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THESIS

REDUCING THE POTENTIAL CONSEQUENCES OF NUCLEAR POWER USING SMALL MODULAR REACTORS

by

Scott Corbin

March 2019

Co-Advisors: Glen L. Woodbury
Thomas J. Mackin (contractor)

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In order for commercial nuclear power to remain successful in the United States, several things need to occur: advancement of newer technologies and replacement of aging infrastructure with a new generation of safe reactors that are reliable, adaptable to the environment, cost-effective, and energy efficient to meet the nation’s energy demands into the future. To accomplish this, the United States must be able to identify true risk rather than the perceived risk of civilian nuclear power and have solutions to manage it. Risk management includes reducing the U.S. carbon footprint, which is contributing to global warming. The nation also must find a way to close the loop on nuclear waste through reprocessing and recycling. Furthermore, by reducing their size as compared to existing commercial power plant operations, the United States can locate new plants where energy is most needed. Finally, this thesis demonstrates how the potential consequences of a nuclear plant accident can be reduced to acceptable levels through the use of small modular reactors.

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REDUCING THE POTENTIAL CONSEQUENCES OF NUCLEAR POWER USING SMALL MODULAR REACTORS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF ARTS IN SECURITY STUDIES
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ABSTRACT

In order for commercial nuclear power to remain successful in the United States, several things need to occur: advancement of newer technologies and replacement of aging infrastructure with a new generation of safe reactors that are reliable, adaptable to the environment, cost-effective, and energy efficient to meet the nation's energy demands into the future. To accomplish this, the United States must be able to identify true risk rather than the perceived risk of civilian nuclear power and have solutions to manage it. Risk management includes reducing the U.S. carbon footprint, which is contributing to global warming. The nation also must find a way to close the loop on nuclear waste through reprocessing and recycling. Furthermore, by reducing their size as compared to existing commercial power plant operations, the United States can locate new plants where energy is most needed. Finally, this thesis demonstrates how the potential consequences of a nuclear plant accident can be reduced to acceptable levels through the use of small modular reactors.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACA	Arms Control Association
AEA	Atomic Energy Act
CDF	core damage frequency
CR	Clinch River
DBA	design-based accident
DEW	distant early warning (line)
EA	exclusion area
EDE	effective dose equivalent
EF	early fatality
EIS	environmental impact statement
EPZ	emergency planning zone
ERA	Energy Reorganization Act
FEMA	Federal Emergency Management Agency
HLW	high-level waste
IEP	ingestion exposure pathway
LF	latent fatality
LOCA	loss of coolant accident
LPZ	low population zone
LWR	light water reactor
MDPI	Modular Diversity Preservation International
MW	megawatt
mW	milliwatt
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
ONWR	Onkalo Nuclear Waste Repository
ORNL	Oak Ridge National Laboratory
PEP	plume exposure pathway
PRA	probabilistic risk assessment
RISMC	risk-informed safety margin characterization
SA	severe accident

SL	stationary low
SMR	small modular reactor
SOARCA	state-of-the-art reactor consequence analysis
SSCs	structures, systems, and components
TVA	Tennessee Valley Authority
UAMPS	Utah Associate Municipal Power Systems
USGS	United States Geological Survey
WIPP	Waste Isolation Program Plant

EXECUTIVE SUMMARY

Nuclear power is critical to the United States; it provides over 20 percent of the nation's baseload energy. There are many concerns throughout the nation about the safety of this form of energy. Much of this is based on the perception of risk associated with nuclear power and radiation in particular. There is a reasonable uneasiness in embracing this form of energy, due to use of atomic energy as a weapon, accidents occurring and waste being generated without a national strategy for recycling; therefore, nuclear power struggles to gain public acceptance. This thesis argues that if the nation pursued newer forms of technologies that advance nuclear power, especially with passive safety features, little disruption to the electrical grid, and improved efficiency, the United States might be able to secure a viable clean energy source well into the future.

Today, there are many forms of energy competing for attention, especially those capable of producing enough capacity to end the planet's dependence on fossil fuels, thereby reducing the carbon footprint. There is only one energy source that can achieve both—nuclear power. As U.S. energy consumption continues to grow, it is using more fossil fuels than ever before to accommodate the demand. At the same time, the nation pours resources into technologies that need to operate under perfect climate conditions or depend on older nuclear technologies that have inherent risks associated with age and degradation. Using a new form of nuclear technology such as small modular reactors (SMRs) permits the nation to address both of these dilemmas. This thesis demonstrates that replacing older nuclear technology reduces risk, thus lowering the consequences associated with nuclear power generation. The SMR is a reliable energy source that preserves the climate for future generations.

The hypothesis in this thesis suggests that if the United States does not have a strategy for replacing its current fleet of commercial nuclear power plants, it might find itself short of the baseload power to sustain the population into the future. To analyze this problem, it was necessary to understand why the public perceives nuclear power as a higher risk than other forms of energy. This was accomplished by finding research already compiled that suggests the cause of these concerns and ways to improve public confidence

moving forward. The research also had to examine what other nations are doing to address the recycling and storage of waste as well as new design models that could be safer and more versatile than traditional, fixed sites.

Using qualitative objectives, the Nuclear Regulatory Commission outlined its goals in a policy statement (51 *Federal Register* 30,028), which states,

> - Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health.
> - Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks.[1]

Using data from probabilistic risk assessments, this thesis concluded that moving ahead with SMRs is in line with the commission's goals and even exceeds its expectations. The results also indicate that other forms of energy have a higher frequency of risk and with more significant impacts on health and the environment than nuclear power. The research also suggests that recycling could be to the nation's advantage by creating additional future fuel for new reactor designs and reducing waste storage. Also, SMRs can operate with a high degree of safety, and the reduction in off-site preparedness could be justified.

Various recommendations include 1) extending the license renewal of current operating facilities only as necessary to replace them with SMRs; 2) changing the national policy to permit the reprocessing of spent fuel reduce long-term repositories and keep fuel available well into the future; and 3) replacing the current nuclear power plant infrastructure with SMRs or passive systems that will reduce negative consequences and improve public confidence.

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[1] Safety Goals for the Operations of Nuclear Power Plants, 51 Fed. Reg. 30,028 (August 4, 1986), 1–2, https://www.nrc.gov/reading-rm/doc-collections/commission/policy/51fr30028.pdf.

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This thesis is dedicated to the memory of my brother, who passed away last year while I was attending the program. Despite the obstacles in his life—and never having the opportunities others have known—he always had a kind heart, gentle smile, and compassion for everyone he encountered. These memories are his legacy and will be shared through me in my private and professional endeavors for many years to come.

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I. INTRODUCTION

Nuclear power plants are an indispensable source of electricity in the United States, providing over 20 percent of total electric power since 1990. Though all forms of commercial energy generation carry some degree of risk, nuclear risks excite the most fear. For nuclear energy, the risk of greatest concern is exposing the population to radiation. This research explores how to manage that risk through the adoption of small modular reactors (SMRs). This thesis shows how such reactors can play an essential role in energy supply while drastically reducing the potential consequences of a plant accident. Reducing impacts from nuclear power plant accidents may be achieved by adopting new reactor designs that eliminate the role of human error and reduce waste by reprocessing spent fuel on site. Other risk reduction benefits are associated with proper site selection.[1] By measuring the risk of accidents related to operations, this thesis quantifies the potential benefits and consequences of SMRs as an alternative approach to nuclear power infrastructure.

A. PROBLEM STATEMENT

SMRs may reduce adverse outcomes through the design of passive safety systems. Passive operations do not require human intervention or electricity to operate. As an additional layer of "defense in depth," passive systems have a distinct advantage over the current fleet of nuclear reactors because they do not require human intervention to cause the reactor to shut down.[2] The Nuclear Regulatory Commission (NRC) defines defense in depth as follows:

> An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single

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[1] "Small Nuclear Reactors," World Nuclear Association, March 2018, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[2] "Postulated Initiating Events," International Atomic Energy Agency, accessed April 1, 2018, https://www.iaea.org/ns/tutorials/regcontrol/assess/assess3215.htm.

> layer, no matter how robust, is exclusively relied upon. Defense in depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures.[3]

For example, poorly designed human interface systems and the resulting confusion contributed to the accident at Three Mile Island, the most significant event in the history of the U.S. commercial nuclear power industry.[4] A passive system would automatically, without human intervention, initiate a series of events that depower the reactor and mitigate damage to the plant. Additionally, the amount of fissile material in a smaller reactor compared to traditional reactors would lower the consequences if a failure were to occur.

U.S. nuclear power plants today are required to have a 10-mile emergency planning zone (EPZ) and a 50-mile ingestion pathway zone. The 10-mile EPZ requires plans to be in place that would ensure exposure to radiation was mitigated, or if a release of radioactive material occurred, decontamination of the public would be conducted. The 50-mile EPZ requires planning to deal with ground contamination that would enter the food supply, e.g., crops, animal populations, and direct exposure. SMRs that include passive safety designs and contain smaller amounts of fissile materials reduce the likelihood and consequences of an accident and may reduce the footprint of these two EPZs considerably.[5]

So far, the United States has produced about 50 metric tons of nuclear waste without a permanent method of disposal.[6] The waste generated by plants resides in spent fuel pools or on-site dry cask storage awaiting a national repository.[7] While there are many safeguards in place to protect this radioactive waste, there is a growing concern from the public

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[3] "Defense in Depth," Nuclear Regulatory Commission, last modified April 10, 2017, https://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html.

[4] Nuclear Regulatory Commission, Special Inquiry Group, *Three Mile Island: A Report to the Commissioners and to the Public*, NUREG/CR-1250, vol. 1 (Washington, DC: Nuclear Regulatory Commission, Special Inquiry Group, January 1980), https://www.hsdl.org/?abstract&did=778476.

[5] "Emergency Preparedness Rulemaking with Regard to Small Modular Reactors and Other New Technologies," Nuclear Regulatory Commission, last modified November 3, 2017, https://www.nrc.gov/reactors/new-reactors/regs-guides-comm/ep-smr-other.html.

[6] Gwyneth Cravens and Richard Rhodes, *Power to Save the World: The Truth about Nuclear Energy* (New York: Vintage, 2008), 269.

[7] Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste, 10 C.F.R. § 72 (2006), https://www.nrc.gov/reading-rm/doc-collections/cfr/part072/full-text.html.

regarding long-term environmental and health impacts of waste being stored on site.[8] By using SMRs, much of this waste can be re-processed in newly designed breeder reactors.[9] While they reduce waste, breeder reactors produce plutonium, which raises even more concern among the general public and political leaders. The reason for this fear is that plutonium is used in the production of nuclear weapons. To alleviate the public fear of plutonium, the nuclear industry has developed ways to reprocess plutonium with uranium. The resulting mixed-oxide fuel can be used to generate even more energy in certain types of reactors.[10] Policymakers at the local, state, and federal levels could use this information to communicate to constituents the importance of this emerging new technology and to make decisions on how to invest government capital for a more stable and sustainable energy future.

SMRs offer a scalable power solution. However, construction of nuclear plants is also a sizable investment for any utility, especially compared with other competitive forms of energy; a recent analysis estimates that a $72–$92 billion investment would be needed to create an assembly plant to manufacture SMRs.[11]

Currently, the aging U.S. energy transmission grid is highly susceptible to failure.[12] The use of a distributed collection of SMRs, strategically placed throughout the nation, would diminish the urgent need to enhance and upgrade transmission capacity and replace U.S. dependence on a few large facilities with a collection of much smaller sources closer to the users. Also, the scalability of SMRs may allow them to operate in zones that were

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[8] "Safer Storage of Spent Nuclear Fuel," Union of Concerned Scientists, accessed May 30, 2018, https://www.ucsusa.org/nuclear-power/nuclear-waste/safer-storage-of-spent-fuel.

[9] John Gilleland, Robert Petroski, and Kevan Weaver, "The Traveling Wave Reactor: Design and Development," *Engineering* 2, no. 1 (March 2016): 88–96, https://doi.org/10.1016/J.ENG.2016.01.024.

[10] Joe Shuster, *Beyond Fossil Fools: The Roadmap to Energy Independence by 2040*, 1st ed. (Edina, MN: Beaver's Pond Press, 2008), 207.

[11] Mark Cooper, "The Economic Failure of Nuclear Power and the Development of a Low Carbon Electricity Future: Why Small Modular Reactors Are Part of the Problem, Not the Solution" (Institute for Energy and the Environment, Vermont Law School, May 2014), https://www.power-eng.com/content/dam/pe/online-articles/documents/2014/May/Cooper%20SMRs%20are%20Part%20of%20the%20Problem%2C%20Not%20the%20Solution%20FINAL2.pdf.

[12] Gretchen Bakke, *The Grid: The Fraying Wires between Americans and Our Energy Future* (New York: Bloomsbury, 2017), 15.

once avoided, e.g., flood and earthquake zones, as well as provide reliable power to communities that have limited access to other energy resources. Last, by rehabilitating existing nuclear power plant sites with SMRs, the spent fuel at those sites can be recycled and used on site for the production of power.[13]

B. HYPOTHESIS

As the current fleet of nuclear power plants is being decommissioned, the plants are not being replaced by newer technologies. Only by investing in the design and construction of new nuclear technologies will future energy demands be met. Though there has been a dramatic shift to natural gas–fired plants and a rise in electricity generation through renewables, there will always be a need for stable and reliable base power.

Public perception of nuclear energy risk dominates policy decisions and sets limitations on the nation's energy options. When policymakers assess the real threat of nuclear power and the underlying circumstances surrounding nuclear power plant accidents, the actual probability associated with nuclear plant risk needs to be addressed and communicated without bias. If the public perception does not change, nuclear power generation may not only stagnate but disappear entirely from the national energy portfolio. While public perception is an essential part of this equation, the United States must also consider the amount of time and financial resources that are required if nuclear power is to be retained as an option in the future. The cost of building a single new nuclear power plant could be around $9 billion.[14] An investment of this magnitude will need consideration sooner rather than later if the nation does decide that nuclear power is an essential element of the energy future.

For many years, nuclear power has operated in this country with minimal impact on life or the environment. According to the Department of Homeland Security, there are 99 active and 18 decommissioning power reactors in 30 states that generate nearly 20

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[13] World Nuclear Association, "Small Nuclear Reactors."

[14] David Schlissel and Bruce Biewald, *Nuclear Power Plant Construction Costs* (Cambridge, MA: Synapse Energy Economics, July 2008), https://www.synapse-energy.com/sites/default/files/SynapsePaper.2008-07.0.Nuclear-Plant-Construction-Costs.A0022_0.pdf.

percent of the nation's electricity. In the United States, there have been no civilian deaths associated with the operation of a nuclear power plant since the technology's introduction over 60 years ago, making nuclear power one of the safest forms of energy in the country.[15]

The rise of electric vehicles and unmanned aerial vehicles will require more electricity generation, not less. The United States and energy sector partners must ask how to meet the increasing demand that will accompany the transition to electric transportation. If the United States decides to increase the percentage of its energy portfolio sustained through nuclear power, a more resilient nation would result from this newfound energy independence.

The focus of this thesis is to evaluate the role of SMRs as a part of the energy portfolio. This topic, through energy security, is a critical part of the homeland security enterprise and energy sector of critical infrastructure.[16] This thesis evaluates trends in electricity consumption and projected future requirements that are motivating the need for nuclear power. It assesses the potential impact of SMRs on the U.S. energy sector as well as the potential consequences of accidents at such plants. This latter topic is addressed using exceedance probabilities to relate the likelihood of consequences of an accident and shows how SMRs can significantly diminish the risks and consequences associated with nuclear accidents.

C. RESEARCH QUESTION

Can SMRs operate with lower risk than traditional nuclear power plants?

D. LITERATURE REVIEW

There are various scholarly sources to determine whether new design-based plans are a viable option for the future. Many design proposals reviewed by the Nuclear Regulatory Commission, the National Energy Institute, renowned researchers, and scientists show exciting possibilities for the future. Also, this research reviews materials

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[15] "Nuclear Reactors, Materials, and Waste Sector," Department of Homeland Security, last modified July 6, 2009, https://www.dhs.gov/nuclear-reactors-materials-and-waste-sector.

[16] Department of Homeland Security.

from the World Health Institute and other environmental agencies that have studied health and environmental impacts of radiation exposure.

A survey by the Nuclear Energy Institute indicates an increase in support from the public for nuclear energy. Since 1983, support for nuclear power among this audience has grown from 49 to 64 percent, and opposition has dropped from 46 to 25 percent.[17] Although these survey results indicate an increasing level of support from the American people, many have wavered on this issue. In particular, following disasters involving nuclear power, such as Three Mile Island, Chernobyl, and Fukushima Daiichi, surveys have shown low levels of public support for nuclear power. This survey is not definitive, so additional methods of gauging the pulse of the American public's perception of the use of nuclear energy are necessary before advancing SMR technologies.

In the book *Risk and Culture*, Mary Douglas and Aaron Wildavsky reveal the perception of risk, how a human's level of uncertainty or experience affects the risk evaluation. By dividing the book into an assessment of four dangers that spur human worry—foreign affairs, crime, pollution, and economic failure—the authors provide insight into how to determine an acceptable level of risk.[18] If SMRs demonstrate risk reduction, this fact would still need to be efficiently communicated to achieve broader public support. The authors argue that bias and culture play a profound role in the perception of risk, and they identify obstacles that policymakers may encounter when introducing newer nuclear technologies.[19]

The article "Nuclear Power and the Energy Crisis" outlines the limited harm radiation presents to human health vis-à-vis other known diseases. Hodgson discusses the misconceptions concerning radiation and displays support for nuclear energy, with a

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[17] Ann S. Bisconti, "64 Percent Favor Nuclear Energy" (press release, Bisconti Research, October 2017), 8, https://www.eenews.net/assets/2017/10/11/document_gw_05.pdf.

[18] Mary Douglas and Aaron Wildavsky, *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers* (Berkeley: University of California Press, 1983).

[19] Douglas and Wildavsky.

compelling argument on the real risks, versus the perception, of nuclear power and statements of conjecture.[20]

To establish the development and expansion of nuclear power, U.S. policymakers must carefully and intellectually consider the nuclear fuel cycle. Without careful deliberation among international partners, the United States could see the proliferation of nuclear weapons produced using the by-products of facilities operating today. Weaponizing spent nuclear material is done through reprocessing it into another highly enriched form of radioactive substance, making it one step closer to weaponized material. The Arms Control Association (ACA), a group working collectively to promote the understanding of arms control, believes there is a legitimate security concern that requires a much-needed change in how the United States handles nuclear waste.[21] The ACA recommends having international nuclear fuel cycle centers established to store and reprocess spent fuel correctly.[22] This method could be overseen by the International Atomic Agency, reducing the risk of proliferation.[23]

The World Nuclear Association outlines the U.S. energy policy, which appears favorable in advancing nuclear power across the country through a variety of methods and funding schemes. The U.S. Congress and the Department of Energy accept that nuclear power can operate safely at a certain level. They offer many facts regarding the use and disposal of nuclear waste, and they also acknowledge the existence of growing support for nuclear energy in the country.[24]

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[20] P. E. Hodgson, “Nuclear Power and the Energy Crisis,” First Principles, October 22, 2008, http://www.firstprinciplesjournal.com/articles.aspx?article=1110&theme=home&page=8&loc=b&type=ctbf.

[21] “About the Arms Control Association,” Arms Control Association, accessed October 27, 2018, https://www.armscontrol.org/about.

[22] Fiona Simpson, “Reforming the Nuclear Fuel Cycle: Time Is Running Out,” Arms Control Association, last modified September 2, 2008, https://www.armscontrol.org/act/2008_09/Simpson.

[23] “Official Website of the IAEA,” International Atomic Energy Agency, accessed October 27, 2018, https://www.iaea.org.

[24] “US Nuclear Power Policy,” World Nuclear Association, accessed October 21, 2017, http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power-policy.aspx.

The NRC notes that a critical consideration for SMRs is siting. According to the NRC, site selection will be significant in reducing or minimizing the risk. The Atomic Energy Act (AEA) of 1954 established by the NRC requires all nuclear power facilities to be licensed. Nuclear power plant facilities are expected to follow the rules and have oversight by the NRC during operations. The AEA of 1954 outlines what regulators have to consider before a new facility can be built by establishing standards for proper site selection, which considers seismology, population, security, and water quality as well as availability for cooling the reactor core.[25] Nuclear power has been in operation in the United States using these criteria and has done so safely. These regulations are modified as required by law to meet the high standards of reasonable assurance, so plants operate safely.

In 2013, the Oak Ridge National Laboratory (ORNL) mapped SMRs in strategic locations to research the feasibility of supporting the national electric supply. The study used industry-accepted approaches and mapping tools to identify suitable locations for these facilities. These mapping tools divide the United States into 700 million cells (one hectare per cell) to determine ideal places for sites.[26] Using the same siting analysis, ORNL also produced a report evaluating power use by the federal government and focused on those locations for consideration.[27]

The NRC's website provides the public with current information on "reasonable assurance" for each facility that operates within regulatory standards. EPZs have also been a question for new SMR designs. The NRC website delineates the plant, federal, state, and

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[25] Nuclear Regulatory Commission, *General Site Suitability Criteria for Nuclear Power Stations*, Regulatory Guide 4.7 (Washington, DC: Office of Nuclear Regulatory Research, April 1998), https://www.orau.org/ptp/PTP%20Library/library/nrc/Reguide/04-007.PDF.

[26] R. J. Belles et al., *Identification of Selected Areas to Support Federal Clean Energy Goals Using Small Modular Reactors* (Oak Ridge, TN Oak Ridge National Laboratory, December 2013), https://energy.gov/sites/prod/files/2015/12/f27/SITINGTask1FinalReportHighFedEnergyClusters.pdf.

[27] Randy J. Belles and Olufemi A. Omitaomu, *Evaluation of Potential Locations for Siting Small Modular Reactors near Federal Energy Clusters to Support Federal Clean Energy Goals* (Oak Ridge, TN: Oak Ridge National Laboratory, September 1, 2014), 1, https://doi.org/10.2172/1224159.

local responsibilities regarding the 10-mile and 50-mile EPZs surrounding nuclear power plants.[28]

The Nuclear Energy Institute (NEI) has prepared a white paper asking the NRC to revise the emergency planning zones around new nuclear technologies, particularly SMRs.[29] In June 2016, the NRC granted permission to its staff to examine the rule-making questions proposed by the NEI. This rule-making review and development would occur over a four-year period to identify the credibility of the NEI's claims. This review process is the first step toward the adoption of a different set of emergency planning standards for new nuclear technologies.

E. RESEARCH DESIGN

This thesis presents a comparative study of traditional commercial nuclear power plants and the SMR. This research focused on the design, nuclear waste, and the size of the EPZ required for off-site protective actions. It did not cover the environmental or economic issues associated with building this infrastructure. Ecological or economic problems in this thesis are mentioned only in generalities. The goal of the research was to determine what is known about current commercial nuclear power plants vis-à-vis SMRs and to ascribe accordingly. As there have been advancements in designing and building this technology in other parts of the world; the research explored different cultural contexts that influence the behaviors of others who decide to use this technology.

First, the research involved capturing data from sources such as press reports, editorials, government documents, and scholarly academic articles. Information was also collected from the Federal Emergency Management Agency (FEMA), the NRC, the NEI, and other well-known groups and organizations; there had been a vast number of studies collected over the years, especially after nuclear power plant accidents. The research

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[28] "Federal, State, and Local Responsibilities," Nuclear Regulatory Commission, last modified January 23, 2018, https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/federal-state-local.html.

[29] Doug Walters, "White Paper on Proposed Methodology and Criteria for Establishing the Technical Basis for Small Modular Reactor Emergency Planning Zone" (National Energy Institute, December 23, 2013), https://www.nrc.gov/docs/ML1336/ML13364A345.pdf.

compiled from these institutions' risk assessments, design limitations, after-action reports from real incidents, and scenario-based exercises revealed possible realities. Second, it was essential to collect and evaluate public perceptions of risk regarding the advancement of nuclear technologies through known studies already gathered from reliable sources. Finally, much of this data was used to determine exceedance probabilities, which provide a quantitative analysis.

II. COMMERCIAL NUCLEAR POWER PLANTS

This chapter explores the public perception of risk associated with commercial nuclear power plants in the United States. It reviews various studies that explore the primary components in shaping public opinion, particularly the concern that aging facilities release radioactive material into the environment. Without appropriate oversight and technical improvements, accidents may occur; however, putting regulation and policy in place to ensure safe operations reduces the risk and improves public confidence.

A. THE PUBLIC PERCEPTION OF RISK

It is essential to break down two words: perception and risk. Perception is the opinions formed by observations or awareness of one's surroundings. Risk is the possibility of harm to oneself or others. How do societies perceive risk, especially regarding forms of energy? Commercial nuclear power has existed since May 26, 1958, when Shippingport Atomic Power Station, located in Shipping, Pennsylvania, was ceremonially opened by President Dwight D. Eisenhower under the "Atoms for Peace" program.[30] Shippingport was the first commercial power plant to become critical. The word "critical" itself may cause some trepidation as it implies to many a dangerous, grave, or life-threatening condition, but it means "when the atom-splitting reactor of a nuclear power plant is operating normally, it is said to be 'critical' or in a state of 'criticality.'"[31] While words like criticality are necessary to articulate the condition of the plant, they do not have a calming effect on the public. Words can have very different meanings to the general public as opposed to the nuclear industry. Words alone can formulate someone's opinion about a particular subject and, therefore, the way electricity is produced in this country and elsewhere around the world.

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[30] "Shippingport Nuclear Power Station," American Society of Mechanical Engineers, accessed July 15, 2018, https://www.asme.org/about-asme/who-we-are/engineering-history/landmarks/47-shippingport-nuclear-power-station.

[31] Wendy Lyons Sunshine, "What Is Criticality in a Nuclear Power Plant? Learn Why It's No Worry," Balance, last modified December 3, 2018, https://www.thebalance.com/what-is-criticality-in-a-nuclear-power-plant-1182619.

A 2008 study from Michigan State University suggests that having trust in government has little to do with influencing public perception of nuclear power; rather, an individual's values do. The study suggests there is a degree of ambivalence on the part of those opposed to it.[32] Uncertainty is growing with every article written and news broadcast aired, as those hearing the message adopt only what already supports their preconceived biases. The American people hear from two sides of the argument, one with a monumental financial investment, the other with a strong environmental focus. Over the years, government agencies like the NRC and the NEI have tried to bridge the gap and provide sufficient evidence about risk, but the hyperbole coming from both sides drowns out any message delivered. Drafting a clear message on how risk is determined can be valuable in improving public discourse.

People's values play a significant role in how they perceive risk. Thus, cultural cognition plays a role in developing those values. There are many risks society faces, such as global warming, contamination of water, and even adverse reactions to experimental drugs. However, people decide very quickly, with little research about the facts, whether they will support a policy, drink a glass of water, or even take a drug that may or may not save their lives.[33] According to an article in the *Journal of Risk Research*, risk is determined by cultural cognition whereby people disregard scientific evidence if it does not fit within their cultural beliefs. The study collected correlational and experimental evidence to support the authors' argument that perception is amiable to one's values.[34]

On the topic of trust, Yeonjae Rye, Sunhee Kim, and Seoyong Kim from Molecular Diversity Preservation International (MDPI) surveyed the trust of residents living around nuclear power plants. The study surveyed 1,014 residents living around four nuclear plant

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[32] Stephen C. Whitfield et al., "The Future of Nuclear Power: Value Orientations and Risk Perception," *Risk Analysis* 29, no 3 (March 2009), https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1539-6924.2008.01155.x.

[33] Dan M. Kahan, Hank Jenkins-Smith, and Donald Braman, "Cultural Cognition of Scientific Consensus," *Journal of Risk Research* 14, no. 2 (February 2011): 147–74, https://doi.org/10.1080/13669877.2010.511246.

[34] Kahan, Jenkins-Smith, and Braman.

facilities in South Korea: Yeongkwang, Uljin, Wulsung, and Gori.[35] While South Korea differs from the United States in many ways, it shares many of the same attributes. Like the United States, South Korea is a democracy that depends on electricity to drive its economy. Living near North Korea, an unstable communist regime, South Koreans have legitimate concerns about security, especially when it comes to nuclear materials, production, and proliferation of nuclear waste. Only a few short years ago, many within the geographical region began to change their attitude about nuclear power. This change in attitude occurred after the Fukushima Daiichi failure, which created a positive relationship between the accident and perceived risk.[36] Using a causal model (see Figure 1), Ryu, Kim, and Kim suggest there are two kinds of trust—in the government and in regulation—with credibility contributing, too, toward the perceived risk and acceptance of nuclear power.[37] When the government actively implements regulation, trust increases. In structural modeling and the reliance on empirical data, there is a strong relationship between trust and perceived risk, especially regarding government institutions. Their findings suggest that when fear rises, particularly about nuclear energy, trust becomes a factor.

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[35] Yeonjae Ryu, Sunhee Kim, and Seoyong Kim, "Does Trust Matter? Analyzing the Impact of Trust on the Perceived Risk and Acceptance of Nuclear Power Energy," *Sustainability* 10, no. 3 (March 2018): 7, https://doi.org/10.3390/su10030758.

[36] Ryu, Kim, and Kim, 10.

[37] Ryu, Kim, and Kim.

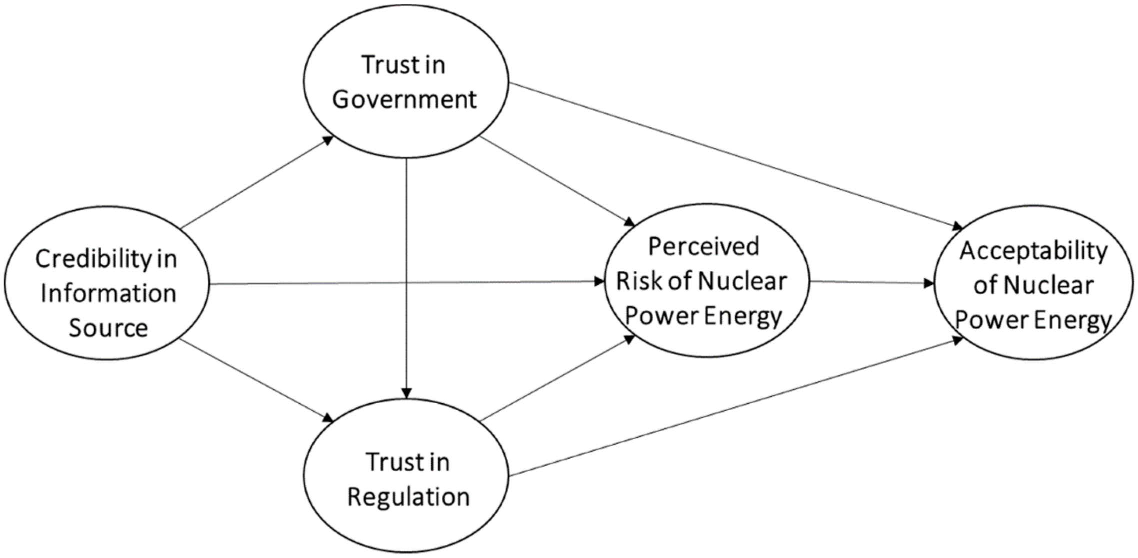

Figure 1. Causal Model of Trust[38]

According to Denise M. Rousseau et al., "Trust is a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behavior of another."[39] If one could be assured that an individual, or in this case a representative of the government, is acting in the best interest of the constituents, credibility will be established, and trust can be achieved. Inevitably, trust and the credibility of those developing regulations can influence acceptance. However, among the three variables—source credibility, trust in government, and trust in regulation—included in this study, confidence in regulation yields the highest correlation with perceived risk.[40]

To validate more clearly how other factors may impact risk, Ryu, Kim, and Kim regressed two variables, perceived risk and acceptance, and added sociodemographic variables such as gender, age, education, and income.[41] The results show that socially constructed perceptions play more of a role in risk perception than sociodemographic

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[38] Source: Ryu, Kim, and Kim, "Does Trust Matter?," 4.

[39] Denise M. Rousseau et al., "Not So Different after All: A Cross-Discipline View of Trust," *Academy of Management Review* 23, no. 3 (July 1998): 395, https://doi.org/10.5465/amr.1998.926617.

[40] Ryu, Kim, and Kim, "Does Trust Matter?," 10.

[41] Ryu, Kim, and Kim, 10.

variables—even upper-income individuals support the advancement of nuclear power.[42] The researchers in this article understood that regression analysis could not portray the causal relationships or impacts between independent and dependent variables. To show these relationships, a structural equation model was designed using the three aforementioned variables as well as perceived risk and acceptance. The diagram in Figure 2 portrays the statistical process, which includes these additional causal chains, Ryu, Kim, and Kim used to support their findings.[43] While the model is not conclusive, one could reasonably assume some of the aforementioned variables do influence the perception of risk. The most important conclusion from this article is that while credibility may have some influence on public perception, having regulation in place is vital in gaining the acceptance of nuclear power.

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[42] Ryu, Kim, and Kim, 11.

[43] Ryu, Kim, and Kim, 11.

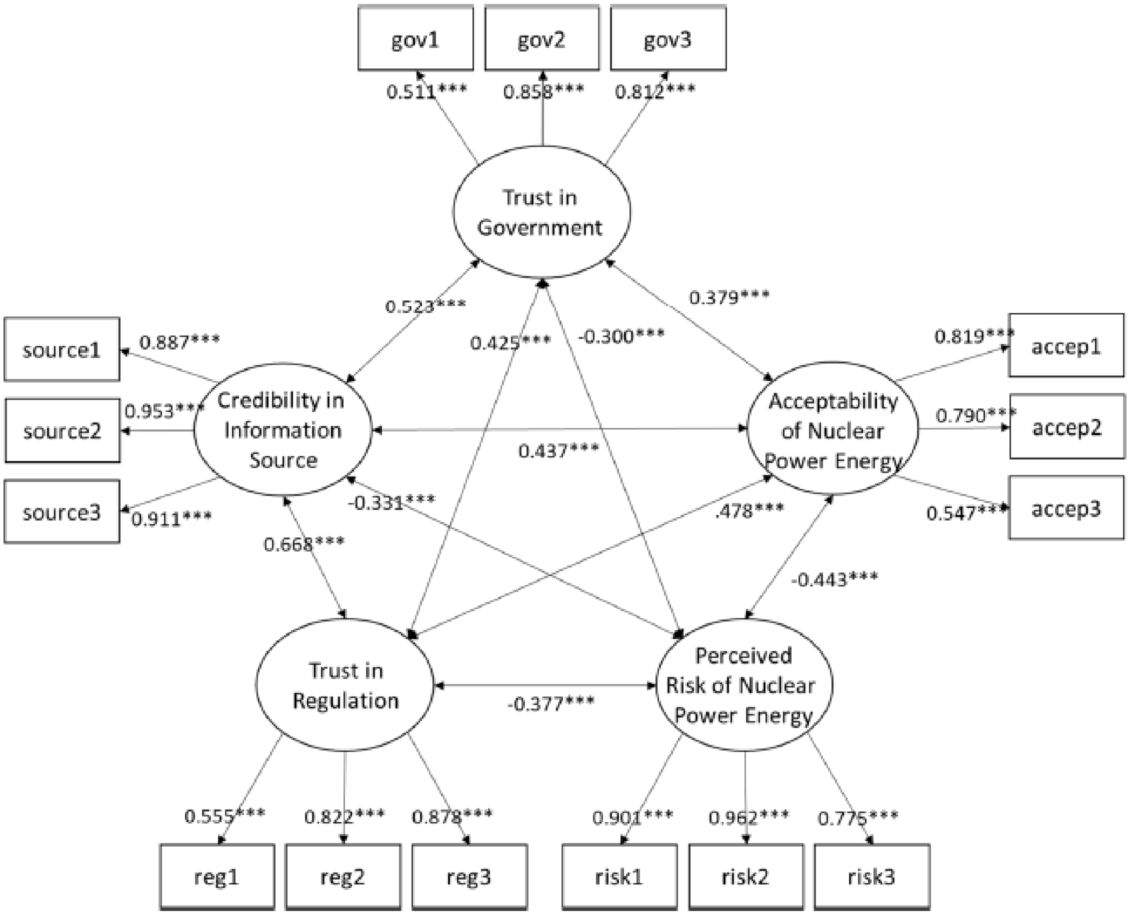

Figure 2. Causal Model of Trust: Structural Equation Model[44]

Recent studies have shown that younger people may be more accepting of the risks of nuclear power. According to the Oak Ridge Institute for Science and Education, the field of nuclear engineering has been growing steadily since 2000 and has returned to levels comparable to 1972, before the Three Mile Island accident in 1979 (see Figure 3).[45] The industry has seen many start-ups trying to find solutions to the nation's rising energy demand, both today and in the future. Most are young engineers who grew up in a time when global warming was being taught in schools across the nation, and today they crusade

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[44] Source: Ryu, Kim, and Kim, "Does Trust Matter?," 12.

[45] "Nuclear Engineering Enrollments and Degrees Survey," Oak Ridge Institute for Science and Education, June 2017, https://orise.orau.gov/stem/workforce-studies/nuclear-engineering-enrollments.html.

to stop global warming with nuclear technologies.[46] This trend is also evident in a Kickstarter campaign for a new documentary called *The New Fire*, showing how a new generation of nuclear engineers are designing nuclear power for the future that is reliable and safe and even addresses the nuclear waste cycle.[47]

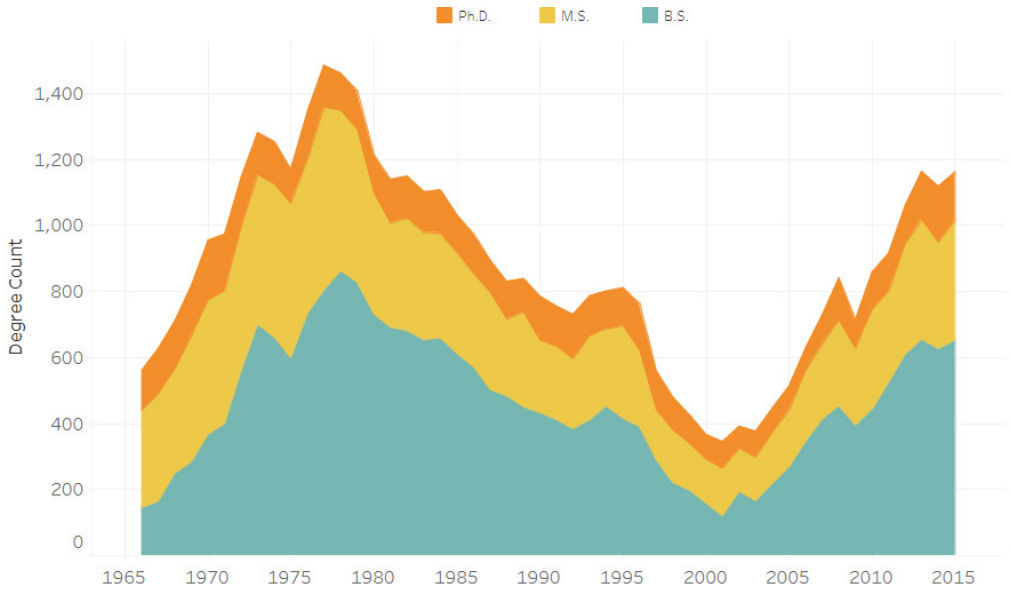

Figure 3. Nuclear Engineering Student Trends[48]

Another way one perceives risk is through availability heuristics. According to Psychology Dictionary, an *availability heuristic* is a

> common quick strategy for making judgments about the likelihood of occurrence. Typically, the individual bases these judgments on the salience of similar events held in memory about the particular type of event. The quicker something springs to mind about an event, (i.e., the more available the information), the more likely it is judged to be. Use of this strategy may lead to errors of judgment (e.g., well-publicized events, such as plane

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[46] Jeff Brady, "As Nuclear Struggles, a New Generation of Engineers Is Motivated by Climate Change," NPR, June 15, 2018, https://www.npr.org/2018/06/15/619348584/as-nuclear-struggles-a-new-generation-of-engineers-is-motivated-by-climate-chang.

[47] "The New Fire," Generation Films, accessed August 20, 2018, https://newfiremovie.com/.

[48] Adapted from: Brady, "New Generation of Engineers Is Motivated by Climate Change."

> crashes) [and] lead people to believe that those kinds of events are more probable than they are.[49]

With the advent of the 24-hour news cycle and social media reporting news about terrorism, gun violence, and other social ills, people's perceptions form their available heuristics, leaving them with a distorted view of society, which differs from reality. There is no greater risk of being a victim in a plane crash or terrorist event than being struck by lightning.[50] By using only an evidence-based approach, could one accurately predict the likelihood of an occurrence happening? In this case, people tend to become overprotective or even globally precautionary, unintentionally causing further harm to themselves or others.[51] In the case of nuclear power, perceptions are influenced by availability heuristics, which could yield unhealthy policy. Going back as far as 1993, "Scientists and policymakers were slow to recognize the importance of public attitudes and perceptions in shaping the fate of nuclear power."[52] Comparing nuclear power to other energy sources, especially their impacts on reducing global warming, would be a fair way to assess the dangers these other energy sources pose (see Table 1).[53] According to Jonathan N. Crawford, the current fleet of nuclear power plants produces 63 percent of carbon-free energy in the United States.[54] In assessing energy sources that produce carbon emissions, it is well-documented that radiation from

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[49] Psychology Dictionary, s.v. "availability heuristic," April 7, 2013, https://psychologydictionary.org/availability-heuristic/.

[50] John Wills, "What We Know about Active Shooters," Officer, March 4, 2013, https://www.officer.com/on-the-street/body-armor-protection/article/10887915/what-we-know-about-active-shooters.

[51] Cass R. Sunstein, "Precautions against What? The Availability Heuristic and Cross-Cultural Risk Perceptions" (working paper, University of Chicago, August 2004), 1, https://doi.org/10.2139/ssrn.578303.

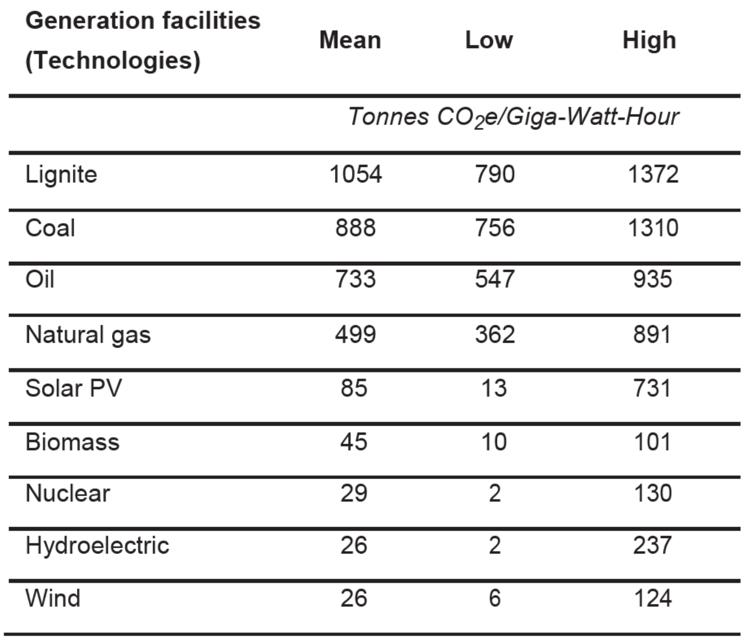
[52] Paul Slovic, "Perception of Risk and the Future of Nuclear Power" (paper presented at the Symposium on Perception of Risk and the Future of Nuclear Power, Washington, DC, April 14, 1993), https://www.aps.org/units/fps/newsletters/1994/january/ajan94.html.

[53] Sayanti Mukhopadhyay, Makarand Hastak, and Jessica Halligan, "Compare and Contrast Major Nuclear Power Plant Disasters: Lessons Learned from the Past," in *Proceedings of the 10th International Conference of the International Institute for Infrastructure Resilience and Reconstruction* (West Lafayette, IN: Purdue University Press, 2014), 163, https://doi.org/10.5703/1288284315360.

[54] Jonathan N. Crawford, "Aging U.S. Nuclear Plants Pushing Limits of Life Expectancy," Insurance Journal, November 29, 2015, https://www.insurancejournal.com/news/national/2015/11/29/390222.htm.

nuclear power has caused some deaths and serious illness; however, its effects are minimal compared to other forms of energy that produce emissions (see Figure 4).[55]

Table 1. CO2 per Giga-Watt Hour[56]



Generation facilities (Technologies)	Mean	Low	High
	Tonnes CO_2e/Giga-Watt-Hour		
Lignite	1054	790	1372
Coal	888	756	1310
Oil	733	547	935
Natural gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

While it is necessary to assess the risks of nuclear power and other forms of energy, both Chapters III and IV compare traditional nuclear power plants to newer design-based models. This seems a logical way to understand the industry and its impact on the future energy portfolio in the United States.

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[55] Anil Markandya and Paul Wilkinson, “Electricity Generation and Health,” *Lancet* 370, no. 9591 (September 2007): 983, https://doi.org/10.1016/S0140-6736(07)61253-7.

[56] Source: Mukhopadhyay, Hastak, and Halligan, “Compare and Contrast Major Nuclear Power Plant Disasters,” 3.

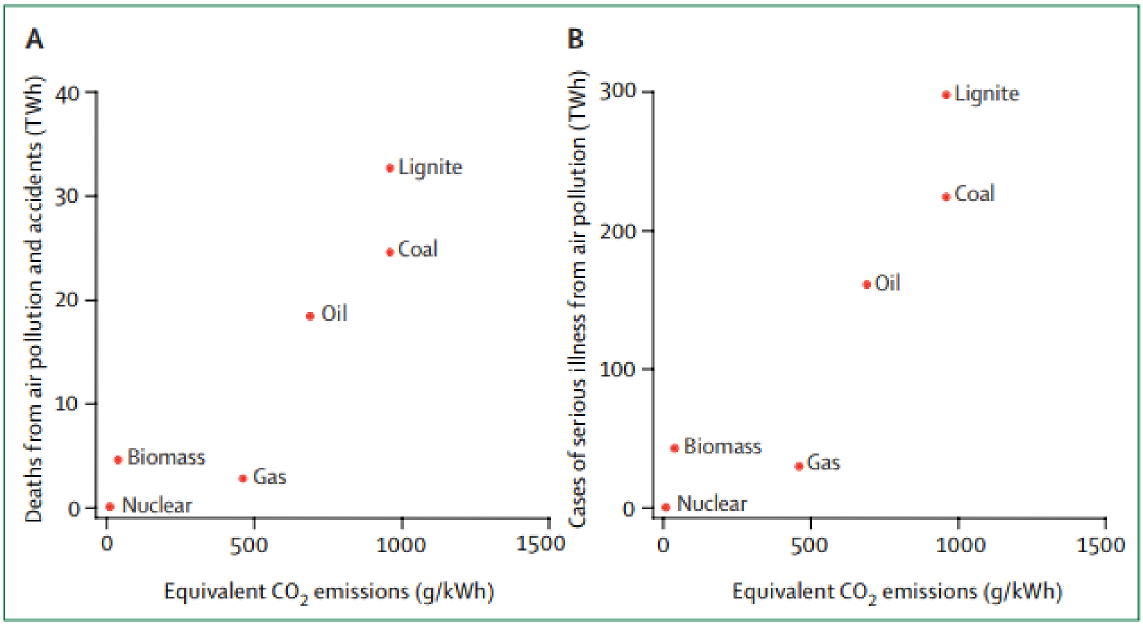

Figure 4. Deaths and Illnesses from Energy Sources[57]

B. AGING INFRASTRUCTURE

In the United States, there are 61 nuclear reactor sites comprising 99 reactors, located in 30 states. South Carolina Electric and Gas Company stopped building two nuclear power plants, citing the rising construction costs, delays, decreasing demand for electricity, and the bankruptcy of Westinghouse, the lead contractor and designer of the reactor.[58] No new reactor sites have been built since 1996 other than Watts Bar Unit 2, completed in 2014. Watts was suspended in 1980 and later finished between 2007 and 2014.[59] All 61 nuclear power plants operating in the United States were initially licensed to work for 40 years. The two oldest power plants were built in 1969, making the average age of U.S. plants 37 years.[60] For example, one of the largest plants operating today is the

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[57] Source: Markandya and Wilkinson, "Electricity Generation and Health," 983.

[58] "South Carolina Utilities Stop Construction of New Nuclear Reactors," Energy Information Administration, August 14, 2017, https://www.eia.gov/todayinenergy/detail.php?id=32472.

[59] Energy Information Administration, "South Carolina Utilities Stop Construction."

[60] "How Old Are U.S. Nuclear Power Plants, and When Was the Newest One Built?" Energy Information Administration," accessed August 20, 2018, https://www.eia.gov/tools/faqs/faq.php?id=228&t=21.

Palo Verde Nuclear Power Plant in Tonopah, Arizona. This plant provides one-third of the baseload power to the state of Arizona and serves large cities in Southern California such as Los Angeles and San Diego. The first reactor at Palo Verde was commissioned in May 1986, 32 years ago. In 2011, Palo Verde received a license extension for an additional 20 years beyond the current 40-year design base of its original license; the plant is expected to continue operation until 2045–2047.[61] This will make the plant 61 years old before decommissioning begins.[62]

Davis-Besse, a nuclear plant located in Oak Harbor, Ohio, was put on line in 1978 and is now 40 years old. In 2002, corrosion on a steel reactor cap nearly caused a release of radioactivity into the containment environment.[63] This incident ranked within the top five most dangerous episodes since the Three Mile Island Nuclear Power Plant accident in 1979, which began a profound change in oversight of the nuclear power plant industry.[64] Vermont Yankee Nuclear Power Plant, owned by FirstEnergy Corporation, while no longer in service, became operational in 1972, making it only 46 years old. In 2010, it had issues with pipes leaking radioactive material, but it posed no serious harm to public health.[65] These types of maintenance items may or may not be a factor in other energy sectors; however, aging infrastructure with the slightest detectable levels of radiation has profound implications for the nuclear power plant industry.

In 1982, the NRC established a program for research on aging nuclear power plants to evaluate life expectancy of components beyond their 40-year license period.[66] Shortly thereafter, a license renewal process was established in 1991 under 10 C.F.R. § 51 and 10

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[61] Nuclear Regulatory Commission, "Reactor License Renewal" (fact sheet, February 2008), 1, https://www.nrc.gov/docs/ML0506/ML050680253.pdf.

[62] Albert William, "Palo Verde Nuclear Power Plant," accessed August 20, 2018, http://nuclear-powerplants.blogspot.com/2010/11/palo-verde-nuclear-power-plant.html.

[63] Nuclear Regulatory Commission, *Davis-Besse Reactor Vessel Head Degradation: Lessons-Learned Task Force Report* (Rockville, MD: NRC, 2002), 42, https://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation/lessons-learned/lessons-learned-files/lltf-rpt-ml022760172.pdf.

[64] Wikipedia, s.v. "Davis-Besse Nuclear Power Station," August 8, 2018, https://en.wikipedia.org/w/index.php?title=Davis%E2%80%93Besse_Nuclear_Power_Station&oldid=853978653.

[65] Crawford, "Aging U.S. Nuclear Plants."

[66] Nuclear Regulatory Commission, "Reactor License Renewal," 1.

C.F.R. § 54. The former considers environmental issues while the latter considers safety issues.[67] In 1995, § 54 was amended to focus more on "managing the adverse effects of aging" during a 20-year life extension.[68] The changes were intended to ensure important components of the facility performed as they were designed. Soon afterward, the NRC developed guidance for license renewal called the generic aging lessons learned, which were incorporated into NUREG-1800.[69] In 2017, the NRC created new guidance for license renewal that focuses on "aging management requirements" for 60 to 80 years, which include structures, systems, and components.[70]

The aging U.S. management requirements focus mostly on two types of reactors that were most common in the country: the pressurized water reactor and the boiling water reactor. As these facilities begin to age, if systems, structures, and components (SSCs) go unchecked, physical components will begin to fatigue, especially those exposed to extreme pressure, heat, and radiation. Without proper maintenance or, perhaps more importantly, a replacement schedule, the United States could see additional failures of these SSCs.[71] The Atomic Energy Act (AEA) of 1954 placed the responsibility for commercial nuclear power under a new agency, the NRC; its mission has been to protect the health and safety of the public, using atomic energy for peaceful purposes.[72] The primary role of the NRC has been to inspect facilities, enforce regulations, license power plant owners, conduct technical research, and modify laws as needed. While the NRC has a role, the AEA places ultimate responsibility on the facility owner, also known as the licensee.[73] Additionally, many industry-wide organizations have been created over the years to help self-monitor, share

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[67] Nuclear Regulatory Commission, 3.

[68] Nuclear Regulatory Commission.

[69] Nuclear Regulatory Commission, *Standard Review Plan for Review of License Renewal Applications for Nuclear Power Plants: Final Report*, NUREG-1800, rev. 2 (Rockville, MD: Office of Nuclear Reactor Regulation, December 2010).

[70] Nuclear Regulatory Commission, "Reactor License Renewal."

[71] U.S. Congress, Office of Technology Assessment, "Safety of Aging Nuclear Plants," in *Aging Nuclear Power Plants: Managing Plant Life and Decommissioning* (Washington, DC: Office of Technology Assessment, September 1993), 38, https://www.princeton.edu/~ota/disk1/1993/9305/930504.PDF.

[72] Nuclear Regulatory Commission, "Reactor License Renewal," 44.

[73] Office of Technology Assessment, "Safety of Aging Nuclear Plants," 44.

best practices, and advocate for operational excellence in the nuclear industry. These organizations include the NEI, the Electrical Power Research Institute, the Nuclear Management and Resource Council, and the Institute of Nuclear Power Operations. Other professional industry organizations weigh in on design, including the American Society of Mechanical Engineers, the Institute for Electrical and Electronics Engineers, and the American Society of Civil Engineers. Having many organizations involved over the years has made the United States a leader in safe nuclear generation today. Many externalities exist with other forms of energy, such as the contamination of surface water or aquifers, respiratory illnesses, de-foresting, destruction of animal habitats, and global warming. Nuclear power is no different, but due to a robustly regulated industry, the nuclear industry has fewer deaths attributed to it than any other source of energy (see Figure 5).[74]

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[74] "Home Page," Next Big Future, accessed September 16, 2018, https://www.nextbigfuture.com.

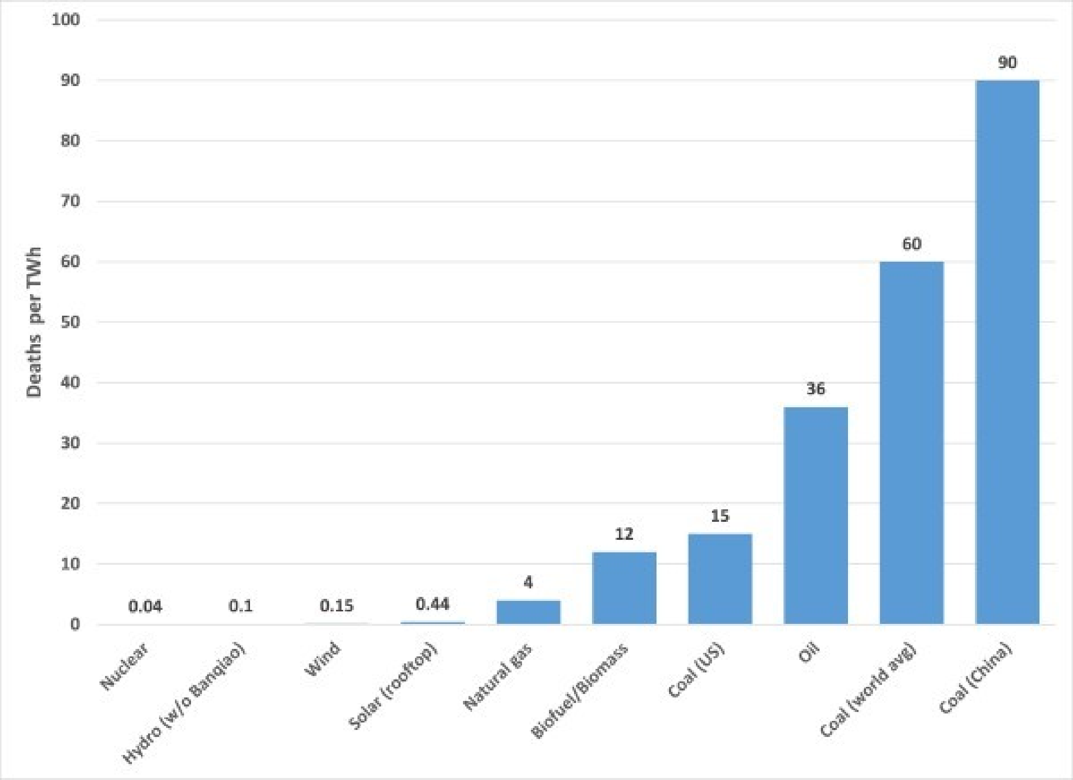

Figure 5. Nuclear Industry Deaths per Terawatt Hours[75]

Today, the United States produces around 20 percent of the nation's baseload energy supply from an aging nuclear power plant fleet and delivers twice the energy of France, which ranks second in energy production and uses nuclear energy to supply 75 percent of its energy needs (see Figure 6).[76]

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[75] Source: "NECG #12 – Deaths per TWh," Nuclear Economics Consulting Group, accessed December 9, 2018, https://nuclear-economics.com/11-nuclear-power-in-summer/12-deaths-per-twh/.

[76] "Nuclear Power in the World Today," World Nuclear Association, last modified April 2018, http://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

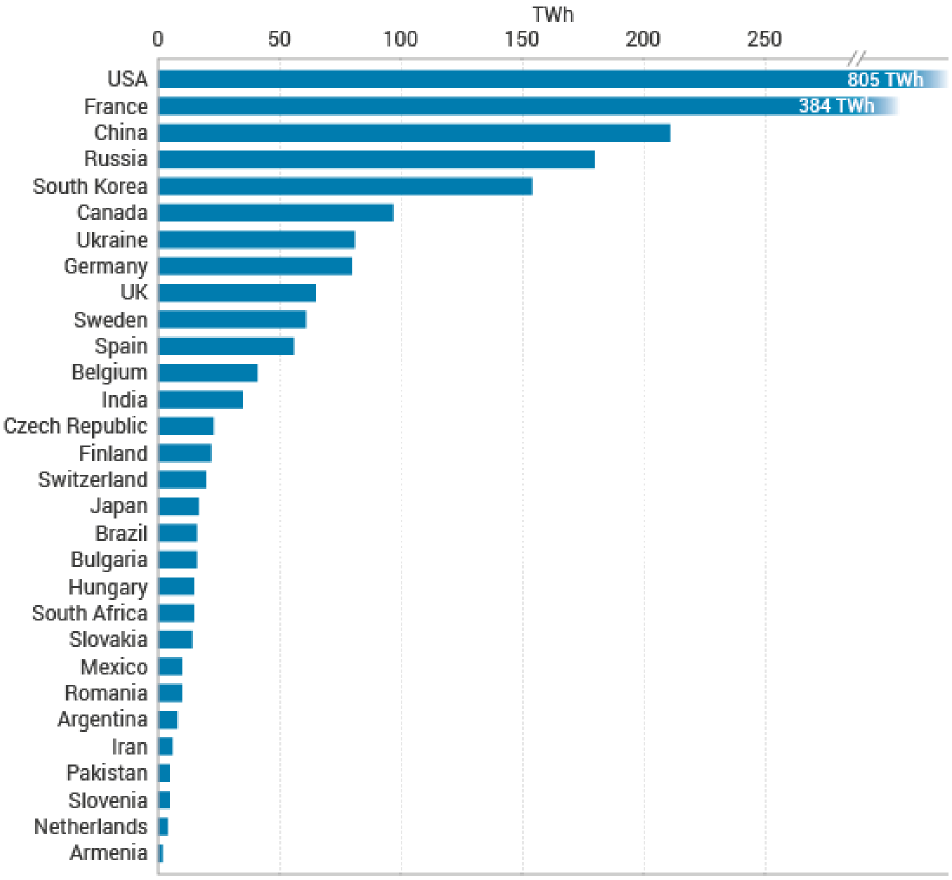

Figure 6. Nuclear Generation by Country[77]

To sustain this energy source, the United States must have confidence that the aging infrastructure can operate safely. The management of aging nuclear power plants begins with design specifications called general design criteria, which were explicitly adopted back in 1971. These criteria "established the minimum requirements for materials, design, fabrication, testing, inspection, and certification of all important plant safety features."[78] Also, good maintenance practices prevent aging degradation and ensure safe operations. Initially, the AEA established a 40-year life cycle for licensing of commercial nuclear power. This was based on industry standards and not for technical or financial reasons. Once standards were established, plants were obligated to meet these minimum industry

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[77] Source: World Nuclear Association, "Nuclear Power in the World Today."

[78] Office of Technology Assessment, "Safety of Aging Nuclear Plants," 48.

criteria well into the future.[79] Finally, before requesting the extension for plant operations beyond the 40-year life expectancy, the owner or operator must complete an integrated plant assessment.[80] This assessment addresses age-related degradation unique to license renewal.[81] The overall safety-related aging research conducted by various professional organizations and the Department of Energy promotes the following goals:

- Understanding SSC aging effects that could impair plant safety if unmitigated;
- Developing inspection, surveillance, monitoring, and prediction methods to ensure timely detection of aging degradation;
- Evaluating the effectiveness of operating and maintenance practices to mitigate aging effects; and
- Providing the technical basis for license renewal.

With all of these considerations, it is apparent why nuclear power in this country and elsewhere around the world has experienced so much success. Rigorous oversight by the NRC, collaboration with professional organizations, and policy that requires maintenance as part of licensing renewal show forward thinking. In addition to oversight, collaboration and regulations, which ensure an aging fleet of nuclear power plants operate efficiently, profitably, and—most importantly—safely, are imperative in maintaining confidence in the industry.[82]

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[79] Office of Technology Assessment, 57.

[80] Office of Technology Assessment, 59.

[81] Office of Technology Assessment, 58.

[82] Office of Technology Assessment, 52.

III. CURRENT NUCLEAR POWER PLANT INFRASTRUCTURE

Risk plays a significant role in determining consequences, especially related to unlikely events. This chapter examines how the United States measures risk, focusing on the various probabilistic risk assessment tools and protective measures being deployed to safeguard the public from radiological exposure. Waste management in the United States is compared to that of other nations, and the placement of fixed nuclear power sites within the current fleet of commercial sites is determined.

A. RISK

Douglas W. Hubbard in *The Failure of Risk Management* claims component testing is valuable so long as the following are taken into account. First, he says when using experts, we should be mindful that mistakes do happen during their analysis. Second, we must be cognizant of various scoring classifications and understand the meaning of their application. We should use a degree of caution, using quantitative models and computer software applications to make sure they are making realistic calculations. Last, any of these methods "should meet the same standard of a measurable track record or reliable predictions."[83]

Hubbard further argues that to ensure risk assessments have been properly conducted, they should be checked for completeness. Many institutions fail to apply these methods to all major risk areas, which could have devastating effects on their operations.[84] Some areas for consideration beyond the physical structure include the environment, the climate, and even the organizational culture. The physical components of a nuclear power plant are well known throughout the industry, but one should never dismiss the other factors that influence risk. Hubbard suggests there are four perspectives of completeness. First, all parts of the organization should be included and not controlled by any single part of the organization, ensuring the analysis is equally evaluated across the organizational

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[83] Douglas W. Hubbard, *The Failure of Risk Management: Why It's Broken and How to Fix It*, 1st ed. (Hoboken, NJ: Wiley, 2009), 46–47.

[84] Hubbard, 47.

structure. Second, make sure outside agencies, vendors and the community are considered, as they see things very differently than the organization does. Doing so provides perspectives on risks never previously identified. Third, think of the impossible, those rare events that are unlikely to occur. Incidents like those at Three Mile Island, Chernobyl, or Fukushima were not even conceivable by most in the industry, looking at the historical context. While not highly probable, they could indeed become a reality. Last, Hubbard argues for combinational completeness, which has more merit than all the others, in other words, mixing variations of the aforementioned factors and scenarios and constructing scenarios that indeed may happen and pose severe harm to others.[85]

In assessing risk, there is a need to include unlikely events, according to Nassim Nicholas Taleb, author of the *Black Swan.* Taleb chides, “What is surprising is not the magnitude of our forecast errors, but our absence of awareness of it.”[86] Taleb suggests that people become complacent and comfortable with traditional ways of assessing risk by looking at things they know rather than the things that are not known. He calls this state “Mediocristan,” a fictional place designed as a utopian province in which no single observation has a meaningful impact on the aggregate. He explains that people concentrate on those events that are most predictable inside the bell-shaped curve. Counter to this type of utopian providence is “Extremistan,” whose events live on the extreme outer edges of the curve and predictability. Taleb continues: “Mediocristan is where we must endure the tyranny of the collective, the routine, the obvious, and the predicted; Extremistan is where we are subjected to the tyranny of the singular, the accidental, the unseen, and the unpredicted.”[87] Mediocristan is a perilous place to reside, and he explains people must consider the extreme possibilities that can disproportionately affect the whole.

While today’s nuclear power plant fleets have passive operating systems built into their design, as previously stated, these systems are aging, and human interaction is still required for operations. Thus, both the age of facilities and human error are likely

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[85] Hubbard, 48–49.

[86] Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable*, 1st ed. (New York: Random House, 2007), l.

[87] Taleb, 35.

vulnerabilities if not identified and managed well. A black swan event may be initiated by SSCs or introduced by humans or both. According to Nick Catrantzos in an article for *Homeland Security Affairs,* "The infiltrator eluding detection or interference is free to operate in the dark corners of insufficient oversight and management, as long as his behavior and work performance do not deviate so much from the norm as to invite invitation."[88] Mechanical and human elements need to be monitored as vulnerabilities; if nuclear operators assume these elements always operate as intended, complacency will bring about Mediocristan. Today's risk assessment process continues to consider many of the components and environmental vulnerabilities of a nuclear power plant but may fall short of including operating culture to assess combinational completeness accurately.

The Light Water Reactor Sustainability Program, developed by the U.S. Department of Energy's Office of Nuclear Energy, identified four objectives:

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the administration's energy security and climate change goals.
3. Develop sustainable nuclear fuel cycles.
4. Understand and minimize the risks of nuclear proliferation and terrorism.[89]

All of these objectives will need to be supported by a risk assessment process or tool that can adequately mitigate mechanistic (deterministic) and stochastic (non-deterministic or random variable) safety margins.[90] As a defense-in-depth, most nuclear power plants are designed with redundant systems and operate safely.[91] Because of the aging nuclear power plants and their increased potential for SSC failures, a risk-informed safety margin

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[88] Nick Catrantzos, "No Dark Corners: A Different Answer to Insider Threats," *Homeland Security Affairs* 6 (May 2010), https://www.hsaj.org/articles/83.

[89] Department of Energy, *Light Water Reactor Sustainability Program: Integrated Program Plan*, INL/EXT-11-23452, rev. 3 (Washington, DC: Office of Nuclear Energy, April 2015), iii–iv, https://www.energy.gov/sites/prod/files/FY-15_LWRS_IPP_Final_0.pdf.

[90] Department of Energy, 36.

[91] Department of Energy, 31.

characterization (RISMC) tool was developed. While mechanistic margins are more conservative in guessing uncertainty, "RISMC Pathway uses the probability margin approach to quantify impacts to economics, reliability, and safety to avoid excessive conservatism (where possible) and threat uncertainties directly."[92] One might argue that deterministic methods provide a safeguard in preventing failures with a greater safety margin. However, if facilities push the maximum life expectancy for SSCs, they run a higher risk of failure. Others may say it allows the industry to align the life expectancy of SSCs appropriately inside nuclear power plants, shoring up the baseload power necessary to achieve the energy objectives.

The United States has come a long way in developing technologies that have computational capabilities essential to run some possible scenarios, helping the industry determine its limitations in running aging systems.[93] The industry should be lauded for trying to extend the life of nuclear power plants, although it is placing a great deal of confidence in SSCs maintaining their physical integrity, as these algorithms suggest. The United States must be realistic regarding these risk assessments, in that the people are frightened at the mere thought of a nuclear accident, considering the risks that are more likely to happen and affect health and safety. These include developing cancer from exposure to toxic chemicals, dying in a car accident, or even having a home catch fire. In September 2018, over 8,000 people were driven from their homes in Andover, North Andover, and Lawrence, Massachusetts, from an over-pressurized gas line.[94] This incident claimed one life and injured a dozen more. Gas line explosions are common in daily life, yet half of the households in the United States continue to use gas.[95]

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[92] Department of Energy, 32.

[93] Department of Energy, 40.

[94] "Gas Explosions Drive Thousands from Homes in Boston Suburbs," Independent Journal Review, September 14, 2018, https://ijr.com/2018/09/1123840-gas-explosion-boston/.

[95] "Uses of Natural Gas," Geology, accessed October 1, 2018, https://geology.com/articles/natural-gas-uses/.

B. WASTE DISPOSAL

Most of the plants operating around the world are aging; many are beginning to close because they are competing against low fossil fuel prices and the high cost of managing nuclear waste. The older facilities are not capable of efficiently burning nuclear fuel. Only about 7 percent of the fissile material is being used; the remaining isotopes are considered waste.[96] There is technology to reprocess or burn current radiological waste in newly designed fast breeder reactors. Instead, the United States continues to stockpile waste and look for alternative energy sources when viable energy could be adapted to meet American needs well into the future.

Many have wondered what happens to nuclear power plant waste. There are many ways to handle waste; exploring what other nations have done may benefit the United States. It is essential to compare countries with similar governmental structures, populations, types of reactors in service, and the percentage of power supplied to the energy grid. Today, about 11 percent of the world's power is produced by nuclear generation.[97] Given the vast differences between each country, it may be impossible to compare all states equally; however, this thesis outlines only similarities and differences when possible. The research includes Japan, Finland, and France.

Dealing with nuclear waste has been a heavily debated topic and prohibits the growth or expansion of nuclear power. The Nuclear Association "estimates that there is around 240,000 tons of spent fuel across the world."[98] Also, at "current rates of production, around 1.1 million tons will be produced worldwide over the next 100 years."[99] Placing this amount of waste into perspective, the average car weighs roughly 4,000 pounds; this amount of waste is equivalent to 551,268 automobiles, or 40 football fields with vehicles

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[96] "Nuclear Fuel Cycle Overview," World Nuclear Association, accessed June 3, 2018, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx.

[97] "Nuclear Power Reactors," World Nuclear Association," last modified October 2018, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx.

[98] Helen Gordon, "Journey Deep into the Finnish Caverns Where Nuclear Waste Will Be Buried for Millenia," *Wired* (UK), April 24, 2017, http://www.wired.co.uk/article/olkiluoto-island-finland-nuclear-waste-onkalo.

[99] Gordon.

stacked 10 rows high. To replace or reprocess fuel, the spent uranium must be placed into spent fuel pools to reduce the fuel source to temperatures that are safe to handle without burning off the first level of protective shielding called zirconium cladding. Zirconium tubes containing uranium pellets make up the fuel rods; putting them together creates the fuel assembly.[100] As described by the Union of Concerned Scientists,

> The spent fuel rods are still highly radioactive and continue to generate significant heat for decades. The fuel assemblies, which consist of dozens to hundreds of fuel rods each, are moved to pools of water to cool. They are kept on racks in the pool, submerged in more than twenty feet of water, and water is continuously circulated to draw heat away from the rods and keep them at a safe temperature.[101]

According to the NRC,

> Once the fuel has cooled, which can take one to five years, it will then be transferred from the pool to a dry steel cask. An inert gas is pumped inside, and then it is placed into another cask made of steel or concrete shielding the material inside. This cask is then placed within a secure location on property waiting to be transferred to the long-term repository.[102]

The Japanese have been looking for a way to store its 18,000 tons of nuclear waste. It has release maps that identify possible locations, despite having to avoid fault lines and volcanic activity, without any significant public opposition. Before storage of this material, the fuel will be reprocessed. Japan has invested in a large-scale reprocessing plant expected to be completed sometime in 2018 in the northern part of the country.[103] The Japanese are in a much better position than the United States because less waste will be stored and the reprocessed fuel will be used to generate additional electricity.[104] Despite the disaster at the Fukushima Daiichi plant in 2011, the Japanese people seem overwhelmingly supportive

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[100] Arthur T. Motta, Adrien Couet, and Robert J. Comstock, "Corrosion of Zirconium Alloys Used for Nuclear Fuel Cladding," *Annual Review of Materials Research* 45, no. 1 (July 2015): 313, https://doi.org/10.1146/annurev-matsci-070214-020951.

[101] Union of Concerned Scientists, "Safer Storage of Spent Nuclear Fuel."

[102] Hoi Ng, "Dry Cask Storage," March 19, 2014, http://large.stanford.edu/courses/2014/ph241/ng2/.

[103] Stephen Stapczynski and Emi Urabe, "Japan Releases Map of Areas Suitable for Nuclear Waste Disposal," Bloomberg, July 28, 2017, https://www.bloomberg.com/news/articles/2017-07-28/japan-releases-map-of-areas-suitable-for-nuclear-waste-disposal.

[104] Stapczynski and Urabe.

of nuclear power.[105] The culture is possibly reluctant to voice opposition because the people fear losing community benefits such as jobs and subsidies to their local units of government for public works projects. Also, they might be less concerned about nuclear power because they have limited oil and gas reserves to fuel their economy and neighborhoods.[106] In contrast, support for nuclear energy in the United States wavers, even though citizens receive similar benefits from the industry. The Japanese nuclear industry states the support it receives from the public has nothing to do with subsidies. Instead, the public has a great deal of confidence in how it runs its operations.[107]

Finland does not have reprocessing capabilities but needs to reclaim about 6,500 tons of nuclear waste already generated by its nuclear energy facilities.[108] Finland is in the process of building a geological repository for spent fuel, called the Onkalo Nuclear Waste Repository (ONWR), on the island of Olkiluoto in Western Finland; it will not be in service until sometime in 2020. The ONWR is the first high-level spent fuel repository in the world.[109] Germany, Finland's neighbor, has been operating a low-level and intermediate-level waste storage facility called Asse II since 1967, similar to the U.S. Waste Isolation Program Plant (WIPP), which has been running since 1999. However, high-level waste facilities require a higher degree of confidence in their integrity.[110] Asse II experienced some problems with the stability of walls and moisture; consequently, WIPP is being evaluated for the same concerns.[111] Finnish citizens are supportive of the ONWR waste facility, unlike citizens' reactions to the Yucca Mountain project in the United States; even

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[105] Martin Fackler and Norimitsu Onishi, "In Japan, a Culture That Promotes Nuclear Dependency," *New York Times*, May 30, 2011, https://www.nytimes.com/2011/05/31/world/asia/31japan.html.

[106] Fackler and Onishi.

[107] Fackler and Onishi.

[108] Tom Turula, "Finland's '100,000-Year Tomb' for Nuclear-Waste Storage Is Gaining the World's Admiration," Business Insider (Nordic), January 25, 2017, https://nordic.businessinsider.com/finlands-100000-year-tombs-for-storing-nuclear-waste-is-drawing-the-worlds-admiration-2017-1/.

[109] Adam Wernick, "Finland's Solution to Nuclear Waste Storage May Set an Example for the World," Public Radio International, July 21, 2017, https://www.pri.org/stories/2017-07-31/finlands-solution-nuclear-waste-storage-may-set-example-world.

[110] "Disposal Plans (Part 4: Low- and Intermediate-Level Waste)," Nuclear Engineering International, July 3, 2012, https://www.neimagazine.com/features/featuredisposal-plans-part-4-low-and-intermediate-level-waste.

[111] Nuclear Engineering International, "Disposal Plans."

though the residents are skeptical, trust in their government to develop a safe repository prevails. Trusting in governmental authority and scientists is a part of the Finnish culture, unlike in the United States. Also, many of the people living in the area benefit from jobs and a tax base provided by the industry. The Finnish people's general acceptance seems similar to that of the Japanese regarding the nuclear industry.[112]

In France, Andra was created in 1979 under the French Waste Act of 1971as a public body to deal with long-term storage of nuclear waste.[113] Andra has identified a possible repository in Bure in northeastern France for relocating 29,000 tons of nuclear waste. France has the technical ability to determine an appropriate site; however, the political debate seems to be the most significant hurdle. France is second to the United Kingdom in the most nuclear waste in Europe. A small group of people has formed on-site camps to protest against the construction. "There is no real local opposition to the project," says Dominique Minière, executive director in charge of the nuclear fleet for France's utility company, Electricite' de France. "We are in front of professional opponents."[114] The government has attempted to engage with the larger community through public outreach, but it does not seem to be changing people's minds. Despite all of the efforts to explain the technical research conducted addressing safety concerns and the economic benefits, many people in the general population have not been swayed to support this project. French opposition starkly contrasts the attitudes of the public in Japan and Finland.

In the United States, there is about 50 tons of nuclear waste. The United States has a repository for low-level and intermediate-level waste at the U.S. WIPP, which has operated since 1999, with a total of 2,150 square feet underground in an impermeable salt bed, free of moisture. A probabilistic risk assessment has determined that the risk of

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[112] Wernick, "Finland's Solution to Nuclear Waste Storage."

[113] "French National Radioactive Waste Management Agency (Andra)," Fund It, January 15, 2016, http://www.fundit.fr/en/institutions/french-national-radioactive-waste-management-agency-andra.

[114] Kalina Oroschakoff and Marion Solletty, "Burying the Atom: Europe Struggles to Dispose of Nuclear Waste," Politico, July 19, 2017, https://www.politico.eu/article/europes-radioactive-problem-struggles-dispose-nuclear-waste-french-nuclear-facility/.

material escaping from the repository is about one in 10 million.[115] However, there was one accident on February 14, 2014, when transuranic waste produced exothermic heat, compromising a container.[116] Even though the release occurred, the Environmental Protection Agency found that "based on the source term measured by DOE [Department of Energy] in the several days after the event, the modeling indicated that the release was very low-level."[117] This finding suggests negative impacts on human health and the environment were negligible. The United States has also built a high-level waste repository at the Nevada Test Site inside Yucca Mountain. The site is 500 square miles, about 90 miles northwest of the Las Vegas valley. In 1978, the Department of Energy studied Yucca Mountain as a potential repository for nuclear waste; in 1987, Yucca Mountain was designated by the Nuclear Waste Policy Act as the site for a nuclear waste repository.[118] The decision to proceed with Yucca Mountain was a political rather than a technical decision because the land was already owned by the federal government, which was a fitting way to build it. The repository was started in 1995, boring a five-mile road into the granite mountain.[119] Currently, the project has halted until more technical studies can ensure the safety of those living near the facility. The pushback from the state of Nevada was successful in stopping this project from moving forward.

The problems are real in the United States regarding the disposal of radiological material. Most of the content today has a half-life of about 100,000 years. To date, there is no precedent in building a structure that lasts many years other than relying on deep geological formations that have existed for millions of years. Identifying a geological

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[115] Rip Anderson and Gwyneth Cravens, "Power to Save the World," Long Now Foundation, September 14, 2007, http://longnow.org/seminars/02007/sep/14/power-to-save-the-world/.

[116] "2014 Radiological Event at the WIPP," Environmental Protection Agency, accessed December 5, 2018, https://www.epa.gov/radiation/2014-radiological-event-wipp.

[117] "Consequence Assessment Review Summary for the February 2014 Radiological Emission Release at the Waste Isolation Pilot Plant," EPA Air Docket A-98-49, Item II-B1-33 (Environmental Protection Agency, August 2014), 1, https://www.epa.gov/sites/production/files/2015-05/documents/consequence-assessment-review.pdf.

[118] "Yucca Mountain Information," Churchill County Nuclear Waste Oversight, accessed May 31, 2018, http://churchillcountynwop.com/yucca.htm.

[119] "Scientific Modeling for the Proposed High-Level Waste Repository at Yucca Mountain," Intera, accessed May 30, 2018, https://www.intera.com/intera-solutions/scientific-modeling-for-the-proposed-high-level-waste-repository-at-yucca-mountain/.

structure that would safely permit the deposit of such materials has been and will be scrutinized for many years to come. In the 1980s, there was a national effort to build a scientific and political consensus for possible repositories placed around the country, very much like France and Japan had determined the best long-term storage in their respective countries. While many sites were identified in the United States, the political pressure drowned out scientific recommendations, and in 1987, the amendment to the Nuclear Waste Policy Act was approved by Congress to use Yucca Mountain as a single repository. Even though the facility was almost completed in 2008, President Obama signed an executive order to prevent any movement of radiological material to the site until further environmental studies were completed.[120] This delay has blocked the transfer of solid nuclear waste to a repository, exponentially increasing the cost to the nuclear power plant industry and taxpayers in maintaining on-site dry cask storage with enhanced security measures.[121] Most suggest the United States has probably outgrown the Yucca Mountain facility even if the site were to open.[122]

The nation is coming to the realization that it has done significant damage to the environment and a balance needs to prevail before it continues to do more harm. The United States has roughly 50 years before its spent fuel storage facilities will be reaching their life expectancies. Whether the nation continues to use nuclear power or phase it out of the energy sector, it needs a solution to deal with the waste. To change course in managing radiological waste, a considerable amount of time and financial resources needs to be allocated. The nation must begin the dialogue that will create a policy to address this issue, set aside the proper funding, and educate the public, who will either benefit from or face the consequences of the decisions made.

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[120] Hannah Northey, “GAO: Death of Yucca Mountain Caused by Political Maneuvering,” *New York Times*, May 10, 2011, https://archive.nytimes.com/www.nytimes.com/gwire/2011/05/10/10greenwire-gao-death-of-yucca-mountain-caused-by-politica-36298.html?pagewanted=2.

[121] Government Accountability Office, Nuclear Waste Management: Key Attributes, Challenges, and Costs for the Yucca Mountain Repository and Two Potential Alternatives, GAO-10-48 (Washington, DC: GAO, November 2009), 1, https://www.gao.gov/assets/300/298028.pdf.

[122] Sarah Zhang, “The Plan for Storing US Nuclear Waste Just Hit a Roadblock,” *Wired*, July 17, 2015, https://www.wired.com/2015/07/plan-storing-us-nuclear-waste-just-hit-roadblock/.

C. SITE SELECTION

The AEA of 1954 and the Energy Reorganization Act (ERA) of 1974 created a new agency, the NRC, to provide oversight of the commercial nuclear power plant industry.[123] The ERA was designed to "encourage widespread participation in the development and utilization of atomic energy for peaceful purposes to the maximum extent consistent with the common defense and security and with the health and safety and public."[124] Furthermore, ERA recognizes the need for "a program of international cooperation to promote the common defense and security and to make available to cooperating nations the benefits of peaceful applications of atomic energy as widely as expanding technology and considerations of the common defense and security will permit."[125] Currently, nuclear power plants fall under 10 C.F.R. § 100, which outlines the site selection process for stationary power reactors. More importantly, the NRC develops regulatory guidance documents to provide more specific details on how to comply with the law. Regulatory Guide 4.7 speaks to general site suitability and significant site characteristics that might affect the health and safety of the public.[126] These characteristics include geology; seismology; atmospheric dispersion; population; emergency planning zones; security; hydrology, which provides for flooding and water availability to cool the reactor core; and accident-prone facilities, such as military installations, volatile industrial facilities, and transportation corridors.[127] The need to consider all the suitability characteristics to build or maintain a fixed site today can be a distinct advantage for small modular reactors, which are discussed in Chapter IV.

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[123] Atomic Energy Act of 1954, Pub. L. 115-246, https://legcounsel.house.gov/Comps/Atomic%20Energy%20Act%20Of%201954.pdf.

[124] Nuclear Regulatory Commission, *Nuclear Regulatory Commission Issuances*, NUREG-0980, vol. 1, no. 10 (Washington, DC: NCR, Office of the General Counsel, September 2013), 16.

[125] Nuclear Regulatory Commission, 23.

[126] Nuclear Regulatory Commission, *General Site Suitability Criteria*.

[127] Reactor Site Criteria, 10 C.F.R. § 100 (2004), https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/full-text.html.

It takes less land to accommodate a fixed nuclear site than it does for wind or solar energy, taking up approximately 1.3 square miles per 1,000 megawatts (MW) produced.[128] The largest facility is the Palo Verde Nuclear Power Plant, which generates 3,937 MW.[129] Site characteristics are vital in deciding where to place a nuclear power plant despite challenges the industry faces with public perception when bringing this technology into the community, as mentioned in Chapter II.

From a geological or seismic perspective, since the disaster of Fukushima Daiichi, many U.S. regulators have been concerned about the current nuclear power plant infrastructure in the country. According to probabilistic seismic risk assessments conducted by the U.S. Geological Survey (USGS) in 2006, there is a slightly higher risk for nuclear plants in the central and eastern United States than was previously understood. In 2009, the NRC reviewed the regulatory guidance for seismic activity and concluded the facilities in question provided adequate levels of protection for this risk.[130] While this may be comforting to many, others worry about those black swan possibilities outside the realm of probabilistic risk assessment. Earthquakes are subtle in most parts of the country and do not cause damage to fixed facilities.[131] Figure 7 displays the existing nuclear power plants overlaid onto a recent USGS seismic map.

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[128] "Land Needs for Wind, Solar Dwarf Nuclear Plant's Footprint," Nuclear Energy Institute, July 9, 2015, https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants.

[129] "How Much Electricity Does a Nuclear Power Plant Generate?," Energy Information Administration, accessed October 6, 2018, https://www.eia.gov/tools/faqs/faq.php?id=104&t=3.

[130] M. Reisi Fard, *Resolution of Generic Safety Issues*, NUREG-0933, rev. 1 (Washington, DC: NRC, Division of Risk Analysis, December 2011), https://www.nrc.gov/sr0933/Section%203.%20New%20Generic%20Issues/199r1.html.

[131] Jim Morris and Bill Sloat, "Regulators Aware for Years of Understated Seismic Risks to Nuclear Plants," Center for Public Integrity, March 18, 2011, https://www.publicintegrity.org/2011/03/18/3700/regulators-aware-years-understated-seismic-risks-nuclear-plants.

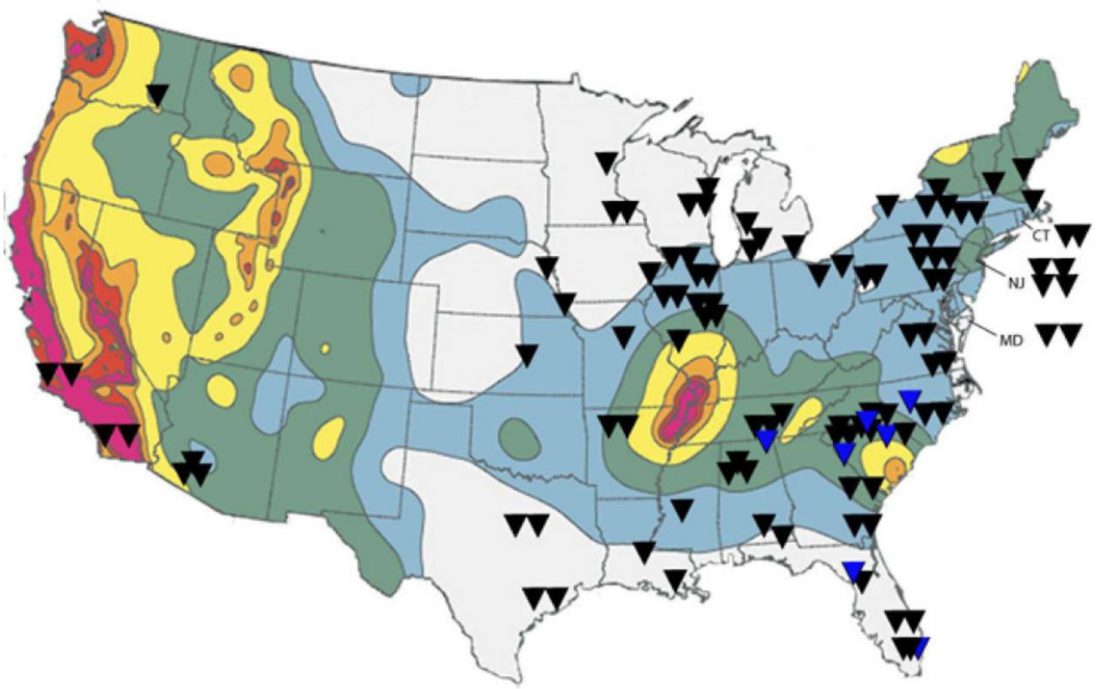

Figure 7. Seismic Risk and Nuclear Power Plant Locations[132]

Atmospheric dispersion is how the air moves radioactive materials around; mixing and dilution (parts of dispersion) control how aerosol-sized particles move downwind, which leads to dose. This is one of the first concerns during an accident because air is the most efficient way to spread radioactive contamination.[133] Dispersing harmful particulates into the environment has long been a concern for much of the energy industry. It cannot be overstated; nuclear energy releases no toxicity detrimental to health or the environment during normal operations—unlike other forms of energy.[134] The U.S. strategy had been to build huge plants to be more cost efficient. This seemed reasonable when power was in high demand, and long-term financial projections could justify the enormous cost in

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[132] Source: Jerry James Stone, "Nuclear Reactors in Earthquake Zones in the U.S.," Treehugger, March 18, 2011, https://www.treehugger.com/corporate-responsibility/nuclear-reactors-in-earthquake-zones-in-the-us-map.html.

[133] "Atmospheric Dispersion," accessed October 6, 2018, European Union, Joint Research Centre, https://rem.jrc.ec.europa.eu/RemWeb/activities/AtmosphericDispersion.aspx.

[134] Pushker Kharecha and James Hansen, "Coal and Gas Are Far More Harmful Than Nuclear Power," NASA, April 22, 2013, https://climate.nasa.gov/news/903/coal-and-gas-are-far-more-harmful-than-nuclear-power.

building nuclear power plants. However, larger facilities yield a great deal more radioactive fuel and waste. Simulation tools help to predict the amount of risk associated with large nuclear facilities, especially when a wide range of variables like environmental conditions and plant size are introduced. Simulation tools lend some degree of certainty in the dose associated with a release, ultimately leading to measures that are logical with respect to protecting the public and the environment.[135]

Across the nation, various forms of energy pose a risk to populations who live near extraction sites, production facilities, or transmission and distribution lines. Nuclear power is not any different in that regard—no harmful effects come from the facility during normal operations unless the plant has an accident causing a "scram," a rapid shutdown of the core, due to a problem with SSCs or a loss of coolant accident. In the event of an accident and upon discovery of a release, the guidance establishes zones to achieve protective action for the population as well as exposure limits. This is called the exclusion area (EA) and the low population zone (LPZ). The facility is required to demonstrate protective measures for populations of more than 25,000 who reside within 1 1/3 miles from the reactor.[136] The NRC uses this protective approach as a "defense-in-depth philosophy."[137] Most facilities around the world follow these same protective measures; however, some have determined it more expedient to own the land around the facility to meet the requirement. Interesting enough, Saudi Arabia, one of the largest oil producers in the world, has started construction on four nuclear power plants for an investment of $163 billion and aims to achieve half of its energy needs by 2050 from renewables and nuclear power.[138] In its construction license, it avoided the establishment of an LPZ through land acquisition and commuting employees

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[135] Theodoros Christoudias, Yiannis Proestos, and Jos Lelieveld, "Atmospheric Dispersion of Radioactivity from Nuclear Power Plant Accidents: Global Assessment and Case Study for the Eastern Mediterranean and Middle East," *Energies* 7, no. 12 (2014), https://www.mdpi.com/1996-1073/7/12/8338/htm.

[136] Reactor Site Criteria.

[137] "Diversity and Defense in Depth in Digital Instrumentation and Controls," Nuclear Regulatory Commission, accessed October 6, 2018, https://www.nrc.gov/about-nrc/regulatory/research/digital/key-issues/diversity-defense.html.

[138] "Nuclear Power in the United Arab Emirates," World Nuclear Association," last modified July 2018, http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-arab-emirates.aspx.

by mass transit. The closest population center is Sila'a-Ba'aya, 48 km (29.82 miles) west-northwest, which provides some additional relief.[139] While it depends on the plant design, the EA and LPZ in the United States are typically 1.5 miles away from the reactor.

While the guidance considers those living near a nuclear power plant, it also speaks to having a plan in place for a plume exposure pathway (PEP) and an ingestion exposure pathway (IEP) (see Figure 8).

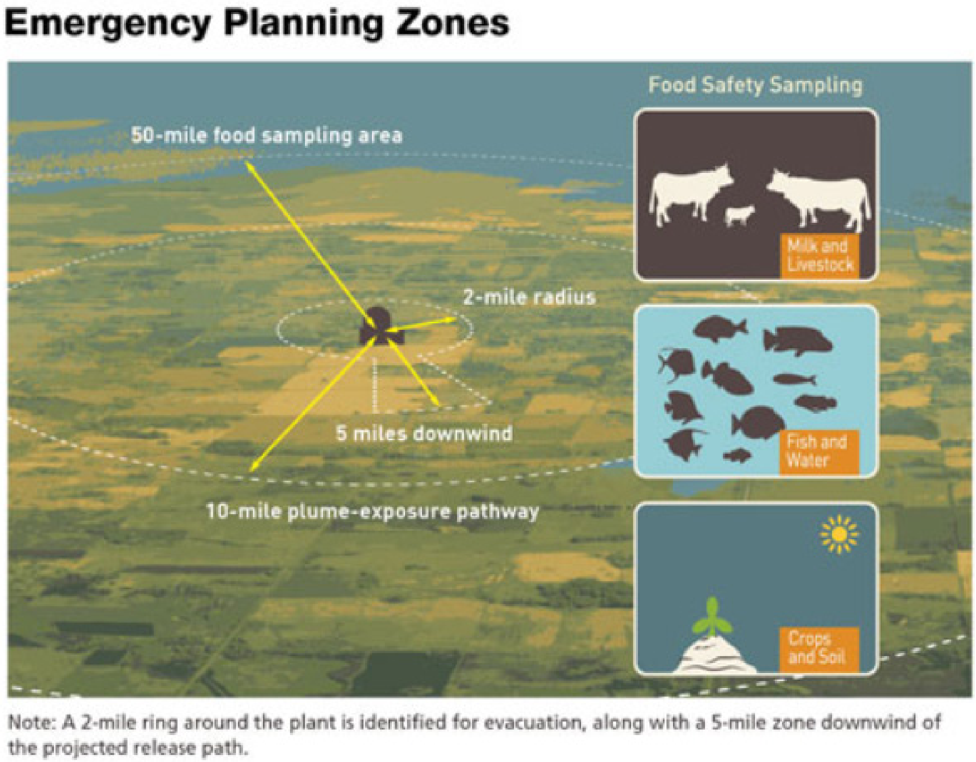

Figure 8. NRC Emergency Planning Zones[140]

The PEP identifies the dose of the release and direction, speed and action appropriate to protect the public. This includes determining whether to evacuate or shelter-

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[139] "Building Barakah," Nuclear Engineering International, September 28, 2012, http://www.neimagazine.com/features/featurebuilding-barakah/.

[140] Source: "Emergency Planning Zones," Nuclear Regulatory Commission, last modified November 16, 2018, https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html.

in-place, identifying those with special needs who cannot help themselves and even public decontamination within 10 miles of the plant if necessary. The IEP determines the food products that can be consumed up to 50 miles from the facility. A handful of reactor meltdowns have been able to provide some insight into the value of these two exposure pathways. The first was in 1952 at a test reactor called BORAX I, a 1.4 MW reactor used for a power excursion (deliberate uncontrolled chain reaction) to aid in early designs of nuclear power for peaceful purposes. Following that, a small modular reactor (SL-1) plant—rudimentary compared to today's technology—designed for remote military facilities was being operated on the remote Idaho desert. On January 3, 1961, the improper manual withdrawal of a control rod caused an explosion, killing three facility operators. There was a release of radioactive materials from these two sites; however, PEP and IEP were not standards and, even if they had been, the exposure was relatively small, with no lasting effects. These two events were followed by meltdowns at Fermi I in Monroe, Michigan, in 1969 and Three Mile Island in 1979, neither of which ever produced an off-site release. The two most devastating nuclear meltdowns were at operating facilities in Russia and Japan. In 1982, Chernobyl, with no containment structure, released a significant amount of radiation into the environment, killing many workers; over 116,000 were evacuated from the exclusion area.[141] Finally, the case of Fukushima Daiichi—arguably a black swan event—exceeded its probabilistic risk assessment after suffering three simultaneous reactor meltdowns. As of today, out the 164,865 people who were evacuated, 115,373 have returned.[142] Notably, while there are and will continue to be health and environmental implications for many years in these countries, both of these accidents were preventable.

Hydrology is another significant consideration under the guidance documents. Hydrology consists of extreme rainfall, seismic activity causing dam failure, or tsunami activity such as that at Fukushima Daiichi. However, the most significant concern under

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[141] "What Was the Extent of the Chernobyl Accident?," Green Facts, accessed October 6, 2018, https://www.greenfacts.org/en/chernobyl/l-2/1-chernobyl-accident.htm#0.

[142] "Transition of Evacuation Designated Zones," Fukushima Prefectural Government, last modified November 12, 2018, http://www.pref.fukushima.lg.jp/site/portal-english/en03-08.html.

the guidance is to ensure the availability of water to cool the reactor core and even spent fuel pools. If water had been appropriately applied in all the situations mentioned, none of these circumstances would have occurred.

Another way SSCs could be at risk is by siting plants near critical infrastructures such as chemical storage facilities, manufacturing plants, and military complexes. These types of facilities could produce shock waves during normal operations or in the event of an accident.[143] These nearby facilities are not only vulnerable to accidents but also targets of U.S. adversaries. If an attack occurred against a current nuclear power plant, panic would ensue upon seeing a cloud rise near or at the site, signaling to ordinary people a release of nuclear material had occurred.

Security measures for nuclear sites include buffer zones, detection equipment, isolation zones, vehicle barriers, and staff. As mentioned under the risk section of this chapter, one cannot rule out an insider threat causing harm to the facility. Credentialing at the highest levels of guests and every staff member is equally essential in protecting the plant from adversaries. According to a 2007 article in *Esquire* magazine, the chief of security at the Palisade Nuclear Power Plant in Covert, Michigan, was able to secure his position with a complete and utter fabrication of his past.[144] These types of mistakes at a single plant could displace families from their homes for generations and collapse an entire industry.

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[143] Reactor Site Criteria.

[144] Tom Junod, "Mercenary," *Esquire*, June 26, 2007, https://www.esquire.com/features/mercenary0607.

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IV. SMALL MODULAR REACTORS

This chapter introduces key features that SMRs offer to reduce the risk associated with nuclear power generation. The review focuses on NuScale Power, which has developed an SMR that considers advanced probabilistic risk assessment tools to reduce the consequences of SSCs. In addition, it examines the benefits of recycling waste and selecting the right site for an SMR.

A. RISK

As mentioned in Chapter III, SMRs in the United States existed previously at the National Reactor Testing Station in Idaho Falls, Idaho, with the small experimental stationery low power reactor. The SL-1 plant was designed for remote military facilities along the distant early warning (DEW) line, "an integrated chain of 63 radar and communication centers stretching 3000 miles from Western Alaska across the Canadian Arctic to Greenland." DEW was established as a line of defense against Russian aviation.[145] At the time, only the U.S. Navy was using this technology, for submarines. The stationary low (SL)–powered reactor is similar to the proposed SMR, and the prototype was operational at Idaho Falls in autumn of 1958.[146] To control the chain reaction, the fuel rods needed manipulating. On January 3, 1961, the plant suffered an explosion, killing three men. There are several theories why this failure occurred—accidental removal of a control rod too quickly, suicide, murder, or even government sabotage.[147] Either way, human interaction with the reactor was the cause of the failure. Today, nuclear power fleets operate on passive systems. SL-1 was designed as a first generation nuclear reactor, and two additional generations have followed since. They have been equipped with electrical

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[145] Adam Lajeunesse, "The Distant Early Warning Line and the Canadian Battle for Public Perception," *Canadian Military Journal* (Summer 2007), http://www.journal.forces.gc.ca/vo8/no2/lajeunes-eng.asp.

[146] "SL-1: Murder by Nuclear Reactor," *Passing Strangeness* (blog), July 20, 2015, https://passingstrangeness.wordpress.com/2015/07/20/sl-1-murder-by-nuclear-reactor/.

[147] *Passing Strangeness*, "SL-1: Murder by Nuclear Reactor."

or mechanical system features that automatically activate or have a human interface.[148] Generation III systems are Generation II facilities that have been modified with passive systems.[149] The latest version of Generation III facilities will add passive systems, eliminating the possibility of human error. In 2012, the Department of Energy sponsored a $450 million competition for the advancement of the country's production of nuclear energy.[150] Examples of these technologies include the 125 MW SMR introduced by Babcock and Wilcox Nuclear, Inc., called mPower, which is scalable, using light water reactor (LWR) knowledge, and entirely passive in design.[151] The other is a 45 MW reactor with similar attributes introduced by NuScale, an international consortium, with Westinghouse leading the way.[152] Unfortunately for the nuclear power plant industry, as of January 2018, Westinghouse has been in financial peril due to the development of its new AP100 nuclear power plant in South Carolina and Georgia while energy prices began to fall exponentially.[153] Currently, the NRC has been conducting a design review for the licensing of the SMR and other new designs that were fostered by this incentive. Many applications were being accepted for the advancement of nuclear energy, placing new reactor designs like the economic simplified boiling water reactor and the AP1000 on existing sites. Both of these proposed styles use passive safety systems under a combined license; however, today, according to the NRC website, most have withdrawn or suspended their applications.[154] The most substantial consideration for this is not safety but the difficulty in competing against other cheaper forms of energy. While this may seem

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[148] Stephen M. Goldberg and Robert Rosner, *Nuclear Reactors: Generation to Generation* (Cambridge, MA: American Academy of Arts and Sciences, 2011), 5.

[149] Goldberg and Rosner, 6.

[150] "mPower Empowered by SMR Funds," World Nuclear News, November 21, 2012, http://www.world-nuclear-news.org/NN-mPower_empowered_by_SMR_funds_121112a.html.

[151] Goldberg and Rosner, *Nuclear Reactors*, 12.

[152] Goldberg and Rosner, 12.

[153] Anya Litvak, "Bankrupt Westinghouse Inks $4.6 Billion Deal to Be Acquired by Canadian Asset Manager," *Pittsburgh Post-Gazette*, January 4, 2018, http://www.post-gazette.com/business/powersource/2018/01/04/Bankrupt-Westinghouse-pittsburgh-4-6-billion-deal-purchased-acquired-Canadian-asset-manager-Brookfield-Business-Partners/stories/201801040139.

[154] "Combined License Applications for New Reactors," Nuclear Regulatory Commission, accessed October 7, 2018, https://www.nrc.gov/reactors/new-reactors/col.html.

complicated for larger Generation III technologies, Utah Associate Municipal Power Systems (UAMPS) is still forging ahead at the Idaho National Laboratory with a combined license called the Western Initiative for Nuclear.[155] UAMPS is working with NuScale, which won a second Department of Energy contest for $33.2 million to advance the SMR and move toward a safe carbon-free power program.[156] These types of collaborative efforts are reducing the U.S. carbon footprint and, at the same time, supplanting aging nuclear power plants in the future.

The WASH-1400 reactor study prepared by Reynold Bartel states the NRC was using both quantitative probabilities and qualitative engineering judgments to regulate the operational activities of nuclear power plants.[157] According to Bartel, quantifying risks involves using the following "risk triplet":

1. What can go wrong?
2. How likely is it?
3. What are the consequences?[158]

The risk assessment process is known as probabilistic risk assessment (PRA), a means of examining some individual failures of SSCs that could predict a significant accident. As stated in this report, it was difficult to identify events that were likely to happen within practical limits of error.[159] The report suggests using "deterministic" events based on design principles and looking only at the initiating event, not the following sequence of failures that cause a catastrophic incident to occur. Thus, predictions are unlikely to happen, or "incredible."[160] On July 20, 1953, a statistician from General Electric at the time introduced an internal document called *The Elevation of Probability of Disaster*, focusing

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[155] "Carbon Free Power Project," NuScale Power, accessed October 7, 2018, https://www.nuscalepower.com/Projects/Carbon-Free-Power-Project.

[156] NuScale Power.

[157] Reynold Bartel, *WASH-1400: The Reactor Safety Study: The Introduction of Risk Assessment to the Regulation of Nuclear Reactors*, NUREG/KM-0010 (Washington, DC: Nuclear Regulatory Commission, August 2016), 1, https://www.nrc.gov/reading-rm/doc-collections/nuregs/knowledge/km0010/.

[158] Bartel, 1.

[159] Bartel, 3.

[160] Bartel, 5.

on a chain of events rather than a single deterministic event.[161] Over a period, General Electric discovered fault tree analysis, using Boolean logic, which had been used by the aerospace and airline industries. In the 1960s and 1970s, fault trees using Boolean logic were introduced to the nuclear industry, leading to a need to update to WASH-1400 in 1975. Possible scenarios went from 16 design-based scenarios to several hundred accident possibilities.[162] The subsequent report noted that specific regulations lacked the ability to prevent small loss of coolant (LOCA) accidents and human errors.[163] Shortly after this was published, the accident at Three Mile Island occurred from a loss of coolant, primarily because an operator failed—the cause was human error—to recognize the harm and ignored alarms related to containment temperatures.[164] After this incident, the NRC began many studies to address concerns indicated in the WASH-1400 report and established new regulations to reduce the possibilities of mechanical failures, human errors, or external influences. WASH-1400 was the precursor to enhance the PRA that is used today.[165] PRA is accomplished today using enhanced computational and simulation software, as noted in Chapter III.

The correct use of PRA should allow one to calculate whether an SMR will operate safely. The World Information Service on Energy suggests in a 2010 article that the cost, safety, and the waste generated by nuclear energy—let alone SMRs—is unacceptable. The opposition to this technology is primarily due to the cost of operation, no prototype to show proof of concept, no regulations for the design integrity, more complex waste problems, and the reduction in staff that leads to security issues or delays in responding to an accident.[166] On March 15, 2017, NuScale submitted its SMR design certification

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[161] Bartel, 11.

[162] "Dr. Robert Budnitz Explains Probabilistic Risk Analysis for Nuclear Power Plants," YouTube video, 1:04:20, posted by A4NR, October 28, 2015, https://www.youtube.com/watch?v=cf9G8vddUjk.

[163] Bartel, *WASH-1400*, 29.

[164] Bartel, 36.

[165] Bartel, 43.

[166] "Small Modular Reactors: No Solution for Costs, Safety and Waste Problems," *Nuclear Monitor*, August 10, 2010, https://www.wiseinternational.org/nuclear-monitor/717/small-modular-reactors-no-solution-costs-safety-and-waste-problems.

application, which included 12,000 pages of technical information.[167] It included a PSA outlining probabilities for failures on the components. The PSA determines the core damage frequency (CDF), which is one core damage event predicted in 300 million operating years, exceeding the goals of the NRC (see Figure 9). The NuScale design offers a completely passive system with a natural circulation flow path; it has no pumps, relying entirely on convection, conduction, and gravity.[168] This is based on a "triple crown" concept of no operator action needed, no AC/DC power necessary, and no additional water to cool the plant if an accident occurs.[169] The system relies on fewer SSCs than a light water reactor uses, reducing the likelihood of failure.[170]

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[167] "NRC Says NuScale SMR Won't Need Backup Electrical Power," *Neutron Bytes* (blog), January 12, 2018, https://neutronbytes.com/2018/01/12/nrc-says-nuscale-smr-wont-need-backup-electrical-power/.

[168] "Passive Systems," NuScale Power, accessed October 8, 2018, https://www.nuscalepower.com/benefits/safety-features/passive-systems.

[169] "Triple Crown for Nuclear Plant Safety," NuScale Power, accessed October 8, 2018, https://www.nuscalepower.com/benefits/safety-features/triple-crown.

[170] NuScale Power, "Submittal of the NuScale Standard Plant Design Certification Application (NRC Project No. 0769)" (official memorandum, NuScale Power, December 31, 2016), https://www.nrc.gov/docs/ML1701/ML17013A229.pdf.

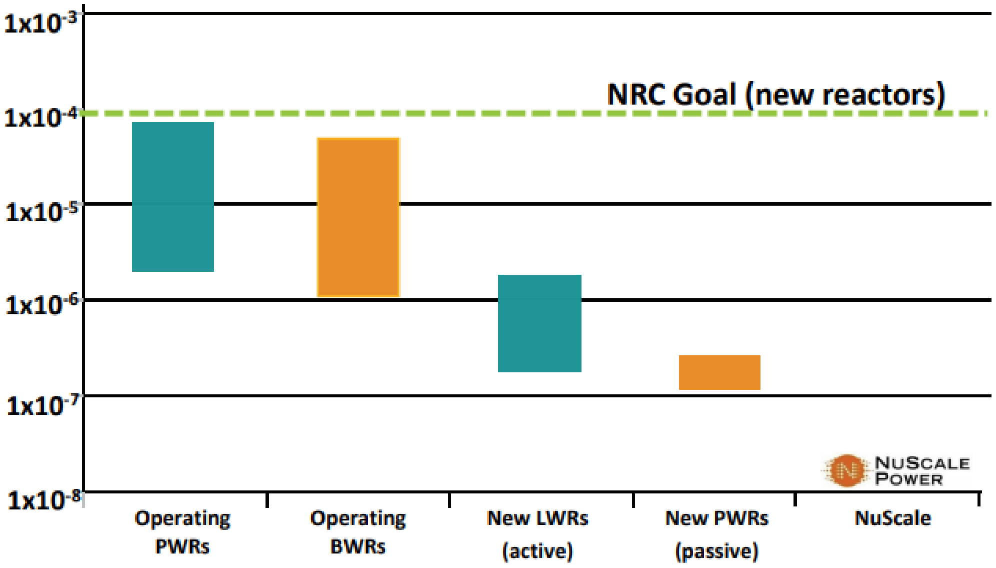

Figure 9. Core Damage Frequency in NuScale versus Current Fleet of Nuclear Power Plants[171]

B. WASTE DISPOSAL

According to the Union of Concerned Scientists, one out of every three Americans lives within 50 miles of nuclear waste.[172] Waste has been and will continue to be a problem well into the future unless a solution is found within the next 60 years, as the life expectancy of dry cask storage comes to an end. The NRC plans to develop an extended storage and transport regulatory program shortly to permit casks to remain on site for up to 300 years.[173] Dry cask spent fuel storage was used for large-scale reactor sites starting in 1986. There are no fuel storage facilities permitted to operate since the Yucca Mountain repository was

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[171] Source: Jose N. Reyes, "NuScale Technology Overview" (presentation, NRC Pre-application Meeting, Rockville, MD, June 2, 2010), 29, https://www.nrc.gov/docs/ML1015/ML101520622.pdf.

[172] "Infographic: Nuclear Power Safety," Union of Concerned Scientists, accessed October 9, 2018, https://www.ucsusa.org/nuclear_power/making-nuclear-power-safer/handling-nuclear-waste/infographic-dry-cask-cooling-pool-nuclear-waste.html.

[173] "Spent Fuel Storage in Pools and Dry Casks: Key Points and Questions & Answers," Nuclear Regulatory Commission, accessed October 9, 2018, https://www.nrc.gov/waste/spent-fuel-storage/faqs.html#21.

de-funded in 2008 under the Obama administration without explanation.[174] Most of the current reactor designs coming to market are integral pressurized water reactors and will continue to produce waste like traditional light water reactors currently in service. The waste from an SMR is no different regarding this dilemma; however, new technologies like SMR burn fuel more efficiently, leaving less waste to dispose of. In addition, SMRs do not require the plant to shut down for refueling. Each SMR in a facility assembly can be removed independently of the others. These units can be transferred to another part of the plant via crane, lowering risk of a traditional re-fueling accident.[175] This not only reduces risk but also allows the facility to continue providing reliable energy to the grid without interruption.

There are other designs being developed as breeder reactors that—in sync with SMR development—could lead to improvements in the fuel cycle. Breeder reactors use fast (energetic) neutrons working without a moderator. The fast neutron exchange in breeder reactors burns more fissile material during the process and generates less waste. These types of reactors use molten metal, liquid sodium, or helium to cool the reactor core.[176] The last two breeder reactors were Enrico Fermi from 1963 to 1972 and the Clinch River Plant in Tennessee until 1983, when Congress cut funding.[177] Both President Carter and President Ford were concerned that breeder reactors were producing plutonium, which could be used in weapons proliferation. In 1976, the nonproliferation policy was introduced, and the demise of breeder reactors throughout the United States was inevitable.[178] Finding a solution whereby both SMRs and breeder reactors can operate in

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[174] Northey, "Death of Yucca Mountain."

[175] NuScale Power, *Refueling Operations Report for the NuScale Power Module*, NP-DEM-RP-RFOP-002-NP (Corvallis, OR: NuScale Power, 2009), 5–4, https://www.nrc.gov/docs/ML0908/ML090850080.pdf.

[176] M. V. Ramana and Zia Mian, "Small Modular Reactors and the Challenges of Nuclear Power," American Physical Society, accessed October 9, 2018, https://www.aps.org/units/fps/newsletters/201701/reactors.cfm.

[177] "How Do Fast Breeder Reactors Differ from Regular Nuclear Power Plants?," Scientific American, accessed October 9, 2018, https://www.scientificamerican.com/article/how-do-fast-breeder-react/.

[178] "Presidential Actions: A Brief History," Frontline, accessed October 9, 2018, https://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/rossin1.html.

harmony has enormous potential for creating a safe, efficient energy source in the future while reducing waste that has already been produced.

C. SITE SELECTION

One major factor for the industry is the reduction of EPZs and PEPs. Currently, to operate a commercial nuclear power plant in the United States, a variety of site characteristics must be met, as was mentioned in Chapter III. The EPZ is generally used to identify areas where emergency planning and exercises take place to ensure the public that its federal, state and local governments can respond appropriately to protect the population within its limitation.[179] The other area of concern is the PEP, where modeling determines radiological contamination in food products that are ingested. If the EPZ and PEP were reduced, significant cost savings would be achieved by the industry. According to NuScale, which has been the only company to submit an SMR application to date, the justification is in having a low CDF; it has four additional barriers protecting the fuel source beyond the traditional three layers of containment required for today's light water reactors. NuScale also mentions the core size is only 5 percent of conventional cores, thus decreasing the chance of radioactive material being released into the environment. Last, using passive systems introduced into the NuScale model, LOCAs are very unlikely. Currently, these arguments are being evaluated by the NRC through the design certification application.[180] If the NRC agrees with the NuScale position on the reduction of the EPZ, it could provide significant savings, reducing reimbursement to federal, state, or local governments for providing the planning, training, and exercises currently required under the regulation. A study by the Idaho National Laboratory in 2014 found that for the 20 sites surveyed, the cost by the industry for emergency planning standards ranges from $755,000 to $6.3 million, for an average of $2.25 million.[181]

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[179] Nuclear Regulatory Commission, *Standard Format and Content for Emergency Plans for Fuel Cycle and Materials Facilities*, REG/G-91001955 (Washington, DC: NRC, 1990), https://doi.org/10.2172/6533759.

[180] "Small Emergency Planning Zone," NuScale Power, accessed October 9, 2018, https://www.nuscalepower.com/benefits/safety-features/emergency-planning-zone.

[181] Nuclear Regulatory Commission, *Standard Format and Content for Emergency Plans*, 8.

V. ANALYSIS AND OUTCOMES

The evidence presented in this chapter suggests that having a greater understanding of why people perceive nuclear power plants as a risky investment could pay off in the deployment of new technologies and help to establish policies that benefit advancements in this industry. However, extreme caution should continue as nuclear power is still, like many other industries, susceptible to failure. This chapter recognizes ways to identify black swan events using a probabilistic risk assessment (PRA), going beyond the traditional use of fault tree analysis and using computational software to give a higher degree of certainty by comparing the NuScale SMR and light water reactor (LWR) risk calculations.

A. RISK

In 1993, the NRC staff indicated to the commission a willingness to consider changing the emergency preparedness requirements because of new designs not already in the commercial nuclear fleet.[182] The commission then directed the staff to submit technical methods to simplify existing EP requirements.[183] Later in 1997, the staff replied to the commission, stating,

> Because the industry has not petitioned for changes to EP requirements for evolutionary and passive advanced LWRs, the staff did not dedicate the resources to fully evaluate these issues. The staff remains receptive to industry petitions for changes to EP requirements for evolutionary and passive advanced LWRs.[184]

However, in 2010 the staff acknowledged the EP was a “key technical” issue to SMR licensing.[185] There is a 13-year deficit in determining whether SMRs could have become a technology complementing other forms of clean energy and safely replacing baseload power in an aging nuclear power plant.

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[182] Nuclear Regulatory Commission, “Emergency Preparedness Rulemaking.”

[183] Nuclear Regulatory Commission.

[184] Nuclear Regulatory Commission.

[185] Nuclear Regulatory Commission.

If the United States continues to grant extensions to nuclear power plants across the nation without serious consideration for the advancement of newer technologies, it is contributing to a greater risk than necessary. A nuclear failure of any type could be the demise of this industry. With a lack of foresight in considering other technologies and being innovative, the U.S. nuclear industry has placed itself in jeopardy and the nation at risk of losing a significant portion of energy independence.

Currently, the United States and the NRC are back on track in considering SMRs as a possible technology in sustaining the nation well into the future—if they are committed to the investment. While it is challenging to construct a cost–benefit analysis, the nation should reflect on its past and lead the way into the development and advancement of nuclear energy. The United States cannot afford to sit back and wait for other nations to take the lead for two reasons. First, some nations like China and India, which have been progressive, may not share U.S. values of stiff regulatory oversight, thus leading to poor design and the increased chance of failure.[186] Second, the United States has existing stockpiles of waste, and by taking an innovative, responsible, and highly regulated approach, it could breed confidence in the next generation.

Public confidence would develop if the United States rid the nation and nuclear power plants of highly unstable radioactive material through reprocessing. The U.S. nuclear industry can accomplish this with emerging technologies and artificial intelligence, which can commutate, correct, and replace human interaction, thereby reducing 80–90 percent of the existing failure rate. Artificial intelligence will allow the choice of better design models and materials that will reduce the remaining 20 percent of failures. With the use of today's technologies, the United States can drive the nuclear industry to another level.

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[186] "America Risks Missing Out on a Global Nuclear Power Revival," Council on Foreign Relations, accessed November 2, 2018, https://www.cfr.org/blog/america-risks-missing-out-global-nuclear-power-revival.

B. WASTE DISPOSAL

Today, the stockpile of radiological waste is growing. How do we fix this problem? Should we re-open another round of debates for a second repository or reprocess spent nuclear fuel to reduce the amount of waste on hand as Japan, Finland, and France are currently doing? This reprocessing argument has some merit.

The radiological content of waste generated is about 95 percent uranium (U), 3 percent fission products and 2 percent transuranic. While this thesis does not detail the methods of reprocessing, if reprocessing became a priority in this country, a majority of the waste could be recycled. Areva, known for building a French reprocessing facility in La Haque, suggests that its facility can process up to 800 tons of spent fuel per year.[187] So what does this mean? Should the United States consider changing its policy that has existed since the late 1970s? The U.S. policy discussion must include a financial commitment to building this reprocessing capability; policymakers can do this by educating the public about the benefits of recycling spent nuclear fuel.

Current U.S. policy discourages the development of newer technological advancements of nuclear power plant designs that can operate more efficiently, thus reducing the amount of waste produced. Most of the nuclear infrastructure was built in the 1970s. Only recently have a few new plant designs been approved for power generation; however, none of the facilities have reprocessing capabilities. In today's political environment, it is challenging to support the advancement of nuclear power for a variety of reasons, such as the proliferation of nuclear weapons, ignorance regarding risk, and concerns for the environment. Policymakers should understand the real threats and benefits of nuclear power advancements.

First, in a reprocessing facility, plutonium is separated from the waste and then mixed with uranium to generate another round of fuel, also called mixed-oxide fuel. The time and cost to extract this element would make fuel more valuable to the industry,

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[187] "Areva Says Decision on China Nuclear Reprocessing Plant Expected Soon," Reuters, May 18, 2017, https://www.reuters.com/article/us-china-nuclear-areva/areva-says-decision-on-china-nuclear-reprocessing-plant-expected-soon-idUSKCN18E0QK.

ensuring its security. More importantly, this highly radioactive source would make it virtually impossible for theft; it would be easily detected and cause immediate death while handling it.

Second, people often refer to the incidents at Three Mile Island, Chernobyl, and Fukushima-Daiichi rather than looking at longstanding safety records of current nuclear power plant operations in this country. While these facilities failed, the reasons were preventable. Placing nuclear power in the proper context of risk is necessary to have a fair comparison with other forms of energy. The electricity generated by nuclear power in the United States has never killed a single American, specifically due to a design failure, unlike other forms of energy. All types of energy pose a risk; it is essential to evaluate nuclear forms of energy using a scientific methodology such a PRA or other computational software rather than untested assumptions. Nuclear power undergoes a rigorous process to determine risk. The NRC states,

> Risk analysts assume each initiating event occurs and then given the response to that event, realistically identify each combination of failures (e.g., pump failure and valve failure), or "sequence," that leads to a specific outcome (e.g., core damage). Analysts then calculate the likelihood of all the sequences that lead to the same outcome. The likelihood of the outcome is the sum of the sequence frequencies.[188]

Last, the United States has signed several international agreements regarding environmental stewardship, particularly to slow the adverse effects of climate change.[189] With the growing demand for energy in the nation, shrinking U.S. consumption of fossil fuels and replacing these fuels with a recyclable carbon-free energy source is a just and responsible thing to do for future generations.

In considering the advancement of nuclear power, it is essential to evaluate the cost of reprocessing vis-à-vis long-term storage needs. Developing breeder technology cost the

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[188] Nuclear Regulatory Commission, "Probabilistic Risk Assessment" (fact sheet, Office of Public Affairs, February 2016), https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/probabilistic-risk-asses.html.

[189] "Congress Climate History," Center for Climate and Energy Solutions, accessed December 10, 2018, https://www.c2es.org/content/congress-climate-history/.

United States about $15 billion in 2014.[190] Nearly five years later, costs have inevitably risen. In testimony to Congress, the Congressional Budget Office estimated the cost of reprocessing to be 25 percent more than that of building and maintaining a long-term storage facility. It also noted there was uncertainty about its financial calculations. Those uncertainties included how much it would be to build and operate such a facility, the lifetime of the facility, and the market value of the reprocessed fuel.[191]

Notably, the Congressional Budget Office's report was generated before any repository in the world was built. Today, we have a better understanding of these expenditures. Japan and France have successfully operated reprocessing facilities and repositories. Energy rates based on a per-kilowatt/hour comparison with fossil prices are still challenging, especially when fossil fuels receive energy subsidies to offset their production costs. While it might be costly to convert the entire U.S. fleet of reactors and build reprocessing facilities, the United States should consider approving the development of newer nuclear technologies that produce less waste or recycle current waste, similar to programs in other parts of the world.

To achieve success with nuclear power, a public relations campaign needs to start well before the development and implementation of such a project. The concern people have about nuclear energy is reasonable when the discussion has only been framed around death and destruction of nuclear weapons. Many of the countries previously mentioned have websites that contain written materials and educational videos to explain how these naturally occurring elements produce energy and how they can be safely controlled and recycled responsibly. Using these methods could help the United States educate the public and solicit new ideas that could drive the industry to improve standards and encourage confidence in this sustainable and renewable source of energy. A nation that understands how energy is created, managed, and delivered can influence the future of nuclear power.

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[190] Sharryn Dotson, "The History and Future of Breeder Reactors," Power Engineering, June 25, 2014, https://www.power-eng.com/articles/npi/print/volume-7/issue-3/nucleus/the-history-and-future-of-breeder-reactors.html.

[191] *Global Nuclear Energy Partnership: Hearing before the Committee on Energy and Natural Resources*, Senate, 110th Cong., 1st sess., November 14, 2007.

C. SITE SELECTION

Site selection is critical in ensuring nuclear power plants can operate safely as well as protect the life and property that surrounds them. A great deal of time and consideration, as well as much in-depth calculation and analysis, go into the selection process before a facility is licensed and becomes operational.

The nuclear power plant industry across the nation has a responsibility to ensure safe operations of their facilities and off-site locations, protecting the public from any potential release of radioactivity into the environment. This includes the two-mile and 10-mile EPZs as well the 50-mile ingestion pathway. There are many in the industry who desire evidence that off-site preparedness is necessary, especially with new nuclear technologies being created and computation software that could provide a deeper understanding of risk and consequences. The NRC's State-of-the-Art Reactor Consequence Analysis (SOARCA) program, indicates a release of radiation into the environment is not as damaging as previously predicted. According to this study, "The calculated cancer fatality risks from the scenarios analyzed in SOARCA are thousands of times lower than the NRC Safety Goal and millions of times lower than the general U.S. cancer fatality risk."[192] The results suggest that regardless of whether accidents were mitigated, there would be no early fatalities from exposure and minimal risk for long-term cancer fatalities (see Figure 10).[193]

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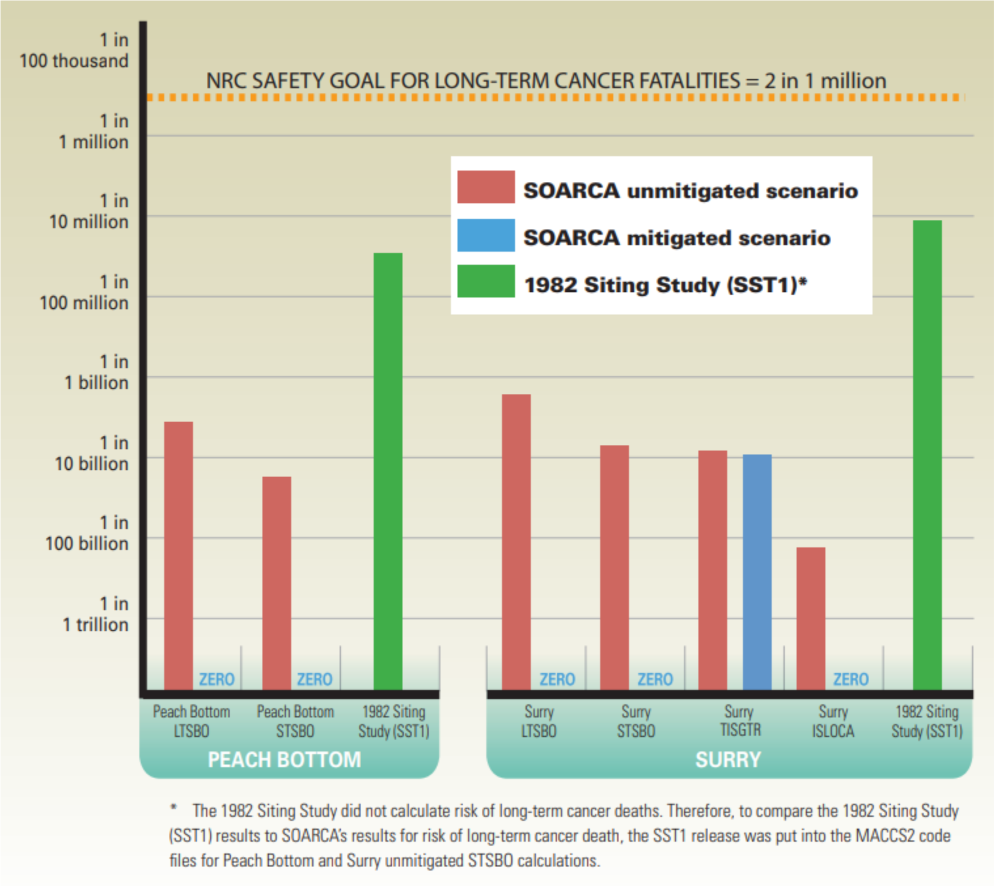
[192] Nuclear Regulatory Commission, *Modeling Potential Reactor Accident Consequences*, NUREG/BR-0359 (Washington, DC: NCR, December 2012), 40, https://www.nrc.gov/docs/ML1234/ML12347A049.pdf.

[193] Nuclear Regulatory Commission, 40.



* The 1982 Siting Study did not calculate risk of long-term cancer deaths. Therefore, to compare the 1982 Siting Study (SST1) results to SOARCA's results for risk of long-term cancer death, the SST1 release was put into the MACCS2 code files for Peach Bottom and Surry unmitigated STSBO calculations.

Figure 10. Scenario-Specific Risk of Dying from Long-Term Cancer for an Individual within 10 Miles of the Plant[194]

Today, over $78 million is spent annually in local and state fees to support this off-site posture.[195] The evidence suggests the United States has improved safety and has better regulatory guidelines to support future activities. This creates the question of whether funds should be used to advance the development of SMRs across the United States or throughout the world. The NRC has developed a draft environmental impact statement (EIS) on behalf of the Tennessee Valley Authority (TVA) regarding the addition of an SMR to the Clinch River Site in Oak Ridge, Tennessee. The draft EIS helped to determine whether the site

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[194] Source: Nuclear Regulatory Commission, "State-of-the-Art Reactor Consequence Analyses" (presentation, Surrey, VA, February 21, 2012), 20, https://www.nrc.gov/docs/ML1204/ML120460985.pdf.

[195] "Emergency Preparedness at Nuclear Plants," Nuclear Energy Institute, accessed October 26, 2018, https://www.nei.org/resources/fact-sheets/emergency-preparedness-at-nuclear-plants.

was suitable for the construction and operation of multiple SMRs under a construction permit and operating license or combined license.[196]

During the early phase of an emergency, nuclear power plants use dose projections to determine protective actions before releases occur, based on the Environmental Protection's *Protective Action Guides*.[197] The NRC uses another methodology, called the linear no-threshold dose-response model, to assess risk regarding exposure. This methodology was derived from experts who have discovered a link between radiation exposure and cancer. The NRC accepts that any amount of radiation is harmful, and small exposures over time could collectively be the same as a single large dose.[198] While the NRC agrees with this model for determining risk, it is aware that the model is conservative and may exaggerate risk associated with exposure.[199] The commission outlined its qualitative safety goals in a policy statement (51 *Federal Register* 30,028), which states the following:

- Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health.
- Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks.[200]

An early site permit and EIS were submitted by the TVA. Two areas considered in the EIS were a design-based accident (DBA) and a severe accident (SA). A LOCA was selected as the DBA, not because it was likely to occur but because it was more likely to

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[196] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement for an Early Site Permit (ESP) at the Clinch River Nuclear Site*: *Draft Report for Comment*, NUREG-2226, vol. 1 (Washington, DC: NRC, April 2018), iii, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2226/v1/.

[197] Environmental Protection Agency, *PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents*, EPA-400/R-17/001 (Washington, DC: EPA, January 2017), 24.

[198] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-71.

[199] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-71.

[200] Safety Goals for the Operations of Nuclear Power Plants, 51 Fed. Reg. 30,028 (August 4, 1986), 1–2, https://www.nrc.gov/reading-rm/doc-collections/commission/policy/51fr30028.pdf.

release radiation into the environment. Four passive models were considered as the proxy SMR based on industry standards, which require no "off-site power, off-site water or operator actions."[201] TVA selected NuScale, which was characterized by all three attributes. Also, it had the greatest power level and could produce a maximum post-accident dose. These were needed to measure the consequences of a release.[202] As part of this analysis, the environmental reviews were conducted using an atmospheric dispersion factor widely accepted in the industry, χ/Q, over four periods using likely meteorological data related to the nuclear site.[203] As a result, the "NRC staff concludes the atmospheric dispersion factors for the CRN Site were acceptable for use in evaluating the potential environmental consequences of postulated DBAs."[204] They added, "On this basis, the NRC staff concludes that the environmental consequences from DBAs at the CRN Site would be of SMALL significance for any of the SMR reactor technologies being considered" (original emphasis).[205] In this same report, the SA identified three pathways that could lead to radiation exposure: atmospheric, surface water, and groundwater.[206] An evaluation of the pathways considers the direction of the plume, the materials deposited on the ground or skin, and contaminates inhaled or ingested. The SA also includes meteorological, population and terrain in determining levels of exposure.[207] The MELCOR Accident Consequence Code System was used to measure consequences quantitatively.[208] These calculations were conducted for the site boundary and the two-mile and 10-mile EPZs.[209] The three types of SAs assessed were human health, economic costs, and land affected by

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[201] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-71.

[202] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-72.

[203] Office of Environment, Health, Safety, and Security, "Atmospheric Dispersion Parameter for Calculation of Co-located Worker Dose," OE-3: 2015-02 (Department of Energy, April 2015), https://www.energy.gov/sites/prod/files/2015/06/f22/OE-3%202015-02%20FINAL.pdf.

[204] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-73.

[205] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-74.

[206] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-74.

[207] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-75.

[208] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-74.

[209] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-74.

contamination.[210] The core damage frequency (CDF) in structures, systems, and components (SSCs) was estimated when the SMR would be at its maximum thermal power rating and included six SA sequences.[211] To evaluate consequences, various SSCs were artificially introduced to cause a failure.[212] Human error was responsible for 80–90 percent of failures while equipment made up the other 10–20 percent.[213] As shown in Table 2, the NRC determined, "The risks calculated for the selected SMR at the CRN Site are lower than the risks associated with the current-generation reactors considered in NUREG-1150; all risk values are also well below the Commission's safety goals."[214]

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[210] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-75.

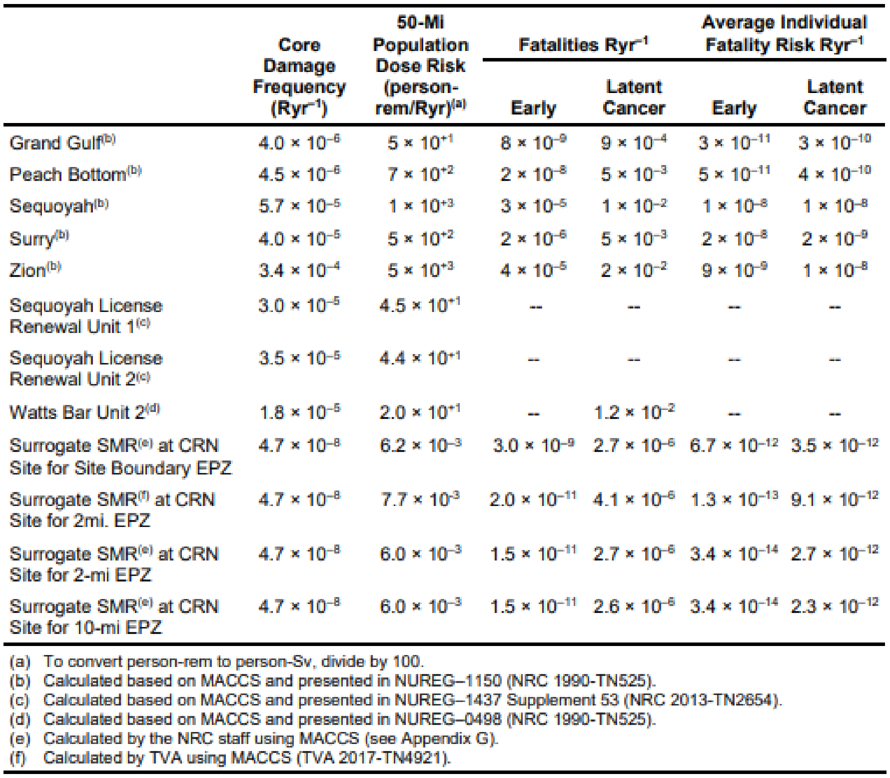
[211] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-76.

[212] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, 5-80.

[213] "Safety of Nuclear Reactors," World Nuclear Association," accessed November 2, 2018, http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx.

[214] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-82.

Table 2. Comparison of Environmental Risks for a Small Modular Reactor at the CRN Site with Risks for Current-Generation Reactors[215]



	Core Damage Frequency (Ryr^{-1})	50-Mi Population Dose Risk (person-rem/Ryr)(a)	Fatalities Ryr^{-1}		Average Individual Fatality Risk Ryr^{-1}	
			Early	Latent Cancer	Early	Latent Cancer
Grand Gulf(b)	4.0×10^{-6}	$5 \times 10^{+1}$	8×10^{-9}	9×10^{-4}	3×10^{-11}	3×10^{-10}
Peach Bottom(b)	4.5×10^{-6}	$7 \times 10^{+2}$	2×10^{-8}	5×10^{-3}	5×10^{-11}	4×10^{-10}
Sequoyah(b)	5.7×10^{-5}	$1 \times 10^{+3}$	3×10^{-5}	1×10^{-2}	1×10^{-8}	1×10^{-8}
Surry(b)	4.0×10^{-5}	$5 \times 10^{+2}$	2×10^{-6}	5×10^{-3}	2×10^{-8}	2×10^{-9}
Zion(b)	3.4×10^{-4}	$5 \times 10^{+3}$	4×10^{-5}	2×10^{-2}	9×10^{-9}	1×10^{-8}
Sequoyah License Renewal Unit 1(c)	3.0×10^{-5}	$4.5 \times 10^{+1}$	--	--	--	--
Sequoyah License Renewal Unit 2(c)	3.5×10^{-5}	$4.4 \times 10^{+1}$	--	--	--	--
Watts Bar Unit 2(d)	1.8×10^{-5}	$2.0 \times 10^{+1}$	--	1.2×10^{-2}	--	--
Surrogate SMR(e) at CRN Site for Site Boundary EPZ	4.7×10^{-8}	6.2×10^{-3}	3.0×10^{-9}	2.7×10^{-6}	6.7×10^{-12}	3.5×10^{-12}
Surrogate SMR(f) at CRN Site for 2mi. EPZ	4.7×10^{-8}	7.7×10^{3}	2.0×10^{-11}	4.1×10^{-6}	1.3×10^{-13}	9.1×10^{-12}
Surrogate SMR(e) at CRN Site for 2-mi EPZ	4.7×10^{-8}	6.0×10^{-3}	1.5×10^{-11}	2.7×10^{-6}	3.4×10^{-14}	2.7×10^{-12}
Surrogate SMR(e) at CRN Site for 10-mi EPZ	4.7×10^{-8}	6.0×10^{-3}	1.5×10^{-11}	2.6×10^{-6}	3.4×10^{-14}	2.3×10^{-12}

(a) To convert person-rem to person-Sv, divide by 100.
(b) Calculated based on MACCS and presented in NUREG–1150 (NRC 1990-TN525).
(c) Calculated based on MACCS and presented in NUREG–1437 Supplement 53 (NRC 2013-TN2654).
(d) Calculated based on MACCS and presented in NUREG–0498 (NRC 1990-TN525).
(e) Calculated by the NRC staff using MACCS (see Appendix G).
(f) Calculated by TVA using MACCS (TVA 2017-TN4921).

According to the NRC's policy statement, "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of 1 percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed."[216] The results in Table 3 indicate that the CDF and 50-mile dose risk is much less at $1.3\text{x}10^{13}$, compared to routine transportation deaths at $1.3\text{x}10^{-4}$ per year or $2\text{x}10^{-3}$ per year for cancer-related deaths not associated with nuclear power.[217] As a nation, America finds it

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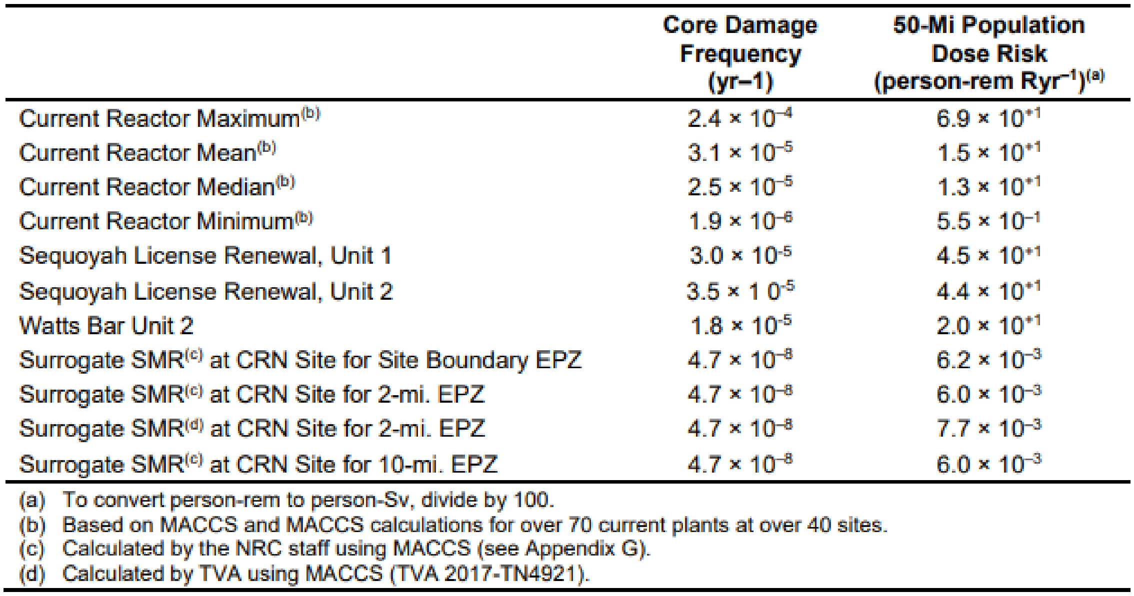
[215] Source: Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-81.

[216] Safety Goals for the Operations of Nuclear Power Plants, 2.

[217] Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-82.

challenging to embrace nuclear technologies; meanwhile, according to the National Safety Council, 40,100 people died in car accidents in 2016 and 40,327 in 2017.[218] According to the American Cancer Society, about 1,670 cancer-related deaths have occurred each day in 2018, and 609,640 people each year.[219]

Table 3. Comparison of Environmental Risk from Severe Accidents for a Small Modular Reactor at the CRN Site with Risks for Current Plants from Operating License Renewal Reviews[220]



	Core Damage Frequency (yr–1)	**50-Mi Population Dose Risk (person-rem Ryr^{-1})(a)**
Current Reactor Maximum(b)	2.4×10^{-4}	$6.9 \times 10^{+1}$
Current Reactor Mean(b)	3.1×10^{-5}	$1.5 \times 10^{+1}$
Current Reactor Median(b)	2.5×10^{-5}	$1.3 \times 10^{+1}$
Current Reactor Minimum(b)	1.9×10^{-6}	5.5×10^{-1}
Sequoyah License Renewal, Unit 1	3.0×10^{-5}	$4.5 \times 10^{+1}$
Sequoyah License Renewal, Unit 2	$3.5 \times 1\ 0^{-5}$	$4.4 \times 10^{+1}$
Watts Bar Unit 2	1.8×10^{-5}	$2.0 \times 10^{+1}$
Surrogate SMR(c) at CRN Site for Site Boundary EPZ	4.7×10^{-8}	6.2×10^{-3}
Surrogate SMR(c) at CRN Site for 2-mi. EPZ	4.7×10^{-8}	6.0×10^{-3}
Surrogate SMR(d) at CRN Site for 2-mi. EPZ	4.7×10^{-8}	7.7×10^{-3}
Surrogate SMR(c) at CRN Site for 10-mi. EPZ	4.7×10^{-8}	6.0×10^{-3}

(a) To convert person-rem to person-Sv, divide by 100.
(b) Based on MACCS and MACCS calculations for over 70 current plants at over 40 sites.
(c) Calculated by the NRC staff using MACCS (see Appendix G).
(d) Calculated by TVA using MACCS (TVA 2017-TN4921).

As Wayne Sheu describes, while only “1% of cancers are caused by natural radiation, exposure from nuclear technology is responsible for an eventual 0.002% increase in cancer risk, the equivalent of less than an hour loss of life expectancy. In contrast,

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[218] “2017 Fatality Estimates,” National Safety Council, accessed November 2, 2018, https://www.nsc.org/road-safety/safety-topics/fatality-estimates.

[219] American Cancer Society, *Cancer Facts & Figures 2018* (Atlanta, GA: American Cancer Association, 2018), 1.

[220] Source: Nuclear Regulatory Commission and U.S. Army Corps of Engineers, *Environmental Impact Statement*, 5-82.

burning fossil fuels is estimated to be 3–40 days loss of life expectancy."[221] When the low frequency of nuclear accidents is considered and then combined with enhanced technologies, it would seem SMRs fill a gap in the U.S. energy portfolio.

In order to reflect how SMRs might reduce risk, a table for comparison is provided in the Appendix. It compares the number of SMRs needed to maintain the same energy capacity provided by today's fleet of commercial nuclear power plants. The categories include CDF, early fatality (EF) rates, and latent fatality (LF) rates. According to the NRC, a surrogate derivation is acceptable for meeting the commission's quantitate health objectives.[222] The acceptable derivation for CDF is 4 x 10^{7}.[223] For an LF, the derivation is 2 x 10^{-6}, and for an EF, it is 5 x 10^{-7}.[224] The 11 nuclear power plants identified with a CDF, an LF, and an EF in Table 2 were incorporated into the Appendix. In the absence of this information for the other nuclear power plants, the surrogate derivations were used.

Developing this assessment requires identifying the number of SMRs to replace the existing infrastructure. This was determined by calculating the total mega-watt (Mwt) generation by all 101 commercially operated nuclear power plants in the United States and then dividing that figure by a NuScale 50-Mwt SMR, identifying the need for 6,374 replacement units. Second, it was necessary to find the mean of the CDF, EF rate inside the one-mile EPZ, and the LF rate, which includes the 10-mile EPZ, both for the LWR and the SMR. Third, the NuScale mean was multiplied by the number of SMR units needed for a total score in three categories. The results indicate in all three categories that the surrogate units could operate at a lower risk than current nuclear power plants. There would also be a 68 percent reduction in the CDF, 80 percent reduction inside the 10-mile EPZ and a 1 percent improvement within one mile.

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[221] Wayne Sheu, "Nuclear Energy Gain and Risk," Stanford University, February 20, 2017, http://large.stanford.edu/courses/2017/ph241/sheu1/.

[222] Nuclear Regulatory Commission, *Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing: Appendices A through L*, NUREG-1860, vol. 2 (Washington, DC: Office of Nuclear Regulatory Research, December 2007), D-1.

[223] Nuclear Regulatory Commission, D-6.

[224] Nuclear Regulatory Commission, D-2–5.

In summary, regardless of whether NuScale or any other corporation were to have similar design specifications, the derivation indicates that SMRs pose little risk off site, thus operating at a lower risk than traditional plants. Having this information available could begin the conversation about whether a 10-mile EPZ is necessary when considering passive systems. The additional expenses for the nuclear industry could be spent on advancing this technology rather than paying for off-site preparedness. Reducing the footprint of the EPZ could allow for permitting on sites not considered before due to population density, available water sources, and off-site power. This assessment indicates future siting may have a great deal of flexibility and adaptability to meet U.S. energy demands in ways that traditional nuclear power plants cannot.

VI. CONCLUSION AND RECOMMENDATIONS

In conclusion, the commercial nuclear power industry has many hurdles to overcome if it wants to flourish in the 21st century. These obstacles include the public perception regarding risk, the trepidation by investors and entrepreneurs to build advanced reactor designs in an uncertain energy market, and spent fuel storage.

The risk from nuclear power production in the United States stemmed from human intervention and mechanical failure of aging facilities. Approximately 80–90 percent of U.S. commercial nuclear power plant accidents have been caused by human error and 10–20 percent by aging mechanical systems. Many in the nation are concerned about the release of radiation by nuclear power plant facilities, but according to this research, the perceived risk is not reality; quite to the contrary, other forms of energy have higher risks to health and safety.

Reprocessing spent fuel to reduce the amount of waste remains a substantial public policy issue in the country. While private industry, bureaucrats, and politicians are deliberating on waste issues, various promising technologies are needed to power the future, especially reactor designs that are more efficient, flexible, and reliable—like SMRs. The use of spent fuel through reprocessing appears worth consideration, instead of storing waste for thousands of years.

The United States has firm federal guidelines for siting large permanent facilities, based on a long history of science and research. The use of innovative computational software, along with information from real-world events, has provided a wealth of knowledge regarding the impact of radiation exposure on human health and the environment. Based on the facts presented in this thesis, the risk would be far less than previously thought, especially if consideration is given to smaller reactor models that have siting flexibility and enhanced passive safety features.

The United States depends on commercial nuclear power plants for 20 percent of its baseload power to sustain its way of life; the country needs to question whether it will continue embracing the extension of older facilities living on borrowed time, build an industry with smaller, safer, and more flexible technology, or abandon nuclear technologies altogether. This thesis offers the following policy recommendations.

(1) Extend the license renewal of current operating facilities as necessary.

- Introduce a new passive system wherever possible to prevent the possibility of human error.
- Continue high-level oversight, ensuring vital parts that are exposed to extreme heat are checked for deformities, and replace SSCs that have the potential for failure, according to the novel computation software models.

(2) Change national policy regarding nuclear waste.

- Build reprocessing facilities to allow more of the waste to be expended before entering into a permanent repository. This will provide a stockpile of fuel well into the future, for the next generation of commercial nuclear power. With the lengthy amount of time it takes to design, build, and test such a facility, the United States needs to begin soon so as not to exceed the limited life expectancy of dry cast storage (50 years).

(3) Begin to replace aging nuclear power plants with new technologies that have passive systems, such as SMRs, which support a carbon-free energy source.

- Research suggests that off-site preparedness activities for current facilities should be re-evaluated and reduced since consequences are less harmful than were previously determined.

- Replace aging nuclear power plants with SMRs on the same site, and reduce the EPZ. This will create an added savings that may make this technology more competitive with other green energy sources.

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APPENDIX. COMPARISON OF CORE DAMAGE FREQUENCY RISK FOR SMR AND CURRENT-GENERATION REACTORS

Commercial Nuclear Power Plant (CNPP)	Mega Watts	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactors(SMR) - Surrogate	Mega Watt	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactor (SMR) Replacements Needed	Replacement Cost Per Site @ 250M per Small Modular Reactor (SMR)
Arkansas Nuclear Unit 1	2,568	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	51.36	$12,840,000,000
Arkansas Nuclear Unit 2	3,026	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	60.52	$15,130,000,000
Beaver Valley Unit 1	2,900	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58	$14,500,000,000
Beaver Valley Unite 2	2,900	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58	$14,500,000,000
Braidwood Unite 1	3,645	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.9	$18,225,000,000
Braidwood Unit 2	3,645	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.9	$18,225,000,000
Browns Ferry Unit 1	3,952	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.04	$19,760,000,000
Browns Ferry Unit 2	3,952	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.04	$19,760,000,000
Browns Ferry Unit 3	3,952	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.04	$19,760,000,000
Brunswick Steam Electric Plant Unit 1	2,923	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58.46	$14,615,000,000
Brunswick Steam Electric Plant Unit 2	2,923	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58.46	$14,615,000,000
Byron Station Unit 1	3,645	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.9	$18,225,000,000
Byron Station Unit 2	3,645	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.9	$18,225,000,000
Callaway Plant Unit 1	3,565	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	71.3	$17,825,000,000
Calvert Cliffs Nuclear Plant Unit 1	2,737	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	54.74	$13,685,000,000
Calvert Cliffs Nuclear Plant Unit 2	2,737	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	54.74	$13,685,000,000
Catawba Nuclear Station Unit 1	4,311	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	86.22	$21,555,000,000
Catawba Nuclear Station Unit 2	3,411	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	68.22	$17,055,000,000
Clinton Power Station Unit 1	3,473	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	69.46	$17,365,000,000
Columbia Generating Station	3,544	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	70.88	$17,720,000,000
Comanche Peak Nuclear Power Plant Unit 1	3,612	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.24	$18,060,000,000
Comanche Peak Nuclear Power Plant Unit 2	3,612	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.24	$18,060,000,000
Cooper Nuclear Station	2,419	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	48.38	$12,095,000,000
Davis-Besse Nuclear Power Station Unit 1	2,817	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	56.34	$14,085,000,000
Diablo Canyon Nuclear Power Plant Unit 1	3,411	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	68.22	$17,055,000,000
Diablo Canyon Nuclear Power Plant Unit 2	3,411	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	68.22	$17,055,000,000
Donald C. Cook Nuclear Plant Unit 1	3,304	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	66.08	$16,520,000,000
Donald C. Cook Nuclear Plant Unit 2	3,468	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	69.36	$17,340,000,000
Dresden Nuclear Power Station Unit 3	2,957	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	59.14	$14,785,000,000
Duane Arnold Energy Center	1,912	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	38.24	$9,560,000,000
Edwin I. Hatch Nuclear Plant Unit 1	2,804	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	56.08	$14,020,000,000
Edwin I. Hatch Nuclear Plant Unit 2	2,804	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	56.08	$14,020,000,000
Fermi Unit 2	3,486	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	69.72	$17,430,000,000
Grand Gulf Nuclear Station Unit 1	4,408	0.000004	4 x 10^{-6}	0.000000008	8 x 10^{-9}	0.0009	9 x 10^{-4}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	88.16	$22,040,000,000
H.B. Robison Steam Electric Plant Unit 2	2,339	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	46.78	$11,695,000,000
Hope Creek Generating Station Unit 1	3,902	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	78.04	$19,510,000,000
Indian Point Nuclear Generating Unit 2	3,216	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	64.32	$16,080,000,000
Indian Point Nuclear Generating Unit 3	3,216	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	64.32	$16,080,000,000
James A, FitzPatrick Nuclear Power Plant	2,536	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	50.72	$12,680,000,000

Commercial Nuclear Power Plant (CNPP)	Mega Watts	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactors(SMR) - Surrogate	Mega Watt	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactor (SMR) Replacements Needed	Replacement Cost Per Site @ 250M per Small Modular Reactor (SMR)
Joseph M. Farley Nuclear Plant Unit 1	2,775	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	55.5	$13,875,000,000
Joseph M. Farley Nuclear Plant Unit 2	2,775	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	55.5	$13,875,000,000
LaSalle County Station Unit 1	3,546	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	70.92	$17,730,000,000
LaSalle County Station Unit 2	3,546	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	70.92	$17,730,000,000
Limeerick Generating Station Unit 1	3,515	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	70.3	$17,575,000,000
Limeerick Generating Station Unit 2	3,515	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	70.3	$17,575,000,000
McGuire Nuclear Station Unit 1	3,411	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	68.22	$17,055,000,000
McGuire Nuclear Station Unit 2	3,411	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	68.22	$17,055,000,000
Millstone Power Station Unit 2	2,700	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	54	$13,500,000,000
Millstone Power Station Unit 3	3,650	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	73	$18,250,000,000
Monticello Nuclear Generating Plant Unit 1	2,004	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	40.08	$10,020,000,000
Nine Mile Point Nuclear Station Unit 1	1,850	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	37	$9,250,000,000
Nine Mile Point Nuclear Station Unit 2	3,988	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.76	$19,940,000,000
North Anna Power Station Unit 1	2,940	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58.8	$14,700,000,000
North Anna Power Station Unit 2	2,940	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	58.8	$14,700,000,000
Oconee Nuclear Station Unit 1	2,568	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	51.36	$12,840,000,000
Oconee Nuclear Station Unit 2	2,568	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	51.36	$12,840,000,000
Oconee Nuclear Station Unit 3	2,568	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	51.36	$12,840,000,000
Oyster Creek Nuclear Generating Station	1,930	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	38.6	$9,650,000,000
Plaisades Nuclear Plant	2,565	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	51.308	$12,827,000,000
Palo Verde Nuclear Generation Station Unit 1	3,990	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.8	$19,950,000,000
Palo Verde Nuclear Generation Station Unit 2	3,990	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.8	$19,950,000,000
Palo Verde Nuclear Generation Station Unit 3	3,990	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	79.8	$19,950,000,000
Peach Bottom Atomic Power Station Unit 2	4,016	0.0000045	4.5 x 10^{-6}	0.00000002	2 x 10^{-8}	0.005	5 x 10^{-3}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	80.32	$20,080,000,000
Peach Bottom Atomic Power Station Unit 3	4,016	0.0000045	4.5 x 10^{-6}	0.00000002	2 x 10^{-8}	0.005	5 x 10^{-3}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	80.32	$20,080,000,000
Perry Nuclear Power Plant Unit 1	3,758	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	75.16	$18,790,000,000
Pilgrim Nuclear Power Station	2,028	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	40.56	$10,140,000,000
Point Beach Nuclear Plant Unit 1	1,800	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	36	$9,000,000,000
Point Beach Nuclear Plant Unit 2	1,800	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	36	$9,000,000,000
Prairie Island Nuclear Generating Plant Unit 1	1,677	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	33.54	$8,385,000,000
Prairie Island Nuclear Generating Plant Unit 2	1,677	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	33.54	$8,385,000,000
Quad Cities Nuclear Power Station Unit 1	2,957	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	59.14	$14,785,000,000
Quad Cities Nuclear Power Station Unit 2	2,957	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	59.14	$14,785,000,000
R.E. Ginna Nuclear Power Plant	1,775	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	35.5	$8,875,000,000
River Bend Station Unit 1	3,091	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	61.82	$15,455,000,000
St. Lucie Plant Unit 1	3,020	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	60.4	$15,100,000,000
St. Lucie Plant Unit 2	3,020	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	60.4	$15,100,000,000
Salem Nuclear Generating Station Unit 1	3,459	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	69.18	$17,295,000,000
Salem Nuclear Generating Station Unit 2	3,459	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	69.18	$17,295,000,000
Seabrook Station Unit 1	3,648	0.0000004	4 x 10^{-7}	0.0000005	5 X 10^{-7}	0.000002	2 X 10^{-6}	NuScale	50	0.000000047	4.7 x 10^{-8}	0.000000000015	1.5 x 10^{-11}	0.0000026	2.6 x 10^{-6}	72.96	$18,240,000,000

Commercial Nuclear Power Plant (CNPP)	Mega Watts	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactors(SMR) - Surrogate	Mega Watt	Core Damage Frequency (CDF)		Early Fatalities Ryr^{-1}		Latent Cancer Fatalities Ryr^{-1}		Small Modular Reactor (SMR) Replacements Needed	Replacement Cost Per Site @ 250M per Small Modular Reactor (SMR)
Sequoyah Nuclear Plant	3,455	0.000057	$5.7 x 10^{-5}$	0.00003	$3 x 10^{-5}$	0.01	$1 x 10^{-2}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	69.1	$17,275,000,000
Sequoyah Nuclear Plant Renewal 1	3,455	0.00003	$3 x 10^{-5}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	69.1	$17,275,000,000
Sequoyah Nuclear Plant Renewal 2	3,455	0.000035	$3.5 x 10^{-5}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	69.1	$17,275,000,000
Shearon Harris Nuclear Power Plant Unit 1	2,948	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	58.96	$14,740,000,000
South Texas Project Unit 1	3,853	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	77.06	$19,265,000,000
South Texas Project Unit 2	3,853	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	77.06	$19,265,000,000
Surry Power Station Unit 1	2,587	0.00004	$4 x 10^{-5}$	0.000002	$2 x 10^{-6}$	0.005	$5 x 10^{-3}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	51.74	$12,935,000,000
Surry Power Station Unit 2	2,587	0.00004	$4 x 10^{-5}$	0.000002	$2 x 10^{-6}$	0.005	$5 x 10^{-3}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	51.74	$12,935,000,000
Susquehann Steam Electric Station Unit 1	3,952	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	79.04	$19,760,000,000
Susquehann Steam Electric Station Unit 2	3,952	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	79.04	$19,760,000,000
Three Mile Isalnd Nuclaer Station Unit 1	2,568	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	51.36	$12,840,000,000
Turkey Point Nuclear Generating Unit 3	2,644	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	52.88	$13,220,000,000
Turkey Point Nuclear Generating Unit 4	2,644	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	52.88	$13,220,000,000
Virgil C. Summer Nuclear Station Unit 1	2,900	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	58	$14,500,000,000
Vogtle Electric Generationg Plant Unit 1	3,626	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	72.512	$18,128,000,000
Vogtle Electric Generationg Plant Unit 2	3,626	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	72.512	$18,128,000,000
Waterford Steam Electric Station Unit 3	3,716	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	74.32	$18,580,000,000
Watts Bar Nuclear Plant Unit 1	3,459	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	69.18	$17,295,000,000
Watts Bar Nuclear Plant Unit 2	3,411	0.000018	$1.8 x 10^{-5}$	0.0000005	$5 X 10^{-7}$	0.012	$1.2x10^{-2}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	68.22	$17,055,000,000
Wolf Creek Generating Station Unit 1	3,565	0.0000004	$4 x 10^{-7}$	0.0000005	$5 X 10^{-7}$	0.000002	$2 X 10^{-6}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	71.3	$17,825,000,000
Zion Unit 1 (De-commisioned)	3,250	0.00034	$3.4 x 10^{-4}$	0.00004	$4 x 10^{-5}$	0.02	$2 x 10^{-2}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	65	$16,250,000,000
Zion Unit 2 (De-commissioned)	3,250	0.00034	$3.4 x 10^{-4}$	0.00004	$4 x 10^{-5}$	0.02	$2 x 10^{-2}$	NuScale	50	0.000000047	$4.7 x 10^{-8}$	0.000000000015	$1.5 x 10^{-11}$	0.0000026	$2.6 x 10^{-6}$	65	$16,250,000,000
									50								
Total	318,737	0.0009490		0.00016055		0.083084		Total	50	0.000004747		0.000000000152		0.0002626		6,374.73	$1,593,683,000,000
Mean	3,156	0.0000094		0.00000159		0.000823		Mean	50	0.000000047		0.00000000002		0.0000026			
Median	3,304	0.0000004		0.00000050		0.000002		Median	50	0.000000047		0.00000000002		0.0000026			
Minimum	1,677	0.0000004		0.00000001		0.000002		Minimum	50	0.000000047		0.00000000002		0.0000026			

Total SMR Replacement CDF		Total Commercial Power Plant CDF
0.00029961240	<	0.000949000

SMR Early Fatalities Ryr^{-1}		Commerical Power Plant Early Fatalities Ryr-1
0.00000009562	<	0.000160548

SMR Latent Cancer Fatalities Ryr^{-1}		Commerical Power Plant Latent Cancer Fatalities Ryr-1
0.016574303	<	0.083084

CDF Reduction with SMR	31.57%
Early Fatality Reduction with SMR (1 mile EPZ)	0.06%
Latent Cancer Fatality Reduction with SMR (10 mile EPZ)	19.95%

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