RADIOISOTOPE INVENTORY OF SPENT NUCLEAR FUEL IN *MATHEMATICA*

BY

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THESIS

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ABSTRACT

While nuclear reactors in the United States have produced economy-driving power for several decades, they have also left behind a significant amount of spent nuclear fuel. The federal government, ultimately responsible for this spent fuel, has a history just as long in attempting to effectively bury, dispose, reprocess, or otherwise deal with this waste. As no attempts to date have been entirely successful, work continues to find an effective waste management solution. To aid planners, policymakers, and scientists in this endeavor, tools are currently needed to model the radioisotope inventory of all spent nuclear requiring disposal or other forms of remediation to accurately frame the scope of the issue. This project describes a simple method of calculating radioisotope concentrations in spent fuel by utilizing a unique approach to solving the diffusion equation eigenvalue problem. Herein, the dissolved boron concentration, essentially a chemical shim, is adjusted over an operational time period to maintain criticality in the reactor, compensating for fuel burnup, burnable poison burnout, and actinide and fission product buildup. It is shown, as an example, that the fractional reduction in boron concentration after a month of reactor operation is 2.3%. The normalized neutron flux in the example scenario is calculated and confirmed to be relatively flat radially and vertically. Similarly, the normalized thermal energy production rate is also shown to be relatively flat, as expected. Radionuclides of interest are tracked and isotopic concentrations are shown at various vertical heights within the core. Upon further refining, these concentrations can be taken to represent the radioisotope inventory of spent nuclear fuel under various burnup scenarios. Ultimately, characterizing the spent fuel requiring disposal will aid in developing an efficient waste management strategy. Even while several shortfalls are noted and described, tools such as this computer code can play a useful role in addressing the nation's nuclear waste disposal dilemma.

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Chapter 1

Introduction

The future pathway of energy production and security in the United States is highly uncertain. As climate change, national security, and economic factors continue to impact U.S. energy policy, accurate extrapolations of energy production by source have proven difficult. However, with a systematic approach based on historical trends, it is possible to extrapolate the performance of the energy sector of the economy, albeit with increasing uncertainty by mid-century and beyond. In this context, age distribution of nuclear power plants operating out through 2050 can be extrapolated in a manner consistent with historical energy sector data. This leads to an estimate of all spent nuclear fuel produced by all of the plants built up through 2050 and by all of those plants through the remainder of their operating lives. As the future of commercial nuclear energy production in the United States is inherently linked to the resolution of the back end of the nuclear fuel cycle, this model can serve as an input into an effective waste management strategy.

An overall economic analysis serves as a starting block for this examination. First, the global economic system is divided into eight regions for the purposes of gross domestic product (GDP) calculations. Each region is outlined with the purpose of making each roughly energy independent, including use, production, and trade across all sources. Since the United States and Canada form an integrated energy market, it is convenient to group those two countries together. China accounts

for almost all energy use in another region, and so as described in detail by von Brevern [1].

Using an Euler-Lagrange technique to maximize a welfare function describing each independent region's economic consumption and production ultimately leads to GDP extrapolations on the timeframe of interest. This calculation is broken down into two parts. First, the welfare function must be strictly characterized to accurately model the energy sector. A Cobb-Douglas function, used to describe capital and labor inputs, is modified to separate energy sector production and non-energy sector production. The new function describes capital and labor available for production in the energy sector and the remaining amount of these quantities. Also included in welfare is a damage function to account for temperature rises due to global warming and the impact on the energy production sources. The second aspect of GDP extrapolations involves population increase models. Census and readily available for this purpose. However, while population increase is relatively predictable from historical trends, the distribution of the population within the United States is somewhat more uncertain. Additional information on the economic modeling and GDP extrapolations can be found in Milligan [2].

As Milligan shows, GDP and energy use within a country or region are related, albeit not in constant ratio to each other. In general, the energy used to produce a specified amount of GDP follows historical and mathematical trends. With this coupling, the energy use rates in each of the eight specified regions can be extrapolated out to 2050. The division of energy production by sector is well known for current data for developed countries, especially the United States [3]. The Energy Information Administration of the United States government records and publishes yearly data on domestic energy production from all sources, including coal, natural gas, nuclear, wind, and others. Longer time series data is collected for over 200 countries by the United Nations.

However, the fraction of total U.S. energy production due to each source is destined to change by 2050. Indeed, uncertainties in the futures of almost every production source may lead to a very different energy picture in the coming decades. The effects of global warming and the consequences of any means taken to address them require careful analysis and are a source of uncertainty.

Furthermore, the repercussions of various political and technical scenarios will undoubtedly have large impacts on the U.S. energy production sector. One such scenario is an international agreement on limiting the use of fossil fuels (along the lines of the Kyoto Protocol), which would greatly reduce the reliance on carbon-producing sources around the world and in the United States. As a result, the fraction of energy production from coal, natural gas, and other carbon sources in the United States would decline. Another possibility is individual nations passing legislation or resolutions placing limits on their own carbon production (similar to the U.S. Clean Air Act), which would also serve to restrict the utilization of carbon sources. While the U.S. Environmental Protection Agency has recently promulgated regulations that could sharply curtail atmospheric carbon emissions from new coal-fired power plants, the political durability and net effect of these regulations remains to be seen.

While use of non-fossil energy sources other than nuclear power is growing, such sources have serious limitations with respect to where they can be deployed, how stable their power output is, or both. Renewable energy sources such as wind and solar will continue to expand, albeit at different rates in different regions, in the coming years. However, as carbon-based fuels currently dominate (approximately two-thirds) the energy market, it is unlikely that renewable sources will be able to completely fill the void left by weaning off fossil fuel sources. The low energy densities typical of renewable energy sources make them poor candidates for accommodating large-scale, baseline electrical loads. Therefore, with anything like current technology, massive reduction in fossil fuel use is likely to be accompanied by increased utilization of nuclear power.

Estimating approximate energy demands in 2050 and carbon limitation strategies, if any, in place by that time, the future of nuclear energy in the U.S. energy production mix can be developed. The number of new nuclear power plants required to meet the energy needs of the country in 2050 after a mandated reduction in carbon-based sources can be deduced. Even with no reduction in fossil fuel usage, an equal number of nuclear power plants will be needed simply to replace aging facilities that are decommissioned by 2050. Regardless of the specific future path taken,

nuclear power may play a critical role in addressing future energy production needs.

With the utilization of nuclear power comes the inherent burden of addressing spent fuel and nuclear waste concerns. Given the number of new nuclear power plants needed by 2050 and the approximate rate at which spent fuel is discharged yields, when combined with current spent fuel in temporary storage, an estimate of total repository space can be obtained. In addition, characterizing spent fuel to be stored is essential, as thermal and radioactive concerns will dictate spent fuel arrangement, canister packing, and environmental issues. Developing an understanding of spent fuel characteristics of current and future reactors will be an integral part of appropriately siting spent fuel management facilities.

History has shown that attempting to site a repository could take an extended amount of time. This process should not be held up by lacking an effective understanding of the material to be stored. As a result, tools are currently needed to model the radioisotope inventory of all spent fuel produced in reactors built before 2050. These tools will aid planners and policymakers in determining size, location, and containment properties of a proposed repository and, thus, its suitability. As technical personnel will not completely decide this issue, attention should be paid to making all decision tools transparent and simple to use, but not sacrificing in accuracy. Ultimately, the process of constructing, citing, and operating a spent fuel repository in the United States will involve a concerted effort on the parts of personnel spanning several technical, social, and political disciplines and, because there is no time to lose, work must begin immediately on tools to aid in this development.

The focus here is on reactors built in the United States by 2050. The idea is that defining a functioning system to manage all of the spent fuel they ever produce should allow continuation for new reactors built later than that. If, on the other hand, alternative technology for electricity production proves more attractive than nuclear power for new builds later in the century, which cannot at this point be precluded, there would be a system in place for effectively managing all of the spent fuel ever produced in the United States. This stands even in the not unlikely event that

nuclear power plants built in the decade or so before 2050 would represent such a large and useful capital investment that they would continue to be operated for the rest of the century.

This project is undertaken to model approximate actinide inventories in spent nuclear fuel utilizing unsophisticated computational resources and commercially available software. The method proposed here of adjusting the chemical shim (boron concentration) to maintain criticality is adopted as proof-of-concept and represents a particularly convenient approach to the modified diffusion equation calculations. Even so, significant additional work must be completed to develop the contained computer code into a fully operational tool in support of analysis and policymaking in support of a successful nuclear waste management program.

Chapter 2

Background

2.1 Spent Fuel Basics

The burden of used nuclear fuel in the United States first became a reality with the inaugural refueling of the Shippingport Atomic Power Station in 1961, four years after becoming the first commercial nuclear generating station in the country [4]. Since then, scientists and engineers have attempted to address the problem of spent nuclear fuel storage and disposal with a mixture of innovation, ingenuity, and technology.

Commercial nuclear power plants work, in the simplest of terms, by turning the energy contained within its fuel into electricity. To do this, the fuel (predominantly U235 usually enriched to a concentration greater than that found in nature) absorbs a neutron and undergoes a process called fission, whereby the U235 nucleus splits, releasing energy, lighter fission fragments, and additional neutrons used to sustain the chain reaction. The energy released, eventually manifest simply as heat, goes on to boil water. This boiling water, now steam, forces a turbine to rotate which, when connected to a generator, produces electricity, the endgoal of the commercial nuclear powerplant. Each fission produces daughter product atoms, many of which are radioactive. Also for each neutron that produces a subsequent fission, an average of more than one neutron is in-

stead absorbed, producing a multitude of radioactive isotopes. In particular, elements present in the fuel that are heavier than uranium can continuously absorb additional neutrons to produce a distribution of highly radioactive actinides includes transuranics (elements with more protons than uranium). While the heat and, by extension, electricity serve as productive outcomes of this fission reaction, the extremely radioactive fission products and transuranics can have detrimental effects on biological lifeforms and, thus, must be handled accordingly [5].

For the reactors cooled by ordinary water that are investigated in this thesis, the uranium fuel, in oxide-form and enriched in U235, is shaped into cylindrical ”pellets” approximately 0.5 inches in diameter and stacked within a cylindrical zirconium sheath to a height of approximately 12 feet [5]. Approximately 200 of these ”fuel rods” are fashioned together to form a ”fuel bundle” or ”fuel assembly,” of which there can be hundreds in an average commercial nuclear reactor [6]. After a prescribed amount of time producing heat and electricity, nuclear reactors are refueled by replacing varying numbers of these ”spent” or ”used” fuel assemblies with fresh fuel. Refueling is done primarily by replacing or relocating the entire assembly, and all subsequent spent fuel handling is done on the assembly level. While all but a minute fraction of radioactive fission products and actinides, are physically constrained within the zirconium sheath, all irradiated assemblies are removed and managed in a remote handling environment due to radiation hazards [6]. These assemblies, bundled collections of spent fuel rods themselves containing spent fuel, fission products and actinides in solid and gaseous forms, are what make up what is typically referred to as ”spent nuclear fuel” or ”used nuclear fuel.” (Note: fuel and cladding sizing, fuel enrichment and material type, rod and bundle numbers, and residence time can all vary by reactor type. Numbers given are merely for illustrative purposes to provide the reader with an overarching impression of nuclear operations.)

As of December of 2011, International Atomic Energy Agency (IAEA) figures indicate that 435 reactors continue to operate in 31 countries, with 104 of those in the United States [7]. Designs, operation, and thus spent fuel production vary considerably. As individual countries may

even operate multiple types of reactors, spent fuel production rates and characteristics can differ. Worldwide, approximately 280,000 metric tons of heavy metal (MTHM) spent fuel have been historically produced. (Heavy metal refers to the uranium and plutonium content of the original fuel when loaded. Plutonium recovered from spent fuel is sometimes added to the uranium.) Of this 280,000 MTHM worldwide, 190,000 MTHM currently require disposal. (90,000 MTHM has been reprocessed, but all of the resulting fission products and much of the recovered actinides have not been fashioned into reactor fuel and still require careful management.) [5]. Recent records indicate that spent nuclear fuel (SNF) is currently being produced at a rate of approximately 11,000 MTHM per year globally [5]. Of this amount, reactors specifically in the United States are responsible for about 2200 MTHM spent fuel produced per year [8]. As of 2011, 55 years of commercial nuclear electric generation in the United States had led to a total of about 65,000 MTHM spent fuel requiring disposal [8]. On a state basis, not all U.S. states have produced, continue to produce, or harbor commercial spent nuclear fuel. Indeed, only 35 of 50 states are responsible for the U.S. commercial spent nuclear fuel inventory. Figure 2.1 displays the distribution of SNF in U.S. states. As the figure indicates, Illinois and Pennsylvania currently harbor the largest amounts of SNF and, more generally, the largest concentrations of SNF can be found in Southeast and Northeast states. Significant amounts can be found in some upper-Midwest and Southwestern states, with very little found in Northwest and mountain states.

As the United States has not licensed an operational repository, nearly all commercial spent fuel remains on the site of the reactor that produced it. The only exception is a mere 670 MTHM from a variety of states shipped to Morris, IL, intended as the location of an ill-fated reprocessing plant, in the late 1970s [9]. While the plant never operated, the SNF has remained on site in storage pools. The facility is the only ”away from reactor” spent fuel pool licensed by the NRC and is slated to operate through 2022 [10]. As a result, the balance of the approximately 65,000 MTHM of commercial spent nuclear fuel produced in the United States since the advent of nuclear power is still stored on the grounds of the reactor that produced it. Because all spent fuel was initially

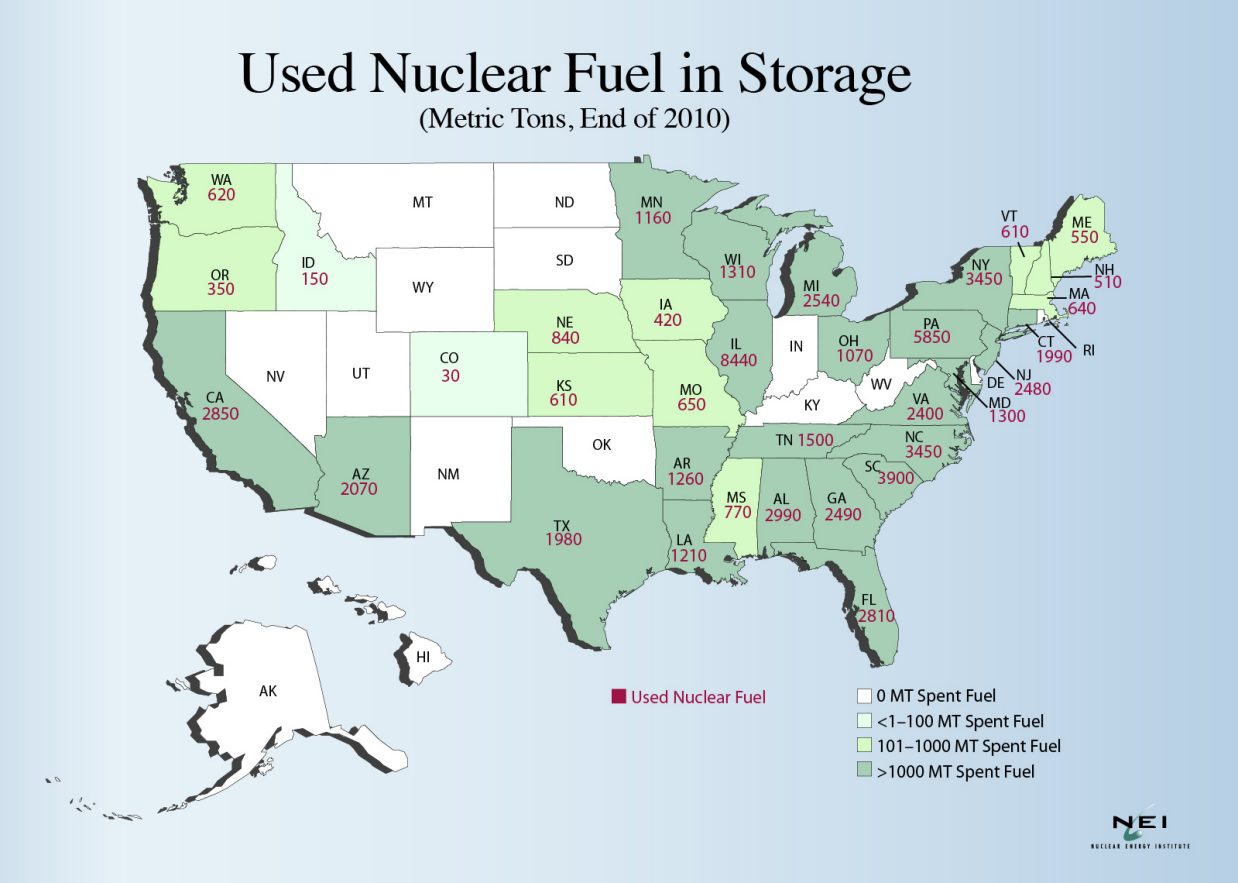

Figure 2.1: Distribution of Commercial Used Nuclear Fuel in U.S. States, 2010 [11]

expected to be punctually removed from the reactor site by the federal government, little attention was paid during reactor construction to including large-scale, on-site fuel storage facilities. Only limited capacity for housing used fuel removed from the reactor was incorporated into the reactor plant design. As the federal government has been unable to open an underground repository as required by law for decades, most of these storage methods are now insufficient and at capacity. With no repository to send their SNF to and diminishing space to store additional SNF onsite, nuclear utilities have been forced to consider alternative temporary means to address nuclear waste concerns.

For years after removal from the reactor, spent fuel remains thermally hot and extremely radioactive and, thus, is most often stored in shielded pools. The circulating water in the pools acts both as a coolant and as a radiation shield, preventing workers above from receiving harmful doses. While every commercial nuclear reactor was built with a spent fuel pool, capacity was limited to approximately a decade's worth of operation [8]. Upon nearing maximum initial capacity, nuclear utilities were permitted (upon receiving approval from the NRC) to pack fuel assemblies more tightly into these pools in a process called "re-racking." Redesigning the "rack" used to suspend the spent fuel in the pool by decreasing the separation distance between assemblies usually required the addition of neutron absorbers, but permitted a significant amount of additional fuel to be stored in the pool. This allowed the utility to continue to operate, produce electricity, and discharge spent fuel as U.S. nuclear waste policy evolved. As aof 2011, approximately 75% of all U.S. commercial spent nuclear fuel was stored in spent fuel pools [8]. While spent fuel pools remain the most common method of temporarily storing spent nuclear fuel, some have reached or are rapidly approaching their ultimate maximum capacity. Without any short-term hope for an underground repository, many nuclear utilities have been forced to utilize dry casks as a supplement to their spent fuel pools in recent years.

Nuclear utilities, short on spent fuel pool space, began transferring older SNF to dry casks. After cooling for a minimum of three to five years (although, in practice, usually much longer) in a spent fuel pool, SNF can be removed from the pool and stored in steel-lined, concrete canisters. These canisters are relocated to a concrete pad outside the reactor building, although still onsite, freeing up space in the spent fuel pool for recently offloaded SNF. In addition, dry cask storage of SNF is generally safer than spent fuel pool storage because active cooling is not required. In spent fuel pools, electrically powered pumps must circulate water throughout the fuel assemblies in order to prevent overheating; dry casks are air-cooled. Indeed, an abundance of SNF stored in the spent fuel pool has been cited as one of many complicating factors of the Fukushima, Japan nuclear disaster in the wake of a tsunami in March 2011 [8]. After tsunami damage caused all

electrical power to be lost to the reactor site, pumps were not available to circulate cooling water in the spent fuel pool, leading to overheating and additional complications. This led the nuclear industry in the United States to reconsider the wisdom of long-term pool storage of spent fuel at commercial nuclear reactors. Currently only 25% of U.S. SNF is stored in dry casks, although this number is expected to rise in the near future [8]. Although spent fuel pools and dry casks have been ”judged adequately safe and secure” by the NRC, it is evidently clear that these waste management techniques were only designed for short-term storage of SNF and that an ultimate long-term solution must eventually take their place [8].

Of particular concern in the United States is commercial spent fuel remaining at reactor sites that have shut down. Dubbed ”stranded fuel,” it is forced to remain on the site of the shutdown reactor with nowhere to go and prevents some sites from being fully decommissioned. Nine shutdown commercial reactors currently still harbor spent nuclear fuel in the United States, and an additional similar facility in Colorado is DOE-owned [8]. Two of the states, Maine and Oregon, have no other commercial nuclear facilities besides the shutdown plant sheltering stranded fuel (See Table 2.1).

Table 2.1: U.S. Stranded Commercial Spent Nuclear Fuel

STATE	Number of Sites Running	Plant Shut Down	Storage Type	MTHM
Illinois	6	Zion 1 and 2	Pool	1019
Maine	0	Maine Yankee	Dry	542
Connecticut	1	Haddam Neck	Dry	412
Oregon	0	Trojan	Dry	359
California	2	Racho Seco	Dry	228
California		Humboldt Bay	Dry	29
Massachusetts	1	Yankee Rowe	Dry	127
Michigan	3	Big Rock Point	Dry	58
Wisconsin	2	La Crosse	Pool	38
Total				2813

[9]

In the general scheme of the nuclear waste management program debate, facilities with stranded fuel are particularly troublesome. In some, the only thing that remains of the former reactor plant is a concrete pad hosting several dry casks of fuel. As a result, potential problems might arise if the fuel should ever need to be recasked for transportation to a repository or if degradation of current casks prevents safe storage; the facility no longer has the capability to effectively handle spent fuel in these scenarios. In addition, the fuel casks and associated security and upkeep are exorbitantly expensive and prevent the complete environmental remediation of the site for other public uses. As no geologic repository currently exists, the sites have become de facto long-term fuel storage sites when they were not intended as such. While the U.S. nuclear waste management program faces many hurdles, effectively addressing stranded fuel sites must be foremost on the list.

Though often lost in the considerations pertaining to nuclear waste disposal, the DOE is also responsible for moderate amounts of non-commercial nuclear waste that require disposal. These wastes, usually resulting from defense programs, also represent significant challenges for disposal. Legacy government reactor fuel and test facilities often utilized unique materials and mechanical configurations. Nuclear weapons programs are responsible for significant amounts of radioactive liquid waste, only some of which has been converted into solid glass forms and stored in canisters. In addition, reactors from decommissioned naval nuclear vessels are currently stored at government laboratories in Idaho and await emplacement in a repository. While the DOE has not, in general, accepted commercial spent nuclear fuel for storage at its government sites, specialized exceptions do exist. One such example is the reactor core from Three Mile Island (TMI), which was damaged in a nuclear accident in 1979 and subsequently shipped to Idaho National Lab (INL) for examination. In addition, DOE has custody of spent fuel from the Fort Saint Vrain commercial reactor in Colorado, which was one of only a few unique High-Temperature Gas-Cooled Reactors (HTGCR) in the United States. These wastes, though representing only a small fraction of the spent nuclear fuel and high level wastes (HLW) in the United States at approximately 2500 MTHM, represent unique waste disposal challenges that also must be addressed [8]. While the

bulk of the U.S. nuclear waste management strategy revolves around commercial spent nuclear fuel, DOE wastes will also play a role in any future disposal arrangement.

In conclusion, considerable quantities of spent nuclear fuel in the United States require long-term disposal. Most spent fuel remains on the site of the reactor that produced it, even though reactors in the United States were not originally intended as long-term storage sites. As original capacity to stored spent fuel has diminished, utilities have had to look to reracking and dry casks as means to accommodate increasing amounts of spent fuel stored on site. Although this commercially produced spent fuel represents the largest portion of material to be ultimately disposed of in an underground repository, DOE holdings of defense and legacy wastes must also be considered in a successful waste management strategy. While nuclear waste management first became an issue several decades ago at the outset of the nuclear industry, the United States has yet to license, build, and open a centralized federal repository. Significant ventures have been undertaken by the federal government spanning many years to address this issue, but none have been completely successful. The history of nuclear waste management in the United States is indeed wrought with misdirection, lack of organization, and failed attempts to address the problem.

2.2 History of Radioactive Waste Disposal in the United States

In the 1940s, with all U.S nuclear operations inherently linked to government weapons programs, waste disposal concerns that developed took a backseat to national security, i.e. weapons systems production, concerns. Attempts to deal with SNF and other high-level wastes (HLW) produced in weapons programs proceeded only as a means to prevent backlog on the front or production aspect of the weapons production operation and often proved insufficient or lacking in long-term consideration. For example, high-level liquid wastes were stored in underground steel tanks that would eventually rust even as government oversight bodies acknowledged the need for additional waste disposal considerations. The Atomic Energy Commission (AEC), the government agency in

charge of all weapons production operations at the time, recognized in 1949 that a ”better means of isolating, concentrating, immobilizing, and controlling wastes will ultimately be required” [8]. In the post-WWII, early Cold War arms race environment, difficulties and concerns surrounding waste disposal first arose, but were often overlooked in the name of national security.

The late 1950s and early 1960s brought the early attempts by the AEC to address waste-specific challenges. Reports published by the National Academy of Sciences as well as academics convinced the AEC to focus research primarily on underground disposal of waste products. Preliminary as well as in-depth studies of various types of rock formations around the United States, most notably underground salt formations, were undertaken [8]. At this time, further research into reprocessing, liquid waste solidification, as well as radioactive waste transportation and other related disposal challenges proceeded.

It is important to note that all wastes up to 1961 the time of the first Shippingport refueling) were government wastes and the result of weapons production activities. These wastes, though different than commercial SNF, present their own individual disposal challenges. However, as more new commercial nuclear power plants come online in the early 1960s, following the lead of the Shippingport Atomic Power Station, the AEC found itself tasked with the duty of creating a waste disposal strategy tailored to both legacy weapons production wastes and commercial spent nuclear fuel. Thus, early disposal solutions often attempted to address both challenges in parallel with limited success.

Early attempts to address waste concerns often centered around fuel reprocessing. Then performed solely by government entities, not commercially, reprocessing allowed for the reduction in the physical volume of waste for disposal, the extraction of uranium for use in new fuel rods, and the extraction of plutonium for use in nuclear weapons. The latter was the reason for U.S. government involvement (however, present day commercial reprocessing facilities do exist in other countries without a focus on weapons material production). While reprocessing can actually refer to one of several different processes, all attempt to take advantage of the solubility (or lackthereof)

of uranium and plutonium at various oxidation states. While a bismuth-phosphate process was initially used at a government site in Hanaford, WA, during WWII to produce plutonium for nuclear weapons, most reprocessing facilities since the 1950s have utilized the PUREX (Plutonium and Uranium Recovery by EXtraction) process. In both cases, the cladding is removed and the fuel pellets are cut into small pieces. The fragments are heated to remove radioactive gases and then dissolved in nitric acid. Upon the addition of tributylphosphate (TBP), the fission products remain in the acidic solution and the uranium-plutonium-TBP mixture is removed. Reducing agents are added in subsequent ”extraction columns” to precipitate out only plutonium in high concentrations [12]. In a similar process, uranium can also be extracted. The individual streams of uranium and plutonium are further processed to enhance purity and concentration before exiting the process as liquid acidic solutions [12]. These solutions can then be utilized for their high concentrations of uranium and plutonium.

After the useful elements are removed, highly radioactive and corrosive liquids remain as byproducts of reprocessing. As a result, considerable effort was also put into researching solidification techniques, called vitrification, for these liquid wastes. In solid form, these wastes can be more easily contained, stored, and transported. In addition, the physical volume requiring ultimate disposal is further reduced. Most vitrification processes involve combining the liquid waste with liquid glass and allowing the mixture to cool into solid form. Conceptually, glass is used because ”it mixes well with wastes of various compositions, casts easily into proper forms, conducts heat well, and resists attack [from water, oxygen, etc] at low temperatures” [13]. Furthermore, the potential for dangerous elements to leech out of the glass form in the presence of water has been shown to be very low [13]. Once stored in sealed canisters, the glass waste could effectively and safely be stored in a geologic repository.

Considerable efforts were put into researching both the reprocessing and vitrification processes as a means of nuclear waste management in the early 1950s. When combined, the concept was that commercial spent nuclear fuel would be reprocessed at U.S. government facilities and turned

into new commercial reactor fuel to be sold back to the utility. At the same time, plutonium would be produced to bolster the U.S. nuclear weapons stockpile during the burgeoning Cold War arms race and the physical volume of wastes requiring disposal would be reduced (compared to placing spent commercial fuel directly into a repository). However, even with a reduction in the volume of waste to be disposed, it quickly became apparent that an ultimate geologic repository would still be required and investigations into the suitability for long-term storage of nuclear wastes in various geologic formations continued in parallel.

In 1970, the AEC publicized plans to investigate the suitability of using a salt mine in Lyons, Kansas as a long-term storage facility for both high-level wastes (HLW) and low-level wastes (LLW). Initial assessments predicted that the facility could start accepting shipments in less than five years [8]. However, with local public support for the project waning, unfavorable geologic conditions were discovered in the salt formations that led the AEC to cancel all aspects of the project by 1972. Subsequent investigations by the AEC into rock formations ranging from salt domes to volcanic tuff located in Michigan, Texas, Utah, Louisiana, Mississippi, Nevada, Washington, and others produced several potential sites for a nuclear waste repository [8]. However, upon learning of AEC investigations in their states, politicians and others were often keen to quickly raise enough public opposition to effectively kill any proposed site in its infancy. After several decades of research and several attempts at finding a legitimate storage site for the country's nuclear waste, the AEC had made very little progress. With the inability of the reprocessing plan to effectively solve the country's nuclear waste dilemma, the need for a geologic repository would soon become even more apparent.

While the reprocessing path to solving the nuclear waste dilemma the United States had initially headed down seemed to be a fix-all, shortcomings eventually became apparent. As significant numbers of commercial nuclear power plants began to come online in the early 1970s, the industry saw its first attempts at commercial reprocessing. Nuclear Fuel Services, Inc., constructed and operated the first commercial nuclear fuel reprocessing facility from 1966 to 1972 in West Valley,

NY. Subject to significant cost overruns, the facility was forced to close after reprocessing only a small amount of nuclear fuel. Additionally, a reprocessing plant was built in Morris, IL, by General Electric ”but was never operated because of startup difficulties.” Another facility in Barnwell, SC, ”was essentially completed....[but] was never operated because of presidential directives” [14]. In the late 1970s, acting on fears of proliferation of nuclear material (specifically plutonium), President Ford signed an executive order temporarily preventing commercial spent fuel reprocessing in the United States; President Carter signed another executive order a year later prohibiting reprocessing ad infinitum [8]. This limitation, based in part on fears arising from the ad hoc admission of India to the list of nuclear weapons states after a short clandestine weapons program, sought primarily to prevent the inadvertent or intentional diversion of amounts of plutonium from the reprocessing stream for use in a nuclear explosive by an unauthorized entity, terrorist, or rogue nationstate. In short, according to the Ford and Carter Administrations, the only way to guarantee that such a travesty would not occur was to prevent commercial reprocessing entirely. Although President Reagan would undo the ban a few years later, many reasons, paramount among them an unjustifiably high cost, led to an industry-wide disinterest in further reprocessing endeavors [8]. As a result, the Barnwell and Morris facilities continue to be to this date very expensive spent fuel temporary storage facilities [14]. As proliferation concerns and the economic infeasibility of reprocessing became apparent, it was clear that a new direction for waste management was required in the United States. After completely phasing out reprocessing, U.S. policy would focus solely on a ”once-through” nuclear fuel cycle, meaning that all irradiated fuel assemblies would be promptly buried in a large geologic repository. However, with efforts to actually site a repository disconnected, lethargic, and essentially stalled, Congress sought to lay down a new set of ground rules.

The Nuclear Waste Policy Act of 1982 (NWPA) attempted to take advantage of the lessons learned from nearly four decades of ineffectual policies pertaining to nuclear waste disposal. It represented a major conceptual step forward and was meant to ”establish a fair and technically

sound process for selecting repository locations" [8]. Several key provisions were revolutionary and put in place concrete procedures and deadlines for waste disposal goals. For the first time, a fee was levied on nuclear-generated electricity with the money going to a so-called "Nuclear Waste Fund" (NWF) dedicated to financing, in part, an ultimate repository. The fee, 0.1 cents per kilowatt-hour utilized, represented only a 1.6% increase to the consumer in the price of electricity, but was forecast to provide a sufficient reserve of funds to pay for researching, locating, licensing, and operating an underground repository [13]. Furthermore, under the NWPA, the federal government pledged to "take title" to all commercial spent nuclear fuel beginning in 1998, for the first time imposing a hard deadline on itself of sixteen years to open a storage facility [8]. Recognizing the difficulty in constructing a complicated, underground facility, provisions were also included for "monitored retrievable storage" (MRS) sites. Although not a permanent solution, MRS facilities could be used as aboveground staging and consolidation locations prior to underground interment while still allowing the government to meet its imposed deadline. Subject to fewer long-term containment restraints as merely a temporary facility, it was thought an MRS facility would be easier to site and could be used as a springboard to siting, licensing, and opening an ultimate repository. The NWPA also sought to address mounting state-level concerns about hosting a permanent repository. Hoping to assure individual states they would not "bear the entire burden of the nation's nuclear waste management obligations" alone, the NWPA included provisions for two underground storage facilities and set a ceiling on the amount of waste the first facility could accept before the second one opened [8]. Furthermore, the NWPA clarified a state's limited ability object or regulate to a federal repository imposed upon it, although this objection could be superseded by Congress [8]. Although government agencies would site and regulate any proposed repository, voluntary or at least complicit participation on the part of the state was assumed. However, with mounting political opposition on the part of individual states to hosting any such a facility within its borders, state representatives were keen to include this state-level veto. Although the NWPA took many measures to address the decades-old waste disposal dilemma in the United States, political

wrangling would continue to inhibit progress.

The Atomic Energy Commission (AEC), split apart by the Energy Reorganization Act of 1974 and the Energy Organization Act of 1977, saw its powers and responsibilities divided amongst two new government agencies, the Nuclear Regulatory Commission (NRC) and what became the Department of Energy (DOE), just before the passage of the NWPA [13]. While the role of the NRC was to come up with enforceable guidelines of operation for all specifically nuclear-related facilities, the DOE was responsible for a wide array of subject matter, from fossil fuels to renewable sources to nuclear power. In spite of taking on all of these additional tasks, it would be the burden of the DOE to now recommend suitable host sites for the nation's two planned underground repositories as stipulated by the NWPA. In 1986, four years after the passage of the NWPA, Secretary of Energy John Herrington did just that by narrowing the scope down to three locations; Yucca Mountain in Nevada, the Hanford Site in Washington, and Deaf Smith County in Texas [8]. In addition, three locations in Tennessee, centered around government facilities at Oak Ridge, were recommended as possible MRS host facilities [5]. Although acting completely in compliance with the NWPA, the DOE had manage to create a political firestorm in the potentially affected states, each hoping to avoid hosting a waste storage facility of any kind. Legal challenges to the selection process, the NWPA, and the storage of waste in general arose and served to complicate the process even more. Combined with the budding realization that NWPA deadlines were unrealistically optimistic and that political and legal objections were impeding progress on the issue, Congress stepped in again.

The Nuclear Waste Policy Act Amendments Act of 1987 was Congress' attempt to address the issues that had arisen since the passage of the original NWPA. The most prominent result was the limiting of additional exploration and research leading to an underground repository solely to Yucca Mountain, Nevada [8]. This served to rule out any possibility of any state east of the Mississippi River hosting the facility and angered western states, most of all Nevada. The result was that Nevada felt bullied by the federal government and, feeling like they could be next, other western

states joined in by letting their objections be known. From the DOE perspective, the cancellation of the second repository was required, as simply one facility was proving increasingly difficult to site, and outdated cost projections were proving insufficient to maintain the original dual-pronged approach. In addition, Nevada was to ”receive financial compensation and special consideration in federal research projects” as incentives for hosting the facility [13]. The issue of utilizing a MRS site was also addressed. Like the compensation offered to Nevada, states volunteering to host a MRS site were also offered economic benefits. However, hearing objections and fears from states that a ”temporary” MRS site could become a ”de facto permanent” storage site stemming from a federal failure to license an ultimate repository, Congress sought to further define the role of such a MRS facility under the very real possibility that a repository would not open for many years. It was decided that the only way to assuage states' fears was to require that an ultimate repository construction license be issued before an MRS site could be built [13]. This would serve to guarantee that an ultimate disposal place existed for spent fuel before it was consolidated and stored at an MRS facility. Finally, the amended act directed research funding to simply technologies relating to the characterization of Yucca Mountain and the associated storage and containment challenges. Borne out of the controversy surrounding the original NWPA, the amended NWPA attempted to further refine the process of siting an ultimate underground repository and direct the country forward in addressing nuclear waste concerns.

The amended NWPA also created several other government entities with specific responsibilities relevant to a repository. In order to ensure the unbiased integrity, both politically and technically, of recommendations and decisions made by the DOE pertaining to nuclear waste disposal, Congress created the Nuclear Waste Technical Review Board (NWTRB) [13]. The NWTRB was tasked with ensuring that the DOE did not become a political arm of the federal government by overseeing technical studies performed by and ensuring that facts were not being misconstrued or interpreted for political gain. The desire for an oversight body again stemmed out of states' fears that they could be bullied by the federal government into taking an unwanted repository based

on the blowing political winds at the time. Secondly, the Office of the Nuclear Waste Negotiator was also created to collaborate with communities in seeking a volunteer host site [13]. Whereas previous attempts at siting a repository had involved local communities only after determining the technical suitability of the site, the Office of the Nuclear Waste Negotiator was tasked with addressing the potential host community from the outset of the process. Serving as an arbitrator between the community and the federal government, the Office of the Nuclear Waste Negotiator would ideally barter a deal between the two entities, negotiating financial incentives, process timelines, and addressing future setbacks. However, very little was accomplished by the Office, and it was subsequently closed in 1995. Though two successive presidential administrations had placed a great deal of hope in the valiant efforts of the Office, it was disbanded after only a short time operating.

Exploratory programs for both a repository and an MRS site under the Office of the Nuclear Waste Negotiator included a system of phases geared toward soliciting community support gradually. It was understood that misinformation and lack of credible transparency had doomed previous relations with potential host site communities, and a system of ”study grants” was devised to overcome this [15]. Without committing themselves, a community could utilize these grants to gauge the social climate pertaining to hosting a facility and still reserve the right to pull out at any time before the site proposal was submitted to Congress, a distant point in the future. Entering the first phase ”gave the community an opportunity to learn about the technical aspects of high-level waste storage” and brought with it $100,000 in compensation [15]. Entrance into Phase II-A doubled the compensation, but required a deeper level of assessment and community response. Finally, Phase II-B consisted of grants of up to $2.8 million, but required the community to enter into deliberate negotiations with the Office pertaining to the suitability of the community to host a storage facility [15]. During this process, the community would incur no obligation, could withdraw at any time, and was still eligible to keep any compensation previously awarded. It was hoped that this unprecedented level of freedom and flexibility would encourage voluntary bids whereas prior

forced attempts had not yielded any interest.

Although an overwhelming response was not evident, four counties submitted proposals for Phase I grants: Grant, ND, Fremont, WY, San Juan, UT, and Apache, AZ. Other counties in various states also expressed interest in applying, but were prevented from doing so by the state governor, a position that retains an overarching veto in spite of county-level interest [15]. The Apache County proposal was the only one not approved for additional study. The North Dakota proposal did not proceed further, as the local populace objected once the grant report was published. In addition, governors in Utah and Wyoming, who had originally given their consent to a Phase I proposal, withdrew consent from any further possible grants in the face of mounting public opposition [15]. In all three cases, the thinly populated, economically underdeveloped, predominantly rural counties that had submitted the proposals faced project-threatening opposition from surrounding well-populated areas, mainly the adjacent counties waste would have to be transported through in order to deliver it to a facility in the receptive county. Political pressure from dissenting constituents forced the hand of politicians; a public show of support for such a project for those in office was impossible. As a result, after a detailed, well-intentioned process to address the need for a voluntary host community for the nation's nuclear waste, the Office of the Nuclear Waste Negotiator had not produced a single viable candidate.

Floundering attempts to negotiate a repository agreement with U.S. counties at this point led the federal government to consider interesting alternatives. Located within U.S borders but technically considered semi-autonomous nations, the federal government had long courted Native American Indian tribes for using reservation lands as temporary and permanent spent nuclear fuel repositories. Not subject to a governor's veto, the Office of the Nuclear Waste Negotiator was free to negotiate without state-level interference directly with tribal councils. While Native American sovereignty as it applies to a variety of topics, specifically rights to conduct gambling enterprises and the issue of collection of taxes, has historically been extensively debated in the American legal system, tribal autonomy can still be a legal grey area. In general, "it remains unclear whether

tribes may fully ignore the laws of the states in which they are located" [15]. In this particular case, it was determined that the state, specifically the governor, has no authority to interfere with agreements between the Office of the Nuclear Waste Negotiator and any Native American tribes. With no U.S. counties willing or able to host a facility, the Office of the Nuclear Waste Negotiator started entertaining proposals from Native American tribes to store spent nuclear fuel under the same system of study grants, even while being unsure of the legal ramifications of doing so. The tack of bypassing states by negotiating with Native American tribes would eventually further alienate states and prove unsuccessful.

This strategy of negotiating with tribes initially appeared to offer a reasonable chance of success. To start off, fully twenty tribes submitted proposals for Stage I grants [15]. The tribes hailed from a variety of states, but mostly from arid, sparsely populated Western mountainous states like New Mexico, Utah, and Wyoming. These states represented the traditional places the federal government had been looking at placing a facility. However, tribes from other regions of the country like Minnesota, Oklahoma, Oregon, and Colorado also submitted proposals, each offering a different but still scientifically feasible geology for such a facility. After a promising start, the negotiation process again started to fall apart. Only 85% of the initial proposals were accepted by the Office, and four of the accepted proposals were withdrawn early in the process with no grant money exchanging hands [15]. After eight of the initial twenty quickly withdrew their proposals after receiving the initial Phase I disbursement, the Office began to question the authenticity of some of the original proposals. While five tribes pursued Stage II-A grants, the Office welcomed four additional new proposals from tribes to directly enter this stage as well. Ultimately, only the Skull Valley Goshute Tribe of Utah and the Mescalero Apache of New Mexico applied for Phase II-B grants. While New Mexico state politicians had no ability to intercede in discussions between the Mescalero Apache and the federal government, they made several attempts to take action that was within their power to complicate, slow, or impede perceived attempts to bring a waste storage site to their state. Amidst these negotiations with tentatively interested tribes, Congress

terminated the study grant program in 1993 and dissolved the Office of the Nuclear Waste Negotiator in 1994 [15]. New Mexico state officials and legislators played a key role in influencing this decision, ultimately circumventing their lack of veto powers over federal negotiations with the Mescalero Apache and achieving their desired end anyway. Without the Office of the Nuclear Waste Negotiator and the study grant program in place, all discussions with previously interested tribes suddenly halted and it appeared that no additional progress would be made.

2.3 Private Fuel Storage

Until this point, the nuclear utilities actually producing the spent nuclear fuel had been rather silent and deferred to the federal government during the negotiations regarding waste storage facilities. Still covered by the umbrella legislation requiring government acceptance of commercial spent nuclear fuel by 1998, utility representatives had quietly been making alternative plans, hedging their bets that the federal government would fail to take title as promised. A consortium of eight nuclear utilities formed and backed their own venture, a non-governmental entity entitled Private Fuel Storage, LLC (PFS). In an attempt to bypass the federal government bureaucracy entirely, PFS resumed negotiations with interested Native American tribes, offering significantly more financial incentives to host a storage site. Finding the Skull Valley Band of Goshute Indians still interested in hosting a site, a partnership was formed on December 27, 1996, with just over a year remaining until the federal government was supposedly going to take title to PFS member-owned spent nuclear fuel. Private Fuel Storage, LLC was not optimistic. Although the state of Utah continued its opposition to storing such waste within its borders, the venture progressed. On June 25, 1997, PFS submitted to the NRC a license application for an above ground storage facility called an Independent Spent Fuel Storage Installation (ISFSI), akin to an MRS. Nearly a decade later, the NRC approved the license on February 24, 2005. After hearing and denying the State of Utah's ultimate appeals by September 9 of the same year, the NRC formally issued a construction

and operating license to PFS on February 21, 2006. The approved license called for a limit of 44,000 tons of SNF, enough to hold approximately two-thirds of the nation's waste at the time, to be stored in dry casks at the site for 20 years [16]. It was recognized as a temporary solution to the waste disposal problem, but nevertheless represented a potential step forward. However, after initial success wading through the treacherous waters of governmental approval, the venture hit several debilitating setbacks. In September 2006, seven months after licensing, two major legal cases were levied against PFS interests. First, the Department of the Interior's Bureau of Indian Affairs rejected the proposal to lease tribal land to PFS, even though the representative body of the tribe itself was in favor of the plan. Second, the Department of the Interior (DOI), Bureau of Land Management disallowed "the necessary rights-of-way to transport waste to the facility, concluding that a proposed rail line would be incompatible with the Cedar Mountain Wilderness Area and that existing roads would be inadequate" [16]. Furthermore, it was claimed that the rights-of-way could not be granted because of uncertainties in the project and that the proposal was not in the best interests of the public. In response, PFS and the Goshutes filed a lawsuit against the Department of the Interior in federal court on July 17, 200, alleging that both of the decisions were politically motivated and that the DOI violated the Administrative Procedure Act in failing to fully and effectively consider the proposals [16]. Three years later, on July 26, 2010, a federal district court judge agreed, vacated the decisions against PFS and the Goshutes, and remanded the rights-of-way and lease application back to the DOI for further consideration [17]. The decision found that the DOI failed to do properly analysis, follow established procedures, and decide on the requests issued by PFS and the Goshutes, essentially judicially affirming unfair political influence on the findings by the DOI. The Department decided not to appeal this decision and, as a result, the permits were sent back for further review. In deciding against the DOI, the judge had no authority to issue the permits in question, but could only require the proper administrative review from the DOI. As of this writing (in April of 2012), no further appraisal has been completed by the DOI,

although investigation apparently continues. While PFS continues to advocate their proposal as a viable solution, however temporary, the future of the project is ”uncertain” [18].

2.4 The Yucca Mountain Project

Even before the NWPA and its subsequent amendments, detailed studies of Nevada's Yucca Mountain had already been initiated. With the passage of the 1987 amendments and the consolidation of all research efforts, money, and focus on Yucca Mountain, these characterization studies continued, if not intensified. The Site Characterization Plan (1988), prepared by the Department of Energy, outlined the technical challenges that needed to be addressed, the plan for investigating these technical challenges, and generalized knowledge pertaining to the site that would need to be determined in order to make an accurate decision on its suitability. Three years later, the DOE was permitted in 1991 by the State of Nevada to proceed with surface studies, investigations that included ”excavating test pits and trenches, drilling bore holes, and monitoring ground water” [19]. Soon thereafter, in September 1994, work began tunneling into the side of the mountain using a tunnel boring machine (TBM). The 25 ft.- diameter TBM carved a 5 mile, U-shaped passageway through Yucca Mountain, starting and terminating in what became known as the North and South Portals, respectively [19]. This main tunnel, officially designated the Exploratory Studies Facility (ESF), serves as the main artery from which additional exploratory and emplacement tunnels were intended to branch off. Completed in 1997, the excavation of the main tunnel went smoothly, but was not without hazard. Unconfirmed reports surfaced in June 1995 suggesting that a small cave-in occurred in the tunnel as the TBM proceeded through the Bow Ridge Fault and fracture zone [20]. Apparently, a ”natural arch cavity” became exposed in the ceiling over the TBM, causing a temporary work stoppage. After evaluation, patching, and reinforcement, work continued. In the DOE after-action report, it was concluded that ”the incident did not constitute a significant geologic condition because personnel fully expected fault zones and associated structures while

tunneling" and that it was safe for tunneling to continue [20]. Shortly after completing the main tunnel, work began on characterizing the rock inside the mountain. Specifically, seven testing "alcoves" and four test "niches" were bored out of the mountain using more traditional mining techniques (as opposed to the TBM) with the goal of characterizing the rock [19]. These offshoots of the main tunnel were to be used to evaluate emplacement strategies as well as "used to investigate the hydrological, hydrochemical, and thermomechanical properties of the rocks underlying Yucca Mountain" [19]. As studying the presence and flow of water around and throughout the mountain is of primary concern in the site characterization process, special attention was paid to the hydrology of the site. In addition, because the canisters would still be warm long into the future, the ability of the Yucca Mountain rock to absorb and transmit heat was of great significance. Several additional tunnels were drilled or bored in the late 1990s, each containing instrumentation and experiments designed to better characterize the site. Even after the federal government failed to meet its NWPA-imposed deadline of 1998 to take title to U.S. spent nuclear fuel, work continued. The DOE site characterization process was extremely detailed and thorough, leading to the slogan that Yucca Mountain was the "Most Studied Place in the World." This site characterization was indeed the result of a significant number of experiments, many thousands of man-hours of work, substantial expenditures, and nearly two decades of waiting.

In 2002, with the successful completion of the site characterization and a "formal finding of suitability" delivered, then-Secretary of Energy Spencer Abraham, head of the Department of Energy (DOE), officially recommended the Yucca Mountain site to President George W. Bush as the nation's nuclear waste repository. The President, in turn, officially recommended the site to Congress. At this stage in the process, opposed to the project since the start, the State of Nevada, through then-Governor Kenneth Guinn, filed a "Notice of Disapproval." By doing this, Nevada exercised its right under the NWPA to a state-level veto attempt to terminate the Yucca Mountain project in its entirety. However, the merits of designating Yucca Mountain as the national repository are weighed in the U.S. Congress, which can override the governor's veto. House Joint

Resolution 87, entitled "Approving the site at Yucca Mountain, Nevada for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel, pursuant to the Nuclear Waste Policy Act of 1982," passed in both houses, but only narrowly so in the Senate in light of opposition by veteran Nevada Senator Harry Reid (D-NV), a staunch opponent of the Yucca Mountain project. With a simple majority required and achieved in both cases, Congress voted to overturn Nevada's veto. Upon receiving President Bush's signature on July 23, 2002, the resolution, now called the Yucca Mountain Development Act (YMDA), made Yucca Mountain the nation's official spent fuel repository in spite of Nevada's objections [8] [21].

The DOE was then responsible for forming and submitting a request for an official license from the NRC to construct and operate a repository facility. The NWPA dictates that this process should occur less than 90 days from receiving the official designation as the nation's repository but, due to several legal challenges, the license application was significantly delayed [8]. This was a direct result of, after seeing its veto overridden, the State of Nevada filing several lawsuits against the NRC, EPA, DOE, and members of the presidential administration. Those lawsuits took over six years to resolve.

Throughout the six years, several significant legal challenges to the Yucca Mountain project were debated, most of which were heard by the United States Court of Appeals for the District of Columbia Circuit. These legal challenges, mostly initiated by the State of Nevada, sought to establish that actions taken by the NRC, EPA, NRC, and others within the administration violated the NWPA or other laws. Nevada was attempting to convince the court of these violations, as a vote in affirmation by the Court would more than likely derail the Yucca Mountain project in its entirety. At the very least, Nevada was attempting to stall progress on the project until political winds shifted, public support faded, or additional challenges could be initiated. However, the Court ruled in favor of the federal government, thereby declaring actions taken as legal, in every case but one, relating to a containment standard set by the EPA [22]. To evaluate the radiation containment of Yucca Mountain over a millennia, the EPA had proposed a 10,000-year time frame.

This was in contrast to a National Academy of Science (NAS) definition of effective containment based upon estimation of cumulative radiation doses over time from ingestion of hypothetically contaminated groundwater from which the NAS derived a containment time covering one million years. Ruling against the EPA, the Court required the EPA to rework its radiation containment compliance regulations to reflect the recommendations from the NAS or to get Congress to define the appropriate compliance timeline. After significant deliberation, the EPA added supplementary regulations on radiation containment for the period of 10,000 years to one million years, keeping its established guidelines for less than 10,000 years [22]. This change, though significant, amounted to approximately a year's delay in processing the license application. After several legal challenges to the project as a whole, including one that unsuccessfully challenged the constitutionality of the project in its entirety, the DOE could continue its work on licensing Yucca Mountain. These legal decisions, though costly in terms of both money and time, paved the road forward for the nation's first waste repository.

Even before the completion of the license application, the Yucca Mountain project was again besieged by controversy, but this time from within. In order to assure diligent science throughout the project, workers were held to a stringent quality-assurance standard. Due to the sensitive nature and exacting standards of the project, it was imperative that all design guidelines were adhered to and that scientific integrity was upheld. Nowhere was this more important than in determining the permeability of the Yucca Mountain rock to water. As water can corrode and compromise the mechanical structure of the waste canisters, knowledge of its passage and flow throughout the mountain is critical. When it was revealed in 2005 that several scientists from the United States Geological Survey (USGS) were suspected of fabricating or falsifying this data, the credibility of all federal agencies, employees, and contractors involved was called into question [23]. In an apparent attempt to satisfy the stringent DOE QA standards, it was widely reported in news media that USGS intra-office emails between participating scientists contained evidence of data alteration. It was claimed that evidence of excessive water infiltration in Yucca Mountain, a potentially

devastating effect, was covered up or altered in order to allow the project to progress on schedule. This publication became a rallying cry for Yucca Mountain opponents, even though it was later suggested that the emails were taken out of context, that no violations occurred, or that any integrity violations that had occurred did not threaten the legitimacy of the site recommendations by the scientists involved. However, in the eye of the public, the damage had already been done. In the subsequent hearings before the Subcommittee on Federal Workforce and Agency Organization of the United States House of Representatives, Committee on Government Reform in April 2005, Kenny C. Guinn, Governor of Nevada, said that any integrity violations pertaining to data alteration constituted "nothing short of criminal behavior" [24]. In addition, in what became a major slogan for Yucca Mountain opposition parties, he said, "For too long in this project, we have watched politics trump science over and over again" [24]. Ultimately, Governor Guinn's testimony was very damaging and called into question the authenticity of the work in its entirety done over the two previous decades on Yucca Mountain. Slowly and to a painful extent, the issue was dragged before the media and the populace over a course of several months. Although most of the political wrangling had previously occurred at high levels, behind closed doors, or over obscure scientific issues, the falsification of water infiltration data was something that was widely publicized and easily understood by the average citizen and served to garner significant nationwide opposition to the entire Yucca Mountain Project.

Although the suspected integrity violations served to significantly wound the project, they were not a knockout blow. The DOE was quick to minimize the extent and damage of the questionable data, saying that all site recommendations were still valid and that its quality assurance standards and practices were sound. Later analysis, significantly less publicized, indicated that some USGS work was merely lacking in documentation, not fabricated. As a result, no criminal charges were filed against USGS employees. While the allegations, however true or untrue, were solely lodged against USGS employees, the entirety of the work by multiple agencies, contractors, and organizations was called into question. As initiated by Governor Guinn, the DOE was accused of

compromising the science of Yucca Mountain to satisfy political backers attempting to force the project on the State of Nevada. In an effort to regain lost credibility, save face with the public, and get the project back on track, the DOE significantly restructured the program in early 2006. This shuffling of contractors, employees, and organizations was an attempt to reinvigorate the stalled license application process and, hoping to shirk the impression of politicking, bring a degree of trusted science back to the process. Early 2006 saw the DOE appoint Sandia National Laboratory as lead contractor, replacing its civilian contractor Bechtel SAIC [25]. Hoping to capitalize on the success of Sandia's oversight of the Waste Isolation Pilot Plant (WIPP), a federal geologic repository for transuranic waste and the only one of its kind in the country, the DOE chose Sandia based on the lab's experience, credibility, and impartiality as a scientific institution dedicated to the good of the nation as a whole. As opposed to a civilian contractor, a national lab was seen as having no regional or political allegiances. In addition, a few months later, the DOE announced that Oak Ridge Associated Universities/Oak Ridge Institute for Science and Education (ORAU/ORISE), an association of universities in partnership with Oak Ridge National Lab, would provide impartial technical review of work performed by Sandia [26]. In light of previous quality assurance lapses, this was an attempt to utilize another trusted national lab to bring the focus of the Yucca Mountain project back to a foundation of sound science and regain a degree of legitimacy. As project opponents had been hammering on the politicization of the process and distrust of civilian contractor scientists in the media in the wake of prior scandals, DOE's reshuffling and direct involvement of national labs attempted to silence both fronts. However, even as work progressed, the future of the Yucca Mountain project from this point would be even more linked to politically motivated decisions.

The controversy and politics surrounding the Yucca Mountain project soon overshadowed any advancements in science and work on the license application, in spite of national lab involvement. The mid-term elections in 2006, in which the Democratic Party regained control of the Senate, proved an ominous sign for Yucca Mountain. In the subsequent turnover, Nevada Senator Harry

Reid (D-NV), a vocal opponent of Yucca Mountain for over two decades, became the Senate Majority Leader and party leader, possessing significant influence. Senator Reid's opposition to the Yucca Mountain project in his home state of Nevada was no secret, and he made it clear from the outset that he would use his newfound powers to attempt to derail the undertaking. From 2006 to 2008, budget allocations for the Yucca Mountain project were erratic, but generally decreased [27] [28] [29] [30]. This was mostly a result of challenging economic times in the United States over this period, though, rather than direct efforts to kill the project. In direct contrast, the Republican Administration of President George W. Bush and a Republican-controlled House of Representatives both generally supported the Yucca Mountain project and would have served as a roadblock to any anti-Yucca Mountain agenda. In spite of facing shrinking budgets, the DOE completed the Yucca Mountain license application process and formally submitted the proposal to the NRC on June 8, 2008 [8]. Even though several other countries were simultaneously working toward their own national underground repositories for spent nuclear fuel, the DOE's submittal marked the first completed license application in the world [8]. The submittal of the formal license application would serve to galvanize opposition efforts in the United States, even as the NRC began to initiate its review.

Three months later, on September 8, 2008, the NRC officially "docketed" the license application. After an "initial look" determined that the DOE's application was "sufficiently complete" and that the Environmental Impact Statement (EIS) withstood cursory skepticism, the NRC formally placed the license application on the docket [31]. This designation paved the way for a three-year long, in-depth technical review by the NRC of the license application. Although the NRC could request an additional year to decide from Congress, full-scale construction of the facility at Yucca Mountain ultimately hinged on approval of the license application. The technical review process, as it encompassed multiple scientific fields, was extremely complex and complicated, as expected. Experts in a wide variety of disciplines analyzed every facet of the proposal, including "geochemistry, hydrology, climatology, structural geology, volcanology, seismology and

health physics, as well as chemical, civil, mechanical, nuclear, mining, materials and geological engineering" [31]. In addition to the technical review, the license application approval process also included adjudicatory hearings. Heard by the Atomic Safety and Licensing Board Panel, a council of 16 permanent judges and several more temporary ones, the adjudicatory process involved interested parties bringing legal and technical challenges to the content of the Yucca Mountain license application [31]. The State of Nevada and Nye County, the county in which Yucca Mountain is located, automatically qualified as interested parties, as did the DOE and NRC. Additional parties included affected Native American tribes and local governments. Conducted much like a trial, interested parties submitted a litigable contention, a "specific concern or issue material to the licensing of Yucca Mountain," that was reviewed by the Board. After pre-hearing arguments and evidentiary hearings, the Board was expected to render judgment on the claim, usually relating to some claim of harm or damage that would befall the contending party if Yucca Mountain were built. As the technical review was underway and adjudicatory hearings proceeded, the political winds in Washington D.C. shifted dramatically, spelling change for the Yucca Mountain project.

In early 2009, after the presidential election in late 2008, president-elect Barrack Obama was inaugurated amid much fanfare and faced many challenges. After two terms and nearly a decade of President George W. Bush's policies, the policies of the Obama Administration marked a dramatic shift in the nation's road forward. This, of course, amid many other things, included the future of Yucca Mountain. The FY2009 budget had previously been passed by the Bush Administration and included appropriations of $288 million for Yucca Mountain, representing an approximately $100 million cut from FY2008 [32]. The new administration, with the support of Senator Reid, sought to reduce this even further. Indeed, the FY2010 budget, the first passed by the new administration, cut all funding for development of Yucca Mountain, except for "minimal funding" required for NRC activities relating to the license application review, as required by the NWPA [33]. The allocations for 2010 represented a record low for the Yucca Mountain project, and much of the project was cut, including research on the transportation of spent nuclear fuel to Yucca Mountain.

In continuing fashion, the FY2011 DOE budget the following year proposed by the administration and passed by Congress abolished funding of any kind for the project. While continuing license application pursuits were funded in FY2010, the FY2011DOE budget eliminated even these allocations. In doing so the Congress in effect passed legislation inconsistent with a previous Congress' enactment of the NWPA as Amended. In addition, the FY2011 budget and associated policies set forth by the Obama administration shuttered the Office of Civilian Radioactive Waste Management (OCRWM), the lead government agency in charge of the repository development [16]. With no agency in charge of its direction and no budget for moving forward, the Yucca Mountain project was essentially dead in the water.

At the directive of the U.S. administration, on March 3, 2010, the DOE filed a motion with the Atomic Safety Licensing Board (ASLB), the NRC extension tasked with reviewing adjudicatory hearings for the license application, to withdraw the license application from consideration "with prejudice" [34]. More than a mere footnote, this distinction would mean that the license application could not be reinitiated in the future. Stating that the application "is not flawed nor the site unsafe," the DOE wished to withdraw the 8600-page document as a "matter of policy" [35]. While still acknowledging its responsibility to take title to U.S. SNF, the DOE stated that the Secretary of Energy had determined that the "repository at Yucca Mountain is not a workable option" [34]. Anticipating objections, the motion also states that the NWPA gives the power to the Secretary of Energy to submit a license application and, while silent on withdrawal procedures, does not explicitly prohibit the Secretary from withdrawing a license application [34]. Several interested parties, including the State of South Carolina, the State of Washington, filed motions with the ASLB to intervene and block the DOE's withdrawal of the application. These motions argued, among other things, that the billions of dollars already spent on the project would be wasted if the application was withdrawn and that the DOE had no right to unilaterally determine what was in the public's best interest [16]. The ASLB agreed with the objectors and, on June 29, 2010, denied the DOE's request to withdraw the license. The Board ruled that the DOE did not have the authority

to single-handedly derail a process set forth by Congress in the NWPA by withdrawing the license application before a judgment had been made based on the merits of the application. Furthermore, it ruled that the responsibility for determining the ”workability” of the site, a reference to the Secretary of Energy’s comment in the license withdrawal motion, had been transferred to the NRC with the official submittal of the license application by the DOE [35]. Simply put, it was the conclusion of the ASLB that ”the DOE lacks the authority to override [the NWPA]” and that the matter was now in the hands of the NRC to approve or disapprove based on the technical merits of the application alone [35]. Almost as a side note, the Board also included a statement saying that the application cannot be withdrawn ”with prejudice,” meaning that it could never be resubmitted, because this would unduly limit the powers of future government agencies and administrations [35]. While the strongly-worded judgment against the DOE’s motion to withdraw the license application clearly outlined the Board’s desire to strictly adhere to the NWPA, the dispute was far from over. Indeed, the day after the decision, June 30, 2010, the NRC Commission, the five-person committee at the head of the organization, invited interested parties to ”file briefs with the Commission as to whether the Commission should review, and reverse or uphold the Board’s decision [to deny the DOE motion to withdraw the license application] [36]. In an appeals-style process, the Commission solicited bids from interested parties to argue the denial of the DOE’s motion to withdraw the license application in front of the NRC’s Commissioners. Less than three weeks later, the DOE wrote and filed with the Commission what essentially equates to a rebuttal of the withdrawal motion denial, where each major contention of the Board’s decision was addressed. In this request to reconsider the denial decision, the DOE argued that no legislation explicitly forbids it from withdrawing the application and that the Board relies on inferred beliefs, not strict statues, from the NWPA that limit the authority of DOE [37]. Furthermore, the DOE claimed that the NWPA does not relieve it of broad powers governing energy matters, nuclear waste, and repository issues that were outlined in the Atomic Energy Act and the Department of Energy Organization Act; therefore, the Department should be legally able to withdraw the license application [37]. As part of

the official appeals process, these arguments, as well as others for and against, were outlined in adjudicatory paper SECY-10-0102, U.S. Department of Energy (High-Level Waste Repository), Review of LBP-10-11, Docket No. 63-001-HLW, tendered to the Commissioners on August 10, 2010 [38]. As per Internal Commission Procedures, the Commissioners then have ten business days in which to submit their vote sheets and associated comments, so there was a deadline of August 25, 2010, for this process to be completed. However, as a subsequent investigation by the Office of the Inspector General (OIG) details, this was not adhered to. The voting submissions for the issue of the DOE request to withdraw the Yucca Mountain license application from the five Commissioners were received as follows:

10AUG2010 - Commissioner Apostolakis announced he would not participate
25AUG2010 - Commissioner Svinicki voted
25AUG2010 - Chairman Jaczko provided initial vote
26AUG2010 - Commissioner Ostendorff voted
30AUG2010 - Chairman Jaczko retracted initial vote
15SEP2010 - Commissioner Magwood voted
29OCT2010 - Chairman Jaczko voted for second time [38]

In a notice to the Commission dated July 15, 2010, Commissioner Apostolakis recused himself from adjudicatory proceedings involving the Yucca Mountain license application because of his prior work at Sandia National Laboratory (SNL). Three years prior, Commissioner Apostolakis had chaired a panel responsible for the long-term performance review of the Yucca Mountain project at SNL and submitted a findings report to senior management. In light of this work, he felt it necessary to not participate in the vote on SECY-10-0102 [39]. It remains unclear whether Apostolakis will continue to abstain on future Yucca Mountain matters. In addition, as can be seen from the voting timeline, the required deadline was not followed. Indeed, only two Commissioners had

voted on time, with one later withdrawing his vote and re-voting. As per procedures, notifications to delayed Commissioners were sent and evidently not acted upon. In addition, communications between Chairman Jaczko and his Chief of Staff entail discussions of not requesting or granting extensions to vote, thereby leaving the Yucca Mountain vote in a procedural limbo. Descriptions of further meetings between Commissioner Jaczko, staff members, and attorneys from the Office of General Counsel have been interpreted as efforts to hold up, stall, and delay the vote [40].

As of this writing (April of 2012), the results of an NRC vote on withdrawal of the Yucca Mountain site license application have not been released, even though approximately 18 months have elapsed since the specified date for a vote. While Commissioners submit their votes individually, an affirmation session of the Commission must be held in order for each member to affirm their votes and agree on a consensus for a binding response to the matter at hand, in this case, the DOE motion to withdraw the license application. After Commissioner Apostolakis' recusal, the Commission was left with an even number of delegates, perhaps leaving 2-2 tie in preferences concerning allowing the DOE to withdraw the Yucca Mountain license application [41]. According to the NRC Internal Commission Procedures, a majority of Commissioners must affirm the motion in order for it to carry; a tie vote would indicate failure. Thus there may not enough votes to affirm the motion and allow the DOE to withdraw the license application. Official confirmation of a tie vote would lead to denial of the motion to allow withdrawal but an affirmation session was prevented and the issue was kept officially in "deliberations," even though all votes had been cast [40].

The position of the Obama Administration and the NRC process have been harshly criticized by members of Congress. In particular, on August 3, 2011, after over 400 days of NRC inaction on the Yucca Mountain site license application, Rep. John Shimkus (R-IL), Chairman of the House Energy and Commerce Committee's Environment and the Economy Subcommittee, publicly criticized Jaczko and the NRC Commission for delaying the affirmation vote to deny the DOE's request to withdraw the license application for political gain. Rep. Shimkus called for Jaczko to "cast politics aside . . . [and] to finally complete action on the Yucca repository licensing application" [41].

To muddy the waters even further, the Commission signed Memorandum and Order CLI-11-07 on September 9, 2011, perhaps in response to Representative Shimkus' comments. It is unclear whether this document was signed in lieu of an affirmation session or where the authorization to take this action originates from. The Memorandum states that "the Commission finds itself evenly divided on whether to take the affirmative action of overturning or upholding the [Atomic Safety Licensing] Board's decision [to deny DOE the right to withdraw the license application]" [42]. While this appears to confirm the existence of a 2-2 split, the Memorandum goes on to state:

> "Consistent with budgetary limitations, the Board has taken action to preserve information associated with this adjudication. In furtherance of this, we hereby exercise our inherent supervisory authority to direct the Board to, by the closure of the current fiscal year, complete all necessary and appropriate case management activities, including disposal of all matters currently pending before it and comprehensively documenting the full history of the adjudicatory proceeding."

As a result of this Memorandum, it appears that the Commission has taken the unilateral action of closing out the Yucca Mountain project and preserving information relating to past proceedings. While a tied vote would prevent the DOE from withdrawing the license application and a majority affirmation vote would allow this action, neither occurrence permits the NRC Commission to single-handedly terminate the project. The execution of and the impetus for this action is not clear; it seems to violate Commission procedures, the NWPA, and judiciary oversight. No further explanation was given by the Commission.

A final proclamation by the Atomic Safety Licensing Board (ASLB) offers only slight reconciliation of these concerns. On September 30, 2011, at the end of the fiscal year (2011) as instructed by the Commission, the ASLB issued Memorandum and Order LBP-11-24, effectively suspending adjudicatory proceedings. In this Memorandum, it is implied that a tied vote by the Commission indeed allows the previous decision of the ASLB to deny the DOE's motion to withdraw the Yucca

Mountain license application to stand.

In denying DOE's motion to withdraw, it would seem that the NRC should continue with the license application review, but in the Memorandum the ASLB also states that no Full-Time Equivalent (FTE) positions for federal employees exist in President Obama's FY 2012 Budget for Yucca Mountain High-Level Waste activities. While the Board states that remaining FY2011 Nuclear Waste Funds "could be carried over into the next fiscal year . . . future appropriated NWF and FTEs for this proceeding are uncertain" [43]. From this, it appears that future budgetary concerns as well as a directive from the Commission have driven the ASLB to suspend all proceedings pertaining to the Yucca Mountain license review. Indeed, the FY2012 budget proposed by the Obama Administration requested no further funding for Yucca Mountain-related activities. However, in spite of the administration's directives, the budget approved for FY2012 by the House of Representatives included $25 million for the Department of Energy and $20 million for the Nuclear Regulatory Commission to resume Yucca Mountain licensing activities [16]. While the amounts of these appropriations pale in comparison to previous years' hundreds of millions of dollars in allocations, they do represent a desire on the part of lawmakers to resolve the remaining uncertainty in the status of the issue, one way or the other. These allotments come with the stipulation that they may not be used for closing out the licensing process unless the Commission formally administratively removes Yucca Mountain from licensing consideration. By including this caveat, lawmakers hope to force the NRC to resume licensing activities or to take the Yucca Mountain option completely off the table, which would then allow utilities to sue the federal government for breaching the NWPA. Recouping funds paid to the NWF would subsequently allow the utilities to pursue alternative SNF storage options. In spite of attempts by lawmakers to use budgetary means to force an official decision from the NRC, the future of the Yucca Mountain spent nuclear fuel repository still remains highly uncertain.

While the NRC has not denied Yucca Mountain a construction and operation license, it is not actively pursuing its investigation either. The ASLB has suspended all adjudicatory proceedings

on the subject, and approaches to restarting this process, if any, are unclear. The DOE has dutifully submitted the Yucca Mountain license application, as required, but cannot withdraw it from consideration. It is also legally prevented from investigating alternative repository sites. As a result, the Department remains in a holding pattern with little additional work to complete on the subject of ultimate geological disposal of spent nuclear fuel. Only Congress has the power to amend the NWPA to allow for the investigation of alternative repository sites or to provide the budgetary allocations necessary to continue pursuing Yucca Mountain licensing, but the Congress did not pass legislation do do so. Thus, in early 2010, at direction of the Obama Administration, a special commission was appointed and tasked with exploring and recommending options for the United States to pursue to solve the country's nuclear waste dilemma.

2.5 Blue Ribbon Commission (BRC)

The Secretary of Energy collectively appointed the Blue Ribbon Commission (BRC) on America's Nuclear Future on January 29, 2010, shortly before the DOE's attempt to withdraw the Yucca Mountain license. Appointees include politicians and professors, entrepreneurs and military veterans, and thus included energy and policy experts from a wide variety of backgrounds. Co-chaired by former Indiana Representative Lee H. Hamilton and Lieutenant General Brent Scowcroft, USAF (Ret.), the 15-member panel was tasked with analyzing policies pertaining to spent nuclear fuel storage and disposal in the United States and recommending a new, but generic path forward. Initially convened at the time of DOE's motion to withdraw the Yucca Mountain license application, the Commission's assignment was not to act as a siting board by recommending specific repository locations alternative to the Nevada project, but rather to devise a skeletal framework for successfully licensing a nonspecific facility. Forbidden from specifically recommending action on the Yucca Mountain project, the BRC was to be the Obama Administration's compass for taking nuclear waste disposal in a new direction in the United States. At a time when

the Administration's waste disposal goals were straying from the advantages offered by the Yucca Mountain project, the BRC was to explore and recommend actions in a new direction.

Starting in early 2010, the BRC met frequently and investigated a wide variety of subjects. Hoping to report back an overview of the entire waste disposal process, the Commission looked into existing and future fuel cycle technologies, transportation of SNF, temporary and permanent waste storage options, as well as economic and social management of historic projects. Subcommittees were formed to address these issues in more depth than would be feasible as a review by the committee of the whole. As a result of distrust in the federal government pertaining to nuclear matters in previous attempts to site waste facilities, the Commission noted early in its investigation the necessity of conducting transparent and comprehensive research to form the basis for its recommendations. To accomplish this, the Commission sought input from a wide variety of experts, members of the public, and current and former political figures. Commissioners took tours of both U.S. and international proposed spent fuel storage sites, visited existing operating facilities, and reviewed historical material. They also familiarized themselves with the established procedures, economics, and operations of the commercial nuclear power industry. All of these experiences and encounters were tabulated, discussed, and formed into a multitude of recommendations prepared by the BRC Commissioners for the Congress.

As per its charter, the BRC prepared a draft report of its findings, published on July 29, 2011. This report summarized a year and a half of investigations and testimony and was released to the public for consideration several months before the final report was due. In the interim period, the BRC received thousands of comments from experts, members of the public, and concerned citizens pertaining to the future of nuclear waste disposal in the United States. In addition, the BRC held five public outreach meetings around the country in the late months of 2011. These gatherings solicited public feedback to the draft report and were hosted in the cities of Boston, Atlanta, Washington, Denver, and Minneapolis, equating to one conference in each regulatory region of the NRC (plus the headquarters in Washington). Interested parties were also able and

encouraged to submit responses to the draft report to the BRC electronically. Months of additional investigations and deliberations led the BRC to submit its final report to the Secretary of Energy in late January, 2012. This final report summarized a series of eight recommendations advocated by the BRC to resolve the nuclear waste storage dilemma in the United States.

First, the BRC proposed a "new consent-based approach to siting" management facilities for high-level radioactive materials [8]. Noting historical difficulties with siting both temporary and long-term storage facilities, the final report emphasizes the necessity of inclusion and cooperation with the community of a future site throughout the entire process. Citing mainly distrust of the federal government's waste management program and attempts to force a facility on an unwilling community as reasons for the failure of past projects, the report calls for a voluntary, transparent siting process in which the local populace and appropriate levels of government are consulted and kept informed. It says that "[a]ll affected levels of government must have . . . a meaningful consultative role" in establishing a "legally enforceable agreement" with the federal government [8]. In other words, the report says that state and local officials should be actively involved in any future siting process and should retain a significant amount of authority over activities within their jurisdiction. However, the BRC also stipulates that affected levels of government "have responsibilities to work productively with the federal government to help advance the national interest" [8]. Although recommending a voluntary siting process for a nuclear waste storage facility is not a new concept, the BRC stresses that this aspect is critical for any future successful venture.

Second, noting that prior attempts to establish waste management facilities have always fallen under the responsibility of the DOE with limited success, the BRC proposes handing over all aspects of future projects to a federally managed corporation purposefully created solely for this task. Given that the corporation has the appropriate "attributes, independence, and resources," the BRC believes that this transition of power offers a greater chance of success than allowing the DOE to retain authority over such matters [8]. The proposal suggests that all aspects of future projects be handed over to this new corporation, from licensing and operation to technological research and

transportation inquiries. Additional suggestions from the BRC pertaining to this matter involve retaining the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA) in their current capacities as regulators, in spite of a new federal corporation. Also, the BRC notes that defense wastes, as opposed to commercial wastes, would perhaps best be left under control of the DOE, although additional investigation into this matter is advised. The BRC notes while that the DOE has achieved some limited successes pertaining to nuclear waste storage in the past, transferring this responsibility to a new federal corporation might offer a greater chance of success in the future.

In their third recommendation, the BRC advocates allowing the newly formed federal corporation access to the Nuclear Waste Fund (NWF) in order to carry out its mission. Originally started by the NWPA, the NWF is a pool of financial resources, populated by a fee on nuclear-generated electricity, and was meant to ensure the availability of capital to dispose of the associated nuclear waste. After thirty years of contributions less expenditures and including an annual percentage increase on the fund balance and, by 2011 the NWF total was about $27 billion. The account accrues about $750 million annually, but is largely ”inaccessible” to waste management projects because expenditure authority requires annual Congressional appropriations [8]. Appropriations from the NWF have often been less than requested by previous administrations and, as noted above, have recently been almost nil. The revenue to the fund is counted as a reduction of the federal deficit, but the accruing liability for SNF management is not counted as adding to that deficit. Thus, the current situation has payments to the NWF giving only the formal appearance of reducing the rate of growth of the national debt. To correct this imbalance, the BRC recommends altering the way these fees from the nuclear utilities are collected, handled, and utilized in the federal accounting structure. Instead of future such payments by utilities being counted against the federal budget deficit, the BRC report argues that any annually unspent future contributions should be diverted to a purpose-built trust . The BRC also suggests that the federal corporation responsible for future waste management activities be given access to the already existing ”corpus” of the NWF at some

unspecified time in the future and that restructuring the financial management of the nuclear waste management system in this manner could help insulate the process from politics of the annual appropriate process that has plagued historical storage and disposal ventures.

The fourth and fifth recommendations from the Commission involve ”prompt efforts” to develop at least one geologic repository and at least one consolidated storage facility, respectively [8]. Recognizing that any path forward would ultimately require some amount of underground storage, the BRC recommends undertaking such a venture rapidly. While not taking a stand on the future of reprocessing spent nuclear fuel or advanced fuel cycle initiatives in America, the final report notes that a geologic repository of some capacity would be required in any case. Furthermore, the report does not take a stand on Yucca Mountain either, even though the figure of 65,000 MTHM mentioned above for the stock of U.S. spent nuclear fuel exceeds the legal limit of 63,000 MTHM of commercial spent fuel allowed to be emplaced in the Nevada mountain. Therefore, the Commission argues that, regardless of the outcome of the Yucca Mountain debate, a new disposal site would be needed anyway and that progress should commence promptly. Secondly, the final report argues in favor of one or more consolidated, centralized, above-ground storage facilities. This approach would allow for additional cooling of the spent nuclear fuel before emplacement in a repository while still allowing the federal government to take title to commercial waste inventories. Ideally, the report states that a facility of this type should be easier and timelier to site and license than an underground repository and that the federal government could begin the ”orderly transfer of spent fuel from reactor sites to safe and secure centralized facilities” as work progresses on an ultimate disposal site. Current law prohibits a MRS from operating while no permanent storage solution exists, but the BRC advocates repealing this stipulation so that progress could be made on a MRS site immediately. In order to prevent this facility from becoming a de facto permanent storage site, the BRC states that specific, measurable progress needs to occur on a deep geologic repository in tandem with operating this centralized storage facility. As it supposes that neither type of site would conceptually commence operations for many years, the BRC also calls for a reliability and

safety study pertaining to the use of on-site dry cask storage of spent nuclear fuel in the interim. Ultimately, the BRC argues that the need for above or below ground storage of nuclear waste is not going away and may be accelerating; as a result, work should begin promptly in constructing the necessary facilities to deal with this issue [8].

As thousands of tons of spent nuclear fuel will eventually need to be relocated to an above-ground or geologic repository, the sixth recommendation of the BRC's final report involves preparing for this undertaking with dispatch. While noting that the historical framework for shipping spent nuclear fuel has functioned well and with a large degree of safety, the BRC calls for a review of current practices to ensure that they will continue this record of success as the number of shipments increases with the opening of storage and disposal sites. Because the shipment of radioactive materials is a great source of public concern, the BRC again calls for a transparent and cooperative atmosphere when dealing with affected communities. To accomplish this, the final report stipulates that local officials should be involved in the planning of SNF shipments and be given the resources, specifically financial, to ensure public safety in their locale. The report argues that this should be extended to include any necessary technical assistance or investigation and should be done with sufficient warning time to fully address concerns. Because the transportation of SNF to any potential storage or disposal site "represents a crucial link in the overall storage and disposal system," transportation considerations must play an integral role in any waste management program and must not be "an afterthought" [8].

The seventh recommendation in the BRC's final report calls for "support for advances in nuclear energy technology and workforce development" [8]. While the BRC itself purposefully avoids making any specific recommendations regarding the future use or role of nuclear power in the mix of U.S. domestic energy policy, it does call on the DOE and the federal government to make these decisions in the context of budgetary allocations, saying that a well-defined "roadmap" will significantly aid a waste management program in succeeding [8]. In addition, a definite plan pertaining to future nuclear use can refine the scope of research and development efforts in making

existing and future, if any, reactors safer and more reliable. In short, a specific plan regarding the future use of nuclear energy can help waste management planners determine the scope of their task as well as achieve the parallel goal of trustworthy energy production. Although not advocating implementation, the BRC does opine that innovations in nuclear technology and advanced nuclear energy systems warrant investigation and makes the case for continuing support of associated projects. Along similar lines, the BRC recommends investment in a skilled workforce via continued programs at the federal and university level. It lends its support for advanced technical training at all levels to support existing and future waste management issues while, at the same time, promoting retention of critical existing faculty. While touching on a range of topics, the seventh assertion from the BRC broadly pushes for the encouragement of future efforts to advance the field of nuclear science in terms of organization, workforce development, and research [8].

The eighth and final recommendation by the BRC in its final report to the Secretary of Energy revolves around maintaining American international stewardship pertaining to nuclear technology matters. It argues that "U.S leadership is urgently needed on issues of safety, non-proliferation, and security/counter-terrorism" [8]. According to the report, this involves aiding fledgling overseas nuclear programs establish a domestic environment that is both safe and secure. Along similar lines, the BRC recommends that the United States should take the lead in offering support for international nuclear organizations and remain stalwart in backing nuclear safeguards. To summarize its emphasis on international relations, the BRC proclaims two, strongly-worded warnings: first, that the "United States will increasingly have to lead by engagement and by example" and, second, that the "United States cannot exercise effective leadership on issues related to the back end of the nuclear fuel cycle so long as its own program is in disarray" [8]. Essentially, the BRC says that the United States will be needed to lead international efforts pertaining to nuclear energy and nuclear waste storage and cannot constructively do so when it lacks the capability or resolve to handle these matters domestically. Somewhat controversially, the BRC advocates strong U.S. support for recent IAEA initiatives to expand peaceful use of nuclear technology, but notes the necessity of

remaining wary of proliferation and terrorism threats. Ultimately, the BRC argues that the United States must get its nuclear waste management program in order so that it may effectively interact on the world stage regarding nuclear matters when it is inevitably called to play party to international negotiations on the subject [8].

These eight recommendations by the BRC create a skeletal framework for an effective waste management program in the United States and represent a monumental step forward. The collection and summary of these ideas in one place in an officially endorsed governmental study marks a starting point for lawmakers and administrators to begin to address the nuclear waste dilemma in the country. Although far from defining a direct, concrete path forward, the final report offers overarching guidance pertaining to what must be done. Because the details of implementation of these recommendations to future projects are still to be largely determined, the success or failure of future projects is still highly uncertain. Significant legal, social, and financial changes must be made in the near future to implement any or all of these suggestions and political disagreement is likely to continue to impede progress. Nevertheless, the BRC report instills a certain degree of urgency to the actions which must be undertaken to effectively resolve the nuclear waste dilemma in the United States.

To achieve the aforementioned goals, several legislative changes are proposed by the BRC. First, to initiate the new consent-based siting process, the NWPA must be amended to establish a framework for voluntarily accepting bids from host communities for a waste repository. This process will replace the 1987 edict that declared Yucca Mountain as the only facility to be investigated. Second, the legislative mandate preventing construction of a monitored retrievable storage site until a repository is licensed should be removed to pave the way for the federal government to take title to commercial fuel at such a facility, however temporary. Multiple interim facilities could be licensed without delay through a new consent-based process similar to repository efforts and funded by the NWF. Legislation will be required to set these actions into motion. Furthermore, establishing a new federal corporation with the proper authority and budget to effectively manage

the nuclear waste program will involve a significant Congressional undertaking. Legislation will be needed to fully lay out the corporation's roles and responsibilities as well as its expectations and oversight. Clearly defining and rerouting funding pathways will be critical to this new corporation's success and will certainly require Congressional resolution. Finally, the BRC states that Congressional action may be required to provide support or guidance for foreign countries' waste disposal efforts to ensure safety and proliferation resistance. None of these legislative changes will be easy. Indeed, all are expected to be extremely controversial and require extensive debate. Even so, each is required to achieve the BRC's nuclear waste management plan forward. As the final report summarizes, difficult decisions must be made to address a national problem because it is not going away. While the capability, will, and expertise exist in the United States to effectively deal with this issue, obstacles must be overcome in order to get the waste management program back on track, and the BRC final report offers a starting point for this effort.

Chapter 3

Future Disposal Options

Each having advantages and disadvantages, several feasible options exist for addressing the U.S. nuclear waste dilemma. Long considered to be the main approach, burial in a repository at a depth just comfortably low enough to avoid erosion for millennia is one of several possibilities. While several other proposed disposal strategies require hurdles to be overcome, they represent viable alternatives to an underground repository that would take the U.S. nuclear waste management program in a new direction. Several require legislative changes to be made and others involved international agreements, but each attempts to remedy decades of failed waste management policy in the United States. Another similarity is that many are extremely controversial. Nevertheless, several options exist for the disposal or remediation of nuclear waste in the United States.

3.1 Deep Boreholes

Utilizing deep boreholes for storage and interment of nuclear waste has until this time received only cursory consideration. However, the recent Blue Ribbon Commission on America's Nuclear Future Draft Report recommends exploring this option further [8]. In contrast to relatively shallow underground disposal options such as Yucca Mountain, utilizing deep boreholes would mean

emplacing nuclear waste canisters several kilometers below the earth's surface. In this strategy, multiple deeply drilled, narrow shafts are constructed in which to vertically stack canisters of nuclear waste. The shafts, reaching down into permanent bedrock, offer the advantage of extreme isolation of the waste. Estimates of the peak dose to be received on the surface from a deep borehole containing 150 MTHM of SNF are "more than a billion times below current limits for releases from geologic repositories" [44]. In addition, water transport, a concern in a geologic repository for cask corrosion and radionuclide dispersion, is of much less concern in deep borehole disposal. Current estimates indicate that hydraulic (water) flow is predicted to be less than 30 meters in 100,000 years [8]. Ultimately, any corrosion and seepage of radionuclides that does occur even over an extremely long period of time will remain suspended kilometers below the surface and out of surface-level water cycles. In addition, deep boreholes can be placed in nearly every U.S. state, as favorable bedrock exists across the country. It has been suggested that a decentralized deep borehole approach to nuclear waste disposal would alleviate concerns of forcing a state with no nuclear power plants to store spent fuel in a shallow underground repository or obliging a single state to entirely shoulder the country's waste disposal burden alone. Further, it might be possible in many cases to construct deep boreholes near or on the grounds of the commercial nuclear power plant that originally produced the spent nuclear fuel. This approach has the added benefit of minimizing transportation of nuclear waste, historically a major public concern. By avoiding a centralized repository, fears of public health effects, traffic accidents, or attacks or interference during the shipping of spent nuclear fuel through nearly every state in the country would be alleviated. Although deep boreholes are not simple or cheap, cost estimates have become more manageable in recent years as technology has improved. Recent boreholes constructed for petroleum exploration, geothermal energy production, and seismic monitoring purposes can offer useful insights into using boreholes for nuclear waste disposal and outline current capabilities. Indeed, according to the U.S. Nuclear Waste Technical Review Board, "[d]rilling deep boreholes for disposal of SNF and HLW [high level waste] is feasible using proven available technology" [44]. Indeed, one estimate

suggests that the cost of disposing of all spent nuclear fuel generated in the United States to date in deep boreholes would amount to ”about 14 percent of the disposal cost estimates for an equivalent amount at Yucca Mountain” [44].

Though deep borehole disposal is expected to be safe and economically feasible, significant hurdles would have to be overcome in order to implement deep borehole disposal of commercial spent nuclear fuel in the United States. Most importantly, the Nuclear Waste Policy Act requires that any ”repository” must ”permit the retrieval” of any SNF stored therein [45]. However, utilization of deep boreholes does not permit the retrieval of the fuel canisters, should the need arise. Once lowered into place, especially if the shaft is plugged and sealed, it would be nearly impossible to bring a fuel canister back to the surface. As a result, a deep borehole spent nuclear fuel disposal strategy is not permissible under the NWPA as written. Overcoming this would entail modifying, overturning, or replacing the NWPA and would surely involve a momentous undertaking. In addition, while it is believed that a deep borehole disposal strategy is manageable with current technology, further research and experience in developing boreholes with the large diameters required is desired. Although by no means the only approach, most credible analyses focus on utilizing boreholes of several feet in diameter in order to accommodate existing spent nuclear fuel, dry cask, and transportation cask designs. As most existing extremely deep boreholes have a diameter on the order of inches, some adaptation and expansion would be required. Furthermore, some concern exists that a canister may become inadvertently lodged in a borehole shaft at an undesirable height above the bottom depth, leading to a situation that would be difficult to remedy [44]. In general, the significant advantages of utilizing a deep borehole spent nuclear fuel disposal strategy seem to, at very least, warrant additional consideration and discussion in current and future attempts to resolve the national nuclear waste dilemma. Indeed, even the ”[Blue Ribbon] Commission recommends further RD&D [research, development, and demonstration]” [8]. As the strategy utilizes a safe yet economical approach with manageable, surmountable

shortcomings, employing deep boreholes as a long-term storage method for spent nuclear fuel represents a viable alternative to a geologic repository.

3.2 Granite Shield

While most underground repository proposals in the United States have involved placement in arid, barren deserts, additional geological options exist. Studies dating back to the 1950s have shown that the geology of upper Midwestern (and even some Eastern) U.S. states may present geology favorable for an underground repository. While waterless mountains in Western states, permeable to oxygen, suffer from conditions leading to the premature corrosion of canisters designed to house any stored spent fuel, granite and crystalline rock formations just south of the Canadian border offer contrary conditions. Oxidizing conditions allow for possible corrosion of steels typically chosen to store, house, and transport nuclear waste in a timeframe that may be unacceptable for containment purposes. In contrast, oxygen-poor environments found in granite bedrock formations, denoted reducing conditions, seem to offer longer containment times. When utilizing copper canisters with steel reinforcements to store spent nuclear fuel in a reducing environment, a passivating layer forms on the outer surface and provides additional corrosion resistance. It is this corrosion resistance that has led to interest in utilizing granite formations near the Canadian border, called the Canadian Shield, to store U.S. commercial spent nuclear fuel. Swedish and Finnish nuclear waste repositories, in various stages of completion, are based upon this premise and could serve as a model for a U.S. nuclear waste repository of a similar design, offering lessons learned and proofs of concepts that may reduce costs and time to implementation.

The type of environment as well as the canister material chosen are just part of a system called an engineered-barrier approach or engineered-barrier system (EBS). This entails the use of multiple layers, or barriers, to prevent or contain the spread of radionuclides in an underground repository to the environment. While the first barrier to the spread of radionuclides is actually the structural

cladding material that the fuel assembly was manufactured with, additional barriers include the canister, clay soils packed around the canister and chosen for their favorable hydrological properties, backfill rock, and finally the repository rock itself. In concept, as one barrier fails over extended periods of time, the next barrier prevents the spread of radionuclides to the environment. In total, the combined EBS approach is designed to meet containment timelines extending up to hundreds of thousands of years into the future, much longer than any single barrier could bear. Not just a feature of Canadian Shield repository proposals, the EBS approach has also been suggested for repositories in general.

In addition to offering longer radionuclide containment times, storing nuclear waste in the Canadian Shield is also seismically favorable. While some concern has been expressed over seismic activity in the vicinity of Yucca Mountain, the Canadian Shield has been relatively inactive for thousands of years. In general, a spent nuclear fuel repository should be placed in a geological formation free of major existing fissures or structural cracks in the rock, as these represent unpredictable paths for potentially canister-corroding water. Earthquakes and seismic events that occur after or during placement stand to open water pathways where none had previously existed, rendering the site unacceptable for use as a waste repository. As a result, the advantage of being seismically sound is of great interest in the search for a U.S. nuclear waste repository. The historic seismic inactivity in the Canadian Shield, "while not an absolute guarantee.....gives considerable confidence that the next ten thousand years will remain relatively quiet" [46]. This confidence makes the geological engineering of siting such a repository in the Canadian Shield, not a completely new idea but hardly pursued, significantly easier and a viable alternative to other proposed options.

As a result of these factors, storing U.S. commercial spent nuclear fuel in the Canadian Shield has proven to be a viable alternative to traditional Western mountainous repositories. Offering longer containment time for potentially harmful, long-lasting radioisotopes and a reasonable guarantee of seismic inactivity, granite storage is a feasible option in the U.S. search for a long-term

repository. Although little resources have been historically allocated to study such a facility, the advantages warrant future additional consideration. In addition, as the Swedish and Finnish granite repositories enter service, additional knowledge and experience will be gained to judge the suitability of a similar facility in the United States [47].

3.3 Global Nuclear Energy Partnership

Recent attempts have also been made to resurrect reprocessing in the United States and encourage its responsible expansion around the world. Detailed as part of the Advanced Energy Initiative in President Bush's State of the Union address in early 2006, U.S. participation in the Global Nuclear Energy Partnership (GNEP) program committed the DOE to developing reprocessing methods more proliferation-resistant than ones that separate out pure plutonium [48]. While encouraging next-generation reactor research, studying various nuclear fuel cycle closure measures, and establishing an international framework for lending nuclear fuel to developing countries that promise not to pursue nuclear weapons, reprocessing represents a cornerstone of GNEP's goal of promoting the safe, economic, and proliferation-resistant expansion of nuclear power worldwide. This is based upon the concept that technological advances since the 1970s, mostly in chemistry, have the potential to address the two major issues historically inhibiting the implementation of reprocessing: waste concerns and proliferation fears.

Unfortunately, U.S. participation in GNEP faced several seemingly insurmountable political pitfalls early on. The U.S. National Academy of Sciences determined in 2007 that "the commercial-scale reprocessing facilities envisaged under GNEP were not economically viable," echoing similar objections of decades past [49]. However, in contrast, it was pointed out that GNEP's focus was to utilize extensive research to determine the best method to make reprocessing economical, noting that research would not be necessary if it already was. Furthermore, it was uncertain if the Academy's diagnosis included the economic benefits of leasing fuel to developing

nations. It seemed that reviving reprocessing in the United States was facing the same hurdles that shelved the issue decades ago. After the presidential election of 2008, a new administration cautiously supported the GNEP initiatives of preventing proliferation and utilizing nuclear energy to fight climate change, but balked at opportunities to expand reprocessing in the United States. In April 2009, four months after taking the reins, the new administration directed the DOE to halt work on near-term commercial demonstration projects [50]. Instead, funding should be directed towards research pursuits only; no operating or test facilities should be built. Only two months later, in June 2009, it was announced that other aspects of GNEP were being canceled, that the DOE would no longer be researching reprocessing technologies, and that the GNEP budget had been reduced to zero [49]. While international ventures involving GNEP were to continue, it seemed U.S. involvement would entail support little more than in principle. As a result, it seems that the second advent of utilizing reprocessing as part of a waste management solution is dormant again in the United States, but continues abroad. Although seemingly stalled in the United States, the issue of reprocessing could be raised again at a future date.

3.4 Yucca Mountain

The spent nuclear fuel repository proposed at Yucca Mountain in the state of Nevada is still technically a viable option for future disposal. While the historical background of the project is previously covered in great detail, the future of the project remains uncertain. With ASLB proceedings suspended, restarting these proceedings represents unchartered territory. As the Obama Administration remains committed to exploring waste disposal options alternative to Yucca Mountain, restarting the NRC license review process seems unlikely. Current or new NRC commissioners would need to take a different position than the current ones or courts would need to force the NRC to start the review process, and legislation would need to be enacted to provide the necessary funds for the review. However, some lawmakers remain committed to the project or at least

to seeing the legal process through to completion, as is evidenced by the House FY2012 budget in which allocations were made for non-closure related activities in direct contrast to the president's proposed budget. As a result, given appropriate funding and a suitable political climate, it is not unreasonable to still consider Yucca Mountain as a potential future option in the U.S. nuclear waste disposal picture. In spite of political opposition, most of the administrative and technical hurdles have already been overcome. The site review was thoroughly conducted and completed approximately a decade ago. In addition, considerable progress was made on the license review before the process was halted. None of the other aforementioned waste disposal options is as well developed. Perhaps most important in this context, Yucca Mountain is the only legally permissible ultimate repository under current U.S. law. Any attempt to deviate from the Yucca Mountain Plan and pursue alternative waste disposal options in any significant fashion would require legislative changes, potentially a challenging undertaking. As a result, in spite of the political opposition to the project and stalled progress on the license review, the Yucca Mountain repository currently still represents the proverbial path of least resistance for the U.S. nuclear waste management program. As the Obama Administration continues to steer the program's focus away from the project, several lawmakers, especially in the House of Representatives, remain steadfast in their commitment to the Nevada repository. Regardless of the ultimate outcome of the Yucca Mountain project, the multi-decade process can serve as a learning experience for future waste disposal ventures.

This list of potential future methods of addressing American nuclear waste and spent fuel is by no means complete or comprehensive. Several additional seemingly less credible alternatives have been considered. It has been proposed to launch spent fuel into deep space, bury it at extreme ocean depths, and place it in subduction zones. Other methods involve emplacement in ice sheets or development of exotic reactor types. While seemingly less likely than the aforementioned strategies, many pathways indeed exist for the future of the U.S. nuclear waste management program to follow. While undoubtedly controversial and requiring significant practical and legal hurdles to be overcome, many of the aforementioned strategies attempt to address an issue that is not going

away. Indeed, actions must be taken, advisably in the near-term future, to tackle the disposal of significant quantities of spent nuclear fuel. The future of nuclear energy in the United States and, perhaps, domestic energy security are inherently linked to the resolution of the back end of the fuel cycle.

Chapter 4

Looking Forward

4.1 Future of Nuclear Energy in the United States

Nuclear power plants in the United States continue to operate, thereby producing both electricity and spent nuclear fuel, even though the question of how to manage the back end of the fuel cycle has not been decidedly resolved by the federal government. Over fifty years of commercial nuclear power generation has produced a sizeable quantity of spent nuclear fuel awaiting disposal. Although several attempts have been made to construct a temporary or permanent repository over the past five decades, none have successfully opened and progress is at a standstill. With the Yucca Mountain project shelved, no alternative legally permissible option exists. As a result, the federal government is not currently significantly pursuing any waste disposal solution. Although options for disposal do exist, a significant amount of time will be needed to implement any waste management plan.

Often already wary of nuclear power in general, states for many years have been dissatisfied with the lack of direction in the federal government's waste management program. When most plants were originally built, state officials expected that the federal government would take title to all spent nuclear fuel after a short cooling period for use in reprocessing or prompt burial. After

the plan described in the NWPA failed to come to fruition, nuclear operators have been forced to retain increasing amounts of spent fuel onsite in alternative storage options. As a result,much SNF has been stored for longer periods than originally intended in methods not meant as a permanent solution. Several states have taken issue with this practice and have sought state-level legislative action to address the issue.

Starting with California in 1976, several states have passed laws inhibiting expansion of the nuclear industry unless a viable national waste management program is devised [8]. Although specifics vary, these ”state moratorium” laws usually require progress of some kind on the part of the federal government toward opening a permanent repository before a new nuclear power plant can be built in the state. While the federal government challenged the California moratorium claiming preemption of state laws by federal nuclear regulations, the Supreme Court upheld the ban. Eight other states–Connecticut, Illinois, Kentucky, Maine, New Jersey, Oregon, West Virginia, and Wisconsin–subsequently passed similar legislation.

The Nuclear Regulatory Commission’s Waste Confidence Rule could potentially the intent of these state moratorium laws. Mostly borne out of public pressure in the late 1970s, the Rule states that the NRC ”would not continue to license reactors if it did not have reasonable confidence that the wastes can and will in due course be disposed of safely” [8]. First applied in 1984, the NRC’s first proceeding resulting from the Waste Confidence Rule ”found reasonable assurance” that existing and future commercial SNF could indeed be stored safely at a future unspecified repository [8]. In the mean time, the NRC deemed onsite storage acceptable for extended periods of time and without undue environmental concern. Reviewing these findings on an as-needed basis (although typically approximately every five years), the NRC has continually reaffirmed its original confidence that a repository could indeed be built. While the initial intent of the Rule was to prohibit licensing new nuclear reactors without reasonable assurance of a future waste management strategy, the NRC has always found that a repository could be on the horizon and that interim, onsite storage of SNF does not pose excessive hazard to the populace in the mean time.

As a result, the Waste Confidence Rule has never in practice been used to strike down a pending license application, but rather acts as a factor in deliberations by nuclear utilities looking to make long-term plans pertaining to future new nuclear facilities.

Because of state-level moratoria on new nuclear power plants and the NRC's Waste Confidence Rule, the future role of commercial nuclear energy in the United States' domestic energy policy mix is inherently linked to a solution for the back end of the nuclear fuel cycle. Furthermore, although less tangible in impact, taxpayers and lawmakers will be less likely to support subsidies or tax breaks for new nuclear power plants if a reliable waste management strategy is not implemented in parallel. U.S electricity net generation has grown approximately 33% in the last two decades, and projections continue to show a rise in the rate of electricity use [3]. With 104 commercial nuclear reactors presently supplying approximately 20% of the nation's electricity supply, nuclear power is an important portion of current and likely future American energy infrastructure. As a result, establishing a sound nuclear waste management program in the United States is not only important for dealing with SNF accumulated so far, but also for the future of U.S. electricity production.

Establishing the scope of the problem is the first step in devising an effective waste management program. As previously mentioned, information regarding the amount and locations of existing spent nuclear is widely available. Operating histories and reactor characteristics allow for accurate extrapolations of future spent nuclear fuel production. Thus, the amount of SNF requiring disposal by some future date may be determined. The second aspect of refining the scope of an effective waste management program involves ascertaining the mechanical and radiological properties of the SNF requiring disposal. The simplest and most cost-effective method of accomplishing this characterization process is through computer simulation. When combined, determining the amount and attributes of all used nuclear fuel requiring disposal can help better define the necessary properties of a future repository and, as a result, influence the search process.

Once the physical amount of existing and future SNF requiring disposal is estimated, the next

hurdle is understanding the properties of the material. The mechanical and radiological properties of spent fuel requiring disposal will dictate the size, containment, storage arrangement (due to heat production), as well as many other many other repository characteristics and, therefore, must be estimated to effectively design storage facilities. Although destructive and nondestructive physical tests could surely be used to establish a radioisotope inventory of spent fuel requiring disposal, these methods are typically expensive, cumbersome, and must be carried out at specialized facilities, few of which exist. In addition, radiation concerns and the sheer scope of undertaking such a procedure for all spent fuel to be placed in a repository often make such a path unrealistic. Fortunately, computer simulation of radioisotope inventories offers a reasonably accurate, flexible, cost-effective means to characterize spent fuel. Improvements in computing technology have allowed for use of refined models, leading to more precise solutions. Modifying the computer simulation code to account for different reactor types, operational histories, and material usage is relatively simple and offers a flexible way to account for a wide variety of issues in spent fuel radioisotope simulation. As this computer simulation technique does not require special fuel handling facilities to be built or radiation hazard concerns to be addressed, it offers a cost effective way to determine material properties of all spent fuel in the United States requiring disposal in a repository.

Using computer simulation to estimate spent fuel radioisotope inventories requires several inputs, all of which are readily available for commercial nuclear reactors. First, initial reactor and fuel characteristics must be known and input into the code. A physical description of the reactor must be known, with core dimensions precisely modeled in the code. Common examples can be found in nuclear engineering textbooks, open-source reactor plant manuals, and in NRC publications [6] [51]. Information regarding the specifics of material usage and compositions is less readily available, but approximations and extrapolations from published resources can be made. While core loading and reloading patterns as well as fuel enrichment are often considered proprietary information by nuclear operators, generic examples exist in literature that give nonspecific,

general information [6]. Second, individual reactor power histories must be obtained. As reactor power levels and duration affect radioisotope concentrations, burnup, and decay, this information is essential in modeling the characteristics of spent fuel. The NRC puts out daily power reports for every reactor in the United States that can be used for this purpose [52]. Finally, the length of time spent fuel is stored and cooled onsite in spent fuel pools must be known. Because spent fuel would be stored for years before emplacement in a repository, radioisotope concentrations will decay during this time. To accurately model radioisotope inventories as concentrations decay before emplacement in a repository, this length of time must be known for individual assemblies. With these inputs, computer simulations of spent fuel characteristics can readily be determined by modeling codes.

Significantly advanced, high-tech computer codes exist to model radioisotope inventories. Such codes are often the result of decades of research and are updated and improved regularly as techniques for handling challenging areas improve. Highly trained, technical personnel typically run them on supercomputers or large clusters, although complex desktop examples do exist. In certain applications, a surplus of human and computing capital allows these codes to address complicated problems and challenges in nuclear engineering. There are many areas within the subject where the rise and decay of radioisotopes plays an important role, and these codes were designed to address a wide variety of scenarios. In tackling complex problems, interpolating across several types of cross sections in a massive, read-in library is normally required. In addition, problems typically require the utilization of several neutron energy groups. As a result, it is at the minimum often necessary to solve a sizable system of coupled linear differential equations and iterate to account for nonlinear effects. Even for the simplest approaches, computing limitations arise from the size of the matrix to be inverted. If excessively small time or geometric steps are necessary to generate a specified level of accuracy, additional resources will be required. While it is certainly possible to accurately model nuclear systems, for very accurate modeling of radioisotope inventories in in existing reactors a significant amount of computing resources and trained personnel are

required.

The purpose of the modeling project described in this thesis is to generate a computer simulation code that is not excessively complex to model radioisotope buildup and decay with application to spent commercial nuclear fuel. The application principally in mind is the estimation of the operationally significant radioisotope inventories in SNF discharge from future reactor operations where the precise fuel loading and reloading patterns are not yet known. In making preliminary assessments of the suitability of potential repository host sites for future SNF production, it is neither necessary nor possible to obtain an exceedingly accurate radioisotope inventory of the fuel to be disposed of. Rather, a modest approximation of the characteristics of the fuel requiring disposal is sufficient. As a result, a computer simulation code run on a desktop personal computer with commercial software that does not require excessive time allocations or tremendous technical training would be beneficial in this application. The method proposed herein attempts to address this issue and provide a workable solution.

Chapter 5

Methods and Results

5.1 Methodology

The commercially available computational tool chosen here to model radioisotope inventories in spent commercial nuclear fuel is $Mathematica$. This software, developed by Wolfram Research, is a globally available mathematical programming language with extraordinary features. One particular advantage of utilizing $Mathematica$ is the capability to perform complex calculations symbolically. Mathematical computations can be performed with in-line descriptions, comments, and explanations. Several dispersed, complicated worksheets can be linked together to form a larger picture or evaluated individually. Most importantly in the current application, the software can be obtained, installed, and run on commercially available desktop personal computers and laptop computers. The ability to obtain results in a reasonable amount of time on personal computers was the main motivation for selecting $Mathematica$. In this scenario, highly-trained experts and supercomputers are not required; a reasonable approximation can be obtained by lay personnel on personal computers.

In most basic terms, the problem involves solving the finite difference approximation to the standard diffusion equation. As an eigenvalue problem, the eigenvalue itself relates to the change

in dissolved boron concentration in the reactor water circulating throughout the core. This dissolved boron used as a non-mechanical means of reactivity control, known as chemical shim, must change with time during reactor operation to account for the loss of reactivity due to fuel depletion, the buildup of actinides and fission product poisons, and the burnout of initially installed burnable poisons. Each of these driving factors must be accurately modeled in order to track the evolution of the eigenvalue over discrete time periods. After a user-specified time of operation (usually the refueling period of a nuclear reactor, approximately two years), the actinide buildup and, therefore, radioisotope inventory of the spent nuclear fuel can be determined.

The calculation to find the reduction in dissolved boron concentration required to maintain criticality after a period of reactor operation can be broken down into several individual problem statements. For each section, an independent $Mathematica$ notebook is utilized to perform the required calculation. These notebooks can be linked together or run in standalone fashion.

5.2 Mathematica Notebooks

Assembly and Water Fractions The first notebook is used to address the inhomogeneity and the associated computational difficulty in reactor material distribution. For the AP1000, the fuel loading diagram can be found in Appendix A and will be used henceforth. Alternative loadings could be utilized with the code with only slight alteration. The AP1000 layout consists of square fuel cells arranged in an approximately circular manner surrounded by water at the radial extremities. Three zones with different U235 enrichments are used here for simplicity. Higher enriched fuel is initially loaded towards the outer edge of the core for flux and power flattening purposes. Although certainly possible, linking flux calculations in each fuel assembly with individual boundary and interface conditions to determine core-wide flux and power rapidly becomes exceedingly difficult and computationally exhaustive. Instead, the function of this first notebook is to very simply average the fuel enrichment cylindrically. The fuel assembly loading pattern of squares, described

in a common $Excel$ spreadsheet, is assumed to have symmetry through eight reflection planes and, therefore, the angle averaging process only needs to be completed for a 45 degree section of the cylindrical angle. In the process, as higher U235 enrichments are encountered expanding radially form the center, a profile is created that describes the average fuel enrichment as a function of radius out to the core boundary. From this, the U-238 concentration as a function of radius is found and, by extension, the radial assembly fraction in the core. The output from this notebook is a function describing the core fraction occupied by assemblies as a function of radius, displayed both in the notebook and output as an $Excel$ spreadsheet.

In a similar fashion, the water fraction of the core determined in the second notebook. This distribution is essential, as the radial distribution of boron dissolved in the water present in the core plays a large role in criticality and flux calculations. It will be this boron concentration that must be adjusted over time to account for reactivity changes during operation.

One Group Flux Calculation Both the assembly and water fractions serve as an input into the iterative one-group neutron flux calculation taking place in the third notebook. When combined with the material cross sections, the assembly and water fractions impact the flux calculation and influence neutron interactions in the core. This process stems from diffusion principles.

The diffusion equation from $Nuclear\ Reactor\ Analysis$, hereafter referred to as $Duderstadt\ and\ Hamilton$ [6], with a constant diffusion coefficient, D, is,

$$-D \bigtriangledown^2 \phi + \Sigma_a \phi = \nu \Sigma_f \phi \tag{5.1}$$

In the cylindrically symmetric approximation with a spatially dependent diffusion coefficient,

$$- \bigtriangledown [D(r,z) \bigtriangledown \phi(r,z)] + \Sigma_a(r,z)\phi(r,z) = \nu \Sigma_f(r,z)\phi(r,z) \tag{5.2}$$

Separating out the absorption due to dissolved boron

$$-\bigtriangledown\left[D(r,z)\bigtriangledown\phi(r,z)\right]+\Sigma_a(r,z)\phi(r,z)+\Sigma_{boron}(r)\phi(r,z)=\nu\Sigma_f(r,z)\phi(r,z) \tag{5.3}$$

The initial dissolved boron concentration in core water is represented by N_{BO} and the reduction in the boron chemical shim by $N_{B,reduction}$

$$\Sigma_{boron}(r)=\Sigma_{BO}(r)-\Sigma_{B,reduction}(r) \tag{5.4}$$

$$-\bigtriangledown[D(r,z)\bigtriangledown\phi(r,z)]+\Sigma_a(r,z)\phi(r,z)+\Sigma_{BO}(r)\phi(r,z)-\Sigma_{B,reduction}(r)\phi(r,z) = \nu\Sigma_f(r,z)\phi(r,z) \tag{5.5}$$

Rearranging yields

$$-\bigtriangledown[D(r,z)\bigtriangledown\phi(r,z)]-(\nu\Sigma_f(r,z)-\Sigma_a(r,z))\phi(r,z)+\Sigma_{BO}(r)\phi(r,z) = \Sigma_{B,reduction}(r)\phi(r,z) \tag{5.6}$$

Equivalently,

$$-\bigtriangledown\left[D(r,z)\bigtriangledown\phi(r,z)\right]-\Sigma_T(r,z)\phi(r,z)+\Sigma_{BO}(r)\phi(r,z)=\Sigma_{B,reduction}(r)\phi(r,z) \tag{5.7}$$

where $\Sigma_T(r,z)=\nu\Sigma_f(r,z)-\Sigma_a(r,z)$.

To nondimensionalize, multiply by the square of the core radius, R^2, and divide by the diffusion coefficient at the reactor center after initial fuel loading, D_o,

$$(R^2/D_o)(-\bigtriangledown[D(r,z)\bigtriangledown\phi(r,z)]-\Sigma_T(r,z)\phi(r,z)+\Sigma_{BO}(r)\phi(r,z)) = (R^2/D_o)\Sigma_{B,reduction}(r)\phi(r,z) \quad (5.8)$$

At this point, it becomes necessary to multiply by the square of the discretized zone height, h^2. This is done for convenience in later defining the eigenvalue and for simplification of the discretization process. More information on the discretization process can be found in Appendix B.

$$(h^2R^2/D_o)(-\bigtriangledown[D(r,z)\bigtriangledown\phi(r,z)]-\Sigma_T(r,z)\phi(r,z)+\Sigma_{BO}(r)\phi(r,z)) = (h^2R^2/D_o)\Sigma_{B,reduction}(r)\phi(r,z) \quad (5.9)$$

As $\Sigma_{B,reduction}$=$N_{B,reduction}(r)\sigma_{a,B}$, inserting this yields

$$(h^2R^2/D_o)(-\bigtriangledown[D(r,z)\bigtriangledown\phi(r,z)]-\Sigma_T(r,z)\phi(r,z)+\Sigma_{BO}(r)\phi(r,z)) = (h^2R^2/D_o)N_{B,reduction}(r)\sigma_{a,B}\phi(r,z) \quad (5.10)$$

Define $f=\phi W$, where W is the volume fraction of water in the core as a function of radius. As a result, $\Sigma_{BO}(r)=\Sigma_{BO}W$ and $\Sigma_{B,reduction}(r)=\Sigma_{B,reduction}W$. Furthermore, the inverse of the water fraction is $w=1/W$. Inserting $\phi=wf$ and the new boron definitions gives

$$(h^2R^2/D_o)(-\bigtriangledown[D(r,z)\bigtriangledown(fw)]-\Sigma_T(r,z)fw+\Sigma_{BO}f) = (h^2R^2/D_o)N_{B,reduction}\sigma_{a,B}f \quad (5.11)$$

The eigenvalue is defined as $\lambda_o = h^2(R^2/D_o)N_{B,reduce}\sigma_B$. The equation becomes

$$(h^2R^2/D_o)(- \bigtriangledown [D(r,z) \bigtriangledown (fw)] - (\Sigma_T(r,z))fw + \Sigma_{BO}(r)f) = \lambda_1 f \tag{5.12}$$

This equation is discretized using standard finite difference techniques (more information can be found in Appendix B) and the resulting matrix of equations is solved for the smallest eigenvalue using $Mathematica$. That eigenvalue, λ_1, is directly proportional to the reduction in dissolved boron concentration in coolant water required to maintain criticality in a reactor after a specified period of power operation. This reduction in boron concentration, essentially a positive reactivity addition, is required to balance the negative reactivity resulting from fuel burnup and fission product poison buildup, notably xenon, after operation.

5.3 Xenon Calculation

The buildup of xenon during reactor operation is described in $Duderstadt\ and\ Hamilton$ [6]. As the period of reactor operation is much greater than the time to reach equilibrium xenon concentration, the functional form of xenon buildup over time is not required here. Only the equilibrium xenon number density must be calculated:

$$N_{Xe,eq} = \frac{(\gamma_I + \gamma_{Xe})\Sigma_f \phi_{eq}}{\lambda_{Xe} + \sigma_{a,Xe}\phi_{eq}} \tag{5.13}$$

where ϕ_{eq} is the equilibrium reactor flux, $\sigma_{a,Xe}$ is the microscopic xenon cross section of absorption, γ_I is the effective fission fraction of iodine,γ_{Xe} is the effective fission fraction of xenon, Σ_f is the fuel macroscopic cross section of fission, and λ_{Xe} is the xenon β-decay rate constant.

Accounting for U235 and U238 fissions yields the following:

$$N_{Xe,eq} = \frac{(\gamma_I + \gamma_{Xe})(\sigma_{f,U235} N_{U235} + \sigma_{f,U238} N_{U238})\phi_{eq}}{\lambda_{Xe} + \sigma_{a,Xe}\phi_{eq}} \tag{5.14}$$

The true flux at equilibrium is utilized here and is obtained from the reactor power. Trials indicate that only one iteration is necessary to calculate the equilibrium concentration to an accuracy of 1 ppm.

5.4 Actinide Concentrations

The final notebook produces the radioisotope inventory, specifically the important actinides, in the approximation of a fixed energy spectrum neutron flux. The neutron flux can be approximated as a constant for an initial short burn period and later as a temporally extrapolated linear function of time at each spatial location over subsequent burn periods. The presence of several specific actinides can have a significant effect on both the fission energy spectrum and on the concentration of problematic radioisotopes in spent fuel reactor discharges. In general, approximately 25 radioisotopes of non-insignificant half-lives can tracked, their buildup and decay carefully modeled. The following represents a simplified diagram of the emergence of important actinides that are tracked in the work reported upon here:

$$U235 \rightarrow U236 \rightarrow Np237 \rightarrow Pu238 \rightarrow Pu239 \tag{5.15}$$

$$U238 \rightarrow Pu239 \rightarrow Pu240 \rightarrow Pu241 \rightarrow Pu242 \rightarrow Am243 \tag{5.16}$$

The general equation describing the number density of a specific actinide as a function of time is described as:

$$\frac{dN_k}{dt} = \alpha_{k-1}\varphi N_{k-1} - r_k \varphi N_k - \lambda_k N_k \tag{5.17}$$

Here, α is the macroscopic neutron absorption cross section, r_k is the removal cross section (sum of fission and absorption cross sections), λ_k is the radioactive decay rate, and φ is the neutron flux. The subscript, k, refers to the k=1,2,3,..... actinide in the decay chain of interest. Several radionuclides of interest are simply a function of the neutron fluence, Φ, between time t_o and t. Since the neutron fluence is a solution to $\frac{d\Phi}{dt} = \varphi$, it is thus convenient to rewrite the number density equation as

$$\frac{dN_k}{d\Phi} = \alpha_{k-1}N_{k-1} - r_kN_k - \lambda_kN_kG \tag{5.18}$$

where G=$\frac{1}{\varphi}$. These equations are utilized to track each individual actinide of interest and model buildup and decay over time. With a complete representation of actinide concentration over time for the aforementioned species, the relevant radioisotope inventory is produced.

5.5 Energy and Spent Fuel Heat Production

With known radioisotope concentrations, the heat produced by spent fuel is a straightforward calculation. The relative flux is integrated over all reactor volume and related to the thermal power of the AP1000 reactor, 3415 MWth, to find the true flux [53]. With the true flux, the energy production as a result of fission is found for all fissioning species and summed, with energy release per fission known.

The heat produced by spent fuel requiring disposal is critical to storage cask, transportation cask, and underground repository design. The emitted thermal energy, in combination with repository design and environmental characteristics, will greatly impact spent fuel cask packing density upon interment. In order to avoid cask damage and mechanical failure, sufficient passive cooling and air circulation must be designed for in an effective waste management storage plan. Typically, this dictates a minimum cask spacing and offset distance. However, economic and limited spacing restrictions indicate that spent fuel in a repository should be stored as closely as possible to min-

imize unused space. Calculating the heat produced by spent fuel requiring disposal will help to balance these competing factors and, perhaps, help outline underground repository design and size criterion.

In the methodology promoted here, the eigenvalue is calculated over a short period of operation time, essentially representing the required decrease in dissolved boron absorption required to maintain criticality. This approach of adjusting the chemical shim to maintain reactor criticality over time is what separates this code from other methods accomplishing similar tasks. The xenon buildup, fuel depletion, and burnable poison burnout are evaluated over this same period of operation, as reactivity changes due to these factors will impact the next iteration.

Over the next timestep, another iteration of the eigenvalue calculation process, now accounting reactivity changes from the previous iteration, yields a new reduction in dissolved boron concentration. This iterative scheme is repeated until the reactor is refueled and fuel assemblies are shuffled, with some being removed from the reactor as fresh fuel is loaded. The new initial boron concentration must then be recalculated. The results of these subsequent timesteps have not been calculated here for the present work, but are a straightforward extension of the method used.

Ultimately, the code consists of a sequence of four individual notebooks. The first two calculate the assembly and water fractions, respectively representing the fraction of the core occupied by fuel and water (including dissolved boron) materials. These distributions essentially serve as weighting functions for the radial effects of materials cross sections and are inputs into the one-group flux calculation. The flux calculation occurs in the third notebook and represents the iterative loop of the code, solving for the eigenvalue representing the decrease in dissolved boron concentration as previously described. Finally, the flux distribution is an input into the calculation of actinide concentrations. This final notebook reports the radioisotope inventory of all actinides of interest in spent fuel considerations. This process is described graphically in Figure 5.1.

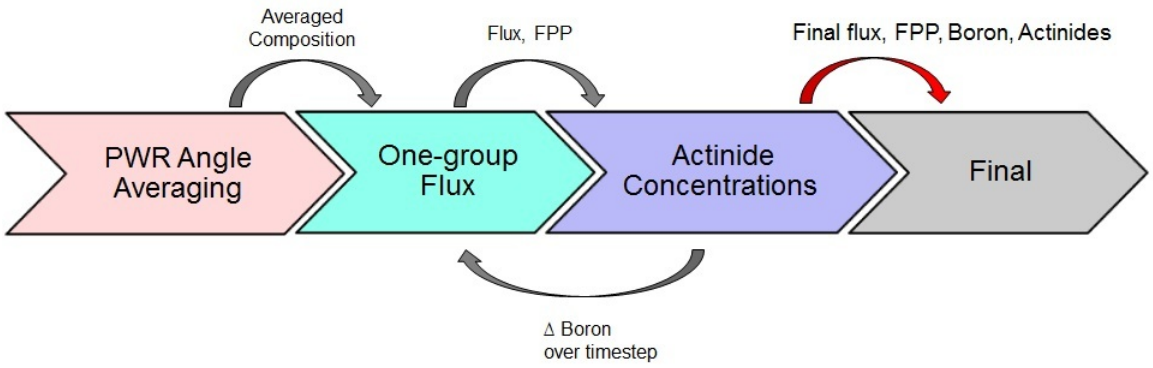

Figure 5.1: Schematic Diagram of Code Flow

5.6 Results and Radioisotope Inventory

Assembly Fraction The volume fraction of the core occupied by fuel assemblies (and therefore fuel material) as a fraction of the maximum radius is shown in Figure 5.2. The figure shows how the fuel assemblies occupy nearly all of the volume near the radial center of the core. At approximately 0.7 of r_{max}, the assembly fraction starts to decrease as the first of the fuel assemblies are replaced by water. The assembly fraction decreases sharply after this point until approximately 0.9 of r_{max}, where all fuel assemblies have been replaced by water out to the radial boundary. The plotted dots in the figure are the direct discrete calculations by the angle-averaging technique and the solid curve represents the fit to through these points. The fit is modeled by a constant plus the algebraic sum of two logistic functions. It is this fit that is used as a weighting function for the fuel materials cross sections in further diffusion equation calculations.

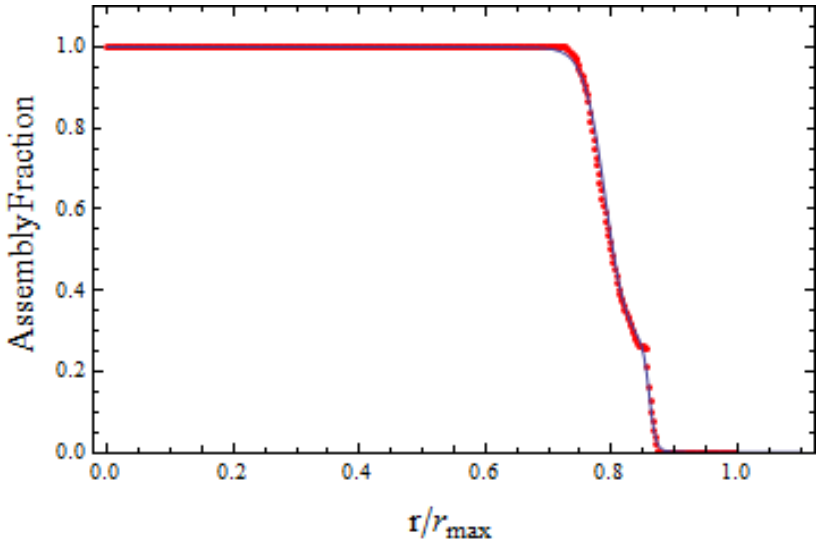

Figure 5.2: Assembly Fraction as a Function of Normalized Core Radius

Water Fraction From the assembly volume fraction of the core, the water fraction can be calculated. Figure 5.3 shows the water fraction. The distribution is low in the center of the core and rises to one near the radial edge. At approximately 0.7 of r_{max}, the first major concentrations of water become apparent in the core and, at approximately 0.9 of r_{max}, the core is entirely water.

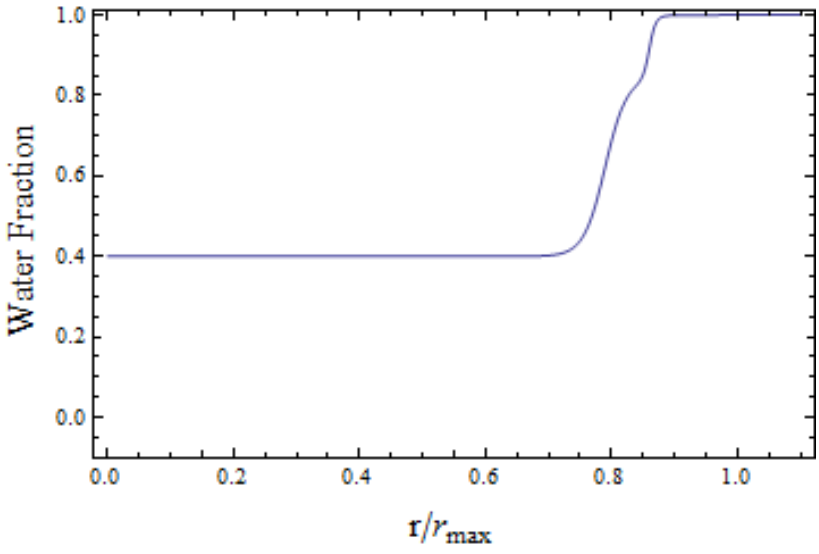

Figure 5.3: Water Fraction as a Function of Normalized Core Radius

The water fraction is significant because it also describes the volume fraction of the boron in the core, as the boron is dissolved in the water. The distribution of boron in the core will be utilized in part to determine neutron absorption and the reactor flux, as the boron cross section will significantly impact these calculations. Ultimately, the eigenvalue, proportional to the reduction in boron, will stem from these calculations.

Combining the core assembly volume fraction with the core loading pattern from Appendix A in the angle averaging technique yields the U235 enrichment profile as a function of radial fraction within the core, as seen in Figure 5.4. The transitions between the three radial loading zones is easily distinguishable. The decrease in U235 fraction due to the extension of the fuel assembly boundaries near the radial edge of the core can also be seen and closely follows the assembly fraction trend. Here again, the plotted dots in the figure are the direct discrete calculations by the angle-averaging technique and the solid line represents the fit to through these points. The fit is modeled by a constant plus the algebraic sum of four logistic functions.

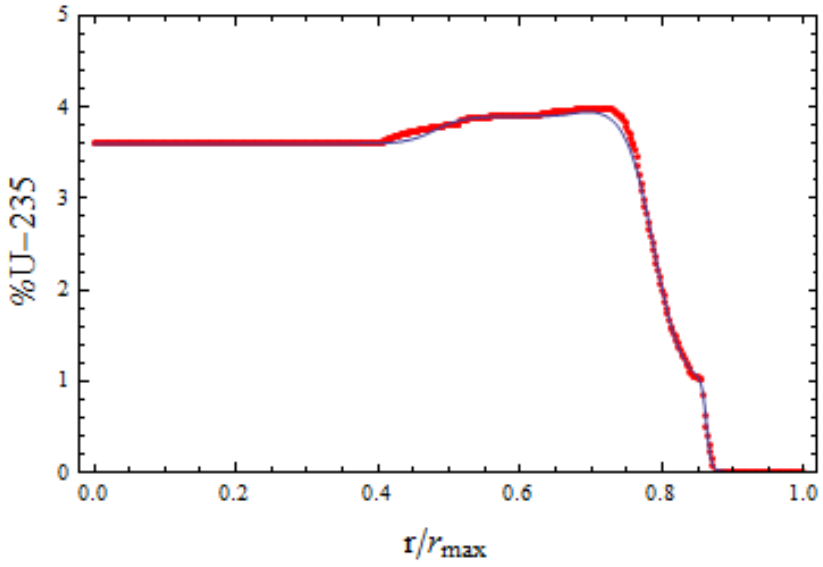

Figure 5.4: U235 Enrichment Profile as a Function of Normalized Core Radius

Boron Concentration While many eigenvalue solutions exist, the smallest positive eigenvalue, designated λ_1, represents the only solution not rapidly varying in time and is chosen to calculate the reduction in dissolved boron concentration. To translate the calculated eigenvalue into a reduction in the boron concentration, note that:

$$\lambda_1 = h^2(R^2/D_o)N_{B,reduce}\sigma_B \tag{5.19}$$

Rearranging gives

$$N_{B,reduce}\sigma_B = \frac{\lambda_1 D_o}{h^2 R^2} \tag{5.20}$$

It is convenient to address this boron reduction in terms of the fractional change. To accomplish this, divide by $N_{B,O}$

$$\frac{N_{B,reduce}}{N_{B,O}} = \frac{\lambda_1 D_o}{h^2 R^2 \sigma_B N_{B,O}} \tag{5.21}$$

$$\text{fractional change } = \frac{\lambda_1 D_o}{h^2 R^2 \sigma_B N_{B,O}} \tag{5.22}$$

Here, the discretized zone height, h=$\frac{2}{40} = 0.05$

The radius of the simplified AP1000 core used here, R=78.5"=1.994m [53]

The diffusion coefficient at the reactor center after initial fuel loading, D_o=0.0923

The boron cross section, $\sigma_{B,O} = 3410 \cdot 10^{-}28\ m^2$

Initial born concentration is $N_{B,O} = 2.43 \cdot 10^{2}5[1/m^3]$

Finally, λ_1 was determined to be $\lambda_1 = 0.0185466$

$$\text{fractional change } = \frac{\lambda_1 D_o}{h^2 R^2 \sigma_B N_{B,O}} \tag{5.23}$$

$$= \frac{(0.0185466)(0.0923m)}{(\frac{2}{40})^2(1.994m)^2(3410 \cdot 10^{-}28\ m^2)(2.43 \cdot 10^{2}5\frac{1}{m^3})} = 0.023 \tag{5.24}$$

With an initial boron concentration of 2210 ppm as specified by $Duderstadt\ and\ Hamilton$, a 2.3% reduction in boron concentration corresponds to a decrease of approximately 51 ppm over the given time period of operation [6].

Neutron Flux and Thermal Energy Production Rate The normalized neutron flux is shown in Figure 5.5. As can be seen from the figure, the flux is fairly flat both radially and vertically, as desired. The flux decreases towards the radial extremity of the core, as the assemblies are replaced by water in that location. A sharp decline is noted at the approximate radial position of 0.7 of r_{max} which, as noted above, marks the general start of the decrease in the assembly volume fraction. By approximately 0.9 of r_{max}, the flux is negligible. The flux also drops sharply at the vertical extremities of the fuel assemblies because the fissile material in a fuel assembly is bounded on the top and bottom by retention springs. This cavity, 7" and 5.635" in height, respectively, is filled with inert gas rather than fissile material and, thus, the flux drops sharply at the top and bottom [53]. For the present simulation, for simplicity regions of seven inches height at the top and bottom of the reactor is included which is devoid of fuel but otherwise has the same properties of the assembly regions between them. The fuel-free regions around the fuel assemblies are large enough that it suffices to impose a zero neutron flux boundary condition at the outer envelop of the finite height cylindrically symmetrically averaged region modeled.

A contour plot of the normalized neutron flux is shown in Figure 5.6 and shows information which may be difficult to discern from the three-dimensional plot. The relatively flat profile radially and axially is apparent from the contour plot. In addition, the rate at which the flux profile rises in relation to the radial and axial zones can be seen.

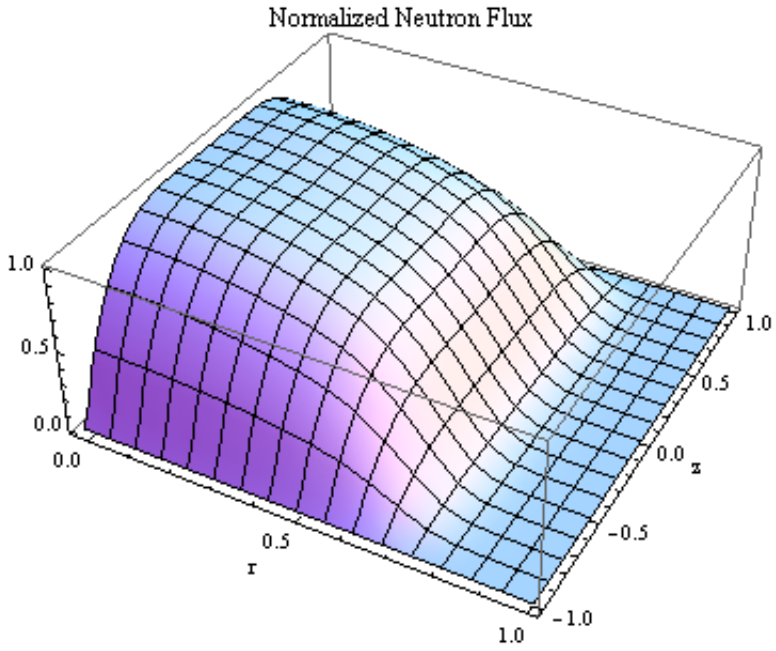

Figure 5.5: Normalized Neutron Flux

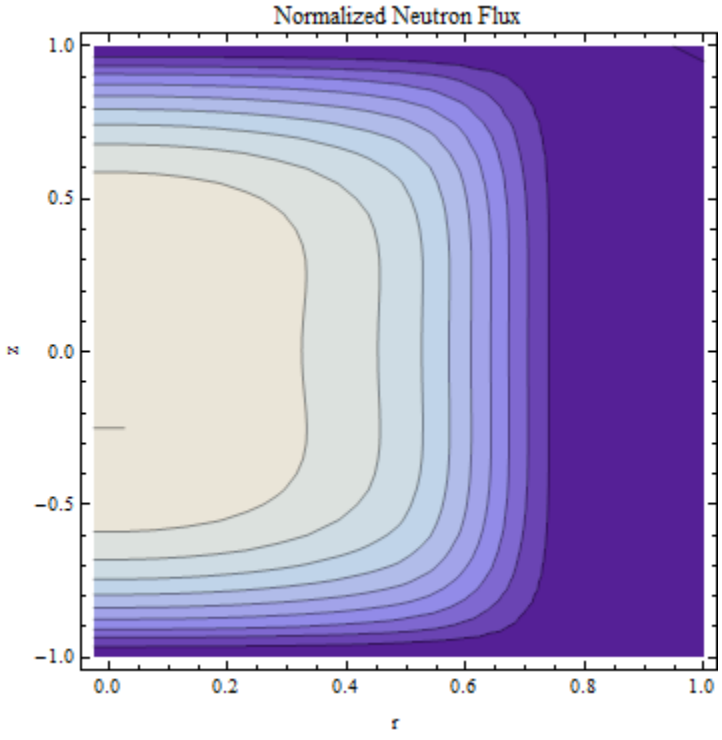

Figure 5.6: Normalized Neutron Flux - Contour Plot

Figure 5.7 shows the normalized thermal energy production rate. As expected, the thermal energy production rate closely models the neutron flux, but appears to display a slightly flatter distribution.

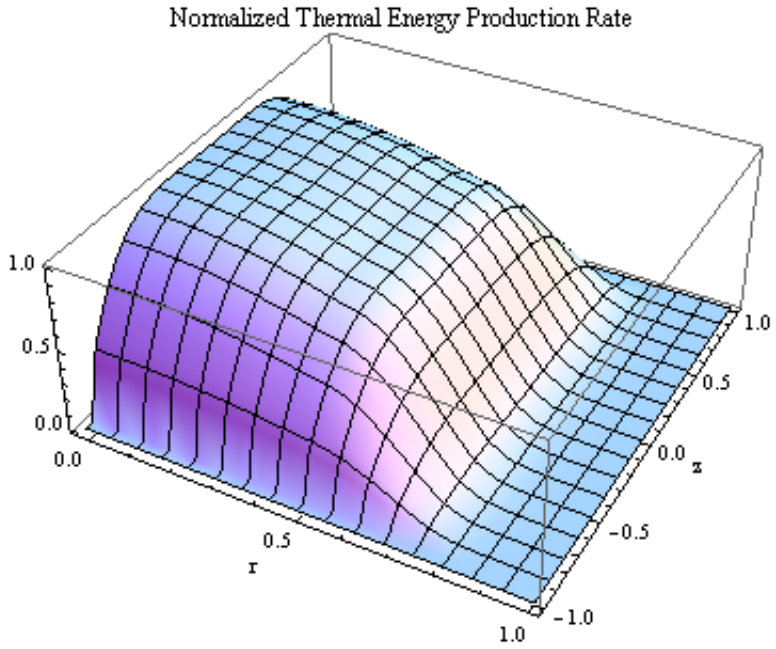

Figure 5.7: Normalized Thermal Energy Production Rate

A plot of the thermal energy production rate is shown in Figure 5.8. The flatness of the distribution is even more apparent on the countour plot.

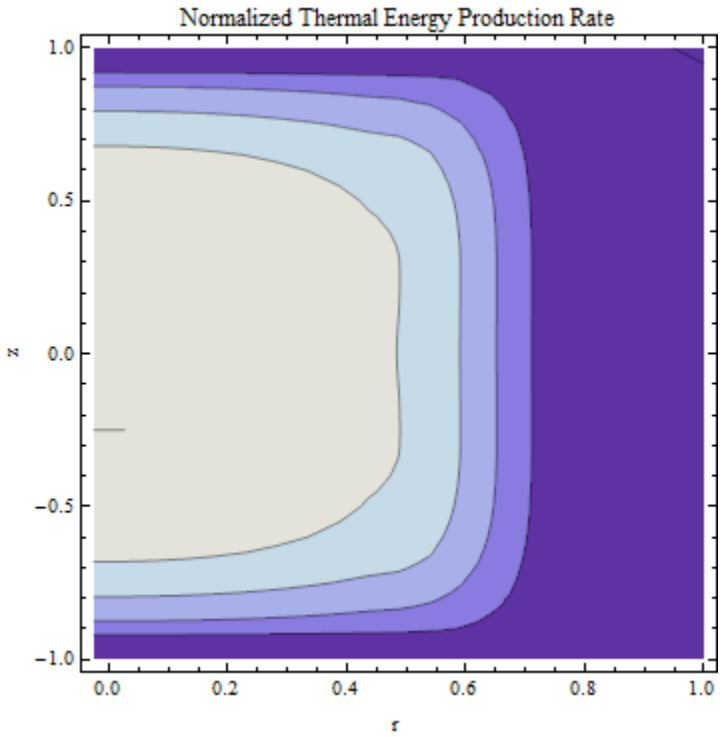

Figure 5.8: Normalized Thermal Energy Production Rate - Contour Plot

Actinide Concentrations The actinide concentrations produced are listed in the following figures (the cross sections utilized can be found in Appendix C). Each figure shows the species concentration, in units of $1/m^3$, as a function of radial zone for various heights. From the aforementioned flux profiles and contour plots, it can be seen that, as expected, the highest transuranic species concentration is near the center of the core and each subsequent distribution with a lower magnitude represents a vertical shift towards the top or bottom of the core. Here, at the vertical extremities, the actinide concentrations are the lowest, as seen from the figures.

The U238 concentration does not vary significantly vertically and has a large magnitude through-

out the assembly, as expected. The Pu239 concentration is highest near the center and decreases radially and axially. While the Pu240 distribution follows the same trend as the Pu240 plot, it has only approximately 3% of the magnitude. Both Pu241 and Pu242 follow similar trends as Pu240, each increasingly heavier isotope representing approximately 2-3% of the magnitude of the previous. Figures 5.12 and 5.13 also show that Pu241 and Pu242 are produced more in the center of the core and less in the radial direction than each previous lighter isotope. The U235 profile closely mirrors the angle-averaged enrichment profile, as expected, and burns out only slightly. The fuel depletion is more noticeable in regions of higher enrichment. The U236 concentration is only a very small fraction compared to the U235 profile, but has an interesting slight peak and then sharp decrease near the twelfth radial zone. This is due to increased radiative capture in U235 in regions of higher enrichment and then a sharp drop as the fuel assemblies give way to water near the radial boundary. The Np237 profile follows in similar fashion, but has a much more subtle effect. The Pu238 distribution shows that only small amounts are produced in the core and mostly in the center region. However, while only small relative amounts of Pu239 are produced from U235, mostly in the center, this additional fissile material is known to significantly contribute to fission power and heat production within the core. While Am243 was indeed tracked in the code, insignificant amounts were produced in the given period of time and, hence, a plot of the concentration was not included. Similarly, very little Pu240 was produced from U235, and a plot of portion of the Pu240 derived from U235 was not included.

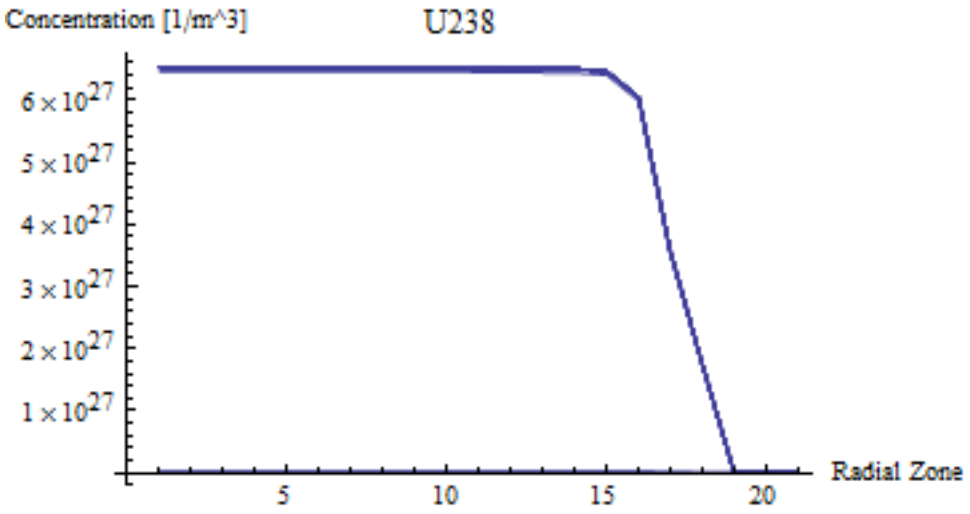

Figure 5.9: U238 Concentration

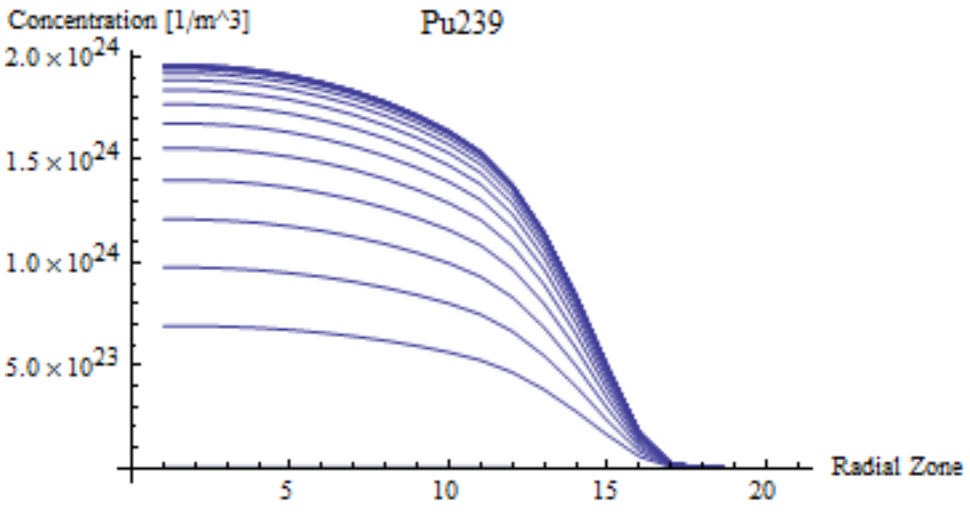

Figure 5.10: Pu239 Concentration

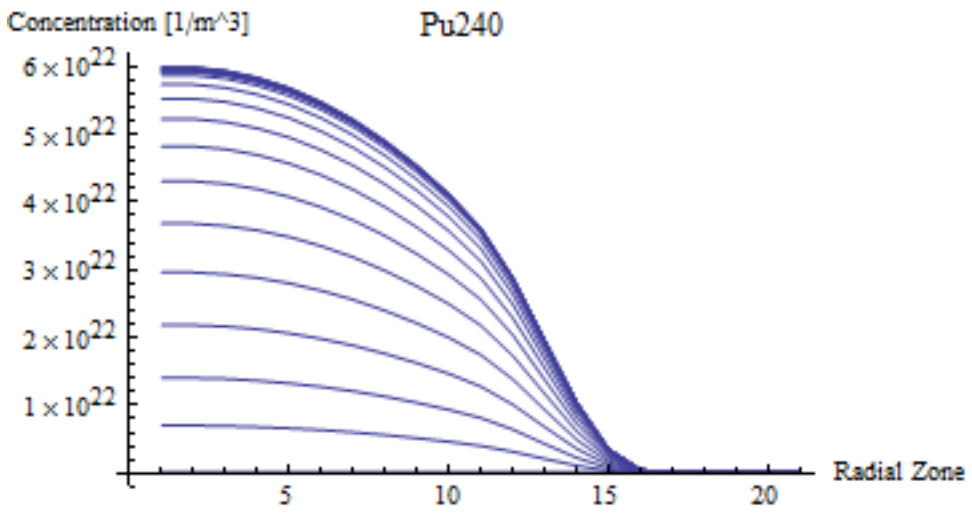

Figure 5.11: Pu240 Concentration

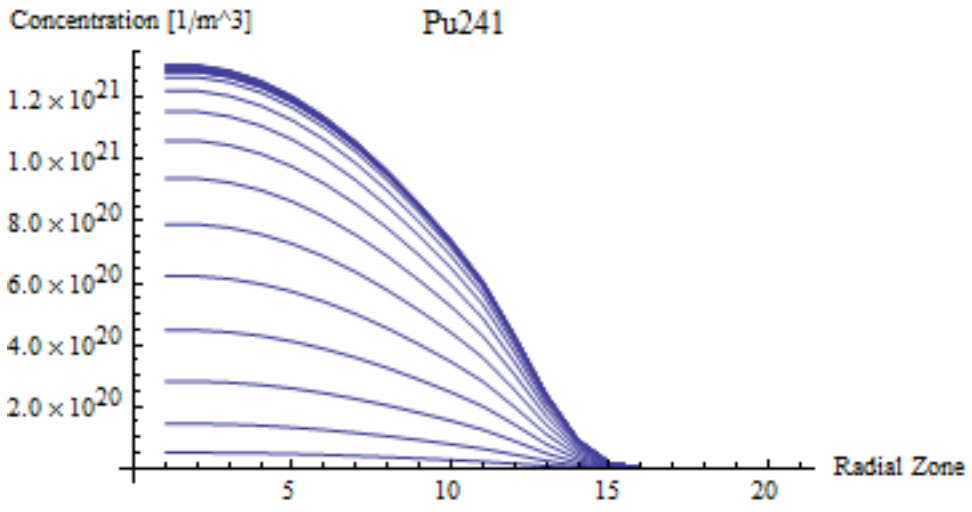

Figure 5.12: Pu241 Concentration

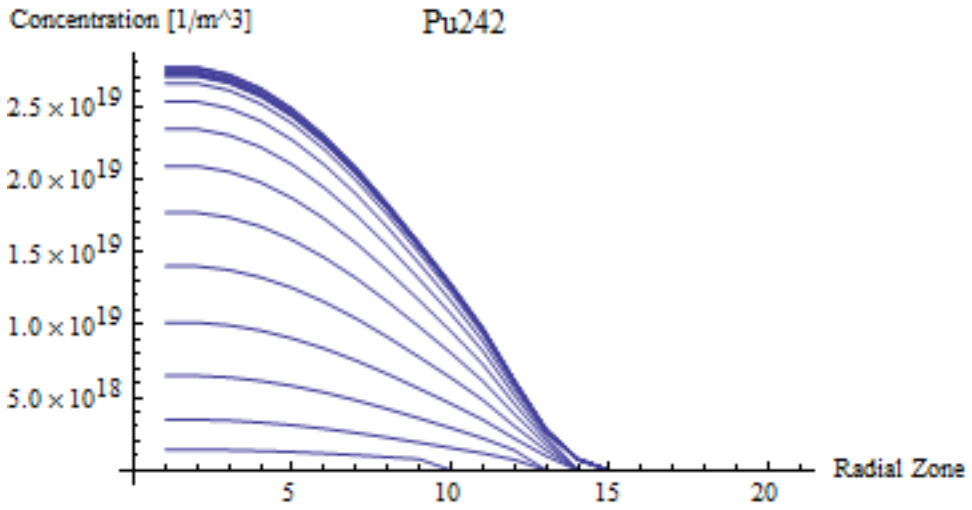

Figure 5.13: Pu242 Concentration

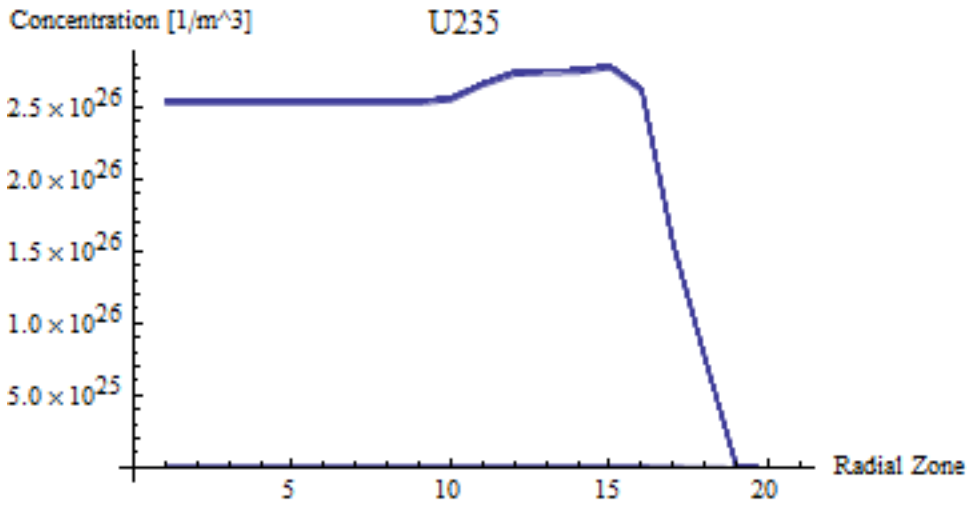

Figure 5.14: U235 Concentration

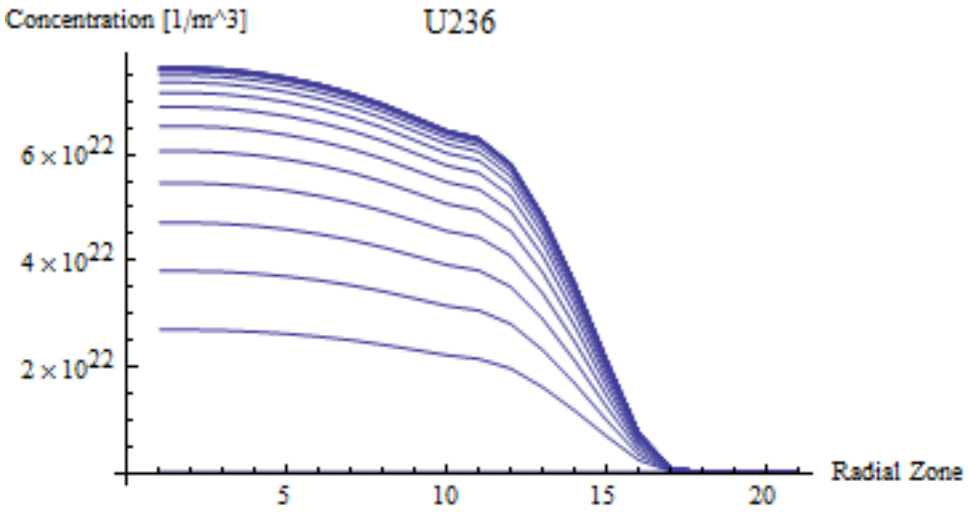

Figure 5.15: U236 Concentration

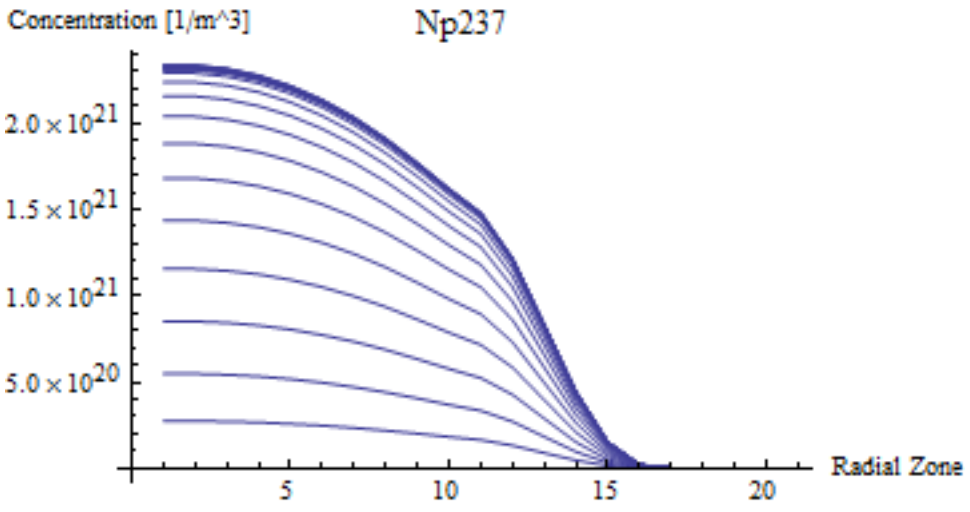

Figure 5.16: Np237 Concentration

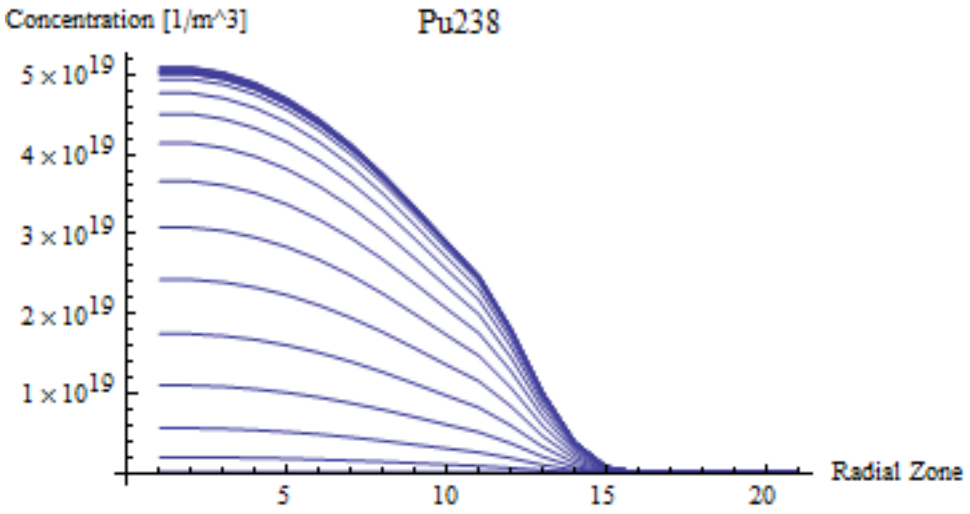

Figure 5.17: Pu238 Concentration

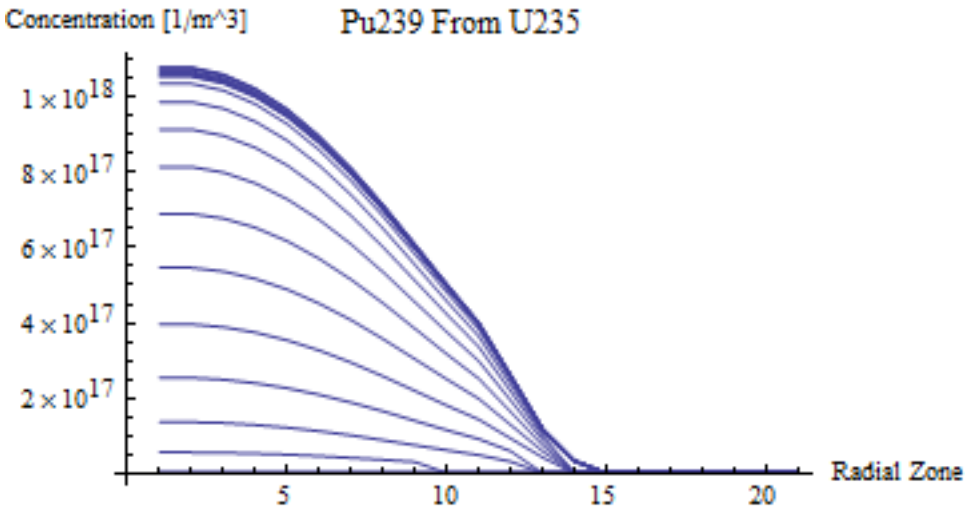

Figure 5.18: Pu239 From U235

The actinide concentration plots model the expected behavior. Production mostly occurs in the radial and axial center of the core and decreases towards the boundaries. Notable exceptions include parts of the U235 chain, as increases in production occur near the higher regions of enrichment near the radial boundaries. The affected radionuclides show visible rises or ”bumps” in the concentration profiles in the radial zones that correspond to the highest U235 enrichment. The flux and thermal energy production rate were also shown and represent reasonable, justifiable distributions. To weight the materials cross sections, the assembly and water fractions were calculated from an angle-averaging, core material homogenizing technique applied to a simplified AP1000 core loading pattern. While several significant approximations were made and suggestions to increase the accuracy of the code are outlined in the ”Future Work” section, the code provides a reasonable, first-order likeness of the expected solutions, distributions, and concentrations for the short burn times illustrated here.

Chapter 6

Conclusion

6.1 Conclusions

So far, the project outlined here has successfully produced approximate actinide inventories of spent nuclear fuel for a short burn time period utilizing unsophisticated computational resources. The radial core volume fractions of both fuel assemblies and water (containing dissolved boron) were first calculated and utilized as cross section weighting factors. The lowest positive eigenvalue solution to the modified diffusion equation was chosen and then related to the reduction in the dissolved boron concentration required to maintain reactor criticality. The reactor flux and thermal energy production rates were subsequently calculated and used to determine radioisotope concentrations of several radionuclides of interest. This method of adjusting the chemical shim (boron concentration) to maintain criticality in diffusion equation calculations is a particularly convenient approach, because the only iteration needed even for the first flux calculation is to estimate the equilibrium xenon concentration, and that converges to about one part per million in a single iteration. Also, the evolution of actinide concentration depends to a good approximation only on the cumulative fluence at each computational mesh point over a burn period, and this can also be computed very rapidly using the techniques adopted here. The xenon concentration can also be

estimated sufficiently accurately during each burn period without the need for additional iterations specific to its relaxation. The work reported upon here thus represents proof-of-concept for this method, even as significant additional work must be done before effective utilization of this code can commence. Finally, to determine the actual spent fuel composition of offloaded fuel, the code would need to be tailored to the actual reactor the fuel was burned in. Specifically, the reactor geometry would require modeling, the operation power history would need to be input, and operating characteristics would need to be accounted for. Since the AP1000 is the type of new reactor actually being built in the United States as of this writing and the project is primarily aimed at estimating characteristics of SNF produced during the lifetimes of reactors to be built over the next few decades, this reactor type was chosen for the results presented herein. Other reactor types both currently in operation and likely to be built over the next few decades also need to be modeled. As a result, although the computer code contained within this project represents a step forward in modeling spent nuclear fuel, significant additional steps must be taken to make it a fully useful tool to support analysis and policymaking for management of spent nuclear fuel.

Chapter 7

Future Work

7.1 Future Work

There is an abundance of future work associated with this project that can be done. Efforts can and should be made to increase the usefulness and accuracy of the documented code. First, the one neutron energy group approximation should be replaced by two neutron energy groups [6]. For a given computational mess space, this will double the length of the eigenvector that defines the core neutron flux distribution. This is the same increase that results from increasing the numbers of radial and vertical computational zones each by the square root of two, which has been done and still allows matrix inversion in few seconds of computation time on commonly available personal computers. It is also straight forward to include the effects of decay of Pu241 during fuel irradiation (and of the small effect of the decay of Pu238), not accounted for during the short burn time results in the previous chapter. For subsequent burn periods after the first actinide profile computation, the neutron flux can be linearly extrapolated at each computational mesh point over succeeding burn periods until fuel reload, using the constant thermal power output approximation. The cylindrical averaging notebook also needs to be modified slightly to cylindrically average all of the actinide concentrations, not just the U235 and U238 profiles as in the first fuel loading. For

boiling water reactors, the void fraction profile also needs to be estimated, which is straightforward in the uniform vertical flow approximation.

The most basic model should then be benchmarked against existing codes. The most practical and widely available codes for this purpose would be ORIGEN, a code produced by Oak Ridge National Lab [54], coupled to a Monte Carlo neutron transport calculation. A well documented and industry-wide code, ORIGEN (and associated updates and versions) would be the natural choice to ensure the accuracy of radioisotope inventories produced by this project. Although the aforementioned approximations are expected to introduce a certain amount of inaccuracy, efforts should be made to generally qualify the results of the contained code with those of ORIGEN. Fortunately, for the level of accuracy needed for the present project it should only be necessary to benchmark the simpler code for a few representative configurations, rather than after each burn period simulated.

In addition, radioisotope inventories should be calculated for a core utilizing what $Duderstadt\ and\ Hamilton$ calls a "scatter-zonal loading," rather than the simpler "zonal loading" scheme used herein [6]. The scatter-zonal loading pattern utilizes fuel of varying enrichment (or burnup) in a checkerboard configuration to achieve power-flattening, as opposed to the tri- radial ring pattern of the zonal loading scheme. Adapting the code described here to accommodate the scatter-zonal scheme will involve slightly altering the angle-averaging technique for determining the average radial actinide concentrations. As previously mentioned, the NRC distributes publicly daily reactor power status reports, and these power levels can be incorporated into the code to determine radioisotope concentrations over the operating life of the core for previous fuel discharges [52]. This information allows an approximate estimate of SNF radioisotope inventories for the entire reactor fleet, including for reactors for which such information is not otherwise accessible. Of particular interest is spent fuel isotope concentrations upon removal from the core. As these concentrations are largely dependent on the reactor operating power level over the fuel's residence time in the reactor, incorporating this aspect into the code will ultimately produce viable

radioisotope inventories pertinent to spent fuel disposal discussions. Upon incorporating historic reactor operating power levels into the code, the spent fuel radioisotope concentration picture will be complete and usable for repository siting considerations. Finally, a potential next step would be to use the established isotope concentrations to determine decay heat production in individual spent fuel assemblies requiring disposal. With well-defined initial isotopic concentrations, the decay process and resulting heat production is well understood and could be modeled in a straightforward manner. This heat production data could be used for the important task of approximating spent fuel cask packing density in a repository. In addition, ascertaining the heat produced by the spent fuel to be stored is necessary to investigate the long-term suitability of any proposed surrounding geology to sustain an underground repository. While several additional steps can be undertaken to improve the accuracy and usefulness of the contained code, each will ultimately improve the functionality in addressing nuclear waste repository siting concerns.

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Appendix A

Simplified Core Layout – AP1000

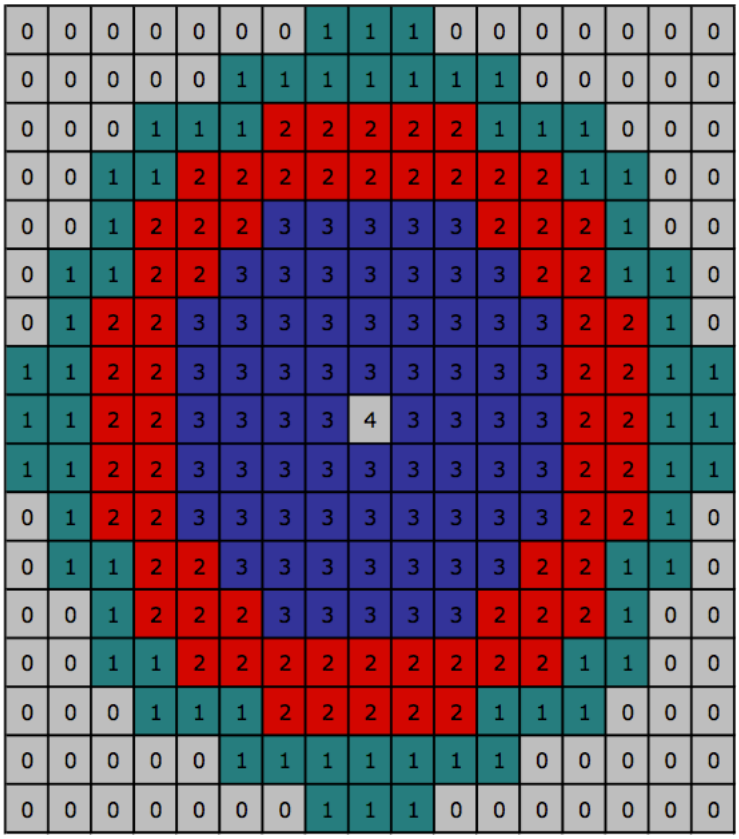

Figure A.1: AP1000 Simplified Core Loading Pattern

Appendix B

Discretization of the Diffusion Equation

Starting from Equation 5.12 in Chapter 5, this Appendix outlines the details of the discretization of the radial diffusion equation with finite cylindrical height utilized by the $Mathematica$ solver:

$$(\frac{h^2R^2}{D_o})[- \bigtriangledown [D(r,z) \bigtriangledown (wf)]) - (\Sigma_T fw + \Sigma_{B,O}(r)f)] = \lambda_1 f \tag{B.1}$$

Focusing solely on and expanding the derivatives:

$$(\frac{h^2R^2}{D_o})(- \bigtriangledown [D(r,z) \bigtriangledown (wf)]) = (\frac{h^2R^2}{D_o})[-\frac{1}{r}\frac{\partial}{\partial r}(rD\frac{\partial}{\partial r}(wf)) - \frac{\partial}{\partial z}(D\frac{\partial}{\partial z}(wf))] \tag{B.2}$$

which includes multiplying the term including the vertical derivatives by the square of the half-height (divided by the same) for convenience.

To nondimensionalize, it is necessary to define (and rearrange for):

$$Change\ of\ variables$$

$$\begin{aligned} \rho = \frac{r}{R} \rightarrow \quad & r = \rho \cdot R \\ \zeta = \frac{z}{\frac{H}{2}} \rightarrow \quad & z = \zeta \cdot \frac{H}{2} \\ \delta = \frac{D}{D_o} \rightarrow \quad & D = \delta \cdot D_o \end{aligned} \tag{B.3}$$

Inserting these definitions yields a nondimensionalized version of the required expanded derivatives:

$$\begin{aligned} (\frac{h^2R^2}{D_o})(- \bigtriangledown [D(r,z) \bigtriangledown (wf)]) = \\ \frac{h^2R^2}{D_o}[-\frac{1}{\rho R}\frac{\partial}{R\partial\rho}(\rho R D_o \delta \frac{\partial}{R\partial\rho}(wf)) - \frac{\partial}{\frac{H}{2}\partial\zeta}(\delta D_o \frac{\partial}{\frac{H}{2}\partial\zeta}(wf))] \end{aligned} \tag{B.4}$$

Simplification and factorization gives:

$$\begin{aligned} (\frac{h^2R^2}{D_o})(- \bigtriangledown [D(r,z) \bigtriangledown (wf)]) = \\ - h^2\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\delta\frac{\partial}{\partial\rho}(wf)) - \frac{R^2}{(\frac{H}{2})^2}h^2\delta\frac{\partial^2}{\partial z^2}(wf) \end{aligned} \tag{B.5}$$

Define:

$$Q = \frac{R^2}{(\frac{H}{2})^2} = \text{"squat"=ratio of the square of reactor radius to half-height} \tag{B.6}$$

Utilizing the definition of Q, for convenience:

$$(\frac{h^2R^2}{D_o})(- \bigtriangledown [D(r,z) \bigtriangledown (wf)]) = -h^2\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\delta\frac{\partial}{\partial\rho}(wf)) - Qh^2\delta\frac{\partial^2}{\partial\zeta^2}(wf) \tag{B.7}$$

At this point, it is convenient to address the radial and vertical terms individually.

Therefore, define:

$$Radial\ Term = -h^2\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\delta\frac{\partial}{\partial\rho}(wf)) \tag{B.8}$$

$$Vertical\ Term = -Q^2h^2\delta\frac{\partial^2}{\partial\zeta^2}(wf) \tag{B.9}$$

Radial Term:

Expanding Derivatives

(note the switch to subscript notation, where the subscript represents the variable which the derivative is taken with respect to)

$$-h^2\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\delta\frac{\partial}{\partial\rho}(wf)) =$$

$$= -h^2\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho\delta(wf_r + fw_r)) \tag{B.10}$$

$$= -h^2\frac{1}{\rho}(\rho(\delta(wf_r + fw_r))_r + \delta(wf_r + fw_r)) \tag{B.11}$$

$$= -h^2((\delta(wf_r + fw_r))_r + \frac{\delta}{\rho}(wf_r + fw_r)) \tag{B.12}$$

$$= -h^2(\delta(wf_r + fw_r)_r + \delta_r(wf_r + fw_r) + \frac{\delta}{\rho}(wf_r + fw_r)) \tag{B.13}$$

$$= -h^2[\delta(wf_{rr} + 2w_rf_r + fw_{rr}) + \delta_r(wf_r) + \delta_r(fw_r) + \frac{\delta}{\rho}(wf_r + fw_r)] \tag{B.14}$$

Discretizing Using Finite Difference Schemes

$$-h^2[\delta(wf_{rr} + 2w_rf_r + fw_{rr}) + \delta_r(wf_r) + \delta_r(fw_r) + \frac{\delta}{\rho}(wf_r + fw_r)] =$$

$$\begin{aligned}
= -h^2[&\delta w_{i,j}(\frac{f_{i+1,j} + 2\delta f_{i,j} - \delta f_{i-1,j}}{h^2}) \\
&+ 2\delta(\frac{w_{i+1,j} - w_{i-1,j}}{2h})(\frac{f_{i+1,j} - f_{i-1,j}}{2h}) \\
&+ \delta f_{i,j}(\frac{w_{i+1,j} - 2w_{i,j} + w_{i-1,j}}{h^2}) \\
&+ w_{i,j}(\frac{\delta_{i+1,j} - \delta_{i-1,j}}{2h})(\frac{f_{i+1,j} - f_{i-1,j}}{2h}) \\
&+ f_{i,j}(\frac{\delta_{i+1,j} - \delta_{i-1,j}}{2h})(\frac{w_{i+1,j} - w_{i-1,j}}{2h}) \\
&+ \frac{w_{i,j}\delta}{\rho}(\frac{f_{i+1,j} - f_{i-1,j}}{2h}) \\
&+ \frac{\delta}{\rho}(\frac{w_{i+1,j} - w_{i-1,j}}{2h})f_{i,j}]
\end{aligned} \tag{B.15}$$

Vertical Term:

Expanding Derivatives

(note the switch to subscript notation, where the subscript represents the variable which the derivative is taken with respect to)

$$-Qh^2\delta\frac{\partial^2}{\partial z^2}(wf) =$$

$$= -Qh^2\delta(w_z f + w f_z)_z \tag{B.16}$$

$$= -Qh^2\delta(w_{zz} f + 2w_z f_z + w f_{zz}) \tag{B.17}$$

Because $w_z = w_{zz} = 0$

$$-Qh^2\delta\frac{\partial^2}{\partial z^2}(w \cdot f)) = -Qh^2\delta w f_{zz} \tag{B.18}$$

Discretizing Using Finite Difference Schemes

$$-Qh^2\delta\frac{\partial^2}{\partial z^2}(wf) = -Qw_{i,j}h^2\delta\frac{(f_{i,j+1} - 2f_{i,j} + f_{i,j-1})}{h^2} \tag{B.19}$$

Combining all discretized terms and inserting into B.1 yields:

$$
\begin{aligned}
&-Q\delta w_{i,j} f_{i,j+1} + 2Q\delta w_{i,j} f_{i,j} - Q\delta w_{i,j} f_{i,j-1} \\
&\qquad - \delta w_{i,j} f_{i+1,j} + 2\delta w_{i,j} f_{i,j} - \delta w_{i,j} f_{i-1,j} \\
&\qquad - \frac{\delta}{2}(w_{i+1,j} - w_{i-1,j}) f_{i+1,j} + \frac{\delta}{2}(w_{i+1,j} - w_{i-1,j}) f_{i-1,j} \\
&\qquad - \delta f_{i,j}(w_{i+1,j} - 2w_{i,j} + w_{i-1,j}) \\
&\qquad - \frac{w_{i,j}}{4}(\delta_{i+1,j} - \delta_{i-1,j}) f_{i+1,j} + \frac{w_{i,j}}{4}(\delta_{i+1,j} - \delta_{i-1,j}) f_{i-1,j} \\
&\qquad - \frac{1}{4} f_{i,j}(\delta_{i+1,j} - \delta_{i-1,j})(w_{i+1,j} - w_{i-1,j}) \\
&\qquad - \frac{h w_{i,j}\delta}{2\rho} f_{i+1,j} + \frac{h w_{i,j}\delta}{2\rho} f_{i-1,j} \\
&\qquad - \frac{h\delta}{2\rho}(w_{i+1,j} - w_{i-1,j}) f_{i,j} \\
&\qquad - (\frac{h^2 R^2}{D_o})(\Sigma_T w_{i,j} + N_B \sigma_B) f_{i.j} = 0
\end{aligned}
\tag{B.20}
$$

Assembling like terms gives the final form of the radial diffusion equation in finite cylindrical height utilized in the code:

$$
\begin{aligned}
&f_{i,j}[2Q\delta w_{i,j} + 2\delta w_{i,j} - \delta(w_{i+1,j} - 2w_{i,j} + w_{i-1,j}) - \frac{1}{4}(\delta_{i+1,j} - \delta_{i-1,j})(w_{i+1,j} - w_{i-1,j}) \\
&\qquad - \frac{h\delta}{2\rho}(w_{i+1,j} - w_{i-1,j}) - (\frac{h^2 R^2}{D_o})(\Sigma_T w_{i,j} + N_B \sigma_B)] \\
&+ f_{i+1,j}[-\delta w_{i,j} - \frac{\delta}{2}(w_{i+1,j} - w_{i-1,j}) - \frac{w_{i,j}}{4}(\delta_{i+1,j} - \delta_{i-1,j}) - \frac{h w_{i,j}\delta}{2\rho}] \\
&+ f_{i-1,j}[-\delta w_{i,j} + \frac{\delta}{2}(w_{i+1,j} - w_{i-1,j}) + \frac{w_{i,j}}{4}(\delta_{i+1,j} - \delta_{i-1,j}) + \frac{h w_{i,j}\delta}{2\rho}] \\
&+ f_{i,j+1}[-Q\delta w_{i,j}] \\
&+ f_{i,j-1}[-Q\delta w_{i,j}] = 0
\end{aligned}
\tag{B.21}
$$

Appendix C

Cross Sections

Table C.1: Cross Sections of Pertinent Isotopes

Isotope	Decay Constant (λ) (yr)	Fission (b)	Removal (b)
U235		312.0 [6]	484.0 [6]
U236		0	5.09
U238		0.638 [6]	2.11 [6]
Np237		0	175.9
Pu238	0.0079 [55]	17.9	557.9
Pu239		748.1	1017.4
Pu240		289.5	579
Pu241	0.0483 [55]	362.1	724.2
Pu242		18.5	37
Am243		0.1959	75.30

Source: [56] (except as noted)