation from the EPZ). A spatiotemporal representation is needed to understand the interaction between hazard and evacuation. This interdisciplinary spatiotemporal approach is not currently in the literature, which mostly uses a spatiotemporal transportation model with a simple dose model.

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[30] A 'keyhole' consists of the 2-mile radius around an NPP and the downwind sectors forming a configuration that resembles a keyhole

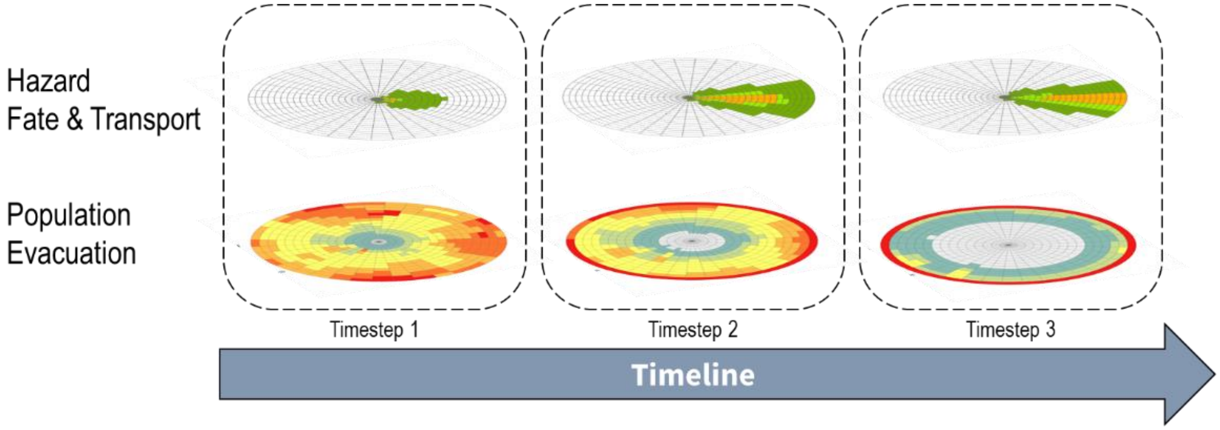

Figure 13: Hazard progression and population evacuation shown over multiple timesteps using a polar coordinate grid with the hazard source at the center. Population shown to accumulate in the outer evacuation ring is simply a depiction of the population that has left the evacuation area.

Microscopic evacuation simulations for large networks can take days to complete and require at least four simulations to capture uncertainty even using the deterministic assumptions in current guidance [20]. The computational expense and duration of evacuation simulations, as in other disciplines, are often used as justification to focus on deterministic assumptions and avoid exploratory analysis. Still, computational expense as a barrier to exploratory simulation has steadily reduced.

One method to achieve a spatiotemporal representation is shown in Figure 13. A spatiotemporal hazard model is overlaid on a transportation model and synced using a common timestep and polar grid map. This approach has the advantage of leveraging well-developed models instead of developing new systems. Separate models also retain the ability to operate independently instead of sequentially, avoiding the computational expense of the entire model chain for each full simulation. Instead, well-planned simulations of transportation models with behavioral, communication, and protective action strategies can be combined with similarly designed hazard models.

To be useful for building an integrated transportation and risk model to calculate consequences, the models must share a common map of spatial cells and standard timesteps. Consequences can be calculated using the combined spatiotemporal model to add representation graphs of consequences per timestep and cumulatively through time. There are multiple ways to accomplish this interface, depending on the characteristics of each model:

1. A standardized spatiotemporal output from both models
2. Existing higher fidelity models that also provide a secondary standardized spatiotemporal model output
3. An intermediate program that uses geographic information systems (GIS) to remap existing model outputs to a standardized spatial model and then resamples outputs over time

Option (3) introduces significantly more complexity and sources of error but is currently the only available choice because of barriers to model interoperability. The cell size and timestep duration determine the resolution of the model. This resolution should not exceed the input model resolution and thereby imply greater accuracy.

4.3 Protective Actions and Evacuation strategies

Targeted evacuation strategies have been suggested but not compared in a decision framework. Evacuation strategies are often not directly compared in studies, and when they are, the results are generalized, assuming average values for important uncertainty parameters. Despite recent work, many questions remain about when and how to select one strategy over another. These questions must be addressed better to inform the decisions that emergency planners have to make.

The NRC has completed several studies related to evacuation and severe accident consequences near NPPs [110], [157], [158], [59], [159]. The three-volume PAR study spanned 2007-2010 and was intended to assess alternative protective actions for severe accidents. The study is comprised of literature and state-of-the-art review, focus groups and telephone survey, and technical basis for protective action strategies [30], [40], [45]. A summary of the PAR study can be found in [160].

NRC guidance provides generalized and prescriptive protective action recommendations based on ETE times for 90% of the population [22]. This frames the performance-based MOE for protective action decisions as time-based instead of risk-based. As noted in Section 4.1, ETE times are point estimates. Weather conditions, such as an inversion, heavy precipitation, or no wind, can change the efficacy of a protective action [22]. NPP licensees may perform additional analyses to determine whether other protective action criteria are more appropriate but are not required to do so. Such analyses would be necessary to understand the effectiveness of the potential protective actions and compare them across multiple criteria.

Evacuation strategies for emergencies at NPP have evolved over time. Three evacuation strategies have been suggested previously: full radial evacuation and two strategies that focus on areas near and downwind from the NPP, keyhole, and lateral. Staged evacuations are a subset of other strategies where strategies are expanded in size as needed over time.

Evaluation of the value of evacuation strategies as a protective action to reduce risk is not commonly part of evacuation research. Most ETE studies only model the mandated radial 2-mile, 5-mile, and full evacuation strategies for evacuation time and do not consider risk [97]. The NRC-sponsored technical basis study, developed in anticipation of updating ETE guidance, only considers full EPZ evacuations [20]. This is in contrast to a downwind keyhole evacuation being the most common protective action strategy to avoid the radiation plume for NPP [100]. A keyhole evacuation with a 2-mile radial evacuation is also the primary guidance for protective action strategy in the EPA PAG manual [96]. A SIP strategy can be an effective protective action in some cases and may not get enough attention in emergency planning [45], [143], [156], [161]. Dynamically scaling the size of the evacuation area relative to hazard dispersion and population parameters has been considered, but the study used a very long 4-day timeline and did not consider transportation or behavior [101].

Advances in real-time situational awareness for emergency planners, understanding of public behavior, and communication technology provide an opportunity for the implementation of more complex evacuation strategies. Geo-targeted alerts and warnings provide a new option for implementing protective actions that could not be previously implemented. Real-time situational awareness and geo-targeted messages could be combined with a risk-based decision model to provide relevant instructions tailored to specific areas.

4.4 Incorporating Uncertainty

There are many areas of uncertainty related to an emergency and evacuation. Some of the main areas of uncertainty that are not currently addressed for NPP protective actions are due to the limited focus on interdisciplinary consequence-based models. This includes roadway network degradation, communication, individual decision-making and behavior, timing, and risk. It is unclear what interaction effects may exist or which have a major impact on consequences. Exploration of these effects is needed to determine what factors warrant further study and if they are significant enough to be included in regulatory guidance.

Uncertainty analysis in the SOARCA studies explores the consequence sensitivity for some variables. The bulk of uncertainty analyses has been directed at reactor failure modes [162], but early warning, road obstruction, and loss of local power have also been mentioned [137], [138], [157]. The SOARCA studies stop short of questioning public behavior variables, including the proportion of shadow evacuation, level of compliance, or immediate actions taken by the public.

The range of uncertainty is not well defined for some of the parameters. For instance, point estimates are used for transportation risk in the PAG guidance without considering ranges of uncertainty [96]. Transportation safety has shifted, and new research is required, as discussed in Section 3.7.2. The impact of new technology, such as the ability to send geo-targeted customized warnings and directions, has not previously been evaluated, and the range of uncertainty is not defined. A duration uncertainty analysis is one method that can be used to understand the interaction of stochastic behavior, risk, and protective actions, as discussed in Chapter 2 and [54].

4.4.1 Timing

Time is a major source of uncertainty in emergency planning. Technological emergencies and PARs are typically depicted as a series of consecutive and discrete steps that progress as a timeline (Figure 10). This simplifies the duration of each stage down to the initiation of that stage and loses the context that prior stages are ongoing (Figure 11). Some models use consecutive discrete stages to simplify the analysis or due to model limitations that prevent concurrent stages [6]. One notable example of discrete stage use due to model limitations is MACCS2 (see Chapter 2), which is the off-site consequence model used for the NRC's State-of-the-art Offsite Consequence Analysis project [38].

Radiological releases could start less than an hour or several hours after an accident and last from minutes to hours [15]. The possibility of an early and large release is an important part of EP despite being very unlikely [135]. To respond to a larger and early release, NPPs are required to be capable of making a PAR within 15 minutes of declaring a general emergency (GE)[31]. It is often assumed in analyses that off-site response organizations (ORO)s will also comply within 15 minutes resulting in a 30-minute timeframe from alert to warning [38], [45], [100], [101], [157]. Uncertainty related to this timeframe is not usually considered in evacuation studies. Guidance for ETE studies assumes that this warning time occurs prior to the evacuation and therefore does not consider this time period or potential overlap with the evacuation process.

Evacuation does not begin instantaneously. After the population receives a warning, they begin a period of preparation to perform the protective action. Several nearly interchangeable terms are used in the literature to describe this period, including preparation, mobilization time, PAI, and trip generation time. A significant change in ETE can occur due to the loading curves used, depending on other evacuation variables [20]. Faster mobilization may reduce overall ETE slightly but will increase evacuee delay time during travel by compressing the loading curve and creating more congestion.

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[31] A general emergency is the highest of four NRC emergency classification levels (ECL) [15].

Smaller EPZs with less tendency to experience congestion have a stronger link between mobilization time and ETE [100].

4.4.2 Public compliance and response

Evacuation models insufficiently account for public behavior [121]. ETE studies for NPPs consider some variation in public behavior, as discussed in Chapter 2. There are two diverging but related metrics for public compliance, shadow evacuation and compliance with a protective action order.

Shadow evacuation is defined as a spontaneous evacuation of a portion of the population that has not been ordered to evacuate. Guidance from the NRC is to assume that shadow evacuation is 20% of the population from 5 miles beyond the edge of the EPZ [97]. This is in contrast to the nearly 50% shadow evacuation during the Three Mile Island accident [47]. The U.S. Government Accountability Office questioned this NRC guidance and recommended more research to understand the extent of shadow evacuation and its effect on overall evacuation [48]. A more recent NRC study evaluates shadow evacuation beyond the EPZ up to 40% and finds little difference in evacuation time but does not consider the effect of shadow evacuation on consequences.

The guidance is to consider shadow evacuation to occur uniformly in the areas it exists. Variation in shadow evacuation based on population cohort, time of day, or area is not considered. Studies of shadow evacuation typically rely on telephone surveys of the permanent population living in the EPZ. This provides a limited understanding of the expected actions of the population. Shadow evacuation might be higher during the day when people are more likely to get unofficial cues, such as seeing other people evacuate, direct interpersonal communication, or social media. These unofficial cues will be reduced at night when most people are sleeping. It is also more likely that people will spontaneously evacuate if they are not from the area and do not have a readily available shelter.

Compliance is assessed as the portion of the population that follows protective action orders, as discussed in Chapter 2. Current guidance and practices do not consider compliance for a SIP strategy or when no protective action is prescribed [38], [96]. The NRC guidance for ETE studies does not consider compliance, but separately the SOARCA studies consider an assumed level of 0.5% non-compliance to be best practice for modeling [38], [97]. Some ETE studies identify large population cohorts (10%) that are expected not to comply with orders to evacuate [163]. Studies of large evacuations show that compliance can vary drastically, with some as low as 25% [46], [47], [106]. It is well understood that communication messaging is one of the causes of compliance variance [46], [52], [110]. This effect is not considered in siloed studies.

4.4.3 Transportation Operation

Demographics and infrastructure within EPZs are as diverse as the regions of the country in which they are located [100]. This variation precludes the use of simple safety rules (e.g., "turn around, don't drown" or "stop, drop, and roll") and requires site-specific evacuation plans. Despite receiving detailed brochures, most inhabitants of an EPZ do not remember the evacuation plan or where to look to find the information [160]. This leads to the population taking routes they are familiar with, resulting in unbalanced roadway demand and congestion [85].

None of the models cited in Section 3.3 can model an evacuation strategy that is provided to the public (e.g., a keyhole). Some cannot model specific actions at all; they simulate vehicles leaving the road network based on roadway capacity. A few models allow roads to be closed, which can be used to set up an off-limits area like a keyhole.

4.5 Robustness

A robustness metric is needed to compare evacuation strategies under uncertainty. Robust planning explicitly recognizes uncertainty and seeks a plan that is desirable under many if not all possible futures [84]. NPP licensees and emergency personnel are well versed in EP and are required to maintain EP by regulation which makes them good candidates for robust planning. Since robust planning takes additional time, cost, and understanding of the risk, it is more difficult to achieve where resources are limited or risks are not well understood. However, robust decision-making should be the standard where it is achievable.

Current emergency plans are designed like NRC fault trees [134] with deterministic assumptions and prescriptive actions. Deterministic assumptions limit the information entered into a model, leading to limited potential outcomes. Uncertainty is more apparent outside of the highly controlled and monitored environment of the NPP. When the public is involved, even ample research to predict behavior based on empirical studies can be proven wrong. When input parameters do not match the deterministic assumption in the fault tree, the decision-maker has no prescribed path forward. This concept would be akin to a fault tree analysis where a branch of the tree was never considered, and therefore the proper response was not determined, as happened at Three Mile Island [164].

It has been shown that uncertainty due to traffic congestion points, public information, and compliance can strongly affect outcomes [46], [121]. Evacuation transportation models have been steadily refined to the point of modeling individual vehicles on a second-to-second basis through a roadway network using a variety of optimization methods on multiple objectives. There is little discussion in many of the presented methods or example studies of the uncertainty included, if any, and how that is used in making the decision recommendation. To be robust, the solution needs to be preferred when considering uncertainty.

Many studies on emergency evacuation are geared towards optimization [98], [107]. Optimization techniques have been utilized to model minimization of evacuation network clearance times, minimize route length, 'assign' evacuation routes for demand balancing, reduce congestion, and assist with the allocation of evacuees among the available emergency shelters [165]. These studies make the unsupported assumption that decision-makers should focus on optimization-based tools to develop efficient emergency evacuation plans. This assumption ignores risk and consequences in favor of metrics exclusive to that siloed research field.

When multiple objectives need to be met, such as when several risk sources are present, then multiple solutions very likely exist on a Pareto optimal frontier. Rarely is the difference between the 'optimal' solution and other, Pareto optimal solutions provided. The optimization method may provide a solution that results in a faster evacuation time, but that is of little consequence if the savings are a few seconds or are much more difficult to implement. If the solution does provide a significant level of benefit, as defined by the decision makers' objectives, then it must be determined if the solution is robust to uncertainty. If there are multiple optimal solutions, or the optimal solution is not significantly advantageous by comparison, then other solutions need also to be considered in the decision-making process. A non-optimal solution could be nearly optimal but more robust to uncertainty or easier to implement. In a sense, this is the risk premium or the difference from the preferred solution a decision-maker is willing to accept to reduce uncertainty.

The proposed metric for robustness calculates the relative portion of a distribution of model iterations for one protective action that dominates another protective action using pairwise comparison.

$$R_{i,j} = \frac{a_{i,j}}{n_i} \tag{1}$$

where,

- n_i is the number of model iterations in a set for a protective action i
- $a_{i,j}$ is the number of model iterations in the subset $\{n_i \mid r_i < \min(r_j)\}$
- r is the summed risk of a protective action
- i and j represent the two protective actions being compared

This metric can be easily visualized using a cumulative distribution function, as shown in Figure 14. The vertical dashed line indicates the minimum value of the "Staged" protective action. The horizontal dashed line marks the intersection of the vertical line and the "Lateral" protective action. The point where the horizontal dashed line intersects the y-axis indicates the robustness of Lateral to Staged, or, expressed differently, it is the portion of the Lateral protective action that dominates the Staged protective action. In this example, the robustness value is 0.28.

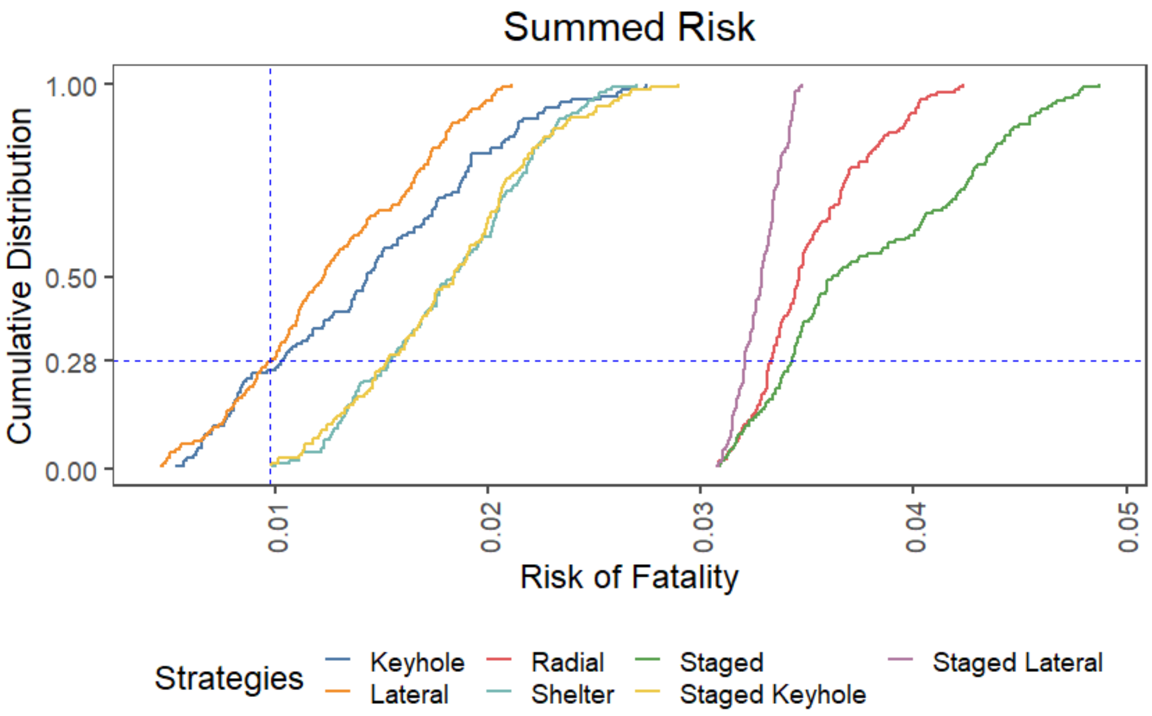

Figure 14: Visualization of robustness using a cumulative distribution. Example of one accident scenario with 8-mph wind from 150 degrees, a long-term station blackout accident, and daytime population

The portion of the distribution $a_{i,j}$ in the above equation does not ensure all factors that go into an iteration match between protective actions. For example, in Figure 14, a high level of shadow evacuation may be near the bottom of the distribution for a Staged strategy, while the same level of shadow evacuation may be near the top of the distribution for a Lateral strategy. If structured scenarios of all parameters are used instead of random Monte Carlo iterations, pairwise comparisons can be made. The downside is that protective action strategy comparisons would need to be made for each matched iteration pair. This limitation of the proposed method will be reserved for future work.

4.6 Decision Making Criteria

The complex and uncertain nature of the problem means that a solution that is "optimal" in the usual, one-dimensional sense will not be available. Even with hindsight, every counterfactual cannot be known. Instead, a robust strategy under uncertainty must be selected—a selection that must be made under time pressure. Thus, an approach is needed that will produce the tradeoff information required to support a relatively quick decision that balances multiple risks and uncertainty.

A decision that might reduce one risk could increase other risks. In the past, decision-makers have narrowed the problem through several methods: focus on ETE as a proxy for risk, reduce degrees of freedom, and ignore uncertainty using deterministic assumptions. Limited influence on implementing a strategy (Figure 12) can make decision-makers select a strategy with a higher perceived potential for success instead of the strategy that could avoid the most risk. A very complex strategy will need better communication, more compliance, and more situational awareness than a simple full EPZ evacuation. The full EPZ strategy has a greater transportation risk than a keyhole strategy (by moving more people) and may increase hazard exposure as well by increasing traffic congestion. This is exemplified in Pennsylvania, where a full EPZ "all-go/no-go" evacuation is mandated to avoid the uncertainty of the successful application of a more targeted strategy (e.g., keyhole) despite the potential to reduce the overall risk [166].

The EPA uses a dose equivalence calculation to determine if the risk of a protective action (e.g., evacuation) is less than the risk of doing nothing. Currently, the EPA PAG manual uses just a transportation risk threshold converted to dose (0.03 rem). The value used for this threshold is discussed in Section 3.7.2. If the projected highest dose is greater than this threshold, a protective action may be warranted. This is done to ensure that using a protective action does not impose more risk than it mitigates. This basis is useful for determining if something should be done, but it does not provide a useful metric to determine what should be done. As shown in Chapter 2, once a protective action is used to mitigate dose, the risk of dose and transportation is of the same order of magnitude and varies by protective action strategy.

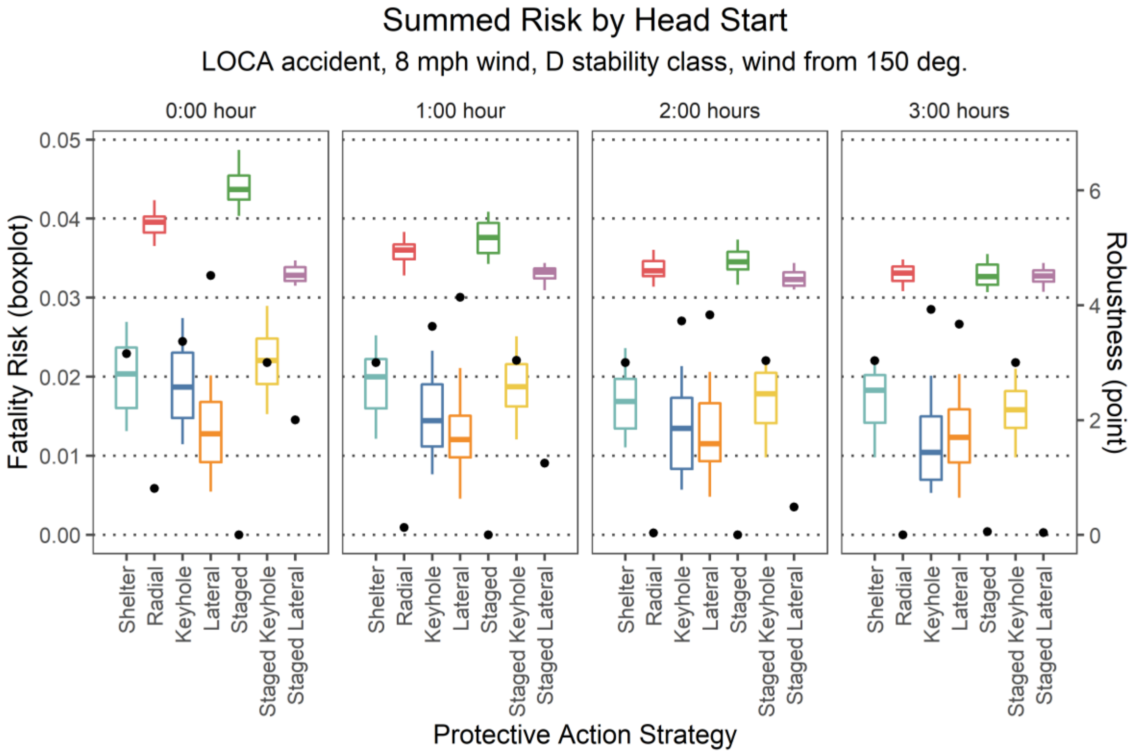

Figure 15: Summed risk and summed robustness for the same example accident scenario as shown in Figure 14

This is a multiple-criteria problem in which the decision-maker would like to minimize risk and maximize robustness. One example accident and decision scenario is shown in Figure 15, where the robustness is the summed value of a strategy to every other strategy, and summed risk is a range of values that consider uncertainty. It would be interesting to explore the tradeoffs between the two for various strategies using a Multi-Criteria Decision Making approach. This is a topic for future work.

4.6.1 Summed Risk as the Measure of Effectiveness

A summation of risks is proposed as the MOE for decision-making. The summed risk is defined at the summation of latent cancer fatality risk from radiation exposure and the transportation risk. Both of the component risks are conditional on an accident event and cumulative for the entire population during the protective action.

The summation of these disparate risks is consistent with the current EPA guidance in the PAG manual, which converts transportation risk to a radiation dose equivalent and uses a MOE of dose. The summed risk MOE retains the fatality risk and skips the step of transforming it to a dose equivalent. The common consequence metric of fatalities allows for direct comparison of transportation and radiation risks. There is an important point of concern that these risk calculations use dose-response metrics that may need to be updated. These concerns are discussed in Section 3.7.

By combining the two risk metrics instead of using multiple metrics, the decision-maker cannot differentiate between prompt or latent consequences (i.e., temporal considerations) or apply weighted preferences. A multicriteria model would allow for more metrics to be included in the decision process. These metrics could include evacuation time, robustness, protective action strategy complexity, or estimated time to a radiation release. A metric for protective action complexity may be a reasonable proxy for the potential for the evacuation to succeed. Protective action strategy complexity is not yet defined in the emergency response literature but briefly mentioned in some references on communication [52], [167]–[169].

4.6.2 Decision-Making Method

There are multiple requirements to meet before a protective action is selected. These are described in the EPA PAG manual [96] and discussed in several sections of this chapter. Once the minimum thresholds have been met, most notably the 1-rem projected dose over a 4-day period, a protective action strategy should be selected. The interdisciplinary framework described in this chapter should be used to model the risk to the population for a range of feasible protective action strategies while considering uncertainty.

Uncertainty may be significantly reduced for several of the parameters used in the model as real-time information is obtained during the emergency. Some examples are wind speed, wind direction, NPP accident type, and time of day. This reduces the decision space of possible outcomes significantly.

Once the summed risk is determined for each model iteration, a central tendency can be found for each strategy. It is important to find the central tendency (usually the mean) only after reducing the decision space to realistic outcomes for the existing emergency. Using the central tendency of the full and unlimited set of model outcomes could lead to incorrect decisions by ignoring the real-time data. Consider, for example, that a protective action strategy is particularly poor when used in a specific region because it moves a large portion of the population and causes congestion. This would increase the overall mean of summed risk for that strategy. However, the same strategy could dominate all other strategies when used in a completely different region.

As previously noted, this is actually a multiple-criteria problem in which the decision-maker would like to minimize risk and maximize robustness. In the present work, the decision problem will be simplified by combining the risk and robustness criteria to create the following decision metric. In doing so, we note the implied value judgment about the relative importance of risk and robustness.

$$\mathrm{u}(x^{\mathrm{i}}) = \frac{\widetilde{\mathrm{r}_{\mathrm{i}}}}{\sum_{\mathrm{i,j}} \mathrm{R}_{\mathrm{i,j}}} \tag{2}$$

where,

$$x^i \mathrm{P} x^j \Leftrightarrow u(x^i) < u(x^j)$$

and

- $\mathrm{u}(x^{\mathrm{i}})$ is the decision metric
- r_{i} is the median of summed risk for a protective action
- x are protective action strategies
- R is the robustness metric
- i and j represent the two protective actions being compared for robustness

The objective of this method is to minimize the decision metric $\mathrm{u}(\mathrm{x}^{\mathrm{i}})$ among the possible protective action strategies. Robustness is used in this equation as the summation of all robustness values when compared to the alternative strategies.

4.6.3 Ethical Considerations for Comparing Risks

The goal of protective action is to reduce consequences. Which consequences take priority, who experiences the consequences, and how is that valued? The problem of "who" counts, and how to count them, is ubiquitous. Everything about what is calculated, how, and what is included in the decision has ethical implications.

The PAG manual guidance is that no protective action is warranted when the dose is expected to be less than the 1-rem threshold. This makes the large assumption of perfect compliance, and therefore not evacuating will avoid doing more harm. That is unlikely because shadow evacuation is expected in and out of the EPZ, which is not usually accounted for in a SIP protective action. The lack of a decision to evacuate does not avoid all transportation risks as shadow evacuation occurs spontaneously despite a protective action recommendation. The decision to evacuate or not is an ethical decision by the decision-maker. Inaction does not push the ethical choice onto the uninformed and untrained public.

No matter the protective action decision, some of the population will be prioritized over others, whether or not it's intentional or explicit. Most NPP emergency plans identify cohorts, some of which are evacuated at earlier stages (i.e., less severe) of an emergency. This is a decision to prioritize that cohort due to a range of reasons, such as sensitivity to radiation dose or long mobilization time. A metric based on demographics or SVI (see Section 3.4) could be included in the multicriteria method. One option could be to determine the range of summed risk across demographics. The smaller the range of summed risk, the more "equitable" the protective action.

Due to the prompt vs. latent characteristics of the two risk metrics, it is reasonable to consider the temporal valuation of fatalities. The elderly might perceive radiation risk to be less than a younger person and therefore take a warning less seriously [170]. Similarly, it is well known that people undervalue transportation risk and might therefore give that risk no or relatively little consideration when evacuating [170].

Age would complicate decisions when comparing these risks as radiation dose risk is generally considered more severe for children and the elderly. Some evacuees have a much higher transportation risk as part of the medically special cohort [153]. The elderly comprise a disproportionate number of evacuation-related fatalities, primarily due to medical complications from leaving a hospital or care home [142], [155]. This attribute is currently addressed by preemptively evacuating special populations at a lower warning level (i.e., a Site Area Emergency) than a General Emergency. Two methods that have been proposed to consider age are quality-adjusted life years [171] and the concept of "fair-innings" that considers life expectancy [172].

5 Future Work

The development of interdisciplinary research provides a wealth of research opportunities. Several specific areas should be considered priorities. First, develop methods for integration of behavioral science research with transportation models. These methods may need to be flexible to match the constraints of each transportation model. Second, output data from transportation models that enable integration with hazard models. Third, maintain the focus on consequences in every step of emergency preparedness research. This includes understanding that the MOE that may seem obvious (e.g., evacuation time) may not always reduce consequences. Fourth, develop a deeper understanding of the interaction of interdisciplinary factors on protective action strategies. Fifth, develop techniques for robust decision-making in the face of multiple, conflicting criteria that can be used by emergency managers under tight time constraints. Finally, create an integrated model based on the framework in this chapter as a step toward identifying the largest effects, interactions, and most important missing factors to guide future research.

6 Conclusions

Interdisciplinary emergency research could provide valuable insight and result in robust decision tools. Many barriers to interdisciplinary research currently exist. This chapter proposed a framework for an interdisciplinary model and addressed many of the limitations of the current siloed approach.

Current MOEs are used as proxies for reducing risk and consequences (e.g., evac time instead of risk) but are not traceable to improved outcomes. Radiation dose has been the MOE for NRC and FEMA PAR decisions for NPPs. An interdisciplinary risk-based framework did not exist to consider protective action decision-making under uncertainty. Instead, deterministic assumptions are used to reduce problem dimensionality and improve tractability. Unless uncertainty is considered, the deterministic assumptions can lead to blind spots.

Risk-based MOEs are needed to ensure the solution is solving for the intended outcome. An interdisciplinary approach is needed to improve the decision-making process. This is well underway for some disciplines, such as behavioral response and transportation. It needs to be networked to the other components of the interdisciplinary framework.

This chapter defines an integrated risk-based framework that can help decision-makers to reduce risk. This chapter presented a risk and consequence-based multicriteria decision method along with a method to determine the relative robustness of protective action strategies. The application of this decision criteria to an interdisciplinary model replaces the need to use criteria that are proxies for the goal of reducing risk.

Chapter 5: An Integrated Risk Model

Abstract

In the very unlikely event of an emergency at a nuclear power plant (NPP) the decision if and how to evacuate must be made. Emergency response decisions have predominantly relied on evacuation time estimate (ETE) studies that are built on a broad set of simplifying and potentially unrealistic assumptions and real-time hazard dispersion models that do not correspond to the evacuation models. The results are evacuation plans that are indirectly based on the time required to evacuate instead of the potential risk to the population. This chapter presents a model that integrates hazard dispersion, protective action, and consequence analysis modules to provide more complete information for early planning, exploratory analysis, and emergency decision-making. This integrated model overcomes the limitations of current models and provides capabilities previously not available for consequence analysis. Using this model, protective actions can be compared across multiple risk-based measures of effectiveness while considering the effects of uncertainty.

Acronyms and Abbreviations

CF	Conversion Factor
EP	Emergency Plan
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
ETE	Evacuation Time Estimate
FEMA	Federal Emergency Management Agency
GE	General Emergency
IPAWS	Integrated Public Alert and Warning System
ISCORS	Interagency Steering Committee on Radiation Standards
MACCS2	MELCOR Accident Consequence Code System, Version 2
MOE	Measure of Effectiveness
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
ORO	Offsite Response Organization
PAD	Protective Action Decision
PAG	Protective Action Guide
PAI	Protective Action Initiation
PAR	Protective Action Recommendation
RASCAL	Radiological Assessment System for Consequence Analysis
SIP	Shelter in Place
SOARCA	State-of-the-Art Reactor Consequence Analyses
TEDE	Total Estimated Dose Equivalent
WEA	Wireless Emergency Alert

1 Introduction

In the unlikely event of an emergency at a nuclear power facility where radiation is released, it is important to select the appropriate protective action. Protective action strategies for emergencies at nuclear power plants have evolved. Early emergency plans specified complete evacuations that were not well coordinated between, as was evident with the Three Mile Island accident [164]. Targeted evacuation strategies have been explored over time [40], [101]. Strategies are often not directly compared in studies, and when they are, the results are generalized. Despite recent work [22], [145], [160], many questions remain of when and how to select one protective action strategy over another. These questions must be addressed for emergency planners can make an informed decision.

An integrated consequence model capable of evaluating protective action strategies based on risk is introduced at the end of chapter 2. This chapter fully develops the integrated model and describes the method of use for protective action decision making. The interdisciplinary framework designed in chapter 4 is used as a basis to ensure the model can address the limitations of current models.

Two major risks are evaluated: radiation exposure and transportation. An integrated consequence model is used to combine radiation exposure modeling with evacuation modeling that is capable of estimating consequences during evacuation. The integrated model demonstrated in the paper provides new insights for emergency planning by combining evacuation analysis with consequence analysis. Monte Carlo simulation is used in conjunction with Markov Chains and parametric analysis to characterize protective actions and the impact of uncertainty on the protective actions' effectiveness.

Advances in real-time situational awareness for emergency planners, understanding of public behavior, and communication technology provide an opportunity for the implementation of more complex evacuation strategies. A better understanding of how to reduce exposure during an evacuation is still needed, as was evident during the Fukushima accident. The exposure and transportation risk could have been reduced further through better communication and evacuation execution [142].

In the event of an accident, a Protective Action Decision (PAD) is made to determine if the population should be evacuated and what strategy should be used. PADs are made using information from several sources. Evacuation Time Estimate (ETE) studies provide time estimates and a better understanding of the challenges that may be experienced during an evacuation. This information is often used as a cut-off; if the population can evacuate before the expected release, they should evacuate; otherwise, it may be better to shelter-in-place (SIP). Most evacuation strategy studies also take this approach; assume the population can evacuate prior to a radiation release.

Differentiating between a calculation of the various individual factors that can contribute to risk and an integrated risk calculation is important for understanding the limitations of current evacuation planning approaches. The typical approach to ETE studies may lead to missing important insights. In a typical ETE report, the focus is solely on characterizing the total time duration needed to complete the evacuation process for a variety of postulated conditions. Such a calculation does not consider the spatiotemporal dispersion of radioactive material concurrent with spatiotemporal population distribution during a protective action implementation. Based on ETE study results, individual local evacuation routes could be revised to reduce congestion or avoid other identified challenges. These interventions may be chosen without considering public health impacts such as dose or evacuation-related injuries or fatalities. Health consequences are not a component in current ETE assessment practices, making them disassociated from any ETE optimization considerations.

This model diverges from typical evacuation models that use deterministic assumptions and prescribed scenarios to reduce the universe of potential outcomes. Instead, this model combines Monte Carlo and scenario capabilities in an exploratory analysis design to confront the complex and uncertain evacuation process. Protective actions can be compared across multiple risk-based measures of effectiveness while considering the effects of uncertainty while using this model.

1.1 Background on Current Emergency Planning Review

Emergency and hazard management is a well-established research area that applies many methods [98]. Most evacuation studies are related to natural disasters. Government agencies have evaluated evacuations not related to NPPs [46], [148], [173]. These studies indicate the public response and characteristics of an evacuation can vary widely by event, which is supported in the peer-reviewed literature [174], [175].

Evacuation from a nuclear power plant risk source is unique due to the significant training and planning. Transportation risk during evacuations is expected to be similar to average transportation risk [96], [148], [153]. More sophisticated interdisciplinary models for quantifying fatalities due to evacuation have been proposed but are not well developed in literature [141].

Emergency planning is required for NPPs by The Nuclear Regulatory Commission (NRC) has guidance for emergency planning [13] and evacuation time estimation [19], [97]. The NRC has completed several studies related to evacuation and severe accident consequences near NPPs [59], [110], [158], [159], [176]. The three-volume protective action recommendation (PAR) study was intended to assess alternative protective actions for severe accidents for potential revision of NUREG-0654 Supplement 3. The study is comprised of literature and state-of-the-art review, focus groups and telephone survey, and technical basis for protective action strategies [30], [40], [45]. A summary of the PAR study can be found in [160]. The PAR study suggests that SIP can be an effective protective action in some cases and does not get enough credit in emergency planning [45]. Evacuation strategies have been compared to SIP in other studies with similar results [143], [156], [161]. Alternative protective actions have been explored to a lesser degree in peer-reviewed studies [101], [177], and industry groups [178]. The value of formal emergency preparedness programs is estimated using consequence reduction as a metric in [92].

Some sites may not have roadways available in the correct direction or capacity to utilize some evacuation strategies. Larger populations may experience more congestion. Local population clusters may have higher non-compliance than the surrounding areas. A recent review attempted to identify common characteristics which would facilitate the grouping and development of the base models. The review identified that demographics and infrastructure within EPZs are as diverse as the regions of the country in which they are located. [100].

Uncertainty analysis has been used to explore consequence sensitivity for some variables. The bulk of uncertainty analysis has been directed at reactor failure modes [162], but early warning, road obstruction, and loss of local power have also been mentioned [137], [138], [157]. The NRC studies stop short of questioning public behavior variables, including the proportion of shadow evacuation, level of non-compliance, or immediate actions taken by the public. The State-of-the-Art Reactor Consequence Analysis (SOARCA) set of studies attempted to provide a more realistic understanding of accident progression and off-site consequences [4]–[6], [137], [138]. The SORACA studies focused on reactor safety failure modes and used existing site-specific protective action practices. The limitations of the consequence analysis in SOARCA and the MACCS2 model used in that project are discussed in Chapter 2. This chapter's integrated model overcomes the limitations identified in the SOARCA studies and provides capabilities previously not available for consequence analysis.

2 Integrated Consequence Model

A risk and consequence model is developed in this chapter to evaluate protective action strategies and the factors that impact these strategies. The model is used to assess the consequences realized in a particular accident scenario under a given set of circumstances. The consequence model assesses protective action strategies by using risk to the population as a metric of effectiveness (MOE) rather than the total time to evacuate. It is desirable to consider the risk consequences because an ETE reduction may not necessarily result in overall dose reduction.

Differentiating between a calculation of the various individual factors that can contribute to risk and an integrated risk calculation is important for understanding the limitations of current evacuation planning approaches. In a typical ETE study, the focus is solely on characterizing the total time needed to complete the evacuation process without considering the geographic dispersion of radioactive material. The typical approach to ETE studies may miss important insights and lead to inferior strategies; for example, local evacuation routes may be designed to reduce evacuation time or avoid congestion but without considering public health impacts such as dose, or evacuation-related injuries or fatalities. Public health consequences are not explicitly included in current ETE assessment practices.

The current evacuation time estimate methods predominantly use deterministic assumptions, which by their nature are static and limited in their ability to provide critical insights available in a stochastic model [59]. To complete a stochastic integrated analysis, it is necessary to understand the impact of the deterministic assumptions. Recent studies by the NRC, based on the risk-informed approach, attempt to create distributions to replace some of the deterministic assumptions [59]. Research needs to continue in this area to improve integrated analysis.

Overall risk impacts can be better considered through the integration of the transportation and dose risk. This integrated analysis functions by joining a hazard dispersion module and a protective action module using a common time-step. NPP emergency planners can apply this integrated consequence model to gain deeper insight into opportunities for time and/or consequence reduction while complying with current guidance.

2.1 Integrated Model Design

The integrated model is comprised of three main modules: a Protective Action module (where the people are), a Hazard Dispersion module (where the radiological hazard is), and a Consequence module (risk and effects to the people). These modules take in several types of information, including data (e.g., weather, population), scenario choices (e.g., NPP accident type), and probability/frequency distributions or deterministic assumptions (e.g., level of compliance) as illustrated in Figure 16 below. Together, the three modules calculate the spatiotemporal progression of the event.

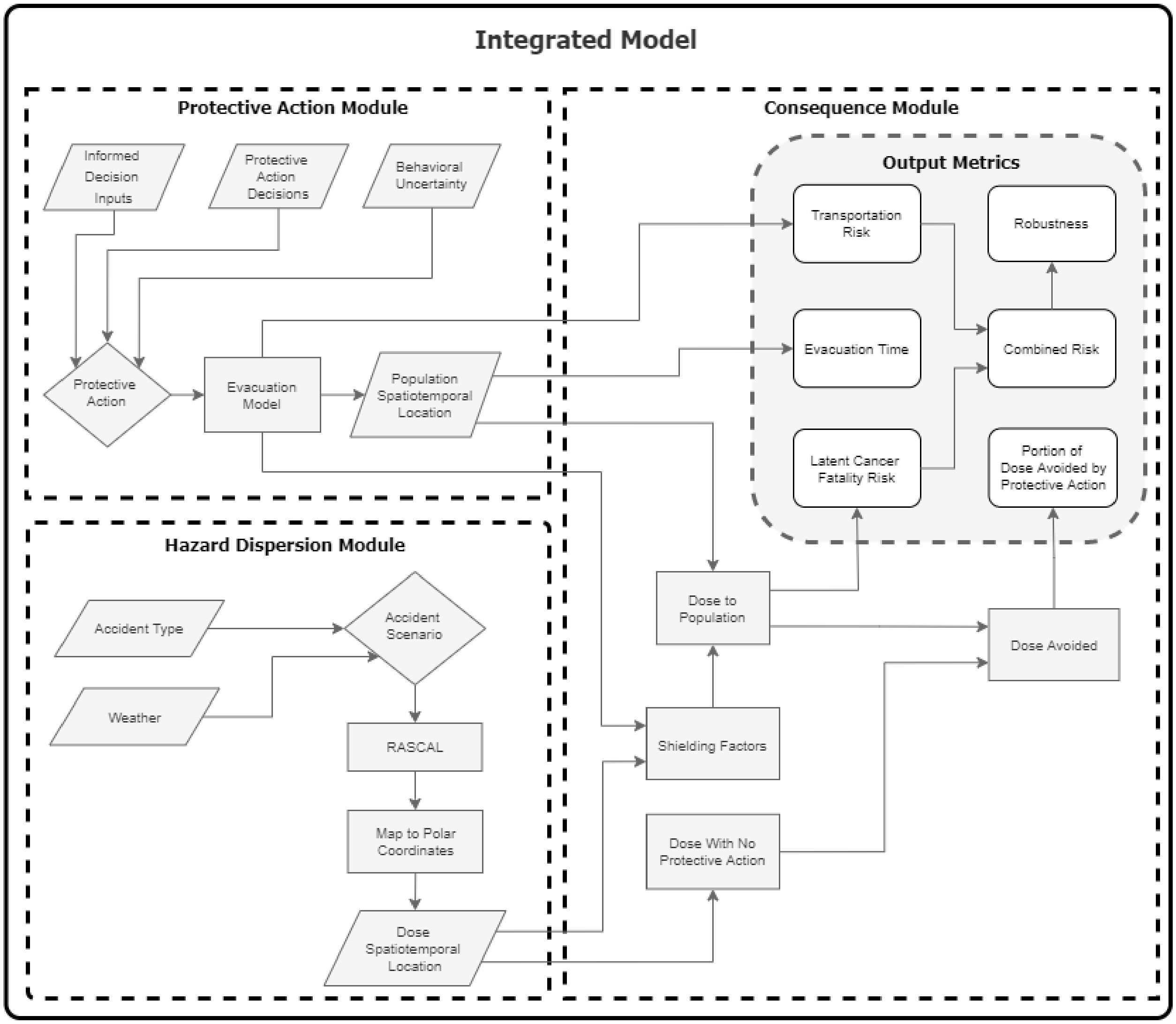

Figure 16: Conceptual Diagram of Integrated Model

The integrated model design allows the decision-maker to evaluate a range of accident progressions and protective actions under uncertainty instead of considering separate ETE and hazard dispersion models side-by-side and attempting to infer the lowest risk course of action. However, the model is not designed to provide optimization of this complex problem with many stochastic parameters. Instead, it is designed to provide information and measures of effectiveness that the decision-maker would find useful in the event of an emergency, which are unavailable with other methods. While the diagram in Figure 16 describes a single model iteration, the decision-maker would utilize the output of a set of simulations.

A modular design allows for the decoupling of the protective action and hazard dispersion models. This provides the opportunity for computational efficiency by eliminating the need to re-run both models for every integrated model realization. For example, a single hazard dispersion scenario can be integrated with multimer protective action module iterations without the need to re-run the hazard dispersion module. The decoupled design provides flexibility for use in stochastic Monte Carlo operation to characterize the sensitivity of variables or as a discrete scenario such as NRC guidance for ETE studies (see Chapter 2). This efficiency also reduces the need for some simplifying assumptions that have been used in other models and guidance to reduce computational load.

2.1.1 Geographically Defined Site Area

The EPZ is the area surrounding the NPP (i.e., typically a 10-mile radius for LLWRs) within which special considerations and management practices are pre-planned, practiced, and exercised in case of a radiological emergency [15]. For ETE studies and emergency planning, the EPZ is typically divided into polar coordinate cells where ***r*** is a radially defined ring and *theta* is an angularly defined sector. The combination of sectors and rings defines cells. The NRC guidance suggests segmenting the area into 1-mile rings and 16 sectors [16]. This study developed a model with ring boundaries every 1-mile out to 15 miles and sectors every 10 degrees (producing 36 sectors) to achieve higher fidelity in the results. These parameters were selected to align reasonably with NRC guidance and studies such as SOARCA to enable refined analysis and not overstate the resolution available in model inputs. Figure 17 illustrates sectors, rings, and cells, in addition to the night population near a representative NPP.

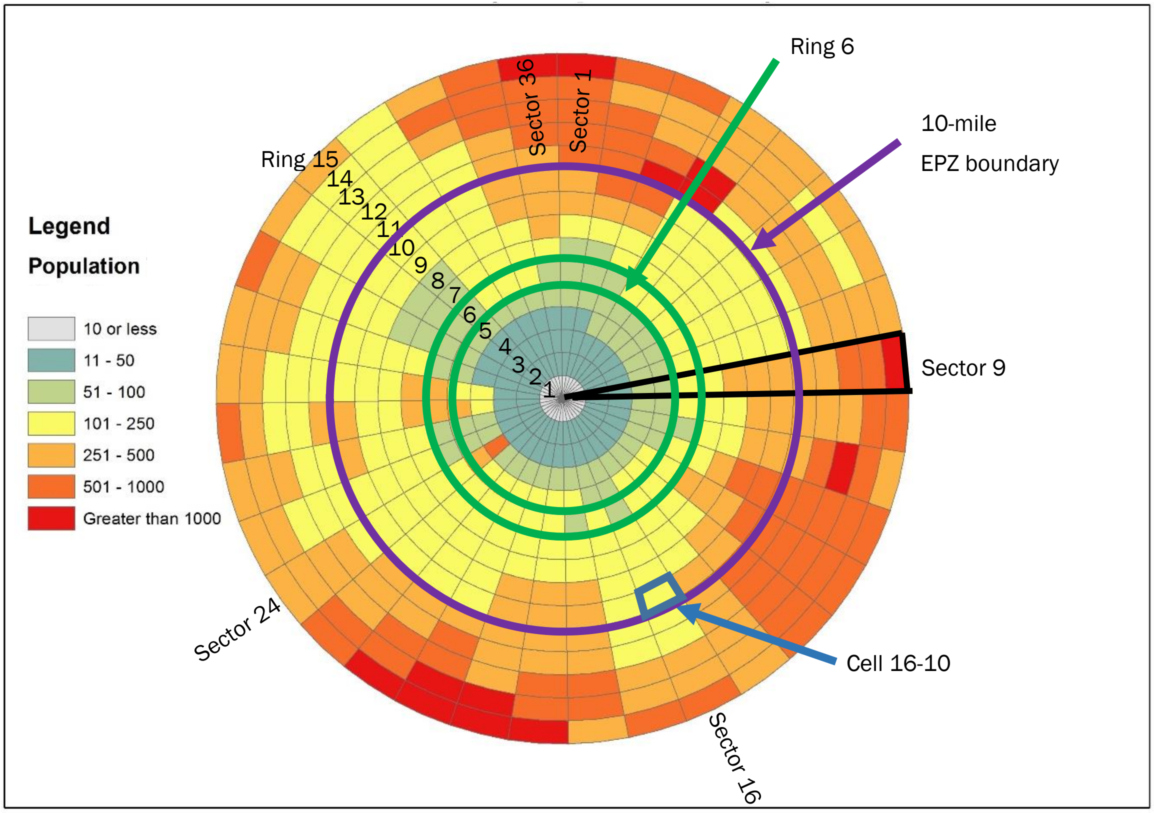

Figure 17: Polar Grid that is used in the Integrated Model. The population around a representative NPP is used as an illustrative example

The polar grid in Figure 17 is used in all modules of the integrated model. When necessary, inputs are re-mapped from source data to the polar grid. Methods for re-mapping are discussed in the appropriate sections.

2.1.2 *Inputs*

The model inputs are shown in Table 17 are categorized into four groups: informed decision inputs, protective action decisions, behavioral response, and constants. The constants are used for the calculation of specific factors. Informed decision inputs consist of factors that the decision-maker will likely have some information for during the decision-making process. Protective action decisions represent the range of strategies a decision-maker could use. In general, the analysis would consider all relevant protective action strategies so a comparison can be made. Behavior response factors specify levels of compliance with protective action orders and the response curve.

Table 17: Description of Integrated model inputs

	Variable	Notes
Informed Decision Inputs	Populations	The number of people in each map cell at the beginning of the simulation.
	Source term (RASCAL) scenarios	Spatiotemporal dose in rem converted from RASCAL output
	Head start	Number of 15-minute time steps the population begins a protective action prior to radiation release
	Roadway capacity	Percentage factor of maximum roadway capacity used to simulate congestion or adverse weather
Protective Action Decision	Strategy	The strategy determines the evacuation zone and how the population move through the evacuation zone
Behavioral Response	Shadow evacuation	The portion of the population outside of the evacuation zone that evacuate. This factor is uniform outside the evacuation zone and begins
	Non-compliance	The portion of the population that refuses an order to evacuate. This factor can be uniform or varied by map sector, ring, or individual cell
	Cell transfer factor	The probability that an evacuee will move to the next cell on the evacuation pathway between a given time-step. This factor can be set for each cell or uniformly.
Constants	Latent Cancer Fatality Factor	Conversion factor from person-rem to latent cancer fatality risk
	Transportation Risk Factor	Transportation induced fatality risk in vehicle-miles
	Vehicle Occupancy	Average number of people per vehicle
	Evacuation distance	The average round-trip distance traveled

2.1.3 Outputs

In addition to providing spatiotemporal exposure (i.e., dose to the population) the integrated model provides six measures of effectiveness (MOE):

- Latent Cancer Fatality Risk
- Transportation Risk
- Combined Risk
- Portion of Dose Avoided by Protective Action

- Protective Action Robustness
- Evacuation Time

The current NRC ETE guidance and guidance for protective action strategies only looks at one of the six decision metrics: evacuation time. Evacuation time is the time required to move 90% of the evacuating population out of the EPZ (see Chapter 2).

Latent cancer fatality risk and transportation risk are the collective risks of a fatality to the population from radiation dose and travel. These are defined in greater detail in Sections 2.4.4 and 2.4.5. Combined risk is the summation of latent cancer risk and transportation risk and is described in chapter 4. Robustness is a metric defined in chapter 4 that indicates the relative effectiveness between two protective action strategies.

The portion of dose avoided is on output MOE in the integrated model that provides insight into effective a protective action strategy is at avoiding exposure. The portion of dose avoided is defined as the portion (percentage) of exposure that can be avoided for a given set of conditions using a particular protective action strategy compared to if no protective action is taken. This metric is a key component of the EPA protective action guidance and would be expected by decision-makers. However, this model provides a significant improvement in resolution and spatiotemporal information over current models.

2.2 Timing

A standard timeline and time-step duration are used to sync separate protective action and hazard dispersion module realizations (Figure 18). The consequence module results (i.e., geographically distributed dose source) can be modeled earlier or later relative to the start of evacuation to simulate early warning and/or the time between initiation of radionuclide release and warning to the public.

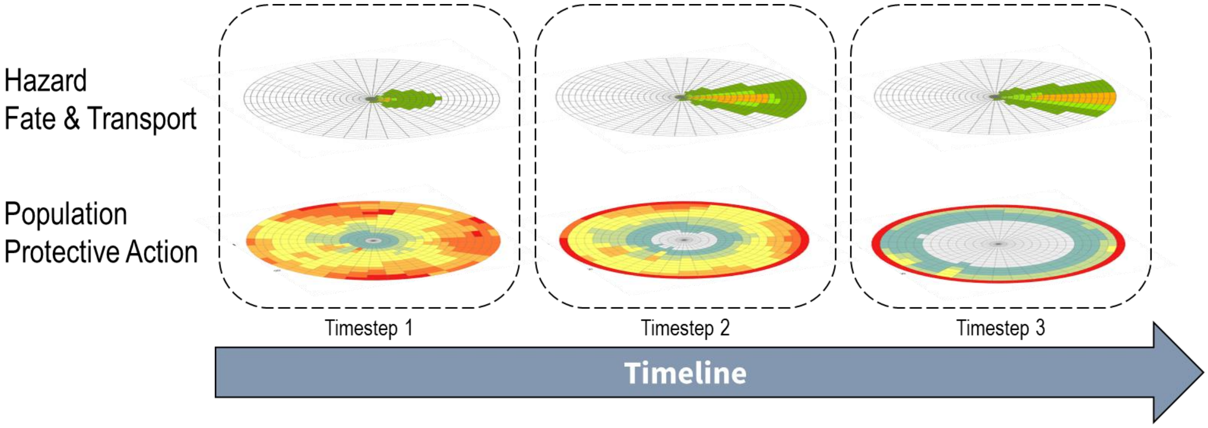

Figure 18: Synchronization of Radionuclide Fate & Transport Model and Population Transport Models. Reproduced from Chapter 4.

Time steps in this model are defined as 15-minute segments. NRC emergency response tools, such as RASCAL, use 15-minute weather time segments [55]. The output is synced between modules by using a consistent 15-minute time-step and a standard geographic reference. A proper sequence of output steps is maintained. To estimate the consequences of the evacuation phase, it is good practice to run the module beyond the number of time steps needed to evacuate the population from the EPZ to avoid truncating the results.

2.2.1 Head start

A standard ETE study does not consider radiation release timing. To perform a consequence analysis, it is necessary to understand the population's location through time relative to the hazard to determine if exposure occurs. Typically, this is accomplished by estimating the time from accident initiation until hazard release. The amount of head start can be varied in the model to simulate various levels of rapid or delayed alert.

This model frames protective action timing relative to hazard release instead of anchoring to accident initiation. This framing is useful for comparing protective action strategies when the timing of hazard release is uncertain. In this model, a head start is defined as the amount of time from initiation of a protective action to the beginning of radiation plume release (Figure 19).

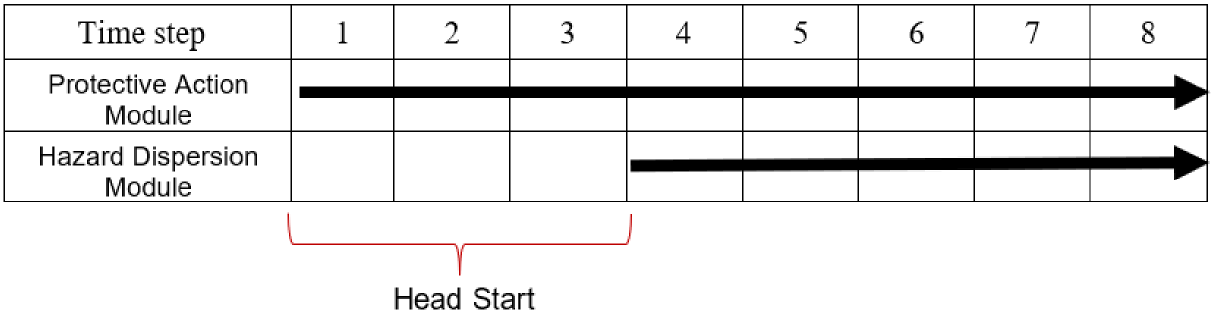

Figure 19: Time step syncing of Evacuation and Exposure Modules

Protective action initiation (PAI) is the time gap between the population receiving the warning and taking protective action. PAI is a complex interaction of many factors that are typically estimated in ETE studies through surveys or the population of the EPZ and varies between NPP sites. Several studies, NRC studies made assumptions of how long it would take the population to prepare to evacuate (e.g., 1-hour) [4], [45].

There are site and event-specific uncertainty related to the time between accident initiation and radiation release, the time to alert the public, and protective action initiation (PAI)[32]. This approach provides more easily transferable results between sites

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[32] Protective action initiation has also been referred to as 'milling time', time to prepare to evacuate, or mobilization time, although definitions are not consistently used.

and events where the initial public response may vary. Timing relative to radiation release instead of accident initiation avoids the need to make site-specific assumptions. Instead of including this uncertainty in the model, analysis was performed to determine the value of information related to these parameters.

The time from event to plume release is divided into two sections, before and during protective action. Mobilization time is defined as the time after the event begins to the start of protective action, including identification of the event, making a protective action decision, and alerting the population, followed by PAI by the population.

1.1 Protective Action Module

To calculate consequences during the progression of a protective action, it is necessary to know the spatiotemporal location of the population over time relative to the hazard. Microscopic traffic simulation models, such as those described in NRC ETE guidance, are not generally capable of modeling specific evacuation strategies, integrating directly with consequence analysis models, or providing spatiotemporal locations of the population to import into a separate consequence model [16], [31], [33], [34], [98]. A new transportation model was required to overcome this barrier.

The protective action module consists of a cell-based macroscopic traffic model that simulates the movement of the population. The transportation model is similar in concept to the widely accepted Cell Transmission Model [179]. A Markov Chain Monte Carlo design is used to simulate decision and probabilistic uncertainty during travel over discrete 15-minute time-steps. This method provides a flexible platform with relatively short computation times (i.e., seconds) but loses some of the detail of microscopic models. However, current microscopic traffic models are not able to integrate with a consequence model. A detailed ETE study using microscopic traffic simulation models can be used to validate and fine-tune the protective action module. Computation time and complexity tradeoffs will need to be considered.

The evacuation time is a function of many variables: population, alert and warning time, public compliance, traffic and road capacity, weather, and protective action strategy. Communication can positively or negatively impact several of these variables either directly or indirectly, including alert and warning timing, public compliance, strategy, and traffic.

2.2.2 *Population*

The spatial population data needs to be accurate and representative of the modeled event's location and time. This model's default spatial population data source is the U.S. Census block-level data for nighttime and the Oak Ridge National Laboratory LandScan database for the daytime population [180], [181]. Local populations can be determined more accurately through surveys, local business employee data, or other sources if necessary. The source data is re-mapped onto the polar grid to be integrated into the model. Consideration should be given to the transient population and special events that may have large impacts on population location and density that are not reflected in the default source data.

Population cohorts may have different departure times, travel rates, transportation dependence, spatial locations, and other characteristics. Special cohorts may have a higher overall risk profile that includes risks other than radiation dose (i.e., hospital patients that incur high health risks just by being moved). The lowest risk evacuation strategy may be different when considering the risk of moving special populations, compared to evacuation planning if only the average population is considered. Cohorts may be identified as needed and modeled separately.

2.2.3 Transportation

Transportation is defined in this model as the movement of the population from cell to cell. A discrete-time Markov chain is used to determine how much of the population moves to another cell and which cell that population moves to during each time step. Population movement between cells is influenced by several factors: protective action strategy, infrastructure (roadway) capacity, the quantity and rate of vehicles loading onto roadways, and population compliance factor.

Roadway capacity is incorporated in the model with a transition limit between cells. Inclement weather (e.g., rain, snow, fog) can be modeled by lowering the maximum capacity to match the type of weather. Guidance on the impact of weather on road capacity is discussed in chapter 2.

2.2.4 Protective Action Strategy

The site-specific ETE study is structured to evaluate the evacuation time to exit the EPZ as designed by the licensee and OROs in the EP. The EP typically is defined using a range of evacuation strategies, often complete EPZ evacuation or a keyhole evacuation along the centerline of the plume. Advanced communication presents the opportunity to use more sophisticated strategies. Delivering tailored warnings and instructions to different populations or geographic sectors could enable coordinated strategies to reduce the overall risk that may include dose, health, and transportation risk. All evacuation strategies have challenges with implementation, such as public understanding, public compliance, and communication barriers [30]. Advanced communication systems help to address these in part but do not necessarily overcome all challenges.

The benefit of alternate evacuation or SIP strategies depends on site-specific characteristics, location of population centers, weather at the time of an accident, local infrastructure, special cohorts and transportation available to these cohorts, availability of communication infrastructure, public compliance and behavior, and real-time information on threats and opportunities, among other factors. The development of alternative evacuation models can help enable comparative assessments of planning options. Protective action strategies can be developed using an integrated analysis model, like the one proposed here, which enables comparisons of traditional and alternate strategies.

Four general evacuation strategies have been proposed and are discussed in the literature:

- In a **Radial** evacuation, the population moves away from the NPP, radially out from the center to the edge of the 10-mile EPZ in the most direct path. Radial evacuation has been the typical method of evacuation in NRC sources [13]. This has resulted in several states adopting radial evacuation, such as Pennsylvania. A radial evacuation strategy can further increase transportation risk by making large portions of the population evacuate, potentially unnecessarily, despite being outside the dose risk-affected areas.
- A **Lateral** evacuation directs the population within the expected plume pathway to move perpendicular to that plume pathway before radially evacuating. The population not within the expected plume pathway could be instructed to either

SIP or evacuate radially. Previous NRC studies found lateral evacuation to provide a benefit compared to radial evacuation in many simulations [40].

- During a **Shelter-in-place (SIP)** strategy, the population is directed to stay indoors with the ventilation turned off and windows closed. The purpose of SIP is to reduce exposure to the plume and therefore reduce dose consequences. A secondary advantage is the avoidance of risk due to travel.
- A **Keyhole** evacuation is a combination of radial and shelter in place. The population in sectors in the path of the exposure plume evacuate radially. The remaining population adopts a SIP strategy.
- **Staged** evacuation is a subset of other strategies in that it moves portions of the population in several stages using an evacuation strategy.

However, the transportation infrastructure may not support all evacuation strategies. For example, the NRC estimated that the roadway infrastructure exists to support lateral evacuation in approximately 75% of the EPZs [40]. This is likely an over-simplification as lateral evacuation may be possible in one sector of an EPZ but not another sector of the same EPZ, depending on plume direction.

The potential effectiveness of the alternate evacuation strategies in reducing consequences has been discussed but has not been explicitly quantified. Historically, the NRC performed ETEs and other studies using a radial evacuation, but recently have other evacuation strategies have been considered [18,42]. Further evacuation strategies can be developed using an integrated analysis model, like the one proposed here, which enables comparisons of traditional and alternate strategies. It is important to note that the site-specific transportation infrastructure may not support all evacuation strategies.

For example, the NRC estimated that the infrastructure exists to support lateral evacuation in approximately 75% of the EPZs [45].

Licensees do not have direct access to notification systems such as the Integrated Public Alert and Warning System (IPAWS) and wireless emergency alert (WEA) system. Licensees can recommend an evacuation strategy, but it is up to the ORO to implement the PAD and communicate it to the public. Some states (e.g., Pennsylvania) currently have limiting policies that specify a full 360-degree EPZ evacuation given a declaration of a GE [50]. For a rapidly progressing accident, the NRC narrowly recommends a staged radial evacuation based on evacuation time thresholds shown in Table 18. This type of simplistic planning is necessary when evacuation time is the only metric available.

Table 18: Reproduction of guidance for a rapidly progressing accident scenario in NUREG-0654/FEMA-Rep-1 Supplement 3 Rev. 1 [22]

Zone	Protective Action
0 to 2 mile	If the 90-percent ETE for this area is 2 hours or less, immediately evacuate.
2 to 5 mile	If the 90-percent ETE for this area is 3 hours or less, immediately evacuate.
5 to 10 mile	SIP, then evacuate when it is safe to do so.

Changes may be necessary to local or state policies to reduce risk, implement alternative protective action strategies, or permit access to notification systems that are needed to enable some alternative protection strategies. Studies demonstrating the risks associated with alternate strategies may influence these policies. This integrated model provides the capabilities needed to go beyond simple time-based decisions by providing risk-based MOEs.

2.2.5 Protective Action Initiation

The time gap between the population receiving the warning and taking a protective action is known as protective action initiation (PAI)[33]. Some activities that may occur during PAI include milling[34], reunifications, search for and confirmation of information, and preparing for protective action. Various communication strategies and technologies can result in either the speeding up or slowing down of PAI through the content and the context of the message. Increased PAI is generally assumed to be harmful due to extending the time before the start of evacuation. Research indicates PAI is a complex interaction of many factors. For example, PAI may be extended due to family reunification, but a reunified family is more likely to comply with an evacuation order.

2.2.6 Public Compliance

History shows that full compliance with alerts, warnings, and protective action should not be expected [30], [41], [44], [49], [160]. Despite this, uncertainty related to the behavior of the public has largely been ignored in NRC consequence studies [6], [38]. Further discussion of protective action compliance is available in chapter 2.

A non-Compliance factor in the integrated model represents the proportion of the public that does not comply with protective action instructions, such as an order to evacuate or shelter-in-place. Non-compliance can be caused by several factors, including not receiving the warning, distrust in the warning, cultural beliefs[35], and socio-economic resource barriers. The non-compliance factor can be set uniformly for the EPZ or by

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[33] PAI may also be referred to as ‘milling time’, time to prepare to evacuate, or mobilization time.

[34] Milling is a period of mental preparation that is usually comprised of warning confirmation or search for more information [182]

[35] Some ETE studies have identified cultural groups who refuse to be evacuated. One example is a cohort of Amish residents inside the Peach Bottom EPZ [163].

map sector, ring, or individual cell to represent the expected response. Studies of evacuations not related to NPPs indicate the non-compliance factor can vary widely by emergency event [19], [46], [148]. Modeling non-compliance is not included in current NRC ETE study guidance.

Surveys are typically used to understand the expected public behavior and compliance for each population in an EPZ. These surveys are generally part of the ETE study and are also used to determine the actions and timing of the public response. The PAR study showed that the public generally underestimated their level of compliance compared to real examples. People refusing to evacuate has a statistically significant association with diminished evacuation efficiency [110]. The NRC assumes a non-compliance of 0.5% for most analyses [6], [92], [138]. However, the PAR study found 4% of survey respondents would not follow directions, and 10% of respondents had low confidence (rated 0-2 out of 7) that they would follow directions to evacuate [30]. In some cases, nuclear power plant ETE reports indicate a higher level of non-compliance (>10%) is expected than the NRC assumed value [183]. The NRC provided a review of literature on non-compliance that showed that the public generally underestimated their level of compliance compared to real examples [45].

A shadow evacuation factor represents the portion of the population outside of the zone under a protective action order (e.g., a keyhole zone) that spontaneously evacuated when not told to do so [97]. The shadow evacuation is a separate cohort of the non-complying population, which also slows down the evacuation speed due to additional traffic and congestion. Current NRC guidance for ETE studies only considers public compliance by implementing a 20% shadow evacuation to 5 miles beyond the EPZ boundary [97].

The model accounts for the shadow effect by evacuating a portion of the population that is outside of the evacuation zone. The shadow evacuation zone extends to 5 miles beyond the 10-mile EPZ, consistent with NRC guidance [97]. In this integrated model, the shadow evacuation factor is set uniformly for all cells outside of the protective action zone. The shadow evacuation factor can be represented with either a point estimate or a distribution of values.

Evacuation models often overlook the existence of shadow evacuation during a SIP protective action. This is despite empirical evidence and survey data that a portion of the population will refuse to comply with an order to shelter and then evacuate [30], [46], [47], [110], [120], [184]. For SIP protective actions, the entire EPZ is considered the non-evacuating zone and is part of the shadow evacuation zone.

Public compliance, both following protective action orders and reducing shadow evacuation, is impacted heavily by the communication channel and content of an alert or warning [52]. Ideally, a warning should result in full protective action compliance and zero shadow evacuation. The potential impact of communication on consequences can be estimated in part by estimating non-compliance.

2.3 Hazard Dispersion Module

The hazard dispersion module is used to model a nuclear power plant accident, radionuclide and radiation release to the environment, and spatiotemporal transportation of the hazard. This module currently uses scenario analysis instead of Monte Carlo for two reasons. First, the decision-maker is likely to have reasonable information to define input values for this module, enabling a scenario approach. Second, the capability to directly control the third-party radionuclide transport model (Section 2.3.1) does not currently exist. This limitation prevents the integrated model from injecting input values and iterating the radionuclide transport model in a Monte Carlo manner. This value of this function is being considered for future research.

2.3.1 Radionuclide Transport Model

The Radiological Assessment System for Consequence Analysis (RASCAL) computer code is used for modeling radionuclide release and dispersion. RASCAL was selected because the majority of federal, state, local, and NPP emergency managers use RASCAL for protective action recommendations (PAR) and protective action decisions (PAD) for NPP incidents [55].

RASCAL has two dispersion models, a Gaussian plume and a Lagrangian Gaussian puff model. The Gaussian plume model assumes a developed flow profile and cannot discretize the dose for each time-step. The Lagrangian puff model is used instead to retain time-step integrity. The puff model output is mapped into a Cartesian square grid, with the square width defined by the selected parameters. For our model, the output dose is re-mapped from the RASCAL Cartesian grid to the previously discussed polar grid (Figure 17) for each time-step, using a separate tool. Shielding factors (Section 2.4.1) are applied to the re-mapped spatiotemporal dose. The re-mapped dose output is then ready to be imported into the integrated model.

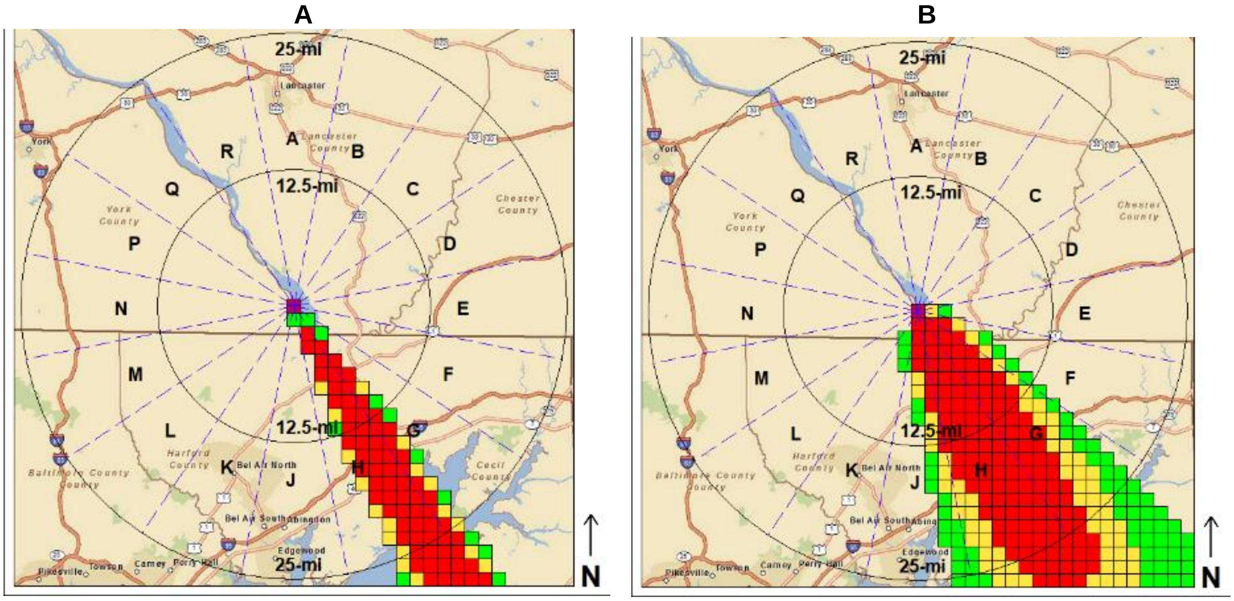

Figure 20: RASCAL plume output over 8 hours for the same LTSBO accident scenario and varying wind speed and stability class values. (A) 12 mph wind, D stability class (B) 4 mph wind, B stability class

The timing and location of radioactive material after an accident are generated using a combination of selected source terms and weather parameters. Figure 20 provides some examples of plume dispersion for one accident scenario with multiple weather scenarios. The figure shows cumulative hazard dispersion over an 8-hour period that does not reflect change over time. This figure also provides an example of the limited information that is currently used for decision-making. An integrated model is needed to understand the interaction and effect of hazard with the population (i.e., exposure) over time during a protective action.

2.3.2 Source Term

Source terms are defined as the radionuclides released during an NPP accident. Using RASCAL, accident parameters can be defined for existing U.S. NPP reactors or user-defined reactors. RASCAL determines the release timing, radionuclide inventory, and dispersion based on site characteristics, weather, accident scenario, and other factors. A description of the methods and operation of RASCAL can be found in [55].

The radionuclide release varies with reactor technology, operating characteristics, release pathway, release time after reactor shutdown, and an accident type. Differences between source terms lead to different risk profiles over time and location. Response strategies may need to be customized for each release scenario, such as a rapidly progressing scenario (Table 18) [22].

2.3.3 Weather

Understanding the potential weather characteristics for each NPP site and the impact that they may have on evacuation may be beneficial for planning. Current guidance is that emergency exercises should now incorporate an all-hazards approach that may include site-specific incidents, natural disasters, or weather conditions [43]. Weather is considered in ETE studies using deterministic scenarios. This design helps consider the range of weather impacts on evacuation planning. However, the weather around an NPP is neither uniform nor deterministic.

Seasonal effects of weather may also provide insights for emergency planning. Evaluating 10-years of weather data from a representative NPP site for seasonal effects suggests that alternate evacuation strategies may be desirable. Wind direction and speed often change seasonally and may have a higher probability of impacting more or less population and potentially more quickly due to higher wind speed. For example, a keyhole area along the most likely summer wind direction may contain a higher population than the most likely winter wind direction, increasing the potential for congestion. However, the predominant winter wind speed may be higher, providing less margin for emergency plan completion. An integrated model approach ensures weather conditions are shared between modules to facilitate the investigation of such effects.

Weather is measured and recorded by every NPP in the country on an hourly basis (i.e., wind speed and direction at several altitudes, precipitation, and humidity). In addition to the on-site weather system, RASCAL has a function to download weather data from the National Weather Service for real-time incident response or specified to simulate a range of potential scenarios. Alternatively, meteorological conditions can be defined to simulate a scenario. These scenarios can be defined to meet stochastic or deterministic scenario requirements, as discussed in chapter 2.

2.3.4 Site Characteristics

RASCAL accounts for site-specific factors, including topography, surface roughness, elevation, and reactor technology. These site-specific factors can affect the dispersion of the radionuclides both spatially and temporally. If a generic site is used, these values must be defined for RASCAL.

2.4 Risk and Consequence Module

The consequence module takes input from the protective action and hazard dispersion modules to estimate the dose received by the population through exposure to the hazard while implementing the protective action. Health consequences are then estimated from the received dose.

2.4.1 Shielding

Shielding prevents some exposure, thereby reducing the received dose. Shielding factors are simplified values that are based on complex factors that may be site-dependent. Different shielding factors were used in the SOARCA studies for the Surry and Peach Bottom due to site-dependent factors [4], [5]. The shielding values used in the SOARCA studies were developed from NRC studies on sheltering [159], evacuation [40], and behavior of the population [185].

In this model, shielding factors are applied to RASCAL output doses in the Hazard Dispersion module. This is accomplished during the same process as re-mapping the Cartesian RASCAL output to the polar grid (Section 2.3.1). The spatiotemporal doses are calculated for all shielding factors and then imported into the Consequence Module.

Shielding factors are applied to individuals based on their activity: normal, evacuating, or sheltering [4]. The application of the shielded dose values is determined in the Consequence Module based on the population behavior in the Protective Action Module. Normal activity shielding factors are applied to individuals prior to receiving an alert and individuals that do not comply with a protective action order. The NRC assumes that the time to identify and verify a general emergency (GE) condition and then communicate to the public is 30 minutes (see chapter 2). The shielding factor for sheltering is applied to the population that has complied with an order to SIP. Evacuation shielding is applied to the population that is in the process of evacuating.

2.4.2 Dose

Total effective dose equivalent (TEDE) is the metric used to represent dose to the population. TEDE is defined as the whole-body dose when all radiation sources (i.e., dose pathways) are considered. It is the sum of the effective dose equivalent (external exposure) and the committed effective dose equivalent (internal exposure) shown in

Equation 1. When radionuclide-specific data is missing, it is common to have the equivalent dose recorded as the TEDE.

$$H = D_{inhalation} + D_{groundshine} + D_{cloudshine} \tag{1}$$

where,

- H is the total effective dose equivalent in rem
- D is the dose in rem
- Groundshine is the external exposure from radionuclides deposited on the ground
- Cloudshine is the external exposure from radionuclides in the radioactive cloud
- Inhalation is the internal exposure from inhalation of radioactive aerosol particles

2.4.3 Exposure

Dose (in rem) from RASCAL output (generated in the hazard dispersion module) is applied at each time-step, to the population in the grid (generated in the protective action module) to calculate exposure (in person-rem) per spatial cell and time interval. Exposure of a population to radiation, measured in person-rem, is calculated as the dose per individual (in rem) multiplied by the number of people exposed. The exposure data can be summed spatially (to obtain exposure over time in one cell), temporally across all cells (to obtain total exposure for each time interval), or spatiotemporally (to obtain total exposure for the model realization (r)). Total spatiotemporal exposure is the default method in the model and is shown in Equation 2.

$$S = \sum_{t}^{r} \sum_{c}^{r} E_S N \tag{2}$$

where,

- S is the collective exposure in person-rem
- E_S is the effective shielded dose in rem
- N is number of people
- r is an integrated mode realization
- c represents a spatial cell in the polar grid map
- t represents a time-step in the model realization

The exposure is currently calculated for the entire population. The ability to track the dose to individual people throughout the protective action is left to future work.

2.4.4 Dose Consequences

The consequences module estimates health consequences to the population in terms of Latent Cancer Fatalities (LCF). LCF is the conditional risk of the exposed population developing additional cases of cancer in the event of an NPP accident. Health consequences from exposure are in the form of latent cancer fatalities (LCF), and the dose is given in TEDE person-rem.

There is disagreement in the literature regarding the method to estimate consequences due to radiation dose. Previous NRC studies have traditionally used a linear no-threshold (LNT) model and have aggregated doses over all individuals projected to receive any exposure [147]. NRC staff provided an extensive review of multiple off-site health consequence models that were considered for use in the SOARCA project [147]. This review included the LNT model and several recommended low-dose threshold models from other organizations. The hormesis model, which suggests low levels of ionizing radiation exposure is beneficial, has also been proposed as a replacement for the LNT model in NRC regulation but was not included in the SOARCA review [149].

One outcome of the NRC review is that the LNT model results in generally higher risk estimates than the other models considered in the review, particularly at low dose levels. This is confirmed in a sensitivity analysis that compared dose-response models as part of the SOARCA project [7]. The models used in SOARCA included the linear no-threshold (LNT) model and three dose-truncation models.

The Interagency Steering Committee on Radiation Standards (ISCORS)[36] provides guidance on converting exposure to consequences that are not included in the previously discussed NRC review [150]. The ISCORS guidance states that LCF can be closely approximated using a conversion factor ζ.

$$R_{LCF} = \zeta\, S \tag{3}$$

where,

- R_{LCF} is the collective risk of latent cancer fatality to the population
- S is the collective exposure in person-rem (1)
- ζ is the exposure to mortality conversion factor

Total LCF risk to the population (R_{LCF}) is used as a decision metric in this model. Using total LCF risk to the population as a decision metric allows it to be compared to

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[36] ISCORS is a United States government committee that is comprised of the Nuclear Regulatory Commission, the Environmental Protection Agency, the Department of Health and Human Service, the Department of Energy, the Department of Defense, the Department of Transportation, and the Department of Labor

other risks to the population (i.e., non-dose consequences). The ISCORS report indicates that using these conversion factors to convert TEDE to risk will usually provide a high-sided estimate of risk [150].

ISCORS provides ζ values of 8×10^{-4} per person-rem for morbidity and 6×10^{-4} per person-rem for mortality. The ISCORS approach is similar to the EPA guidance in the PAG Manual that uses a risk of 3×10^{-4} cancer deaths per person-rem [96]. Considering the EPA is part of the ISCORS, it is unclear why there is inconsistency in the LCF conversion factors. However, the inconsistency is indicative of the ongoing research into the effects of radiation dose and the multitude of dose-response models [147]. The ISCORS conversion factor ζ is the standard factor used in this model due to the broad government agency agreement, but other conversion factors can be used at the user's discretion.

2.4.5 Non-Dose Consequences

The population incurs risk during a protective action from hazards other than radiation exposure. Evacuating populations experience potential impacts during travel that sheltering populations do not. The only non-dose risk considered significant enough by the EPA to be included in protective action decision making is the risk due to transportation.

Evacuations are usually completed without incident, but fatalities have occurred. During an evacuation, people are generally expected to behave rationally, not panic, and drive with extra caution during an emergency [44]. Despite the extra caution, inclement weather can significantly increase the occurrence of transportation fatalities [34]. Consequences due to other hazards associated with evacuation, such as fatalities related to evacuation of hospitals and elderly care homes, have become more important to ORO decision-making based on lessons from recent emergencies [46], [142], [186].

The EPA considers the risk due to transportation during an evacuation to be the same as usual travel [96], [151]. The NRC study completed in 2004 found that only one transportation fatality occurred out of 230 major evacuations [44]. The major hurricane season in 2005 prompted the NRC to perform a second study. The second study focused on 11 large-scale evacuations that resulted in a range from zero to over one hundred evacuation-related deaths [46]. Despite evidence that transportation risk should be considered in protective action analysis, NRC off-site consequence and protective action studies such as the SOARCA project do not consider non-dose consequences (see Chapter 2).

This chapter's integrated model estimates risk due to transportation based on the protective action strategy selected and the population's response to that strategy. Transportation risk (R_T) can be estimated by using a risk factor (γ) for average fatalities per vehicle-mile traveled. The average vehicle occupancy (ν) is used to adjust from vehicle miles to person-miles, then multiplied by the number of evacuees and the round-trip distance traveled.

$$R_T = \frac{\gamma}{\nu} N_{evac} \mathrm{D}_{\mathrm{evac}} \tag{4}$$

where,

- R_T is the collective risk of transportation fatality to the population
- γ is the transportation risk factor
- ν is the average vehicle occupancy

- N_{evac} is the number of people evacuation the EPZ
- D_{evac} is the average round-trip distance traveled during an evacuation

The literature related to transportation risk during an evacuation is outdated. Studies that provide risk factors (γ) as a function of distance traveled are more than forty years old. Significant updates have been made to road safety, evacuation planning, and vehicle safety. A few examples of vehicle safety improvements include anti-lock brakes, seat belts, airbags, and crumple zones. Air conditioning is also a vehicle safety feature for evacuees with medical conditions, as became apparent in the Hurricane Rita evacuation [46].

Table 19: Transportation fatality risk per person-mile

Source	Year Published	Transportation Risk	Units
EPA [148]	1974	9x10-8	person-mile
Aumonier and Morrey [153]	1990	0.0 - 8.8x10-8	person-mile ‡
NRC [46]	2008	0.0 - 4.3x10-5 §	person
NHTSA [152]	2016	7x10-9 §	person-mile

‡ converted from person-kilometers is source
§ calculated from data in source

A literature review published in 1990 provides a range of fatality during an evacuation from zero to 8.8×10^{-8} per person mile traveled [153]. The transportation fatality risk factor of 9×10^{-8} per person-mile used in the PAG guidelines is based on a 1974 report which concluded that transportation risk during an evacuation is approximately the same as normal transportation [148], [187]. However, the average motor vehicle transportation risk is an order of magnitude lower now than it was in 1974. In 2016 the fatality rate for motor transportation was approximately 1.2 per 100 million vehicle miles (1.2×10^{-8}), a third of the risk of transportation in 1974 [152]. The fatalities per person-mile can be estimated using the average vehicle occupancy rate of

1.7, resulting in a 7 x 10^{-9} fatality risk per person-mile [34], [152]. The NHTSA value is a measure of annual fatalities and is not limited to evacuation conditions.

The round-trip distance to evacuate the EPZ and return is used to estimate the total transportation risk induced by the protective action (i.e., evacuation). A 100-mile round trip is widely used as a conservative estimate in the literature, including in the PAG manual [96], [148], [151]. Some more recent studies try to estimate evacuation destination and distance and find it is primarily event and site-specific [188], [189]

Another way to estimate the evacuation fatality risk is to use the realized risk of prior evacuation. The NRC study of eleven large-scale evacuations resulted in a realized risk ranging from zero to 4.3x10^{-5} per evacuee. It is important to note that the upper bound is several orders of magnitude higher than normal transportation risk and only represents a one-way risk instead of a round-trip risk. There are several limitations to this approach, including that the sample size is small, the outcomes vary significantly in the sample, and the results were the complete opposite of a similar NRC study published just one year prior.

The integrate model uses general values as a base case: 1.2 x 10^{-8} fatalities per vehicle-mile, 1.7 persons per vehicle, and 100-mile round trip. These values can be adjusted to match the site-specific characteristics. Current NRC guidance requires the ETE studies to include estimates of vehicle occupancy that can be used in the integrated model. Site-specific destination and distance studies can be used to estimate the round-trip distance.

The mental health and financial impact of long-term relocation has become a more active area of research after the Great East Japan earthquake and subsequent accident at the Fukushima Daiichi NPP [155], [190], [191]. These risks are not part of the initial protective action phase of an emergency, and are therefore not considered in this model. The potential addition of these long-term risks may give a more complete understanding of protective action decision-making and will be considered for future work.

3 Conclusions

The integrated model developed in this chapter allows for potentially deeper insights into an emergency response by creating a more complete model for emergency response, addressing functional limitations in existing methods and tools, and providing decision-making metrics that are currently not available. Consideration of a broader range of uncertainty and potential emergency response actions allows for quantifying factors that are not included in current topic-specific guidance (e.g., ETE studies), such as early protective actions and population compliance. This cohesive, integrated model provides capabilities beyond the cumulative capabilities of separate topic-specific studies, such as evaluating risk over time, comparing protective action strategies, replacing deterministic assumptions with probability distributions for key variables, and comparing dose and non-dose risks.

The integrated model is designed to use the current guidance and best practices from the normally topic-specific analyses (e.g., hazard dispersion, ETE) when appropriate to meet NPP and ORO requirements. A modular design allows for a flexible operation that can be utilized for detailed analysis for emergency planning or prompt analysis for emergency situations by providing short computation times that meet NRC PAR guidance. The RASCAL model is used as the basis for the hazard dispersion module to provide identical results that a decision-maker would receive in an actual emergency with short computation times.

A key advantage of this model is that in addition to providing decision-making support in an emergency, this model can be used for exploratory analysis. This allows for analysis of the effect of each factor, interaction with other factors, and impact on MOE relative to other factors. Chapter 6 provides analysis and results in the form of a site-specific case study.

4 Appendix – Chapter 5

4.1 Population

The population is re-mapped from the source data into the polar grid using the intersect function in ArcGIS. The population is calculated using the population density and area of each original population zone that is contained in the polar grid cell.

Nighttime population location using U.S. Census 2010 TIGERline block-level data. [180]

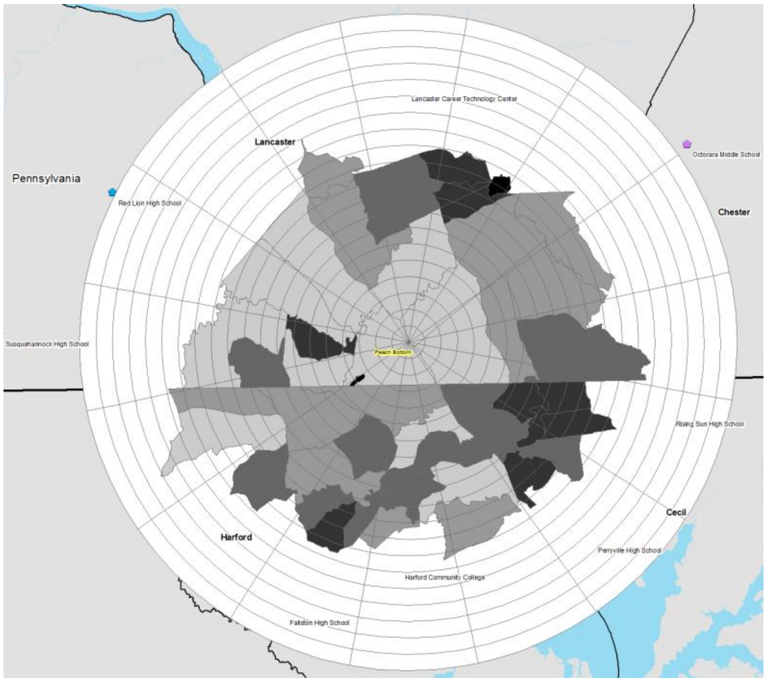

Figure 21: Polar grid overlaid on a map of Peach Bottom Nuclear Power Station and surrounding Census blocks that correspond to the Emergency Planning Zone.

Using the map and census data in Figure 21 that corresponds to the EPZ, a polar grid is used to split and re-map the census block populations into the polar cells.

Daytime population in the EPZ surrounding Peach Bottom NPP in Figure 22 is derived from LandScan 2017 1km level data. [181]

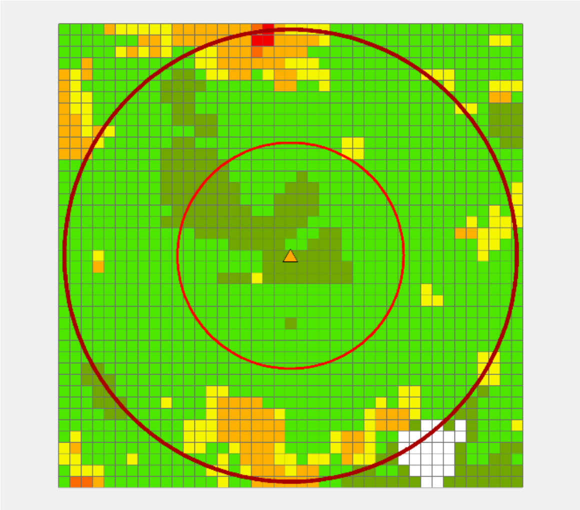

Figure 22: Landscan data for the Peach Bottom EPZ from 0-20 miles

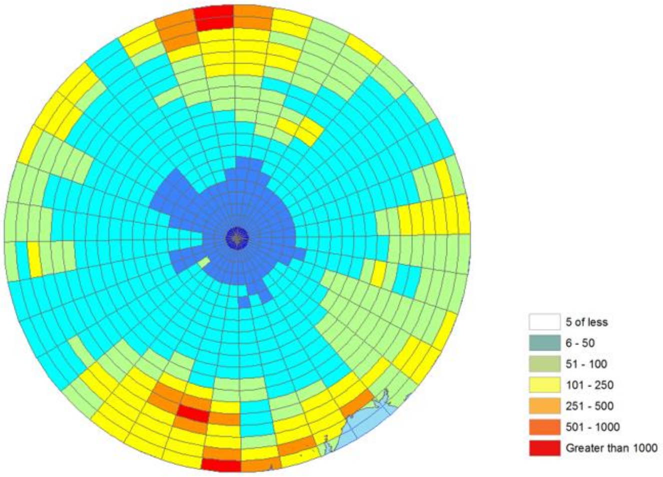

Figure 23: Nighttime population data re-mapped to the polar grid from U.S. Census block data

4.2 Mapping of RASCAL cartesian grid to polar grid

A cartesian coordinate grid shapefile from RASCAL was segmented into the polar grid using the intersect function in ArcGIS. The portion of RASCAL output doses from the cartesian grid was re-mapped to the polar grid by area by using the same method as population mapping. The RASCAL user manual justifies this approach by indicating that the puff model's cartesian grid assumes a uniform distribution of dose in each grid square. The dose contained in each polar grid is the resulting summation of portions of intersecting cartesian grid squares.

Equation 1: Conversion of RASCAL cartesian dose to polar grid cells

Polar gird dose = SUM of each (% of grid area * grid dose)

$$E_{S,P} = \sum\nolimits_{c} E_{S,C}\delta \tag{5}$$

where,

- $E_{S,P}$ is the effective shielded dose in rem in the polar grid cell
- $E_{S,C}$ is the effective shielded dose in rem in an intersecting RASCAL cartesian cell
- δ is the portion of the cartesian cell that is intersecting the polar grid cell
- c represents a spatial cell in the polar grid map

4.3 Total Effective Dose Equivalent

TEDE is the Total Effective Dose Equivalent, or the equivalent combined whole-body dose when all radiation sources (i.e., dose pathways) are considered along with the effect on specific organs.

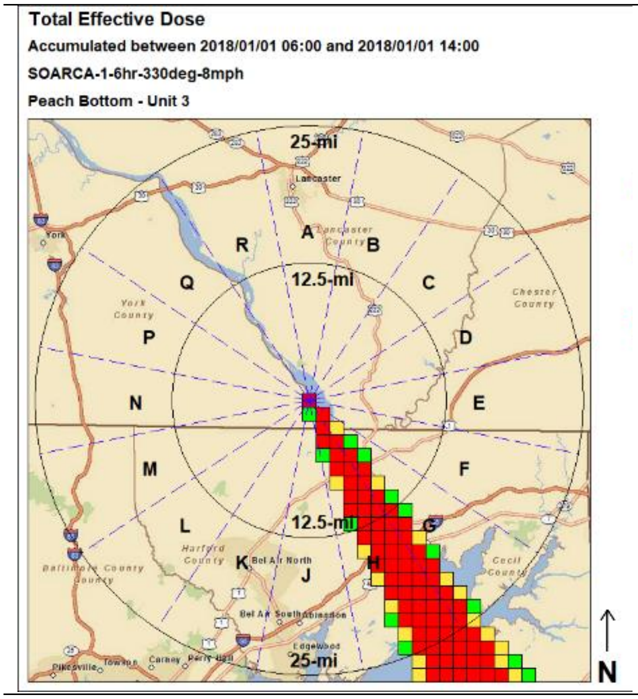

Figure 24: RASCAL plume output for scenario run 17. Cumulative 8-hour exposure, 8 mph wind from 330 degrees with stability class D.

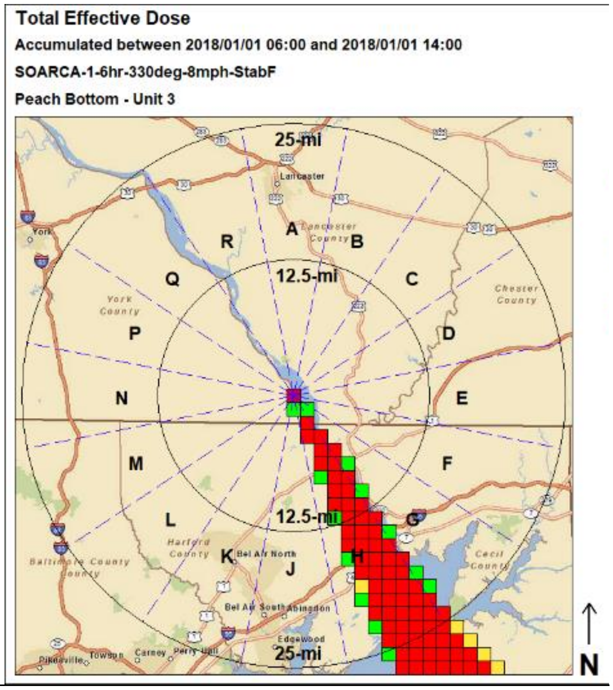

Figure 25: RASCAL plume output for scenario run 22 Cumulative 8-hour exposure, 8 mph wind from 330 degrees with stability class F.

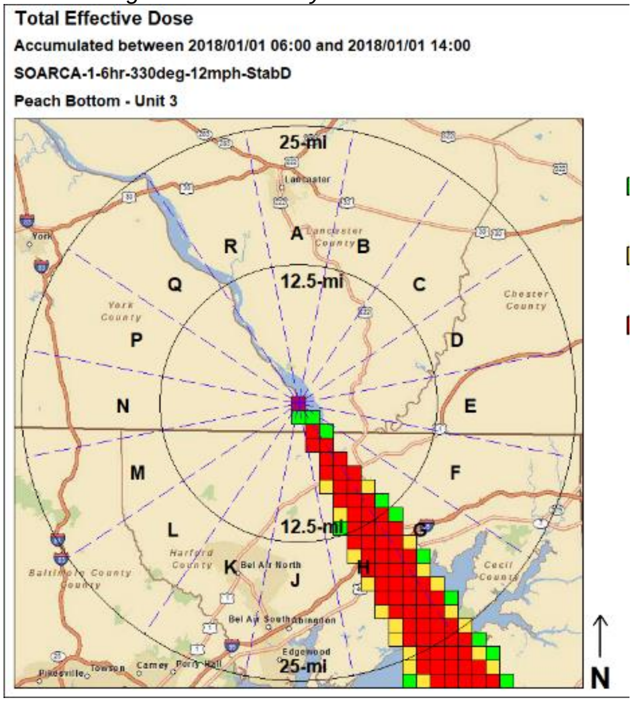

Figure 26: RASCAL plume output for scenario run 23. Cumulative 8-hour exposure, 12 mph wind from 330 degrees with stability class D.

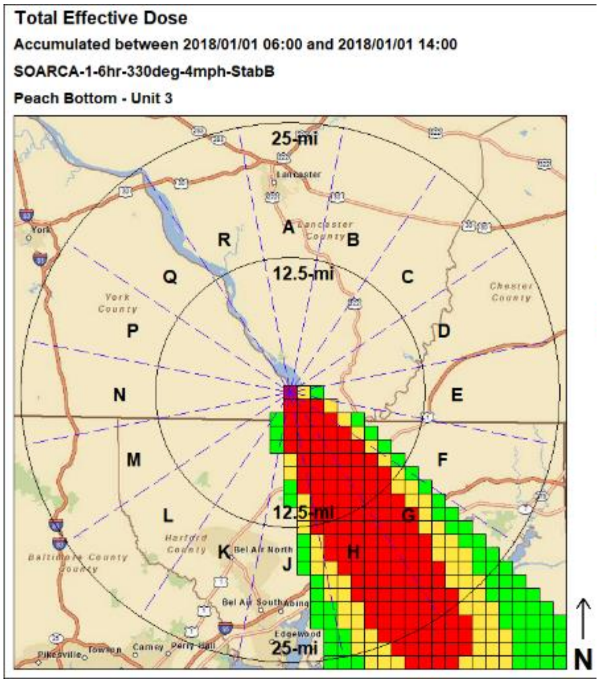

Figure 27: RASCAL plume output for scenario run 29. Cumulative 8-hour exposure, 4 mph wind from 330 degrees with stability class B

4.4 Shielding factors

Shielding factors represent the protection given from radiation dose in certain situations. Shielding is provided primarily by physical barriers for cloud or ground shine, and by preventing aerosol or gas infiltration to a space for inhalation.

Table 20: Shielding factors from NUREG/CR-7009 page 4-24

Activity	**Dose pathway**		
	Groundshine	**Cloudshine**	**Inhalation**
Shelter-in-place	0.1	0.5	0.33
Evacuation	0.5	1.0	0.98
Normal Activity	0.18	0.6	0.46

Shielding factors are applied by multiplication with the corresponding dose for each dose pathway and activity. The resulting equivalent shielded dose is the summation of shielded dose pathways (e.g., inhalation dose). There is an equivalent shielded dose for each activity (e.g., shelter-in-place).

$$E_{S,a} = \sum^{p} Hs \qquad (6)$$

where,

- E_S is the effective shielded dose in rem
- H is the total effective dose equivalent
- s is shielding factor
- i represents the dose pathway
- a represents an activity

Chapter 6: Application of the Integrated Model to Peach Bottom Atomic Power Station

Abstract

In the event of an emergency at a nuclear power plant (NPP) that radiation escape containment into the environment, a decision must be made if protective action is necessary and which protective action should be used. Emergency response decisions have predominantly relied on evacuation time estimate (ETE) studies that are built on a broad set of simplifying and potentially unrealistic assumptions. The results are evacuation plans that are indirectly based on the time required to evacuate instead of the potential risk to the population. This research presents a case study in risk reduction opportunities during evacuation using the integrated model developed in chapter 5. Potential risk reduction utilizing several evacuation and shelter-in-place protective action strategies are explored under varying radiation exposure and weather conditions. Sensitivity to public response uncertainty is considered.

We find that the protective action decision is more nuanced than can be determined with a static ETE study. While evacuating the population prior to the arrival of the radiation hazard can be completely effective at avoiding dose risk, it is not always possible. When there is insufficient time to evacuate, defaulting to the protective action with the shortest evacuation time does not always result in the lowest risk to the population. In some situations, lower levels of public compliance can reduce risk by

reducing traffic congestion. The selection of a protective action strategy is influenced by many factors that have not previously been considered important or have not been estimated due to limitations with previous models. A key finding is that some of the historically most common protective action strategies can result in a greater risk than no protective action.

Acronyms and Abbreviations

ANS	Alert and Notification Systems
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
ETE	Evacuation Time Estimate
FEMA	Federal Emergency Management Agency
ISCORS	Interagency Steering Committee on Radiation Standards
LOCA	Loss of Coolant Accident
LTSBO	Long Term Station Blackout
MOE	Measure of Effectiveness
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
ORO	Offsite Response Organization
PAG	Protective Action Guide
PAI	Protective Action Initiation
PAR	Protective Action Recommendation
RASCAL	Radiological Assessment System for Consequence Analysis
SIP	Shelter in Place
SOARCA	State-of-the-Art Reactor Consequence Analyses
TEDE	Total Estimated Dose Equivalent

1 Introduction

In the unlikely event of an emergency at a nuclear power facility where radiation may be released to the environment, a protective action must be selected. It is important to select the appropriate protective action to reduce risk to the population. To dynamically evaluate the risk to the population during a protective action, it is necessary to understand the spatiotemporal location and interaction of the population and the hazard. A model that integrates these components and calculates risk and consequences is designed in chapter 5. The work in the preceding chapters is applied in this chapter to evaluate the Peach Bottom Atomic Power Station as a case study. An exploratory analysis approach is used to evaluate the factors that affect protective action decision-making. Real data sets are used where possible and realistic assumptions are made for other inputs.

A wide range of factors are considered, including nuclear power plant (NPP) accident type, population spatiotemporal location, and the amount of time between initiating a protective action and initial release of radiation. Several factors that have previously been included in topic-specific studies as simple deterministic assumptions may have wide ranges of uncertainty. Some factors are important in both evacuation efficiency and avoiding radiation exposure, but the effects may be divergent. A factor, such as low public compliance, may reduce evacuation times by reducing traffic congestion but increase overall exposure to the population.

This chapter will briefly review the function of the integrated model, review the Peach Bottom site characteristics, evaluate the integrated model decision metrics across multiple protective action strategies, and perform sensitivity analysis for multiple factors. While data from specific sites are used in this study, results are not intended to be interpreted as direct recommendations to any specific site. Instead, this study provides a method and model to quantify parameter sensitivity, the effect of behavioral uncertainty, and make informed decisions. The case presented in the paper is a light-water NPP accident inside a 10-mile EPZ. The model described can also be applied to other hazards that create a plume-like release, such as a chemical treatment plant.

1.1 Model

The integrated model is comprised of an exposure model and evacuation model that are synchronized using a common timeline. The model illustrated in Figure 28 is an extension of a model previously developed in chapter 5. The hazard dispersion module determines the timing and location of radioactive material during an NPP accident progression. A scenario analysis method is used to consider site-specific variation and uncertainty. The scenarios are generated using a combination of selected source terms and weather parameters. Exposure to the public is estimated using a tool such as the Radiological Assessment System for Consequence Analysis (RASCAL). Total estimated dose equivalent (TEDE) is the metric used for the dose to the population during the evacuation phase. A range of forty exposure scenarios is generated using RASCAL (see Appendix).

The protective action module consists of a macroscopic traffic model that simulates the movement of the population. A Markov Chain Monte Carlo design is used to simulate decision and probabilistic uncertainty during travel over discrete 15-minute time-steps. The model is simplified compared to a modern microscopic traffic model but provides flexibility to model alternative evacuation strategies systematically.

The consequence module combines the spatiotemporal output of the hazard dispersion module and the protective action module to calculate six output metrics (Figure 28). Emergency planners and decision-makers can use these output metrics as measures of effectiveness (MOE) for a protective action decision.

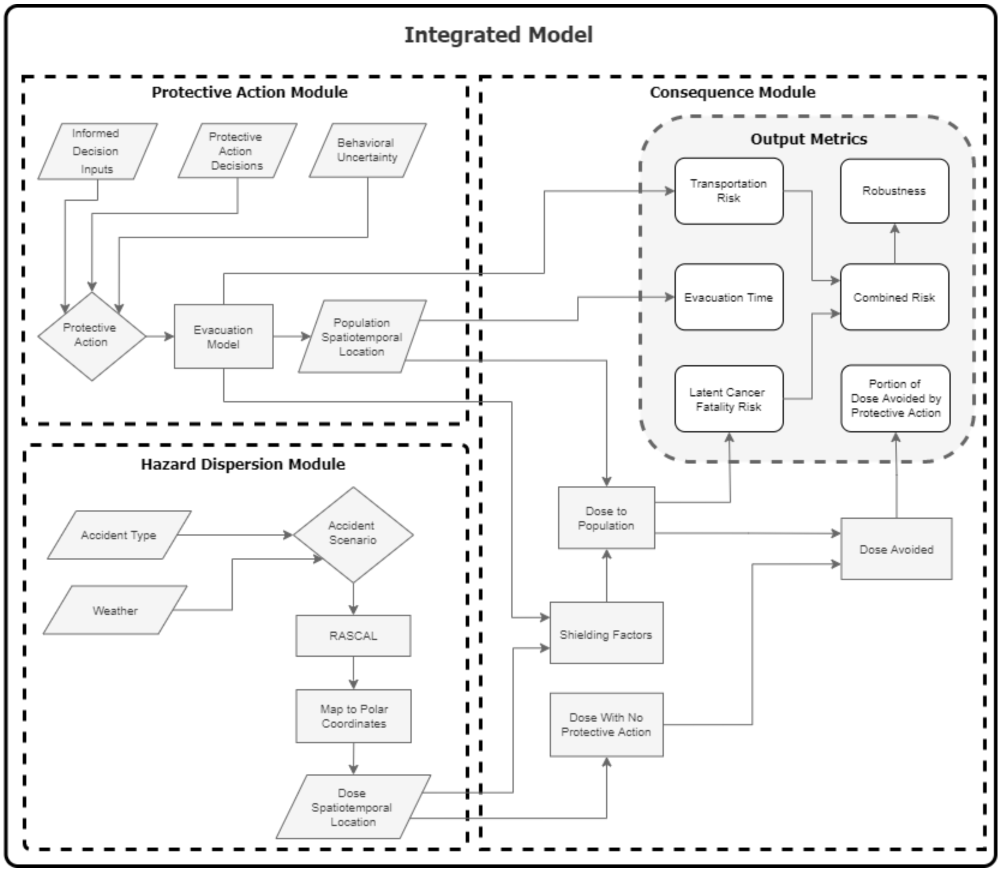

Figure 28: Conceptual Diagram of Integrated Model from Chapter 5

The model is not designed to provide optimization of this complex problem with many stochastic parameters. Instead, it is designed to provide information that the decision-maker would find useful in an evacuation event, which would have previously been unavailable with other methods. While the flowchart in Figure 28 describes a single model simulation, the decision-maker would utilize the output of a set of simulations. For further information on the function of the integrated model, see chapter 5.

2 Case Study - Peach Bottom Atomic Power Station

This chapter's methods combine the integrated model developed in Chapter 2 with the interdisciplinary approach and decision methods developed in Chapter 4. This chapter uses the Peach Bottom Atomic Power Station as a basis for applying the integrated model.

Peach Bottom Atomic Power Station is owned by Exelon Generation Co. and is located on the Susquehanna River near the southern Pennsylvania border. The NPP operates two General Electric Type 4 boiling water reactors with Mark 1 containments, initially licensed in 1973 and 1974 [192]. Peach Bottom is the second NPP to apply for, and receive, two license extensions, permitting operation for up to 80 years (2053 and 2054) [192]. Both reactors are licensed to produce 4,016 megawatts thermal and 2,600 megawatts electric. The plant annually produces approximately 2,200 gigawatt-hours of electricity.

The emergency planning zone (EPZ) is an area around an NPP defined by an approximately 10-mile radius where emergency planning is needed to assure prompt and effective actions can be taken to protect the public in the event of a radiological incident [15]. The EPZ around Peach Bottom is typical for large light-water reactors in the United States.

Site-specific characteristics can play a significant role in the dynamics of hazard release and dispersion. The area around Peach Bottom is predominantly characterized by forests, farmland, and multiple other power generation stations. The NPP is situated on the riverbank with steep tree-covered banks that may contribute to hazard dispersion in the event of an accident.

The State-of-the-Art Consequence Analysis (SOARCA) project uses Peach Bottom NPP as one of three representative sites for technology and site characteristics. The SOARCA project considers the existing Peach Bottom evacuation and emergency plan as the basis for its modeling to develop a more detailed understanding of accident progression. This chapter looks at opportunities beyond the tightly scripted existing emergency plan to explore the potential benefits of alternative protective actions. While data from a specific site is used in this study, results are not intended to be interpreted as direct recommendations to any specific site. Instead, this study provides a method and model to quantify parameter sensitivity, the effect of behavioral uncertainty, and make informed decisions.

2.1 Basic inputs

This case study is primarily focused on understanding the impact and effect of emergency response factors. Input ranges were defined based on the literature discussed in preceding chapters while respecting characteristics of Peach Bottom NPP. Uniform distributions were used for all factor ranges to allow for exploratory analysis. A Latin Hypercube method was used to stratify sampling of the input probability distributions and ensure the dataset represents the entire decision space [58]. Due to stratified sampling, Latin Hypercube designs possess the property of projective uniformity with regard to each factor individually, even with large numbers of factors, resulting in all or nearly all sample means within a small fraction of the standard error [65].

Table 21: Input variables in the integrated model

	Variable	Value Range
Informed Decision Inputs	Populations	Night (Census), Day (Land scan)
	Source term (RASCAL) scenarios	40 scenarios
	Head start	0-3 hours (15-minute time steps)
	Roadway capacity	85%, 100%
Protective Action Decision	Evacuation strategy	Radial, Keyhole, Lateral, Staged, Staged Keyhole, Stage Lateral, Shelter in Place
Behavioral Uncertainty	Shadow evacuation	0% - 50%
	Non-compliance	0% - 20%
Constants	Latent Cancer Fatality Factor	6×10^{-4} per person-rem
	Transportation Risk Factor	1.2×10^{-8} per person-mile
	Vehicle Occupancy	1.7 persons per vehicle
	Evacuation distance	100 miles

The polar grid shown in Figure 29 is used for the integrated model operation. Inputs and outputs for all three modules are calculated based on the polar gird. The method to re-map input values to the polar grid is discussed in chapter 5.

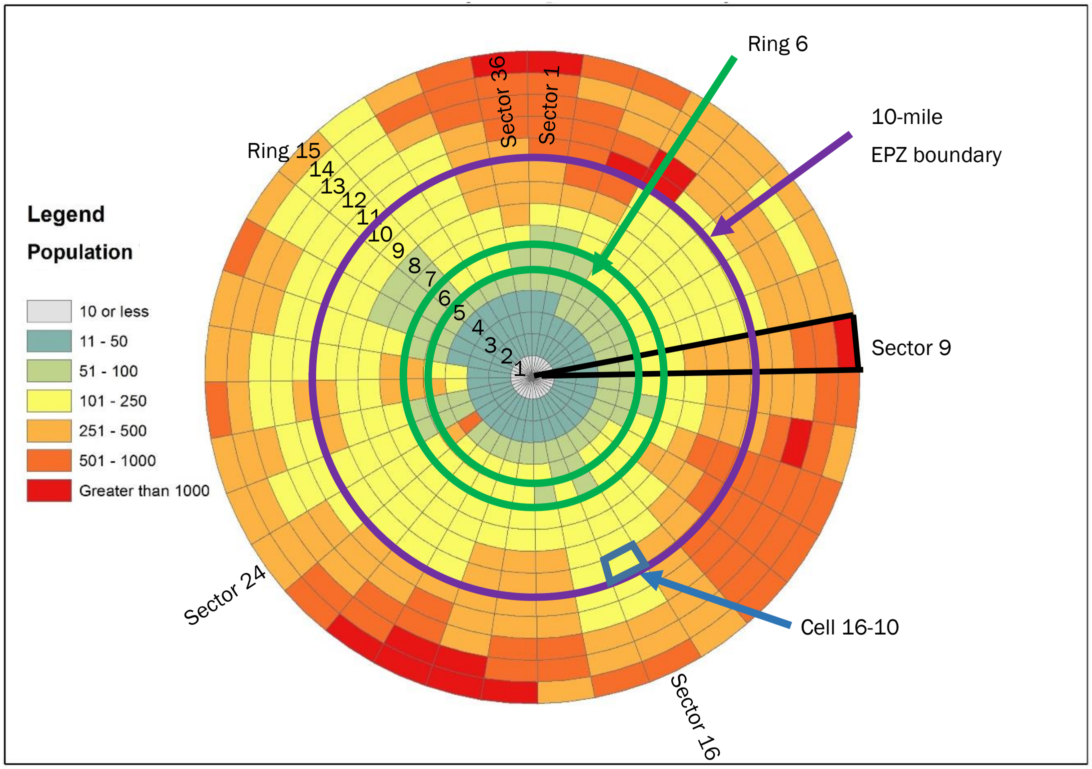

Figure 29: Polar Grid Illustrative Example – Night Population around a representative NPP

2.2 Populations

Polar grid cells are used to segment the population spatially using the intersect function in ArcGIS. The polar grid (Figure 29) is defined with 1-mile radius rings and 10-degree sectors to create cells. Cell area increases in rings that are farther from the NPP. A population density method is used to transfer population values from the intersected source GIS features into the polar grid. This study uses population counts that are derived from Census block-level data and LandScan data for nighttime and daytime, respectively [180], [181].

Table 22: Population counts for Peach Bottom NPP

Population Set	0-10 miles (EPZ)	10-15 miles
Daytime	28,671	66,277
Nighttime	45,966	100,105

Total populations for the EPZ and beyond the EPZ (10-15 miles) are provided in *Table 22*. NPP sites with a lower population would typically have fewer evacuation challenges [100]. Peach Bottom is considered a high population NPP site by the NRC [157] and would be representative of a challenging evacuation.

2.3 Population Transport Model

A variety of traffic models are available for evacuation modeling [31], [33], [97]. Traffic simulation models are not generally capable of modeling specific evacuation strategies. Further, the available traffic models cannot integrate directly with a consequence model or provide sufficient output data for the same. The integrated model used a cell transfer method to simulate traffic and congestions.

It is reasonable to assume that emergency planners can control transportation-dependent evacuees' evacuation routes separately from the general population. Emergency resources are generally already assigned to these populations in emergency plans. Typically, these resources are dispatched by the emergency operations center in real-time. Hospitals and nursing homes similarly have resources allocated to evacuation procedures. The need to evacuate health centers to alternate health centers outside of the evacuation zone further constrains potential evacuation routes. While these transport vehicles contribute in a small way to overall traffic, they should not be considered a vital component of the general population protective action strategy.

For this study, the population is not split into separate cohorts. Instead, the population enters the roadway with a specified probabilistic loading rate, typically called a trip generation time. If needed, specific cohorts can be modeled with the presented method.

The effect of adverse roadway conditions is considered by limiting traffic capacity and speed to 85% of full capacity. Roadway capacity has also been observed to reduce in some evacuations compared to non-emergency peak travel capacity [193]. Allowing the capacity to be variable also allows for modeling of this evacuation characteristic. Background traffic is not considered part of evacuation transportation risk because it cannot be attributed to a protective action decision.

2.3.1 Protective Action Strategies

Historically, the NRC required a radial evacuation, but recently other evacuation types have been proposed [16], [44]. Four general evacuation strategies are discussed in the literature, including Radial, Keyhole, Lateral, and Shelter-in-Place (SIP). Protective action strategies are inherently site-specific, based on roadway configuration, topology, population, and other factors. This paper considers one NPP site as a case study, but the methodology is transferable to other locations.

Seven protective action strategies are examined in this study:

1. **Shelter-in-Place (SIP)** directs the population to stay indoors with the ventilation turned off, and windows closed during SIP. The purpose of SIP is to reduce exposure to the plume and therefore reduce dose consequences.
2. In a **Radial Evacuation**, the population moves away from the NPP, radially out from the center to the edge of the EPZ in the most direct path.

3. **Keyhole Evacuation** is a combination of Radial and Shelter-in-place. The population in sectors along the path of the exposure plume and near the NPP evacuate in a radial manner. The remaining population adopts a SIP strategy.
4. **Lateral Evacuation** directs the population along the expected plume pathway to move perpendicular to that plume pathway before radially evacuating. The population not along the expected plume pathway could be instructed to either SIP or evacuate in a radial manner.
5. **Staged Evacuation** is a subset of the Radial strategy in that it moves geographic areas (rings) of the population in a radial manner using consecutive stages.
6. **Staged Keyhole Evacuation** –The Keyhole zone and 0-2 miles (ring 1-2) evacuate immediately with 2-5 miles (rings 3-5) evacuating in a second stage. The area from 5-10 miles (rings 6-10) shelter-in-place. This evacuation strategy design helps to test the effectiveness of a partial evacuation with partial staging. This strategy is consistent with EPA PAG guidance.
7. **Staged Lateral Evacuation** – The Lateral zone and 0-2 miles (rings 1-2) evacuate immediately, 2-5 miles (rings 3-5) evacuate in a second stage, 5-10 miles (rings 6-10) evacuate in a third stage. This evacuation strategy tests the effectiveness of a full staged evacuation combined with a lateral evacuation in the plume pathway.

A protective action zone width of 60 degrees is used in this study for all Keyhole/Lateral scenarios. The 60-degree value was determined to be appropriate for the plume pathway of the source terms selected. General evacuation model best practices further support the 60-degree value [194]. The effect of proper evacuation zone width selection as a potential source of uncertainty is evaluated in Section 3.11.

The potential benefit of a staged evacuation is to allow the populations most at risk to evacuate first, reduce the potential for congestions, and avoid transportation risk for populations that may not need to evacuate at all. Staged evacuation strategies result in a more rapid roadway loading when the order to evacuate is given. This is because the population has time to prepare to evacuate while sheltering-in-place and waiting for the order to evacuate [40]. Loading the roadway too quickly can create congestions that ultimately increases evacuation times [100]. This is converse to one of the primary potential benefits, controlling congestion. It is not obvious when to evacuate the remaining stages with just an ETE study. The integrated model provides the capability to simulate when the next stage should begin evacuation based on scenarios or real-time traffic information while considering radiation risk.

2.4 Behavioral uncertainty

The public is expected to generally follow prescribed protective actions and not panic [44]. However, history shows that full compliance with alerts, warnings, and protective action should not be expected [30], [41], [44], [49], [160]. Individuals make their own decisions on how to respond to an emergency which creates significant uncertainty for the emergency planner. An Individual's decision is influenced by a wide range of factors, including risk perception, the warning message content, desire to reunite with family, desire to return home before evacuating, and resources to evacuate, among other factors [44], [45], [105], [120], [160], [184], [195]. Despite this, uncertainty related to the behavior of the public has largely been ignored in NRC consequence studies [6], [38]. This study considers uncertainty related to public behavior with two factors: compliance with protective action orders and shadow evacuation.

2.4.1 Shadow Evacuation

A shadow evacuation factor represents the portion of the population outside of the zone under a protective action order (e.g., a keyhole zone) that spontaneously evacuated when not told to do so [97]. The over-evacuation of people not threatened by the direct effects of a hazard can create additional traffic and congestion within a network and prohibit the movement of evacuees who are directly threatened [115]. Shadow evacuation also increases cumulative transportation risk to the population by increasing the number of people traveling.

The current NRC standard value for shadow evacuation is 20% of the population outside of the defined evacuation zone. Empirical studies find that shadow evacuation can range from zero to 50% of the population, depending on the event [20], [47], [49], [110], [115]. Recent studies suggest shadow evacuation does not have a significant impact on evacuation time [20], [49]. However, these studies do not consider the effect of shadow evacuation on risk. This study uses the full range of shadow evacuation (0 - 50%) supported by the literature to fill that gap.

2.4.2 Population that does not evacuate

Non-compliance is the portion of the population that does not follow protective action orders and continues normal activities. A non-compliance factor of 0.5% is the current NRC assumed value [176]. However, NPP ETEs reports indicate a range of expected non-compliance levels that differ from the default NRC guidance and assumptions. For example, the 2012 Peach Bottom ETE study indicates that a clustered non-complying cultural group in Pennsylvania comprised 10% of the total EPZ population [196]. A review of literature that comprises empirical data, expert opinions, and public surveys were used to develop a reasonable range for the non-compliance factor [41], [45], [47], [110], [113], [160]. A range of zero to 20% non-compliance (80% - 100% compliance) was determined to represent the literature.

2.5 Hazard Dispersion Model

The RASCAL code is used for modeling radionuclide release and dispersion using a Lagrangian Puff model. RASCAL also determines the release timing, inventory, and dispersion based on site characteristics, weather, accident scenario, and other factors [55]. Accident parameters can be defined for existing US rectors or user-defined generic reactors. This study utilizes the built-in parameters for Peach Bottom Unit 3.

This case study focused on large early releases (LER) for precautionary planning. Severe LER accidents are commonly considered as a bounding condition for emergency planning and were selected to ensure a PAG level is reached, and a protective action is needed. A loss of coolant accident (LOCA) and long-term station blackout (LTSBO) represent current regulatory guidance and the recent state-of-the-art studied [6], [197]. In the unlikely event of an accident, there is an even smaller probability of a LER.

If smaller, more plausible, design-based accidents are selected, the results are expected to indicate reduced risk to the population. Short-term releases tend to be related to pressure release events used to avoid containment failure and prevent long-duration events. A SIP strategy may be comparatively more effective as a strategy for short-term plumes, particularly when the dose is primarily from inhalation exposure

[96]. A short-term plume was not modeled as part of this study as it would generally not involve a major evacuation.

2.5.1 Variation in Weather

Weather creates epistemic uncertainty and integrated effects. The fate and transport of hazardous material are dependent primarily on how the source term of hazardous material interacts with the weather, including wind speed, wind direction, atmospheric stability, and precipitation. Further interaction effects exist when determining exposure and dose between the spatiotemporal location of the population and the fate and transport of hazardous. If evacuation is used as a protective action, inclement weather can reduce roadway capacity, slow evacuation speeds, and increase transportation risk [97], [110].

The probability of exposure to the population varies depending on how the hourly weather data is analyzed. An analysis of ten years of hourly weather data for Peach Bottom from 2007-2017, seasonal variation in weather results in very different potential exposure curves (Figure 30). An evaluation of hourly wind speeds and direction indicates that a much larger population could be exposed one hour after the start of an accident in February compared to April or August. Prevailing winds affect different population centers during the year.

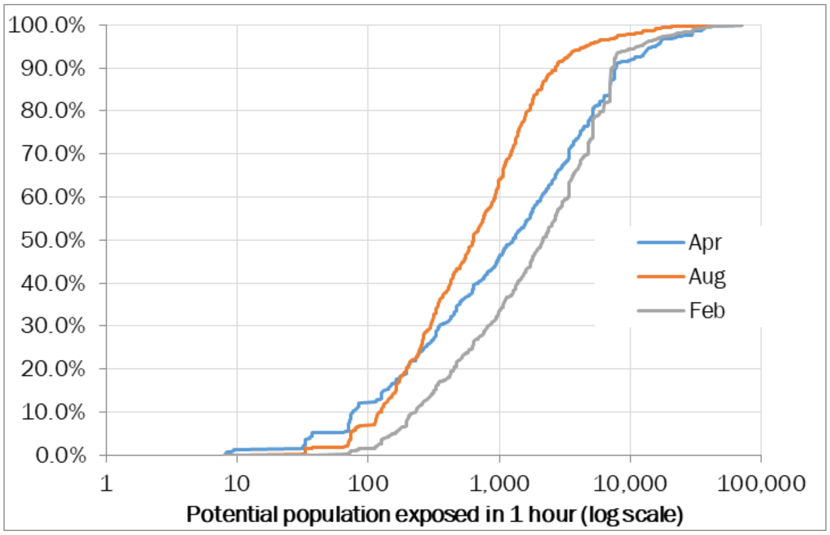

Figure 30: Potential population in the EPZ exposed in 1 hour based on hourly wind speed and direction, using Peach Bottom NPP weather data 2007-2017

Understanding the probability that a cell could receive exposure in 1 hour using a large historical dataset can be useful for planning. Figure 31 shows that some cells have almost zero probabilistic risk of exposure in a 1-hour timeframe. Analyzing historical weather can give emergency responders insight on how to most effectively plan and train for an emergency response through the year.

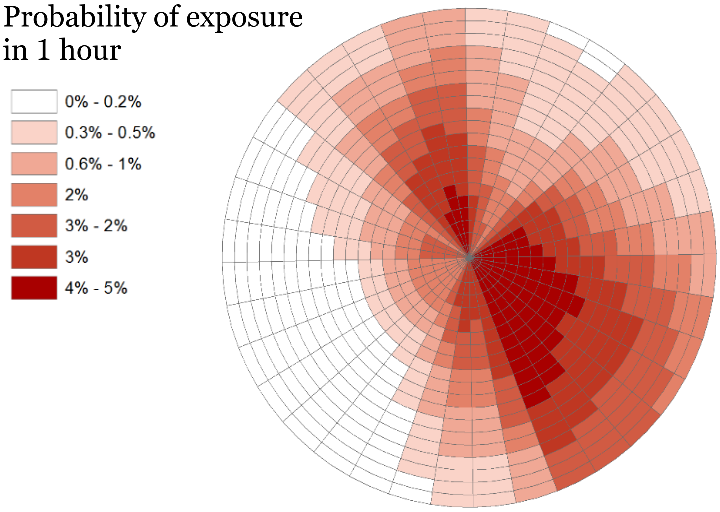

Figure 31: Percentage of time cell will have deposition 1 hour after the beginning of hazardous release based on hourly weather data from Peach Bottom NPP 2007-2017.

Note that the probabilistic risk shown in Figure 31 considers the likelihood that an event or condition will occur. This differs from conditional risk, which focuses on a specific scenario, such as a specific wind direction or wind speed, which is used in the integrated model analysis later in this chapter.

2.5.2 Source Terms

The radionuclide release varies due to reactor technology, operating characteristics, release pathway, release time after reactor shutdown, and accident type. Emergency plans are required to include the ability to respond to a severe, rapidly progressing accident [22]. In this analysis, a fast release that bypasses the containment building was selected to simulate a rapidly progressing and severe scenario. Two source terms were selected for analysis: loss of coolant accident (LOCA) and long-term station blackout (LTSBO). An LTSBO was identified as the most significant accident type for Peach Bottom in the SOARCA study [6]. A LOCA is the main accident scenario considered for LLWR siting decisions [197].

2.5.3 Source Term and Weather Scenarios

The weather has a significant effect on the dispersion of hazardous materials, primarily through wind speed, direction, and stability class. The weather data described in Section 2.5.1 and source terms defined in Section 2.5.2 are used to determine forty hazard dispersion scenarios. These scenarios can be found in Table 25 in the Appendix.

2.6 Integrated Consequence Model

The integrated model is comprised of three main modules: a Protective Action module (where the people are), a Hazard Dispersion module (where the radiological hazard is), and a Consequence module (risk and effects to the people). These modules take in several types of information, including data (e.g., weather, population), scenario choices (e.g., NPP accident type), and probability/frequency distributions or deterministic assumptions (e.g., level of compliance) as illustrated in Figure 28. Together, the three modules calculate the spatiotemporal progression of the event, consequences, and decision metrics.

2.6.1 Transportation Risk

The transportation fatality risk conversion factor of 9 x 10^{-8} used in the PAG guidelines are based on a 1974 report which concluded that transportation risk during an evacuation is approximately the same as normal transportation [148], [187]. However, the average motor vehicle transportation risk is much lower now than it was in 1974. In 2016 the fatality rate for motor vehicle transportation was approximately 1.2 per 100 million vehicle miles (1.2 x 10^{-8}), and an average vehicle occupancy rate of 1.7 results in a 7 x 10^{-9} fatality risk per person mile [34], [152].

A 100-mile round trip was assumed for the evacuating population to be consistent with EPA guidance [96]. Actual evacuation destinations and distances are expected to vary by event and individual [188]. More detailed analysis can be performed to calculate transportation distance and risk to emergency shelters or other destinations and reduce conservatism in the results.

2.6.2 Radiation Dose

Total Effective Dose Equivalent (TEDE) is a summation of dose incurred from inhalation, cloud shine, and ground shine dose pathways. Dose timing and location are affected by many weather characteristics, including wind speed, direction, stability class, and precipitation. Regional characteristics, including topography and surface roughness. Site and accident characteristics, including release height, release rate, and release velocity.

Most studies that compare strategies do so over 4-day periods based on EPA guidance [96]. This conflates the evacuation and relocation concepts and is not informative for the dose received solely during a prompt evacuation. Therefore a 4-day period is not a reasonable basis for comparing these protective action strategies. Doses presented are only for the model time period and do not consider committed doses from inhaled exposure over the individual's lifetime.

Shielding should be considered when evaluating alternative protective action strategies [40]. The shielding factors presented in SOARCA for Peach Bottom NPP (Table 20) are used for this analysis [4]. Consistent with the EPA PAG manual, the metric of avoided consequences is used to evaluate a protective action's effectiveness. For this study, avoided consequences are defined as the difference between the dose received during a protective action strategy or if no protective action was used. The exposure to the population when no protective action is taken (i.e., baseline) is determined by modeling normal activity shielding factors and no evacuation or sheltering strategy.

Table 23: Shielding factors for Peach Bottom from the SOARCA [4]

Activity	**Dose pathway**		
	Groundshine	Cloudshine	Inhalation
Shelter-in-place	0.1	0.5	0.33
Evacuation	0.5	1.0	0.98
Normal Activity	0.18	0.6	0.46

The risk of individual latent cancer fatality is scenario-specific. The Interagency Steering Committee on Radiation Standards (ISCORS) provides a basis for converting

TEDE dose to latent cancer fatality (LCF) risk using a conversion factor of $6x10^{-4}$ [150]. The most recent guidance from the EPA is a risk of $3x10^{-4}$ cancer deaths per person-rem [96]. The divergence of recommended values is indicative of the ongoing research into the effects of radiation dose and the multitude of dose-response models [147]. The risks using either factor are in the same order of magnitude and have a linear relationship that does not alter protective action rankings in this analysis. The ISCORS guidance is used in this analysis.

3 Results

The primary purpose of a protective action strategy is to avoid consequences to the population. This section evaluates and discusses the six decision metrics included in the integrated model The MOE are listed below with location of definition:

4. Latent Cancer Fatality Risk (Chapter 5)
5. Transportation Risk (Chapter 5)
6. Combined Risk (Chapter 4)
7. Portion of Dose Avoided by Protective Action (Chapter 5)
8. Protective Action Robustness (Chapter 4)
9. Evacuation Time (Chapter 2)

The seven protective action strategies identified in Section 2.3.1 are used for this analysis. Three datasets are used in this analysis. The primary dataset contains 250,000 integrated model iterations and considers the full range of input values. The second data set is used to simulate the current NRC behavioral assumptions. Results from the second set are compared to the main set in Section 3.9. The third set re-evaluates the

Lateral and Keyhole protective actions using matched pair scenarios. The results of this dataset are discussed in Section 3.12.

Although this model's primary objective was to compare actionable protective action strategies under uncertainty, other factors were considered. Most of the following sections analyze the complete dataset to identify and discuss important factors. However, for a specific emergency event, uncertainty and the range of inputs should be reduced to the extent possible, and direct comparisons of protective action strategies should be made.

3.1 Portion of Dose avoided

The portion of dose avoided is used as a measure of effectiveness to compare each strategy. The portion of dose avoided is defined as the portion (percentage) of exposure that can be avoided for a given set of conditions using a particular protective action strategy compared to if no protective action is taken. Higher values indicate a greater portion of the baseline dose is avoided.

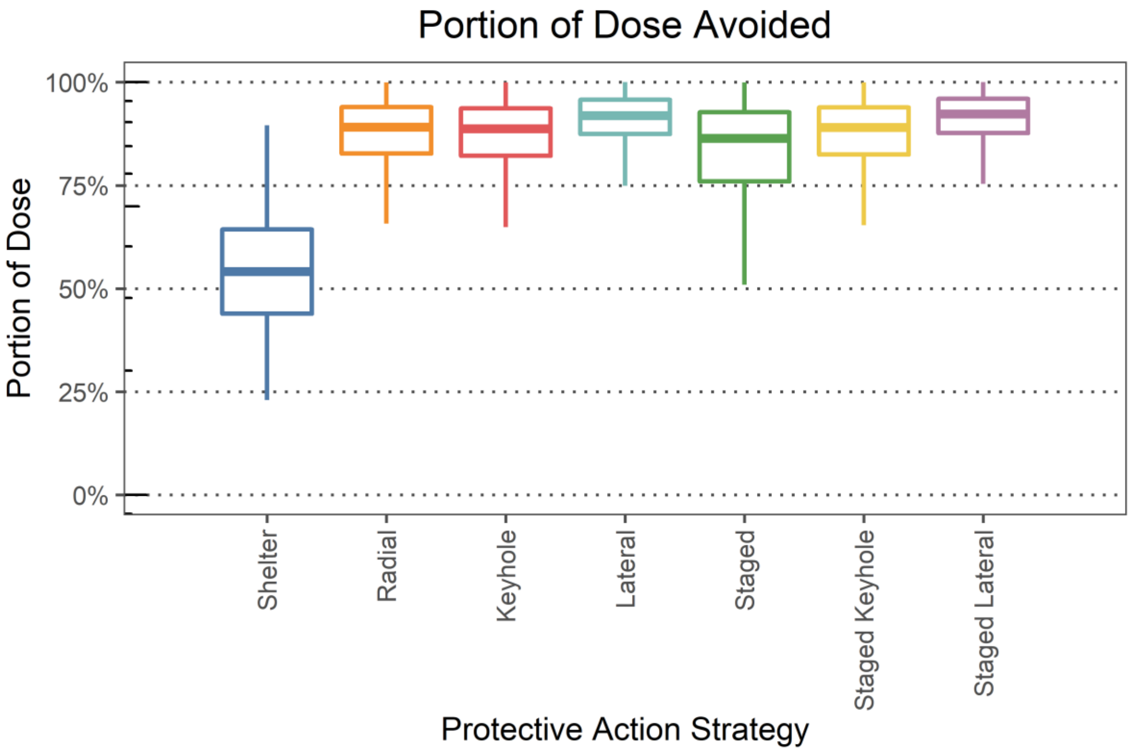

Figure 32: The portion of dose avoid by implementing a protective action strategy.

The results in Figure 32 represent the entire portion of dose avoided for the entire primary dataset (N=250,000). This figure includes the entire range of behavioral uncertainty, accident scenarios, and weather scenarios, which occludes the variation between the protective action strategies for a specific event.

A SIP strategy results in a higher dose than the other protective action strategies. While the public is shielded to a large extent during SIP, they continue to receive a dose during the entire emergency. Leaving the shelter to evacuate later could expose them to residual radionuclide particles from the plume. While SIP can be an effective strategy for reducing dose consequences, especially for hazards that end quickly, evacuation has the potential to avoid all dose consequences if the population can leave the exposed area before the arrival of the hazard. For long-duration accidents, populations will continue to accumulate consequences during SIP well after the 8-hour model window, causing the dose to be higher than indicated in these results.

3.2 Head Start

Head start allows the population to begin a protective action prior to the initial release of radiation from the NPP. As expected, the head start factor has a very large impact on the risk to the population. A slight increase in head start improves the portion of dose avoided significantly for all strategies (Figure 33).

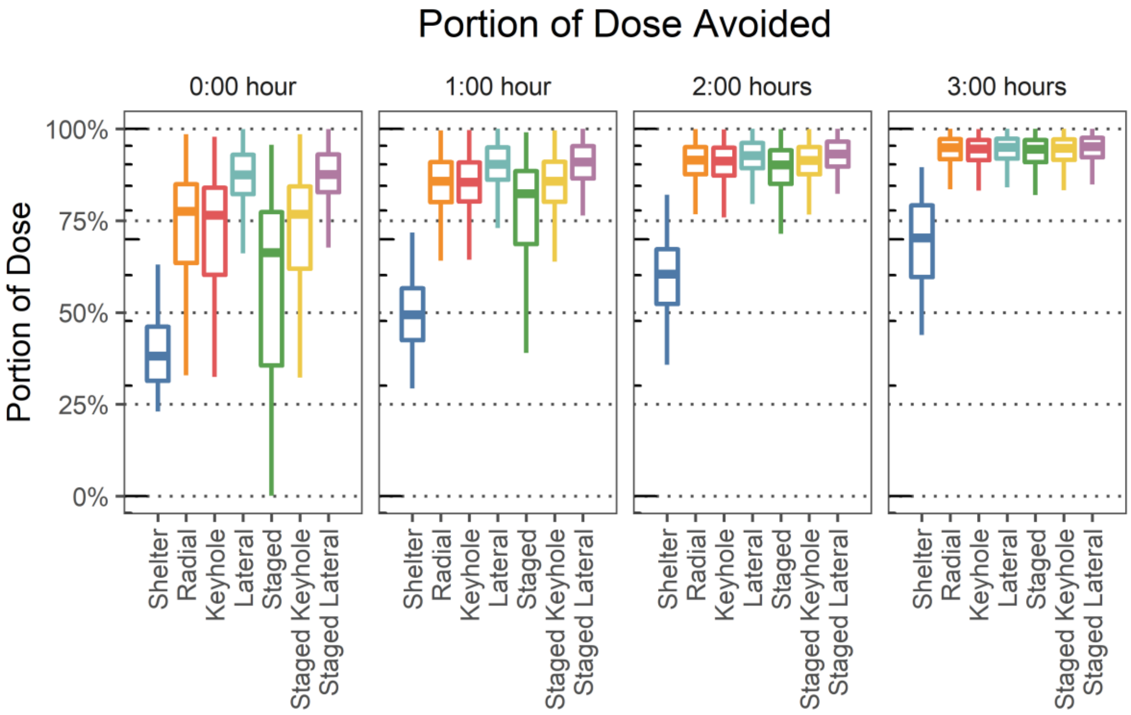

Figure 33: The portion of dose avoid by implementing a protective action strategy, factored by the amount of head start

When the population has less head start, the Lateral strategy avoids the greatest portion of the dose, but all evacuation strategies perform similarly when approaching three hours of head start. Most NRC guidance state that SIP is the preferred strategy if the ETE time is more than 2 hours [22]. This study finds an evacuation-type protective action strategy performs better than SIP even without any advanced warning and head start. Determining the point at which SIP and evacuation strategies break even is left to future work. However, based on the results in Figure 33, the radiation release would have to begin before the start of an evacuation to break even with SIP.

3.3 Risk Metrics

The integrated model evaluates three risk metrics: latent cancer fatality risk, transportation fatality risk, and combined risk. These risk metrics quantify realized conditional risk for each protective action strategy. Realized conditional risk assume that the accident occurs and shows the risk that is experienced during an event. Realized risk excludes probabilities of initiating conditions such as reactor failure, hazard release, or if a particular protective action will be selected. The conditional risk quantifies the cumulative likelihood of fatality to the defined population. It is incorrect to assume that the population should be multiplied by the risk factors calculated in this chapter.

For comparison, the sum of cancer fatality risks resulting from all causes for an individual in the U.S. is $2x10^{-3}$ (or two in one thousand) [4]. The NRC Safety Goal for latent cancer fatality risk from nuclear power plant operation $2x10^{-6}$ (or two in one million), which is set 1,000 times lower the average cancer risk [4]. Note that these are individual risks, not population risks as presented in this chapter, which are cumulative on thousands of people.

3.3.1 Dose-related Risk

Latent cancer fatality (LCF) risk is a function of dose and a conversion factor (Section 2.6.2). In general, Lateral results in the lowest LCF risk, followed by Staged Later, Radial, Keyhole, Staged Keyhole, and then SIP.

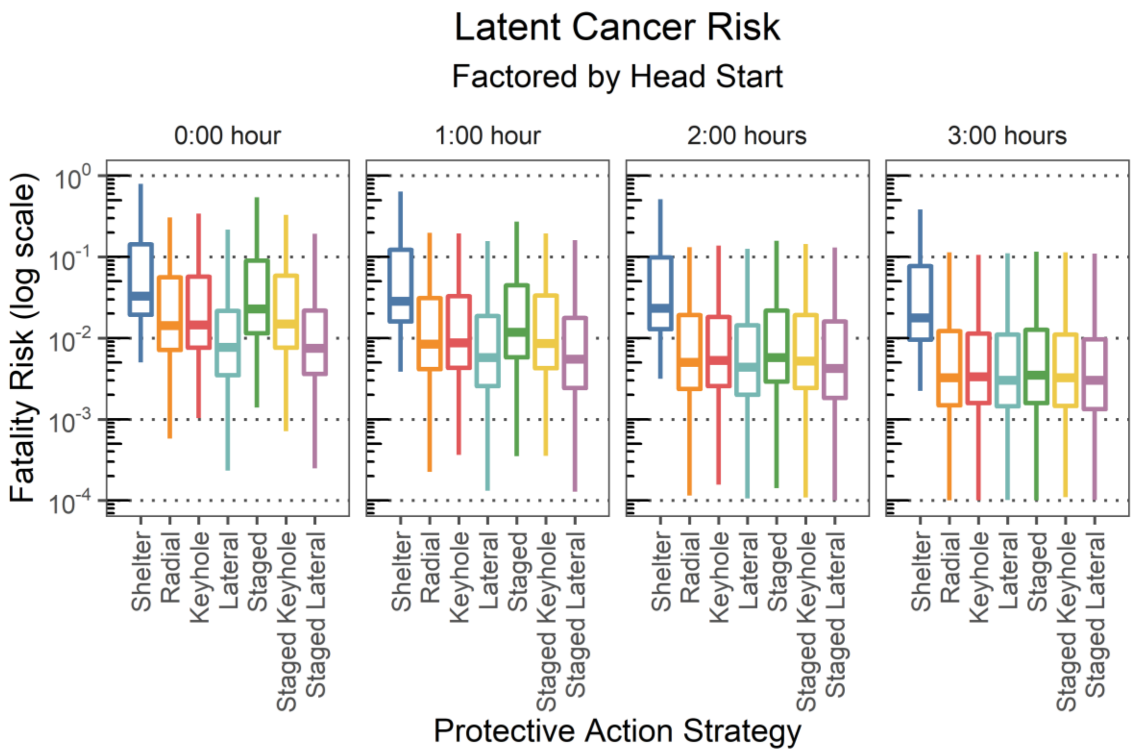

Figure 34: Comparison of risk across multiple protective action strategies

3.3.2 Transportation risk

There is a risk of fatality due to traffic crashes with any evacuation. The conditional risk to the population was determined for each protective action strategy and amount of head start in Figure 35. Note that the SIP protective action is generally considered to have no evacuation risk. However, it has a non-zero risk due to shadow evacuation. After SIP, which has the lowest risk, Lateral and Keyhole have the next lowest due to only moving the population under the plume exposure pathway. The transportation risk is not affected by head start because it is not impacted by dose exposure.

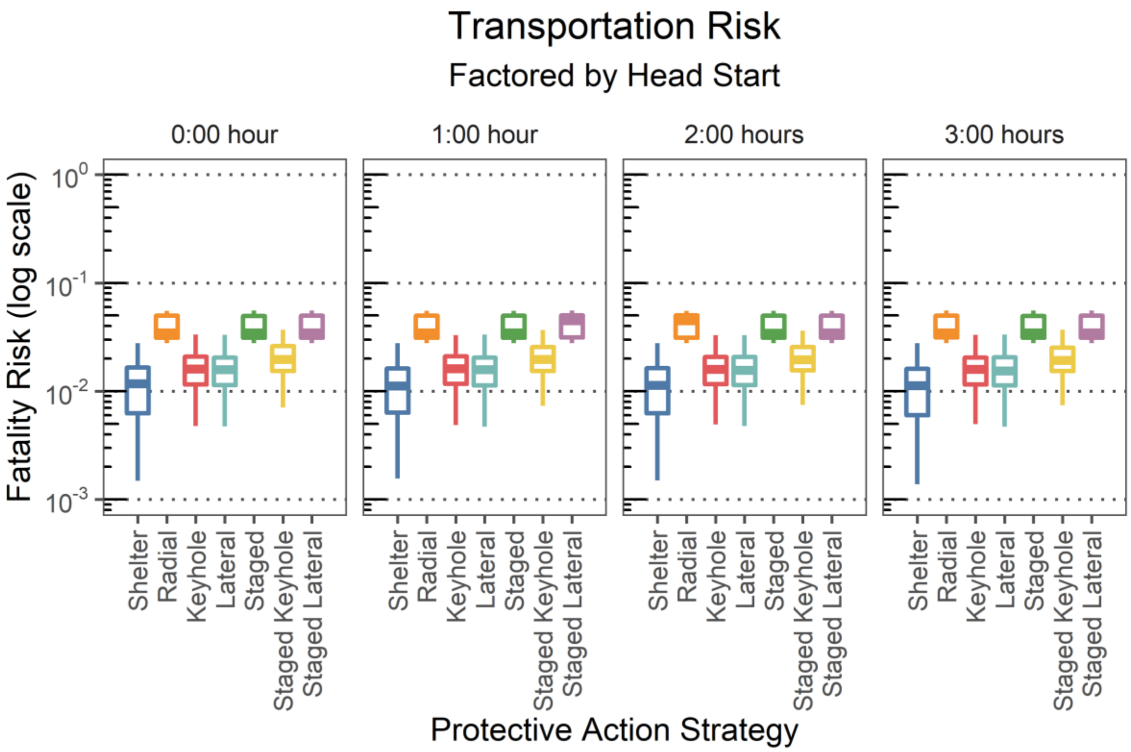

Figure 35: Cumulative risk of fatality to the population due to transportation risk.

3.3.3 Combined Risk

Combined risk is a decision metric developed in chapter 4 to give the decision-maker insight into the overall risk of a protective action strategy. This is necessary because the threshold approach used in the EPA PAG manual is not informative for comparing and balancing multiple risks. This is especially true for the portion of the population out of the risk-affected area and only experiences transportation risk. The combined risk metric is the summation of dose risk (i.e., LCF) and transportation risk for each model iteration.

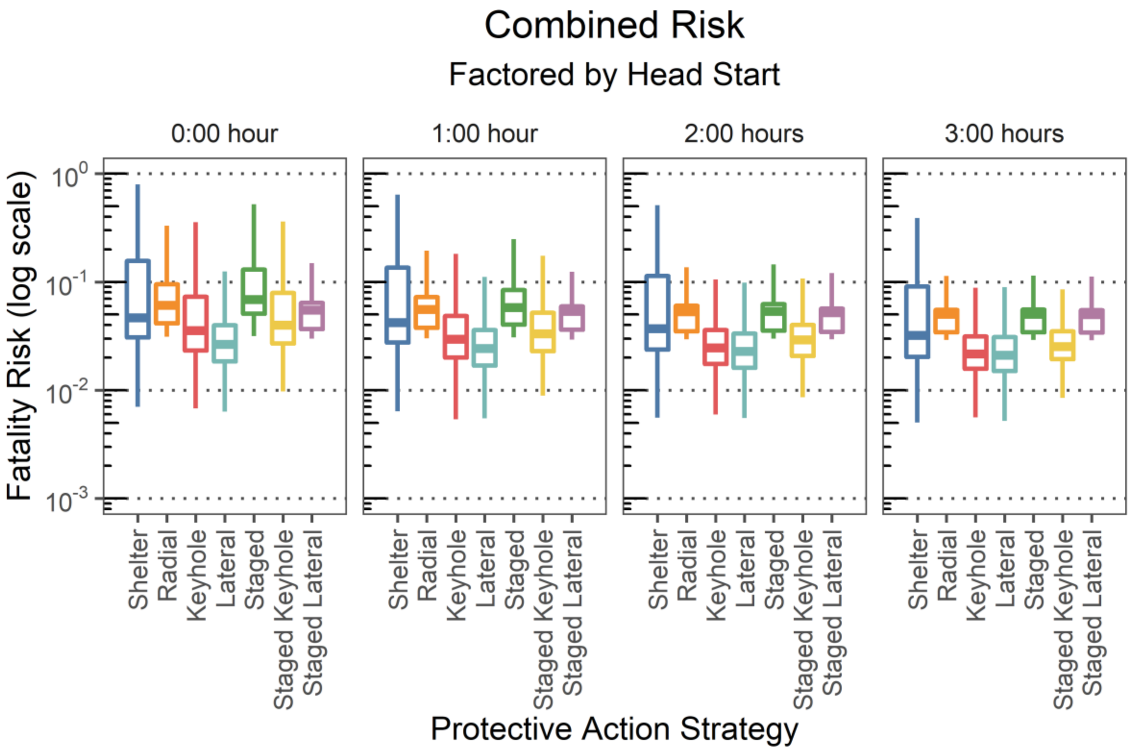

Figure 36: Cumulative combined risk to the population, factored by head start and protective action strategies

The results in Figure 36 indicate a Lateral strategy may be the best choice for reducing risk with the overall lowest mean value, less variance than most strategies, and consistent performance compared to head start. Combined risk is less impacted by head start than when dose risk is considered alone. The transportation risk is an order of magnitude higher than the LCF risk, which buffers combined risk against the variation in dose risk due to head start.

The results in Figure 36 provide limited insight into how the risks combine for each protective action strategy. For example, a Radial strategy moves the entire population, including many who were not at risk of radiation exposure. Figure 37 provides more context on how the component risk values combine and how the combined risk compares to the baseline LCF risk if no protective action is taken.

The counterfactual comparison of baseline LCF to transportation risk when no strategy is used (i.e., normal activity) is not informative as protective action-induced transportation risk would be zero. However, it is useful to compare the counterfactual risk to the realized risk of a protective action to ensure risk is reduced.

All seven strategies are effective at reducing LCF risk compared to taking no action. However, the relatively high transportation risk associated with full EPZ evacuation greatly impacts combined risk. A key finding is that the combined risk for Radial, Staged, and Staged Lateral strategies exceed the baseline LCF nearly half of the time. That means the population would experience less risk by carrying on with normal activities than using one of those protective action strategies a large portion of the time. While a SIP strategy is not as effective at avoiding dose relative to other strategies (Figure 32), the combined risk metric shows it would be preferred relative to Radial, Staged, and Staged Lateral strategies because SIP does not exceed the baseline risk. This risk comparison method was proposed in chapter 4 and has not been used for protective action decision-making previously. Note that Staged Keyhole does not have the same issues because it does not evacuate the 5-10mile portion of the EPZ.

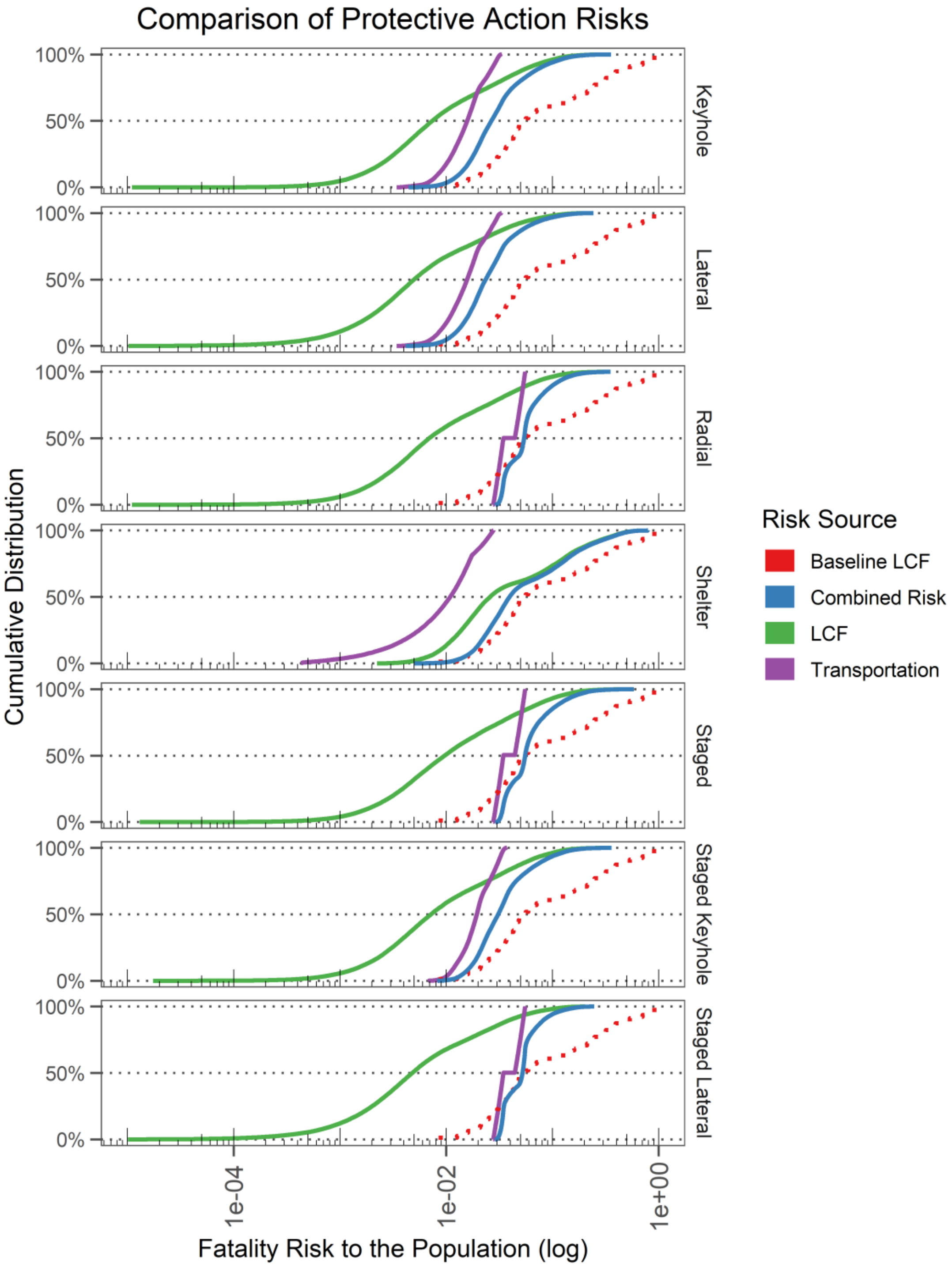

Figure 37: Cumulative distributions of risk factors, separated by protective action strategy

3.4 Robustness

A robustness metric is needed to compare evacuation strategies under uncertainty. Robust planning explicitly recognizes uncertainty and seeks a plan that is desirable under many possible situations. The robustness metric (see chapter 4) calculates the relative portion of model iterations for one protective action that dominates another protective action using pairwise comparison.

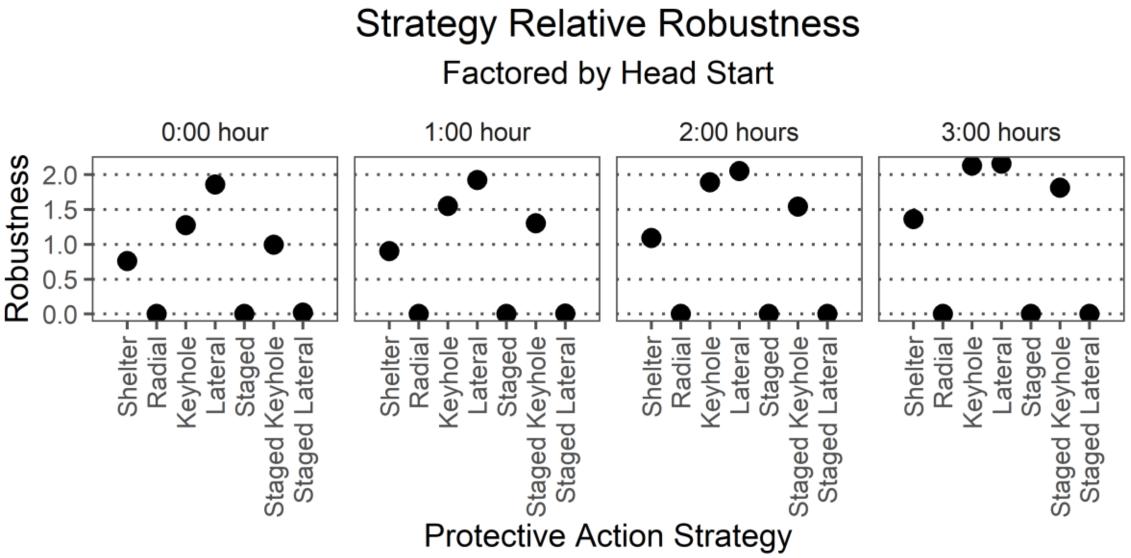

Figure 38: Cumulative robustness of a given strategy relative to the other strategies

A higher robustness value is preferred. A zero robustness value indicates that the protective action strategy does not dominate any other strategy. The results in Figure 38indicate that a Lateral protective action strategy is the most robust, followed by Keyhole, Staged Keyhole, and Shelter-in-Place.

3.5 Evacuation Time

The portion of the population that travels varies by protective action strategy, defined evacuation zone, and public behavior. Staged evacuations only move a portion of the evacuating population at a time. Figure 39 shows the portion of the total population that evacuates with each protective action strategy.

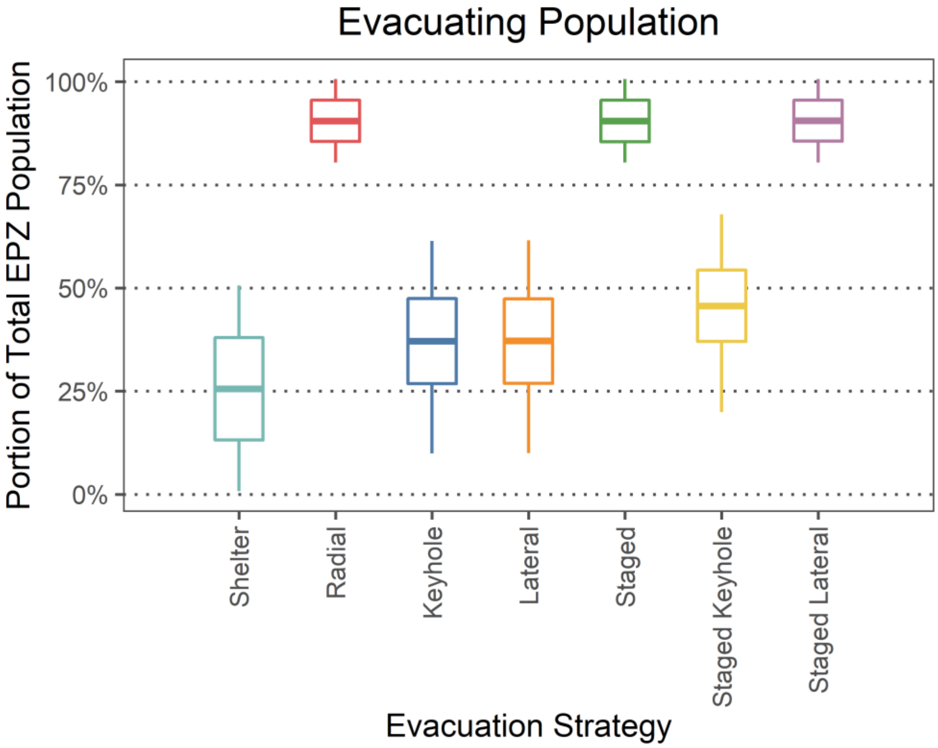

Figure 39: Portion of the population that evacuates from the EPZ

Evacuation time includes the population that is told to evacuate and the shadow evacuation. The portion of the population that is evacuated varies by protective action (Figure 39). This portion of the population is directly correlated to the transportation risk imposed on the population. Strategies that evacuate only a portion of the EPZ have significantly reduced transportation risk.

Evacuation time includes the population that is told to evacuate and the shadow evacuation. Evacuation time varies by strategy and uncertainty, as shown in Figure 40. Evacuation time is the MOE used in ETE studies and most evacuation studies unrelated to NPP emergency planning. However, this metric is not a direct proxy for population risk and may erroneously exclude effective protective action strategies.

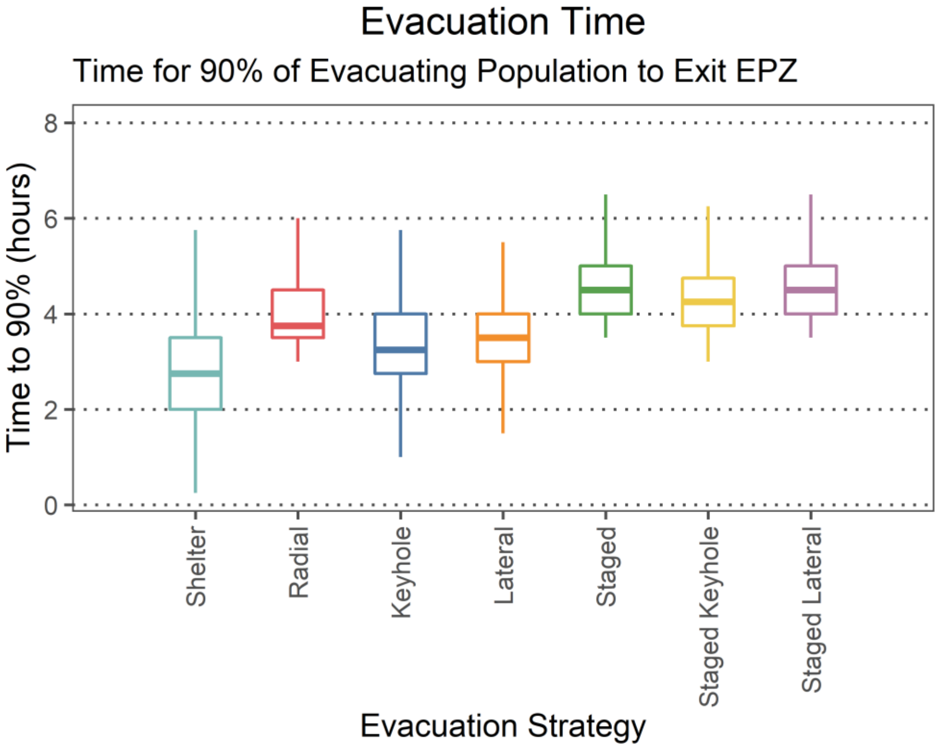

Figure 40: Time from beginning of evacuation to 90% of population outside of the EPZ (N=111004)

Evacuation times are determined for 90% of the evacuating population to clear the EPZ boundary [97]. This is due to the last 10% of the population taking a disproportionate amount of time to evacuate [99]. Many simulations did not achieve an evacuation level of 90% due to >10% of the population not complying with the order to evacuate. Integrated model evacuation times are validated against industry ETE reports and the Real-time evacuation Planning Model[37] (see Appendix).

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[37] Developed by and available at http://rtepm.vmasc.odu.edu/

These results do not support the claim that staged evacuation can reduce ETE, most likely due to the lack of congestion experienced. Roadway clearance times generally follow loading patterns unless congestion is created due to a secondary cause [100]. However, prolonged loading rates may result in the network being underutilized [198]. Traffic congestion becomes less of a concern with smaller evacuated areas such as those used with a Keyhole or Lateral strategy.

3.6 Population

The population count and location are considered major factors in ETE studies. The Peach Bottom EPZ is considered a highly populated EPZ. The impact of the population on the effectiveness of a protective action strategy is shown in Figure 41. Two population sets (i.e., Day, Night) are used in this study. In this study, the hazard dispersion scenarios used all four quadrants of the polar grid to account for population and site characteristic variation. Wind direction can be used as a direct proxy for spatial location because the evacuation area aligns with the plume centerline. The results in Figure 41 indicate a minimal effect on protective action effectiveness caused by population variations.

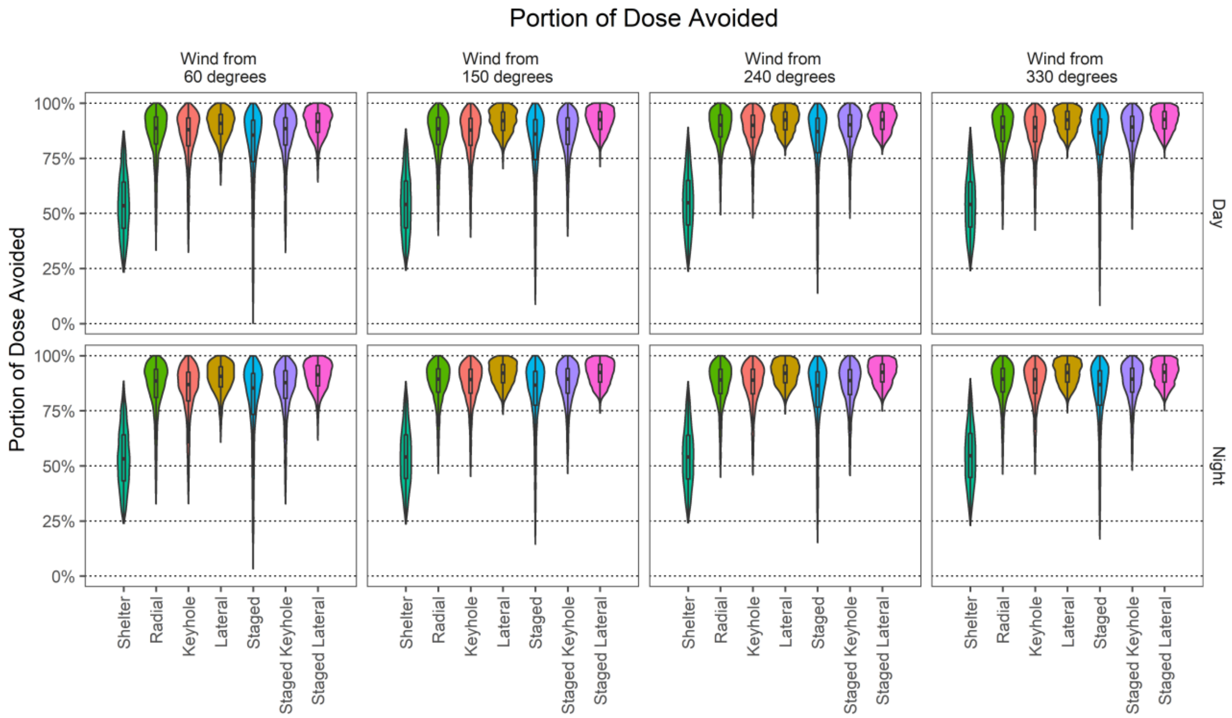


Figure 41: Portion of dose avoided separated by population set in terms of the time of day and spatial location.

3.7 Accident scenario

This study primarily focused on large early releases (LER) for severe accident emergency planning. Two source terms were selected for analysis: loss of coolant accident (LOCA) and long-term station blackout (LTSBO). The difference in dose between accident types is apparent in the left panel of Figure 42. It is evident that the two accident types have different risk profiles, as indicated by the inconsistent ranges in the figure.

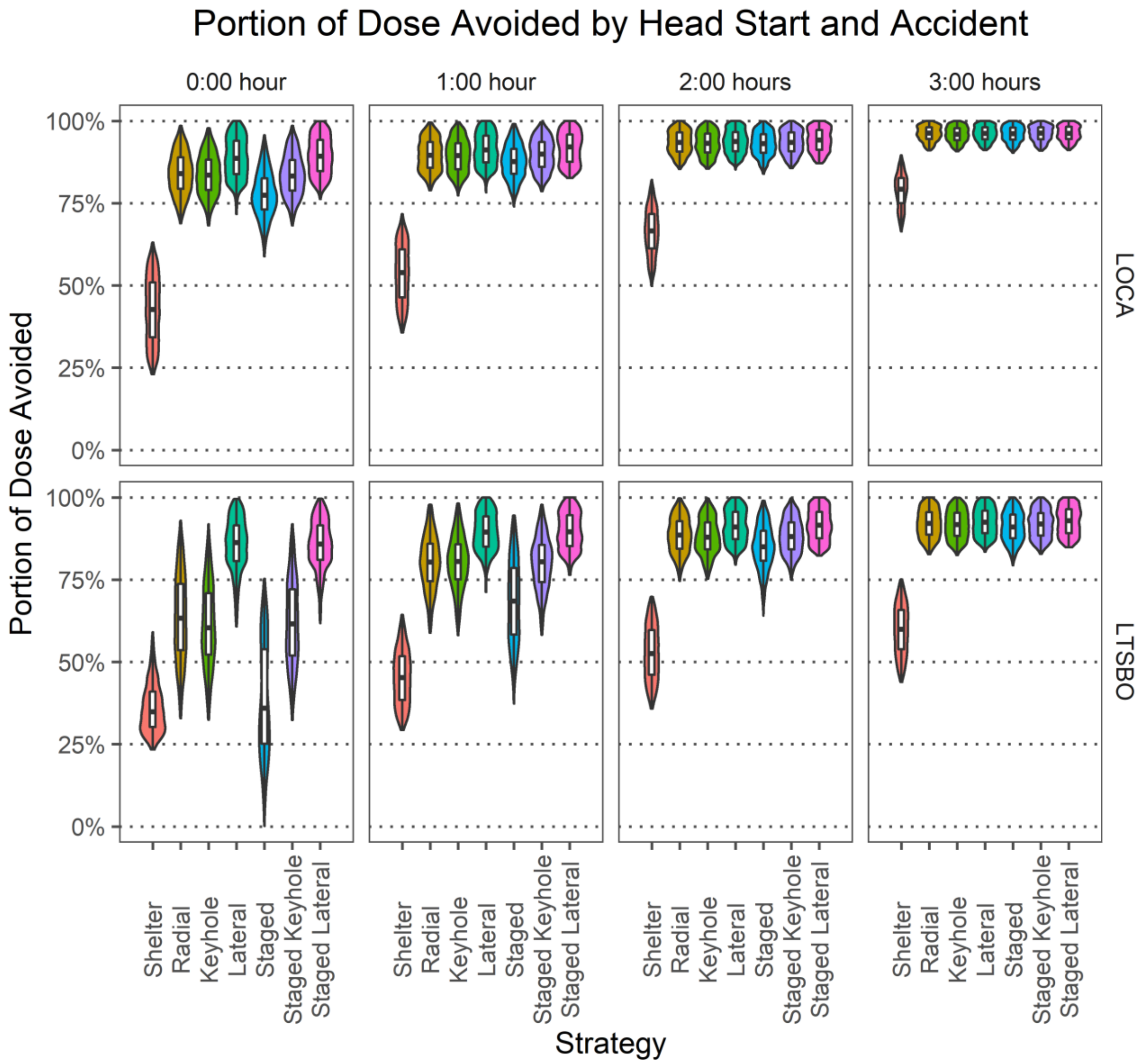


Figure 42: Portion of dose avoided by protective action strategy and amount of head start before radiation release. Evacuation strategies are less effective at avoiding dose with a short head start during an LTSBO accident type.

More head start does not consistently increase the portion of dose avoided between protective action strategies. Protective action strategies are less effective against an LTSBO accident type than a LOCA accident. In contrast, all of the evacuation-type protective action strategies effectively avoid most of the dose from a LOCA accident without the benefit of a head start.

3.8 Roadway Capacity

Simulation roadway capacity is considered an important factor in current NRC ETE guidance, more recent NRC evacuation modeling guidance, and Federal Highway Administration traffic engineering manuals [20], [97], [199]. Recent studies contradict the claim that small reductions in capacity due to mild to moderate congestion, inclement weather, or a partial obstruction will severely increase evacuation time [7], [49], [100].

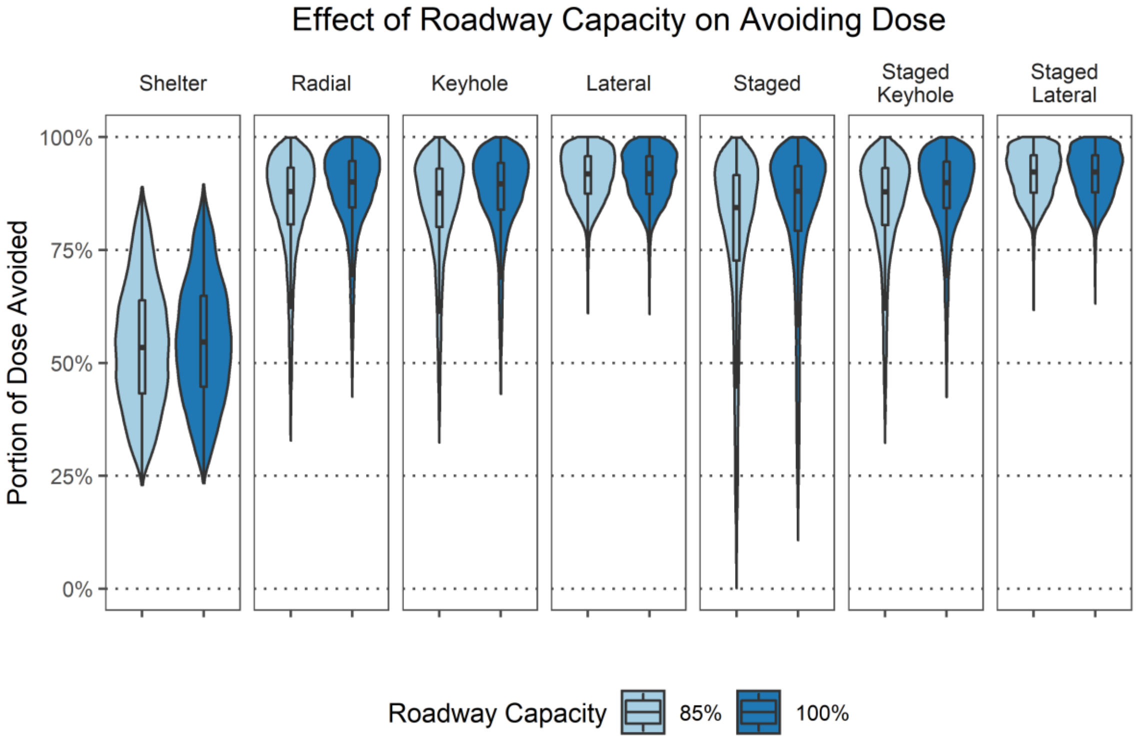


Figure 43: The impact of roadway capacity reduction on protective action strategy effectiveness

This study's results support the position that small reductions in roadway capacity will not significantly impact the evacuation process. While evacuation time did increase

15-30 minutes on average (1-2 time-steps), the protective action's effectiveness (Figure 43) was not severely impacted.

3.9 Behavioral Response

The NRC uses standard assumptions of a 0.5% portion of the population that does not comply with protective action orders and a 20% shadow evacuation in evacuation and consequence models. A dataset consisting of 10,000 integrated model iterations limited to the current NRC assumptions was generated to compare behavioral responses. The distributions of results, provided in Figure 44, compare the full range of uncertainty to the NRC assumed values. The results indicate a potential overestimation of protective action effectiveness (i.e., the potential to avoid dose). The NRC assumptions provide the decision-maker with a limited view of potential outcomes, potentially affecting protective action decisions.

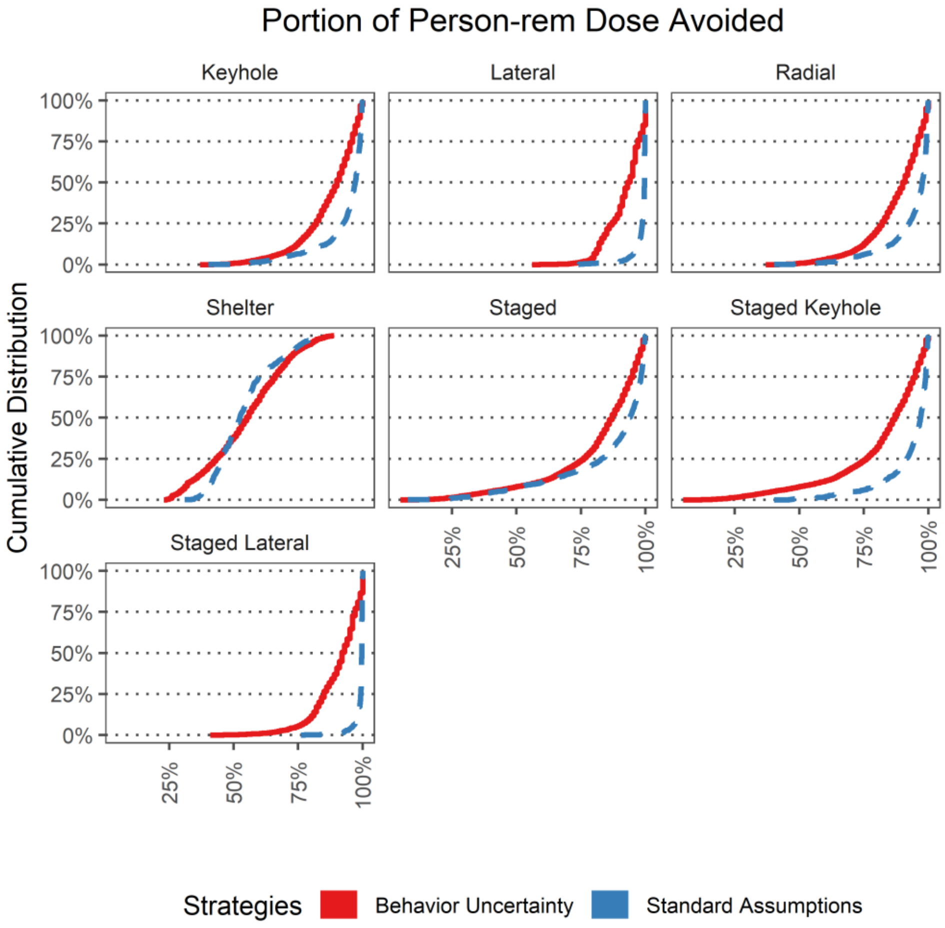


Figure 44: Portion of does avoided cumulative distribution comparing standard assumptions and uncertainty simulations

3.10 Weather

Weather is a factor in the overall dose and strategy selection, as shown in Figure 45. Wind speed and stability class affect the portion of dose avoided for all evacuation strategies, which is expected but not previously quantified. Wind speed is directly related to the amount of time available for the population to perform a protective action prior to risk exposure. Protective action head start is significantly related to reducing the population dose, especially at high wind speeds. Stability class is a measure of the turbulence present in the atmosphere and is an indicator of the plume behavior. In very unstable atmospheric conditions (i.e., stability class B), the plume can cycle down to the ground in a phenomenon called loping. In very stable conditions (i.e., stability class F), the plume can become stagnant instead of diluting, which concentrates dose in a broad zone closer to the NPP.

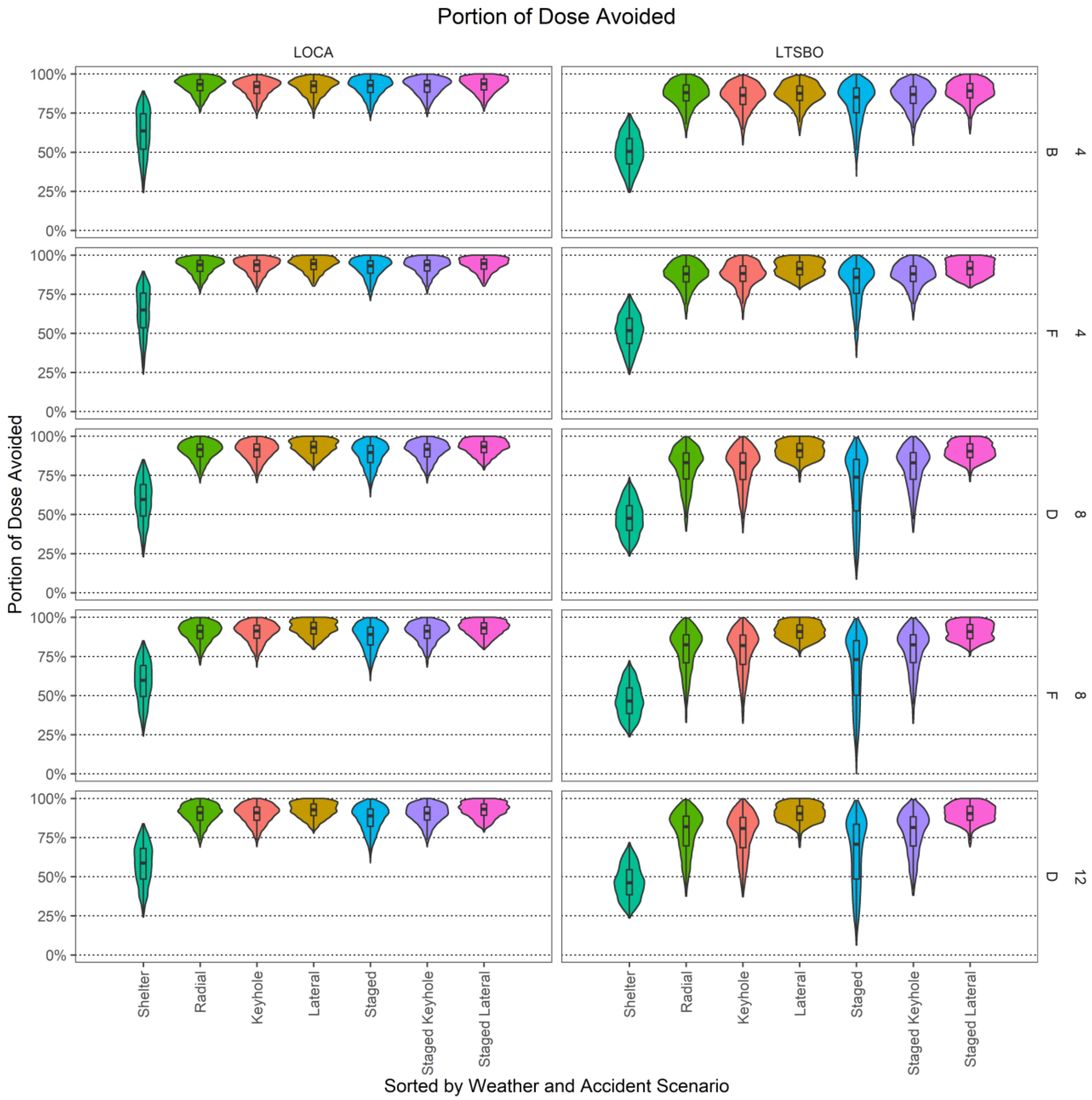


Figure 45: Distribution of portion of dose avoided separated by protective action strategy, wind speed, and atmospheric stability class

An LTSBO accident is much more volatile to weather changes than a LOCA accident. This is in part due to the underlying assumptions made by the NRC in defining the LOCA and LTSBO accident release scenario, which is represented in the RASCAL model.

3.11 Evacuation Area

The evacuation area must match the hazard area under the plume to be effective. Despite a Lateral strategy resulting in a lower dose in most situations, Figure 45 shows a Radial strategy can result in a lower dose with a 4-mph wind speed and B stability class. This is because a slow wind speed with an unstable atmosphere results in a very wide plume. A complete EPZ evacuation, instead of just in the highest risk keyhole zone, compensates for the plume width, especially near the NPP where the Keyhole is narrow. If the Keyhole zone is narrower than the plume, then the benefit of reduced transportation risk and congestion in the keyhole zone can be overshadowed by the additional consequences received by the sheltering portion of the population outside of the keyhole zone.

Poor wind forecasting or evacuation decision-making can have serious consequences for the keyhole and lateral strategies. Evacuation cone alignment with the plume path is important. Significant reduction in consequences can be achieved with a lateral evacuation if the evacuating cone is appropriately placed and sized.

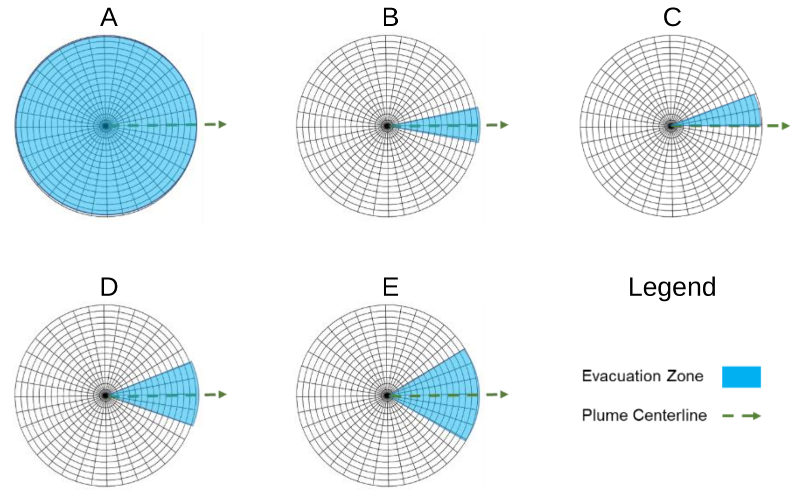


Figure 46: Evacuation zones used for scenarios in Table 24

Table 24 illustrates how a misplaced evacuation zone can lead to an increase in consequences. Radial evacuation (iteration A) has lower consequences than a Lateral evacuation (iteration C), for the example shown in Figure 19, due to an evacuation zone misaligned with the plume pathway. Uncertainty in weather forecast may require a wide evacuation zone or radial evacuation out of precaution. An evacuation zone that is wider than the plume pathway can compensate for this uncertainty but increase non-dose risk by moving a larger portion of the population.

Table 24: Change in dose by evacuation cone size and accurate alignment to a plume centerline between sectors 9-10 of the polar grid (see Figure 46) for a LOCA accident, 4 mph wind speed, F stability class

Iteration	Cone Size	Sectors	Change in dose from full EPZ evacuation
A	Full EPZ	All	N/A
B	Lateral 20º	9-10	-80%
C	Lateral 20º	8-9	+56%
D	Lateral 40º	8-11	-80%
E	Lateral 60º	7-12	-94%

3.12 Lateral and Keyhole Strategy Comparison

Input values for each model iteration are selected semi-randomly (see Section 1.1) in the primary dataset. While that approach is useful for exploratory analysis, a limitation is that each protective action strategy cannot be directly compared because input values are not consistently sampled. A set of input value scenarios was designed to directly compare protective action strategies while including important values identified in prior sections. A total of 16,950 model iterations were completed for this analysis. These input scenarios are used to compare Lateral and Keyhole strategies, which are the two strategies that have performed well in all prior sections.

As previously shown, a Lateral protective action strategy is more efficient than other protective action strategies at rapidly moving only the population that is at risk. Evacuation time for the population in the plume exposure pathway is lower than other strategies, but the total time to evacuate the EPZ is increased by moving the population laterally before moving radially to the EPZ border.

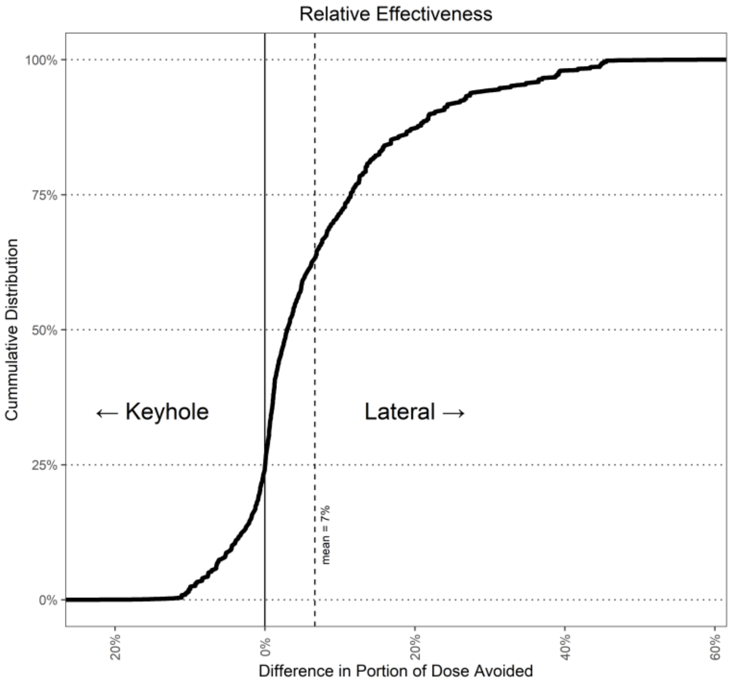


Figure 47: Comparison of the portion of dose avoided between Lateral and Keyhole evacuation strategies. Lateral avoids more dose that Keyhole in 75% of iterations and on average avoids 7% more dose.

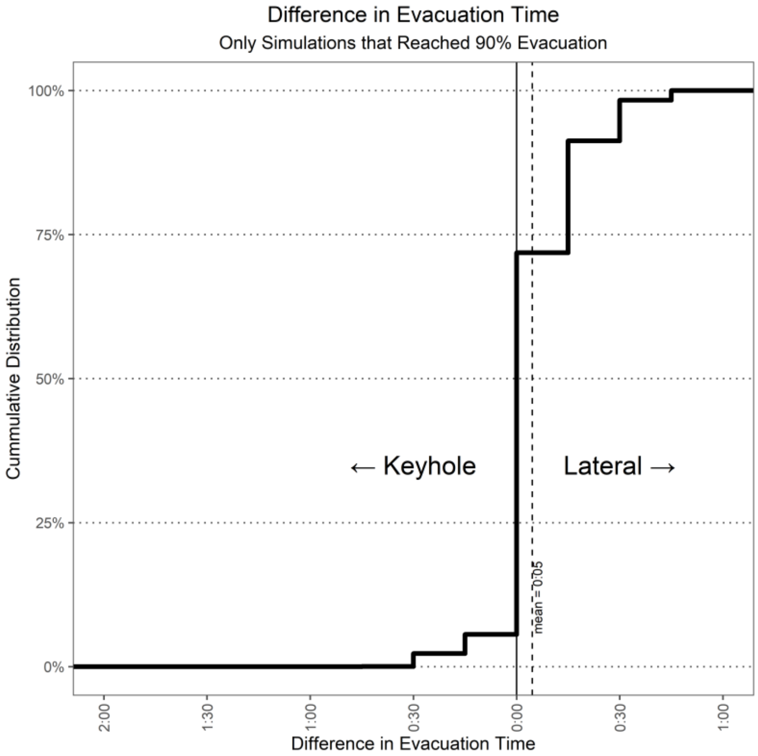
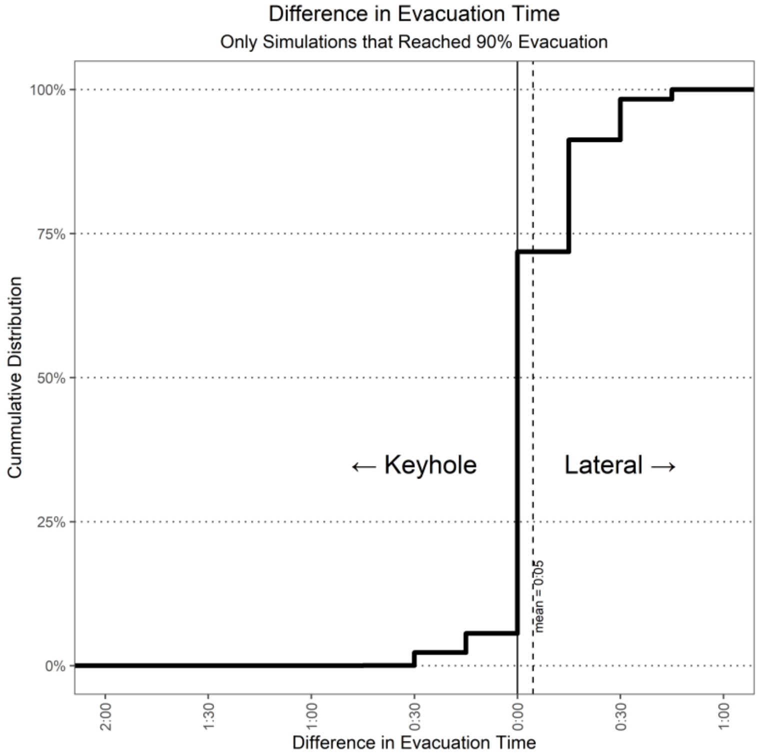


Figure 48: Comparison of evacuation time between Lateral and Keyhole evacuation strategies. Lateral evacuation times are longer than Keyhole in 30% of iterations. On average Lateral evacuation takes 5 minutes longer.

Current NRC guidance states, "*strategies that reduce evacuation time also reduce public health consequences*." [22] However, as discussed at length in previous chapters, ETE time should not be used alone to measure effectiveness. Evacuation time is at best a proxy for evacuation progress but does not provide any information related to the effectiveness of the evacuation relative to avoiding risk. As shown in Figure 47 and , a Lateral strategy results in longer evacuation times on average than a Keyhole strategy but avoids a more significant portion of potential dose to the populations. This provides some evidence that evacuation time cannot be the sole decision metric for selecting a protective action strategy, even between two effective strategies.



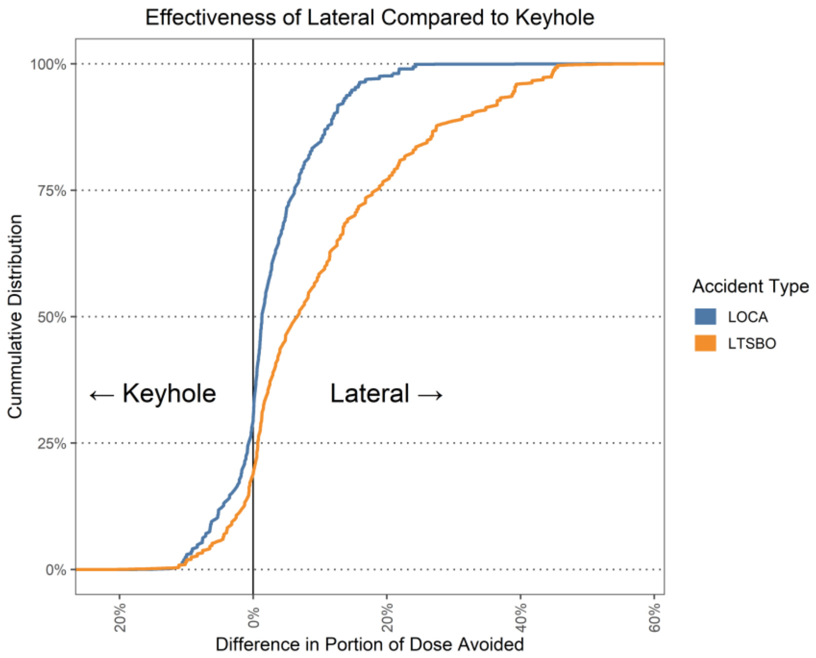


Figure 49: Comparison of portion of dose avoided between Lateral and Keyhole evacuation strategies relative to accident type

Figure 49 shows a Lateral protective action strategy is capable of avoiding a larger portion of dose than a Keyhole in 75-80% of simulations, depending on accident type. A Keyhole strategy provides comparatively better performance for a LOCA accident type than an LTSBO accident, but it does not change the overall preference to use a Lateral evacuation strategy. The selection of a Lateral strategy will not change if the accident type is not known during the decision-making process.

4 Conclusions

The integrated model provides insights and decision-making tools that are not available in other models. This allows for deeper insights than previously possible.

Several effects are quantified or identified in this case study that previously has not been described in the literature.

The source term in the form of radiation release, timing, and weather conditions are important for protective action decisions. The amount of head start that is possible before radiation release drastically affects the dose risk (i.e., LCF). A large portion of the dose can be avoided with only one hour of a head start. With three hours of a head start, all evacuation-type protective action strategies perform nearly identically relative to avoiding dose risk.

Public behavior can vary widely due to planning, event type, time of day, and other factors: consequences and the effectiveness of protective action strategies to reduce those consequences depending on public response. The variation in dose risk can be explained in part by head start, population subset, weather, and accident scenario. However, when each of these factors has been examined in prior sections, large variation remained. This underscores the effect behavior can have on risk in an emergency.

The variation in evacuation time in Figure 40 illustrates the effect behavioral uncertainty can have on ETEs for every protective action strategy. This uncertainty is currently reduced to a single value deterministic assumption in NRC guidance; 20% shadow evacuation. ETE survey responses should inform an understanding of site-specific behavior in the same way that vehicles per household are currently informed.

The primary decision metrics defined in chapter 4 are combined risk and robustness. The Lateral protective action strategy is preferred in both metrics (Sections 3.3.3 and 3.4) on average. In an emergency, the decision-maker would determine inputs that reflect the event to reduce the range of possible scenarios. This study utilizes 40 hazard dispersion scenarios. Distributions of combined risk for each of the hazard dispersion scenarios (accident type, wind speed, and stability class), separated by wind direction, are provided in Figure 51, Figure 52, Figure 53, and Figure 54 in the Appendix. The Lateral strategy is preferred in all of the hazard dispersion scenarios, illustrating that historically common protective action strategies (e.g., Radial, Keyhole) may not provide the most protection.

A key finding is that the combined dose and transportation risk for a specific protective action strategy can exceed the baseline LCF risk. Based on the insight gained in Section 3.3.3 from comparing combined risk to baseline LCF risk, the decision-maker should avoid a Radial, Staged, and Staged Lateral protective action strategy as they may increase the overall risk to the public.

While this study quantifies effects and presents recommendations for Peach Bottom NPP, the recommendations are not universally true. It is recommended that all emergency plans include an integrated consequence and protective action analysis to design evacuation plans that improve consequence reduction for that specific site.

5 Appendix – Chapter 6

5.1 RASCAL Simulations

RASCAL has two dispersion models, a Gaussian plume and a Lagrangian Gaussian puff model. The Gaussian plume model assumes a developed flow profile and cannot discretize the dose for each time-step. Therefore, the Lagrangian Gaussian puff model in RASCAL is used in the demonstration integrated model to retain time-step integrity.

The puff model is mapped into a Cartesian square grid, with grid width defined by the selected parameters. For use in the demonstration integrated model, the output dose is re-mapped from the Cartesian grid to the previously discussed polar grid for each time-step, using a separate tool. The re-mapped dose output is then imported into the dose exposure module.

5.1.1 RASCAL Parameters Output file for LOCA Scenario:

Case Summary

Event Type	Nuclear Power Plant
Case description	Modeling Run LOCA Delay: hr Wind Direction: 330 deg Wind Speed: 4 mph Stab: F
Location	Name: Peach Bottom - Unit 3 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 ft³
Design pressure: 56 lb/in²
Design leak rate: 0.50 %/d
Coolant mass: 1.73E+05 kg
Assemblies in core: 764

Source Term

Type: LOCA (NUREG-1465)
Shutdown: 2018/01/01 00:00
Core uncovered: 2018/01/01 00:00
Core damage estimated by: Core recovered status
Core recovered: No
Inventory: Default

Release Pathway

Type: BWR - Release Through Dry Well
via direct, unfiltered pathway
Release height: 100. ft

Release events
2018/01/01 00:00 Leak rate (% vol) Design
2018/01/01 00:00 Sprays Off

Meteorology

Type: Actual Observations
Dataset name: PEAC 2019-12-12 - 330 4 F
Dataset desc: Obs/fcsts for Peach Bottom - Unit 3

Summary of data at release point:	Type	Dir deg	Speed mph	Stab class	Precip	Temp °F
2018/01/01 00:00	Obs	330	4.0	F	?	---
2018/01/01 08:00	Obs	330	4.0	F	?	---

Dataset options: Est. missing stability using: Wind speed, time of day, etc.

Modify winds for topography: Yes

Calculations

Case title: LOCA-drywell-1-6hr-330deg-4mph-StabF
End of calculations: 2018/01/01 08:00
Start of release to atmosphere + 8 h
Distance of calculation: Close-in + to 25 miles
Close-in distances: 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0 miles
Analyst name: Dose Analyst
Inhal. dose coefficients: ICRP 60/72

5.1.2 *RASCAL parameter output file for LTSBO scenario:*

Case Summary

Event Type Nuclear Power Plant

Case description

Modeling Run
SOARCA
Delay: 6 hr
Wind Direction: 240 deg
Wind Speed: 12 mph
Stab: D

Location

Name: Peach Bottom - Unit 3
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 ft³
Design pressure: 56 lb/in²
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: 2018/01/01 00:00
Release from core starts: 2018/01/01 06:00
Core damage estimated by: Core recovered status
Core recovered: No
Inventory: Default

Release Pathway

Type: BWR - Release Through Dry Well
via direct, unfiltered pathway
Release height: 100. ft

Release events

2018/01/01 06:00	Leak rate (% vol) Design
2018/01/01 06:00	Sprays Off

Meteorology

Type: Actual Observations
Dataset name: PEAC 2018-12-16 - 240 12 D
Dataset desc: Obs/fcsts for Peach Bottom - Unit 3

Summary of data at release point:	Type	Dir deg	Speed mph	Stab class	Precip	Temp °F
2018/01/01 00:00	Obs	240	12.0	D	?	---
2018/01/01 08:00	Obs	240	12.0	D	?	---

Dataset options: Est. missing stability using: Wind speed, time of day, etc.

Modify winds for topography: Yes

Calculations

Case title: SOARCA-1-6hr-240deg-12mph-StabD
End of calculations: 2018/01/01 14:00
Start of release to atmosphere + 8 h
Distance of calculation: Close-in + to 25 miles
Close-in distances: 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0 miles
Analyst name: Dose Analyst
Inhal. dose coefficients: ICRP 60/72

5.1.3 RASCAL model scenarios

Table 25: weather and source term scenarios for use in rascal

Rascal_Run	Source Type	Wind Direction (Degrees From)	Wind Speed (mph)	Stability Class
1	LTSBO	330	4	B
2	LTSBO	330	4	F
3	LTSBO	330	8	D
4	LTSBO	330	8	F
5	LTSBO	330	12	D
6	LOCA	330	4	B
7	LOCA	330	4	F
8	LOCA	330	8	D
9	LOCA	330	8	F
10	LOCA	330	12	D
11	LTSBO	240	4	B
12	LTSBO	240	4	F
13	LTSBO	240	8	D
14	LTSBO	240	8	F
15	LTSBO	240	12	D
16	LOCA	240	4	B
17	LOCA	240	4	F
18	LOCA	240	8	D
19	LOCA	240	8	F
20	LOCA	240	12	D
21	LTSBO	150	4	B
22	LTSBO	150	4	F
23	LTSBO	150	8	D
24	LTSBO	150	8	F
25	LTSBO	150	12	D
26	LOCA	150	4	B
27	LOCA	150	4	F
28	LOCA	150	8	D
29	LOCA	150	8	F
30	LOCA	150	12	D
31	LTSBO	60	4	B
32	LTSBO	60	4	F
33	LTSBO	60	8	D
34	LTSBO	60	8	F
35	LTSBO	60	12	D
36	LOCA	60	4	B
37	LOCA	60	4	F
38	LOCA	60	8	D
39	LOCA	60	8	F
40	LOCA	60	12	D

5.2 Statistical Tests on distribution equivalence

Statistical distribution equivalence was tested using the Kolmogorov–Smirnov test (KS test) and the Wilcoxon test. The KS test is a non-parametric test to compare if samples are drawn from the same distribution by calculating the distributions' maximum distance. The Wilcoxon test is a non-parametric test that compares the distribution and median of two samples. The null hypothesis that the two samples were drawn from the same distribution is rejected if the p-value is less than 0.05. The ks.test and wilcox.test function in R provides a p-value of 0 if the estimated value is < 2.2e-16.

Portion (%) of avoided dose

	Strategy 1	Strategy 2	KS statistic	KS p-value	Wilcoxon W statistic	Wilcoxon p-value
1	Shelter	Radial	0.803300524	0	48142852	0
2	Shelter	Keyhole	0.796496888	0	51858184	0
3	Shelter	Lateral	0.940136489	0	5255395	0
4	Shelter	Staged	0.68357	0	145611493	0
5	Shelter	Staged Keyhole	0.800755985	0	49737860	0
6	Shelter	Staged Lateral	0.94747	0	4263127	0
7	Radial	Keyhole	0.021644173	1.08E-07	655833797	5.21E-11
8	Radial	Lateral	0.184241474	0	477838376	0
9	Radial	Staged	0.13566	0	747626604	0
10	Radial	Staged Keyhole	0.0081405	1.87E-05	643673696	3.19E-02
11	Radial	Staged Lateral	0.19637	0	460509093	0
12	Keyhole	Lateral	0.201685613	0	458399418	0
13	Keyhole	Staged	0.12214	0	731756374	0
14	Keyhole	Staged Keyhole	0.016868434	7.72E-05	625589244	9.96E-06
15	Keyhole	Staged Lateral	0.21443	0	441205860	0
16	Lateral	Staged	0.315758526	0	892533321	0
17	Lateral	Staged Keyhole	0.190785605	0	804007017	0
18	Lateral	Staged Lateral	0.024752	6.28E-10	617832497	4.95E-13
19	Staged	Staged Keyhole	0.12981	0	533110387	0
20	Staged	Staged Lateral	0.32648	0	368301646	0
21	Staged Keyhole	Staged Lateral	0.20187	0	454199025	0

5.3 Evacuation Time Validation

Comparison between the results from this chapter, a validated third-party evacuation model (RtePM), and prior ETE studies for Peach Bottom.

	LOW	HIGH
PEACH BOTTOM ETE [183]	2:15	3:10
RTE PM	3:00	3:30
THIS STUDY	Strategy dependent	See Figure 50

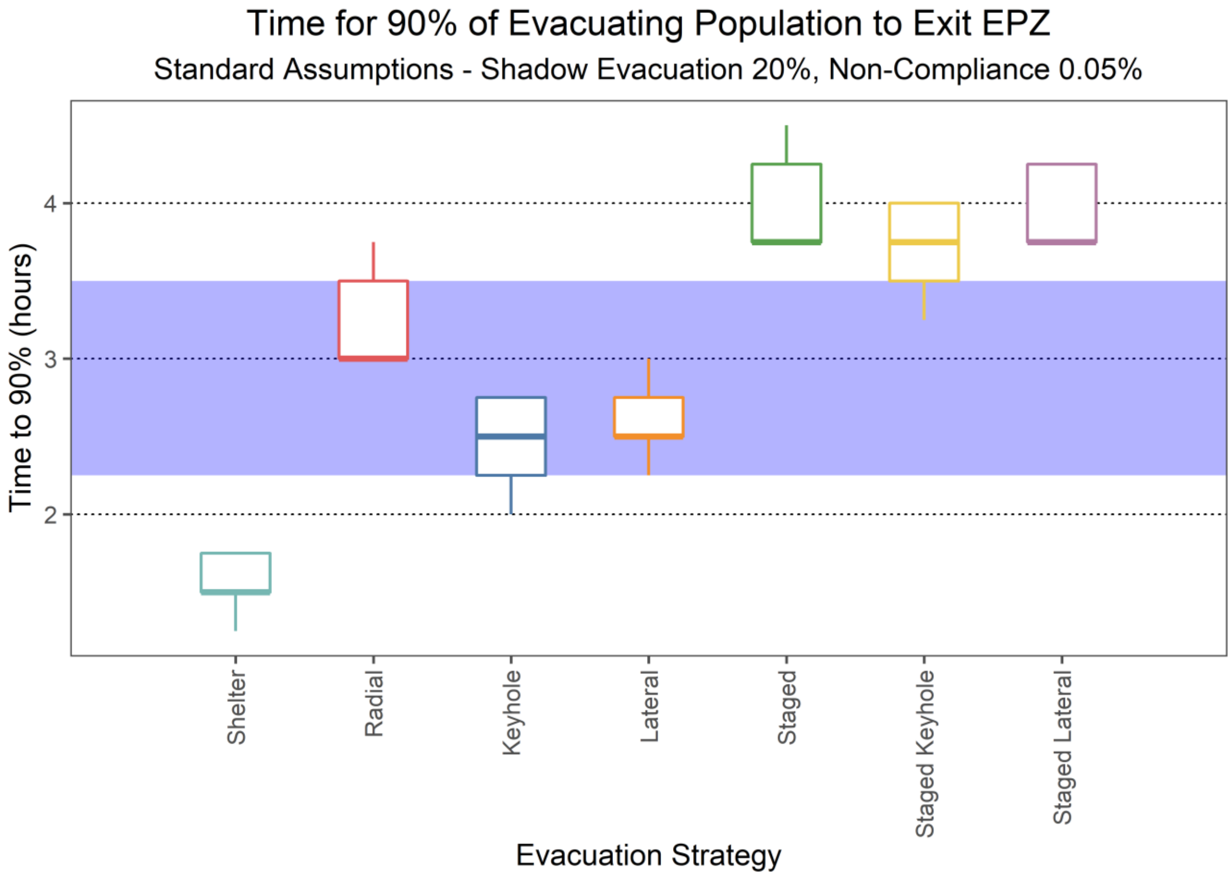
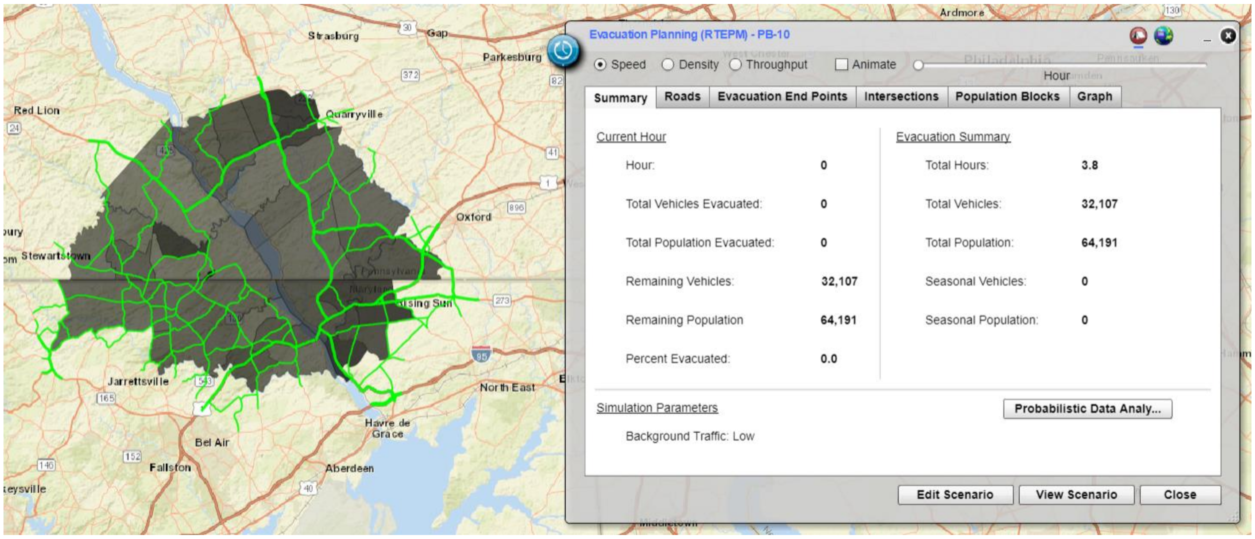


Figure 50: Resulting ETE from this analysis. Colored box indicates ETE range from other Peach Bottom ETE analyses

5.3.1 *Using RtePM*

RtePM is the Real-time evacuation Planning Model developed to provide evacuation time planning for any location using a web browser interface. The figures below show 0-4 hours of evacuation time in 1-hour time-steps. The settings used for this analysis are below the figures in

.



Evacuation Planning (RTEPM) - PB-10

● Speed ○ Density ○ Throughput ☐ Animate

Hour

Current Hour

Hour: 0

Total Vehicles Evacuated: 0

Total Population Evacuated: 0

Remaining Vehicles: 32,107

Remaining Population 64,191

Percent Evacuated: 0.0

Evacuation Summary

Total Hours: 3.8

Total Vehicles: 32,107

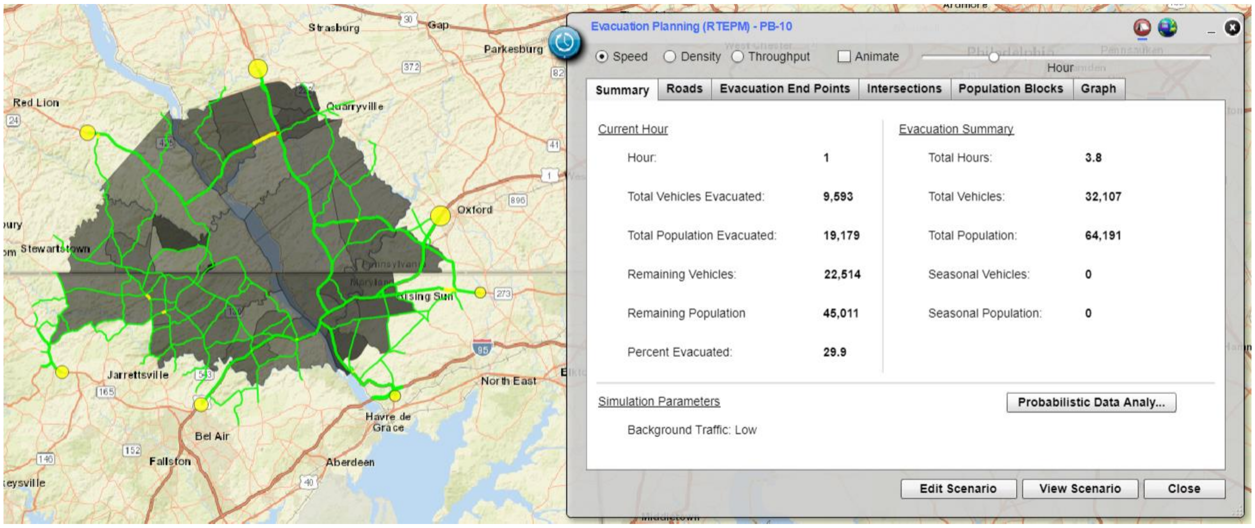
Total Population: 64,191

Seasonal Vehicles: 0

Seasonal Population: 0

Simulation Parameters

Background Traffic: Low



Evacuation Planning (RTEPM) - PB-10

● Speed ○ Density ○ Throughput ☐ Animate

Hour

Current Hour

Hour: 1

Total Vehicles Evacuated: 9,593

Total Population Evacuated: 19,179

Remaining Vehicles: 22,514

Remaining Population 45,011

Percent Evacuated: 29.9

Evacuation Summary

Total Hours: 3.8

Total Vehicles: 32,107

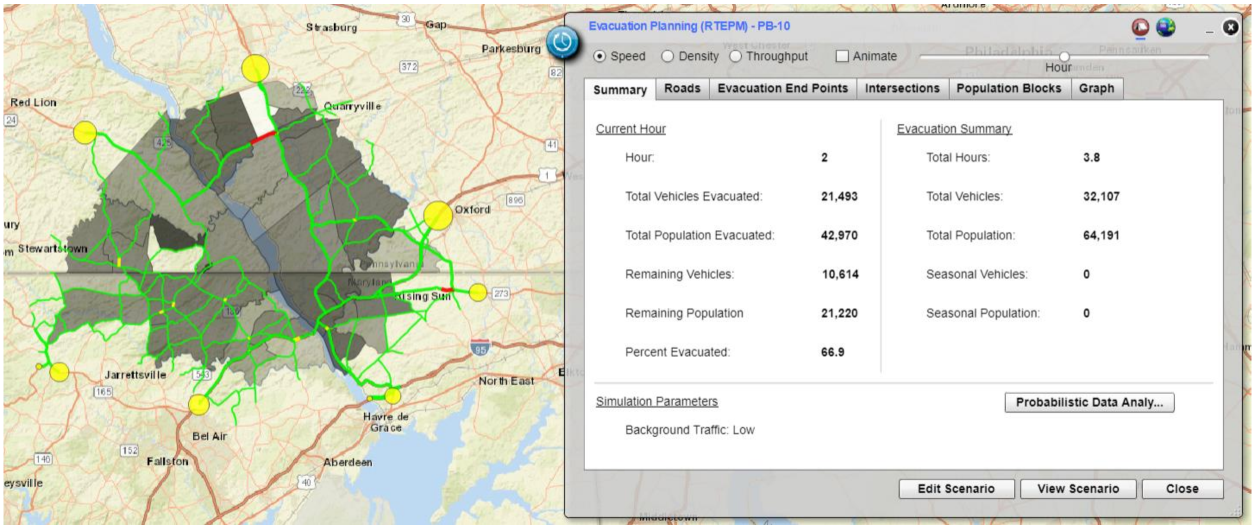
Total Population: 64,191

Seasonal Vehicles: 0

Seasonal Population: 0

Simulation Parameters

Background Traffic: Low



Current Hour

Hour: 2

Total Vehicles Evacuated: 21,493

Total Population Evacuated: 42,970

Remaining Vehicles: 10,614

Remaining Population: 21,220

Percent Evacuated: 66.9

Evacuation Summary

Total Hours: 3.8

Total Vehicles: 32,107

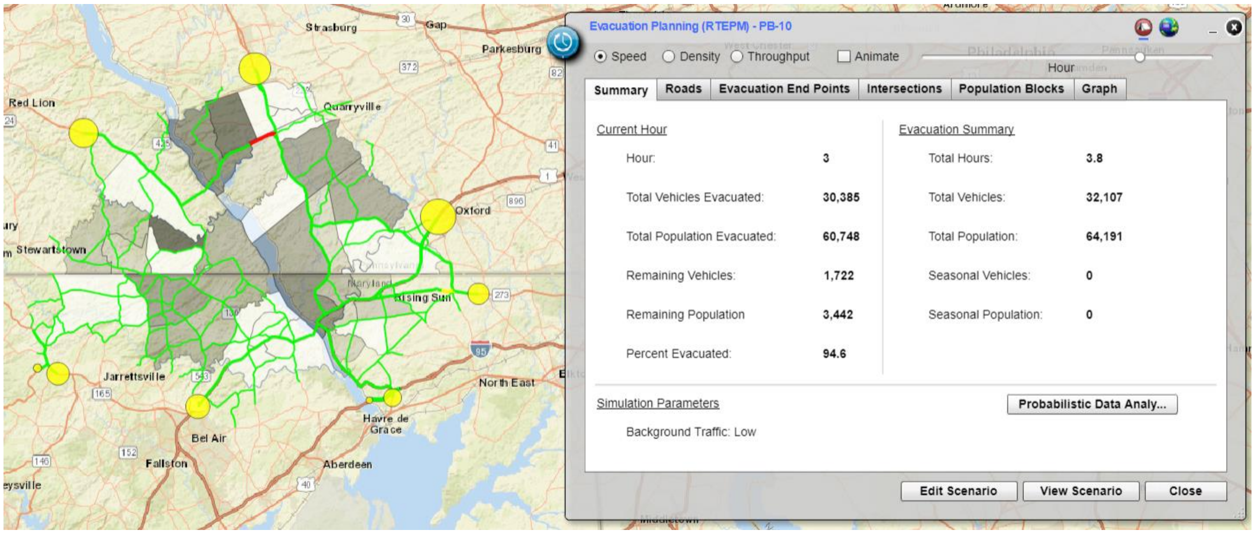
Total Population: 64,191

Seasonal Vehicles: 0

Seasonal Population: 0

Simulation Parameters

Background Traffic: Low



Current Hour

Hour: 3

Total Vehicles Evacuated: 30,385

Total Population Evacuated: 60,748

Remaining Vehicles: 1,722

Remaining Population: 3,442

Percent Evacuated: 94.6

Evacuation Summary

Total Hours: 3.8

Total Vehicles: 32,107

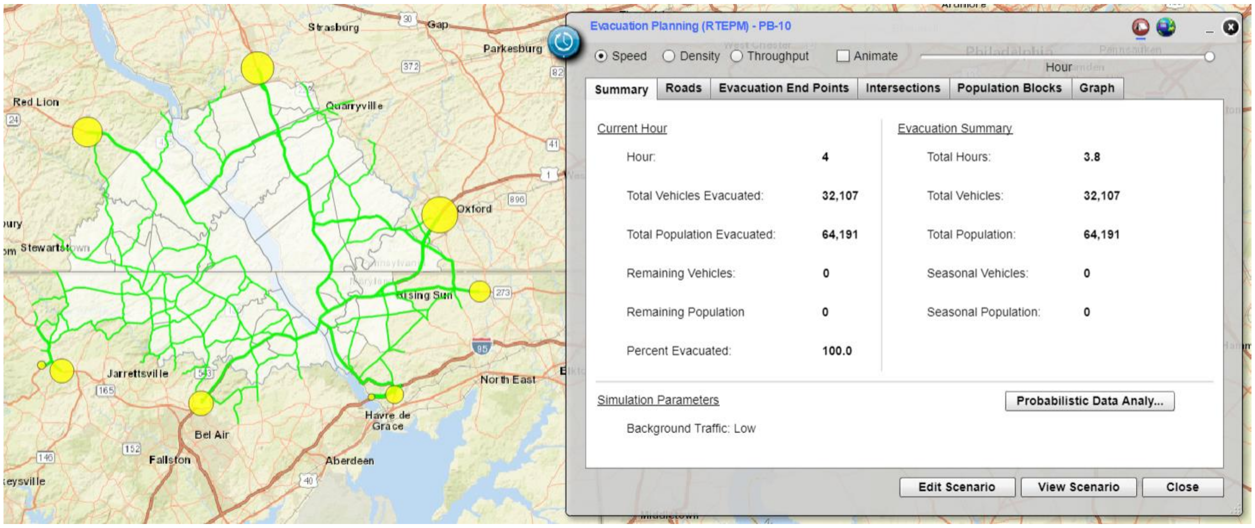
Total Population: 64,191

Seasonal Vehicles: 0

Seasonal Population: 0

Simulation Parameters

Background Traffic: Low



Current Hour

Hour: 4

Total Vehicles Evacuated: 32,107

Total Population Evacuated: 64,191

Remaining Vehicles: 0

Remaining Population: 0

Percent Evacuated: 100.0

Evacuation Summary

Total Hours: 3.8

Total Vehicles: 32,107

Total Population: 64,191

Seasonal Vehicles: 0

Seasonal Population: 0

Simulation Parameters

Background Traffic: Low

Table 26: RtePM model settings

RtePM Parameter	**Value**	**Technical rationale**
Level of detail	Regional Evacuation	The size and scope of the evacuation are not local.
Population blocks and evacuation zone	10-mile circular region center around Nuclear Power Plant	The EPZ is not perfectly represented by census blocks. The census blocks intersecting a 10-mile radius circle provides a good approximation of the EPZ boundary
Population change (%)	none	The base population reported for the RtePM census blocks bounded or bisected by the 10-mile circular EPZ totaled 64,191 compared to the Peach Bottom ETE 59,595. The increase is reasonable and associated with the additional census block area that is beyond the EPZ boundary but included in the approximation used in the RtePM analysis.
People per vehicle	2.0	The Peach Bottom ETE indicates a person/vehicle ratio of 1.83. Since RtePM will only accept increments of 0.5, the value was rounded to 2.0.
Vehicles towing (%)	0%	No towed vehicles are assumed in the evacuation.
% of population evacuating	99%	It is assumed that 0.5% of the EPZ population does not evacuate. RtePM only allows integer values for % of the population evacuating. Therefore, 99% was chosen.
% of evacuees to shelters	0%	Evacuee relocation to shelters was not assumed in this analysis and only the evacuation time for the population to reach the outer boundary of the EPZ was calculated.
% using private vehicles	98%	It is assumed that 1.5% of the EPZ population is transit-dependent. RtePM only allows integer values for % of using private vehicles. Therefore, 98% was chosen.
% using public transit	2%	It is assumed that 1.5% of the EPZ population is transit-dependent. RtePM only allows integer values for % of using public transit. Therefore, 2% was chosen.
% as pedestrians	0%	All evacuees were assumed to either evacuate with cars, buses, or other vehicular means.
Evacuation response	One Day 2-hour response	Initial mobilization time of approximately 2 hours is assumed in the Peach Bottom ETE
Additional Roads	None modeled	Additional roads were not added

Shelters	None modeled	Evacuee relocation to shelters was not assumed in this analysis and only the evacuation time for the population to reach the outer boundary of the EPZ was calculated.
Seasonal populations	None modeled	Seasonal population regions were not chosen on the RtePM map.
Population data source	Nighttime census	
Model Type	Probabilistic	Ten simulations were performed. All resulted in 100% evacuation in 3.7-3.8 hours.
Traffic incident modeling	Low rate	Populations tend to drive more cautiously during an evacuation, according to some studies. Additionally, the lack of congestion reduces opportunities for small accidents
Background traffic	Low	The Peach Bottom ETE indicates a maximum transient population of 5,700, less than 10% of the resident population

5.4 Results

This section contains additional information about the integrated model output.

5.4.1 Combined Risk for all-hazard dispersion (RASCAL) scenarios

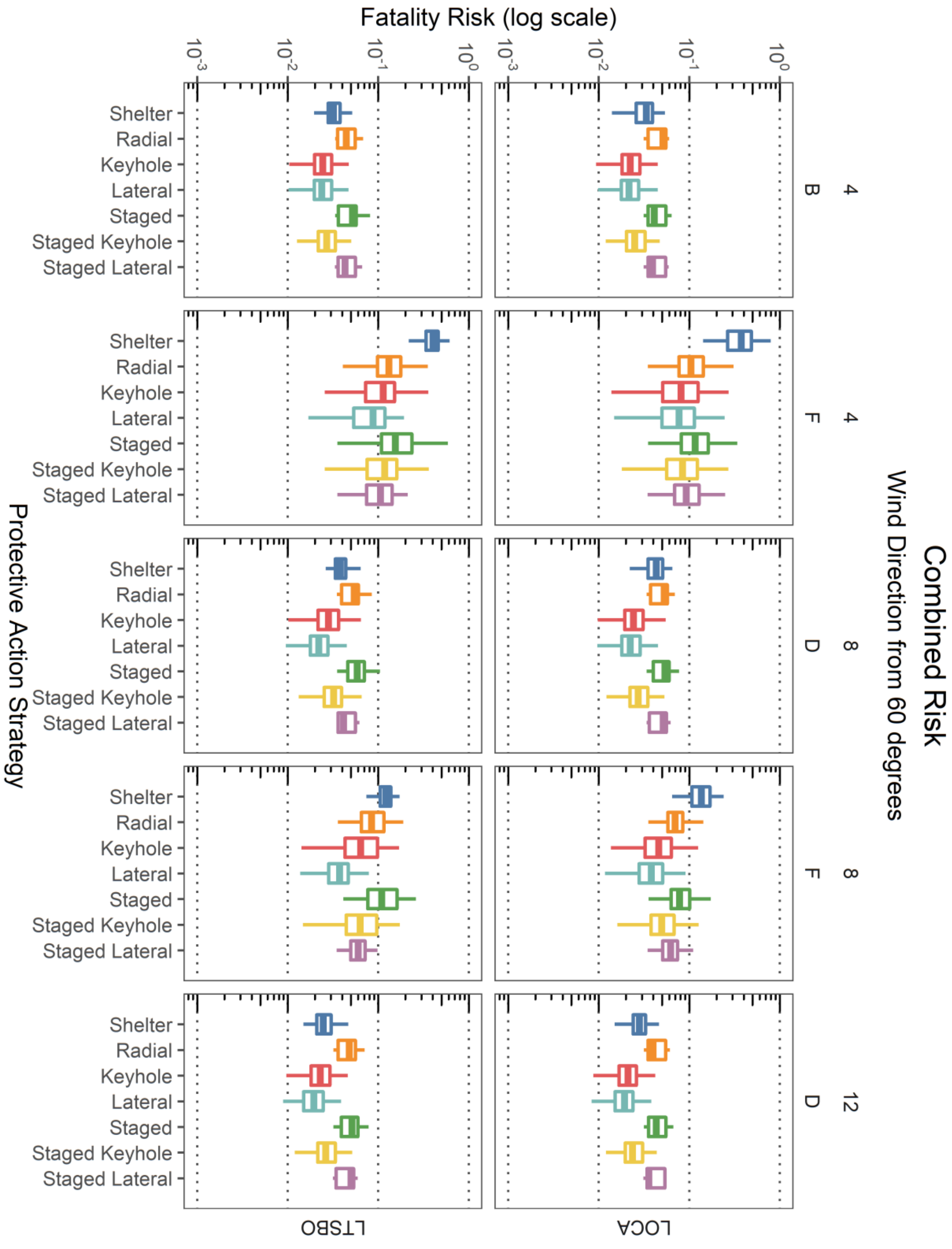


Figure 51: Combined risk for all weather scenarios with wind from 60 degrees

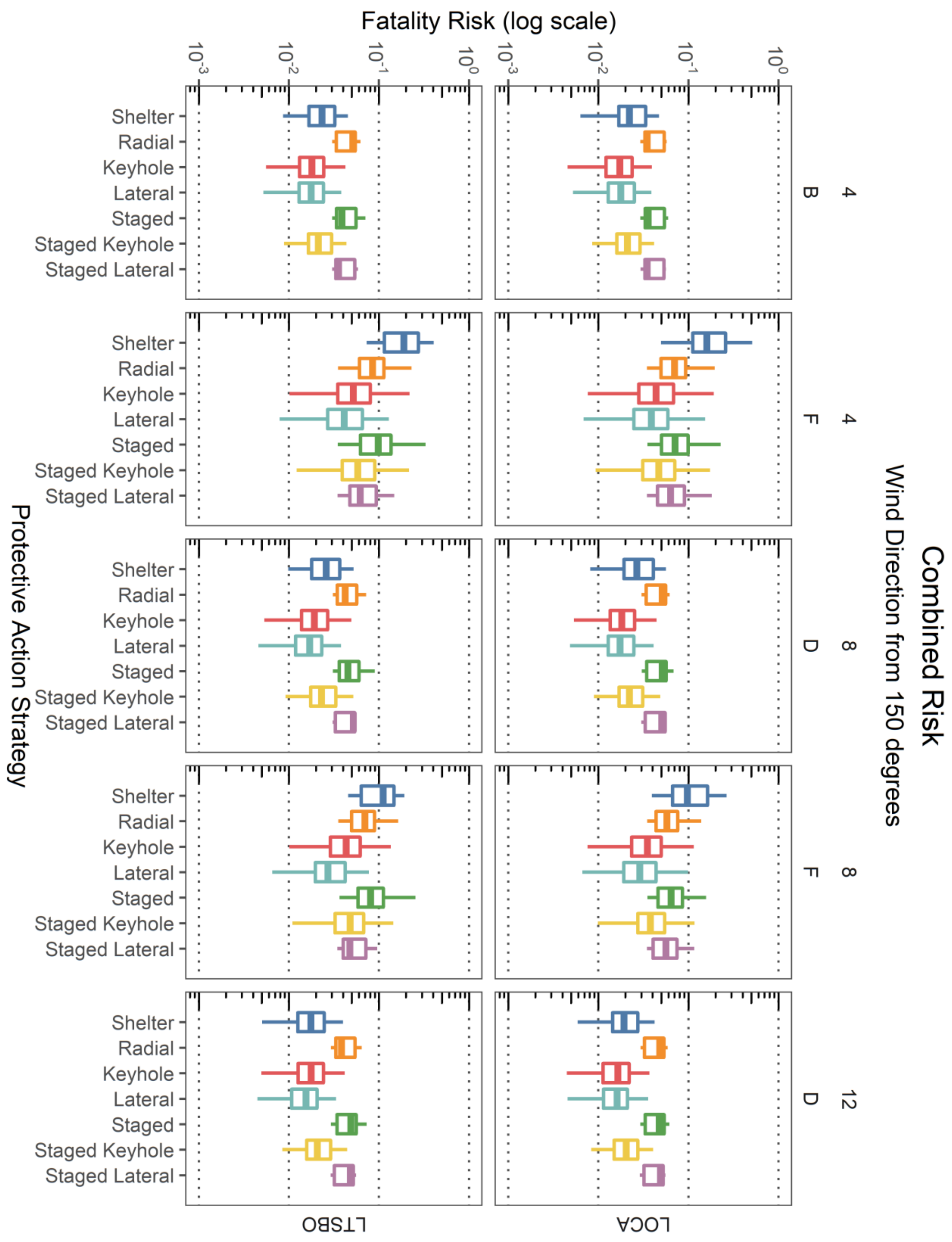


Figure 52: Combined risk for all weather scenarios with wind from 150 degrees

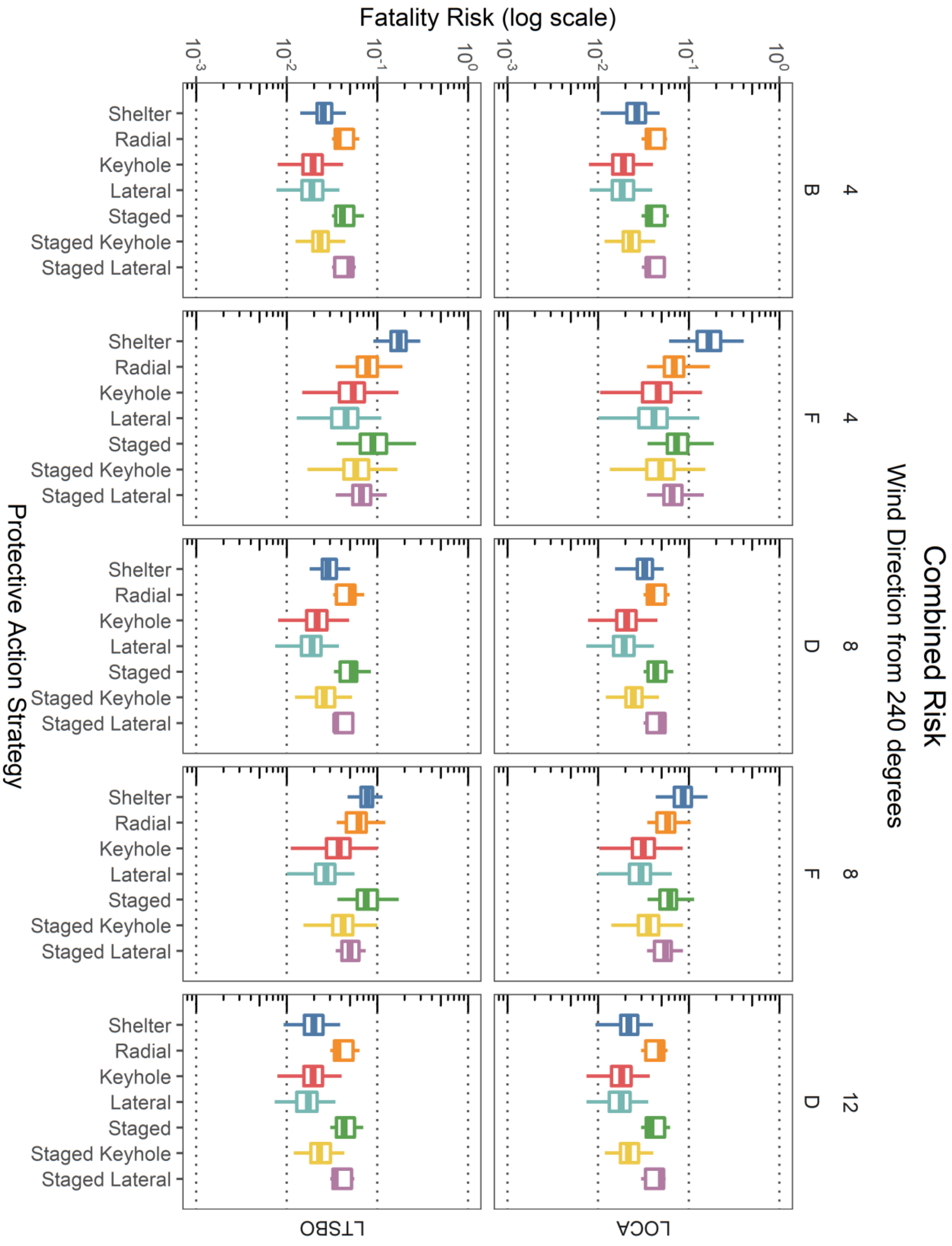


Figure 53: Combined risk for all weather scenarios with wind from 240 degrees

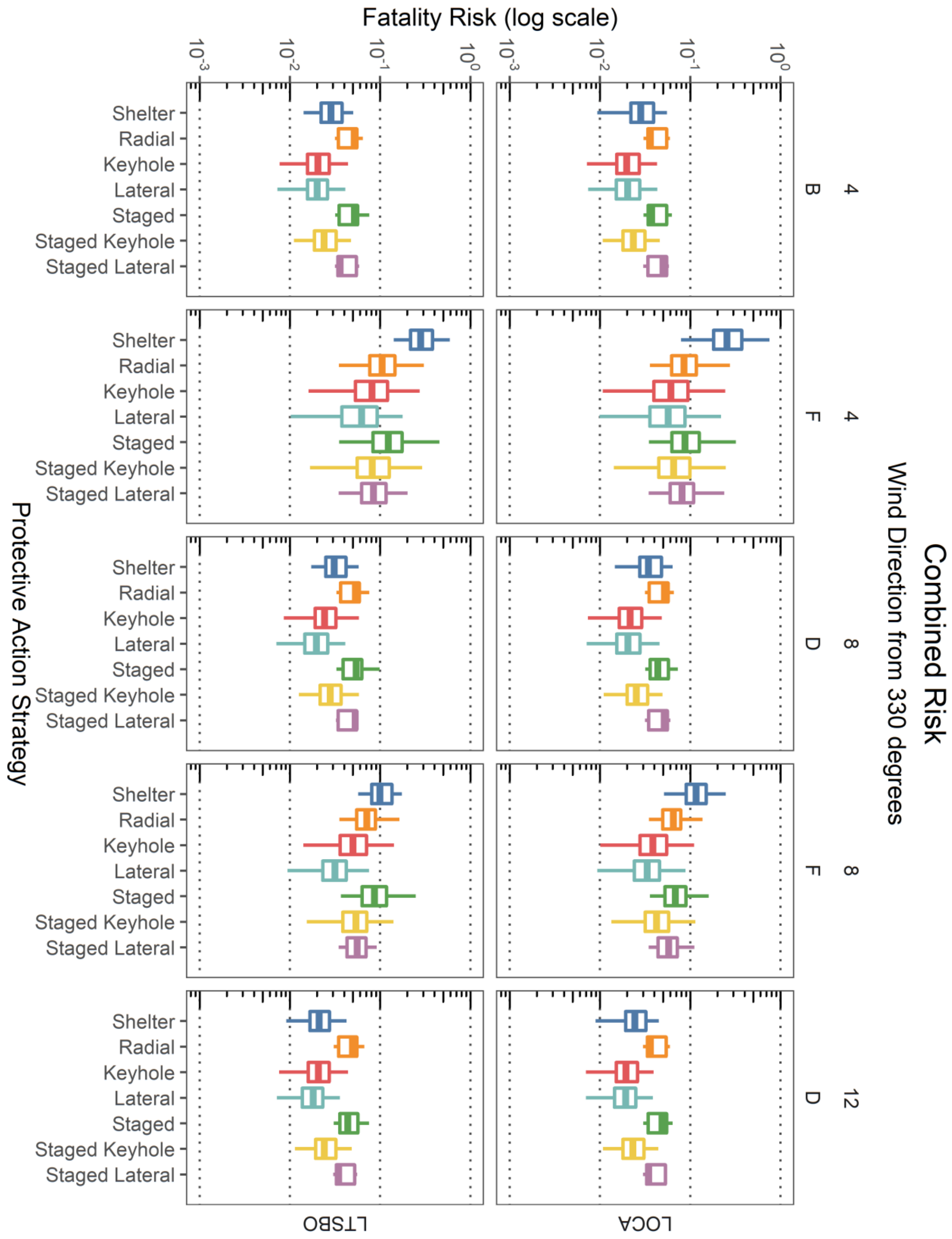


Figure 54: Combined risk for all weather scenarios with wind from 330 degrees

5.4.2 *Other Useful Figures*

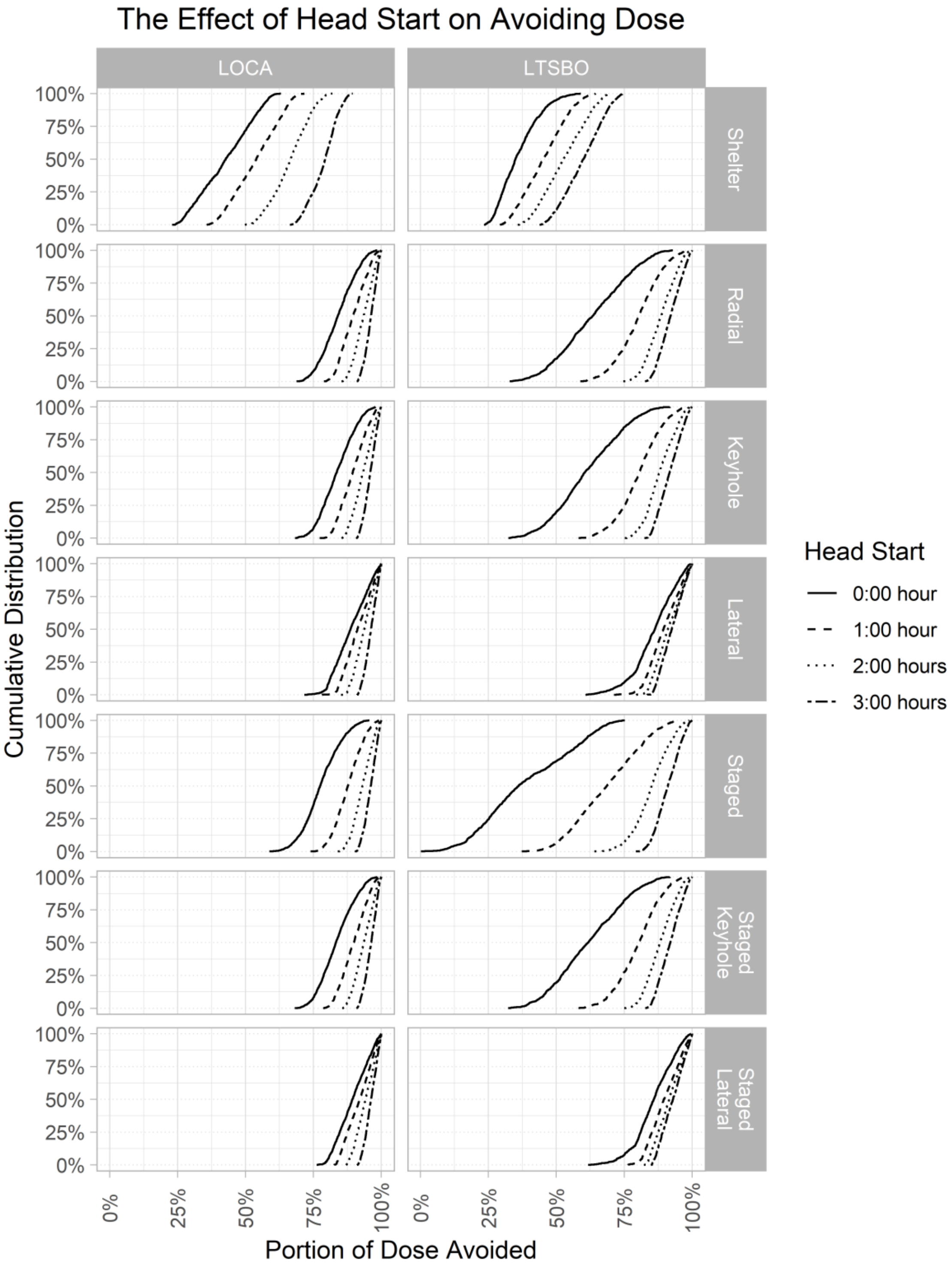


Figure 55: Portion of dose avoided by protective action strategy and amount of head start before radiation release

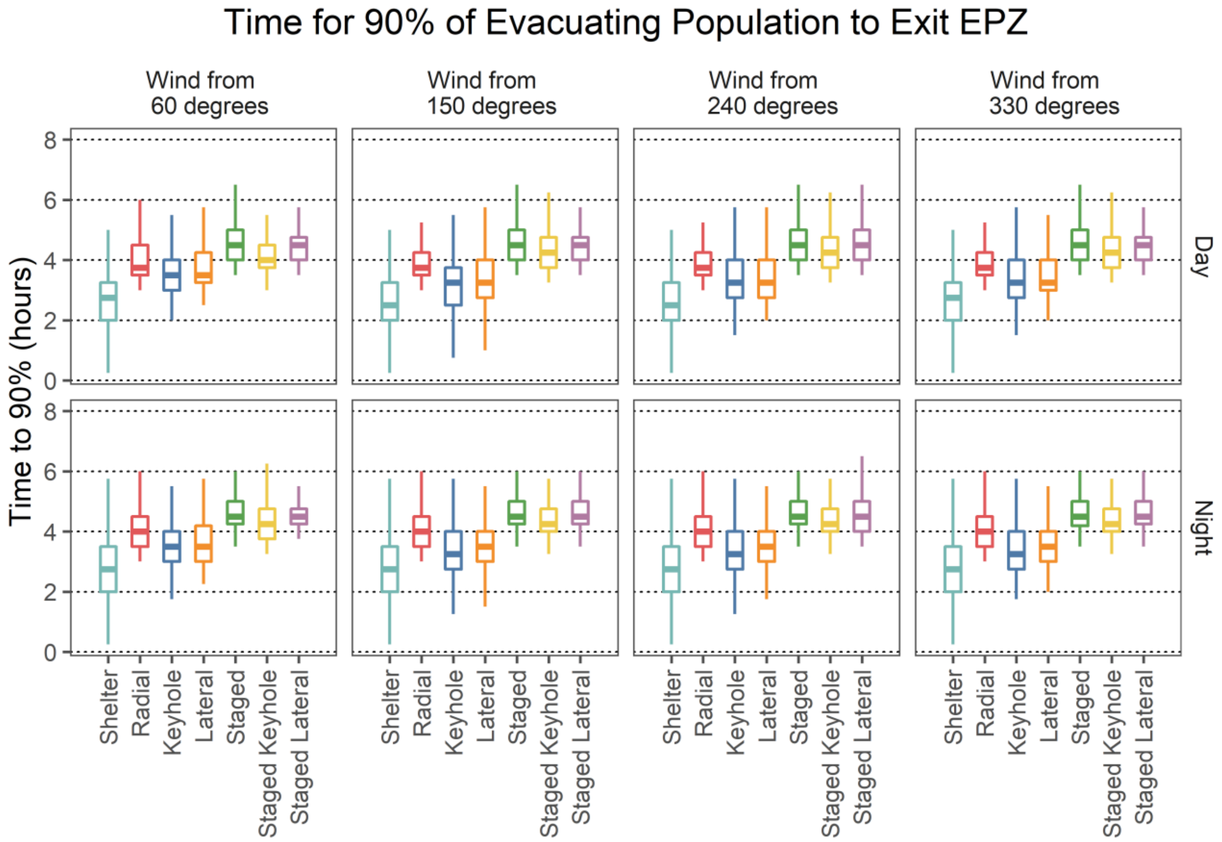


Figure 56: Evacuation time estimates for 90% clearance separated by population set in terms of time of day and spatial location.

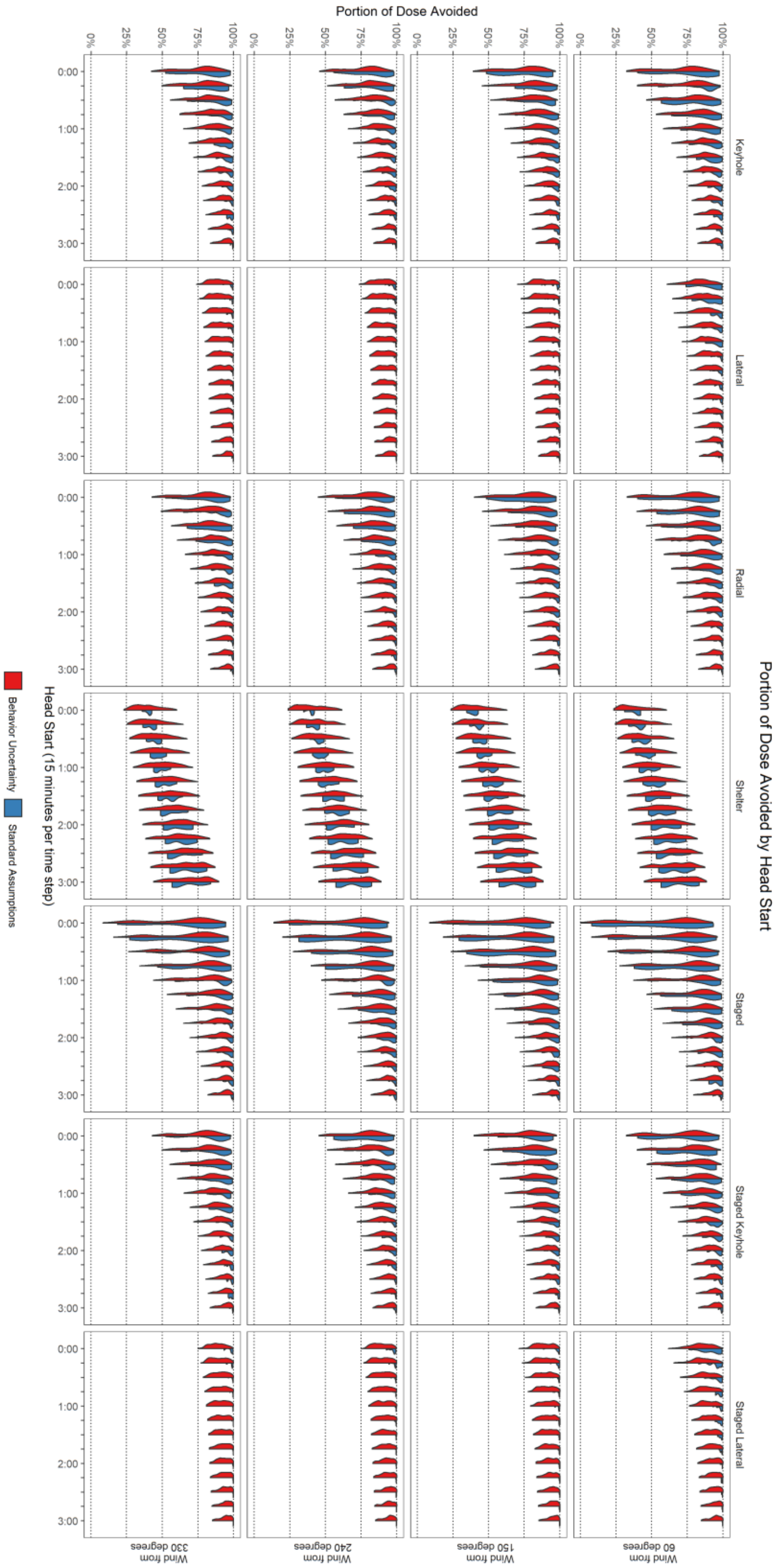
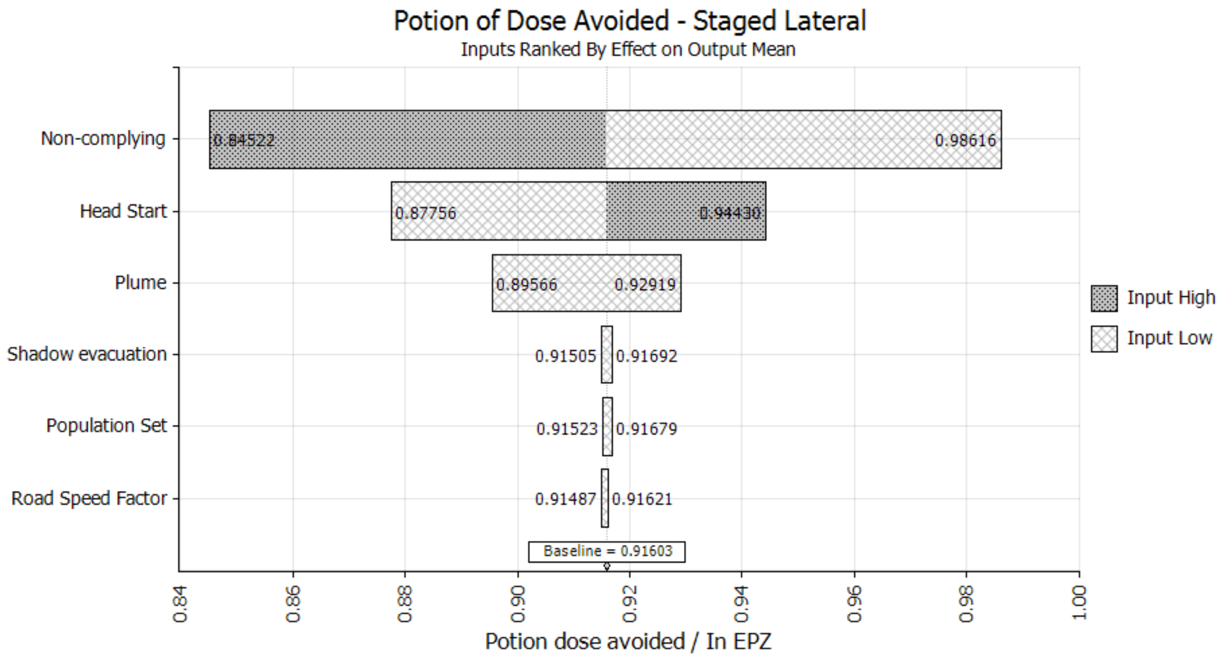
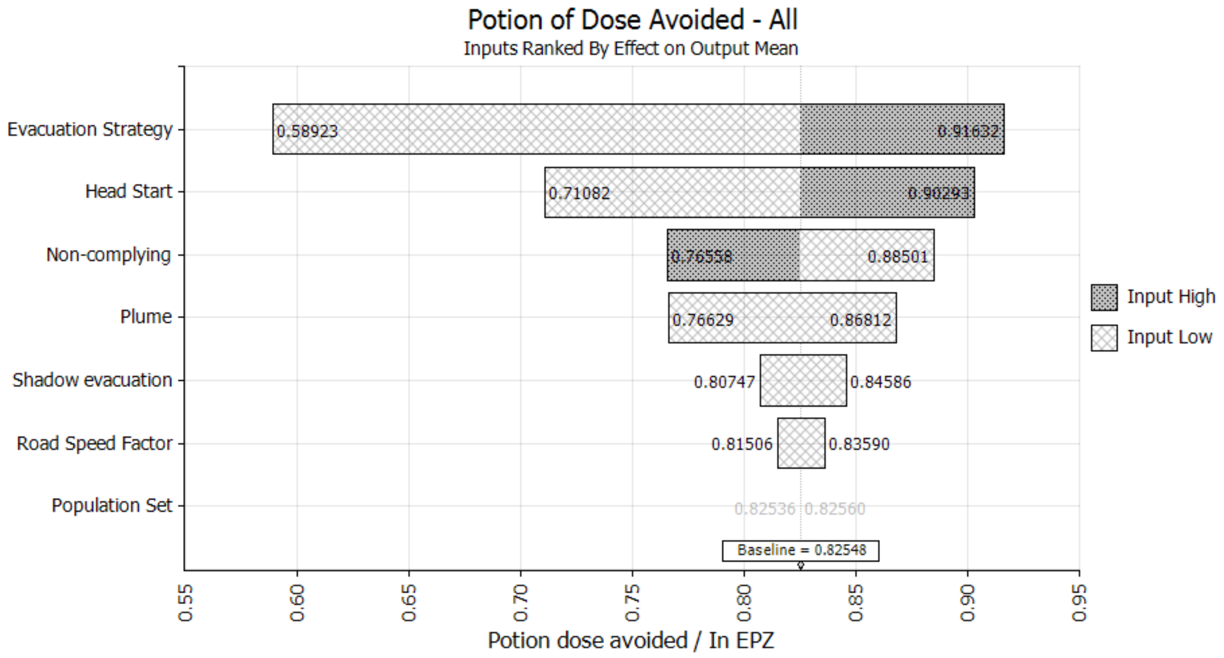
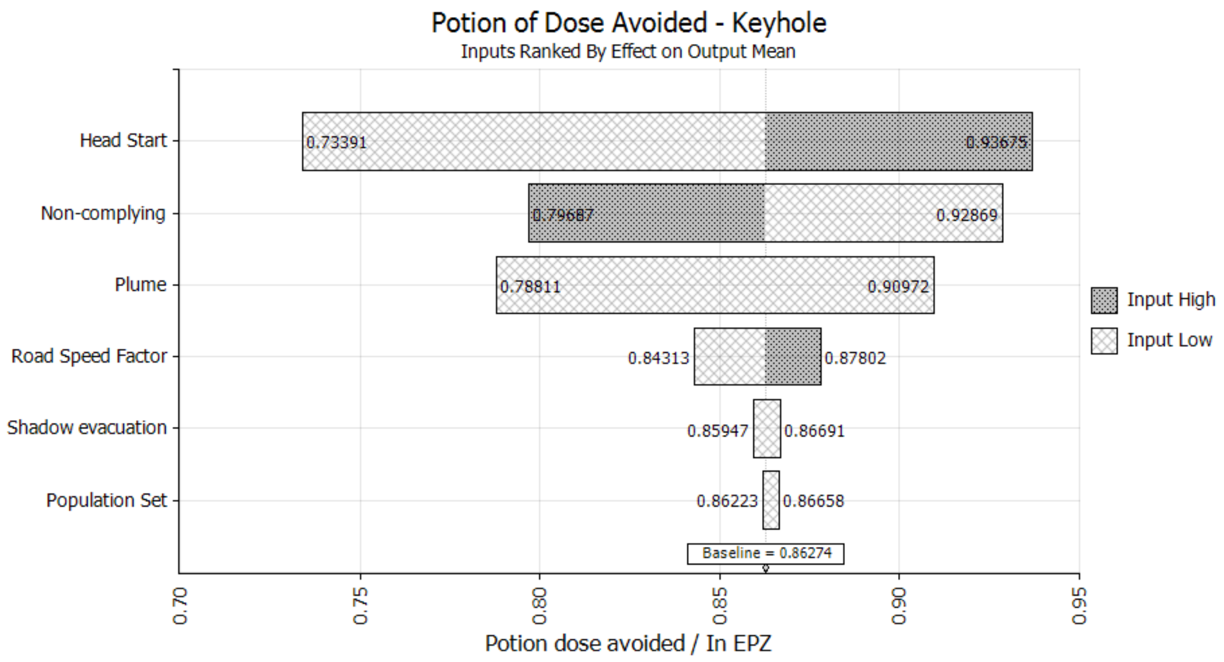
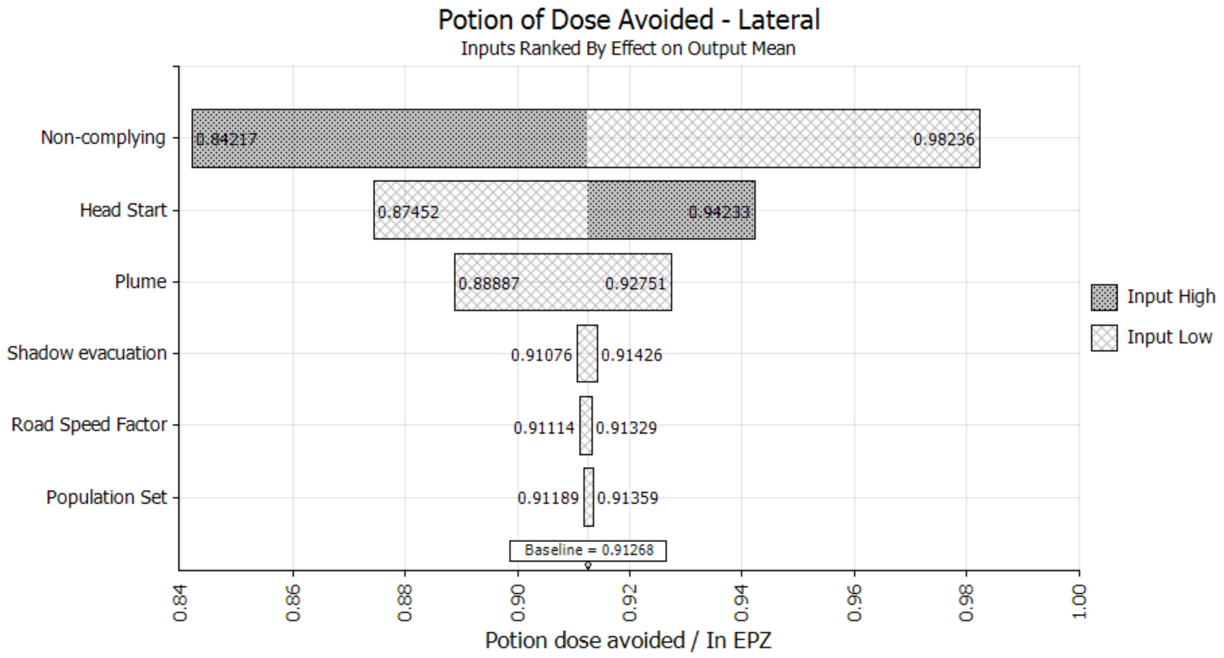


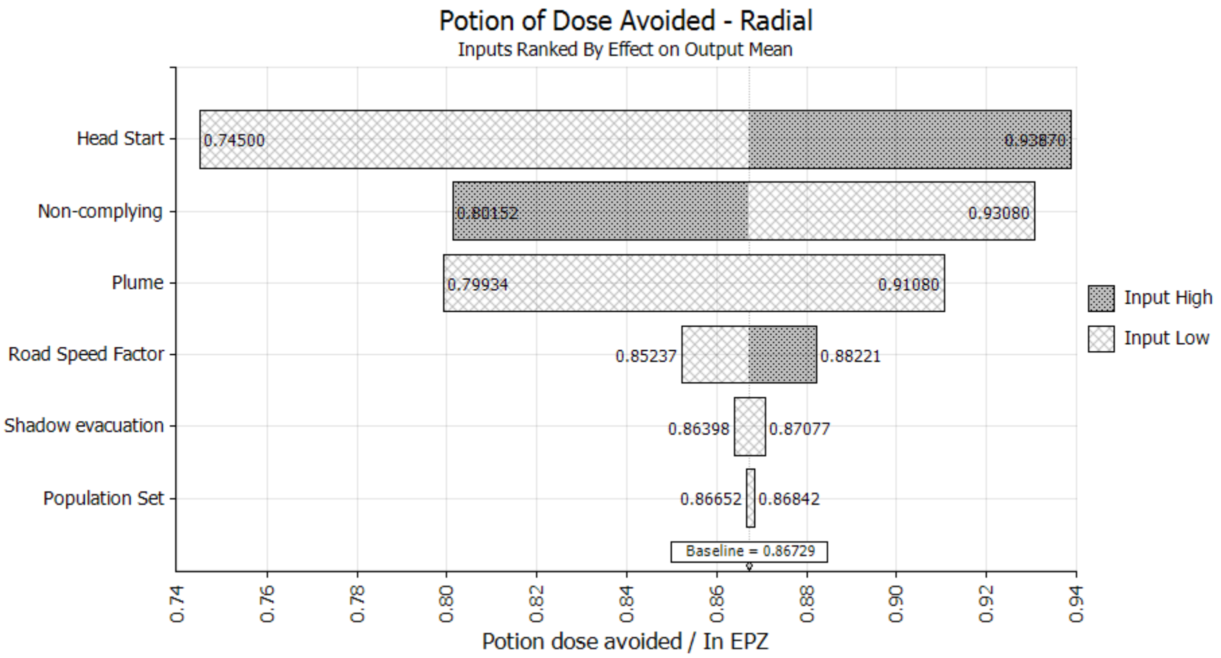
Figure 57: The Portion of dose avoided through the range of head start and separated by evacuation strategy and wind direction.

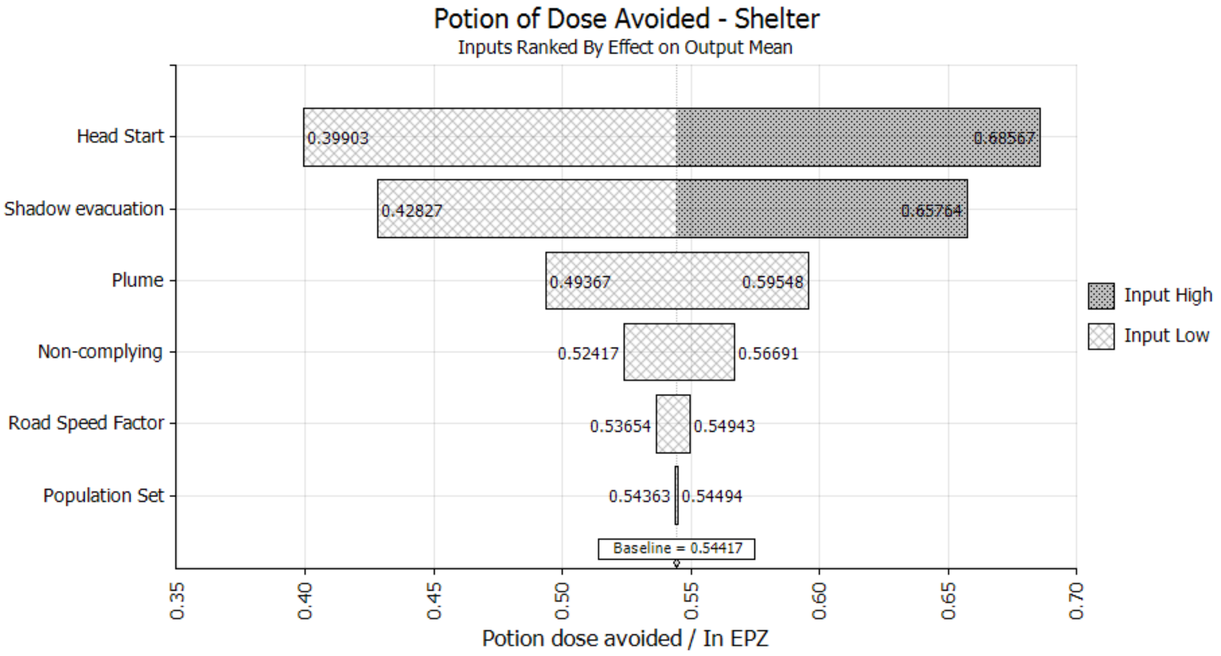

Potion of Dose Avoided - Staged Lateral
Inputs Ranked By Effect on Output Mean
Non-complying
0.84522
0.98616
Head Start
0.87756
0.94430
Plume
0.89566
0.92919
Shadow evacuation
0.91505
0.91692
Population Set
0.91523
0.91679
Road Speed Factor
0.91487
0.91621
Baseline = 0.91603
Input High
Input Low
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Potion dose avoided / In EPZ

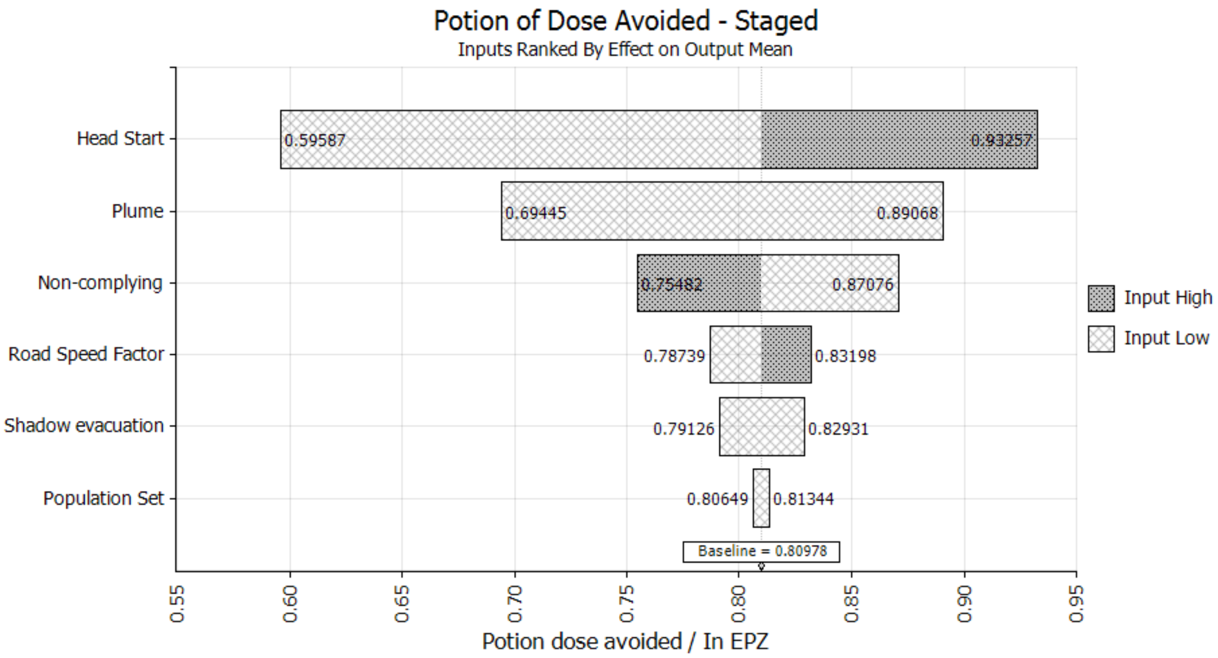

Potion of Dose Avoided - All
Inputs Ranked By Effect on Output Mean
Evacuation Strategy
0.58923
0.91632
Head Start
0.71082
0.90293
Non-complying
0.76558
0.88501
Plume
0.76629
0.86812
Shadow evacuation
0.80747
0.84586
Road Speed Factor
0.81506
0.83590
Population Set
0.82536
0.82560
Baseline = 0.82548
Input High
Input Low
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
Potion dose avoided / In EPZ

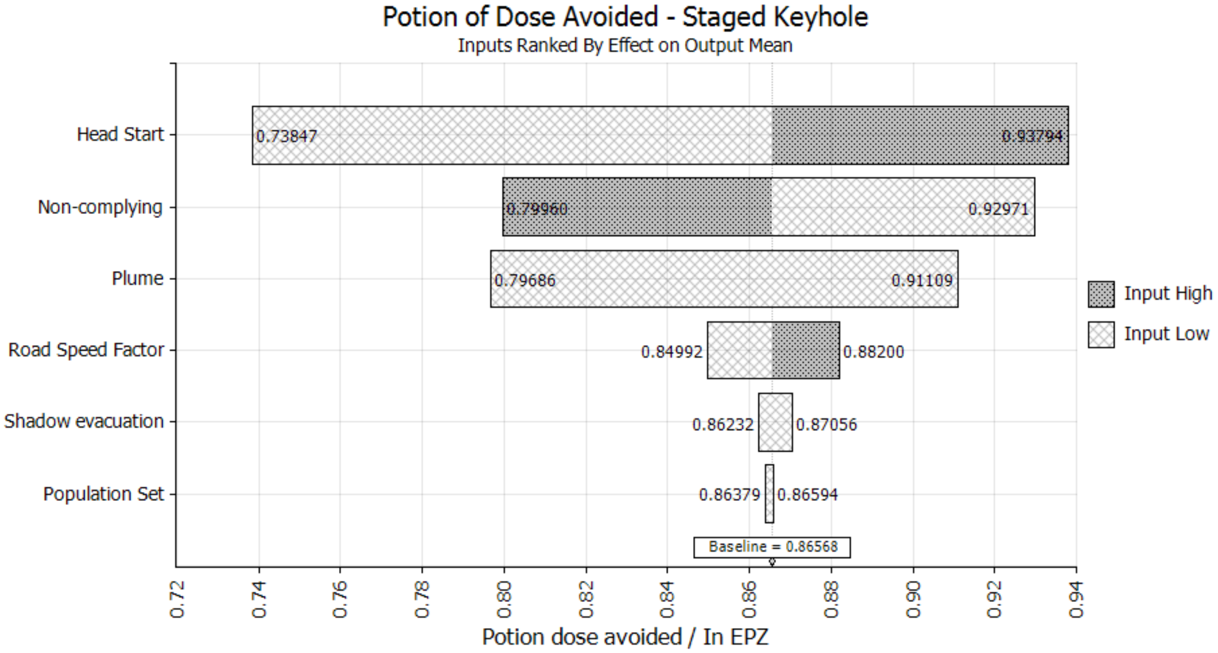

Potion of Dose Avoided - Keyhole
Inputs Ranked By Effect on Output Mean
Head Start
0.73391
0.93675
Non-complying
0.79687
0.92869
Plume
0.78811
0.90972
Road Speed Factor
0.84313
0.87802
Shadow evacuation
0.85947
0.86691
Population Set
0.86223
0.86658
Baseline = 0.86274
Input High
Input Low
0.70
0.75
0.80
0.85
0.90
0.95
Potion dose avoided / In EPZ


Potion of Dose Avoided - Lateral
Inputs Ranked By Effect on Output Mean
Non-complying
0.84217
0.98236
Head Start
0.87452
0.94233
Plume
0.88887
0.92751
Shadow evacuation
0.91076
0.91426
Road Speed Factor
0.91114
0.91329
Population Set
0.91189
0.91359
Baseline = 0.91268
Input High
Input Low
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Potion dose avoided / In EPZ


Potion of Dose Avoided - Radial
Inputs Ranked By Effect on Output Mean
Head Start
0.74500
0.93870
Non-complying
0.80152
0.93080
Plume
0.79934
0.91080
Road Speed Factor
0.85237
0.88221
Shadow evacuation
0.86398
0.87077
Population Set
0.86652
0.86842
Baseline = 0.86729
Input High
Input Low
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
Potion dose avoided / In EPZ


Potion of Dose Avoided - Shelter
Inputs Ranked By Effect on Output Mean
Head Start
0.39903
0.68567
Shadow evacuation
0.42827
0.65764
Plume
0.49367
0.59548
Non-complying
0.52417
0.56691
Road Speed Factor
0.53654
0.54943
Population Set
0.54363
0.54494
Baseline = 0.54417
Input High
Input Low
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
Potion dose avoided / In EPZ


Potion of Dose Avoided - Staged
Inputs Ranked By Effect on Output Mean
Head Start
0.59587
0.93257
Plume
0.69445
0.89068
Non-complying
0.75482
0.87076
Road Speed Factor
0.78739
0.83198
Shadow evacuation
0.79126
0.82931
Population Set
0.80649
0.81344
Baseline = 0.80978
Input High
Input Low
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
Potion dose avoided / In EPZ


Potion of Dose Avoided - Staged Keyhole
Inputs Ranked By Effect on Output Mean
Head Start
0.73847
0.93794
Non-complying
0.79960
0.92971
Plume
0.79686
0.91109
Road Speed Factor
0.84992
0.88200
Shadow evacuation
0.86232
0.87056
Population Set
0.86379
0.86594
Baseline = 0.86568
Input High
Input Low
0.72
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
Potion dose avoided / In EPZ

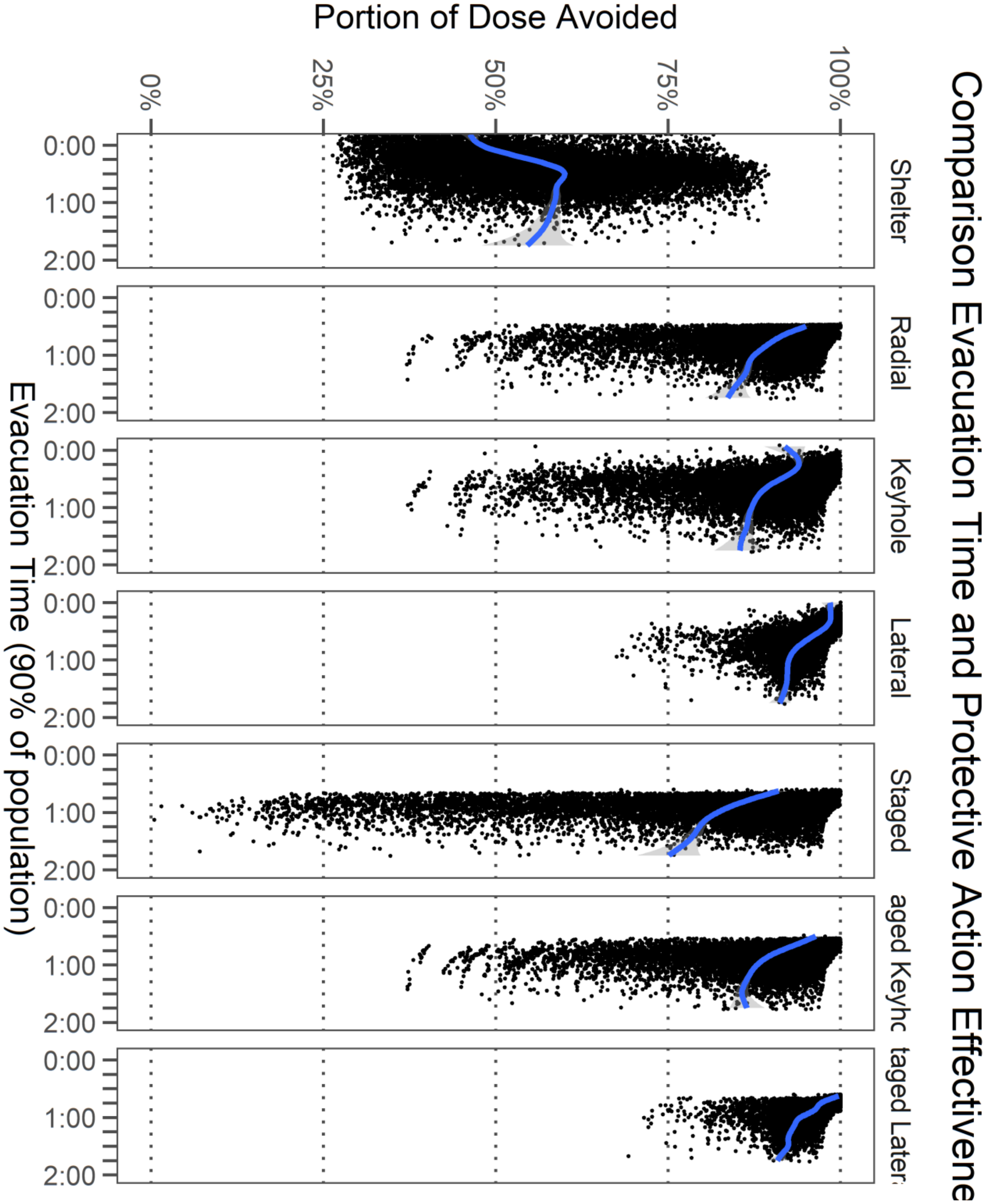


Figure 58: Portion of dose avoided vs. evacuation time with a lowess smoothed curve

The effect suggests that reducing evacuation time reduces risk in general. However, a linear downward slope is not present. Additionally, large variations exist between protective action strategies and within the mid-range of each strategy.

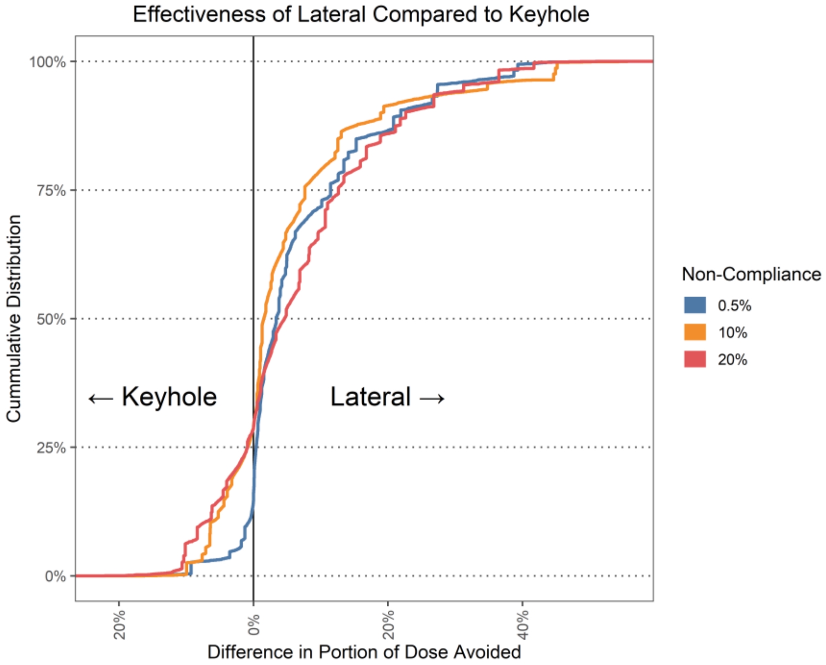


Figure 59: Comparison of portion of dose avoided between Lateral and Keyhole evacuation strategies relative to population compliance

The effectiveness of protective action strategies can have a complex interaction with levels of non-compliance. As shown in Figure 59, a 0.5% and 20% level of non-compliance avoids a more significant portion of the dose than a 10% level. This suggests that there is a point between 0.5% and 20% where the effect of moving the population away from the risk and balanced against reducing congestion.

Chapter 7: Conclusion

The Nuclear Regulatory Commission and the nuclear industry is undergoing a transformation. The Nuclear Regulatory Commission (NRC) has shifted to a risk-informed and performance-based approach to adapt. Many regulations related to safety and licensing have been updated or are in the process of being updated.

Emergency planning is critical for the effective protection of the public in an emergency and a requirement for nuclear power plant licensing. Some regulations related to emergency planning specifically, such as emergency planning zone size and distance to population centers, are in the process of being updated to risk-informed standards. However, guidance and methods related to emergency response are lagging. Instead of building on the extensive and useful for of the State-of-the-Art Reactor Consequences Analysis (SOARCA) project, the approach to emergency planning and response remains entrenched in discipline-specific practices that use deterministic rules to make protective action decisions. New guidance was published in 2020 that furthers the discipline-specific traffic modeling approach to emergency response planning, without consideration of being risk-informed or performance-based.

Chapter 2 identified the current regulations associated with emergency response, current evacuation modeling practices and discussed the value and limitations of the SOARCA project. The key takeaway is that emergency planning and response currently does not have a method or tool available for risk analysis. In addition, uncertainty needs to be considered with all factors but is especially unsatisfactory related to the populations' behavioral response. There are many technologies available for emergency response that are not considered in NRC guidance or emergency response research, such as geo-targeted wireless emergency alert warning messages, real-time traffic information, social media, and navigation software.

Some of the computer models used for emergency planning are outdated. Other models cannot be easily used as replacements because they are not validated as providing correct results. This creates a need to apply the existing outdated or limited functionality models that are already validated to new use cases that they were not designed to handle. Chapter 3 provides a framework to select an analysis method for computer codes. While the motivation was due to the limited functionality codes for emergency planning, this framework is broadly applicable to most computer modes. A case study using the ARCON96 emergency planning code is provided, and results are useful for reduced size emergency planning zone analysis.

An interdisciplinary approach is needed to identify and model all of the critical and interactive components of an emergency and response. Chapter 4 provides that framework. Additionally, three decision metrics are introduced as new tools for evaluating emergency response in a risk-based, instead of time-based, context. One of these metrics is the total risk of a protective action, including dose and non-dose (i.e., transportation) risk. A robustness metric is used to determine the portion of model iterations (under uncertainty) one protective action dominates the other simulated protective actions. Finally, a decision metric that combines the other two metrics is provided.

To this point, previous chapters have identified challenges and limitations and then provided frameworks to build a solution. Chapter 5 takes the previous work and builds that solution in the form of an integrated model, as introduced in Chapter 2. This model provides the capability to evaluate the risk and consequences of a nuclear power plant accident, determine the effectiveness of protective actions at mitigating the risk, and compare the protective actions to select a specific strategy. The model provides an interdisciplinary approach by including multiple factors to simulate behavioral response, communication, transportation, and risk. The model uses a Monte Carlo approach to explore possible outcomes across a range of inputs and uncertainty. The model has a very short runtime, making it capable of use for decision-making during an emergency, not just for pre-planning.

Chapter 6 provides a case study of the well-studied Peach Bottom Atomic Power Stations. Several important insights emerged from the analysis. First, when combined dose and non-dose risks are considered, many historically common protective action strategies become inadvisable by creating more combined risk than taking no action. Second, the amount of head start the population has to evacuate prior to the initial release of radiation significantly impacts risk. With just three hours of head start, all protective action strategies are essentially equivalent at avoiding dose risk. Third, behavioral uncertainty accounts for a large portion of the variation in the results. Including behavioral uncertainty in emergency planning models is necessary to make informed decisions. The current NRC standard assumptions are not sufficient for this role. Several factors that are typically considered important in traffic models, such as reduced roadway capacity, had little impact on risk relative to other factors. Finally, in the event of an actual emergency, the decision-maker would have information (e.g., accident type, wind direction) that be used to reduce the potential decision space. Model inputs should be defined to reflect the conditions present to provide more informative results. While this chapter quantifies effects and presents recommendations for Peach Bottom NPP, the recommendations are not universally true. It is recommended that all emergency plans include an integrated consequence and protective action analysis to design evacuation plans that improve consequence reduction for that specific site.

A substantial amount of research and regulatory work needs to be done to move nuclear power plant emergency planning and response from deterministic thresholds and general best practices to be risk-informed performance-based. Shifting to this new approach is more important than simply updating old methods to current. It can lead to better, more informed decision-making and potentially could save lives. The compendium of chapters presented here provides the first six steps in that direction and a basis for more to come.

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