Monitoring Under the Plutonium Management and Disposition Agreement: The Prospects of Antineutrino Detection as an IAEA Verification Metric for the Disposition of Weapons-Grade Plutonium in the United States

by
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Abstract

After the end of World War II, the world entered an even more turbulent period as it faced the beginnings of the Cold War, during which the prospect of mutually assured destruction between the world's largest nuclear weapon states was ever-present, and often provoked tense confrontations. Although fears of a nuclear holocaust significantly subsided after the dissolution of the Soviet Union in 1991, the world faced a potentially more dangerous prospect: the proliferation risks associated with the insecurity and unauthorized acquisition of Soviet-era nuclear warheads. Although all Soviet-era weapons were eventually acquired by Russia, concerns about the excessively large weapons stockpiles of the United States and Russia, combined with the goal of nuclear disarmament, led to the Plutonium Management and Disposition Agreement (PMDA). During the Cold War, the US and the Soviet Union respectively produced approximately 100 and 150 metric tons of weapons-grade plutonium (WGPu). Under the terms of the PMDA, both nations formally each agreed to irradiate 34 MT of excess military plutonium in the form of mixed oxide fuel (MOX) in nuclear power reactors. One of the major issues of concern associated with this agreement relates to the verification measures that will be implemented to ensure actual WGPu disposition. Additionally, despite a commitment (Article VII.3 of the PMDA) to engage and consult with the International Atomic Energy Agency (IAEA) to establish arrangements to monitor its plutonium disposition process, a formalized IAEA role within a potential multilateral verification regime has yet to be determined.

In this work, the ability of the US to achieve the goals of its plutonium disposition campaign by 2018 is assessed. The suitability of the IAEA as an objective party to a multilateral verification regime under the auspices of the PMDA is also analyzed. In an attempt to aid the IAEA with such expected verification procedures, the applicability of antineutrino detection as a potential monitoring technology which could significantly enhance current monitoring procedures is considered. Although there has not yet been a formal demonstration of this technology under the auspices of the PMDA, the technology has been successfully fielded and nonintrusively operated at US and Russian reactors for years at a time, with the explicit aim of demonstrating potential relevance to a range of safeguards and verification tasks. The sensitivity of an antineutrino detector to antineutrino count rate measurements was analyzed through a hypothesis testing procedure which sought to identify statistically significant differences between the count rate evolutions of a designated baseline and potential diversion scenarios. With a specified set of parameters, the test demonstrated that the detector was capable of identifying the replacement of 7 WGPu MOX fuel assemblies with conventional LEU fuel assemblies within 360 days of the fuel cycle operation at a ≥95% true positive rate and a 5% false positive rate limit. These results were essentially still maintained even with a non-reactor-based antineutrino event background signal as high as 25%. Although pitfalls with regard to systematic uncertainty and operator malfeasance were revealed, potential solutions to such issues are also presented and discussed. All in all, the results obtained in this work confirm the potential efficacy and viability of antineutrino rate based measurements for a range of reactor safeguards and verification tasks.

Thesis Supervisor: Richard C. Lanza
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Acknowledgements

We can rejoice, too, when we run into problems and trials, for we know that they help us develop endurance. And endurance develops strength of character, and character strengthens our confident hope of salvation.

Romans 5:3-4

With the completion of this thesis, I would like to acknowledge and appreciate the overwhelming support I have received from many individuals and organizations throughout this undertaking.

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I would also like to recognize the countless contributions of Dr. Adam Bernstein, who was immensely instrumental in the development and concise definition of this thesis regarding one of the many applications of antineutrino detection—monitoring and verifying the disposition of excess weapons-grade plutonium via antineutrino detection. Dr. Bernstein was extremely helpful in the editing process, continually pointing out key issues of concerns to be addressed.

Regarding the policy implications associated with antineutrino detectors, I would like to acknowledge the expertise gained in various aspects of this thesis by Matthew Bunn and Olli Heinonen of the Harvard Kennedy School, Julian Whichello of the International Atomic Energy Agency, and Guy Lunsford and Dwight Williams of the U.S. Department of Energy. To Thomas Downar and Andrew Ward of the University of Michigan as well as Anna Hayes of Los Alamos National Laboratory, thank you for the allocation of data toward this work.

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Many thanks to the Lemelson Foundation for the financial support during my first year.

In closing, I present this thesis as my contribution to nuclear science and technology policy, with the hope that this work will not only benefit the reader in developing his/her knowledge, but may also aid in a worldwide aspiration toward *Global Zero* of nuclear weapons.

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List of Acronyms

BWR	Boiling Water Reactor(s)
CISAC	Committee on International Security and Arms Control
CoK	Continuity of Knowledge
DCS	Duke Cogema Stone and Webster
DOE	Department of Energy
GAO	Government Accountability Office
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
IWG	Interagency Working Group
LANL	Los Alamos National Laboratory
LEU	Low Enriched Uranium
LLNL	Lawrence Livermore National Laboratory
LTA	Lead Test Assembly(s)
LWR	Light Water Reactor(s)
MFFF	MOX Fuel Fabrication Facility
MOX	Mixed Oxide Fuel
MT	Metric Ton(s)
NAS	National Academy of Science
NDA	Non-destructive Analysis
NNSA	National Nuclear Security Agency
NPT	Nuclear Nonproliferation Treaty
NRC	Nuclear Regulatory Committee
NNSA	National Nuclear Security Administration
NNWS	Non-nuclear Weapon State(s)
NWS	Nuclear Weapon State(s)
PDCF	Pit Disassembly and Conversion Facility
PDI	Person-Day(s) of Inspection
PEIS	Programmatic Environmental Impact Statement
PFPF	Plutonium Fuel Processing Facility
PMDA	Plutonium Management and Disposition Agreement
PPRA	Plutonium Production Reactor Agreement
PWR	Pressure Water Reactor(s)
RGPu	Reactor-Grade Plutonium
ROD	Record of Decision
RSI	Remote Safeguards Inspection(s)
S&S	Safeguards and Security
SFS	Spent Fuel Standard
SORT	Strategic Offensive Reductions Treaty
S/RSAC	State and Regional Systems of Accounting and Control
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratory
SQ	Significant Quantity(ies)
SRS	Savannah River Site
START I	Strategic Arms and Reduction Treaty of 1991

START II	Strategic Arms and Reduction Treaty of 2009 (New START)
TVA	Tennessee Valley Authority
UMS	Unattended Monitoring System(s)
VHLW	Immobilization through Vitrification with High Level Waste
WGPu	Weapons-Grade Plutonium
WSB	Waste Solidification Building

Chapter 1: Introduction

1.1 Motivation

The Strategic Arms Reduction Treaties (START) I & II and the Strategic Offensive Reductions Treaty (SORT) between the United States and Soviet Union are considered by many to be the largest and most complex arms control treaties in history; ultimately seeking to limit the number of deployed strategic weapons delivery systems and deployed strategic nuclear weapons, respectively. Although the START and SORT treaties have been the backbone of joint US and Russian efforts toward nuclear disarmament, the treaties have not addressed the discontinuation of weapons-grade fissile material production and disposition of excess weapons-grade materials. The ratification of the 1997 Plutonium Production Reactor Agreement[1] (PPRA) between the US and Russia signaled a move to cease production of plutonium for weapons production; further strengthened by the included provisions for monitoring [1]. However, Russia still operates nuclear reactors, previously slated as plutonium production reactors, in order to generate heat and electricity for its country. As a result, plutonium volume within the country continues to rise.

During the Cold War, the US and the Soviet Union respectively produced approximately 100 and 150 metric tons (MT) of weapons-grade plutonium (WGPu). In an attempt to design a verification system of significantly reducing these immensely large stockpiles of WGPu—primarily resultant from a Cold War mentality of mutual assured destruction—the International Atomic Energy Agency (IAEA), Russia, and the US launched the Trilateral Initiative[2] [2]. However, because of US and Russian suspicions regarding their counterparts' technical capabilities, the initiative was slow to develop. With the conclusion of a separate bilateral agreement in 2000 between the US and Russia known as the Plutonium Management and Disposition Agreement[3] (PMDA), the Trilateral Initiative was eventually terminated due to diminishing attention and political backing from the two weapons states. The PMDA endeavors to ensure that the US and Russia transparently convert their respective surplus WGPu stocks into a physical form that makes it inherently difficult to recover and reuse the material for any military purpose. Although the PMDA shared a common target with the Trilateral Initiative in developing verification techniques, this target was compromised in order to achieve the agreement's primary goal of plutonium disposition.

1.2 Thesis Objective

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[1] The actual title of the agreement is *The Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors*. The agreement prohibits the resumption of operations at 14 shutdown US plutonium reactors and 13 shutdown Russian plutonium reactors. Under the agreement, both the US and Russia are permitted to conduct monitoring visits once each year at the other's shutdown reactors to monitor the non-weapons use of

[2] This initiative was a six-year (1996-2002) endeavor aimed at developing a verification system in which Russia and the US could submit classified forms of weapons-origin fissile material to IAEA verification and monitoring in a irreversible manner for an indefinite period of time.

[3] This actual title of the agreement is *The Agreement Between the Government of The United States Of America and the Government of The Russian Federation Concerning the Management and Disposition of Plutonium Designated as no Longer Required for Defense Purposes and Related Cooperation.*

Contemporary policy concerning military plutonium disposition in the United States, as reflected in the PMDA, lacks detailed steps and metrics for verification. As previously noted, one of the major concerns associated with the PMDA is how monitoring and inspection activities will occur in each state. The target of US verification strategy should be a mutually agreed upon verification mechanism that ensures the integrity of each respective parties' WGPu disposition activities, both from a bilateral and multilateral perspective. Another concern is that despite a US and Russian commitment, as stated in Article VII.3, that "each Party, in cooperation with the other Party, shall begin consultations with the International Atomic Energy Agency (IAEA) at an early date and undertake all other necessary steps to conclude appropriate agreements with the IAEA to allow it to implement verification measures with respect to each Party's disposition program," the US has yet to engage in detailed discussions with the IAEA of facility safeguards as they relate to the MOX Fuel Fabrication Facility or plutonium disposition designated reactors selected to irradiate WGPu mixed-oxide (MOX) fuel[4].

In an effort to counter these two concerns with a potential technological solution, the prospects and capabilities of antineutrino detection as a solution will be analyzed as the objective of this thesis. Antineutrino detectors have the ability to estimate fissile content through rate measurements and/or provide independent power measurements of LEU and MOX-fueled reactors. Current experiments show that these detectors are capable of measuring event rates of hundreds to a few thousand events/day at approximately a 25-meter standoff from the core of a 3 GW_t civil power reactor with an active detector volume of approximately one cubic meter. Collected measurements have been used to specify thermal power at the 2-3% level in one week, relative to a known initial value [3]. Absolute power estimates are also possible at the 10% level with detectors of simple design, or better with more complex detectors. With longer durations of data accumulation, anomalous reactor operations, including malicious diversion scenarios as low as the replacement of 82 kg of plutonium with uranium, have the potential to be detected by antineutrino detection [4]. Antineutrino detectors with such capabilities currently cost approximately \$200K-\$400K [5], and can readily be reduced through value engineering and modest economies of scale. The capabilities of these detectors for purposes of reactor monitoring are being investigated by the US Brazil, and France with the SONGS1 and SONGS2 projects, the Angra Project, and the Nucifer Detector, respectively [5].

Although antineutrino measurements have demonstrated their potential to assist the IAEA in safeguarding reactors operating with LEU under their unattended monitoring systems (UMS) strategy [3], less research has been done on the potential of antineutrino detection for effectively monitoring other fuel cycles (i.e. MOX, thorium). The attributes and advantages of antineutrino detection in monitoring reactors operating with partially loaded WGPu MOX fuel cores, as designated by the PMDA, will be examined here, incorporating core simulations provided by researchers at Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and the University of Michigan[5]. Furthermore, potential diversion and misuse scenarios will be investigated in

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[4] The inclusion of the IAEA in the PMDA differs significantly from the Trilateral Initiative, in that the IAEA was an equal party in the latter rather than a party synonymous with an expert consulting aid like that of the former.

[5] Successful incorporation of these detectors into a safeguards regime will require further analysis, including additional reactor simulations.

order to quantify the effectiveness of antineutrino measurements. This thesis also seeks to determine the practicality of seamlessly and effectively incorporating this technology into the contemporary verification procedure of the plutonium disposition campaign.

1.3 Background

1.3.1 Goals Toward a World Without Nuclear Weapons

On April 5, 2009, before a crowd of world citizens gathered at Hradcany Square in Prague, President Barack Obama declared "America's commitment to seek the peace and security of a world without nuclear weapons. I'm not naive. This goal will not be reached quickly—perhaps not in my lifetime. It will take patience and persistence. But now we, too, must ignore the voices who tell us that the world cannot change [6]." He further pledged to "reduce the role of nuclear weapons in [US] national security strategy" and to "put an end to Cold War thinking."

Albert Einstein's discovery of the mass-energy equivalence principle brought about a revolution in the way mankind conceived the notion of matter and energy production as well as destruction and devastation. This, in part, yielded the gift of nuclear physics; providing the world with the valuable ability to harness the power of the atom as well as a converse; the development of nuclear weapons of mass destruction and the possible demise of mankind. The Nobel Prize winning Swedish Physicist Hannes Alven made the great analogy that the "peaceful atom" and the "military atom" are intimately linked like "Siamese twins" [7]. As countries developed expertise in nuclear physics, a global race began to rapidly develop nuclear arms; one in which nine countries developed the means for a nuclear arsenal. In historical order, they are the United States, Russia, the United Kingdom, France, China, Israel[6] [8], India, Pakistan and North Korea [7]. US and Russian nuclear stockpiles, which account for approximately 95% of the world's nuclear-weapon stocks, peaked at approximately 30,000 for the United States in 1965 and 40,000 for Russia in 1985 [9].

World leaders have committed their countries to designated steps in order to strengthen the notions of a nonproliferation regime in a universal endeavor to prevent the potential catastrophes associated with nuclear terrorism. The possibilities of terrorist groups and hostile states buying, stealing, or building nuclear weapons pose the most immediate and extreme threat to global security. Not only is the protection and security of nuclear weapons essential, so is the security of the hundreds of MT of fissile materials spread around the world at various sites. Unfortunately, many of these sites lack adequate security. As little as 22 kg of highly-enriched uranium (HEU) or 5 kg of WGPu is enough to fashion a nuclear device that could easily be smuggled into a state and detonated [10].

Although there is no evidence that terrorist groups or hostile states have either acquired a nuclear weapon or the weaponizable fissile material needed to manufacture one, both terrorists and states have attempted and continue to attempt to attain such items.

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[6] Israel has not publically revealed testing of a nuclear weapon, however, Western intelligence experts believe Israel conducted an underground nuclear test in the Negev in 1963, and that preparation of nuclear material for assembly into nuclear weapons began soon thereafter. The main suspected test, however, is a nuclear explosion that took place in the atmosphere of the coast of South Africa on September 22, 1979, where a US Vela satellite reported a flash resembling a clandestine nuclear detonation in the southern Indian Ocean.

According to the IAEA, there were more than 400 confirmed cases of illicit trafficking in materials that could be used in nuclear terrorism between 1993 and 2004, and 21 that involved material that could be used to produce a nuclear bomb [11]. If successful, the international community could be faced with a terrifying future.

In order to combat such threats, world leaders have proposed two major initiatives: a Fissile Material (Cutoff) Treaty (FMCT) and an internationally controlled reactor fuel bank coupled with an enforceable Comprehensive Test Ban Treaty. An FMCT would prohibit the production of materials that can be made into nuclear weapons. For example, an internationally controlled reactor fuel bank coupled with an enforceable Comprehensive Test Ban Treaty (CTBT), would significantly reduce the likelihood of more states becoming nuclear powers. Strengthening the Nuclear Nonproliferation Treaty (NPT), establishing more intrusive inspections by the IAEA, and burdensome penalties for irresponsible withdrawal, as well as continual reductions and protections of "vulnerable nuclear and radiological materials located at civilian sites worldwide" as designated by the Global Threat Reduction Initiative (GTRI) are essential in order to safeguard nuclear weapons and nuclear-ready materials [10].

There have been significant recent reductions in the nuclear weapon arsenals of nuclear weapon states (NWS); however, in order to make significant strides toward global zero, both NWS and non-nuclear weapon states (NNWS), and more specifically the US and Russia, must continue to reduce their nuclear arsenals (See Table 1.2).

Table 1.1: Estimated Total Nuclear-Weapon Stockpiles as of 2010

Country	Number of Nuclear Warheads
United States	~9,100[A]
Russia	~11,000[B]
France	<300
United Kingdom	<225
China	~240
Israel	100-200
Pakistan	70-90
India	60-80
North Korea	<5

Courtesy of Global Nuclear Weapon Inventories, 1945-2010 [12]

[A] Currently approximately 5,100 are deployed and 4000 are awaiting dismantlement.

[B] A large fraction is awaiting dismantlement (however, there are large uncertainties associated with the number of warheads awaiting dismantlement) [13]

1.3.2 Nuclear Weapons-Grade Materials

Although the isotopes ^{233}U, ^{237}Np, and ^{241}Am are able to sustain a nuclear chain reaction, and argued to be weapons-grade fissionable materials [14] capable of being fabricated into a nuclear weapon, all known fission-based nuclear weapons tested have primarily made use of two materials: highly-enriched uranium (HEU)[7] and weapons-grade

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[7] Although HEU is uranium with a ^{235}U isotopic concentration of 20% or greater, sometimes denoted as weapons-usable, HEU is used in this context to be weapons-grade which possesses an ^{235}U isotopic concentration of 85% or greater.

plutonium (WGPu)[8]. The International Panel on Fissile Material (IPFM) estimated the global HEU stockpile in 2010 to be approximately 1475 ± 125 MT (enough for more than 60,000 weapons) [13]. The large uncertainty in the estimate is due to undeclared Russian HEU produced prior to its production termination in the late 1980s. The US, which ended production in 1992, has published an official history of its HEU production [15]. The NPT NWS—US, Russia, UK, France, and China—account for about 98% of all HEU material, with the largest HEU stockpiles being held by Russia and the US Although it is believed that India and Pakistan are the only producers of HEU, maintaining relatively small-scale programs, HEU global stockpiles are shrinking as the US and Russia blend down HEU declared excess to military needs to low-enriched uranium (LEU) for power reactor fuel at a rate of over 30 MT/year with reduction agreements like that of US-Russia HEU Purchase Agreement. Non-NPT NWS—India, Pakistan, and North Korea—account for approximately 20 MT of HEU; most of this material was provided to them as research reactor fuel by NPT NWS.

The IPFM estimated the global stockpile of separated plutonium in 2010 to be approximately 485 ± 10 MT[9] [13]. About half of this stockpile was produced for military purposes, while the other half is resultant of NWS civilian programs. The NWS account for about 98% of all separated, where more than 10 MT of plutonium are in NNWS, most of which exists in Japan (the only NNWS with a large plutonium-separation program).

Unlike HEU, the stockpiles of separated plutonium for military purposes continues to increase due to continued production in Israel, India, and Pakistan [9]. Only the United States, United Kingdom, Russia, France, North Korea[10], and China (unofficially) have officially announced an end to their production of plutonium for weapons. Commercial reprocessing programs, on the other hand, like those in France, Russia, India, and the United Kingdom as well as currently planned reprocessing programs expected in China [16] and Japan's upcoming Rokkasho plant (estimated to begin operations in late 2012) [17] will dwarf the comparatively small-scale weapon plutonium production programs. However, the growth of the global civilian plutonium inventory has slowed down to less than 5 MT/year temporarily due to shutdowns and delays of reprocessing centers worldwide[11]. Current estimates of global plutonium stockpiles by countries can be seen in Figure 1.1 below.

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[8] WGPu, in this context, is plutonium with an ^{240}Pu:^{239}Pu isotopic-ratio no greater than 0.1 (Some sources estimate WGPu to have a maximum ^{240}Pu concentration of 7%). Supergrade Plutonium ($\leq$4% ^{240}Pu) is used in US Navy weapons stored in proximity to ship and submarine crews, due to lower radioactivity. US demonstrations incorporating less than weapons-grade quality plutonium (comparable to reactor-grade plutonium) have also been demonstrated.

[9] Estimates for separated plutonium stockpiles is not offset by the fabrication of excess Russian and US weapon plutonium into reactor fuel.

[10] Reportedly declared an inventory of separated plutonium of 37 kg as part of its 2007 agreement to end its nuclear program.

[11] A shutdown at the Thorp reprocessing plant in the U.K. due to an accident as well as continued delays in Japan's Rokkasho reprocessing plant.

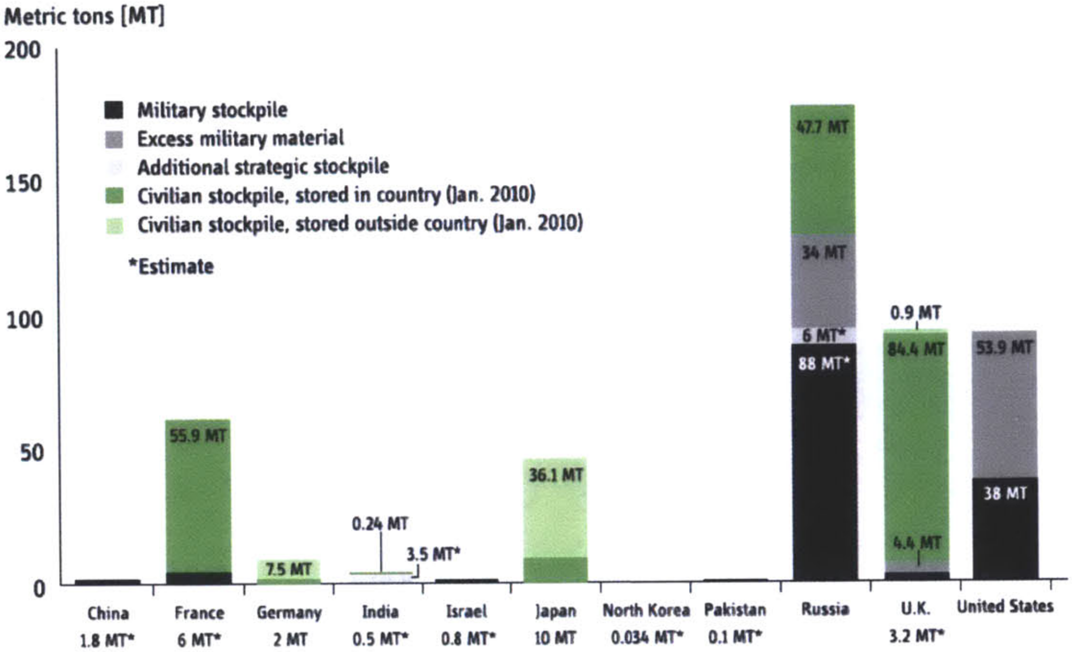

Figure 1.1: Global Plutonium Stockpiles by Country

Courtesy of Global Fissile Material Report 2010 [13]

Civilian stocks are based on the most recent January 2010 INFCIRC/549 declarations (listed by ownership, not location) were used for civilian stock calculations. Excluding the US and U.K. who have provided declarations, the military stockpiles were calculated using non-governmental estimates (hence uncertainties on the order of 10-30% exist for China, France, India, Israel, Pakistan, and Russia). "Strategic" is used to categorize India's separated plutonium from spent heavy-water power-reactor fuel has and 6 MT of WGPu in Russia has not been declared excess, but has been deemed to not be used in weapons manufacturing.

1.3.3 The US and Russian Plutonium Landscape

1.3.3.A United States

The US has published official historical records of their plutonium production, uses, and stocks, as of the end of 1994, based on data in the national Nuclear Material Management and Safeguards System, in the report *Plutonium: The First 50 Years* [18], which is expected to have an upcoming update associated with more recent history [19]. The US had produced and acquired an estimated total of approximately 110 MT of plutonium[12], where approximately 47 MT of WGPu and 15 MT of non-WGPu[13] have been declared "excess to its national security needs [20, 21]."

Although the US has reduced its WGPu plutonium stocks[14], there is still a

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[12] The US had used about 10 tons of this total stockpile resulting in a remainder of approximately 85 MT of WGPu and 15 MT of non-WGPu but weapon-usable plutonium.

[13] 7.6 MT of this plutonium is in unreprocessed government-owned spent fuel form.

[14] Unlike the obsolete gun-type designed nuclear weapons previously employed by the US, contemporary nuclear weapons are designed as two-stage explosive systems with plutonium (~4kg WGPu) in a fission pit and tritium-HEU in a fusion-fission secondary pit.

remaining stockpile sufficient for the manufacture of approximately 10,000 nuclear weapons.

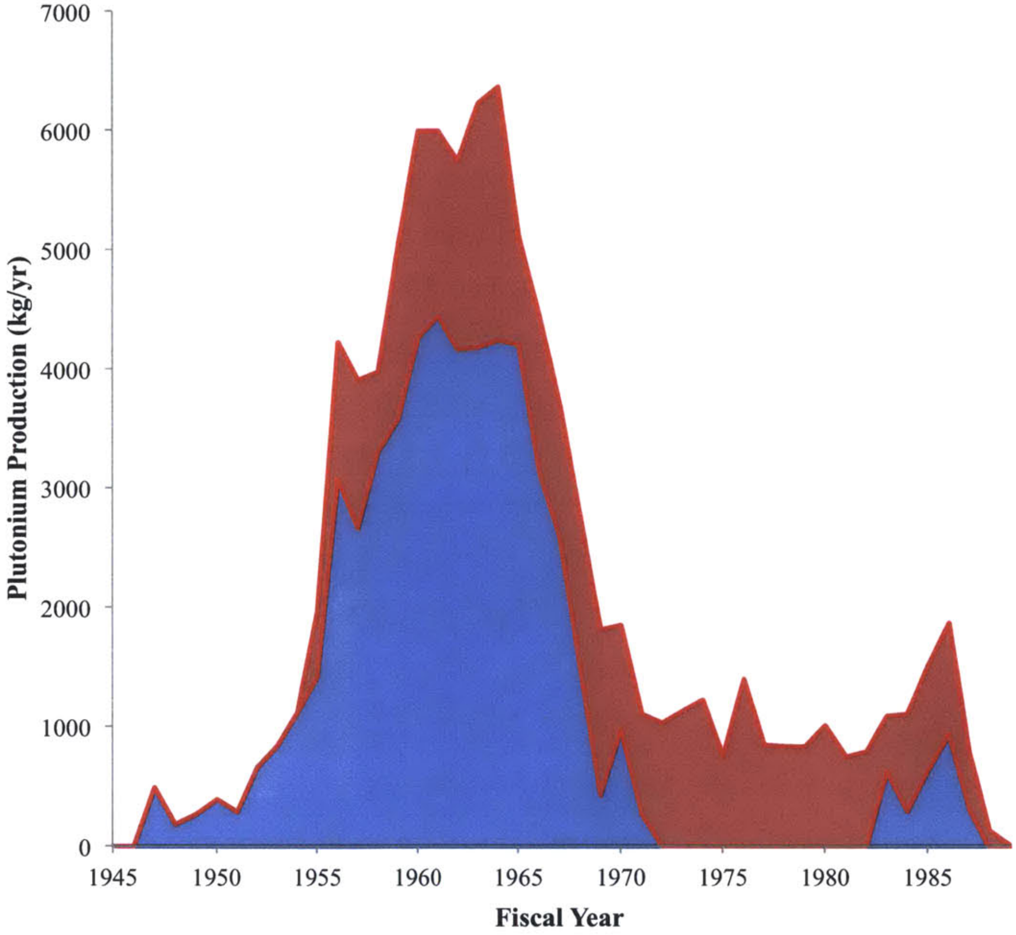

Figure 1.2: United States Weapon Grade Plutonium Production
Courtesy of Plutonium: The First 50 Years [18]
Declared historical plutonium production in the United States via the Hanford (blue accumulation) and Savannah River Sites (red accumulation) producing a total of approximately 91 MT of WGPu.

Figure 1.2 shows the declared historical production of plutonium at the two US production sites—the Hanford Site and the Savannah River Site. According to the production records, the Hanford reactors and the Savannah River reactors produced cumulatively 55 MT[15] and 36 MT of WGPu, respectively [19].

A total of 38.3 MT of WGPu remains available for nuclear weapon use [19] in the forms of: weapons; "reserve" pits stored at the DOE's Pantex warhead assembly/disassembly plant in Texas [22]; experiments at LANL, where plutonium R&D and pit production is carried out; and for criticality experiments in the high-security Device

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[15] The Hanford reactors produced 67 MT of plutonium, however, approximately 12 tons were not WGPu but were considered weapons-usable (4 MT was never separated from irradiated fuel).

Assembly Facility (DAF) on the Nevada Test Site (See Table 1.2).

Table 1.2: Excess Weapons Grade Plutonium (MT) by Site

Location	Metal	Oxides	Reactor Fuel	Irradiated Fuel	Other Forms	Total
Pantex/Future Dismantlements	21.3	N/A	N/A	N/A	N/A	21.3
Rocky Flats	5.7	1.6	N/A	N/A	4.6	11.9
Hanford Site	<0.1	1.0	N/A	0.2	0.5	1.7
LANL	0.5	<0.1	<0.1	N/A	1.0	1.5
Savannah River	0.4	0.5	N/A	0.2	0.2	1.3
INL	<0.1	N/A	0.2	0.2	<0.1	0.4
Other Sites	<0.1	N/A	N/A	<0.1	<0.1	0.1
Total[A]	**27.8**	**3.1**	**0.2**	**0.6**	**6.4**	**38.2**

Courtesy of Plutonium: The First 50 Years [18].

[A] Totals may not add due to rounding to the nearest tenth of a MT.

Most of the excess WGPu is still in the forms of warheads and pits at the Pantex Plant in Amarillo, Texas[16] where it will remain until plutonium extraction capabilities are achieved at the Savannah River Site. At the Savannah River Site, at least 34 MT of the excess US separated WGPu, including that from excess pits, is to be manufactured into MOX fuel for commercial nuclear power reactors as agreed under a US-Russian PMDA [23]. A MOX fuel-fabrication plant is currently being built for this purpose[17] [24].

The plutonium in spent fuel is to be disposed of eventually with other spent fuel in a deep underground repository and plutonium in dilute waste is being shipped to the Waste Isolation Pilot Plant (WIPP) in New Mexico [25]. About three MT from the former Rocky Flats pit production facility have already been deposited there [24].

The remainder of the plutonium that has been declared excess is being shipped to the former K-production-reactor building at DOE's Savannah River Site (SRS), which has been converted into an interim plutonium-storage facility. Four MT of plutonium from the Zero Power Plutonium Reactor, currently at the Idaho National Laboratory, have been declared excess for weapons use but some of this plutonium may be shipped to the DAF at the Nevada Test Site [26].

1.3.3.A Russia

Although Russia has not published a comprehensive account of its military-use fissile-material production during its Soviet and post-Soviet periods, non-governmental analysts have made estimates of the state's WGPu volume based on power history publications [27, 28] and historical documents and memoirs on the designs and operation

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[16] US warheads are assembled and disassembled at this site.

[17] Some impure plutonium may be reprocessed in the "H-canyon," where the HEU "driver fuel" of the Savannah River production reactors was formerly reprocessed. The extracted plutonium would either be used as feed for the MOX plant or vitrified and disposed of in canisters of solidified radioactive waste that are being produced from high-level reprocessing waste there.

[29] of former production reactors. Based on available public information, such analysts estimated that Russia has produced 145 ± 8[18] MT of WGPu [30] (See Figure 1.3). This includes 15 MT of plutonium produced after September 1994, when production for weapons ended, by three plutonium-production reactors that continued operating to supply district heat and electricity to the Siberian cities of Tomsk and Zheleznogorsk. Under the PPRA, the Russian government committed that this plutonium would not be used in weapons; storing this resultant plutonium in oxide form on-site, subject to bilateral transparency measures in order to provide assurance that it is not intended for military purposes.

Upon successful disposition of its 34 MT of surplus WGPu[19] as designated by the PMDA, a resultant Russian WGPu stockpile of 88 ± 8 MT will still be available for military use. Note, this is much more than the US active stockpile of 38 MT and much more than the 25 MT or so needed to sustain the stockpile of about 4,600 operational and active reserve warheads that Russia is believed to retain [31].

Almost all Russia's plutonium was produced in fourteen graphite-moderated water-cooled production reactors[20], each built around cylindrical stacks of graphite blocks [32]: six at the Mayak Production Association[21] in Ozersk (formerly Chelyabinsk-65) near Chelyabinsk in the Urals, five at the Siberian Chemical Combine in Seversk (formerly Tomsk-7) near Tomsk, and three at the Mining and Chemical Combine in Zheleznogorsk (formerly Krasnoyarsk-26) near Krasnoyarsk.

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[18] The estimates of the Russian WGPu stockpile is uncertain due to the lack of knowledge pertaining to the power levels of the individual production reactors and the assumed durations of their operation at those power levels. The IPFM identifies that the most important uncertainty is associated with the rates the reactor powers were increased above original design schematics; estimates were made under the assumptions that first and second generation reactors (A, AV and I) power ramp-up processing was 6-12 years and third generation reactors power ramp-up processing was 3-5 years leading to ± 5 MT uncertainty in plutonium production. The assumption that upgraded reactor power levels is ± 5 %, yields another ± 6 tons uncertainty. Further assumptions assuming that the uncertainties are random/uncorrelated results in a total uncertainty of Russia's cumulative production of WGPu at approximately ± 8 MT. Approximately 17 MT of Russia's weapon-grade plutonium are estimated to have been used in nuclear-weapon tests, lost in waste, or lost in warheads in three submarines that sank.

[19] Under the PMDA, the Russian Government has committed that 25 MT of the military stock plus 9 MT of its post-September-1994 stock will be fabricated into fuel for Russia's demonstration breeder reactors.

[20] 12 were designed to produce plutonium and 2 to produce tritium and other isotopes.

[21] Four additional heavy-water-moderated production reactors were operated at the Mayak site.

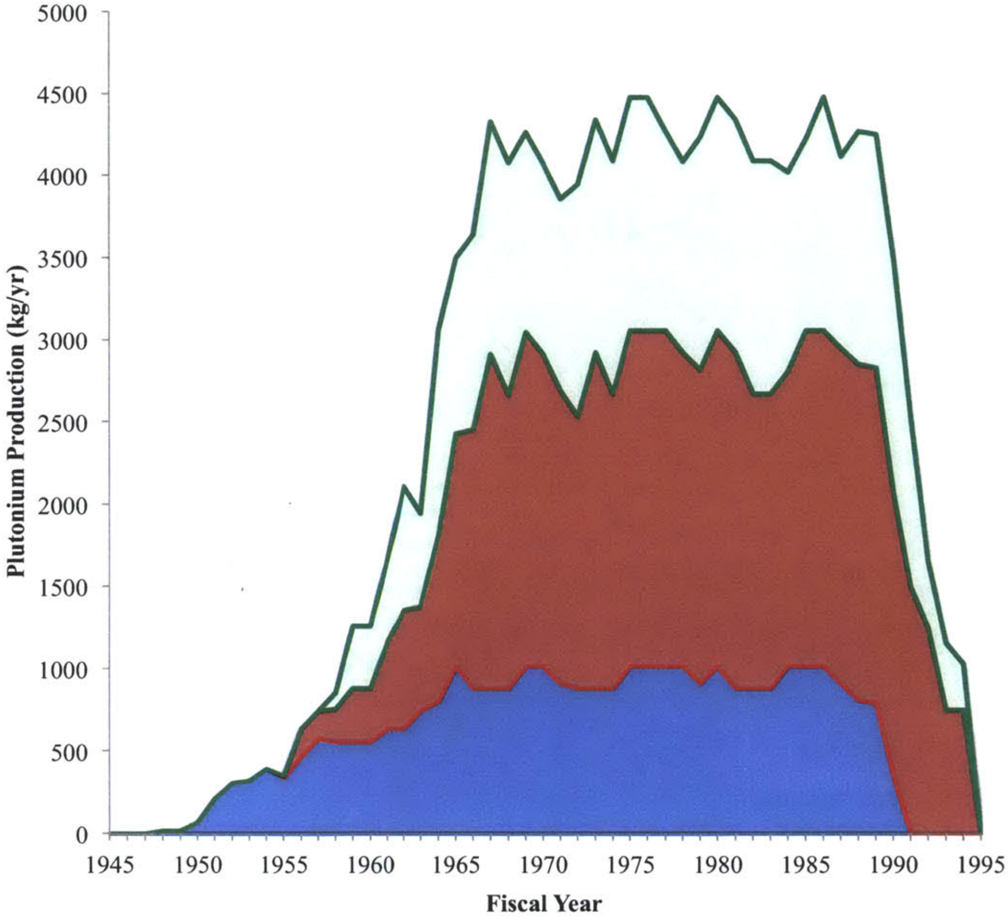

Figure 1.3: Russia's Estimated Annual Production of Weapon-grade by Site
Courtesy of Global Fissile Material Report 2010 [30]
Estimated historical plutonium production in the Russia via the Mayak (blue accumulation), Tomsk-7 (red accumulation), and Krasnoyarsk-26 (green accumulation) sites producing a total of approximately 145 ± 8 MT of WGPu.

1.4 Plutonium Management and Disposition Agreement

The PMDA is an agreement between the largest NWS designed to demonstrate arms reductions in an irreversible manner such that the US and Russia could ensure transparent disposition of WGPu attained from weapons designated surplus to each state's defense program into a form in which the plutonium could never be reused for military applications. As acknowledge, both states agreed to dispose of no less than 34 MT of WGPu via conversion into fuel to be irradiated in civil reactors for electricity production. Although a minimum of 34 MT of WGPu disposition is required by both states, the PMDA also endorses additional WGPu declared surplus as arms reductions progress should also be disposed of in the same or comparable transparency terms.

Although the agreement, and its endeavors, appears promising toward a global aspiration of nuclear weapons disarmament and disposition, several unresolved issues are still present even after the 2010 update that may threaten the prospects for successful implementation of the agreement. For example, the design of the MOX fuel fabrication facility (MFFF) and reactor modifications require technical investigation. Furthermore, verification and monitoring/inspection regimes, negotiation of liability provisions, and total funding acquisition for program operation have yet to be fully resolved. All of which serve as key implementation issues with the agreement [33].

1.4.1 Early Developments

The Strategic Arms Reduction Treaties (START) I & II and most recently, the New START Treaty, between the United States and Russia are considered by many to be the largest and most complex arms control treaties in history, seeking to limit the number of deployed strategic weapons delivery systems and deployed strategic nuclear weapons, respectively[22]. The international security issues that arose as a result of increasing nuclear weapons stockpiles from dismantlement programs led to a March 1992 request to conduct a full-scale study of plutonium management and disposition options by the National Academy of Science[23] (NAS) Committee on International Security and Arms Control (CISAC) [34, 35].

The *US Nonproliferation and Export Control Policy*[24] was issued in 1993 to address the domestic commitment to undertake a comprehensive management approach to the growing accumulation of fissile materials to the increasing fissile materials stockpiles resultant from the dismantlement of nuclear weapons [36]. This was followed by the *Joint Statement Between the United States and Russia on Nonproliferation of Weapons of Mass Destruction and Means of Their Delivery* [37] in 1994, which sought: to secure nuclear materials in the former Soviet Union; to ensure safe, secure, long-term storage and disposition of surplus fissile materials; to establish transparent and irreversible nuclear reductions; to strengthen the nuclear nonproliferation regime; and to control nuclear exports. A 1995 US announcement demonstrated its commitment to these objectives by designating 200 MT of domestic fissile materials, of which approximately 38.2 MT was WGPu, would be declared surplus to US nuclear defense needs.

As identified in the Moscow Nuclear Safety Summit [38], the G-8 endorsed the need to render surplus plutonium in Russia and the US as proliferation resistant as possible

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[22] Under START and subsequent unilateral initiatives, approximately 10,000-20,000 each in the US (and a greater number in Russia) have been declared surplus to national security needs. Although the START treaties had been the backbone of joint US and Russia efforts toward nuclear disarmament, the treaties did not addressed the discontinuation of weapons-grade fissile material production and disposition of excess weapons-grade materials.

[23] NAS later formed the Panel on Reactor-Related Options for Disposition of Excess Weapons Plutonium in November of 1992.

[24] As stated in the policy, the US was directed to: "(I) Seek to eliminate, where possible, accumulation of stockpiles of highly enriched uranium or plutonium, and to ensure that where these materials already exist they are subject to the highest standards of safety, security, and international accountability and (II) Initiate a comprehensive review of long-term options for plutonium disposition, taking into account technical, nonproliferation, environmental, budgetary and economic considerations. Russia and other nations with relevant interests and experience will be invited to participate in the study."

and that the threat of diversion and the safe, secure, irreversible, and expedited removal of excess Pu from weapons programs should be the major criteria for consideration of disposition options [39]. There is a significant nuclear threat posed by surplus fissile material due to the number of sites at which it is stored and associated management difficulties which, some argue, yields a much more dangerous environment than the nuclear tensions of the Cold War era. For this reason, the world audience is extremely concerned the adequacy of safeguards and security (S&S) for WGPu, the dangers associated with the potential proliferation of nuclear weapons, and with the potential for adverse environmental, safety, and health consequences if surplus fissile materials are not properly managed.

In both the 1994 and 1995 NAS reports, CISAC and the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium concluded that two plutonium disposition alternatives were the most promising: use as MOX fuel (without reprocessing) in nuclear reactors and immobilization through vitrification in combination with high-level radioactive waste (VHLW). Although both methods were identified as promising[25], the MOX fuel approach was judged to pose greater proliferation risks than the vitrification option. It was also recommended that the US and Russia jointly pursue these alternative disposition strategies, which was later done in 1996[26]. All parties recommended pursuit of both the MOX and immobilization approaches in their respective final reports.

1.4.2 Spent Fuel Standard

The DOE engaged in an environmental impact analysis regarding long-term storage and disposition of weapons-usable fissile materials. The primary goal of disposition is to render weapons-usable fissile materials inaccessible and unattractive for weapons use while protecting human health and the environment. In order to achieve this task, NAS recommended that plutonium disposition strategies should seek to attain the *Spent Fuel Standard* (SFS)[27].

DOE revised the SFS definition, with a more explicit focus on material attractiveness, a concept implicit in the NAS definition. The SFS does not imply that conversion of plutonium to spent nuclear fuel (SNF) is the only way to achieve the nonproliferation objective, but that disposition approaches should provide an equivalent level of proliferation resistance as SNF. Achieving SFS provides increased proliferation

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[25] Through their analyses comprised of assessments of each alternative based three proliferation-risk factors: risk of theft, risk of reversal, and impact on arms reduction

[26] Many collaborative studies resulted such as the US-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium, US-Russian Plutonium Disposition Steering Committee, and Joint US-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition

[27] "We believe that options for the long-term disposition of weapons plutonium should seek to meet a "spent fuel standard"—that is to make this plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors;" See NAS *Management and Disposition of Excess Nuclear Plutonium,* 1994. This definition was later revised by DOE, "The surplus weapons-usable plutonium should be made as inaccessible and unattractive for weapons use as the much larger and growing quantity of plutonium that exists in the spent nuclear fuel from commercial power reactors," See DOE *Storage and Disposition of Weapons-Usable Fissile Materials and Final Programmatic Impact Statement,* 1996.

resistance by transforming surplus fissile materials into a less accessible form; it leads to decreased reliance on institutional barriers to protect the material from theft or diversion.

Consistent with 1994 and 1995 NAS reports, the US and Russia each agreed to dispose of 34 MT of surplus military plutonium into a more proliferation-resistant form via MOX irradiation and VHLW over a twenty-year period under the terms of the original 2000 PMDA. Although the options for the most effective proliferation-resistant disposition method for WGPu have been discussed and debated for more than 15 years, both US and Russian authoritative reports have always primarily focused on the two aforementioned options towards disposition [40]. However, maintaining consistency with their original SFS definition coupled with strong encouragement from Russia, MOX irradiation was solely chosen as the method of disposition for all 68 MT of WGPu under the modified 2010 PMDA. As designated for both parties under the *Annex on Technical Specification* of the PMDA, the SFS corresponds to a "radiation level from each spent plutonium fuel assembly [of] no less than 1 sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation has been completed."

1.4.3 Verification under the PMDA

As designated by the PMDA's *Annex on Monitoring and Inspection*, the purpose of verification through monitoring[28] and inspection[29] under the PMDA is:

> *In accordance with paragraph 1 of Article VII*[30] *of the Agreement, monitoring and inspection activities shall be designed and implemented to ensure that the monitoring Party has the ability independently to confirm that the terms and conditions of the Agreement with respect to disposition plutonium*[31]*, blend stock*[32]*, conversion product*[33]*, spent plutonium fuel, and disposition facilities are being met."*

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[28] Monitoring, as defined in the PMDA, *means a set of measures and activities, including inspections, use of special equipment, and review of documents (records and reports), that together provide data to the monitoring Party on disposition plutonium, blend stock, conversion product, spent plutonium fuel, or disposition facilities.*

[29] Inspection, as defined in the PMDA, *means a monitoring activity conducted by the monitoring Party on-site at a facility in order to obtain data and make observations on disposition plutonium, blend stock, conversion product, spent plutonium fuel, or disposition facilities.*

[30] *"Each Party shall have the right to conduct and the obligation to receive and facilitate monitoring and inspection activities in accordance with this Article and the Annex on Monitoring and Inspections, which is an integral part of this Agreement, in order to confirm that the terms and conditions of this Agreement with respect to disposition plutonium, blend stock, conversion product and spent plutonium fuel, and disposition facilities are being met."*

[31] The 34 tons of Pu slated for disposition.

[32] Any plutonium other than disposition plutonium—and possibly including reactor-grade plutonium—which may be used as part of the disposition campaign.

[33] Disposition plutonium which, prior to its irradiation in a reactor, may or may not have been mixed with blend stock, has been received at an entrance of a fuel fabrication facility, and has no properties that are considered by the United States of America as classified information or by the Russian Federation as state secret. In addition to the above specifications, the agreement states that the ratio of ^{240}Pu/^{239}Pu in the conversion product must not exceed 0.1.

Currently, each party is working to fulfill their remaining requirements to bring the PMDA, as amended by the 2010 protocol, into force. Both Russia and the United States plan to begin disposition activities by 2018. In December 2010, the US Deputy Secretary of Energy and the Russian Director General for the State Corporation Rosatom issued the Joint Statement on the Results of the Nuclear Energy and Nuclear Security Working Group Meeting. The Statement identified concrete steps for the near term as a result of the Working Group meeting[34].

Although the verification task of disposition primarily aims to satisfy US and Russian interests, the goals of the PMDA are to eventually involve the IAEA in the development and implementation of verification measures under a multilateral regime, as was reaffirmed with the amendments of the 2010 protocol in Article VII.3:

> *Each Party, in cooperation with the other Party, shall begin consultations with the International Atomic Energy Agency (IAEA) at an early date and undertake all other necessary steps to conclude appropriate agreements with the IAEA to allow it to implement verification measures with respect to each Party's disposition program.*

However, specific verification arrangements have yet to be finalized. The joint letter to IAEA Director General, Yukia Amano, signed by both Russia and the US requests that "the IAEA engage in all necessary efforts to undertake this important verification role, with the goal of preparing the necessary legally-binding verification agreements in 2011 [41]." Actual disposition will not begin until 2018. Given the significance of irreversibility to nuclear disarmament efforts and the need for transparency highlighted in the Final Document of the 2010 NPT Review Conference, ensuring effective verification under the auspices of the PMDA will be essential to the ultimate success of the process and its wider impact on the NPT regime [42].

Nonetheless, although each state, and ultimately the IAEA, possesses the inherent right to conduct monitoring and inspection measures to confirm the success of disposition procedures pursued by the other state, the PMDA states that:

> *The number, intensity, duration and timing of inspections, and the intensity of other monitoring activities, shall be kept to the minimum consistent with the effective implementation of agreed monitoring activities... [where] procedures for monitoring shall be designed so as to minimize, to the extent possible, interference with the operation of facilities, and to avoid affecting their nuclear safety or the safety of inspectors.*

With a targeted goal of minimal and effective mechanisms of inspection and monitoring, the parties still seek to agree upon specific and detailed measures and procedures for monitoring and inspections of disposition plutonium, blend stock, conversion product, spent plutonium fuel, and disposition facilities. In order to aid in

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[34] These steps included ensuring entry into force of the amended PMDA and associated liability provisions as soon as possible; and considerations of a set of milestones as envisioned by the amended PMDA with a view to reach an agreement by the end of February 2011.

mitigating this task as well as engage the IAEA as the ultimate verification party for this endeavor, we argue that antineutrino detection should be used as a monitoring tool for some of these verification responsibilities due to its effectiveness and noninvasive nature as an unattended monitoring system (UMS).

1.4.3.A Verification Prospects with Antineutrino Detection

As acknowledged, the PMDA confers to each party the right to verify that the disposition plutonium, conversion product, and spent plutonium fuel all have particular attributes at various stages throughout the disposition campaign. Although the agreement specifies that some of these attributes are to be verified at MFFF, others could potentially be verified onsite at the reactor by antineutrino detection. We argue that, in likely order of applicability, these are (1) confirmation of burnup, (2) confirmation of conversion product mass and isotopic composition, (3) confirmation of annual WGPu irradiation volume, and (4) maintenance of continuity of knowledge (CoK) [43].

1.5 Thesis Organization

Chapter 2 explores the current US attempts to identify customer reactors to irradiate manufactured WGPu MOX fuel assemblies as part of the US plutonium disposition campaign.

Chapter 3 discusses the underlying policy and technical concepts in achieving a successful verification multilateral regime through a brief case analysis of relevant strategies for verification under a multilateral regime. The implications of the findings as they related to the PMDA are concluded.

Chapter 4 provides an overview, from a policy context, of the relationship between the US and IAEA which is used in an attempt to consider how the PMDA verification regime will look within the US upon full inclusion of the IAEA.

Chapter 5 provides an overview of antineutrino detection physics as well as proposed practical detector operation in aiding the PMDA in achieving some of the aforementioned tasks at hand. This chapter also prefaces the statistical analysis of Chapter 6 with the designated assumptions and procedures followed in order to attain the estimated antineutrino signal used in the simulation.

Chapter 6 outlines the model selection, testing procedure, and cases considered for a simulation in which a statistical analysis is performed in order to test the quality of the antineutrino detection as a tool used for monitoring under the PMDA.

Chapter 7 summarizes the findings of the report, discusses the implications of the findings, and presents recommendations for future work.

Appendix A provides an associated background on manufacturing technologies and construction statuses, benefits, and pitfalls of the US WGPu MOX conversion strategy.

Appendix B provides the data, functions, and simulators used for the analysis in this thesis.

Chapter 2: WGPu MOX Fuel Use in the US

The MOX approach for WGPu involves fabrication of the mixed oxide fuel by combining PuO_2 powder with natural uranium oxide powder similar to the commercial process implemented in Europe for the fabrication of fuel from reactor-grade plutonium (RGPu). WGPu MOX requires an extra step, in which the WGPu is transformed from its original form (weapon pit or metal) into pure PuO_2 power with the removal of any impurities[35] associated with its original form [39]. Once the MOX fuel assemblies have been irradiated in commercial reactors, the plutonium is expected to be no longer readily available for nuclear weapons use—fulfilling its PMDA burnup requirement[36]. The MOX fuel fabrication process is important in maintaining US efforts to minimize the proliferation risks associated with nuclear weapons, while simultaneously generating electricity for citizens [44]. In this chapter, we explore the current US efforts to identify customer reactors to irradiate such WGPu MOX fuel assemblies as part of the US plutonium disposition campaign. For additional information regarding associated manufacturing technologies and construction status, benefits, and pitfalls of the WGPu MOX conversion strategy, see Appendix A.

2.1 Viable Customers

As of the writing of this thesis, the expected production schedule for the fabrication of WGPu MOX fuel assemblies has been established by the NNSA [45]. Production is to begin in 2018 with 8 WGPu MOX fuel assemblies, increasing to a maximum of 151 fuel assemblies by year 2023, to create a total of 1,700 fuel assemblies (with an approximate WGPu mass of 20 kg per assembly) designed for pressurized water reactors (PWR) during its 15-year operation lifetime (See Figure 2.1). Once a reactor is approved to aid in the US plutonium disposition campaign, the reactor licensee would collaborate with Shaw AREVA MOX Services to test the MOX fuel through initial operations with a few lead test assemblies (LTA) for at least two operating cycles[37]. Upon successful review of LTA performance by the NRC, the full employment of WGPu MOX fuel could begin in the selected reactors [46].

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[35] This includes plutonium-gadolinium alloys as well as trace amounts of other materials.

[36] In Section I.2-3 of the PMDA's *Annex on Technical Specifications*, it states that, "each spent plutonium fuel assembly is [to be] irradiated to a fuel burn-up level of no less than 20,000 megawatt days thermal per metric ton of heavy metal; [where] the radiation level from each spent plutonium fuel assembly is such that it will become no less than 1 sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation has been completed."

[37] Lead test assemblies are tested in the reactor in order to verify the ability of the models to predict fuel performance and the applicability of the European database to the US MOX fuel.

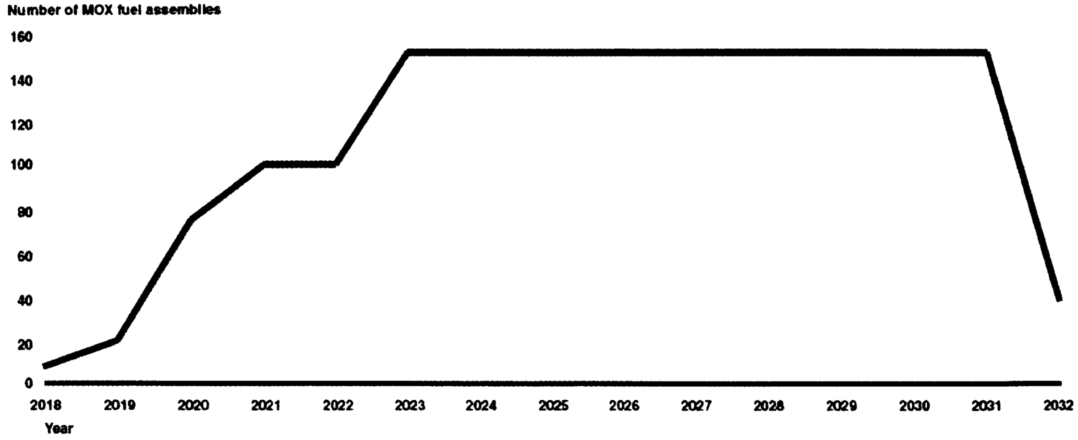

Figure 2.1: MFFF Planned Production Schedule for MOX fuel assemblies
Courtesy of GAO, DOE Needs to Address Uncertainties with and Strengthen Independent Safety Oversight of Its Plutonium Disposition Program [45]

Given the general specifications of the PMDA, many US LWR are capable of incorporating WGPu MOX fuel into their fuel cycles. At the disposition campaign's infancy, DOE obtained expressions of interest from 18 utilities (totaling approximately 38 reactors) for using WGPu MOX fuel in their reactors [47]. Unfortunately, the current customer landscape is much dire, where many of the DOE-identified customer reactors are no longer interested. Nonetheless, we review the most viable customers below; which include likely parties, although they may be no longer interested.

2.1.1 Virginia Electric Power Company & Duke Energy Carolina, LLC

In 1999, DOE awarded a contract to the consortium Duke Engineering & Services, COGEMA Inc., and Stone & Webster (DCS) to aid in the US plutonium disposition campaign as designated by the PMDA through reactor irradiation of WGPu MOX fuel at Virginia Electric Power Company's North Anna Nuclear Station (2 PWR) as well as Duke Power's (now known as Duke Energy Carolina, LLC) Catawba and McGuire Nuclear Stations (4 PWR)[38] [48, 49]. Under this conceived Mission Reactors Irradiation Plan, DCS was to dispose of WGPu MOX in these six selected reactors[39] which would demonstrate the feasibility of disposing of surplus plutonium between 2007-2022[40]. In determining the feasibility of these mission-specified reactors completing the task, Clark et al. [50]

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[38] Duke Power and Virginia Electric Power determined a fuel management strategy coupled with fuel cycle studies to verify that the core designs developed could accomplish the program objectives and meet all of the assumptions and constraints. Duke Power performed its nuclear analyses using the CASMO-4 and SIMULATE-3 MOX computer codes, whereas Virginia Power performed its nuclear analyses using the MCNP and PDQ computer codes (at the time, these analytical methods were consistent current nuclear analyses methodologies used by utilities).

[39] Then referred to as mission reactors. A Mission Reactors Licensing Plan was also developed in order to designate a specified approach to obtaining NRC approvals needed to carry out the Mission Reactors Irradiation Plan.

[40] Created prior to the 2010 Plutonium Disposition Protocol update to the 2000 PMDA.

conducted an analysis using two baseline MOX fuel assembly designs[41], where after several transition cycles, the plants achieved "equilibrium" partial MOX fuel cores with close to a 40% MOX fuel core[42]. It was ultimately shown that the core design analysis performed demonstrated that 34.8 MT of WGPu could be disposed of under this planning through the burning of 1743 WGPu MOX fuel assemblies in the six reactors (See Figure 2.2).

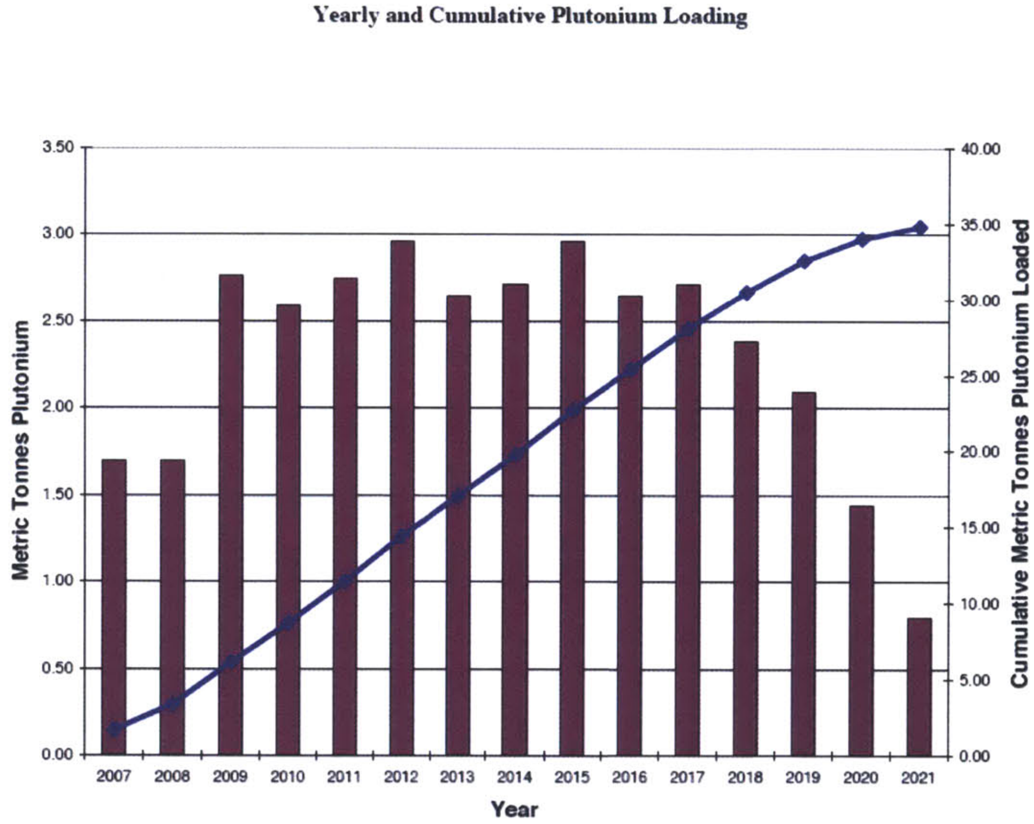

Figure 2.2: Annual and Cumulative US WGPu Disposition Estimate

Courtesy of MOX Fuel Irradiation Program for Disposition of Surplus United States Plutonium [50].

The core design analyses demonstrated that 51 planned operating cycles for the six mission reactors between 2007 and 2022 are capable of disposing of 34.8 MT of surplus weapons plutonium. This corresponds to 1743 MOX fuel assemblies in the six reactors. Plutonium disposition amounts by year, and cumulatively.

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[41] These were referred to as High MOX and Low MOX, which designated the amount of plutonium loaded per fuel assembly.

[42] "For McGuire and Catawba, the "equilibrium" partial MOX fuel cores would vary each cycle between 36 and 40 feed MOX fuel assemblies [out of 84 total feed (LEU + MOX) assemblies]. For North Anna, the "equilibrium" partial MOX fuel cores would vary each cycle between 28 and 29 feed MOX fuel assemblies [out of 68 or 69 total feed (LEU + MOX) assemblies respectively]."

Unfortunately, however, Virginia Electric Power's involvement in the plutonium disposition campaign ended soon thereafter, when Virginia Electric Power ultimately abandoned its agreement with DCS. Jim Norvelle, then spokesman of the utility, stated that this decision was "indicative of the changes that are occurring in the electric industry today," and at the time of its decision to join DCS in the consortium, "it fit [the Virginia Electric Power Company's] strategy. Today it does not," as the company merged with Consolidated Natural Gas of Pittsburgh to concentrate on Midwest and Northeast, a region that did not correlate with the MOX mission [51].

Upon the loss of Virginia Electric Power, Duke Energy Carolinas, LLC agreed to the purchase up to 75% of MOX fuel produced at a discount relative to the price of normal reactor fuel (LEU), to be disposed of in their seven nuclear reactors at the Catawba, McGuire, and Oconee Power Sites in June of 2000 through a subcontract with NNSA. In February 2003, Duke initiated the process to begin incorporating WGPu MOX LTA at either Catawba or McGuire power plants[43]. In August 2008, Friends of the Earth and the Union of Concerned Scientists revealed that the LTA used for testing in Duke's Catawba Unit 1 reactor had failed due to abnormal fuel assembly performance[44] and was pulled from the reactor after completing only two of the then NRC-required three necessary 18-month irradiation cycles [52].

Unfortunately, an official agreement was never negotiated with Duke Energy Carolinas, LLC, and the original subcontract automatically terminated on December 1, 2008 [45]. The LTA failure at Catawba Unit 1 in conjunction with MFFF project and construction delays and NNSA's inability to guarantee a reliable MOX delivery schedule to Duke's power plants, may have been the overarching reasons for Duke's loss of interest in supporting the US plutonium disposition campaign. Nonetheless, Duke has communicated to MOX Services that it continues to support the objectives of the surplus weapons disposition program and is interested in receiving a future proposal from MOX Services for the use of MOX fuel [53]. However, future reactors seeking to use WGPu MOX fuel will have to abide by the preliminary testing as designated by the NRC causing further uncertainty, delays, and cost escalation.

2.1.2 Tennessee Valley Authority

According to NNSA, three utilities have responded to MOX Services' request and have expressed interest in the MOX fuel program. Most notably, in February 2010, NNSA and the Tennessee Valley Authority (TVA) executed an interagency agreement "to evaluate

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[43] Duke filed a license amendment request to use four WGPu MOX LTA which was eventually restricted to the Catawba Power Plant. This request was then followed by a file for a "Request for Exemption from Certain Regulatory Requirements in 10 CFR 11 and 73 to Support MOX Fuel Use."

[44] The LTA were analyzed at Oak Ridge National Laboratory, however, information regarding the analysis of these assemblies is not available. It is expected, however, that abnormal growth was seen in the LTA, which offers broader safety implications. AREVA informed the NRC that the problem has yet to be determined, although it may be related to an experimental alloy known as "M5" AREVA uses in the "guide tubes" where the control rods that shut down the reactor are inserted; a problem that may indicate the inadequate NRC licensing process.

the irradiation of MOX Fuel in up to 5 TVA reactors[45] [54]." Although TVA has not yet formally decided to use MOX fuel, it will continue to cooperate with the DOE in determining the preparation and review of specified sections regarding reactor operations within the Surplus Plutonium Disposition Supplemental Environmental Impact Statement[46] [55]. TVA's decision occurred somewhat as a response to Duke's decision to abandon the program. TVA spokesman Terry Johnson stated, unlike what was communicated to Duke Energy Carolinas, reliable fuel services would be part of the supply contract if the utility decides to use MOX fuel in any of the three Brown's Ferry boiling water reactors (BWR) or two Sequoya PWR. Nonetheless, TVA has been especially impressed with the expected prices of WGPu MOX fuel—forecasted to be much cheaper than conventional LEU fuel—resulting in a jointly signed letter of intent [56] by TVA and AREVA for MOX fuel use in TVA's five reactors.

Although the more recent addition of TVA's five reactors appear promising for the US plutonium disposition campaign, some issues arise with the incorporation of these reactors. To begin with, the diversity of TVA's LWR reactors (incorporating both BWR and PWR designs) is not well matched to NNSA's intent to produce MOX assemblies for use in PWR only (i.e. those situated at the Sequoyah Site) [57]. However, MFFF's design does offer the capability to switch between MOX fuel assembly production for PWR or BWR in a 10-20 day conversion timeframe[47]. Furthermore, the utility's charter requires it to support national defense initiatives, which may be inconsistent with the nonproliferation aspects of WGPu disposition in commercial reactors[48] [53]. In addition, the three BWR at the Brown's Ferry Site might not be permitted to use WGPu MOX assemblies due to their status as backup reactors in DOE's tritium production program[49] [58]. Assuming NRC licenses are secured for use of MOX fuel provided by MOX Services in Brown Ferry's BWR reactors, operation would begin no earlier than 2025[50] [54]; much later than the anticipated 2018 disposition start date. TVA's two Sequoya PWR, may also be needed to aid in the DOE Tritium Readiness Program [59], perhaps complicating the use these reactors PMDA MOX irradiation.

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[45] According to NNSA officials, using MOX fuel in five of TVA's reactors could account for up to 85 percent of the MFFF's output. These reactors are the three boiling water reactor units at the Brown's Ferry Site and the two pressurized water reactors at the Sequoya Site.

[46] DOE issued a revised Notice of Intent in September 2010 announcing revision of the scope of the Surplus Plutonium Disposition Supplemental Environmental Impact Statement and the additional 60-day public scoping period. To the date of this thesis, no significant progress has been made towards NRC-licensing of MOX fuel use by TVA.

[47] However, even with these capabilities, additional testing for the operation of these MOX fuel assemblies in BWR will still need to be conducted. Whether or not these additional tests and/or the MFFF's PWR/BWR fuel assembly conversion timeframe will delay the MOX production schedule is still unclear.

[48] Public scoping meetings conducted by TVA show that TVA is currently on track to have enough information to make an official decision by 2012.

[49] These reactors were slated for this program during there initial operations in 1974, 1975, and 1977 for Units 1, 2, and 3, respectively.

[50] The FY2012 NNSA budget request appears to appropriate funding for such activities and testing—"qualification of MOX fuel designs for pressurized water reactors and boiling water reactors from multiple fuel suppliers, and execution of fuel supply agreements with TVA and potentially other utilities."

2.1.3 Energy Northwest

In February 2011, Friends of the Earth obtained DOE documents showing Energy Northwest was "formally evaluating the potential use of MOX fuel [60]" in its Columbia Generating Station reactor [61]. Energy Northwest spokesman Michael Paoli commented that " It's no secret [Energy Northwest] plans to use MOX, we've been looking at MOX since the mid-1990s [53]." Apparently, the current plan by Energy Northwest and DOE calls for the irradiation of 10-20 fuel pins (fabricated by Pacific Northwest National Laboratory[51]) to commence sometime between 2013-15 followed by further testing with 8 LTA around 2019 [62]. However, considering NRC stipulations for LTA use to occur for at least two successful fuel irradiation cycles, official MOX fuel use would not begin until at least 2023. Energy Northwest does not plan to incorporate MOX fuel use into its fuel cycle until the evaluations have proven successful with the "unique characteristics of the Columbia reactor [53]." In addition to the technical risks, operational changes, licensing issues, and fuel specifications, Energy Northwest wants the fuel needs to be competitively priced as well in order to sign on with the program, and refuses to pay for "MOX fuel that costs more than what [they're] paying now [53]."

2.2 Overview of US Considered Reactor Types

2.2.1 PWR

Typical PWR are composed of a mixture of fuel assemblies (usually LEU) that are either in their first, second, or third cycle of irradiation. These reactor cores are designed and shuffled to yield the maximum energy output with minimum fuel costs[52].

PWR implementing MOX fuel require analytical methods capable of accurately modeling mixed cores[53] [50]. Because the control rod worth in MOX fuel assemblies is smaller in comparison to LEU fuel assemblies (where such differences are considerably decreased by decreasing moderator temperature, increasing burnup, and increasing rod internal pressures), core designs need to be adjusted to account for these differences. MOX fuel, as compared to LEU, tends to burn at higher powers, higher fuel temperatures, and higher cladding temperatures when assembly burnup is increased. These drawbacks, coupled with higher transient fission gas releases, further increase the defect probability of MOX fuel above a certain burnup threshold. Therefore, MOX fuel typically does not reach the same burnup levels as conventional LEU fuel. Nonetheless, both MOX and LEU fuel rods of identical designs share the same defect threshold in the case of a potential Loss of Coolant Accident (LOCA) [63].

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[51] Pacific Northwest National Laboratory (PNL), under DOE jurisdiction, will aid Energy Northwest in evaluating its options for MOX fuel use. Engineers performing analyses for MOX fuel use in this reactor estimate that up to 30% (229 fuel assemblies) of the BWR's 764 fuel assemblies could potentially be replaced by MOX fuel.

[52] The designs of cores are constrained by many factors (energy requirements, cycle length, individual assembly and fuel rod peaking limits, reactivity coefficient limits, soluble boron limits, burnup limits, and maximum enrichment limits) where loading patterns, enrichments, and integral and lumped burnable poison are all manipulated in order to obtain designs that maximize economic feasibility and practicality while meeting specified constraints.

[53] This is inclusive of the neutron flux gradients between LEU and MOX fuel assemblies.

Of the viable reactors for potential WGPu MOX fuel use, the only PWR identified from the contemporary environment are those provided by TVA. TVA's Sequoya Power Plant has 2 PWR units built by Westinghouse implementing a wet, ice condenser (PWR-ICECND) reactor/containment type and a Westinghouse 4 Loop nuclear steam system supplier and design type. These reactor types have four steam generators, four reactor coolant pumps, and a pressurizer. Both units can produce a power output of 3.455 GW_t and 1.199 GW_e. These reactors[54] have 193 fuel assemblies arranged inside of their reactor vessels (with an internal diameter of 173 inches) with the fuel pins in each fuel assembly arranged in a 17x17 array [64].

2.2.2 BWR

MOX fuel implemented in BWR has little impact on its performance. Because there are large water gaps between bundles, the thermal flux is able to recover and yields unchanged control rod worth. For this reason, the core is usually distributed with scattered MOX fuel assemblies—usually one or two MOX assemblies assigned to each control rod. Negative moderator temperature and void coefficients have an extreme effect on the cold shutdown reactivity balances, transients with coolant pressure increases, and moderator cool-down. Because of the higher concentrations of Pu in WGPu MOX as compared to typical RGPu MOX, a shift to less negative values of the void coefficient may result. However, all in all, MOX fuel has a generally small impact on BWR transients and does not restrict reactor operations under circumstances of licensed MOX ratios for these reactors [63].

Of the viable reactors for potential WGPu MOX fuel use, the only BWR identified from the contemporary environment are those provided by TVA and Energy Northwest. The TVA's Brown's Ferry Power Plant has 3 BWR units built by GE implementing a wet, MARK 1 reactor/containment type[55] and a GE Type 4 nuclear steam system supplier and design type. All three units can produce a power output of 3.458 GW_t with Unit 1 having an electrical power of 1.125 GW_e and Units 2 and 3 of 1.155 GW_e[56]. Modern reactors of this type have around 800[57] fuel assemblies (about 4 m long) arranged in the reactor core, each with approximately 74-100 fuel rods within zirconium alloy cladding [65].

Energy Northwest has recently identified themselves as a viable customer for WGPu MOX disposition in their Columbia Generating Power Station. The BWR at this station is built by GE implementing a wet, MARK 2 reactor/containment type and a GE Type 5 nuclear steam system supplier and design type with a potential power output of 3.486 GW_t and 1,190 GW_e. This reactor shares the common characteristics of any modern BWR as previously stated.

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[54] Reactors of the four-loop design in the US are Braidwood 1 and 2, Byron 1 and 2, Callaway, Comanche Peak 1 and 2, D. C. Cook 1 and 2, Diablo Canyon 1 and 2, Indian Point 2 and 3, McGuire 1 and 2, Millstone 3, Salem 1 and 2, Seabrook, South Texas Project 1 and 2, Vogtle 1 and 2, Watts Bar 1, and Wolf Creek.

[55] This is similar to the reactor types and styles that were damaged as a result of the Fukushima Daiichi accident, where both reactors 2 (784 MW_e with 548 fuel assemblies in the reactor each with 60 fuel rods) and 3 (460 MW_e with 400 fuel assemblies in the reactor each with 60 fuel rods).

[56] TVA plans to increase the capacity of all three reactors to 1.280 GWe pending NRC approval.

[57] The number of fuel assemblies in a specific reactor is based on considerations of desired reactor power output, reactor core size and reactor power density.

2.3 MOX Production and Use in Selected Customer Reactors

All in all, NNSA has had trouble finding and sustaining customers for its WGPu MOX fuel. Based on publically released statements, the current viable customer reactors (including design type and license expiration date) are shown in Table 2.1 below.

Table 2.1: Viable Customer Reactors

Plant Name (Unit #)	**Reactor and Containment Type (Design Type)**	**Operating License Expiration Date**
Sequoyah Nuclear Plant (1)	PWR-ICECND (WEST 4LP)	9/17/2020*
Sequoyah Nuclear Plant (2)	PWR-ICECND (WEST 4LP)	9/15/2021*
Browns Ferry Nuclear Plant (1)	BWR-MARK 1 (GE 4)	12/20/2033
Browns Ferry Nuclear Plant (2)	BWR-MARK 1 (GE 4)	6/28/2034
Browns Ferry Nuclear Plant (3)	BWR-MARK 1 (GE 4)	7/2/2036
Columbia Generating Station (2)	BWR-MARK 2 (GE 5)	12/20/2023*

Reactor Types provided by the NRC: Appendix A: US Commercial Nuclear Power Reactors, vol. 22 [66]

*Renewed Operating License has yet to be issued.

The Sequoyah and Browns Ferry Nuclear Plants are licensed to TVA while the Columbia Generating Station is licensed to Energy Northwest.

Given this current viable customer landscape, unless renewed operating licenses are issued, half of these reactors will have only begun initial irradiation of WGPu MOX fuel before being decommissioned[58]. Additionally, with the NRC-designated MOX core concentrations for each reactor being 40%, it is highly unlikely that the US will be successful in achieving and maintaining the required disposition rate of 1.3 MT/year, as stated in Article IV of the PMDA. Furthermore, given the diversity of these reactor types[59], timely delivery of MOX fuel may not be as realistic as initially perceived based on the original proposal for MFFF fuel assembly production. NNSA claims that the fuel assembly type conversion factor, the number of customer-specified fuel designs[60], availability of feed material at the plant, and fuel outage plans, all serve as reasoning for expected low production rates of MOX fuel at MFFF [53]. Despite the majority of the current customer landscape consisting of BWR, NNSA has failed to provide an updated estimate and

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[58] This is assuming a best-case scenario that such reactors will have had successful LTA performance prior to the official launch of the US plutonium disposition campaign in 2018 as outlined by the PMDA.

[59] There are two types of fuel assemblies MFFF can manufacture, BWR and PWR. They have different configurations, and a one-third change out of conventional for MOX fuel for each type involves a different number of fuel assemblies, and fuel material, for each reactor type.

[60] Customer demand would be determined by core replacement rates for the specified reactor, with none exceeding 50% of the total number of fuel assemblies.

forecast than their original proposal of 34 MT of WGPu disposition via 1,700 PWR MOX fuel assemblies. Given these and the previously discussed issues, maintaining the timeline forecasted by NNSA in Figure 2.1 is highly unlikely. For these reasons, it will prove beneficial that NNSA continue to seek more customer reactors.

The US Government Accountability Office (GAO) conducted interviews at utility companies and found that despite NNSA incentives, as of October 2009, the majority expressed little or no interest in becoming MOX fuel customers. However, GAO found through their interviews that what potential utility company customers found to be most attractive was [45]:

- *Knowledge that the MOX program would have consistent congressional funding,*
- *timely delivery of MOX fuel,*
- *timely delivery of a backup supply of uranium fuel,*
- *a lower WGPu MOX fuel cost compared to standard reactor fuel, and the opportunity to test MOX fuel in their reactors prior to full-scale use.*

Successful disposition of WGPu remains important; it is one of the largest expenses of the Defense Nuclear Nonproliferation program as of the NNSA FY2012 budget request[61] [67]. Although they have already separated themselves from the US plutonium disposition campaign, the previously identified viable customers, or as we will refer to them here, the *potential* customers (See Table 4.2 below), remain the strongest prospective customer base (given their previous acknowledged interests in the disposition campaign) if NNSA adapts changes, such as those identified by the GAO. The benefits in the acquisition of former customers, like these identified in Table 2.2, is a solely PWR customer-base consistent with MFFF's original production targets and much longer operational lifetimes given their later license expiration dates.

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[61] NNSA asked for $645,721,000 for the Fissile Materials Disposition related activities [60% of the funding ($385,172,000) would be allocated to MFFF]. Although the budget request is smaller than previous years requests (most likely due to FY2011 budget cuts), MOX related expenses still account for a quarter of the $2.5 billion that NNSA has requested for its Defense Nuclear Nonproliferation program.

Table 2.2: Potential Customer Reactors

Plant Name (Unit #)	Reactor and Containment Type (Design Type)	Operating License Expiration Date
Catawba Nuclear Station (1)	PWR-ICECND (WEST 4LP)	12/5/2043
Catawba Nuclear Station (2)	PWR-ICECND (WEST 4LP)	12/5/2043
McGuire Nuclear Station (1)	PWR-DRYAMB (WEST 4LP)	6/12/2041
McGuire Nuclear Station (2)	PWR-DRYAMB (WEST 4LP)	3/3/2043
Oconee Nuclear Station (1)	PWR-DRYAMB (B&W LLP)	2/6/2033
Oconee Nuclear Station (2)	PWR-DRYAMB (B&W LLP)	10/6/2033
Oconee Nuclear Station (3)	PWR-DRYAMB (B&W LLP)	7/19/2034
North Anna Power Station (1)	PWR-DRYSUB (WEST 3LP)	8/21/2040
North Anna Power Station (2)	PWR-DRYSUB (WEST 3LP)	2/6/2033

Reactor Types provided by the NRC: Appendix A: US Commercial Nuclear Power Reactors, vol. 22 [66]

Potential is used rather than viable since, although these customers have identified themselves to no longer be customers of the WGPu MOX program from a current perspective, given the potential changes as outlined by GAO, interests could potentially be reignited. For this reason, total neglect should not be given to these facilities, especially since they once considered supporting US endeavors associated with the WGPu disposition campaign. The Catawba, McGuire, and Oconee Nuclear Stations are licensed to Duke Energy Carolinas, LLC and the North Anna Power Station is licensed to Virginia Electric & Power Company.

Although there is no US, let alone global, experience in irradiating WGPu MOX fuel in the LWR fuel cycle, there is massive experience using RGPu MOX fuel in LWR on the international landscape. MOX fuel was first irradiated in a reactor in 1963, however, it was not used commercially until the 1980s. As of 2006, approximately 180 MT of MOX fuel has been burned in over 30 reactors in Europe alone, and a total of approximately 2000 MT of MOX fuel has been fabricated and loaded into power reactors globally [68].

Currently, MOX is integrated in LWR fuel cycles throughout Europe (Belgium, Switzerland, Germany, and France) and Japan, where about 50 reactors can use MOX fuel. These licensed reactors generally use MOX fuel for about 33%[62] of their core, however, some use up to 50%[63]. More novel advances in LWR designs plan to implement 100%[64]

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[62] France seeks to have all of its 900 MWe and Japan seeks to have all of its reactors implementing a 33% MOX fuel core in the near future.

[63] The operating characteristics of a reactor do not change when implementing a 50% of MOX fuel load, however, the reactor must be designed or slightly modified (more control rods) to withstand such loads. Reactors requiring core loads exceeding 50% MOX must be adapted significantly with reactor needs designed accordingly.

MOX fuel cores. However, there are also interests for the potential design adaptations for 100% MOX cores in existing LWR, with feasibility studies for BWR[65] [63, 69] and PWR that have determined core designs capable of successfully implementing 100% MOX core loads while meeting licensing requirements; allowing for increased amounts of irradiated plutonium at a reduced level of heterogeneity of the core. The experience gained from core loadings of contemporary levels as well as the knowledge of MOX impacts on neutronic design and safety aspects, confirms that modern design codes can implement current plutonium levels and offers basis for even higher plutonium concentrations and increased discharge burnups.

International MOX use in LWR supports NRC's contention that MOX fuel could be used in domestic LWR. The NRC claims that since domestic reactors were designed to use RGPu MOX, the incorporation of WGPu MOX fuel should pose no threat. Upon the successful operation of LTA in the reactor for "at least two operating cycles [46]," and verifying the ability of the models to predict fuel performance, reactor licensees would be allowed to implement a maximum MOX fuel core of 40%[66] [70, 71].

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[64] Japan plans to develop a 1383 MWe reactor with a complete fuel loading of MOX at their Ohma plant in late 2014, with other advanced LWR like the EPR or AP1000 able to accept complete fuel loadings of MOX (if required) soon to follow.

[65] An ABWR to be constructed in Japan will be the first plant with an in-built 100% MOX core capability.

[66] Although no WGPu core concentrations have been formally specified by any of the customer reactors, some knowledge can be gained regarding the expected MOX concentrations in PWR and BWR from initial estimates provided by current and former customers. During Duke's interest in WGPu MOX fuel, experts estimated that up to 40% of the core would need o be replaced during an outage with WGPu MOX fuel. PNL engineers and evaluators working with Energy Northwest estimate that up to 30% of the reactor can be comprised of WGPu MOX fuel.

Chapter 3: Verification Under a Multilateral Regime

The PMDA's transparency and monitoring provisions are the most extensive and informative *official* groundwork available. They illustrate the complexity and sensitivity of transparency and monitoring procedures for weapons-grade material from the perspective of these leviathan nuclear weapon states. CISAC acknowledges key attributes to note in the passages of this agreement are: (a) the extensive attention given to how monitoring can be accomplished while protecting information about the composition of each country's WGPu (which remains classified to varying degrees on both sides) and (b) the delicate and ambiguous interplay of bilateral versus multilateral (IAEA) responsibilities and privileges in the verification process—leaving unresolved the question of what the IAEA role actually will be [72].

Although the IAEA's primary role, as designated by the Nuclear Non-proliferation Treaty (NPT), is the verification of the non-proliferation commitments of all NPT signatories, Article III.A.5[67] of the treaty outlines the potential for the agency to play a role in assisting signatories in the verification of nuclear disarmament. This role is consistent with the expectations of the agency outlined in the amended PMDA.

Ensuring that the disposition of 68 MT of WGPu and beyond can be verified in an effective and unbiased manner will be essential in order to convince the international community that this material will remain "permanently" outside the realm of defense programs; a task that may only be achieved through verification procedures managed under IAEA inspection and monitoring. Despite the promising nature of IAEA verification involvement, involving NNWS—which logically applies to international organizations like the IAEA which is comprised of personnel from both NWS and NNWS—in dismantlement verification is especially problematic as it risks breaching the NPT's ban on the sharing and/or transfer of proliferative material between NWS and NNWS [73].

Nonetheless, multilateral verification arrangements are necessary to ensure credible, unbiased verification that: (1) the material subject to disposition was weapon grade, (2) disposition actually took place, and (3) the material will not be fabricated into a weapon(s). Although virtually no progress has been made in negotiating specifics of such monitoring arrangements, based on the it's past experience with the verification of weaponization activities[68], research for disarmament verification, and actual disarmament verification (in South Africa in the 1990s) [73], the IAEA is well-equipped to engage with verification activities beyond safeguards and non-proliferation [74]. It is clear that further efforts to develop and clarify the legal and political aspects of any such 'other' activities, like disarmament, are needed if a verification regime of this capacity is to fall within its jurisdiction.

In this chapter, we perform a case analysis on relevant multilateral verification endeavors like the Trilateral and UK-Norway Initiatives in an attempt to gain insight regarding successful implementation of multilateral verification arrangements in the PMDA.

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[67] Allows the IAEA the right to apply safeguards "to any bilateral or multilateral arrangement, or at the request of a state, to any of that state's activities in the field of atomic energy."

[68] Relevant to disarmament in terms of the secrecy concerns.

3.1 The Trilateral Initiative

In the efforts of designing a successful verification regime for WGPu disposition, knowledge can be gained from the experience of the Trilateral Initiative. The intent of this initiative was to broaden the scope of IAEA monitoring to include classified items such as WGPu and HEU (acquired from nuclear warheads, warhead components, pits, or secondaries) in a manner that ensured permanent safeguarding of these items[69]. The US and Russia needed a unique system, different from the IAEA safeguards system which was insufficient for monitoring military nuclear materials and facilities; a framework which not only ensured US and Russian obligations under Article I[70] of the NPT [75] but also shielded classified information. As noted in the Initiative's experience, although a system was proposed, designing such a system had proven to be quite difficult because of the clear need to restrict IAEA's access to information, in order to prevent the dissemination of nuclear secrets [2].

Toward the concluding exercises of the Initiative, all parties determined that new agreements were needed in order to bring this newly proposed verification system into force with the IAEA voluntary offer safeguards agreements between the Russia and the US Some of the main issues of concern noted regarding any potential multilateral verification system of this kind were:

> (1) Insufficient resource allocation to such a system coupled with the system's inconsistencies with obligatory verification requirements would limit the prospects of voluntary offer agreements;
>
> (2) Such a system would require US and Russian declarations of classified WGPu submitted to the regime despite compromising not only their obligations to Article I of the NPT, but also their respective national laws associated with declarations of classified materials; and
>
> (3) Because of the classified/state-secret nature of the submitted material, limited measurements and analyses could only be performed; significantly differing from typical IAEA safeguard procedures that allow for unrestricted measurements and analyses of samples' nuclear characteristics in order to attain the highest standards of precision and accuracy [76].

3.1.1 Considered Verification Objectives

In construing the scope of the verification procedures to be implanted under the proposed regime for the Trilateral Initiative and in an endeavor to increase global confidence of successful disarmament and disposition, four verification scenarios were

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[69] In 1993, 10 MT of HEU and 2 MT of plutonium were submitted to voluntary IAEA safeguards by the US under the condition that they could be withdrawn at will.

[70] Essentially prohibits NWS signatories to the NPT from assisting, encouraging, or inducing any NNWS to manufacture or acquire nuclear weapons; an obligation which is inclusive in IAEA operation or any other multilateral entity. This requirement is also codified in the US Atomic Energy Act.

investigated and ranked in order of intrusiveness (as identified by Shea [2]):

> **Level 1:** Initiative is to only accept unclassified materials; successfully preventing reuse of these selected materials;
> **Level 2:** Initiative is to accept classified forms of fissile material *without* attempting to verify the origin of the materials (nuclear warhead, specified weapons components, etc.);
> **Level 3:** Initiative is to verify the origin (nuclear warhead, specified weapons components, etc.) of presented classified materials including specific model identifications;
> **Level 4:** Initiative is to begin monitoring at the site of the state's weapons dismantlement program (or subsequent stages) in order to attest to the validity of warhead removal from delivery systems.

A pictorial representation of these verification scenarios as they fit within the disarmament procedure can be seen below in Figure 3.1.

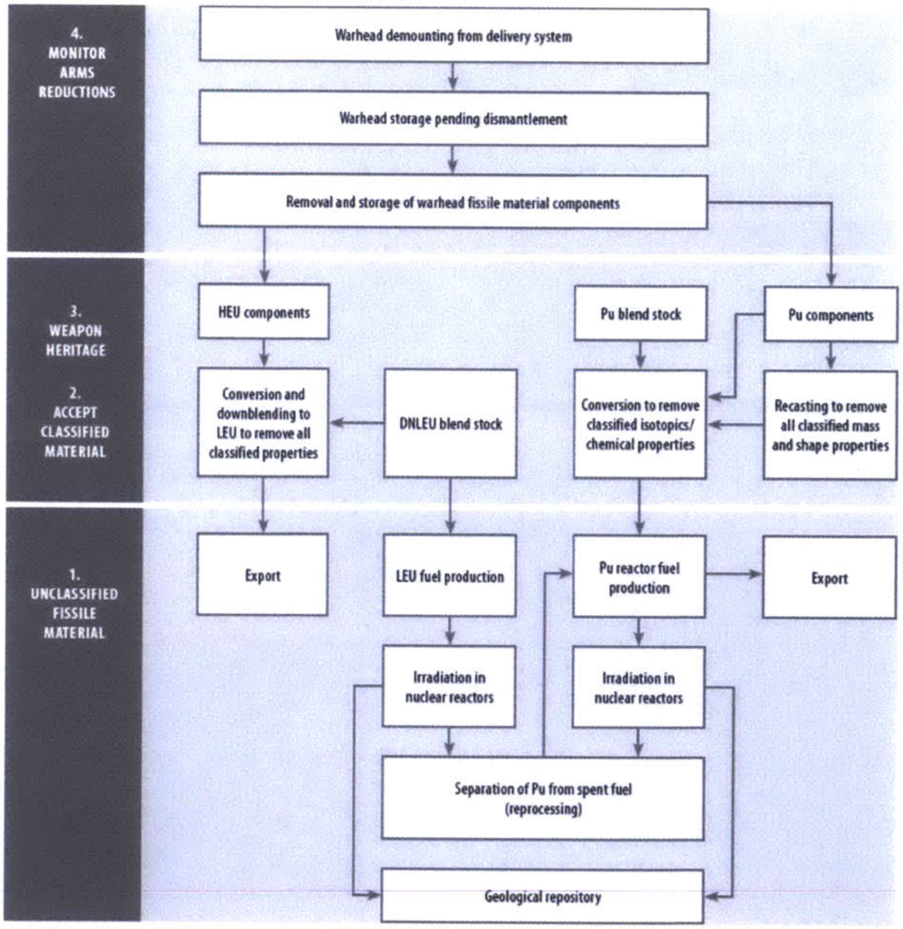

Figure 3.1: Multilevel Verification Levels for Dismantlement and Disposition Process
Courtesy of Verified Warhead Dismantlement: Past, Present, Future [77, 78]
NOTE: DNLEU alludes to depleted, natural, low-enriched uranium.

Although never officially implemented and posing significant challenges, the participants involved in the Initiative selected Level 2 as the most practical and achievable. Level 1, it was argued, would not have required a new framework from contemporary procedures and would have involved significant delays costs as classified materials were converted to unclassified forms. Levels 3 and 4 were synonymous with previously conceived verification scenarios proven unsuccessful in the mid-1990s by the DOE Dismantlement Study Group through Storage Monitoring and Chain-of-Custody techniques[71], which employed continuous monitoring of the existence or presence of items deemed accountable under specified treaties.

This Storage Monitoring and Chain-of-Custody combined system, deemed "Option 1" by the study group, was identified as the most effective and lowest cost option (through an evaluation procedure consisting of seven criteria[72]) with prospects of becoming operational in a year's time and an expected routine cost of $120,000. The level of intrusiveness of this option depends on the measurement system(s) instituted and restrictions of measurement information provided to the inspectors. The primary target was inspectors' ability observe the actual dismantlement process either remotely or directly [77, 79]. Ultimately, these levels proved to be unpractical because of acknowledged and significant security concerns and challenges that would arise due to the need for authentication of warhead templates that could be used by the IAEA [78].

The steps required in Level 2 for the verified conversion of fissile materials from classified to unclassified forms to eventual disposition was given significant consideration. IAEA monitoring would begin with the arrival of classified material at the entry point of a conversion facility and would then measure all fissile material containers leaving the conversion facility using normal IAEA safeguards procedures. Seals would then be placed on containers prior to their storage or transport to fuel processing facilities. Initiative participants felt that if such a scheme were to work successfully, conversion facilities in which IAEA verification took place would need to be based on standard architectural plans. However, no further discussion of such plans took place.

In regards to the CoK challenges associated with the chain-of-custody problem, Initiative participants perceived the ideal solution to be implementing unattended monitoring of all items en-route to storage. However, agreement was only reached on the verification of the stored inventory according to a sampling plan, making assumptions on what constituted a 'strategic change' in the inventory. The outcome became known as the "one percent solution[73] [77]."

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[71] A concept determined by the Dismantlement Study Group, established by the DOE, which was composed of technical experts from its own Office of Arms Control and Nonproliferation, the Office of Defense Programs, the Office of Security Affairs, the Lawrence Livermore National Laboratory (LLNL), the Los Alamos National Laboratory (LANL), the Pacific Northwest National Laboratory (PNNL), the Sandia National Laboratories (SNL), the Pantex plant, and Y-12.

[72] These criteria were: level of confidence; negotiability (or likely acceptability to the Russians); inadvertent loss of classified information; impact on normal plant operations; amount of preparation needed; cost to prepare and host the initial inspection; and routine cost of hosting each inspection thereafter.

[73] A break-out involving on the order of one per cent of the monitored inventory could portend a strategic change. This solution was never formally adopted, but served as the de-facto reference for determining the subsequent sample plan.

3.1.2 Verification Techniques and Associated Technologies

The Trilateral Initiative developed the "template" method and the "attribute" method for identifying and confirming the authenticity of a nuclear weapon[74]. The template method proposed identifying a nuclear weapon or weapon component by matching certain characteristics (i.e. radiation signatures) to the characteristics of a weapon or component that is known or believed to be authentic. It was perceived that for potential treaty applications, the authorization of reference signatures coupled with the storage and retrieval of templates would pose a difficulty. The attribute method, on the other hand, sought to employ a designated set of characteristic requirements (i.e. features of radiation signatures) to identify the authenticity of nuclear weapons and/or components. Propositions for a system employing a combination of the strengths of template and attribute methods have proven to be the best strategy, one where, as identified in *Arms Control and Nonproliferation Technologies: Technology R&D for Arms Control* "data gathered for a template, for example, could be analyzed to determine whether the object contains certain general characteristics or attributes…such as the presence of a certain minimum amount of weapon-grade plutonium metal [80]." Although these methods were considered for purposes of the Initiative's Level 4 verification procedure (which was not considered to be the practical and achievable by Initiative participants) with prospects for the inclusion of information barriers[75], we consider them here because many of the technologies explored in this endeavor correlate with the confirmation of the ^{240}Pu/^{239}Pu ratio[76] in the conversion product as outlined in the PMDA:

> *The monitoring Party shall have the right to confirm the mass and relevant isotopic composition of the conversion product (even if it contains United States "sensitive" information or Russian Federation "konfidentsial'naya" information), using agreed measurement procedures, without the application of "yes/no" techniques or information barriers.*

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[74] During the Initiative, the US and Russian nuclear weapon laboratories performed considerable collaborative work to develop both approaches for arms control purposes and have produced several prototype systems to identify both nuclear weapons and weapon components. Both approaches require measuring an agreed set of characteristics. Most of the template and attribute systems that have been developed use measurements of the radiation (gamma rays and neutrons) emitted during the natural radioactive decay of plutonium and uranium isotopes.

[75] An information barrier, as considered by the Initiative, would contain the detector system, computer system, and template storage, so to impede the leakage of sensitive data, transmission of electronic signals, or other surreptitious access to the sensitive data contained inside the verification technology. An example of such a system would be one which produces a "yes or no" response or "green or red" light if an object matches or doesn't match the specified template or attributes of the comparable object within specified tolerances, respectively. Countries were to build the systems used to inspect their own weapons, so they could be sure there were no hidden transmitters or storage devices or intentional flaws in the information barrier. Because information barriers prevents access to the data and the analysis upon which the results of an inspection are based, the inspecting party must authenticate the system.

[76] As stated in the PMDA, "The monitoring Party shall be allowed to confirm, using an agreed method, that the Pu-240/Pu-239 ratio of the conversion product is no greater than 0.10. Confirmation of this ratio shall occur using agreed methods based on measurement of the isotopic composition of the conversion product upon its receipt at a fuel fabrication facility."

For purposes of this thesis however, we focus on the potential applications of antineutrino detection in confirming the mass and isotopic composition of the conversion product, which do not include information barriers. The elimination of the prospects of augmenting verification technologies with information barriers from the Trilateral Initiative to the PMDA may have proven extremely beneficial in that authenticating that such an information system will produce accurate results of the inspected entities without any clandestine or concealed features that could prevent, interfere, or bypass proper analysis by the verification technology was a difficult, if not impossible, feat.

3.1.3 Challenges Faced and Implementation Failures

As noted, Article I of the NPT provided the greatest hindrance to the development of a verification regime for the disposition of surplus WGPu under the PMDA. Although these challenges are perplexing, they were not solely faced by the Trilateral Initiative but are common to many potential arms control and arms reduction treaties and agreements[77] [80].

Furthermore, many additional reasons were acknowledged for the Initiative's failure into being brought into force. One of the prime reasons was the US desire for Russia to submit roughly the same amount of WGPu in roughly the same forms as the US[78]. A second reason was the lack of authorization gained within each of the legislative processes of the US and Russia[79] [2].

A decision of whom should be the creator of verification technology augmented with information barriers, the inspector or the inspected state, was also undetermined. The inspected-state argument contends that it should develop its own systems for weapons or weapons materials inspection; therefore, confidence would be established that the information wouldn't be flawed or tampered with [81]. However, this poses a one-sided perspective in favor of the inspected state. In order to develop confidence for the inspector, and the world audience at large, it was argued that the inspected party should, upon decision of the design of the verification technology to be used, build multiple identical units that could be examined by the inspecting party (including removal of selected components for testing). Upon authentication by the inspecting party, "tamper-revealing seals" could potentially be placed onto prime locations—preventing any and all attempts at altering or modifying the technology [81]. However, this argument posed to be unconvincing by the inspected NWS.

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[77] These include future agreements involving transparency in warhead dismantlement procedures, US inspections of the Russian Mayak Fissile Materials Storage Facility, and, of course, plutonium management and disposition within the US and Russia as designated under the PMDA.

[78] The US wanted all WGPu under direct verification, whereas Russia wanted to blend/melt their pits into two kilogram spheres; leading to dissension amongst the two states and requiring continual IAEA intrusion for the maintenance of the pace of the development of activities.

[79] Another sticking point was a lack of authorization. Ambassador Mikhail Ryzhov, Russia's former IAEA Governor, attempted to gain Moscow's approval to engage in negotiations of a Trilateral Initiative Agreement with the IAEA, in which he failed. With new administrations in the US and Russia at this time, both holding different agendas and priorities than their predecessors, interest in the Initiative waned, where the focus was directed toward the Plutonium Management and Disposition Agreement.

3.1.4 Accomplishments

The Trilateral Initiative served as the first, official endeavor for the development of international verification procedures for WGPu disarmament and disposition. The yielded documents from the initiative were done "in confidence," with a limited distribution network to key officials only involved in the process. Although nearly a decade has passed since the conclusion of the initiative, little information has been released to the public, mostly focusing on the technical aspects of the initiative, which focused on authentication, inventory monitoring, and verification of the conversion of classified fissile material to unclassified forms.

All in all, the accomplishments and potential future steps of the initiative can be summarized from the following excerpts of the 2002 Final Report of the Joint Working Group to the Trilateral Initiative[80] [2]:

> *Excerpt 1: "Over the course of six years, the Joint Working Group addressed the technical, legal and financial issues associated with implementing IAEA verification of weapon-origin and other fissile material released from defense programs and can now recommend the successful completion of the original task. The enabling technologies developed under the Initiative could be employed by the IAEA on any form of plutonium in nuclear facilities, without revealing nuclear weapons information. The Working Group found no technical problem that would prevent the IAEA from undertaking a verification mission in relation to such fissile materials released from defense programs, and believes that many of the technical approaches could have broader applicability to other forms of fissile materials encountered in conjunction with nuclear arms reductions."*
>
> *Excerpt 2: "On the basis of the technical, legal and financial work completed, the Joint Working Group believes that each State may now proceed to negotiate a verification agreement with the IAEA in accordance with its national programs for managing weapon-origin and other fissile material released from its defense programs. Further work remains to prepare for such inspections, and the Joint Working Group recommends that technical work continue in relation to inspection procedures and authentication and certification methods applicable to possible future IAEA verification of weapon-origin fissile material with classified properties."*

Although not likely, given the event that the US and Russia decided to transition into a bilateral agreement under the stipulations of the PMDA, the IAEA or future verification regime could still play an integral role in the verification procedures. This is based on the IAEA's role to actively gather evidence regarding weaponization. In addition,

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[80] It would have been possible in 2002 for the Russian Federation and/or the United States to conclude separate verification agreements based upon the Model Verification Agreement of November 2001. The details of implementation would still require further work to resolve but, from a legal perspective, the Model Verification Agreement was essentially finished and the Trilateral Initiative has been ready for implementation since September of 2002. As indicated in Excerpt 1, all the technical work focused on verifying plutonium in classified components.

the IAEA may be given or even unintentionally 'come across' evidence arguing development of a nuclear weapon(s). Note in Article VIII.A of the NPT, member states are allowed to provide the IAEA with information that they deem potentially beneficial to the IAEA[81].

At the conclusion of the Initiative, many important questions still remain unanswered—from both a technical and political perspective. These included: How will one (i.e. inspector) authenticate that the equipment he/she is to use has not previously been tampered/altered with prior to its implementation? In addition, if an anomaly is detected, how would it be resolved and during this resolution phase, what would be the status of the remaining items?

Although no solutions were inherently identified for the latter question, the Working Group identified two potential solutions for the former question: (1) an equipment system produced by the IAEA and reviewed by the US and Russia[82] or (2) multiple equipment systems produced individually by the US and Russia and reviewed by the IAEA. Solution 2 was deemed to be the more reliable solution by the Group [2] and apparently consistent with what is transpiring with the research associated within this thesis as well as beyond.

3.2 UK-Norway Initiative

Since the establishment of the NPT, there has been deep division between NWS and NNWS; a division which resulted in the failure of an adoption for a final outcome of an agreed upon document at the 2005 NPT Review Conference. This conference revealed that this divide must be conquered in order to make the NPT truly viable in accomplishing its goals, especially in realizing its *third pillar*[83] of nuclear disarmament [82, 83]. In order to tackle this divide, the United Kingdom and Norway constructed the UK-Norway Initiative[84] which was the first of its kind to engage a NWS (the UK), a NNWS (Norway), and the IAEA in a joint-endeavor toward nuclear dismantlement verification [77, 84, 85].

Although the UK-Norway Initiative had a distinct focus on more upstream verification metrics comparable to the Trilateral Initiative's Level 3 or 4 verification procedures—which, of course, is much further up the verification procedural chain than the prospects of aid gained from antineutrino detection—the UK-Norway Initiative's investment in acknowledging NNWS as a vital stakeholder and potential inspector in the disarmament process may provide key insight in regards to the contention associated with

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[81] Note that contemporary IAEA practices to search for clandestine fuel cycle activities could potentially result in evidence regarding the nuclear weapon development activities, even if the IAEA is not specifically performing them for this purpose.

[82] One problem with this approach, however, was that any such review might take as long as 18 months.

[83] Experts in the field argue that the goals outlined in the NPT are based on the "three main pillars system" which, in descending order of importance, are: (1) nonproliferation, (2) peaceful use of nuclear technology, (3) nuclear disarmament. Although an implicit balance is expected for all three of these goals within the treaty, perusal of the treaty reveals that there is an extreme unbalance amongst all three pillars further perpetuated by the title of the treaty which has an overwhelming focus on the prevention of nuclear proliferation.

[84] From this initiative, a Norwegian study group was established to explore the technical basis for disarmament and nonproliferation and to identify areas where nuclear weapon and non-nuclear weapon states could collaborate to enhance the goals of nuclear disarmament and nonproliferation.

IAEA involvement in the PMDA disposition process due to its potential legal definition as a NNWS associated with its composition of personnel from both NWS and NNWS as discussed earlier.

3.2.1 An Additional Stakeholder in the Disarmament Process: NNWS

Through their collaborations under the umbrella of this Initiative, two discussion papers were published on the perspectives of disarmament verification from both NNWS and NWS, respectively [84, 85]. Discussion Paper 2 [84] acknowledges the problem that "[verification technologies] has been largely restricted to government scientists in NWS." Furthermore, Norway argued that it is "extremely important to involve NNWS in the development of information barrier technology at an early stage." Even if and when a technology had been deemed useful and effective, a lack of trust in its actual verification activities may spur simply because of the lack of input from the NNWS community.

Nonetheless, the peer group also posed questions, which they felt should be further clarified in future discussions prior to initial trials for dismantlement. These included:

> *What size of defect must the authentication process be able to detect?*
> *How can information relevant to authentication but obtained from other sources (e.g. by ensuring CoK) be used in the verification process?*
> *Can a necessary degree of assurance be provided without recourse to 'high tech' information barrier systems?*

Although historically NWS have insisted that they must be the sole developers and manufacturers of verification equipment that is to be used on their weapons, the UK-Norway Initiative sought in real-time the places where a NNWS can and should be involved in the selection of verification methodologies/technologies already at hand as well as aiding in the development of verification methodologies/technologies not yet conceived that are much needed in order to combat specified verification goals. Through the Initiative, the UK sought to enlighten the NNWS community on the complexities involved in a nuclear weapons disarmament process [77, 84].

Although nuclear disarmament can only be accomplished by states with nuclear arms, consistent with the goals of nuclear disarmament under the NPT, it should be done so in a method that establishes assurance amongst its NPT NNWS signatories. The research being performed on the application of antineutrino detection for safeguard purposes demonstrates the capabilities and benefits of NWS and NNWS jointly collaborating to enhance the verification of peaceful nuclear activities within nuclear reactors and offers prospects in extreme detection capability, CoK maintenance, and assurance without information barriers. Since WGPu disposition, as outlined in the PMDA, will take place through irradiation at commercial reactors during the disposition cycle, this poses a significant location for verification as well as joint research collaborations for both NWS and NNWS to determine optimal solutions for this endeavor. As outlined within the *IAEA Final Report: Focused Workshop on Antineutrino Detection for Safeguards Applications* [3], the IAEA, in collaboration with expert personnel from both NWS and NNWS, outlined "applicable inspection needs" and the usefulness/effectiveness of antineutrino detection/monitoring in meeting these needs[85]. There have already been completed independent demonstrations depicting the application of antineutrino detection through the Rovno Project, SONGS1 Project, and KASKA Prototype in Russia, the US, and Japan, respectively. Future demonstrations are actively being sought to provide further information of the effectiveness of antineutrino detection for safeguards purposes in France (Nucifer Project), Brazil (Angra Project), the US (SONGS2, SONGS3, and EARTH Projects), and Russia (DANSS Project)[86]. Although still relatively in its infancy, it was concluded that "antineutrino detectors have unique abilities to non-intrusively monitor reactor operational status, power and fissile content in near real-time, from outside containment" with completed demonstrations showing "robust, long-term measurements...at operating power reactors [3]."

3.2.2 The Inspector Challenge

The UK-Norway Initiative focused on on-site inspections simulations, which, although represents a prime component of any verification regime and successfully provided much knowledge on this concept that had not previously been encountered by other initiatives and efforts, it failed at accomplishing other key traits of the verification process. For example, the link between the information barrier and detector technology[87] were not acknowledged. In addition, although discussed at several meetings, the Initiative failed to sufficiently acknowledge issues associated with equipment authentication—an issue which was also not resolved during Field Test 34[88] [86] or the Trilateral Initiative. How is the inspecting party to know that a given verification technology has not been altered or manipulated prior to its use? However, as already stated, some experts reiterate the notion that the inspected party should "produce the [verification] equipment in multiple

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[85] There was particular focus on the implementation of safeguards for reactor facilities. Interesting scenarios for monitoring and implementation already posed include power and fissile inventory monitoring at both power and research reactors, providing demonstrations for these scenarios as well as expected timelines for completion and relative costs for planned demonstrations of antineutrino capabilities at these scenarios.

[86] Countries currently researching the application of antineutrino detection for power reactor monitoring of fissile content (specifically for MOX fuel cycles and WGPu disposition) are the US, Brazil, and France. These detectors, which will need to implement state-of-the-art neutrino detection capabilities, will seek to provide accurate measurements of the fissile content with neutrino rate measurements and independent power measurements.

[87] In particular, the UK-Norway Information barrier concept did not address the sensitive link between the barrier and the sensor itself. It is generally assumed that the detector will always provide a complete picture, which poses a nonproliferation risk, in that the full picture can provide pathways for reverse-engineering of weapons through alteration of the detector so that information can be attained prior to being protected and disguised by information barrier software.

[88] In the summer and fall of 1967, the US conducted an investigation designated as Field Test 34 based on a theoretical 'basic concept' of demonstrated destruction involving three principal stages: (1) weapon introduction; (2) weapon disassembly; and (3) component disposition. The Test involved 40 nuclear weapons scheduled for normal retirement as well as 32 fakes. Inspection teams, of different sizes levels of access (and including members of the Soviet Union), monitored the destruction of the weapons presented to them and assayed the fissile material contained therein. Evidence was then gathered relating to the amount of classified information revealed and the credibility of the dismantlement process. Toward the conclusion of the Test, it was noted that the disposition of fissile materials presented "a number of potential difficulties" because it "offered subtle possibilities for the disclosure of sensitive information," despite prime opportunities to assure inspectors that weapons are indeed being destroyed.

copies [where] the inspector can then take a sample away for review." Similar to the Trilateral Initiative, sufficient attention was not yielded to the establishment and maintenance of a credible and robust chain of custody[89]. Although an extremely challenging problem, it is not a irresolvable one, and can be potentially resolved through further research of technologies and methodologies already developed.

Once again, as acknowledged in similar inspection exercises, a balance must be identified between the inspecting party's need or access and the inspected party's need for confidentiality. The nonproliferation risks associated with the process of verification disarmament could be potentially large dependent on the access given[90]; a danger that needs to be fully addressed, especially in instances involving NNWS, given the nonproliferation obligations of NWS as outlined in the NPT. However, NWS will need to accept some level of intrusiveness in order to establish a culture of risk management with sensitive information in order to enhance the global nuclear disarmament goals. The UK-Norway Initiative, in addition to the Trilateral Initiative, have found that considerable access can be given to an inspecting party while simultaneously protecting classified information of the inspected party. For purposes of this thesis, we argue that antineutrino detection can provide considerable access and insight to the NNWS audience through joint collaborations in the technologies development and operation as well as simultaneously protecting the classified nature of US and Russian WGPu due to its placement further down the verification process. All in all, it must be acknowledged that the inspecting and inspected parties have "competing interests," they both share common priorities in demonstrating compliance and developing a successful verification regime [77]. Future exercises, especially between IAEA and the US and Russia in regards to the PMDA, should seek to identify the "optimal intersection" between the inspector's demand for information and the inspected party's willingness to supply. As the former UK Minister of Defense Des Browne said, "[it is] of paramount importance that verification techniques are developed which enable us all—nuclear-weapon states and non-nuclear-weapon states—to have confidence that when a state says it has fully and irrevocably dismantled a nuclear warhead, we all can be assured it is telling the truth [87]."

3.3 Influence on the PMDA and Beyond

The PMDA acknowledges that the IAEA should be the verifier for WGPu disposition between the US and Russia, where the US and Russia are expected to begin "early consultations" with the IAEA in order to develop such verification procedures. As acknowledged in the predecessor to the PMDA, the Trilateral Initiative determined that although the safeguards and verification of unclassified forms of plutonium should mirror

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[89] The chain of custody "demonstrates that an unaltered or uninterrupted custody or control of an item has been maintained by the owner or inspector, depending on the monitoring protocol, that provides confidence that deceptions have not been introduced." The chain begins with entry of the warhead into the dismantlement facility and ends with its placement in an extracted pit within a monitored storage facility, as identified by the UK-Norway Initiative. For applications to the PMDA in the US, this should extend all the way through until the WGPu has achieved the spent fuel standard.

[90] Chillingly, the UK Study Series acknowledge that it is possible to reverse engineer design information from raw radiometric data. Field Test 34 showed that some design secrets were exposed even at the lowest access levels and the Trilateral Initiative essentially discovered that the proliferation/security risks associated with monitoring arms reductions were "too high for comfort."

contemporary safeguards for NNWS, due to the siting of such unclassified forms within US and Russian nuclear weapons complexes, site security restrictions may pose a major hurdle for normal safeguards implementation [76].

Based on the notions learned from previous endeavors to determine verification procedures as well as the early negotiations surrounding the PMDA, it is important to reiterate the significance of coordination amongst the verification technologies identified by the US and Russia. The US has initiated unilateral openness initiatives striving to increase transparency of its nuclear activities[91]. Informal international cooperation between the US and Russia has also arisen with lab-to-lab cooperation on scientific projects and bilateral cooperation for the acquisition and accounting of nuclear materials. In addition, open visits between both countries to their respective nuclear sites have aided in improving understanding of one another's nuclear activities. Although further nuclear transparency is still sought from both countries, intense opposition from each country's respective nuclear security bureaucracies often counters it. Nonetheless, in recent history both countries have sought to limit the access to potentially sensitive site and information as Russian security services reassert their control and US security services retrench and reclassify previously open materials in response to the September 11th attacks.

Nonetheless, international cooperation between both countries, as well as partners beyond, will be essential to successfully verifying nuclear weapons disarmament and disposition. It has been argued that transparency between the US and Russia serve as the "greatest obstacle" in strengthening cooperation between both countries and one of the "principal barriers to reducing the danger that [nuclear explosive materials] will fall into the hands of terrorists, agents of proliferant states, or black marketeers who would sell to either [88, 89]." In order to combat this potential danger, agreements regarding the appropriate balance between secrecy and openness of information relating to each nation's respective national security interests should be determined and enforced[92]. The reciprocity associated with potential declarations of information from one party in order to gain information from the other party may have an ultimate beneficial effect in establishing clear and agreed upon measures for better transparency. Nonetheless, in defining information that should be revealed to global partners in the endeavor of weapons disposition, it is important to be conscience of the advantages and disadvantages of information exchanges whether it be bilaterally between the US and Russia, multilaterally with the IAEA, amongst other NWS, amongst all NPT parties, or the public in general.

Lab-to-lab cooperation will indeed be an important step in establishing the future verification technologies that are credible, legitimate, and salient to the US and Russia. In 1994, US and Russian laboratories began joint endeavors to develop and demonstrate transparency technologies[93]; where laboratory exports began working directly together demonstrating successful technologies and promoting government-to-government

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[91] This includes declassification of radiation experiments on humans, US nuclear tests, as well as open visits to nuclear facilities to the public and even Russian representatives. Although the declassified information is not complete, the nuclear-related information released by Russia is not comparable (although significantly more transparency than the Soviet Union era).

[92] This includes access provided to each nation's facilities

[93] An initial endeavor was the joint effort for remote monitoring technologies, where video cameras used to monitor material storage (minimizing the on-site inspection requirements) were installed to monitor HEU at the Kurchatov Institute in Moscow, and at Argonne National Laboratory-West in Idaho, with the images and data uplinked via satellite.

agreements while simultaneously establishing trust and developing a constituency to expand similar programming [90]. Since then, joint research endeavors continue with collaborative projects on a range of technologies applicable to confirming warhead dismantlement without revealing sensitive information[94] (and to other transparency and monitoring tasks) and detection of explosives and of nuclear materials for counterterrorism purposes [91].

With the PMDA serving as one of the introductory steps towards global zero, it is necessary to reiterate that the world audience is and will be an extremely important stakeholder in proving the verification of plutonium disposition in both countries. Verification technologies upstream, closer towards the weapons dismantlement processes, are difficult to include the parties of the global audience due to confidentiality issues regarding NWS defensive strategies as well as stipulations regarding communication between NWS and NNWS as outlined in the NPT. Nonetheless, scientific collaboration between NWS and NNWS should continue to be both a sensible and achievable goal. Cliff et al. note that benefits are accomplished for all included stakeholders of this global issue. NWS laboratories are able to escape the "intellectual confines of their classified environment [77]," while on the other hand, NNWS are allowed to "grasp the many intellectual and practical problems [77]" that NWS face. These benefits essentially spill over into the global audience by allowing "the public to gain some idea of the many scientific, technical and procedural steps, and obstacles, that lie ahead [77]."

Ultimately, establishing world confidence of the irreversibility of US and Russian nuclear weapons is essential as a first-step towards global nuclear disarmament; one that will benefit from a multilateral regime rather than simply a bilateral one. Successful reductions of the two largest weapons stockpiles would potentially spur weapons reductions initiatives of other NWS. In order to be prepared for such a future, it is vital that an international monitoring operation with systematic mechanisms be already established to take on these potentially large future challenges; one that should fall within the jurisdiction of the IAEA (based on its nature, experience, credibility, and capabilities) rather than some new multilateral verification institution. In order for the IAEA to take on such a role, it would need to be strengthened in the area of weapons-grade material safeguarding[95] requiring increased funding substantiated not just by the US and Russia, but all IAEA member states interested in verified weapons disarmament and disposition (which should be independent of current identified interests within the IAEA budget).

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[94] These included approaches implementing template and attribute procedures to confirm the presence of nuclear warheads or specified nuclear material in containers.

[95] The IAEA's responsibilities in recent decades have begun expanding into safeguards for civil nuclear material and detection of clandestine nuclear weapon programs.

Chapter 4: Safeguards Regime in the US

4.1 U.S-IAEA Safeguards Agreement

In 1967, during preliminary NPT negotiations, Japan and European NNWS opposed the NPT provision that requires only NNWS signatories to the Treaty to accept IAEA safeguards in all of their peaceful nuclear activities. In an effort to break that impasse and allay the concerns embodied in the impasse, President Johnson stated that the US was not asking any country to accept safeguards that the US was unwilling to accept and that, "when such safeguards are applied under the Treaty, the United States will permit the International Atomic Energy Agency to apply its safeguards to all nuclear activities in the United States—excluding only those with direct national security significance [92]."

The result of this endeavor was the US-IAEA Safeguards Agreement[96] which is a voluntary agreement between the US and IAEA for the application of international safeguards on US nuclear material. Under the agreement, the US is expected to provide data on declared nuclear material to the IAEA, which determines whether or not the nuclear material has been diverted for weapons development [93]. The US currently has 265 facilities (of which approximately 240 are NRC licensees) which are eligible for selection of IAEA inspection based upon a need to verify information provided by the licensee [94]. This flexible agreement, upon its conception, is expected to continue to be a crucial agreement for shaping US nonproliferation and arms control policy throughout the next century, especially with regards to the multilateral verification regime expected to fall under the PMDA [92]. The agreement was further strengthened by the Additional Protocol in 1998, which called for strengthened safeguards on US nuclear material and expanded access rights of selected facilities by the IAEA [94]. The US Additional Protocol is based on the Model Additional Protocol[97], with the exception of the National Security Exclusion[98].

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[96] It was submitted to the IAEA Board of Governors for the Board's approval in 1976. Upon submission to the US Senate, its advice and consent to ratification was given unanimously, with understandings, on July 2, 1980 and entered into force on December 9, 1980. Also referenced as the Voluntary Offer since the US was under no obligation to accept safeguards on its nuclear material based on the stipulations of the NPT, this agreement was signed to demonstrate to NNWS that the implementation of safeguards presented no economic disadvantages

[97] In May 1997, the IAEA Board of Governors approved the *Model Protocol Additional to the Agreements between the States and the IAEA*, and the IAEA Department of Safeguards immediately began negotiating "Additional Protocols" to the States' safeguards agreements. This was a by-product of the IAEA Program 93+2, which sought to provide the most effective and efficient overall approach to strengthen safeguards through new measures while simultaneously reducing the frequency of other measures and thereby saving costs.

[98] In Article 1.B of the US-IAEA Agreement Additional Protocol it states, "The United States shall apply, and permit the Agency to apply, this Protocol, excluding only instances where its application would result in access by the Agency to activities with direct national security significance to the United States or to locations or information associated with such activities." Hence, the US, since it is an acknowledged NWS under the NPT, is entitled to exclude from declaration and deny access to locations, activities, and information it determines to have, or be associated with, direct national security significance.

4.2 LWR Safeguards

As stated in Article III.2.a-b of the amended 2010 PMDA, the United States is expected to dispose of their designated WGPu through irradiation in a minimum of four LWR while Russia is to dispose of their designated WGPu through irradiation in their BN-600 and BN-800 fast reactors. In this section, we explore and examine the potential safeguards and security environment, from both a domestic (NRC) and international standpoint (IAEA), for the US selected LWR under the PMDA. All IAEA safeguards implementation is fundamentally regulated by the IAEA Statute[99] and by the Safeguard Agreements. The IAEA currently has safeguards programs implemented on more than 160 LWR[100] in the US, where their technical objective at the LWR is the "timely detection of the diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by risk of early detection... [seeking to] provide credible assurance not only about the declared nuclear material in a State but also about the absence of undeclared material and activities [93]." The IAEA safeguards approach primarily focuses on *Item Accountancy* and *Containment and Surveillance (C/S) Measures* to achieve inspection goals through three main elements (physical protection, materials control, and materials accountancy) [3, 95]:

> **Item accountancy:** This includes item counting, serial number identification, book auditing, annual evaluations of nuclear material balances, examination of operating records, reconciliation with accounting records, non-destructive analysis (NDA) and other qualitative measurements, and examinations to verify the continued integrity of the fuel assembly prior to core loading.
>
> **Containment and surveillance (C/S) measures:** These are used to complement the accountancy verification methods for safeguarding the core fuel and spent fuel through monitoring technologies. LWR cores are usually not opened more than once per year, and for this reason, surveillance systems are vital in surveying the area where spent fuel is store stored; providing the IAEA with the capabilities of detecting undeclared movements of nuclear material as well as potential tampering with containment and/or IAEA safeguard technologies.

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[99] In paragraph 2 of The Structure and Content of Agreements Between The Agency and States Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons [INFCIRC/153 (Corrected)], the model for safeguards agreements, stipulates more specifically that safeguards will be applied "...for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices..."

[100] Reactor safeguards are implemented at about 200 power reactors and at several hundred more research reactors worldwide.

The inspection goal for a facility consists of a quantity component[101] and a timeliness component[102], where the IAEA strives for the full attainment (criteria relevant to the material types and categories present at the facility) of both components [95]. In addition to the aforementioned tasks, the IAEA has emphasized that, "safeguards inspectors will increasingly need not only to be knowledgeable about traditional and advanced fuel cycles and plant operations, but also to possess sophisticated analytical skills in the detection of early signs of weapons development [96]."

In addition to the economic, technical, legal, security, safety, environmental and other burdens faced by reactor licensees, the IAEA believes safeguards should be a precaution that should not add additional strain to reactor operators, especially in the case for those specified for WGPu disposition. Historically, IAEA safeguards at nuclear power plants have been applied mainly to existing or already designed plants, hence, its implementation at designated US WGPu LWR should not pose a major hindrance from this standpoint. However, a couple of the specific developments affecting the application of safeguards to nuclear power plants are "the use of MOX fuel in some reactors [and the] use of remote interrogation of installed safeguards equipment, leading to more efficient safeguards coupled with fewer on-site inspections [93]." Nonetheless, with the incorporation of a safeguards regime for an LWR, the IAEA seeks to: (1) minimize the burden on plant operations; (2) promote better understanding of safeguards operations and needs by reactor designers; (3) ensure the effectiveness of the safeguards regime and promote advances in the quality, methods of acquisition and integrity of safeguards data; (4) minimize the cost of safeguards, including the burden on IAEA inspection resources; (5) improve, for both operators and inspectors, the conditions under which inspections are carried out; and (6) take advantage of advances in safeguards technologies [93].

Prior to IAEA inspections commencing at a US LWR, they must first engage with the NRC who is responsible for notifying the selected facility that it must submit to IAEA safeguards. The NRC is the US domestic safeguards entity responsible for "ensuring that special nuclear material within the United States is not stolen or otherwise diverted from civilian facilities for possible use in clandestine fissile explosives and does not pose an unreasonable risk owing to radiological sabotage [97]." Domestic safeguards serve as part of a nation's internal security activities where key parts of their activities incorporate many of the physical protection, materials control, and materials accounting procedures similarly performed by the IAEA's international safeguards system[103]. Although they share many of the same traits and the IAEA may advise the NRC on the results of its observations made during normal safeguards activities, either informally or by request, the IAEA has "no responsibility either for the provision of a State's physical protection system or for the

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[101] The quantity component relates to the scope of the inspection activities necessary in order to provide assurance that there was no diversion of a significant quantity (SQ) of nuclear material over a material balance period (MBP).

[102] The timeliness component relates to the periodic inspection activities necessary to provide assurance that no abrupt diversion has taken place.

[103] As noted in the IAEA's INFCIRC/225: The Physical Protection of Nuclear Material, "the objective of the State's physical protection system should be: (1) To establish conditions which will minimize the possibilities for unauthorized removal of nuclear material or for sabotage, and (2) To provide information and technical assistance in support of rapid and comprehensive measures by the State to locate and recover missing nuclear material."

supervision, control or implementation of such a system [98].” The key challenge for any domestics safeguards program is detecting and identifying potential threats, both externally (thieves, terrorists, hackers, etc.) and internally (employees, contractors, etc.). Unfortunately, internal threats present the most commonly encountered threat[104], accounting for 41% of crimes committed against assets [99, 100]. As it relates to the intentions of the PMDA, the internal threat of diversion scenarios associated with a perceived US interest in maintaining WGPu volume, may also serve as a credible threat from the perspective of those outside the US. For this reason, collaboration between the NRC and IAEA onsite at US LWR will be essential in ensuring confidence of WGPu disposition at this section of the plutonium disposition chain.

The NRC is to provide technical assistance to the IAEA, supporting US initiatives to extend and enhance international safeguards and other verification programs, as described in the PMDA. The reactor/facility operator, IAEA, and NRC[105] are then to negotiate the terms of the inspection all guided by the terms described in the NPT, the US-IAEA Safeguards Agreement, and the Additional Protocol [94]. However, upon IAEA requests to access facilities associated with the DOE security interests, DOE is to assume responsibility for implementing the Additional Protocol at the facility. Because of the managed access clause, any activity, component, process or otherwise proprietary information deemed sensitive by the government can be concealed/excluded during the inspection visit[106]—however, assuming the IAEA is to play a multilateral role in the verification of WGPu disposition under the PMDA, means of verifying actual disposition should not fall under this clause. In addition, although the disposition of the fuel will take place in LWR, the WGPu MOX fuel still falls under DOE jurisdiction and hence, both parties will have to work with IAEA regarding inspections and verification measures at the reactors designated for the irradiation of the WGPu MOX fuel. For this reason, we briefly investigate the WGPu MOX fuel safeguards landscape, which is expected to mimic normal MOX fuel safeguards protocols, by examining the collaborative exercises expected to take place between the DOE and IAEA.

4.3 MOX Fuel Safeguards

In this section, we explore the potential safeguards environment, both domestically and internationally, for the WGPu MOX fuel to be irradiated in US LWR as defined by the PMDA in an attempt to examine the security landscape incorporating the collaboration of the IAEA and NNSA[107].

MOX fuel poses more of a safeguards risk than conventional LEU fuel due to its plutonium content. For this reason, facilities implementing MOX fuel programs under IAEA safeguards require monthly verification inspections through item counting, serial

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[104] This may be due to insiders having access to the knowledge of operations and security plans and unescorted access.

[105] The NRC’s participation is intended to protect proprietary, sensitive, or classified information at the location.

[106] The licensee must, however, make a reasonable effort to allow for the collection of necessary data through other possible means.

[107] Although initially acknowledged as falling within the jurisdiction of DOE, DOE interests related to the “management and security of the nation’s nuclear weapons, nuclear nonproliferation, and naval reactor programs,” are all to fall within the NNSA, a separately organized agency within DOE.

number identification, and seal verification (assuming that the MOX fuel is received from an IAEA safeguarded facility). Although not applicable to the expected practices associated with WGPu MOX fuel that will be received from MFFF (which is expected to also fall under some sort of IAEA-NNSA monitoring regime), in specific cases where fresh MOX fuel is received from unsafeguarded facilities, additional NDA measurements are performed[108] [95]. Contemporary NDA techniques of MOX fuel includes relatively straightforward use of portable detection equipment, optical and/or neutron plus gamma surveillance system, and monitoring systems to detect movements of the assemblies after they have been placed in dedicated locations in the pool for MOX fuel storage (dry storage presents an easier safeguard pathway than wet storage). We envision the addition of antineutrino detection to contemporary NDA techniques as a means of strengthening MOX fuel safeguards; for purposes of the PMDA and eventually beyond to the more global safeguards environment. Since MFFF is expected to fabricate the number of MOX fuel assemblies consistent with customer demand, storage should be relatively nonexistent, which is desirable from a safeguards perspective [93].

In 1998, fresh MOX fuel was loaded into 14 reactor cores, where 6 plutonium conversion and MOX fabrication plants were under IAEA safeguards. This required 10,000 person-days of inspection (PDI) effort; of which, 25% of this workforce was strictly devoted to facilities using unirradiated plutonium. Because of the massive costs associated with inspection personnel, the IAEA has sought means of reducing its inspection costs while still maintaining credible assurance[109] that plutonium is not diverted from MOX conversion facilities, fabrication facilities, and reactors using MOX fuels [101] in a global environment where MOX use is expected to increase dramatically in Europe and Japan. It can safely be assumed that a similar perspective is also given to the US and Russian plutonium disposition campaign of the PMDA.

The IAEA's current approach in combating this hydra of a problem is through concentration of NDA verification activities at MOX fuel sites by maintaining CoK on fresh MOX during shipment, storage, and core loading at LWR using conventional C/S techniques[110] [102]. Verification of the category change of MOX fuel (from unirradiated to irradiated direct-use material) is of prime concern is also of prime concern, where the

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[108] If kept in dry storage, the fuel is monitored through seals, and if kept in wet storage, it is monitored through surveillance. Seal verification and/or surveillance evaluation is also carried out on a monthly basis in addition to the usual accountancy verification methods.

[109] With posing issues of costs associated with increased staffing, it is vital that the IAEA continue to attract and retain high-quality professionals required to complete these highly specialized missions of maintaining peaceful, global nuclear use.

[110] Consistent with contemporary safeguard practices, MOX shipping containers are sealed by metal cap seals and/or Canberra VACOSS seals, where until core loading, fresh MOX fuel is monitored through digital surveillance devices such as the All in One System (ALIS) and the Digital Multi-Channel Optical Surveillance (DMOS) system. VACOSS seals are removed at the reactor by an IAEA inspector prior to placing the fuel into storage. The ALIS is an intelligent camera system for safeguards surveillance applications that enables the user to perform a quick set-up of the system as required for a specific surveillance application without additional equipment. The DMOS system was designed to replace the analog multi-channel system used for safeguards, bringing digital processing capabilities to analog systems currently in use. The system is designed for unattended safeguards operations, but can easily be adapted for remote monitoring operations.

current practice is simply surveillance mechanisms[111] used to confirm the transfer of individual MOX fuel assemblies to the core and to monitor the movement of these fuel assemblies until the core has been closed [95]. In addition, the seals on reactor cores are directly verified for proper operation quarterly during IAEA inventory verification exercises, and serve as the best method for maintaining verification knowledge of reactor core fuel during inspections associated with inventory verification exercises. Although this serves as the best means for verification knowledge maintenance, some reactors pose issues with access to seals, either because it is located in an area of high radiation dose rate (thus not accessible during reactor operation) or because there is a high risk of contamination in the area surrounding the seal. Optical surveillance of the reactor vessel sited within the high radiation area then serves as the only means of maintaining verification to meet the specified timeliness goals. Regardless of the methods used, ascertaining that all fuel assemblies are placed into the core and that none are removed, concealed as a dummy, or discharged as spent fuel, still appear to be credible risks to the contemporary MOX safeguard practices.

The IAEA falsely finds these approaches justifiable since safeguarded reactor areas are constantly under surveillance beginning when the detachment of the reactor vessel containment seal[112]. The weakness with these core verification approaches, however, is that knowledge of the reactor core following such verification exercises are strictly maintained through an optical surveillance system. This system, unfortunately, is incapable of detecting all transfers of fuel between the core and spent fuel pool[113].

For these reasons, potential design mechanisms that could be implemented, as identified by the IAEA, that would significantly aid in safeguards of MOX fuel in the reactor core include [93]:

1. *Suitable, accessible reactor core sealing systems which are simple to install and damage-resistant*
2. *Surveillance equipment capable of monitoring reactor operations during opening of the reactor vessel*
3. *Underwater illumination coupled with sufficient water clarity—this would aid inspectors' abilities to physically count fuel assemblies and read their identifiers*
4. *Means of monitoring reactor fuel while simultaneously minimizing the radiation exposure to inspectors and reactor staff*

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[111] This can be provided through two flavors: human surveillance (presence of inspectors during relevant operations) and/or unattended video surveillance (underwater cameras). Dependent on the reactor type, the human surveillance option requires a verification effort of 20-30 PDI (where the surveillance option typically requires 6-10 PDI).

[112] The assumption here is that spent fuel was transferred directly from the core to the spent fuel pool (and no spent fuel transport container movements were detected) and replaced with fresh fuel. Fresh fuel assemblies recently loaded into the fuel core are usually distinguishable from irradiated once-used and twice-used fuel assemblies that are to remain in the fuel core.

[113] Possible propositions that have been made to resolve this issue include the design/implementation of a more robust surveillance system capable of monitoring the movement of items into and out of the reactor core itself. Potential diversion strategies at this level, in which the IAEA seeks to combat, include instances where the plutonium-rich irradiated fuel are substituted by fresh/dummy fuel where it is assumed that the diverted irradiated fuel may be potentially removed from the spent fuel pool under "contrived surveillance failure."

Although (1) and (3) serve as vital needs in strengthening IAEA MOX safeguards, mechanisms (2) and (4) can be successfully achieved via unattended monitoring systems (UMS) and remote safeguards inspections (RSI).

4.4 UMS and RSI

As already stated above, the classical safeguards approach at LWR consists of a combination of routine interim and physical inventory verification inspections incorporating nuclear material item accountancy, containment and surveillance, and other measures required to establish confidence that no unsafeguarded nuclear activities have taken place. The push to deploy UMS began in the late 1980s and increased dramatically with the introduction of Program 93+2[114]; rapidly advancing along with technological leaps in the capability and reliability of hardware, firmware, and software designed to improve LWR safeguards [95].

A UMS is defined as any automated monitoring system, permanently installed in a nuclear facility, with a single/multiple set(s) of sensors[115] capable of maintaining CoK about the content and location of all nuclear material of interest in a facility 24 hours/day and 365 days/year without the need for human interaction. The intent is that the system may provide the necessary assurance for the IAEA to draw rapid, comprehensive and definitive conclusions that nuclear material is not being diverted from peaceful use which directly relates to goal quantity and conversion times and abrupt and protracted diversion. There are currently more than 130 UMS around the world, with the majority based off of radiation, thermo-hydraulic, and process-monitoring designs [33].

The IAEA believes the introduction of UMS will yield significant cost savings (inspector worldwide travel), reduced inspection effort (either announced or unannounced) and on-site activities (unattended assay, monitoring systems with data collection, and review/evaluation at remote locations), 100% verification with reduced levels of intrusiveness to the operation of nuclear facility, minimized interruption to facility operations, and reduced radiation exposures[116] to IAEA inspectors and plant operating staff [102]. Although massive costs reductions have been observed with the integration of UMS, a cost-benefit analysis on a case-by-case basis is needed, where all boundary conditions, state-specific factors, capital costs, and human resource requirements for its implementation and maintenance are all considered prior to its application [103].

A high level of reliability is vital to efficient LWR safeguards verification; loss of

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[114] In response to Iraq successfully circumventing IAEA safeguards by exploiting the agency's system of inspection and monitoring activities limited to facilities or materials explicitly declared by each state in its safeguards agreement with the agency, the IAEA established the safeguards improvement plan known as "Program 93+2" which sought to eliminate this "undeclared facilities" loophole. The plan's name reflects the fact that it was drafted in 1993 with the intention of being implemented in two years.

[115] It may use a variety of sensors such as radiation, pressure, temperature, flow, vibration, optical, and electromagnetic fields to collect qualitative or quantitative data.

[116] Exposure control methods are generally well known to reactor designers because of the desire to minimize radiation exposure of the operations staff. The trend towards greater use of remote monitoring for safeguards purposes is helpful from this perspective; one in which design measures should include mechanisms to minimize such exposures and to provide the necessary radiation protection supplies and services such as protective clothing, dosimeters, and showers for IAEA inspectors.

CoK requires extensive efforts to reestablish inventories of safeguarded material and can cause concern if such inventories cannot be reestablished. Redundancy, diversity, and quality assurance are key conceptual approaches used to achieve high reliability in nuclear power plants [93]. These concepts can be coupled with RSI while transitioning to Information Driven Safeguards[117]. Verification and monitoring through RSI are required to satisfy IAEA's requirements for authenticity[118], completeness[119], and correctness[120]. RSI aim to join and extend remote monitoring with potential novel opportunities for enhanced cooperation for optimized safeguard approaches. They provide a very promising pathway for potential optimization and joint effort while still maintaining credible safeguards practices; one which signals a mindset transition from one of a "passive tolerance of safeguards implementation by most S/RSAC and operators" to one of "an active and enhanced support role...promot[ing] peaceful use of nuclear energy [103]."

It should be noted that the RSI approach does not target to eliminate the need for on-site inspections but merely to reduce its frequency beyond present levels shifting resources from routine to non-routine activities[121]. Nonetheless, IAEA capacities to draw its own conclusions based on information provided by State and Regional Systems of Accounting and Control[122] (S/RSAC) and the operator should be established in order to validate their information are also vital; one in which the RSI concept aims to increase beyond present levels. Article 7 of the Comprehensive Safeguards Agreement states that the IAEA should acknowledge its technical effectiveness of a State's system by avoiding duplication during its verification and inspection efforts. The IAEA should seek enhanced cooperation with an effective, technically competent and independent S/RSAC partner during joint inspections [103].

UMS employing RSI are extremely important in nuclear facilities with highly automated capabilities and where access to nuclear material is virtually impossible; high neutron/gamma radiation fields limit human inspection time where RSI could play a vital role in overcoming these limitations. Approximately 8,000 PDI of IAEA effort is spent globally per year—a place where considerable savings through UMS complimented by RSI (using randomized, unannounced inspections) could be implemented. LWR implementing MOX fuel programs, like PMDA-selected US LWR, provide further areas where further potential in savings could be realized [103]. Although US experience with MOX fuel is dated and scarce, IAEA experience with a typical LWR implementing a MOX fuel

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[117] IDS applies enhanced analysis of all information available to the IAEA together with physical verification using up-to-date equipment and methodologies, complemented with, to ensure that States have fully complied with their non-proliferation undertakings. It is designed to provide an uncompromised level of assurance of non-diversion of declared nuclear material and the absence of undeclared nuclear material and activities in a State.

[118] Authenticity of data is a pre-requisite to ensure a valid interpretation of the collected data.

[119] Completeness essentially means no gaps in the data which provides assurance that all items are monitored.

[120] Correctness of data is necessary for qualification and quantification of the verified and monitored nuclear items.

[121] These include complementary access activities, unannounced inspections, validation or authentication of operator's data, other activities in order to increase the assurance of the absence of undeclared nuclear material and activities, and activities related to resolution of the specific safeguards concerns.

[122] This term is used here to denote all US domestic safeguards practices, which, as acknowledged may reside within the terms of the NRC or NNSA depending on the facility or process considered.

program requires an inspection effort of approximately 200 PDI compared to "normal" LWR, implementing conventional LEU fuel cores, which requires only approximately 10 PDI. As noted, MOX use is expected to increase dramatically, especially with the targets of the US and Russia plutonium disposition campaign. Because a proportional increase in budgetary resources is unexpected and highly unlikely, transitions from routine field activities towards RSI would prove beneficial in decreasing inspectors' inspection burden and the complex information evaluation process[123] [103].

Although RSI aims to potentially minimize inspections at the reactor site, it does not seek to eliminate them. Domestic and international safeguards inspections are seen as "interruptions" to the nuclear facility operator's routine activities[124] [95]. As already acknowledged, attaining customer reactors to aid in the US plutonium disposition campaign has been tumultuous endeavor; one which may prove to be even more difficult with customer knowledge that increased inspections would be resultant WGPu MOX use. For this reason, we argue that the application of UMS should be the primary focus sought in order to make future safeguard measures more considerate for the desires of nuclear facilities operators. Overall success in the application of safeguards, from both the inspector and inspected party perspectives, will be realized by minimizing routine inspection activities, making better use of inspector's time in seeking to detect undeclared nuclear material and activities, delivering more timely safeguards data coupled with quick feedback/instructions for follow-up action to the field inspectors [103].

Nonetheless, further developmental and deployment strategies are essential for continued success of UMS, which serve as the foundation for RSI. Field trials at various facilities have been initiated and already demonstrated, seeking to investigate the feasibility and practicality of deploying RSI in developing a coherent model for its implementation. In addition, preparations for future field trials may reveal areas where revisions in current policy [104] are necessary and the proposed revisions could be tested during the field trials under an adaptive management mindset. It should be noted, however, that adaption of a regime strengthened by UMS coupled with RSI will require endeavors for negotiated agreements between the IAEA and S/RSAC authority, defining all of the operational conditions[125] [103]. Future UMS developments should lack extensive user training and expensive equipment logistics and should be completely compatible with current-use safeguard instrumentation and seek standardization/modularization of equipment. Additionally, future UMS developments should be familiar with the specified requirements designated by the IAEA technical experts to enable IAEA independent verification and monitoring capabilities intended for joint use by IAEA, S/RSAC, and other operators.

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[123] RSI will play an increasingly important and versatile role in aiding inspectors to make better use of their time in the field with the assistance of technology that would provide them with improved data gathering and enhanced analysis tools and that would connect them in near real-time with IAEA managers, safeguards experts, and IAEA databases.

[124] Questions of concern that have been asked to develop more considerate safeguard measures include: How do facility operators regard safeguards inspections during a refueling outage when their time is heavily occupied with maintenance and shutdown activities? How much time is involved for a normal routine safeguards inspection?

[125] This includes the technical agreement with the operators to implement the RSI measures, which should also address security concerns of operators and S/RSAC towards the remote transmission of process data beyond obligatory declarations.

4.4.1 Successful UMS: Antineutrino Detection at LWR

In the 2010 protocol to the PMDA, the US and Russia agreed on a revision to seek methods of placing their surplus WGPu under IAEA safeguards and monitoring [105]. In September 2010, both nations submitted a joint letter to the IAEA requesting that the Agency establish verification measures with respect to their excess weapon-grade plutonium disposition programs[126] [13]. The US, Russia, and the IAEA have set the goal of preparing the appropriate verification agreements in the near future.

One of the most vital locations for safeguards and verification procedures to exist, as they relate to the PMDA, will be located at point of the disposition chain where the WGPu is to be transformed from a potential proliferation threat into its proliferation-resistant disposed form. In the US, this point in the disposition chain occurs at the LWR site[127] when the WGPu MOX fuel is irradiated until it reaches a burnup level of at least 20 GWd/MTHM.

As noted, US LWR currently under safeguards implement item accountancy supported by C/S. The application of antineutrino detection by a safeguard regime would provide the ability to measure—in near real-time—the reactor operational status, power history, and core fissile inventory; all of which are key aspects addressing many of the inspectors needs [3]. In the case of measurements involving the antineutrino rate alone, a product of fissile inventory and power is constrained throughout the cycle. By contrast, measurement of the antineutrino energy spectrum allows both quantities to be constrained independently, without knowledge of the other. In the context of plutonium disposition, it is expected that the initial isotopic contents of fuel assemblies will have been verified upstream by other means, and that a verified core map will be available to the inspectorate. In this case, a rate-based measurement alone would constrain subsequent burnup and isotopic content, without further operator input.

This technology's ability to provide insight into elemental and isotopic composition of the reactor core should prove to be extremely advantageous. In addition, while the core is operational, it meets a key safeguard interest of maintaining CoK at the reactor core as discussed in Section 4.2. Such insight could be useful as an independent means of resolving and/or detection shipper-receiver differences, or confirming the consistency of fuel composition prior to and after refueling periods. Such successful prospects of antineutrino detection as they relate to PMDA associated LWR monitoring are discussed in further detail in the following chapter. Although beyond the scope of this thesis, for future LWR designs, antineutrino detection should be considered as part of *Safeguards by Design* simple, concise, formalized, and integrated approach to nuclear facility designs incorporating principles of nonproliferation, international safeguards, and US national safeguards [106].

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[126] Although the IAEA was an equal partner in the Trilateral Initiative, in the PMDA, a different team of US officials carried out the bilateral negotiations, and the IAEA was informed of the PMDA for the first time when the negotiations were essentially concluded. Because the agreement did not include provisions for taking classified forms of fissile material into IAEA monitored operations, the process of engaging the IAEA has appeared to be of minimal importance.

[127] The Gas Turbine Modular Helium Reactor is also mentioned in the agreement as a potential reactor to be used in aiding either the US or Russian plutonium disposition campaign. However, since plans of developing such a reactor in the US in the near future is highly unlikely, it is not considered in this work.

Chapter 5: Antineutrino Detection

5.1 Overview of Antineutrino Detection Physics

In 1914, Chadwick measured the energy spectrum of beta particles produced in the beta decay reaction:

$$^{214}_{82}Pb \longrightarrow ^{214}_{83}Bi + \beta^-$$

The energy spectrum observed was continuous, and showed that the beta particles produced had an energy, E_β, less than that of the difference between the rest mass energies of the parent and daughter nuclei, E_0. These observations contradicted the energy conservation principle, which essentially states that if the nuclei are at rest (prior to and following the decay process), every beta particle produced should have left the decay reaction with an energy equal to E_0. However, this was not seen, and it was apparent that there was energy unaccounted for—leading to the hypothesis of the production of another particle [107, 108].

This particle was the neutrino, and in 1930, Wolfgang Pauli identified the existence of this particle through the reconciliation of the energy conservation principle with the process of beta decay [109]. He hypothesized that the neutrino was escaping the decay reaction undetected with energy of $E_0 - E_\beta$. This hypothesis was further developed into a theory of beta decay by Fermi in 1934, which predicted that the probability of interaction amongst neutrinos was extremely small [110]. Experimental confirmation of this theory occurred approximately two decades later in 1956 by F. Reines and C. Cowan, who discovered the production of neutrinos' antiparticles, antineutrinos, at the Hanford nuclear reactor by measuring the elusive particles[128] [2]. Reactors of this period produced antineutrinos at a rate of approximately 10^{19} particles/second, a large flux Reines and Cowan thought necessary to overcome the barrier to detection of the neutrino posed by the small cross section of the inverse beta decay process [107]. Although Reines and Cowan were successful in providing evidence for the existence of the neutrino particle, conclusive evidence of the particle wasn't observed until an improved experiment was conducted at the Savannah River reactor site in 1958 [111].

Antineutrinos are produced when a nucleus undergoes beta decay. These decays occur in fission products and their daughters in nuclear reactors, where, on average, each fission event yields approximately six antineutrinos. The actual number and energy distribution of these antineutrinos, however, is dependent upon the isotope undergoing fission. The inverse beta decay reaction is the primary method used in the detection of antineutrinos, and can occur either with a proton or a deuteron as demonstrated in the equations below:

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[128] The difficulty in detecting antineutrinos arises from the fact that they are uncharged, nearly massless leptons, and therefore are not affected by either the electromagnetic or the strong nuclear force. The only force that significantly affects antineutrinos is the weak nuclear force, which has a shorter range and is much weaker than the aforementioned forces.

$$\bar{\nu} + p \longrightarrow \beta^{+} + n$$
$$\bar{\nu} + d \longrightarrow \beta^{+} + n + n$$

However, for purposes of our detection mechanism of interest, we focus on the proton-related equation. The produced positron, which carries away most of the antineutrino energy, loses energy via ionization in the detection medium, and then quickly annihilates with an electron in the medium, producing two simultaneous photon emissions. The combined ionization from the positron, and from the Compton electrons generated as the annihilation gammas scatter within the detection medium, is deposited within a few nanoseconds. This very rapid energy deposition is referred to as the *prompt signal*. The produced neutron is thermalized and is eventually captured by an absorbing nucleus. Hydrogen capture is possible and does occur, but often a dopant is added to the detection medium (i.e. Gd, Li, Eu, etc.)—which captures and then decays via a cascade of γ-emissions. The thermalization and capture time is determined by the medium and the dopant. For example, with 0.1% doping of Gd in typical liquid scintillator media, a significantly delayed (~30 μs) signal relative to the prompt signal occurs: this is sensibly referred to as the *delayed signal*. Both of these energy depositions are identified via coincidence detection, which dramatically suppresses backgrounds. Figure 5.1 below illustrates this reaction as it may occur in a detector.

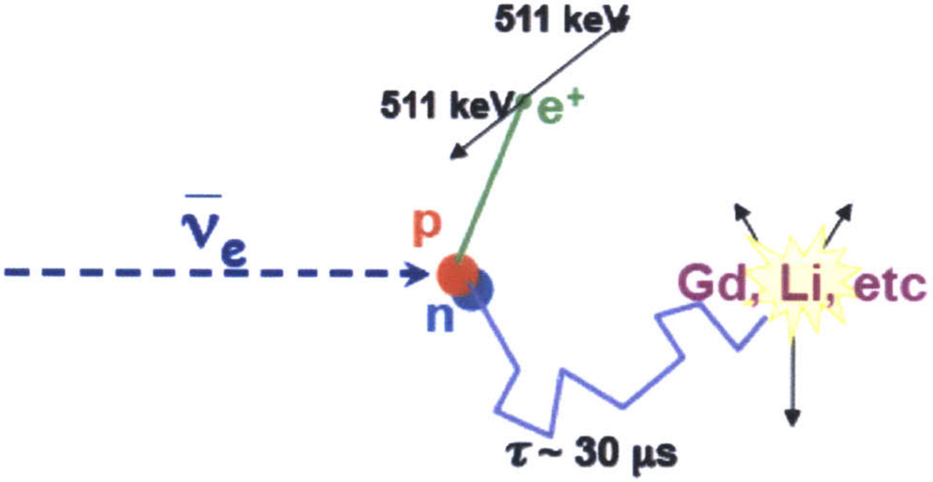

Figure 5.1: Inverse β-decay Reaction in Antineutrino Detector.
Courtesy of [112].

Because the production of antineutrinos results from nuclear fission, many applications of interest have to do with nuclear nonproliferation. The antineutrino measurements of interest for nonproliferation applications are the antineutrino rate produced by the reactor, the antineutrino energy spectrum, and the antineutrino direction.

5.2 Detector Field Trials

A successful recent application of near-field antineutrino detection is the SONGS1 detector deployed by a research team from the LLNL and Sandia National Laboratory (SNL) at the San Onofre Nuclear Generating Station (SONGS) in Southern California (See Figure 5.2 below).

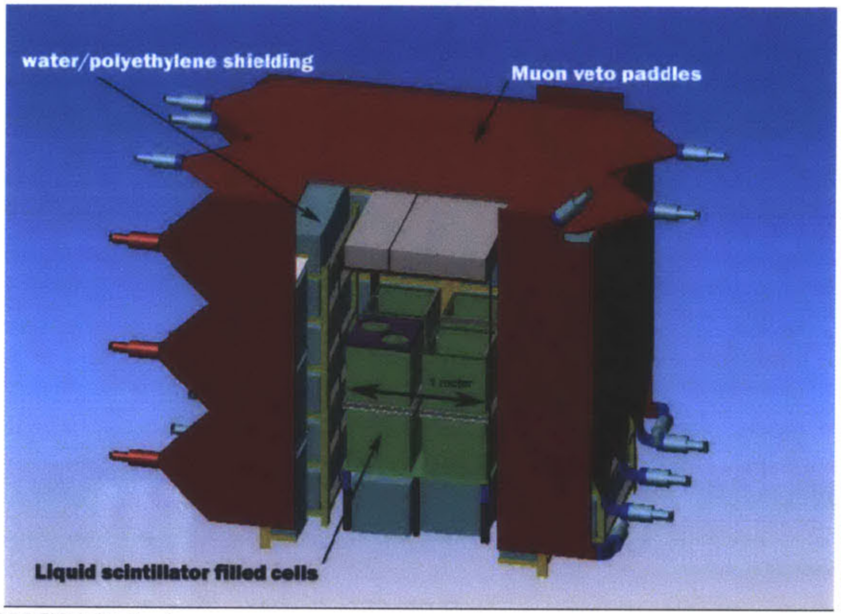

Figure 5.2: SONGS1 Detector.

SONGS1 was used to non-intrusively monitor the operational status, relative thermal power, and changes in fissile content of a 3.64 GW_t reactor from 2004 through 2008 [113]. The detector had a mass of 640 kg and operated at a standoff distance of 24.5 m[129]. It uses a proton-rich liquid scintillator detector doped with gadolinium to facilitate inverse beta-decay interactions. The resultant traveling positron and the positron-electron annihilation create a prompt scintillation flash, while the neutron-gadolinium interaction induces a delayed scintillation flash. Both flashes are detected via photomultiplier tubes. SONGS1 has the ability to detect the reactor operational status (on or off) within 5 hours of shut down or start up at the 99% confidence level and is able to measure the reactor power, relative to a known initial value, with 3% accuracy in one week [113].

Although the SONGS1 detector has proven successful in its field trial, drawbacks still exist with the technology. To begin with the detector is large: accounting for a water/polyethelyene shield, the entire system weighs about 25 tons and has a volume of about 25 m^3. Furthermore, the selected liquid scintillator is flammable, toxic, and carcinogenic, requiring the unit to be transported as hazardous material—a perceptual if not

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[129] It operates approximately 10 m underground in an area known as the tendon gallery so that facility personnel are not disrupted from day-to-day operations. This gallery also protects the detector from cosmic radiation that can also produce antineutrino events. At this location, the detector has an antineutrino pass rate of approximately 1×10^{-5} antineutrinos produced by the reactor. Of this probability, only an estimated 10% will result in a detectable signature for this detector.

actual safety problem for a technology with expectations for worldwide deployment. It should be noted that at many reactors, large underground galleries exist which can accommodate detectors of this size without significant interference with reactor operations. This was demonstrated by the SONGS deployment campaign, which has operated for nearly 8 years (including upgraded detectors) without interfering with plant operations at the SONGS site. Moreover, owing to advances in the field of scintillation detector development, there are now commercially available high performance doped liquid scintillator formulations which have significantly improved safety characteristics, and in particular which need not be transported as hazardous material. Additional research effort can be expected to yield further improvements. For example, spectral measurements providing a more robust constraint on the reactor evolution are also possible [114]. The team has designed and fielded two additional prototypes, the SONGS2[130] and SONGS3[131] detectors, which have mitigated the drawbacks of the SONGS1 detector by operating with less hazardous material[113]. Current work relates to shrinking the detector footprint by decreasing the amount of shielding material required to achieve a given level of sensitivity [5].

SONGS and similar detectors like Brazil's Angra Project and France's Nucifer Detector hold strong prospects as successful verification metrics for WGPu disposition under the stipulations of the PMDA.

5.3 Expected Antineutrino Signal Estimation

Antineutrino detection for reactor monitoring exploits the relationship between (1) the antineutrino count rate and energy spectrum and (2) the reactor power and the fissile isotopic content of the core. As fuel is irradiated within the reactor core, the isotopic masses and fission rates vary in time[132]. This variation in fissionable isotope content also results in the variation of antineutrino flux during the core evolution because of the differences in the average number of antineutrino emissions per fissionable isotope.

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[130] SONGS2 uses a plastic, instead of a liquid, scintillator. Gd, which cannot be mixed with the plastic because Gd compounds degrade the plastic's transparency, is mixed into a paint and applied on the walls of plastic sheets which were then alternated with pieces of plastic scintillator in the detector design. The detection mechanism implemented in this detector occurs when an antineutrino collides with a proton within the plastic scintillator resulting in scintillation light while the resultant neutron travels randomly through the plastic until it is captured by a gadolinium nucleus in the paint. Similar to the SONGS1 mechanism, the neutron–gadolinium reaction produces γ emissions resulting in additional scintillation light.

[131] SONGS3 uses water mixed with gadolinium and measures Cerenkov light rather than liquid or plastic scintillation devices as used in SONGS1 and SONGS2, respectively. Cerenkov light, predominantly ultraviolet, occurs as a result of charged particles traveling faster than light through a specified medium, in this case water. The detection process in this detector follows the same inverse beta decay reaction when an antineutrino collides with a proton in the detection medium, yielding positron and neutron. The decelerating positron emits Cerenkov radiation until its annihilation. The resultant neutron is captured in the Gd nucleus in the water producing the familiar gamma-ray cascade which generate fast Compton-scattered electrons resulting in a second flash of Cerenkov light. Although more benign than its former detector designs, the interactions in the SONGS3 detector results in approximately a 100 times less light than the SONGS1 and SONGS2 detectors. This detector design does boast, however, less attribution to background radiation since it is impervious to high-energy neutron radiation caused by cosmic muons, which can mimic the antineutrino signature in scintillator detectors.

[132] This variation in turn causes a systematic shift in the antineutrino flux, known as the "burnup effect." The effect has long been recognized and corrected in reactor antineutrino physics experiments.

In order to estimate the expected antineutrino signal produced from a reactor based on the specified parameters of interest, it is necessary to understand not only the absolute efficiency of the detector, but also the number of antineutrinos expected to interact with the detector from the reactor. Due to the lack of detectors operating with disposition plutonium MOX, the antineutrino flux emerging from MOX reactors is estimated by modeling the core and extracting the total fission reaction rates of the relevant isotopes. In order to consolidate computational time, we concentrate on the fission reaction rates associated with the relevant uranium and plutonium isotopes (^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu) because they are responsible for virtually all of the thermal power (accounting for $\geq$98% of the thermal power)[133] and antineutrino emissions. Measurements of the antineutrino yield per fission and energy spectra were adapted from [115-117]. The resulting absolute fission reaction rates are then ultimately converted to an antineutrino spectral density. By acquiring this spectrum in conjunction with estimated cross sections for inverse beta decay and knowledge of the detector specifications (detector distance, volume, etc.) an estimation can be made of the antineutrino interactions per day expected in the target mass of the detector. The methods of these three aforementioned steps are discussed further below.

While not elaborated on in detail in the current work, it is important to distinguish between methods involving absolute versus relative estimates of the number of antineutrino interactions per day expected in the detector target [118]. An absolute estimate requires a full accounting for all sources of experimental uncertainty, such as the precise number of proton targets in the detection medium, the precise surveyed distance of each assembly from the detector, and other systematic effects. However, for the verification methods described here, a measurement relative to an initially calibrated value may suffice. This has the effect of removing or greatly reducing many of the systematic uncertainties that enter into the absolute measurement. For example, the SONGS1 experiment was able to specify the count rate and the thermal power throughout the cycle to an accuracy of 3% relative to a known initial value with one week of accumulated data, limited only by Poisson statistics, provided the initial fuel loading was known. By contrast, the absolute uncertainty in the SONGS1 measurement was closer to 20%, arising primarily from the poor knowledge of the mass of scintillator in the active volume of the detector. With more careful engineering, other experiments have demonstrated that the absolute uncertainty in the count rate can be reduced to 4% level.

5.3.1 Reactor Fission Reaction Rates

5.3.1.A Referenced Data Benchmark Background

The dataset referenced for this analysis is supplied via the OECD/NEA and US NRC PWR MOX/UO$_2$ Core Transient Benchmark [119] adopting a simplified 3D geometry. In the model, the core was assumed to have had uniform fuel composition in axial direction with an axial reflector[134] of the same width as the fuel assembly pitch. In their analysis, the authors design a core partially loaded with MOX up to approximately

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[133] Other plutonium isotopes like ^{240}Pu and ^{242}Pu are bred in the core but only contribute to an extremely minute portion of the total fission reaction rate.

[134] Axial reflector contains fixed moderator at the same condition as the core inlet and outlet for the bottom and top axial reflector, respectively.

25%[135]. We assume many of the same reactor and fuel characteristics as depicted in Table 5.1 below.

Table 5.1: Core and Fuel Assembly Parameters

Number of fuel assemblies	193
Power level (MW_t)	3565
Fuel lattice (fuel rods per 17x17 assembly)	264
Active fuel length (cm)	365.76
Assembly pitch (cm)	21.42
Fuel Volume/Assembly (cm^3)	47354.81
Pin pitch (cm)	1.26
Baffle thickness (cm)	2.52
Target cycle length (GWd/MTHM) (months)	21.564 (18)
Capacity factor (%)	90.0
Target effective full power days	493

In our analysis, we assume a one-batch equilibrium cycle consisting of fresh LEU (with adapted descriptions in Figure 5.3 and Table 5.2) and MOX (with adapted descriptions in Figure 5.5 and Table 5.3) fuel types. The initial isotopic masses for each of the analyzed fuel types can be found Table 5.4. From each of these assembly fuel types, the isotopic fission reaction rates corresponding to the LEU (Figure 5.4) and MOX (Figure 5.6) fuel assemblies were extracted across their respective burnup allocation and eventually translated into a timescale of days. A tabulated form of the fission reaction rates can be found in Appendix B. For more detailed descriptions regarding these, and other, fuel types associated with different pin cell geometries, nonburnable materials, cross-section modeling information, as well as other specificiations please see [119].

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[135] Given this concentration, they designate the following guidelines: "(1) No fresh MOX on the core periphery, (2) No MOX assemblies facing each other, (3) No MOX assemblies in control rod position, (4) Maximum 1/3 of the core loaded with MOX fuel, (5) No Integral Fuel Burnable Absorbers (IFBA) in MOX assemblies, (6) A three-batch equilibrium cycle with once-burned fuel at an average burnup of 20.0 GWd/tHM and twice-burned fuel at an average burnup of 35.0 GWd/tHM."

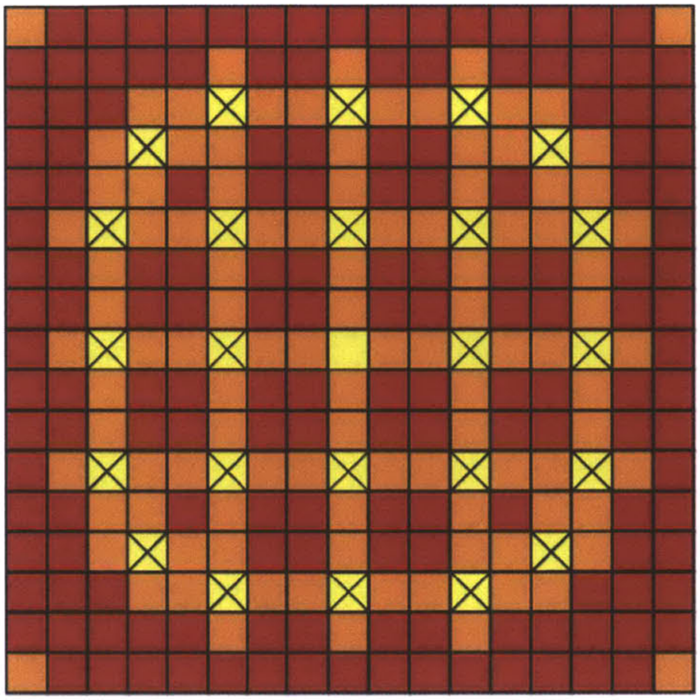

Figure 5.3: LEU Fuel Assembly Configuration

Table 5.2: LEU Fuel Assembly Configuration Details

Diagram	Pin Type	Number of Pins (per assembly)	Density (g/cm^3)	Isotopic/Material Composition
🟥	LEU Fuel	160	10.24	4.2 wt% (^{235}U) 95.8 wt% (^{238}U)
🟧	LEU IFBA	104	1.69	ZrB_2
☒	Control Rod Guide Tube	24	1.84	B_4C
🟨	Instrumentation Guide Tube	1	1.84	B_4C

NOTE: Based on the published information associated with this benchmark, we assume an average cycle burnup of 20.625 GWd/MTHM which correlates to the total analyzed cycle length of 493 days.

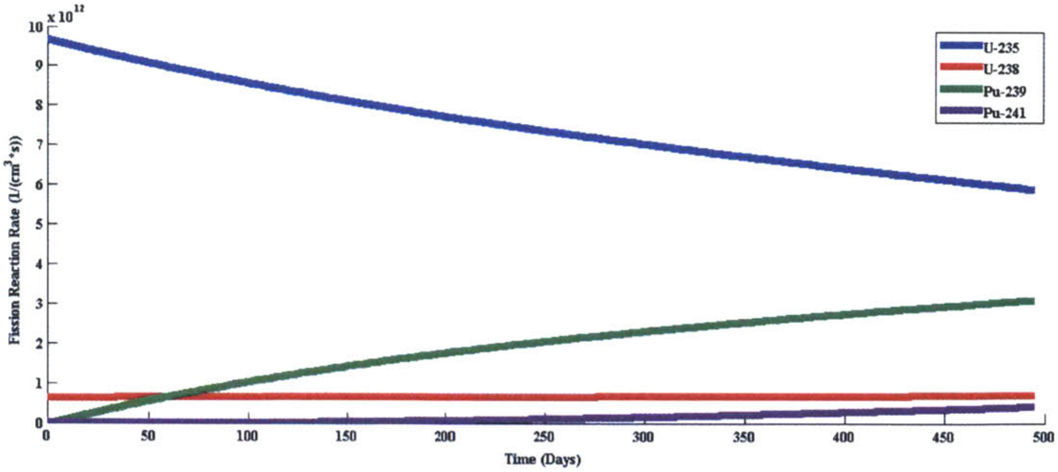

Figure 5.4: LEU Assembly Isotopic Fission Reaction Rates

This figure depicts the estimated isotopic fission reaction rates for ^{235}U (blue line), ^{238}U (red line), ^{239}Pu (green line), and ^{241}Pu (purple line) yielded from the irradiation of a fresh LEU assembly over the course of an entire cycle (493 days).

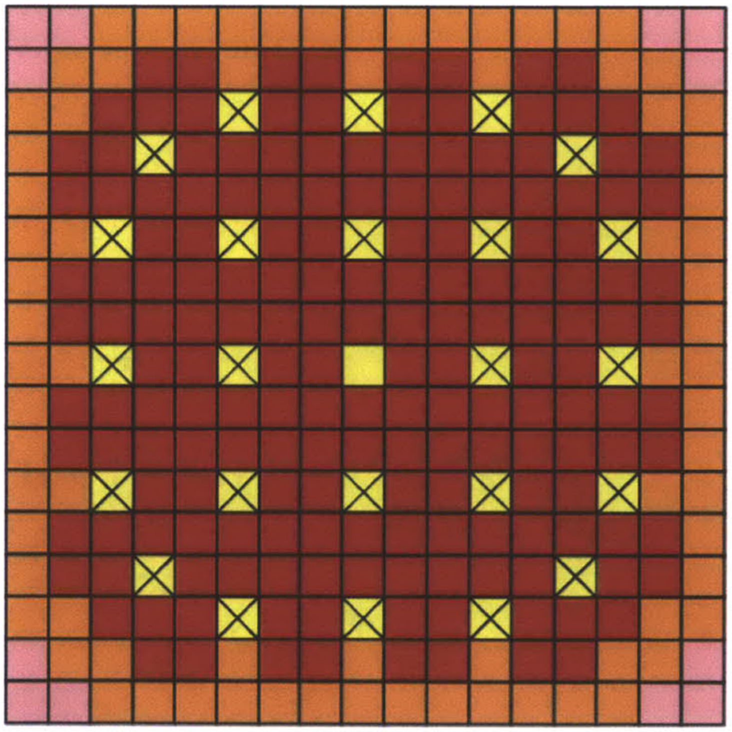

Figure 5.5: MOX Fuel Assembly Configuration

Table 5.3: MOX Fuel Assembly Configuration Details

Diagram	Pin Type	Number of Pins (per assembly)	Density (g/cm^3)	Material Composition
🟫	5.0 MOX	188	10.41	5.0 wt% (Pu)[a] 95.0 wt% (U)[b]
🟧	3.0 MOX	64	10.41	3.0 wt% (Pu)[a] 97.0 wt% (U)[b]
🟥	2.5 MOX	12	10.41	2.5 wt% (Pu)[a] 97.5 wt% (U)[b]
☒	WABA Pin	24	3.56	Al_2O_3-B_4C, 10.0 wt% (B_4C)
🟨	Instrumentation Guide Tube	1	1.84	B_4C

NOTE: Based on the published information associated with this benchmark, we assume an average cycle burnup of 17.5 GWd/MTHM which correlates to the total analyzed cycle length of 493 days.

[a] Isotopic Composition for Pu is 93.6 wt% (^{239}Pu), 5.9 wt% (^{240}Pu), 0.4 wt% (^{241}Pu), and 0.1 wt% (^{242}Pu); note, this correlates to an estimated plutonium content of 4.56% of the total fuel mass (21.21 kg).

[b] Isotopic Composition for U is 0.002 wt% (^{234}U), 0.2 wt% (^{235}U), 0.001 wt% (^{236}U), and 99.797 wt% (^{238}U)

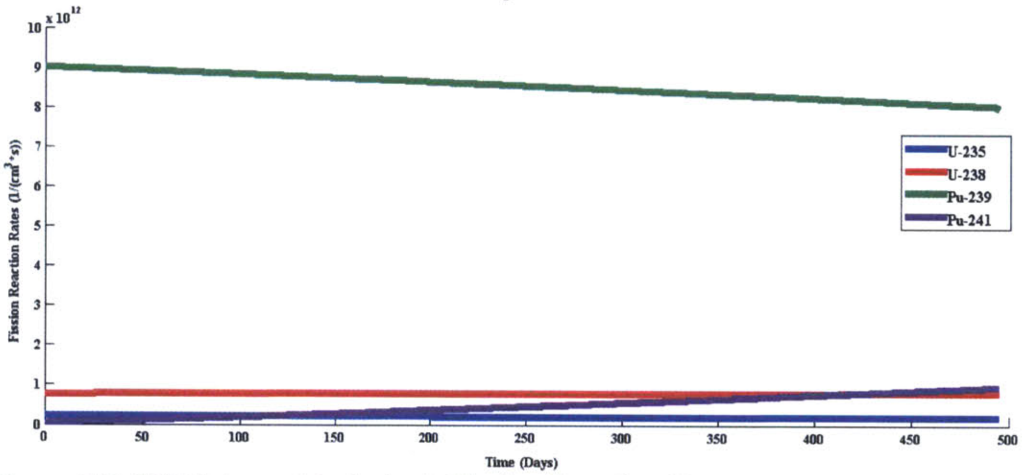

Figure 5.6: MOX Assembly Isotopic Fission Reaction Rates

This figure depicts the estimated isotopic fission reaction rates for ^{235}U (blue line), ^{238}U (red line), ^{239}Pu (green line), and ^{241}Pu (purple line) yielded from the irradiation of a fresh MOX assembly over the course of an entire cycle (493 days).

Table 5.4: Initial Isotopic Masses (kg) for Each Fuel Assembly Type

Isotope	LEU	MOX
^{235}U	17.9556	0.8294
^{238}U	409.5531	413.8772
^{239}Pu	—	18.6564
^{240}Pu	—	1.1760
^{241}Pu	—	0.0797
Total	427.5087	434.6187

Isotopic Atomic weights used in this calculation courtesy of NIST measurements [120].

For simplicity, Helios models only the fission reaction rate yielded for the assembly given the initial fuel composition. We estimate the fission reaction rate by fabricating a fuel core with specified numbers of LEU and MOX fuel assemblies based on the designated core concentration case of interest. An equilibrium factor is also incorporated in the estimated fission reaction rates of the two fuels such that the estimated power production of the reactor remains essentially constant (within approximately ±1%) regardless of the core concentration case to be analyzed. Although fission energies will vary slightly for different cores due to neutron capture—with uncertainties ranging 0.30-0.47%—the estimated fission energies, referenced from Kopeikin et al., associated with the isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu are 201.92 ± 0.46, 205.52 ± 0.96, 209.99 ± 0.60, 213.60 ± 0.65, respectively[136] [121]. Uncertainties in the model output can be separated into those resulting from inaccuracy of the inputs and those intrinsic to the algorithm used by the code itself.

5.3.1.B Irradiation Scheme

The distribution of fuel composition in a reactor will depend, among other things, on the schedule for loading and unloading fuel and on the way the fuel is moved through the reactor. During a power cycle, the fuel composition of both the LEU and MOX fuels change as both uranium and plutonium isotopes are depleted and plutonium isotopes are bred. Therefore, the total fission rate is a function of both the thermal power of the reactor and the total burnup of the fuel in the core.

There are two main modes of irradiation: (1) batch irradiation and (2) continuous irradiation. Continuous irradiation[137] as it relates to LWR is not a practical mode, and hence not considered in this analysis, since these reactors require shut downs in order to replace fuel elements[138]. Batch irradiation is a scheme in which the reactor is supplied with either a complete or progressive replacement of fuel at the conclusion of the irradiation period. In the former case, and the case considered for purposes of this analysis, all fuel elements are removed at the conclusion of the irradiation period, sent to processing, and replaced with fresh fuel elements[139]. In the latter case—and the case more consistent with

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[136] Approximately 5% of the referenced isotopic fission energies is disregarded as energy associated with antineutrino emissions and, as such, not calculated into the thermal energy contribution.

[137] The best scheme for neutron economy, this scheme implements a procedure where the reactor contains, at any instant, a large number of fuel elements which vary in fuel-exposure time and fuel composition, but from a general perspective, maintaining the distribution of exposure time at constant level as fuel moves through the reactor. At some time during its irradiation history the fuel element will produce more neutrons than the average fuel element in the reactor—because of its higher-than-average content of fissionable material—and at other times the fuel element will absorb more neutrons than the average—because of its high content of fission products. Arrangement of the fuel elements can occur in a mechanism to maintain the over-all production and consumption rates of neutrons in equilibrium throughout the reactor. The addition neutron absorbers or increased leakage, is unnecessary to keep the reactor in neutron balance.

[138] Although impractical, this scheme is closely approximated (as far as neutron balance is concerned) when an intermittent charging of fresh fuel elements every few weeks, and a discharge of spent fuel elements at these intervals, occurs since the fuel-composition changes occur so slowly with time.

[139] The composition of the fuel will change during the irradiation, due to fissionable isotope depletion, fission product generation, and build-up of nuclides resultant from the non-fission capture of neutrons in fissionable and fertile material. In order to maintain neutron balance during the reactor's irradiation history, it is

the typical operation of LWR due to its advantage of obtaining extended individual fuel element exposure time—the individual fuel elements have a varied distribution of exposure times and are reloaded on a progressive schedule so that the reactor always contains some fresh fuel elements with reactivity greater than the average and some nearly spent elements with reactivity less than the average [122]. During a refueling cycle implementing a batch-wise scheme with progressive replacement, approximately one third of the fuel elements are replaced and the remaining elements are shuffled to optimize the heat production of the core yielding fuel elements that are *fresh*, *once-burned*, and *twice-burned.*

5.3.2 Acquiring the Estimated Antineutrino Spectrum

As noted, the total fission reaction rates of the four primary isotopes were derived from modeling the reactor core based on the designed core concentration case of interest. The four fission reaction rates were then translated to their respective fission rates through a procedure incorporating the total fissionable fuel volume. The tabulated calculated fission rates can be found in Appendix B. The fission antineutrino spectra were acquired by following a procedure outline by Miller [118]. The observed beta spectra were fitted to hypothetical beta-branches using the calculated spectra for ^{235}U, ^{239}Pu, and ^{241}Pu adapted from [115, 116] and ^{238}U adapted from [123]. In order to use the measured data more conveniently, an exponentially fitted version of the data was used in order to attain the isotopic fission antineutrino production as a function of energy. The results of this can be seen in the Figure 5.7 below. As can be seen in the figure, ^{238}U emits the most antineutrinos per fission, whereas ^{239}Pu emits the least; there is only a minute difference in the antineutrino emissions resultant from the fissioning of ^{235}U and ^{241}Pu.

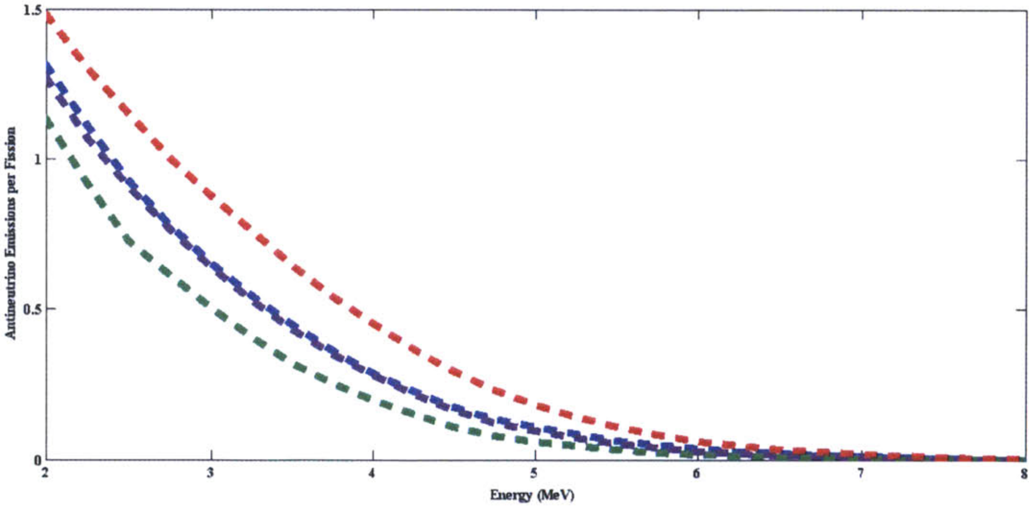

Figure 5.7: Fission Antineutrino Spectra

Exponentially fitted function of the antineutrino spectra measurements resultant from the ab initio approach as defined [124] by for the isotopes ^{235}U (blue dashed line), ^{238}U (red dashed line), ^{239}Pu (green dashed line), and ^{241}Pu (purple dashed line) corresponding to a 12 hour, 12 hour, 1.5 day, and 1.8 day irradiation time, respectively.

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necessary to insert extraneous neutron absorbers (e.g. control rods) or allow increased leakage of neutrons at some times during the irradiation cycle.

5.3.3 Acquiring the Antineutrino Estimated Expected Signal

The acquired neutrino spectrum emitted by the simulated reactor (based on the core concentration case of interest) must be translated into the expected positron spectrum in the experiment. In order to conceive this calculation, three contributions to this calculation must be considered [118]:

- the detector distance from the core
- the inverse beta decay cross section
- the number of protons in the detector volume

From the perspective of our analysis, we considered a detector placed approximately 25 ± 1 m from the reactor core, based on the SONGS1 and San Onofre LWR experiment and practice identified by Bernstein et al [5]. A further supporting point for this assumption is the demonstration site's similarity to potential and former customer reactors at the McGuire and Oconee generating sites [66], which should expect similar detector implementation and operating requirements. Because the detector distance from the core can be surveyed by plant personnel, it ultimately will not have a significant contribution to the expected signal uncertainty.

The cross section for the inverse beta decay was adapted from [125]. Similar to Miller's procedure, the lowest order cross section was modified for several effects (e.g. neuron recoil, weak magnetism, and radiative corrections) resulting in an estimated accuracy of 1%. The estimated energy dependent inverse beta decay cross section can be seen below in Figure 5.8.

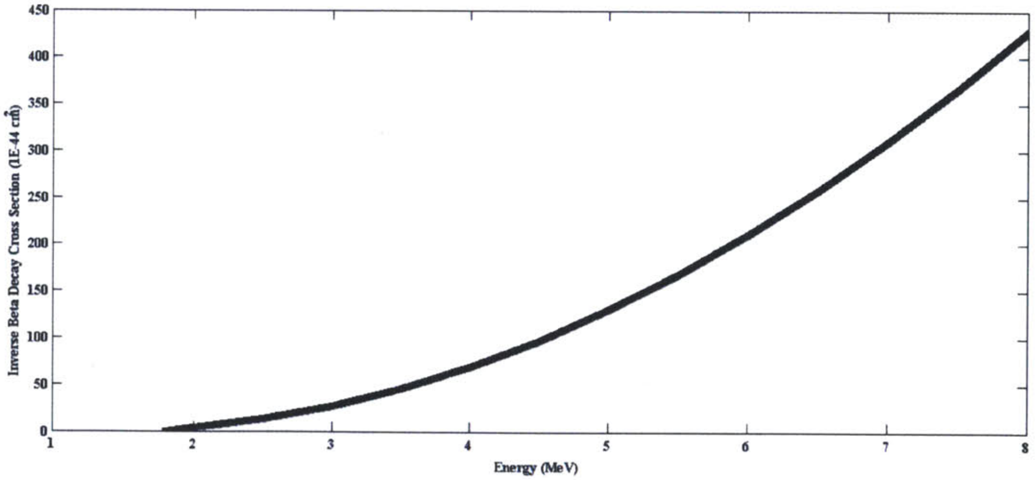

Figure 5.8: Energy Dependent Inverse β-decay Cross-section
Courtesy of [5, 123, 125].

In addition, because we are considering an antineutrino detector similar in design to the SONGS1 detector due to its successful demonstration, for purposes of this analysis, we assume the number of protons in the scintillator detector target to be approximately

$8.79\times10^{29} \pm 1\%$[140] based on the stated assumptions as designated by [118].

The energy dependent isotopic antineutrino interaction spectra are then calculated for the detector target, given these assumptions, in Figure 5.9 below.

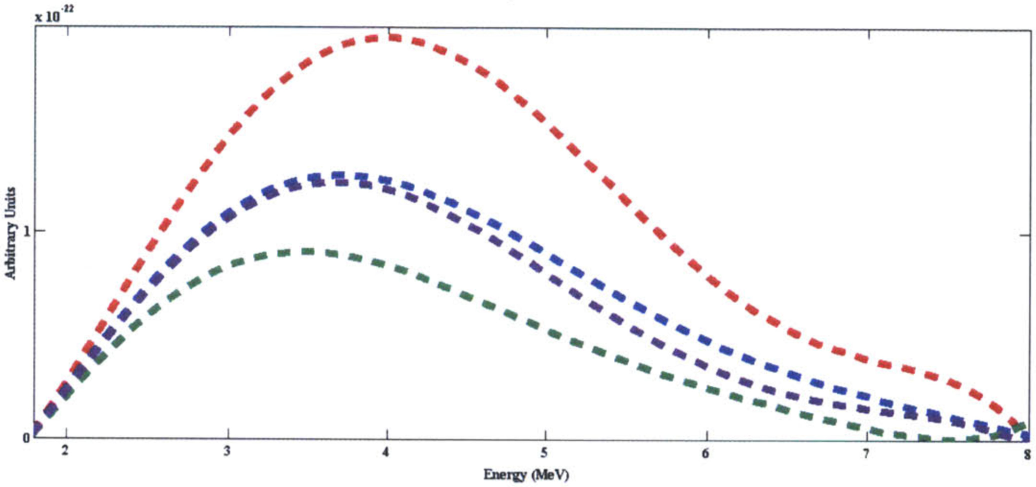

Figure 5.9: Energy Dependent Isotopic Antineutrino Interaction Spectra
The estimated antineutrinos per fission expected to interact with the detector target, when assuming the energy dependent detector efficiency remains constant at 100%, can be seen for the respective isotopes: ^{235}U (blue dashed line), ^{238}U (red dashed line) [141], ^{239}Pu (green dashed line), and ^{241}Pu (purple dashed line).

The expected antineutrino signal measured by the detector as a function of time, or burnup step, can than be predicted as

$$\frac{dN_{\bar{\upsilon}}}{dt} = \frac{N_p}{4\pi D^2}\cdot \sum_i \frac{dN^i_{fission}}{dt}\cdot \int \varepsilon(E_{\bar{\upsilon}})\cdot \sigma(E_{\bar{\upsilon}})\cdot \frac{dN^i_{\bar{\upsilon}}}{dE_{\bar{\upsilon}}\cdot fission}\, dE_{\bar{\upsilon}}$$

where N_p corresponds to the number of protons in the detector target and D corresponds to the detector distance. The term $\frac{dN^i_{fission}}{dt}$ corresponds to the isotopic fission rate in the core, as a function of time, where the index i corresponds to all of the considered isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The terms $\varepsilon(E_{\bar{\upsilon}})$[142] and $\sigma(E_{\bar{\upsilon}})$ correspond to the detector

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[140] The number of protons estimated in the detector target were actually approximated to $10.45 \times 10^{29} \pm 1.3\%$, which includes not only protons in the scintillator ($8.79\times10^{29} \pm 1\%$) but also protons in the acrylic tanks that hold the detector ($1.66 \times 10^{29} \pm 5\%$). Although the acrylic cells housing the scintillator offer some efficiency for antineutrino interaction to be detected, it is difficult to identify the detection contribution attributed to the surrounding housing, and hence only concern ourselves with scintillator protons. Uncertainty for the scintillator proton count is attributed to the filling and mixing of the liquid, mass of the liquid, knowledge of the chemical composition of the scintillator, and generalization of the liquid as primarily composed of hydrocarbons (C_nH_{2n+2}). Uncertainty for the acrylic protons count is attributed to acrylic cell dimension estimates and density estimates from acrylic samples.

[141] The absolute contribution from ^{238}U is much lower after the accounting of relative fission rates.

[142] The detector efficiency is assumed to be 1.

efficiency, defined as the ratio of detected to interacting events in the detector target, and inverse beta decay cross-section, depending on the antineutrino energy. The term $\frac{dN^{i}_{\bar{v}}}{dE_{\bar{v}} \cdot fission}$ corresponds to the isotopic fission antineutrino spectrum in units of events per MeV and fission. In the above equation, the sum corresponds to all fissioning isotopes (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) and the integral over the antineutrino energies (1.8-8 MeV). It is evident that the produced antineutrino rate is heavily dependent on the isotopic fission rates, which is related to the reactor operating thermal power. Through this relationship, it becomes clear that the energy spectrum of the antineutrinos can be further exploited to extract or constrain the individual isotopic masses throughout the cycle.

5.4 Sources of Non-Antineutrino Events

An additional important factor to consider when estimating the antineutrino signal measured by the detector, is the contribution associated with false positives, or those which produce a signal which is not resultant from antineutrinos produced by the reactor. The aspects of such non-reactor related antineutrino events are discussed further in the statistical analysis performed for cases of interests. An example of such non-antineutrino events is the background radiation related to cosmic muons, which must be shielded since a product of one of their decay chains is the antineutrino as seen in the decay scheme below. Fortunately, active shielding around the antineutrino detector can significantly reduce the background signal contribution to antineutrino detection experiments[143].

$$\mu^{-} \longrightarrow e^{-} + \nu_{\mu} + \bar{\nu}$$

Neutrons are another source of false positive measurements, where the neutron can cause detector protons to recoil in a scattering interaction resulting in scintillation light. Partially following the procedure under inverse beta decay detection, the neutron can then be absorbed by a Gd nucleus in the detection medium, resulting in secondary scintillation light. An interacting neutron following this procedure can be mistaken for the prompt and delayed signals of an antineutrino absorption through coincidence detection.

5.5 Relevant PMDA Verification Criteria Met with Antineutrino Detection

In this section, we analyze the specific applicability of antineutrino detection for PMDA verification. As pointed out in Chapter 1, we argue that antineutrino detection will aid in such verification endeavors, in likely order of applicability, through the (1) confirmation of burnup, (2) confirmation of conversion product mass and isotopic composition, (3) confirmation of the amount of WGPu irradiated in each cycle, and (4) maintenance of CoK [43].

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[143] Early detector designs implemented Geiger-Müller tubes around the active detector volume. Modern day detectors, however, implement an active shield design composed of plastic scintillator panels.

As noted, both the US and Russia have the right to confirm the required burnup levels[144] of one another's WGPu MOX fuel after irradiation in their specified reactors. In the US, this required burnup level for each WGPu must be at least 20 GW_d/MTHM. In addition, each party also has the right to confirm that the conversion product used in the fuel is still designated as WGPu, defined as plutonium with an ^{240}Pu:^{239}Pu isotopic ratio of no more than 10%. Article IV of the PMDA requires that each state dispose of a minimum of 1.3 MT annually. The US annual disposition volume can be confirmed via verification of the disposition LWR MOX core concentration; potentially serving as an element of accountancy that is needed in order to verify that total inventory and throughput were in accordance with US specifications. Finally, although not mentioned in the agreement, maintenance of CoK is not only likely to be desired by each party through bilateral verification measures, but will be vital toward the Agreement's intended goals of ultimately submitting to multilateral verification in conjunction with the IAEA. As noted in Chapter 4, from a LWR and MOX safeguards perspective, CoK maintenance at the reactor core and during the reactor's operation is also essential[145]. In addition, such maintenance will be fundamental to confirmation of conversion product mass and isotopic composition as well as annual WGPu irradiation volume.

As discussed in earlier sections, antineutrino rate measurement and energy spectrum data provide a range of measurement abilities capable of successfully achieving each of the applicability goals outlined above, either alone or in combination with another verification activity. Such prospects are discussed in the following sections.

5.5.1 Antineutrino Rate Measurement

An antineutrino rate measurement alone has already demonstrated the capability of monitoring the thermal power of an operational reactor [126]. This feat can be translated into antineutrino detection prospects of CoK maintenance regarding operational status at the designated LWR aiding in the plutonium disposition campaign.

An antineutrino rate measurement alone can provide continuous knowledge that the reactor used for disposition is operational. Bernstein argues that using a simple antineutrino detector, similar in design to the SONGS1 detector and calibrated only with radioactive sources or natural background radiation, and without any additional knowledge (e.g. initial isotopic inventory) the absolute thermal power of the selected LWR can be estimated to approximately 10-15%[146]. Unfortunately, antineutrino rate measurements alone are unable to address the other three stated applicability goals. Further inputs, such as the initial verified fuel inventory, would be required.

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[144] Russia's required burnup level, as designated by the PMDA, is 3.9-5% HM atoms depending on the reactor type and commissioning stage. For purposes of this thesis, however, we only concern ourselves with the disposition procedure followed in the US.

[145] As already acknowledged, antineutrino detection may aid in establishing CoK in the event of reactor shut-down or in situations when contemporary safeguard procedures of reactor seals and/or C/S techniques are compromised. Although not sufficient justifications for antineutrino implementation, such aforementioned benefits of this technology are innate.

[146] The uncertainty is yielded due to the numerous combinations of fuel composition and thermal power that is also capable of resulting in identical antineutrino emission rates.

5.5.2 Antineutrino Rate Measurement and Initial Isotopic Inventory

An antineutrino rate measurement coupled with an independent verification of the input isotopic declaration within the reactor core would allow for the attainment of an additional applicability goal, confirmation of the burnup. Both the fissile isotopic mass and position of all the fuel assemblies (including both LEU and WGPu MOX) within the core, we argue, could potentially be independently verified prior to irradiation in the reactor and at the beginning of the cycle via contemporary domestic or international safeguard mechanisms implemented further up the disposition procedural chain. Following the same mechanisms outlined in the preceding section, the antineutrino rate could be measured continuously throughout reactor operation, where the detector could be calibrated with radioactive sources or natural background radiation in order to gain insight about the detector efficiency. Given this initial knowledge regarding the detector efficiency, initial isotopic declarations, and the antineutrino rate measurements, the total core burnup and isotopic masses at later times in the cycle can be determined following the latter portion of the procedure and equation described in section 5.3.3 in conjunction with a reactor core simulation. Iterative steps of this procedure over the entire fuel cycle duration should result in the estimated end of cycle burnup (and isotopic inventories) for each assembly.

Following the procedure described above, both CoK of the WGPu MOX fuel during its time within the reactor core is maintained and confirmation that the WGPu fuel assembly reached its designated minimum burnup requirement of 20 GWd/MTHM is achieved[147]. This method provides continuity of knowledge on the presence of MOX fuel in the core, and, provided a validated core model is used to assign burnup values to individual assemblies, a measure of the burnup of each MOX assembly. As noted, antineutrino rate measurements alone are unable to address the applicability goals of confirmation of conversion product mass and isotopic composition and confirmation of annual WGPu irradiation volume; however, assuming independent verification of the initial isotopic inventory within the core addresses these two goals.

The notional procedure just outlined assumes, for simplicity, that the WGPu MOX fuel is able to achieve the minimum burnup requirement within one fuel cycle. If, as is likely, multiple cycles are used in order to achieve the required burnup standard, verification becomes more complicated, since item accountancy and C/S techniques must be added to the regime during reactor off periods, during which the antineutrino detector has no sensitivity. Because the produced simulation must now extended beyond one cycle, its precision on the burnup estimates for the individual fuel assemblies will significantly degrade without further input. If, however, C&S or other techniques can ensure that the reshuffled assemblies have not been tampered with, the sensitivity of antineutrino detection is maintained, and may serve to verify declarations of burnup and of discharged isotopic masses within the core.

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[147] If the minimum WGPu MOX assembly burnup through a typical reactor cycle is slightly larger (~10%) than the PMDA-designated burnup requirement, the requirements on the precision of the antineutrino detector data are not severe and can be achieved by a simple antineutrino detector with performance capabilities similar to the SONGS1 detector.

5.5.3 Antineutrino Rate Measurement and Reactor Thermal Power

An antineutrino rate measurement coupled with an independent verification of the reactor thermal power would allow for the attainment of confirmation of conversion product mass and isotopic composition, partial confirmation of annual WGPu irradiation volume, and maintenance of CoK. A verification approach implementing these two metrics is essentially a complement to the previously described procedure above where the confirmation of burnup was inferred from the antineutrino rate measurements and the goals of mass and isotopic composition as well as annual WGPu irradiation volume were solely verified through initial isotopic declarations. In this case, however, confirmation of burnup is essentially inferred solely through the independent verification of the reactor thermal power rather than in combination with the antineutrino rate measurement.

The reactor operational thermal power throughout a cycle and other reactor parameters (e.g. fuel assembly geometry, positions, etc.), we argue, could potentially be independently verified either by a domestic/international inspecting party or by the reactor operator. It must be noted that if verification is achieved through the acceptance of operator declarations, the independence and credibility of such a verification exercise is dramatically reduced. As originally acknowledged from the inspected and operator perspectives in Chapters 3 and 4, however, attaining an independent power measurement is a relatively intrusive requirement and will increase the difficulty in implementing such an approach. Nonetheless, it is also assumed in this case—although more unrealistic than the approach assumed in the preceding section—that initial isotopic inventories are provided by the inspected state and not verified by other means

Once again, following the same mechanisms outlined in the section 5.5.1, the antineutrino rate could be measured continuously throughout reactor operation, where the detector could be calibrated with radioactive sources or natural background radiation. Given this initial knowledge regarding the detector efficiency, inspector and/or operator declared thermal power measurement, and the antineutrino rate measurements, the core-wide isotopic composition (with sensitivity to the MOX core concentration) as well as a range of mass[148] compositions and can be inferred following the latter portion of the procedure and equation described in section 5.3.3. Because the specified verification procedure in the PMDA does not specify individual assembly verification, only total amount of conversion product, a core-wide inference is sufficient. A validated core simulation would additionally allow assignment of masses to individual assemblies. The range of masses that yielded reactor simulation-produced antineutrino rate measurement consistent with the actual antineutrino rate measurement serve as possible values of the actual fissile inventory[149]. Such mass compositions can be extrapolated in order to partially

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[148] The specific fissile mass is a bit more difficult to determine since, as noted earlier, a unique solution does not exist. However, this may potentially be combated through the implementation of additional constraints arising from the reactor simulation. The reactor simulation, implementing the initial isotopic inventories declared by the state as well as varying inputs, will yield a predicted antineutrino rate measurement, which can then be compared to the actual antineutrino rate measurement in order to estimate the detector sensitivity to deviations from the declared value.

[149] A declaration of initial isotopic inventories by the state is considered false if it deviates significantly from the ongoing actual antineutrino rate measurement.

verify that the disposition campaign is consistent with the annual 1.3 MT WGPu disposition requirement as outlined in the PMDA.

5.5.4 Antineutrino Energy Spectrum Measurement

An antineutrino energy spectrum measurement could, in principle, allow for the attainment of all four of the applicability goals[150] stated above. The antineutrino energy spectrum is acquired over the duration of the fuel cycle, where, again following the same mechanisms outlined in the section 5.5.1, the detector could be calibrated with radioactive sources or natural background radiation in order to gain insight about the detector efficiency. Unlike the antineutrino rate measurement based verification approaches described in the preceding sections, no additional independent verification of the fissile isotopic mass or thermal power is required in order to determine the core-wide fissile isotopic and mass compositions as well as the reactor power and fuel burnup[151]. This occurs because these factors are simultaneously constrained by the variation in the antineutrino energy spectrum measured through the cycle. Although the knowledge gained through this metric may be beneficial, in regards to the required annual WGPu throughput as it applies to the PMDA, the designated accountable metric is the disposition plutonium isotopic mass, which will likely constitute a subset of the core. Although only partially verified through the spectrum measurement, if the disposition MOX fuel core fraction and positions are independently verified by other means, full verification of this goal may potentially be achieved[152]. Similar to the antineutrino rate measurement approach, CoK is provided for WGPu MOX presence within the core as well as burnup of the fuel consistent with the operational status of the reactor. Although the prospects associated with an antineutrino energy spectrum measurement are promising, the following analysis only considers the prospects of antineutrino rate measurements. Nonetheless, we acknowledge that testing procedures implementing antineutrino energy spectrum measurements are vital to analyzing the overall prospects of antineutrino detection and should be considered in future work.

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[150] Only partial verification of the annual WGPu disposition throughput requirement goal is achieved

[151] Experimental uncertainty resultant from the spectrum measurement is the only contributor to the expected uncertainty for the reconstructed power and mass inventories of the individual fissile isotopes.

[152] Bernstein argues that the declared WGPu MOX assembly positions can be incorporated into the reactor simulation to predict the expected antineutrino spectrum throughout the reactor cycle. Performing a reactor simulation produced antineutrino spectrum and comparing it to the actual antineutrino spectrum measurement could establish the validity of WGPu MOX irradiation declarations by the State. Although promising, sensitivity to ill-declared disposition fuel composition and location declarations still serve as a potential threat to this approach. For example, Hayes et al. have performed simulations that have shown that substituting WGPu MOX fuel with conventional RGPu MOX fuel may result in nearly identical antineutrino spectral evolutions.

Chapter 6: Will It Work (A Statistical Analysis)

6.1 Model Selection for Antineutrino Count Rates

Upon the extraction of the isotopic fission reaction rates from each of the assembly fuel types, we then simulated the antineutrino count rates for both the LEU and WGPu MOX fuel types over the course of the fuel cycle. We use a Helios-2 simulation of each fuel assembly originally published in the OECD/NEA Working Party benchmark[153] [119] which employed many of the characteristics of the NEACRP L-335 PWR benchmark proposed by Finnerman[154] [127]. We then extrapolated the associated antineutrino count rates for each fuel type to a simulated core consisting of various concentrations of these fuel types for different cases for use in our hypothesis testing.

Following a similar procedure as outlined by Bulaevskaya et al. [4], we describe the PWR core antineutrino count rate evolution $N_{\bar{\nu}}(t)$ at time *t* in days of the fuel cycle as

$$N_{\bar{\nu}}(t) = \sum_f \sum_i R_{fi}(t) \cdot V_f \cdot \psi_i \qquad (6.1)$$

where $R_{fi}(t)$ is the fission reaction rate as a function of time *t* for each fuel type *f* (LEU or WGPu MOX) and each isotope *i* (^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu)[155]. The term V_f corresponds to the core volume associated with a given fuel type. The term ψ_f is a factor used to convert fission rate to antineutrino production for a given isotope defined by the integral function across all energies of interest[156]:

$$\psi_i = \alpha \int N_{\bar{\nu}} \cdot \sigma_{fi}(E) \cdot dE \qquad (6.2)$$

where α is a constant related to the detector mass, efficiency, and standoff distance[157] [128]. The terms $N_{\bar{\nu}}$ and $\sigma_{fi}(E)$ correspond to the number of antineutrinos produced per fission for a given isotope and the isotope's fission cross-section at a specified energy, respectively. The conversion factor for each isotope is found below in Table 6.1.

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[153] This benchmark adds the complexity of modeling a rod eject in a core fueled partially with WGPu MOX basing the core simulation from a four-loop Westinghouse PWR power plant design.

[154] The benchmark was designed to assess the ability of spatial kinetics codes to model rod ejection transients.

[155] It can be similarly argued that this term is related to the reactor thermal power simply because of its neutron flux factor. This isotopic fission reaction rates are well approximated by a cubic and sextic polynomial functions for WGPu MOX and LEU fuel types, respectively (note that polynomial regression of data has an inherent danger of faulty extrapolation). At minimum, 95% of the variation of the reaction rates are accounted for by these polynomial relationships with time (days).

[156] We concern ourselves with the energy range of 1.8-8 MeV.

[157] For purposes of this simulation, we assume a fully efficient detector with a mass of 0.64 MT at a standoff distance of 25 m.

Table 6.1: Isotopic Antineutrino Conversion Factor

Isotope	Conversion Factor ψ ($\times 10^{-17}$)
^{235}U	5.16
^{238}U	3.36
^{239}Pu	7.25
^{241}Pu	4.80

The estimated antineutrino counts associated with the variation in PWR core concentrations being considered in this work are well approximated by a quadratic function of time[158]:

$$N_{\bar{v}}(t) = \beta_0 + \beta_1 t + \beta_2 t^2 \qquad (6.3)$$

Based on the statistical procedure performed in this analysis, the quadratic model appears to be valid for PWR core with WGPu MOX fuel concentrations of up to 48.4%[159]. The coefficients β_0, β_1, and β_2 in (6.3) associated with our quadratic approximation will be used to detect a potential departure from the baseline scenario, which will be described in further detail.

6.1.1 Validity for Quadratic Response Function

In order to test the validity of the selection of a quadratic function as the best approximation of the baseline and measured count rates, the effectiveness of the quadratic effect coefficient, β_2, was tested. The purpose of this testing was to determine whether or not this term could be dropped from the model. In order to achieve this, the following hypotheses were tested:

$$H_{0_i} : \beta_2 = 0$$

where H_0 implies the notion that no quadratic effect exists in the response function and H_a implying the counter. A t-test was used for this hypothesis testing, such that the test statistic was:

$$t^* = \frac{\beta_2}{se\{\beta_2\}}$$

At a standard level of significance such as 0.05 for a 493-day cycle period [i.e. t(0.975, 492)=1.965], our decision rule is as follows:

If $|t^*| \leq 1.965$, conclude H_0

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[158] Please note—although concerns arise regarding the implementation of complex polynomial models and over-fitting the data and false extrapolation—for purposes of this analysis, we find this model to be sufficient since the specific time period (one cycle) is only considered and we do not intend to predict estimated counts past this time period (further detail regarding its validity can be found in the following section).

[159] Please note that this limit is based on the design parameters of the MOX and LEU assemblies described in this work below; this limit may change if these parameters are varied.

If $| t^* | > 1.965$, conclude H_a

Although multiple iterations (100,000) were performed, resulting in the generation of t^* values, the overwhelming data set always resulted in $| t^* | >> 1.965$; providing credible support in concluding H_a, that a quadratic effect does exist and that the quadratic effect coefficient should be retained in the model[160].

6.1.2 Set-up for Testing of Diversion Activities

Following the model approximations described in (3), the true baseline evolution of antineutrino count rate as a function of time t in the fuel cycle is given by

$$N_{\bar{\nu}_B}(t) = \beta_{0_B} + \beta_{1_B} t + \beta_{2_B} t^2 \qquad (6.4)$$

where the baseline evolution, described in equation 6.4 above (and for the remainder of this work) with the superscript "B", is obtained from our reactor simulation. Because our predicted baseline evolution is obtained from a reactor assembly simulation, subject to both random and systematic errors, we modify the following equation so that $\mu_B(t)$ is the baseline evolution antineutrino count rate value at time t predicted by the simulation.

$$\mu_B(t) = \beta_{0_B} + \beta_{1_B} t + \beta_{2_B} t^2 \qquad (6.5)$$

We approximate the baseline count rate at time t as a Gaussian random variable with the stated mean above equal to the predicted simulation value and standard deviation equal to 3%[161].

$$N_{\bar{\nu}_B}(t) \sim Gaussian\left[\mu_B(t), 0.03\mu_B(t)\right] \qquad (6.6)$$

The assumed 3% random error is the maximum random error for these and other HELIOS simulations when scaling up to a total reactor capacity [119, 129]. In order to simulate the measured count rate evolution, which will be tested against the baseline count rate evolution, we approximate its count rate at time t as a Poisson random variable, based on the statistical uncertainty associated with actual antineutrino count rate measurements of a reactor core [126].

$$\mu_M(t) = \beta_{0_M} + \beta_{1_M} t + \beta_{2_M} t^2 \qquad (6.7)$$

$$N_{\bar{\nu}_M}(t) \sim Poisson\left[\mu_M(t)\right] \qquad (6.8)$$

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[160] Similarly, as noted by Neter et al., a partial F test could also have been used, and was used in this analysis, providing further fodder for the notion that the quadratic effect coefficient should be retained in the response function.

[161] Bulaevskaya et al. argue that simulations for these purposes are "limited in accuracy by systematic errors, arising from bias in the input antineutrino spectral densities, as well as other factors...[and] can be removed by a calibration procedure."

By construction, the modeled baseline count rates are Gaussian, and the high Poisson statistics of the measured count rates make them approximately Gaussian as demonstrated by McCullagh [130] such that

$$N_{\bar{\nu}_M}(t) \sim Gaussian\left[\mu_M(t), \sqrt{\mu_M(t)}\right] \qquad (6.9)$$

The linear effect coefficient, β_1, and the quadratic effect coefficient, β_2, of the estimated response function for the regression model will often be highly correlated for a sample because of the simple correlation between t and t^2; meaning small values of t will be associated only with small values of t^2 and, similarly, large values of t only with small values of t^2. In order to remove such instability between these coefficient estimates, the standard practice, as identified by Neter et al. [131], of performing the polynomial regression on the independent variable as a deviation from its mean is used, such that

$$\tau = t - \bar{t} \qquad (6.10)$$

Expressing the independent variable as a deviation from its mean reduces the multicollinearity substantially. As such, the approximations for the baseline and measured antineutrino count rates can be reparameterized as:

$$\mu_B(\tau) = \gamma_{0_B} + \gamma_{1_B}\tau + \gamma_{2_B}\tau^2 \qquad (6.11)$$

$$\mu_M(\tau) = \gamma_{0_M} + \gamma_{1_M}\tau + \gamma_{2_M}\tau^2 \qquad (6.12)$$

6.1.3 Residual Analysis of Selected Approximations

In order to study the aptness of the polynomial regression models adapted for the baseline and measured count rates, the residuals were plotted against both the estimated evolution approximations [$\mu_B(\tau)$ and $\mu_M(\tau)$] as well as the independent variable τ, as an exploratory analysis of our assumption. It was noted that no systematic departures from 0 were evident in the residuals as either $\mu_B(\tau)$, $\mu_M(\tau)$, or τ progressed suggesting that the quadratic response function was a good fit. Furthermore, there was no tendency noted in the analysis for the spread of the residuals to vary systematically, suggesting that a constant error variance assumption is reasonable.

6.2 Testing Procedure

Based on the specifications of our testing set-up, the testing procedure consisted of the following steps, where the subscript i is used to denote the subscripts 0, 1, and 2, associated with each coefficient. Each of the aforementioned coefficients (γ_{i_B} and γ_{i_M}) can be compared to its counterpart through hypotheses testing following the process:

$$H_{0_i} : \gamma_{i_M} = \gamma_{i_B}$$

where H_0 implies the notion that the two coefficients are equal and H_a implying the counter. In order to attain these coefficients, we first begin by generating the baseline $\{N_{\bar{v}_B}(t)\}$ and measured $\{N_{\bar{v}_M}(t)\}$ evolutions according to equations (6.11) and (6.12) above. We then perform a polynomial regression on the generated baseline and measured evolutions in order to develop a modeled count rate and to obtain the coefficient estimates [γ_{i_B} and γ_{i_M}] and their respective standard errors [$se^2(\gamma_{i_B})$ and $se^2(\gamma_{i_M})$]. We then obtain the test statistics from the respective function

$$t_i^* = \frac{\gamma_{i_M} - \gamma_{i_B}}{\sqrt{se^2(\gamma_{i_M}) + se^2(\gamma_{i_B})}}$$

And their corresponding p-value, given by

$$p_i = P(T \ge |t_i^*|)$$

We use a Student's t distribution with 2 · (n - 3) degrees of freedom[162]. Although it can be argued that a one-tailed test should be used for purposes of this analysis—based on the presumption that irradiating more WGPu MOX fuel than originally declared is not a concern to the world audience—a two-tailed test is selected because of the potential safety risks associated with the prospect of burning more WGPu MOX fuel than originally intended. We propose that the selected statistical testing procedure is well adapted for power and robustness providing a credible performance metric in our hypothesis testing both "sensitive to change in the specific factors tested [and] insensitive to changes, of a magnitude likely to occur in practice, in extraneous factors [132]."

6.2.1 Statistical Error

In statistical test theory the notion of statistical error is an integral part of hypothesis testing, where the variation between two sample distributions, like those described above, can be explained by chance or not. Hence, in order to test the validity of the aforementioned null and alternate hypotheses, a level of significance, α, must be selected. Essentially, the level of significance is a threshold value set by the user in order to accept or reject H_0 (the counter being to reject or accept H_1). Typical levels of significance are 10%, 5%, 1%, 0.5%, and 0.1%[163].

Although our testing procedure, like any testing procedure, provides insight in regards to the comparison of two sample distributions, the possibility of the test result disagreeing with what is actually taking place does exist. For example, if a significant

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[162] Our selected degrees of freedom is allocated from the fact that we implemented a polynomial regression (synomous with multiple regression) on our selected data with two variables following the function k*(n-k-1) where k are the number of variables used. Please note that the implementation of more variables results in the erosion of one's ability to test the model (i.e. the statistical power of the model declines).

[163] The lower the significance level, the stronger the evidence required. Choosing the level of significance is a somewhat arbitrary task, but for many applications, a level of 5% is chosen, for no better reason than that it is conventional.

difference is found in at least one of the tested coefficients when in actuality the coefficient was yielded from the baseline scenario (which should result in the acceptance of H_0), our testing procedure will result in a p-value that will fall below α (resulting in the rejection of H_0). This error is known as a Type I Error[164] or False Positive. Its complement is the True Negative, which is defined as the correct inference that none of the coefficients differed from its baseline counterpart when the evolution being tested was yielded from the baseline scenario. On the other hand, the potential counter is known as a Type II Error or False Negative. This would occur if our testing procedure failed in perceiving a significant difference in all three coefficients when in actuality the evolution spawned from a case other than the baseline scenario. Its complement is the True Positive, which is defined as the testing procedure's ability to determine a significant difference in at least one of the coefficients from its baseline counterpart when the evolution being tested was in fact different from the original baseline scenario. All four potential outcomes in a statistical testing procedure can be described by a Contingency Table (Table 6.2 below).

Table 6.2: Contingency Table

	H_0 is True	H_1 is True
Accept H_0	True Negative	Type II Error
Accept H_1	Type I Error	True Positive

As stated, the level of significance will determine the false positive rate resultant from a statistical analysis. In order to determine the acceptable false positive rate, we employ the false discovery rate procedure described by Benjamini and Hocherg [133] to determine whether to reject the H_{0_i} in favor of H_{a_i}, where—following a similar procedure as outlined by [4]—if at least one of the null hypotheses is rejected, we conclude that the measured evolution deviates significantly from that of the baseline. However, generally speaking, there is an inherent tradeoff associated with the goal of minimizing the false positive rate; the true positive rate is also minimized. In order to analyze the tradeoff associated with these two characteristic metrics of our statistical testing procedure, receiver operating characteristic (ROC) curves are generated for each case considered so that a true positive rate (sensitivity) can be determined at an acceptable false positive rate (1-specificity).

6.3 Cases Considered

As previously noted, we consider the antineutrino detector's ability as a potential monitoring technology to be integrated in the monitoring regime as described by the PMDA. The assumptions being considered in this analysis again are: (1) an independently measured thermal power, (2) a core model using the declared (not actual) initial isotopics provided in order to determine the baseline case to be analyzed, and (3) an antineutrino detector with systematic error controlled at the 3% level[165]. Under the PMDA, US LWR

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[164] In many practical applications, type I errors are more delicate than type II errors. In these cases, care is usually focused on minimizing the occurrence of this statistical error.

[165] Note: this assumption does not include detector and other related errors such as the error associated with the antineutrino emitted energy spectrum. For this reason, this analysis is an optimistic, best-case scenario

selected to operate with WGPu MOX fuel would only "insert a maximum of 40% of the reactor core with [weapons-grade] MOX fuel[166] [46]." As noted, since current forecasts generated by the NNSA expect produced MOX fuel assemblies to be implemented in PWR, we only consider the irradiation of WGPu MOX fuel as it relates to the core concentration of PWR core, which comprises of 193 total fuel assemblies. Therefore a maximum of a 40% MOX PWR core concentration corresponds to 77 of the reactor's 193 total fuel assemblies being comprised of WGPu MOX fuel. Hence, if a state claims to have irradiated 77 fuel assemblies, we seek to identify the potential capabilities of antineutrino detection in uncovering diversion scenarios outside of this claim. Although a 40% MOX equilibrium core appears to be the most likely reactor operational scenario given the contemporary US MOX fuel usage forecasts and lack of US customer reactors as described in Chapter 2, based on European and Japanese experience of burning reactor-grade MOX fuel, often referenced by the NRC and NNSA in their safety analyses of the irradiation of WGPu MOX fuel in LWR, we also consider the additional cases of irradiating one-third, one-quarter, and one-fifth WGPu MOX core concentration cases (corresponding to 64, 48, and 39 WGPu MOX fuel assemblies, respectively). The simulated antineutrino count rate evolution for each of these cases along a one-cycle lifetime can be seen below in Figure 6.1.

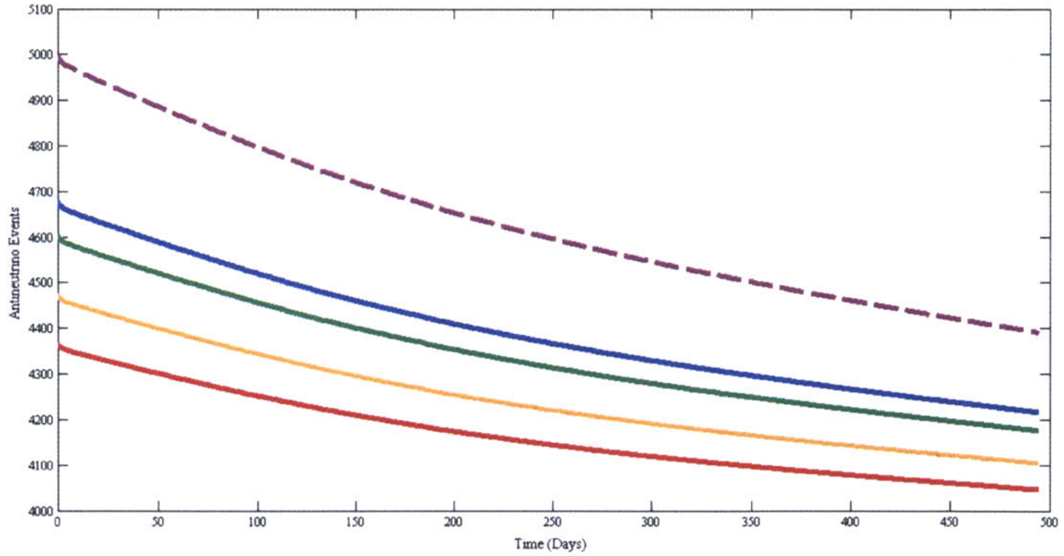

Figure 6.1: Antineutrino Count Rate Evolutions for Varying MOX Core Concentrations

This plot depicts the antineutrino count rate evolutions expected for the irradiation of 0 (dashed purple line), 39 (blue line), 48 (green line), 64 (orange line), and 77 (red line) WGPu MOX fuel assemblies. The remaining assemblies in each of these cases (193, 154, 148, 129, and 116, respectively) are assumed to be LEU.

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which depicts the achievable prospects of antineutrino detection and limitations of rate-based measurements (whether absolute or relative), without knowledge of the true initial core load. Bernstein et al. have generated an analysis which indicates that verifying burnup with high confidence in the disposition campaign can be achieved through independent verification of the initial core load, combined with a crude absolute antineutrino rate measurement without an independent thermal power measurement.

[166] The remainder of the fuel (60% or greater) is expected to be typical LEU fuel.

6.4 ROC Curve Analysis

As previously noted, in order to study the inherent tradeoffs associated with the true positive and false positive rates, a simulation was performed to estimate the true positive rate at a given false positive rate. Consistent with the target goals of the IAEA safeguards regime—which, as designated by the PMDA Article VII.3, is expected to "implement verification measures with respect to each Party's disposition program"—we assume that a credible and acceptable metric would be at least a 95% true positive rate at maximum false positive rate of 5%.

For each of the specified scenarios, a simulation was conducted in order to estimate the true positive rate at the 5% false positive rate limit, where 100,000 pairs of the baseline and diversion scenario count rate measurements were generated, with the former from Gaussian distribution and the latter from a Poisson distribution as referenced in equations (6.6) and (6.8), respectively. As an example, Figure 4 below shows the baseline antineutrino count rate evolution as well as its associated count rate measurements for the case of the irradiation of 77 WGPu MOX fuel assemblies. The diversion scenario count rate measurements were generated for the diversion case of irradiating one-less MOX assembly than originally intended, or 76 WGPu MOX fuel assemblies.

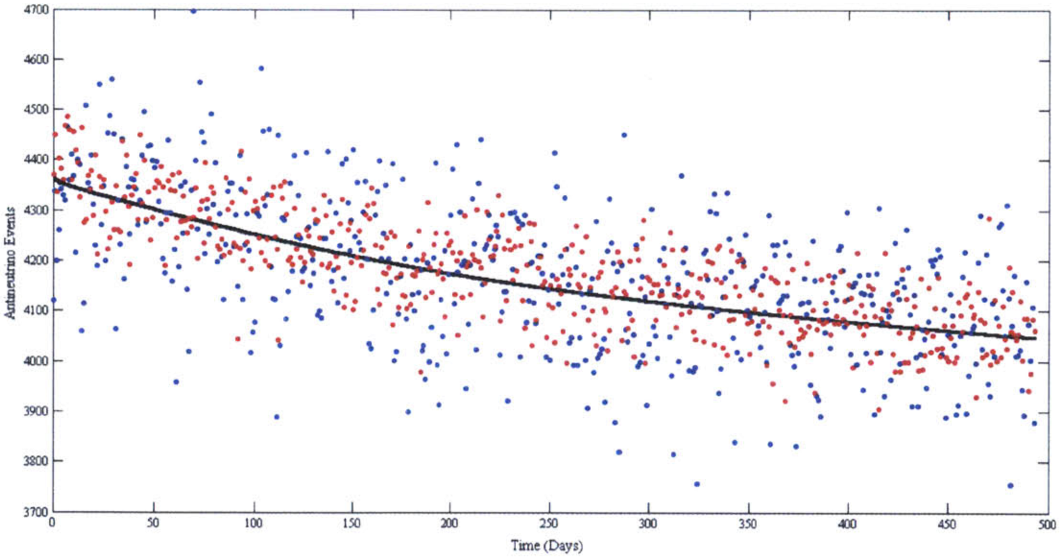

Figure 6.2: Antineutrino Count Rate Evolution and Measurements
This plot depicts the antineutrino count rate evolution (black line) as well as its associated count rate measurements (blue points) for the case of the irradiation of 77 WGPu MOX fuel assemblies. The corresponding diversion scenario count rate measurements (red points), associated with the irradiation of 76 WGPu MOX fuel assemblies, are also displayed.

Upon the generation of each of the pairs of count rate measurements associated with the baseline and diversion scenario cases, the procedures as outlined in the "Set-up for Testing of Diversion Activities," and the "Testing Procedure" were followed in order to test the detector's capabilities and limits in identifying diversion cases from the original intended amount of MOX fuel to be irradiated. As stated, a 100,000 pairs[167] were generated and tested at varying levels of significance in order to estimate both the true positive and false positive rates. The false positive rates, and their corresponding true positive rates found at each of these varying levels of significance, were then plotted against each other in order to generate the ROC curve associated with the given baseline to diversion scenario case comparison. Following the previous example, Figure 6.3 below explores the generated ROC curve associated with the 77:76 baseline:diversion-scenario case comparison to review the estimated true positive rate as the false positive rate varies. In addition, the generated ROC curves associated with the 77:73 and 77:70 baseline:diversion-scenario case comparisons are also constructed in order to show the transition, and better true positive rate acquired, in the antineutrino detector's capability. As can be seen in Figure 5, we do not achieve at least a 95% true positive rate at the 5% false positive rate limit until the 77:70 baseline:diversion-scenario case comparison. A similar procedure was also followed for the three additional cases (one-third, one-quarter, and one-fifth MOX cores) to determine the true positive rate at the 5% false positive rate limit for the diversion-scenario case of the irradiation of one-less WGPu MOX assembly than originally intended and the diversion-scenario case of the irradiation of a lower concentration of WGPu MOX assemblies in which the antineutrino detector is capable of achieving at least a 95% true positive rate at the 5% false positive rate. The results of which can be seen in Table 6.3 below.

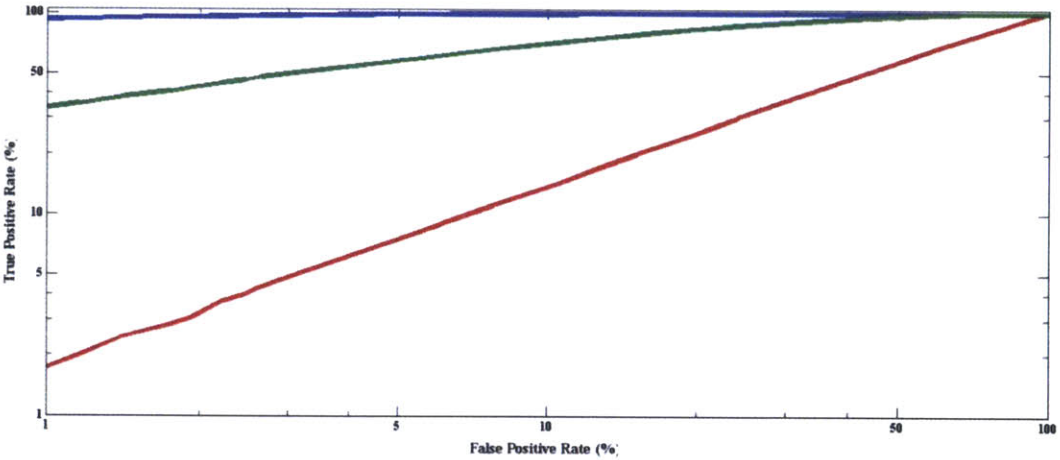

Figure 6.3: ROC Curves for Baseline:Diversion-Scenario Case Comparison
This plot depicts the generated ROC curves associated with the 77:76 (red line), 77:73 (green line), and 77:70 (blue line) baseline:diversion-scenario case comparisons in order to review the estimated true positive rate as the false positive rate varies.

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[167] Similar to the procedure implemented by Bulaevskaya et al., a 100,000 generated evolutions was selected in order to ensure that every true positive rate estimate would be within 1% of the relevant "true" true positive rate.

Table 6.3: ROC Curve Analysis Results for Baseline:Diversion-Scenario Case Comparisons

Case	Baseline (Assembly Number)	One-Less MOX Assembly Diversion TP (at 5% FP)	Detectable Assembly Number (TP ≥95% and ≤5% FP)*
1	77	7.5%	7
2	64	7.2%	7
3	48	6.9%	7
4	39	6.7%	7

*If minor reductions are allowed at the true positive rate level from our initial assumption of a true positive:false positive rate comparison of 95%:5%, it may pose of some interest to note that at one assembly number above those stated (i.e. six-less MOX assemblies from baseline case) true positive rates of 92.9%, 91.4%, 90.1%, and 89.9%, respectively, were all noted at the 5% false positive rate.

6.5 Effect of Non-Reactor Based Antineutrino Events

Bernstein et al. [126] have noticed that non-reactor based antineutrino events in the detector, spurred by background radiation, can mimic actual antineutrino signals generated from fission in the reactor core. Based on their measurement analyses, they show that background radiation, measured during reactor-off periods, is distributed as a Poisson random variable. These non-reactor based antineutrino events dilute the detector and test sensitivity. In the previous simulation analysis, we depicted the sensitivity of our detector for purposes of the PMDA in the absence of background. In these examples, it was found that the detector was successful in identifying diversion scenarios up to a maximum of approximately seven MOX fuel assemblies below the baseline scenario, or the amount originally intended.

In order to study the effect of the background on the sensitivity of our testing procedure, a Poisson-distributed background term is incorporated into the testing structure with its mean proportional to the given evolution's initial count rate. The true positive rates are then recalculated at the 5% false positive rate limit for the cases of backgrounds with means equal to 5%, 10%, and 25% of the initial antineutrino count rate. Our maximum background mean of 25% is comparable to the observed background rate as identified by in the SONGS1 antineutrino detector "reactor-off" background measurement [134]. An example in the variation of the true positive and false positive rates at the 77:70 baseline:diversion-scenario case comparison as a result of the addition of this background can be seen in Figure 6.4 below.

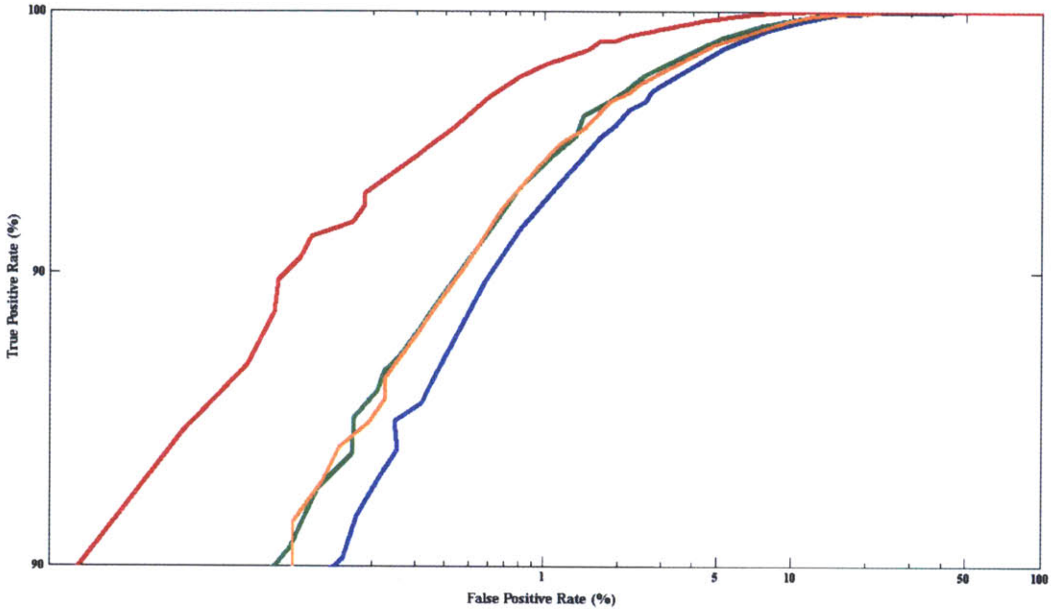

Figure 6.4: ROC Curve for 77:70 Case Comparison at Varying Background Rates
This plot depicts the generated ROC curves associated with the 77:70 baseline:diversion-scenario case comparison with no background term (red line) and including a background term with a mean equal to 5% (orange line), 10% (green line), and 25% (blue line) of the initial antineutrino count rate.

The variation in the true positive rates at the 5% false positive rate limit for the other baseline:diversion-scenario case comparisons conducted in this analysis can be seen below in Table 6. It is interesting to note that at even at a background mean of 25% of the initial antineutrino count rate, the test performance slightly degrades by a maximum of approximately 2%. Similar to the results determined by Bulaevskaya et al., such success in the test performance would be expected to degrade substantially when the background rate increases and approaches that of the signal.

Table 6.4: ROC Curve Analysis Results for Baseline:Diversion-Scenario Case Comparisons at Varying Background Rates

Background (% of signal)	**0**	**5**	**10**	**25**
Case Comparison (baseline:diversion-scenario)				
77:70	100	98.8	98.6	98.1
64:57	100	98.6	98.5	98.1
48:41	99.9	98.4	97.9	97.5
39:32	99.8	99.4	98.1	97.9

6.6 Effect of Measurement Duration

As expected in any measurement exercise, for purposes of this analysis, the estimates of the evolution coefficients, γ_{i_M}, and the test performance are expected to improve as longer durations of measurements are allowed. In the previous analyses, we considered measurements accounted for along the entire lifetime of the cycle (493 days). In order to gain insight into the effect associated with the duration of measurement and the capabilities of the antineutrino detector's ability to successfully identify diversion scenarios at earlier periods, we investigate the following three duration periods outside of the previously considered full cycle length: the first year (approximately 360 days), the first 6 months (approximately 180 days), and the first 3 months (approximately 90 days) of operation. An exploration was conducted for the success of the testing procedure at the first 30 days, however, initial simulations depicted that the test performance is highly unfavorable at such low measurement durations.

Still consistent with the designated credible and acceptable metric of a true positive rate of at least a 95% at maximum false positive rate of 5%, the diversion-scenario cases are found for each of these measurement duration periods and each MOX core concentration case. The results of which can be seen in Table 6.5 below. Consistent with the previous analysis associated with the effect of the background rate, it is interesting to note that the test performance is largely maintained.

Table 6.5: ROC Curve Analysis Results for Baseline:Diversion-Scenario Case Comparisons at Varying Measurement Durations

Baseline Case (Number of MOX Assemblies)	**77**	**64**	**48**	**39**
Duration Period				
First 90 days	65	51	35	26
First 180 days	68	55	38	29[a]
First 360 days	70	57	40	31[b]

[a] Although not 95%, a true positive rate of 93.4% was reached at 30 WGPu MOX assemblies

[b] Although not 95%, a true positive rate of 93.7% was reached at 32 WGPu MOX assemblies

Excluding one-fifth WGPu MOX core case (39 WGPu MOX assemblies), it appears that our test performance for the measurement duration of the first year (~360 days) is essentially identical to the test performance for the measurement duration of the entire cycle (493 days). In addition, excluding the one-fifth WGPu MOX core case again, our test performance for the case comparisons are only reduced by 5 WGPu MOX assemblies when the measurement duration is reduced to the first 3 months (~90 days).

6.6.1 Sensitivity Analysis

To investigate the impact in the detector sensitivity associated with the measurement duration, we investigate the sensitivity associated with our testing procedure at the extremes of our measurement duration periods, 90 days and 493 days. In addition to analyzing the sensitivity of our detector at the maximum MOX core concentration case (77 WGPu MOX assemblies), we also investigate the sensitivity of our testing procedure in potentially identifying the introduction of WGPu MOX assemblies into a fuel core expected to only be operating with LEU; a case that may prove beneficial for the IAEA not only in its aspirations for successful verification mechanisms as related to the PMDA but, more generally, in its continual aspirations to safeguard MOX fuel use.

As previously acknowledged, the selection of a level of significance (α) is an extremely delicate task, where many tradeoffs emerge depending on its magnitude. A relatively large α, like 5%, as compared to relatively small α, like 0.1%, allows the user the benefit of successfully differentiating between various MOX core concentrations (true positive rate), at the downfall of an increase in the rate of falsely differentiating between various MOX core concentrations (false positive rate). With a target false positive rate limit of 5%, the associated level of significance was often found between 1-2%. In each of these analyzed cases, 100,000 iterations are performed in which the testing procedure determines the MOX core concentration that it perceives as being different from the baseline cases (77 and 0 WGPu MOX assemblies). In Figures 6.5 and 6.6, the sensitivity analyses for the case of 77 WGPu MOX assemblies with the measurement duration periods of 90 and 493 days, respectively, are presented. Similarly, Figures 6.7 and 6.8 depict the sensitivity analyses for the case of 0 WGPu MOX assemblies with the measurement duration periods of 90 and 493 days, respectively. As can be seen in the each of these analyses, the determined case comparisons appear to be Gaussian distributed, following the function:

$$f\left(x;\sigma,\overline{x}\right)=e^{\frac{-\left(x-\overline{x}\right)^2}{2\sigma^2}} \tag{13}$$

where x, $\overline{x}$, and σ correspond to the number of assemblies, the sample mean, and the standard deviation, respectively. In addition, a corresponding 95% threshold value is selected either below (for the 77 WGPu MOX assemblies case) or above (for the 0 WGPu MOX assemblies case) for each of these cases. For the cases analyzed, this 95% threshold value correlates to the minimum (for the 77 WGPu MOX assemblies case) or maximum (for the 0 WGPu MOX assemblies case) limit in which our testing procedure can successfully identify a potential diversion act outside of original core concentration as designated by the state (assumed to be the baseline scenario).

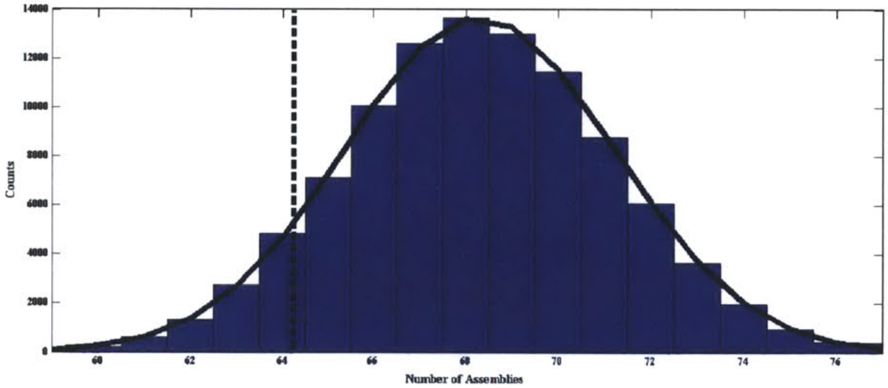

Figure 6.5: Sensitivity Analysis for 77 MOX WGPu Assemblies (90 days)
A histogram and corresponding Gaussian distribution approximation for the sensitivity analysis performed for the 77 WGPu MOX assemblies case at a 90-day measurement duration period. With a level of significance set at 1%, the false positive rate was 2.84% with a 95% threshold value set at 63.47 WGPu MOX assemblies. The Gaussian distribution approximation has a mean of 68.2846 with a standard deviation of 2.9285.

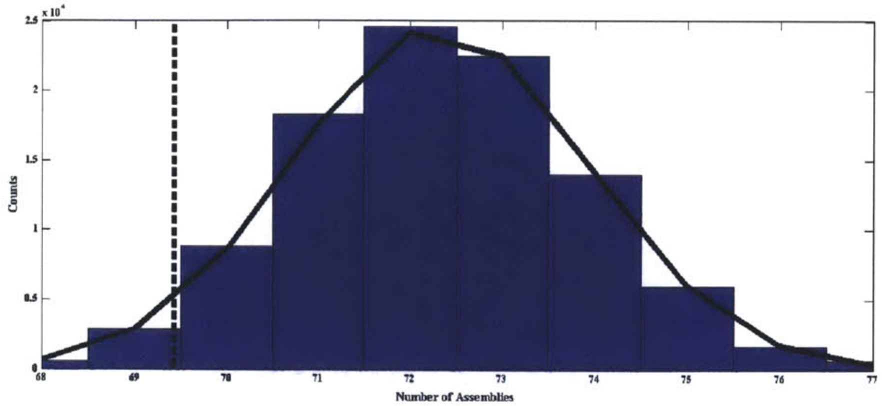

Figure 6.6: Sensitivity Analysis for 77 MOX WGPu Assemblies (493 days)
A histogram and corresponding Gaussian distribution approximation for the sensitivity analysis performed for the 77 WGPu MOX assemblies case at a 493-day measurement duration period. With a level of significance set at 1%, the false positive rate was 2.77% with a 95% threshold value set at 69.68 WGPu MOX assemblies. The Gaussian distribution approximation has a mean of 72.3122 with a standard deviation of 1.6004.

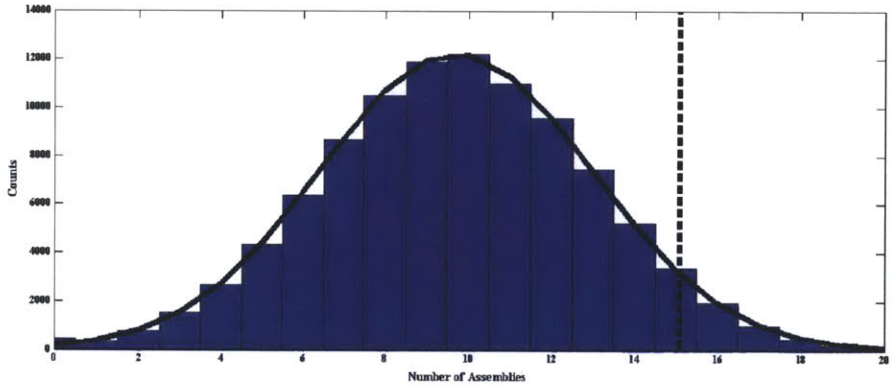

Figure 6.7: Sensitivity Analysis for 0 MOX WGPu Assemblies (90 days)
A histogram and corresponding Gaussian distribution approximation for the sensitivity analysis performed for the 0 WGPu MOX assemblies case at a 90-day measurement duration period. With a level of significance set at 1%, the false positive rate was 2.83% with a 95% threshold value set at 15.10 WGPu MOX assemblies. The Gaussian distribution approximation has a mean of 9.6888 with a standard deviation of 3.2842.

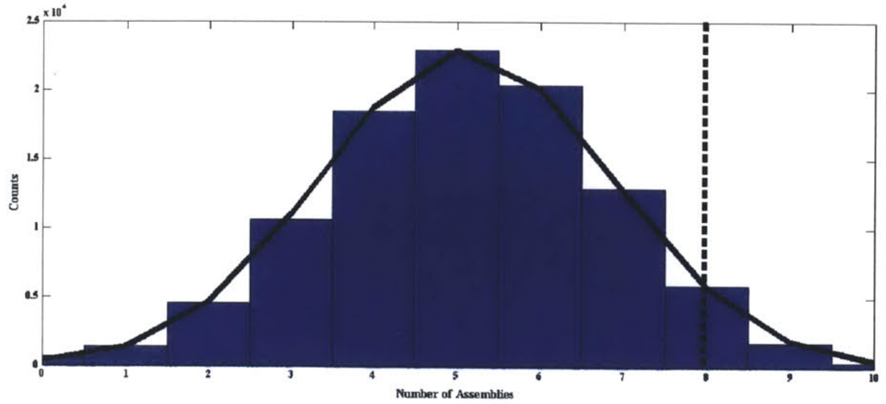

Figure 6.8: Sensitivity Analysis for 0 MOX WGPu Assemblies (493 days)
A histogram and corresponding Gaussian distribution approximation for the sensitivity analysis performed for the 0 WGPu MOX assemblies case at a 493-day measurement duration period. With a level of significance set at 1%, the false positive rate was 2.71% with a 95% threshold value set at 7.98 WGPu MOX assemblies. The Gaussian distribution approximation has a mean of 5.1070 with a standard deviation of 1.7417.

6.7 Effect of Systematic Uncertainty and Operator Malfeasance

With any measurement exercise, the prospects of falling victim to systematic uncertainty[168] in the predicted and/or measured antineutrino count rate for our testing procedure are quite likely to happen. Uncertainties in our predicted and/or measured count rates have the potential to cause the measurements collected by the detector to deviate significantly from the predicted baseline evolution. This has the potential to cause massive increases in our false positive rate due to the increased prospects associated with large deviations even in the absence of diversion scenario action. In our simulation, the absolute count rate of reactor antineutrinos was predicted with 3% systematic uncertainty. In similarly related reactor-based antineutrino measurement experiments, Bemporad et al. determined that errors arising from detector-related systematic uncertainties[169] are smaller at around the 1.5% level[170] [135].

Beyond the scope of systematic uncertainties, the prospects of operator malfeasance can also pose extreme threats to the associated predicted and measured antineutrino count rate. As originally shown in equation (6.1), both thermal power of the operating reactor and the fissile isotopic content in its fuel core can be altered and may result in dramatic effects associated with the antineutrino count rate. For example, in an attempt to conceal the intent to irradiate less WGPu MOX assemblies than originally stated, the reactor operator may report a lower operating power than the power the reactor truly operated[171]. Such

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[168] Systematic uncertainty is inclusive of examples like instrumental effects, incorrect calibration, etc.

[169] For example, this may relate to imperfect knowledge of the number of target atoms in the detector.

[170] Note, this is the best-case scenario for the detector uncertainties. Spectral densities also have a 3% systematic error as described in Bemporad et al. and later publications, which can't be neglected in this kind of analysis unless we have a prior high statistical measurements of the baseline core for comparison.

[171] The assumption is made that misreporting power is only a sensible strategy for the operator who is truly irradiating less fuel than originally intended. Therefore, a false positive incident would only occur if the operator were indeed operating the reactor at the reported power (but different from the original baseline scenario), for example, in order to generate a different amount of electricity. However, it is vital to note that

information introduced into the hypothesis testing procedure would cause the simulation to incorrectly predict a systematic downward shift in the baseline evolution. Please note, although fissile isotopic content of the fuel core can effect the associated antineutrino count rate, the effect associated with fissile isotopic content (i.e. the irradiation of reactor-grade MOX fuel or higher-burnup LEU fuel) is not considered in this analysis as this appears to be too difficult of a task for any potential rate-based testing procedure to identify under the limitations of antineutrino monitoring [136].

In order to address the impact of a misreported power history as well as systematic uncertainty with the detector[172], we considered the most extreme case in which the operator—truly operating with a core composed of 0 WGPu MOX fuel assemblies despite original statements that he/she would operate with a core composed of 77 WGPu MOX fuel assemblies—published a lower operating power such that the antineutrino count rate on the initial day was comparable to that of the antineutrino count rate associated with the predicted baseline of a reactor operating with a core composed of 77 WGPu MOX fuel assemblies. To totally eliminate the inconsistencies associated operator malfeasance or systematic uncertainty for the hypothesis testing procedure, a relative comparison, as compared to an absolute comparison, of the antineutrino count rate evolutions is proposed. Although seeking to maintain consistency with prior analyses at the 77:70 baseline:diversion-scenario case comparison along a full cycle-length measurement duration, Figure 6.9 depicts how similarly related these measurements are; such that the measurement error associated with the diversion-scenario associated with the irradiation of 70 WGPu MOX assemblies resides within the error associated with the baseline evolution.

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often times the state of each core is recorded hourly in a plant history file, among other places. In many of the antineutrino detection experiments, this is how personnel monitored the state of the plant to extracted the fission rates produced from the core.

[172] We assume that this scenario addresses impacts associated with operator malfeasance and systematic uncertainty based on the assumption that the error associated with operator malfeasance is much greater than that associated with systematic uncertainty. In an analysis of the effect associated with systematic bias in detector response, Bulaevskaya et al. considered the scenarios of false overall upward and downward systematic shifts (at 1% of the original evolution). Both scenarios, generated in order to simulate miscalibration of the detector (i.e. incorrectly estimating the detector volume or detector distance from the reactor core), resulted with nearly equivalent effects. resulting from a miscalibration of the detector, such as an underestimate of the detector volume. The directions of both shifts were chosen to undermine the statistical power of the test. A 1% absolute systematic error was found to be more than sufficient to illustrate the strong impact of such shifts, and the performance of both scenarios chosen to undermine the statistical power of the test.

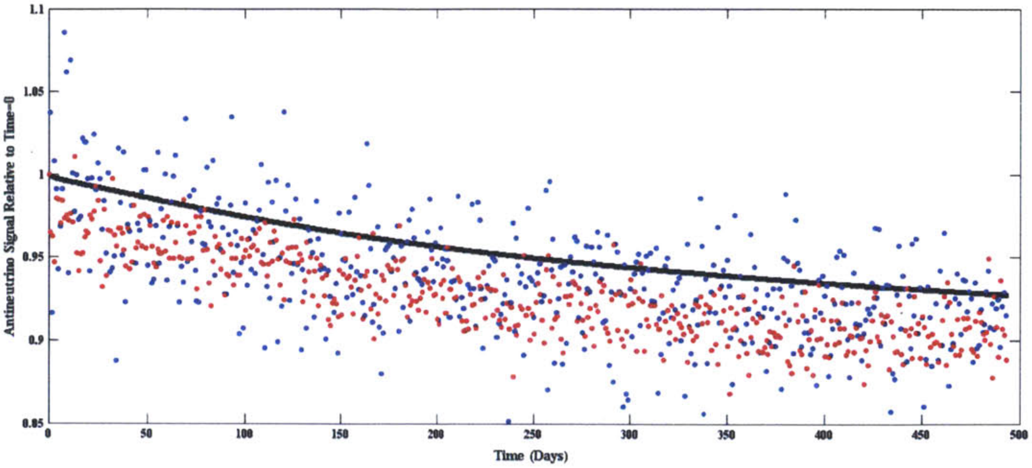

Figure 6.9: Relative Antineutrino Count Rate Evolution and Measurements

This plot depicts the relative antineutrino count rate evolution (black line) as well as its associated count rate measurements (blue points) for the case of the irradiation of 77 WGPu MOX fuel assemblies. The corresponding diversion scenario count rate measurements (red points), associated with the irradiation of 70 WGPu MOX fuel assemblies, are also displayed.

For this reason, we analyze the capabilities of the hypothesis procedure in successfully identifying the diversion scenario of the aforementioned extreme case of the 70:0 baseline:diversion-scenario case comparison as seen in Figure 6.10 below. Figure 6.11 below highlights how the resulting baseline prediction is much less distinguishable from the diversion scenario than their original counterparts as seen in Figure 6.1.

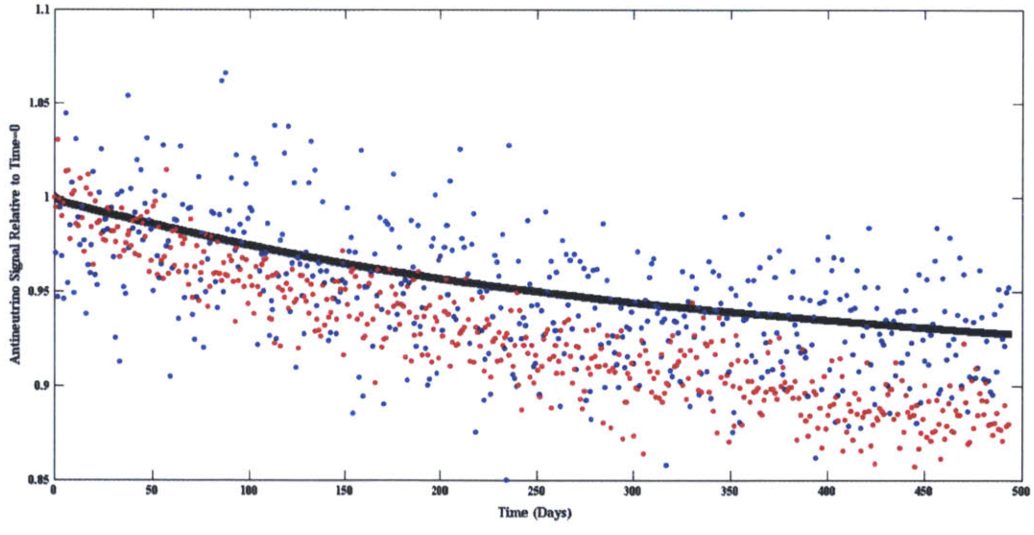

Figure 6.10: Relative Antineutrino Count Rate Evolution and Measurements

This plot depicts the relative antineutrino count rate evolution (black line) as well as its associated count rate measurements (blue points) for the case of the irradiation of 77 WGPu MOX fuel assemblies. The corresponding diversion scenario count rate measurements (red points), associated with the irradiation of 0 WGPu MOX fuel assemblies, are also displayed.

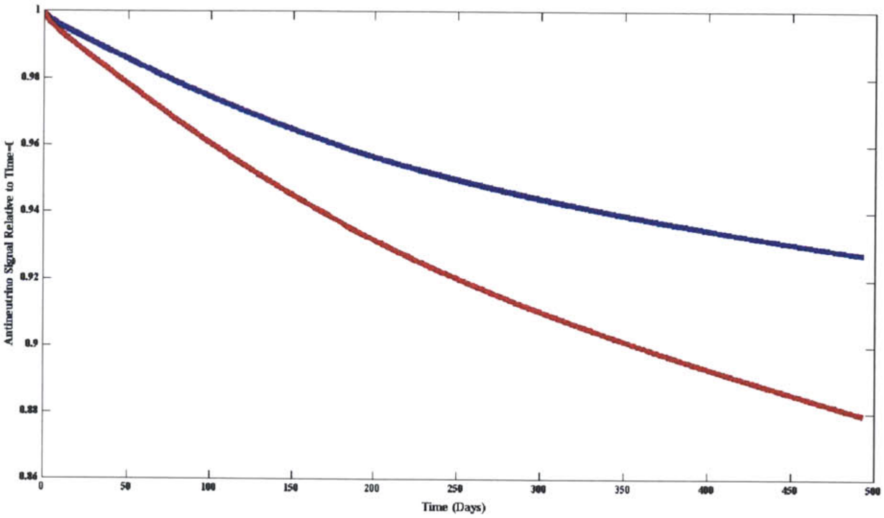

Figure 6.11: Relative Antineutrino Count Rate Evolutions
This plot depicts the relative antineutrino count rate evolutions expected for the irradiation of 0 (blue line) and 77 (red line) WGPu MOX fuel assemblies. The remaining assemblies in each of these cases (193 and 116, respectively) is assumed to be LEU.

However, despite analyzing the most extreme (and least likely) case comparison and the absence of other considered variables in the broader analysis such as background count rate and/or reduced measurement duration periods, the false positive rate could only be reduced to a minimum of 55.7%, resulting in a true positive rate of approximately 97.2%[173].

In an attempt to reduce the false positive rate further, the hypothesis testing was reconfigured such that the latter days of the full cycle length measurement duration period was only considered in hopes that the hypothesis testing procedure would be strengthened by analyzing the count rate measurements where the two cases would differ the most. We considered the cases of the last 90, 60, 30, and 10 day periods of the full cycle measurement duration period. For the last 90 days of the measurement duration period, the false positive rate could only be reduced to a minimum of 15.1%, resulting in a true positive rate of 53.4%. For the last 60 days of the measurement duration period, however, the 5% false positive rate was achieved with a true positive rate of 34.6%. Similarly, for the last 30 and 10-day periods of the measurement duration period, a true positive rates of 35.7% and 26.9%, respectively, were achieved at the 5% false positive rate limit.

As can be seen, combating systematic uncertainty and operator malfeasance via a relative analysis of the baseline and diversion-scenario cases proves to be an unpromising tactic. Table 6.6 shows the percent decrease in the evolution count rate at the specified measurement duration period relative to the count rate measurement at the beginning of the fuel cycle. Given the slight decreases in the evolution count rate relative to the count rate measurement at the beginning of the fuel cycle, more novel testing procedures and analytical processes must be introduced to combat more specifically the small differences

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[173] The level of significance was reduced to the order of 1×10^{-20}; well beyond the scope of traditional statistical testing criteria.

associated with the relative changes in each of these evolution's trajectories and more broadly the consequences produced as a result of systematic uncertainty and/or operator malfeasance.

Table 6.6: Relative to Beginning of Cycle evolution count rate Change at Specified Measurement Duration Periods

Baseline Case (Number of MOX Assemblies)	**0**	**39**	**48**	**64**	**77**
Duration Period					
First 90 days	-3.61%	-3.01%	-2.86%	-2.58%	-2.34%
First 180 days	-6.33%	-5.24%	-4.97%	-4.46%	-4.03%
First 360 days	-10.03%	-8.21%	-7.75%	-6.90%	-6.17%
Full Cycle Length (493 days)	-12.06%	-9.78%	-9.21%	-8.15%	-7.24%

Chapter 7: Summary, Conclusions, and Future Work

7.1 Thesis Summary and Conclusions

As the 2018 start year for plutonium disposition exercises approaches, securing the necessary multilateral verification measures needed to ensure proper and successful disposition as outlined in the PMDA will be vital. In this thesis, an overview and assessment was provide with regards to the US developmental process and current customer landscape in its endeavor to fulfill its 2018 target start time for WGPu MOX fuel irradiation. Although the PMDA states that both the US and Russia are to engage the IAEA "to implement verification measures with respect to each Party's disposition program," discussions have yet to proceed beyond initial discussions in 2011 [41]. From current estimates, it appears that the agreement will again face extreme delays as experienced in early engagements with the original agreement in 2000. Nonetheless, in an attempt to characterize the role of the IAEA as a neutral, objective party to the prospective multilateral verification regime to be constituted through the PMDA, an exploration into the underlying policy and technical concepts in achieving such a regime was pursued through a brief case study of relevant initiatives. Furthermore, and specifically tailored to the interests of this thesis, the expected safeguards landscape under such a multilateral regime within the US was also explored, revealing many promising attributes with regards to the UMS characteristics of antineutrino detection. All in all, the purposes of this thesis was intended to increase access to available information regarding this topic and subjects relevant to the contemporary strategy concerning disposition of surplus military plutonium via US LWR irradiation.

The principle accomplishment of this thesis was the introduction of a testing procedure that sought to determine whether a given antineutrino rate evolution[174] significantly deviates from that of the baseline, in an attempt to analyze the prospects of antineutrino detection as a tool in identifying potential diversion scenarios from declared specifications under the PMDA. Not only were the specific applications of antineutrino detection to potential verification and confirmation goals outlined within the text of the PMDA introduced, but the practical viability of such an approach was also assessed. It is vital to note that the results of this thesis, which implemented credible reactor simulations [119, 136], are resultant of only a preliminary investigation. I acknowledge that further research, both from technical (further reactor simulations, actual demonstration of WGPu MOX irradiating LWR, etc.) and policy (state and IAEA perspectives, etc.) standpoints, will be required in order to fully appreciate the applicability of such a detector for PMDA-related verification purposes. The analysis shows that antineutrino rate based measurements in which the thermal power is well known by independent means, and for which the measurement uncertainty from all sources is at the level of 3%, would reveal substitution of as few as 7 LEU assemblies for MOX assemblies with high confidence. It further revealed

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[174] It is vital to note again that the antineutrino rate evolution in these simulations were represented by an analytic function of time. Similarly, a function of burnup also follows the same procedure. The procedure described in this work, initially implemented by Bulaevskaya et al., implemented least squares estimation procedures for the identified analytic model for the antineutrino rate measurement evolution. This, in turn, was used in the hypothesis testing procedure in order to discover the specified false discovery rate, which in turn was used to determine whether or not the given scenario differed significantly from the baseline scenario.

that rate based measurements seeking to identify a switch in MOX and LEU assemblies that do not include the independently measured thermal power are subject to spoofing if the operator misreports the power.

Current studies of antineutrino-based verification methods for PMDA are focused on making use of a validated initial MOX inventory and core map, combined with an absolute measurement of the antineutrino rate (i.e. without reference to a previously measured value) in order to specify the burnup of the MOX assemblies at discharge. The measured thermal power would not be required as an input, and the precision requirements on the antineutrino rate measurement are relaxed considerably compared to the assumptions used here. This method evades the weaknesses of the method analyzed in the present work, which depends on an operator input (thermal power) that is relatively difficult to otherwise control or verify, as well as an antineutrino detector at the limit of absolute precision (~3%) achieved so far.

The work performed in this thesis serves as an element to an integrated effort to analyze the practicality of antineutrino detection as an IAEA verification metric primarily as it relates to the PMDA, but also possible similar future plutonium disposition campaigns conducted by other NPT NWS as well as domestic and international LWR and other reactor-type safeguarding practices. The results of which will be combined with a continued effort and the ongoing work being conducted by Adam Bernstein and the rest of the LLNL Advanced Detectors Group. Therefore, it is possible that not all of the calculations and evaluations documented in this work may carry significant relevance and meaning when viewed alone. The end product of this continuing effort, however, seeks to reveal crucial knowledge regarding the expected performance and overall efficacy of the multiple antineutrino detection verification approaches. Although the antineutrino detection system proposed in this thesis for PMDA multilateral verification purposes has yet to be fully designed and deployed, the analysis performed revealed many interesting findings; disclosing many of the technology's inherent strengths and weaknesses as they relate to contemporary verification mechanisms.

The antineutrino detection's independent capability of successfully identifying potential diversion scenarios—at a threshold of seven WGPu MOX assemblies less than original declarations—appears to be somewhat promising. From an IAEA perspective, this is the identification of 17.5 SQ over the entire cycle lifetime and, for most of the considered cases in this exercise, within the first year of operation[175]. Quite obviously, the high counting statistics expected with a fully efficient detector[176] over the longer periods of time—the maximum in this exercise being the full cycle length—resulted in the best detector performance in attaining the 95% true positive rate at a 5% false positive rate limit. Although this 17.5 SQ identification over a 360-day period is well beyond IAEA

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[175] Although other cases were considered, the 40% WGPu MOX core concentration case (an implementation of 77 PWR WGPu MOX fuel assemblies) serves as the most important case considered. We argue this perspective not only because of it serves as the maximum WGPu MOX fuel fraction as designated by the NRC [46], but also since it is the most likely LWR operating scenario that will be needed in order for the US to maintain the annual PMDA-required WGPu MOX throughput given the likely customer landscape as outlined in Chapter 2.

[176] The results of the simulation highlighted the effective capabilities associated with a 100% effective detector—of similar scope, design, and demonstration parameters as the SONGS1 experiment—as an important characteristic in ensuring and promoting the viability of such a potential verification approach.

timeliness goals for plutonium [95], it is highly probable that minor adjustments will be made to such requirements due to IAEA's scope and expected roles within the PMDA. As acknowledged in Chapter 5, coupling the detection capabilities with contemporary safeguard and/or verification procedures antecedent, during, and subsequent to WGPu MOX irradiation however, will significantly strengthen the technology in achieving many of the specified applicability goals.

Beyond the considered WGPu MOX core concentrations and measurement duration periods, the simulation revealed the efficiency costs resultant from, non-reactor based antineutrino events constituent to the overall antineutrino rate measurement, detector systematic uncertainty, and potential operator malfeasance scenarios, all as they relate to WGPu MOX implementation in LWR operation. The effect associated with non-reactor based antineutrino events did not appear to significantly deter the effectiveness of antineutrino detection capability. Unfortunately, however, the effects associated with detector systematic uncertainty and/or potential operator malfeasance scenarios proved to be extremely detrimental. When implementing a testing procedure considering the antineutrino rate evolutions from the baseline and measured scenarios relative to their initial day measurement to combat such effects, the procedure proved futile. Based on the results of this exercise, it appears that antineutrino rate measurements alone are unable to provide significant means in combating such scenarios. However, beyond the prospects of antineutrino rate measurements coupled with additional independent verification means, we acknowledge that future research in this endeavor should consider direct measurement of the antineutrino spectrum, as initially described in Chapter 5 and by Huber and Schwetz [2]. Such a measurement would provide sufficient information that would simultaneously constrain both power and fissile isotopic content; significantly minimizing and even eradicating the prospects of thermal power misreporting by the operator[177].

All in all, given the simulation-provided capabilities presented with regards to the antineutrino rate measurements from an operating LWR, it becomes evident that antineutrino detection cannot exclusively resolve the probable PMDA verification goals at the US LWR site. As demonstrated from a qualitative perspective, this technology's primary strength when operating as a purely independent verification metric is maintenance of CoK. However, in conjunction with other safeguard and security procedures, this technology can enhance knowledge regarding numerous variables associated with the US plutonium disposition campaign, no matter the party responsible (IAEA or Russia) for verification. As noted earlier in this thesis, a hybrid system incorporating a validated core simulator, an independent mechanism to verify the initial isotopics of the incoming WGPu fuel, WGPu fuel positions within the reactor fuel core, or independent verification of the reactor thermal power, coupled with antineutrino rate measurements has the prospect of confirming that the WGPu MOX fuel achieves the minimum burnup criterion, that the discharged fuel possesses the declared mass and isotopic composition criterion, and that the US or Russia are meeting the total annual WGPu mass throughput requirements outlined in the PMDA.

Additionally, as a UMS, this technology would aid in achieving RSI at the site

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[177] Bulaevskaya et al. argues that the statistical power of the testing procedure implementing antineutrino energy spectrum measurements, however, may be compromised due to the expected reductions in the antineutrino rate per energy bin. Such pitfalls could be combated however by more efficient detectors (i.e. larger detector mass/volume).

during the entire fuel cycle by maintaining CoK in near real-time. Assuming that the IAEA will be responsible for the verification procedures at the time of initial operations in 2018, such a technology will prove extremely beneficial from a cost-reductions perspective with expected growth in IAEA safeguarded LWR and MOX fuel. Furthermore, such a technology will not inhibit or retard normal operation—as was demonstrated with SONGS1 [5]—at the reactor site, significantly reducing the expected domestic or international PMDA-related inspections required during reactor operation. From an operator's perspective, such attributes may possibly serve as additional advantageous features; aiding NNSA interests in appealing to potential and future customer reactors to assist in the US disposition campaign.

7.2 Recommendations for Future Work

An obvious and primary recommendation that should be considered towards attaining support of the applicability of antineutrino rate measurements towards PMDA-related verification purposes would be similar testing procedures applied to the identification of potential diversion scenarios at the Russian-selected disposition reactor types (i.e. the BN-600 and BN-800 fast neutron reactors). Similarly, verifying the PMDA specified burnup levels[178] for Russian WGPu MOX fuel will also be essential. The number of fuel cycles as well as the cycle duration needed to achieve PMDA verification specifications associated with WGPu MOX fuel in both US and Russian designated reactors must also be determined and will require further research.

In order to make more practical simulation and supporting testing procedures for the discussed targets, it will be necessary to couple such computational methods with more actual demonstrations of antineutrino rate measurements at varying reactor sites and types, detector designs, and detector parameters (mass, distance, efficiency, etc.). For purposes of the analysis performed in this thesis, a 100% efficient detector was considered. Although considered from a theoretical standpoint, we acknowledge that this assumption is however highly unlikely given the scope of various antineutrino detector experiments that have been demonstrated. Related detector experiments to the SONGS1 experiment [112], of similar scintillator design, that have been demonstrated and may are at Rovno 2 [137], CHOOZ [138], Palo Verde [139], and Bugey [140] depict the variability in such reactor and detector characteristics and have been summarized below [4]:

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[178] Section II of the Annex of Technical Specifications of the PMDA defines the burnup level required for Russian WGPu MOX fuel assemblies as a minimum burnup criterion of "five (5) percent of heavy-metal atoms for assemblies from the BN-600 reactor; three and nine-tenths (3.9) percent of heavy-metal atoms for assemblies from the BN-800 reactor during the two-to-three year reactor commissioning stage; and four and one-half (4.5) percent of heavy-metal atoms for assemblies from the BN-800 reactor during the stage of operation of the reactor with rated parameters," must be achieved. Moreover, it states that the "average fuel burnup level of any batch of such spent plutonium fuel assemblies discharged during the same refueling outage from the reactor core is no less than: six and one-half (6.5) percent of heavy-metal atoms for the BN-600 reactor; five (5) percent of heavy metal atoms for the BN-800 reactor during the two-to-three year reactor commissioning stage; and six (6) percent of heavy metal atoms for assemblies from the BN-800 reactor during the stage of operation of the reactor with rated parameters."

Table 7.1: Reactor Characteristics and Detector Parameters for Previous Antineutrino Detection Experiments

Demonstration	Reactor Power (GW_t)	Detector Mass (MT)	Detector Distance (m)	ε (%)	Background:Signal (%)
SONGS1	3.4	0.64	25.0	11	18.6
Rovno 2	1.375	~0.2	18	30	35.2
CHOOZ	4.1	5.0	1000	69.8	5
Palo Verde	11.6	11.3	800	10	150
Bugey*	3.4	0.60	15.0	30	3.8

* Although the referenced antineutrino detectors are all based on scintillator detector designs, we Bugey implemented a Li-doped scintillator detector design whereas the rest implemented a Gd-doped scintillator design.

As a more practical exercise, design decisions that aim to increase the expected detection range and capabilities at the expense of financial and operational costs should be vigorously examined as it relates to multilateral verification measures. If the IAEA is to be responsible for the verification measures at the reactor site as it relates to the plutonium disposition campaign, an important future exercise that experts within the organization should conduct is a fuller analysis of implications associated with this technology. From a financial perspective, all considered parties (US, Russia, and IAEA) should employ a cost-benefit analysis with regards to an actual system of verification techniques employing antineutrino rate based, and potentially spectrum based, measurements.

Finally, applications of a hypothesis testing procedures, similarly performed in this work, should also be applied to antineutrino spectrum based measurements, including realistic statistical and systematic uncertainties, in an endeavor to quantify any additional sensitivity attributes inherent in a spectral analysis. From a qualitative perspective, it has already been acknowledged that an antineutrino energy spectrum measurement would allow for the attainment of all four of the applicability goals[179] stated above. Furthermore, as proposed for rate based measurements, the number of fuel cycles as well as the cycle duration needed to achieve PMDA verification specifications associated with WGPu MOX fuel in both US and Russian designated reactors must also be determined and will also require further research.

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[179] Only partial verification of the annual WGPu disposition throughput requirement goal is achieved

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Appendix A: The WGPu MOX Conversion Approach

A.1 Associated Technologies And Construction Status

In order to fulfill the requirements of MOX fuel fabrication as designated to the US by the PMDA, construction of a series of facilities[180] to carry out these roles is taking place at the Savannah River Site (SRS) near Aiken, South Carolina. MFFF construction began in August 2007, where significant process has been made achieving completion of eleven of the auxiliary buildings needed to support construction and operation of the MOX facility. Current expectations for operations start-up of MFFF are October 2016 with a 20-year operating license[181] [141].

Although SRS contains many facilities, the three most crucial facilities in fulfilling the US plutonium disposition program are the Pit Disassembly and Conversion Facility (PDCF), which will convert both surplus weapons plutonium pits and plutonium metal into plutonium oxide; the MOX Fuel Fabrication Facility (MFFF), which will covert plutonium oxide into MOX fuel; and Waste Solidification Building (WSB), which will process radioactive wastes from PDCF and MFFF [44].

Extensive delays have occurred with regards to the construction and start-up time frames associated with these facilities (See Table A.1), which is a joint-ventured collaboration called Shaw AREVA MOX Services LLC[182] that was intended to begin construction in October 2003 [142]. Furthermore, PDCF, with an expected start-up time by March 2006 has been delayed until December 2021, as revised in the in the PMDA. However, more recently due to unforeseen safety issues, inadequate oversight, insufficient management resources, and ill-prepared required technologies, DOE suspended construction of PDCF and is now assessing considerations to incorporate the intended capabilities of PDCF into the Plutonium Preparation Project facility also at the Savannah River Site[183].

Table A.1: Changes in Estimated Operating Dates for Savannah River Site Facilities

Facility	Approximate Operating Date in 2000	Current Approximate Operating Date
Pit Disassembly and Conversion Facility	03/2005	TBD (previously 12/2021)
MOX Fuel Fabrication Facility	04/2006	10/2016
Waste Solidification Building	N/A	09/2013

Courtesy of *updated PMDA, "Annex on Schedules and Milestones"*

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[180] These infrastructure projects serve as one of the largest construction projects in the southeastern US, employing more than 1,800 construction workers, designers, and engineers providing a massive economic impact to domestic national security and energy policy.

[181] MFFF will help provide a pathway out of South Carolina for the surplus plutonium brought to SRS for disposition

[182] Shaw and AREVA will split responsibility for the project 70:30.

[183] The effects of PDCF's uncertain status and continued delays of sites in SRS on progression of the US disposition plan are still uncertain.

A.2 Benefits of MOX Conversion Approach

NNSA in selection of the MOX conversion approach argue that the MOX fuel fabrication is a well-established and mature technology—the fuel is used in more than 30 commercial reactors worldwide. MFFF in SRS is based on a French technological approach implemented at the MELOX and LaHague facilities and is "literally turning swords into plowshares," as stated by MFFF advocate Senator Lindsey Graham of South Caroline [143]. The facilities being developed and built at SRS have met domestic conventions, codes, standards, and regulatory requirements, and were authorized for construction by the US Nuclear Regulatory Commission (NRC) in 2005. Although delays in the review of the contractor's application for an operating license proceeded, the NRC officially overrode its own Atomic Safety Licensing Board[184], who recommended that additional security of the facility be required [144].

NNSA further argue that the MFFF will aid in reducing security and storage costs associated with WGPu[185]. Nonetheless, the nonproliferation benefits attributed to this approach support the missions of DOE, holistically, and its subsidiary NNSA, by facilitating efforts to reduce the size of the NNSA security enterprise by consolidating materials to SRS from national laboratories and other sites[186], establishing capabilities for future efforts of WGPu weapon dismantlement, and adhering to our domestic nonproliferation commitments through dismantlement of our nuclear arsenals in a transparent, irreversible manner [44]. DOE evaluations reveal that despite the delays in operation, disposition through MOX conversion still proves to be the fastest method of disposing of surplus WGPu (See Table A.2) [145]. However, this has often been debated prompting opponents to claim that the DOE's own data reveals that "even under the most optimistic scenario for MOX disposal, immobilization could begin sooner, complete the job more rapidly, and require fewer facilities to manage and safeguard[187] [146]."

Table A.2: 2002 DOE WGPu Disposition Option Completion Date Estimates

Disposition Option	Disposition Completion
MOX Conversion ONLY	FY 2019
MOX Conversion and Immobilization	FY 2020
Immobilization ONLY	FY 2021 or 2023

Courtesy of *NNSA Report to Congress: Disposition of Surplus Defense Plutonium at SRS [145]*

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[184] The NRC determined, however, that MOX expected to be encased in heavy assemblies, would not be attractive to potential terrorists and other nuclear proliferation threats as pure plutonium, and hence does not require the same level of security.

[185] Estimated at hundreds of millions of dollars annually, associated with surplus WGPu

[186] Lawrence Livermore National Laboratory, Los Alamos National Laboratory, the Pantex Plant, the Hanford Site, and the Rocky Flats Site

[187] Furthermore, the technical and environmental risks associated with immobilization are far smaller than those associated with MOX and that spreading limited resources through pursuing a dual track could delay disposal.

A.3 Pitfalls of MOX Conversion Approach

The recent signing of the Plutonium Disposition Protocol in April 2010, reaffirmed the US and Russian commitments to nuclear disarmament and an "aspiration for global zero" through goals of disposing 68 MT of WGPu[188]. In this section, the pitfalls, risks, and feasibility of the MOX conversion approach to WGPu disposition are discussed. Nonetheless, in the process of identifying the weaknesses attributed to this approach, the strengths of the previously considered immobilization through vitrification (VHLW) strategy are also highlighted.

A.3.1 Nuclear Proliferation Risks

Prior to the US decision to dispose of 34 MT of WGPu through MOX conversion, the studies produced by NAS in comparing risk factors (risk of theft, risk of reversal, and impact on arms reduction) associated with the many disposition options, found the MOX conversion approach to be extremely risky.

The MOX conversion option presents a greater risk of diversion primarily because of the fuel fabrication stage, a process that is particularly difficult to safeguard effectively in view of plutonium's characteristic of sticking to the surfaces of processing equipment, and of the large, unavoidable uncertainties in the measurements of this "held-up" material. This stage is susceptible to systematic diversion schemes by state operators of the plants, or by individual plant workers in collaboration with outside states or groups; a stage avoided entirely with the VHLW option, making it a proliferation risk unique to the MOX option.

Difficulties at the Plutonium Fuel Processing Facility (PFPF) in May 1994 in Japan suggest that even purportedly state-of-the-art MOX fabrication plants are difficult if not impossible to safeguard effectively. It was disclosed that a major plutonium inventory discrepancy had been building up at the PFPF since the plant began operating in 1988 [147]. The IAEA, which identified that the unaccounted amount was a significant quantity (SQ)[189], requested that Japan physically produce the held-up plutonium for the purpose of establishing the plant's inventory [148]. This controversy over the plutonium holdup problem at MOX fuel fabrication plants holds valuable lessons for WGPu disposition because of unacceptable uncertainties and risks associated with accountability and verification of the material.

The transportation of WGPu-MOX fuel from MFFF to reactor customers also poses risks of theft, susceptible to hijackings and attacks by terrorists. VLHW, on the other hand, does not require a fuel transportation stage, and does not pose a commensurate risk. Through a VHLW approach, WGPu is only vulnerable to diversion prior to placement in the smelter. After that, it is mixed with molten glass and highly radioactive fission products, making it inaccessible for all practical purposes. Under this approach, safeguards efforts should be focused on preparation of WGPu for the smelter[190]. Numerous VHLW methods have been identified, one most promising being a strategy that allows WGPu to be added in an unaltered, metallic form [149]. This would avoid the conversion stage entirely and eliminate the potential diversion vulnerability.

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[188] Enough material for approximately 17,000 nuclear weapons

[189] 8 kg of plutonium, capable of constructing a nuclear weapon

[190] Preparation includes conversion from metallic or pit form to oxide form

The proliferation resistance of the final waste forms largely determines the potential reversibility of plutonium disposition, and is a function of the amount of residual or isotopic concentration of ^{239}Pu remaining in the final waste form and its retrievability.

In the first factor, MOX would leave less ^{239}Pu in the final waste form than in the VHLW approach, prompting assurance for NNSA's decision. However, under the MOX approach, all of the WGPu is not consumed during the irradiation process—no more than 25-30% of the total plutonium present in the fresh MOX would be fissioned [150]. From a retrievability perspective, separation of Pu from MOX fuel is a fairly straightforward chemical process based on a proven technology, like PUREX. Chemical separation from immobilized WGPu, is also possible through similar chemical process, however, it is roughly more difficult in comparison. From an isotopic concentration perspective, the MOX conversion approach reigns supreme in that it contains a significantly smaller proportion of ^{239}Pu after irradiation whereas the VHLW approach leaves the WGPu in its original form.

However is this criterion appropriate? Hans Blix, former director general of the IAEA, declared that even high burn-up reactor-grade plutonium is weapons-usable [151], a claim further strengthened upon the DOE release of details involving a 1962 nuclear device test using reactor-grade plutonium [152]. Hence, even with lower isotopic concentrations, the US could reconfigure weapons designs and reconstitute a large arsenal from Pu isotopically degraded to reactor-grade by irradiation in MOX[191]. Therefore, isotopic degradation may not constitute a compelling criterion for the MOX-option reigning supreme over immobilization.

Most important, the MOX conversion option sends a fuel cycle policy signal contrary to those administered since the Carter administration [143]. In its nonproliferation policy statement, the Clinton administration declared that "the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes [153]." However, previous worries regarding plutonium recycling and its contribution to the nuclear proliferation have appeared to diminish since the 2000 PMDA and more recently with the Obama administration considering whether to recommend a return to recycling through his Blue Ribbon Commission [154]. Though it does not necessarily involve further reprocessing through additional fuel cycles, the MOX conversion option clearly encourages the civil use of plutonium and legitimizes the use of MOX in civil nuclear power programs, confusing and complicating US nonproliferation diplomacy. At this time, it becomes more difficult and reduces US credibility in denying other nations the right to use civil nuclear plutonium. In the 1994 report, NAS emphasized the importance of the "Fuel Cycle Policy Signal[192]". Although selection of the MOX option appears to reverse long-standing US policy of not burning plutonium in commercial power plants, the US has said use of this

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[191] Additional methods of reversibility like laser-isotope separation discussed in *The MOX and Vitrification Options Compared: A Non-Proliferation Perspective*, P. Leventhal

[192] "[P]olicymakers will have to take into account the fact that choosing to use weapons plutonium in reactors would be perceived by some as representing generalized US approval of separated plutonium fuel cycles, thereby compromising the ability of the US government to oppose such fuel cycles elsewhere. Conversely, choosing to dispose of weapons plutonium without extracting any energy from it could be interpreted as reflecting a generalized US government opposition to plutonium recycling. Either choice could have an impact on fuel cycle debates now underway in Japan, Europe, and Russia." See NAS *Management and Disposition of Excess Nuclear Plutonium*, 1994

option would not represent such a change in its policy against civilian reprocessing and recycling of plutonium[193] [155].

A.3.2 Safety and Health Risks

The introduction of MOX fuel into civil LWR reduces the effectiveness of the materials used to absorb neutrons in the core[194] and increases the likelihood of a severe accident [156].

The 1999 DOE Surplus Plutonium Disposition Environmental Impact Statement (EIS) [48] performed an analysis depicting the consequences resultant of four severe reactor accident scenarios at three different reactors sites[195] using two different reactor core assumptions: (1) a reference case with a 100% LEU fuel core and (2) a case with a mixed core of approximately 40% MOX fuel and 60% LEU fuel. With the severe accident assumed to progress for each case in the same manner, the consequences to the public estimated ranged from 4% lower to 22% higher[196] relative to the reference case and dependent on the reactor studied for the specified accident scenario. The higher concentration of radioactive actinides present in the WGPu MOX fuel were postulated to be the prime cause for the higher estimated consequences, however, the differences were modest compared to the uncertainty associated with such low probability events.

In 2000, when customer changes resulted in the DOE awarding a contract to a consortium including Duke Cogema Stone and Webster (DCS) to dispose of 33 MT of WGPu MOX fuel in four US commercial PWR, Lyman [157] estimated the increase in risk to the public from use of WGPu MOX fuel at these reactors and determined that they exceeded recently established NRC guidelines. This supported initial propositions by the NRC with technical basis for prohibiting the use of MOX fuel at these sites unless the risk experienced in the event of a severe accident can be significantly reduced. In comparison to PWR implementing LEU cores, Lyman noted the number of latent cancer fatalities resultant from a meltdown accident and early containment failure of reactors with WGPu MOX cores could be as high as 131% (depending on the fraction of released actinides) proposing particular concern to the DCS consortium, Catawba and McGuire.

Although these results have not been ignored or disputed by NNSA and other related officials, they argue that the true health consequences are less severe than actually predicted. Kenneth Bromberg, the assistant deputy administrator of NNSA, stated "[the risk] is not that significant—10% or less [143]." In any event, officials argue, a major release of plutonium would require an accident so severe that the additional health effects would amount to a "sliver on top of a mountaintop [143]."

The recent events at the Fukushima Daiichi plant can provide some insight into the severity of such incidents. Officials of AREVA, who supplied the MOX fuel used in the

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[193] According to US officials, any MOX facilities built for the disposition purposes of surplus Pu are to be dismantled upon completion of their mission

[194] These include control rods and the boron dissolved in the coolant. The reduction in effectiveness of these materials makes controlling nuclear reactions more difficult, reducing the margin of availability to shut down the reactor and giving reactor operators less control over reactor transients and the time available to respond.

[195] These were the Catawba and McGuire sites of Duke Power and the North Anna site of Virginia Electric Power Company

[196] Most cases resulted in consequence increases of 10% or less.

core of Reactor Number 3, argue that "MOX was not the cause of that accident, and the consequences of [the accident] have not been impacted by MOX" during on-ground assistance to Japan during this time. Reactor Number 3 is one of three at the Fukushima Daiichi site that was judged to have undergone at least partial meltdown [158]. At the time of the earthquake, Unit 3 was operating with 32 MOX fuel assemblies[197] compared to 516 LEU fuel assemblies in its reactor core (totaling an approximate 6% MOX fuel core). No other new, in operation, or used MOX assemblies were present at the Fukushima Daiichi plant at the time of the accident. The American Nuclear Society Special Committee on Nuclear Non-Proliferation [159] argues that:

> *MOX fuel has been used safely in nuclear power reactors for decades. The presence of a limited number of MOX fuel assemblies at Fukushima Daiichi Unit 3 has not had a significant impact on the ability to cool the reactor or on radioactive releases from the site due to damage from the earthquake and tsunami.*

As of now, no clear evidence exists of plutonium release due to the MOX-loaded reactor. Full meltdowns, high heat, and rupture of the containment vessel would be necessary to release substantial plutonium into the environment. Although the dangers associated with an accident depend on its chain of events, meltdown of a MOX-loaded reactor would indeed result in more deaths than one using only LEU. If similar accident scenario calculations were performed on Unit 3 as was implemented in the 1999 Surplus Plutonium Disposition EIS, assuming the reactor implemented a 40% reactor-grade MOX fuel core, as currently used in Europe and Japan, the estimated consequences to the public would have been significantly higher than those cited for the WGPu MOX fuel core cases[198]. The much larger consequence estimates can again be attributed to the higher concentrations of radioactive actinides present—more radioactive actinides are present in reactor-grade MOX fuel than in WGPu MOX fuel [159].

AREVA, part of the venture constructing MFFF, designed and fabricated the MOX fuel assemblies that will be tested in the US However, these tests faced mishaps because of inherent design defects [160]. The Union of Concerned Scientists, as well as other critics of the MOX conversion approach, have requested that AREVA repair what they describe as the "potentially serious defect" in the design of the fuel assemblies and hence, repeat and perform additional testing to verify its suitability [161]. Nonetheless, AREVA argued that a repeat testing was not needed, and that the US should continue to progress in their already delayed process of WGPu disposition [162].

A.3.3 Costs and Economic Feasibility

In March 2009, the Government Accountability Office (GAO) released a report

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[197] These were loaded into the plant for the first time in the Fall of 2010; they were used for less than 5 months after at the time of the accident

[198] With a 40% reactor grade MOX core, and applying a bounding factor of four increase relative to weapons grade MOX, Raap et al. estimate the overall increase in severe accident consequences to be on the order of 40% relative to the all LEU fuel case. However, Unit 3 was loaded with only 32 MOX fuel assemblies and 516 LEU fuel assemblies—less than a 6% MOX fuel core—during refueling operations in the fall of 2010.

criticizing the DOE's oversight of key parts of the current US plan[199], especially its plans to acquire customers due to delays[200] [163]. In another complication, the MOX conversion-only approach of the current US plan has suffered massive cost over-runs. When the DOE conducted a cost-estimate of different plutonium disposition options in 2002, this approach was projected to cost roughly twice as much as immobilization-only option (See Table A.3).

Table A.3: 2002 DOE Total Life-Cycle Cost Estimates

Disposition Options	**2002 USD (Estimated 2007 USD)**
MOX Conversion ONLY	3.8-5.0 Billion (4.0-6.0 Billion)
MOX Conversion and Immobilization	4.6-5.4 Billion (5.6-6.5 Billion)
Immobilization ONLY	2.0-3.2 Billion (2.4-3.9 Billion)

Courtesy of *NNSA Report to Congress: Disposition of Surplus Defense Plutonium at SRS* [145]

Despite its price being higher than an Immobilization ONLY approach, DOE deemed the MOX Conversion ONLY approach as supremely better because it was more advantageous in engaging Russian interests and commitment, fulfilling domestic commitments, and fulfilling international and nonproliferation objectives [145]. Five years later, however, the DOE's total life cycle cost estimate of the MOX conversion-only approach to US plutonium disposition tripled[201]. As of March 2010, cost estimates of the MOX Conversion approach have leveled off to those seen in previous years (See Table A.4) [45]. However, Shaw and AREVA as well as others argue that a true economic comparison cannot be made simply because each approach has different impacts on the environment that are difficult, if not impossible, to characterize and assess [164].

Table A.4: Escalation of DOE Total Life-Cycle Cost Estimates

Disposition Option	**2002 DOE Cost-Estimate (Constant 2007 USD)**	**2007 DOE Cost-Estimate (Constant 2007 USD)**	**Current Cost Estimate**
MOX Conversion ONLY	4.6-6.0 Billion	14.0 Billion	Still Pending

Courtesy of *NNSA Report to Congress: Disposition of Surplus Defense Plutonium at SRS [145]*

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[199] "The [MFFF's] schedule, in addition to other problems, does not adhere to a key practice that is fundamental to having a sufficiently reliable schedule—specifically, MFFF project staff have not conducted a risk analysis on their current schedule using statistical techniques.... Consequently, NNSA cannot adequately state its level of confidence in meeting the MFFF project's completion date, and NNSA's schedule for the project therefore may not be reliable." See GAO, *Department of Energy: Contract and Project Management Concerns at the National Nuclear Security Administration and Office of Environmental Management*, March 2009

[200] "Utilities are nervous if their need for a reliable schedule for fuel delivery can be met."

[201] Moreover, in the face of the current plan's delays and cost overruns, the DOE has not issued a current estimate of the extent to which a programmatic shift to partial immobilization or immobilization-only approaches would implement the PDMA's terms any faster and cheaper than the current US plan.

Current costs estimates cannot yet be assessed since NNSA has yet to determine whether or not it will proceed with the PDCF facility at SRS, or pursue other alternatives to obtain the PDCF's intended conversion capability. However, Zarate argues that if the Immobilization ONLY approach were to escalate at a comparable rate as the MOX Conversion ONLY approach, the Immobilization ONLY approach would still be the cheapest of the two options [142]. Nonetheless, from the cost perspectives associated with reactor-grade MOX, MOX fuel offers an advantage over LEU in that its fissile concentration can be increased easily by the addition of more plutonium, whereas higher uranium enrichments is relatively expensive. With reactor operators seeking to burn fuels at higher levels and longer time scales, increasing burnup from around 30 GWd/MTHM a few years ago to over 50 GWd/MTHM now, MOX use becomes more attractive. Assuming increasing uranium prices, plutonium reprocessing for MOX fabrication becomes increasingly attractive from an economic perspective as well as from the perspective of reducing the volume of spent fuel. It is estimated that seven LEU fuel assemblies produces one MOX fuel assembly (in addition to vitrified high-level waste) resulting in only about 35% of the volume, mass and cost of disposal [68].

However, although it appears that an economic benefit could be derived from using WGPu as a substitute to LEU in conventional civilian reactors, under the assumption that the plutonium would be essentially free (paid for through deference spending), MOX is not economically competitive at present and is unlikely to become so in the near future [155]. Bunn et al. performed an assessment of the capabilities of a plutonium market where they found that reprocessing and recycling plutonium in LWR was more expensive than direct disposal of spent fuel[202]. Unless the price of uranium, currently approximately $40/kg, were to increase to over $360/kg, reprocessing is not economically ideal in the near [165]. Furthermore, contrary to the DOE's earlier assumption that the utilities would reimburse the government at a rate equivalent to the cost of conventional fuel (fuel displacement credit), it now appears more likely that utilities would expect to receive an incentive for using MOX.

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[202] Under the assumption that uranium has a price of $40/kgU (comparable to current prices), reprocessing and recycling at a reprocessing price of $1000/kgHM would increase the cost of nuclear electricity by 1.3 mill/kWh. Since the total back-end cost for the direct disposal is in the range of 1.5 mill/kWh, this represents more than an 80% increase in the costs attributable to spent fuel management (after taking account of appropriate credits or charges for recovered plutonium and uranium from reprocessing).

Appendix B: Data, Functions, and Simulators

B.1 Data

Table B.1: LEU Assembly Fission Reaction Rates ($cm^{-3} \cdot s^{-1}$)

Irradiation Time (days)	^{235}U	^{238}U	^{239}Pu	^{241}Pu
0	9.6839E+12	6.4071E+11	2.6588E-04	2.6810E-04
1	9.6709E+12	6.4076E+11	5.5430E+09	5.7569E+04
2	9.6579E+12	6.4081E+11	1.1086E+10	1.1514E+05
3	9.6450E+12	6.4085E+11	1.6629E+10	1.7271E+05
4	9.6322E+12	6.4090E+11	2.2172E+10	2.3027E+05
5	9.6193E+12	6.4095E+11	3.6448E+10	2.9647E+06
6	9.6066E+12	6.4100E+11	4.8165E+10	4.9147E+06
7	9.5938E+12	6.4105E+11	5.9883E+10	6.8647E+06
8	9.5811E+12	6.4110E+11	7.1600E+10	8.8147E+06
9	9.5685E+12	6.4115E+11	8.3317E+10	1.0765E+07
10	9.5559E+12	6.4120E+11	9.5034E+10	1.2715E+07
11	9.5433E+12	6.4125E+11	1.0675E+11	1.4665E+07
12	9.5308E+12	6.4130E+11	1.1847E+11	1.6615E+07
13	9.5183E+12	6.4135E+11	1.3122E+11	2.0743E+07
14	9.5058E+12	6.4140E+11	1.4386E+11	2.6192E+07
15	9.4934E+12	6.4146E+11	1.5644E+11	3.3088E+07
16	9.4810E+12	6.4151E+11	1.6896E+11	4.1489E+07
17	9.4687E+12	6.4156E+11	1.8142E+11	5.1453E+07
18	9.4564E+12	6.4162E+11	1.9382E+11	6.3038E+07
19	9.4442E+12	6.4167E+11	2.0617E+11	7.6302E+07
20	9.4320E+12	6.4173E+11	2.1846E+11	9.1303E+07
21	9.4198E+12	6.4178E+11	2.3069E+11	1.0810E+08
22	9.4077E+12	6.4184E+11	2.4286E+11	1.2675E+08
23	9.3956E+12	6.4189E+11	2.5498E+11	1.4731E+08
24	9.3835E+12	6.4195E+11	2.6704E+11	1.6984E+08
25	9.3715E+12	6.4200E+11	2.7904E+11	1.9440E+08
26	9.3595E+12	6.4206E+11	2.9099E+11	2.2105E+08
27	9.3476E+12	6.4212E+11	3.0288E+11	2.4983E+08
28	9.3357E+12	6.4218E+11	3.1471E+11	2.8082E+08
29	9.3238E+12	6.4224E+11	3.2649E+11	3.1407E+08
30	9.3120E+12	6.4229E+11	3.3822E+11	3.4964E+08
45	9.1391E+12	6.4323E+11	5.0770E+11	1.2008E+09
60	8.9740E+12	6.4425E+11	6.6582E+11	2.7827E+09
75	8.8162E+12	6.4537E+11	8.1361E+11	5.2744E+09
90	8.6652E+12	6.4659E+11	9.5250E+11	8.6991E+09
180	7.8745E+12	6.5570E+11	1.6449E+12	5.1545E+10
270	7.2241E+12	6.6765E+11	2.1725E+12	1.2904E+11
360	6.6572E+12	6.8186E+11	2.5976E+12	2.3356E+11
493	5.9039E+12	7.0573E+11	3.1060E+12	4.2104E+11

Table B.2: LEU Assembly Fission Rates (s^{-1})

Irradiation Time (days)	^{235}U	^{238}U	^{239}Pu	^{241}Pu
0	5.3195E+19	3.5195E+18	1.4605E+03	1.4727E+03
1	5.3124E+19	3.5198E+18	3.0448E+16	3.1623E+11
2	5.3053E+19	3.5201E+18	6.0897E+16	6.3247E+11
3	5.2982E+19	3.5203E+18	9.1345E+16	9.4870E+11
4	5.2911E+19	3.5206E+18	1.2179E+17	1.2649E+12
5	5.2841E+19	3.5208E+18	2.0022E+17	1.6286E+13
6	5.2770E+19	3.5211E+18	2.6458E+17	2.6997E+13
7	5.2700E+19	3.5214E+18	3.2894E+17	3.7709E+13
8	5.2631E+19	3.5217E+18	3.9331E+17	4.8420E+13
9	5.2561E+19	3.5219E+18	4.5767E+17	5.9132E+13
10	5.2492E+19	3.5222E+18	5.2204E+17	6.9843E+13
11	5.2423E+19	3.5225E+18	5.8640E+17	8.0555E+13
12	5.2354E+19	3.5228E+18	6.5076E+17	9.1266E+13
13	5.2285E+19	3.5230E+18	7.2079E+17	1.1394E+14
14	5.2217E+19	3.5233E+18	7.9022E+17	1.4388E+14
15	5.2149E+19	3.5236E+18	8.5932E+17	1.8176E+14
16	5.2081E+19	3.5239E+18	9.2811E+17	2.2791E+14
17	5.2013E+19	3.5242E+18	9.9656E+17	2.8264E+14
18	5.1946E+19	3.5245E+18	1.0647E+18	3.4628E+14
19	5.1878E+19	3.5248E+18	1.1325E+18	4.1914E+14
20	5.1811E+19	3.5251E+18	1.2000E+18	5.0154E+14
21	5.1744E+19	3.5254E+18	1.2672E+18	5.9381E+14
22	5.1678E+19	3.5257E+18	1.3341E+18	6.9626E+14
23	5.1611E+19	3.5260E+18	1.4006E+18	8.0921E+14
24	5.1545E+19	3.5263E+18	1.4669E+18	9.3297E+14
25	5.1479E+19	3.5266E+18	1.5328E+18	1.0679E+15
26	5.1413E+19	3.5269E+18	1.5984E+18	1.2142E+15
27	5.1348E+19	3.5273E+18	1.6638E+18	1.3724E+15
28	5.1282E+19	3.5276E+18	1.7288E+18	1.5426E+15
29	5.1217E+19	3.5279E+18	1.7935E+18	1.7253E+15
30	5.1152E+19	3.5282E+18	1.8579E+18	1.9206E+15
45	5.0202E+19	3.5333E+18	2.7888E+18	6.5964E+15
60	4.9296E+19	3.5390E+18	3.6574E+18	1.5286E+16
75	4.8429E+19	3.5451E+18	4.4693E+18	2.8973E+16
90	4.7599E+19	3.5518E+18	5.2322E+18	4.7786E+16
180	4.3256E+19	3.6019E+18	9.0354E+18	2.8314E+17
270	3.9683E+19	3.6675E+18	1.1934E+19	7.0885E+17
360	3.6569E+19	3.7455E+18	1.4269E+19	1.2830E+18
493	3.2431E+19	3.8767E+18	1.7062E+19	2.3128E+18

Table B.3: MOX Assembly Fission Reaction Rates (cm^{-3}·s^{-1})

Irradiation Time (days)	^{235}U	^{238}U	^{239}Pu	^{241}Pu
0	2.2707E+11	7.7676E+11	9.0180E+12	4.5716E+10
1	2.2703E+11	7.7683E+11	9.0164E+12	4.7173E+10
2	2.2700E+11	7.7690E+11	9.0147E+12	4.8633E+10
3	2.2696E+11	7.7698E+11	9.0131E+12	5.0095E+10
4	2.2692E+11	7.7705E+11	9.0114E+12	5.1560E+10
5	2.2688E+11	7.7712E+11	9.0098E+12	5.3026E+10
6	2.2684E+11	7.7720E+11	9.0082E+12	5.4495E+10
7	2.2680E+11	7.7727E+11	9.0065E+12	5.5966E+10
8	2.2677E+11	7.7734E+11	9.0049E+12	5.7439E+10
9	2.2673E+11	7.7741E+11	9.0032E+12	5.8914E+10
10	2.2669E+11	7.7749E+11	9.0016E+12	6.0392E+10
11	2.2665E+11	7.7756E+11	8.9999E+12	6.1872E+10
12	2.2661E+11	7.7763E+11	8.9982E+12	6.3354E+10
13	2.2657E+11	7.7770E+11	8.9966E+12	6.4838E+10
14	2.2653E+11	7.7778E+11	8.9949E+12	6.6325E+10
15	2.2650E+11	7.7785E+11	8.9933E+12	6.7814E+10
16	2.2646E+11	7.7792E+11	8.9916E+12	6.9305E+10
17	2.2642E+11	7.7799E+11	8.9899E+12	7.0798E+10
18	2.2638E+11	7.7806E+11	8.9883E+12	7.2293E+10
19	2.2634E+11	7.7814E+11	8.9866E+12	7.3791E+10
20	2.2630E+11	7.7821E+11	8.9849E+12	7.5290E+10
21	2.2626E+11	7.7828E+11	8.9832E+12	7.6792E+10
22	2.2622E+11	7.7835E+11	8.9816E+12	7.8296E+10
23	2.2619E+11	7.7842E+11	8.9799E+12	7.9803E+10
24	2.2615E+11	7.7850E+11	8.9782E+12	8.1311E+10
25	2.2611E+11	7.7857E+11	8.9765E+12	8.2821E+10
26	2.2607E+11	7.7864E+11	8.9749E+12	8.4334E+10
27	2.2603E+11	7.7871E+11	8.9732E+12	8.5849E+10
28	2.2599E+11	7.7878E+11	8.9715E+12	8.7366E+10
29	2.2595E+11	7.7885E+11	8.9698E+12	8.8885E+10
30	2.2591E+11	7.7892E+11	8.9681E+12	9.0407E+10
45	2.2533E+11	7.7999E+11	8.9426E+12	1.1348E+11
60	2.2474E+11	7.8104E+11	8.9167E+12	1.3702E+11
75	2.2415E+11	7.8207E+11	8.8905E+12	1.6102E+11
90	2.2355E+11	7.8310E+11	8.8639E+12	1.8546E+11
180	2.1989E+11	7.8901E+11	8.6977E+12	3.4064E+11
270	2.1607E+11	7.9458E+11	8.5212E+12	5.0845E+11
360	2.1209E+11	7.9989E+11	8.3363E+12	6.8623E+11
493	2.0588E+11	8.0746E+11	8.0518E+12	9.6174E+11

Table B.4: MOX Assembly Fission Rates (s^{-1})

Irradiation Time (days)	^{235}U	^{238}U	^{239}Pu	^{241}Pu
0	8.2798E+17	2.8323E+18	3.2883E+19	1.6670E+17
1	8.2784E+17	2.8326E+18	3.2877E+19	1.7201E+17
2	8.2770E+17	2.8328E+18	3.2871E+19	1.7733E+17
3	8.2756E+17	2.8331E+18	3.2865E+19	1.8266E+17
4	8.2742E+17	2.8334E+18	3.2859E+19	1.8800E+17
5	8.2728E+17	2.8336E+18	3.2853E+19	1.9335E+17
6	8.2714E+17	2.8339E+18	3.2847E+19	1.9871E+17
7	8.2700E+17	2.8342E+18	3.2841E+19	2.0407E+17
8	8.2686E+17	2.8344E+18	3.2835E+19	2.0944E+17
9	8.2672E+17	2.8347E+18	3.2829E+19	2.1482E+17
10	8.2658E+17	2.8350E+18	3.2823E+19	2.2021E+17
11	8.2644E+17	2.8352E+18	3.2817E+19	2.2561E+17
12	8.2630E+17	2.8355E+18	3.2810E+19	2.3101E+17
13	8.2616E+17	2.8358E+18	3.2804E+19	2.3642E+17
14	8.2602E+17	2.8360E+18	3.2798E+19	2.4184E+17
15	8.2587E+17	2.8363E+18	3.2792E+19	2.4727E+17
16	8.2573E+17	2.8365E+18	3.2786E+19	2.5271E+17
17	8.2559E+17	2.8368E+18	3.2780E+19	2.5815E+17
18	8.2545E+17	2.8371E+18	3.2774E+19	2.6360E+17
19	8.2531E+17	2.8373E+18	3.2768E+19	2.6906E+17
20	8.2517E+17	2.8376E+18	3.2762E+19	2.7453E+17
21	8.2503E+17	2.8379E+18	3.2756E+19	2.8001E+17
22	8.2489E+17	2.8381E+18	3.2750E+19	2.8549E+17
23	8.2475E+17	2.8384E+18	3.2744E+19	2.9099E+17
24	8.2460E+17	2.8386E+18	3.2737E+19	2.9649E+17
25	8.2446E+17	2.8389E+18	3.2731E+19	3.0199E+17
26	8.2432E+17	2.8392E+18	3.2725E+19	3.0751E+17
27	8.2418E+17	2.8394E+18	3.2719E+19	3.1303E+17
28	8.2404E+17	2.8397E+18	3.2713E+19	3.1856E+17
29	8.2390E+17	2.8399E+18	3.2707E+19	3.2410E+17
30	8.2376E+17	2.8402E+18	3.2701E+19	3.2965E+17
45	8.2162E+17	2.8441E+18	3.2608E+19	4.1379E+17
60	8.1948E+17	2.8479E+18	3.2513E+19	4.9963E+17
75	8.1732E+17	2.8517E+18	3.2418E+19	5.8714E+17
90	8.1514E+17	2.8554E+18	3.2321E+19	6.7625E+17
180	8.0178E+17	2.8770E+18	3.1715E+19	1.2421E+18
270	7.8786E+17	2.8973E+18	3.1071E+19	1.8540E+18
360	7.7334E+17	2.9167E+18	3.0397E+19	2.5022E+18
493	7.5069E+17	2.9443E+18	2.9359E+19	3.5068E+18

B.2 Functions

The following functions were generated using MATLAB 7.12.0 (R2011a)

B.2.1 Expected Counts Function

```
function [ y ] = expectedcounts( x )

%EXPECTEDCOUNTS provides the simulated antineutrino expected counts

%   This function simply simulates the expected counts for a given
%   trajectory by taking a random sampling of the given expected point
%   from a Gaussian PDF. The character '?' is used here to correspond to
%   the percentage multiplier of the mean which corresponds to the
%   expected standard deviation value. For purposes of this analysis, a 3%
%   multiplier was used.

n=size(x);
y=zeros(n);

mu=x;
sigma=?*mu;
y=round(normrnd(mu,sigma));

end
```

B.2.2. Observed Counts Function

```
function [ y ] = observedcounts( x )

%OBSERVEDCOUNTS provides the simulated observed counts

%   This function simply simulates the observed counts for a given
%   trajectory simply by taking a random sampling of the given expected
%   point from a Poisson PDF, where for large samples, which is
%   considered for this analysis, follows a Gaussian PDF with a
%   standard deviation equal to the square root of the mean.

n=size(x);
y=zeros(n);

mu=x;
sigma=sqrt(mu);
y=round(normrnd(mu,sigma));

end
```

B.2.3 Trajectory Function

```
function [ y ] = trajectory( MOXCorePercent, timespan, TotalAssemblies,
                             FuelAssemblyVol )
%TRAJECTORY calculates the expected antineutrino trajectory

%   This function calculates the expected antineutrino trajectory given the
%   MOX core concentration percentage (MOXCorePercent), the measurement
%   duration lifetime in days (timespan), the number of assemblies in the
%   core (TotalAssemblies) which, for purposes of this analysis, was always
%   193, and the fuel assembly volume in cm³ (FuelAssemblyVol)

% Designated Constants--Antineutrino Rate per day converters for each
% isotope
U235_Anti=5.16336E-17;
U238_Anti=7.25345E-17;
Pu239_Anti=3.36024E-17;
Pu241_Anti=4.79755E-17;

% Initiate Testing Procedure

% Measure array length for considered MOX core concentrations array
n=length(MOXCorePercent);

% The measurement duration lifetime variable must allow for 2 additional
% rows to include core composition column and day 0 column
y=zeros((timespan+1),n);
y(1,:)=MOXCorePercent;

    for k=1:n

    % Determine the actual number of MOX and LEU assemblies in core
        MOXAssemblies=round(MOXCorePercent(k)*(0.01)*TotalAssemblies);
        LEUAssemblies=TotalAssemblies-MOXAssemblies;

    % LEU Antineutrino Rate generated per day (for each isotope and total)
    % The referenced file corresponds to the LEU fuel isotopic fission rates
    % for the four considered isotopes: U-235, U-238, Pu-239, and Pu-241
        values=importdata('Data Values/UOX_42.mat');
        U235_AntiLEU=values(:,1)*U235_Anti*FuelAssemblyVol*LEUAssemblies;
        U238_AntiLEU=values(:,2)*U238_Anti*FuelAssemblyVol*LEUAssemblies;
        Pu239_AntiLEU=values(:,3)*Pu239_Anti*FuelAssemblyVol*LEUAssemblies;
        Pu241_AntiLEU=values(:,4)*Pu241_Anti*FuelAssemblyVol*LEUAssemblies;
        LEU_AntiTotal=U235_AntiLEU+U238_AntiLEU+Pu239_AntiLEU+Pu241_AntiLEU;

    % MOX Antineutrino Rate generated per day (for each element and total)
    % The referenced file corresponds to the MOX fuel isotopic fission rates
    % for the four considered isotopes: U-235, U-238, Pu-239, and Pu-241
        values=importdata('Data Values/MOX_43.mat');
        U235_AntiMOX=values(:,1)*U235_Anti*FuelAssemblyVol*MOXAssemblies;
        U238_AntiMOX=values(:,2)*U238_Anti*FuelAssemblyVol*MOXAssemblies;
        Pu239_AntiMOX=values(:,3)*Pu239_Anti*FuelAssemblyVol*MOXAssemblies;
        Pu241_AntiMOX=values(:,4)*Pu241_Anti*FuelAssemblyVol*MOXAssemblies;
        MOX_AntiTotal=U235_AntiMOX+U238_AntiMOX+Pu239_AntiMOX+Pu241_AntiMOX;
```

```
    % Total Antineutrino Rate for Core
        AntiTotal=LEU_AntiTotal+MOX_AntiTotal;

    % Store values in resultant y matrix
        y((2:(timespan+1)),k)=AntiTotal(2:(timespan+1));

    end

end
```

B.2.4 Trajectory with Background Function

```
function [ y ] = trajectoryWbackground( MOXCorePercent, timespan,
                                        TotalAssemblies, FuelAssemblyVol,
                                        BackgroundPercent )
%TRAJECTORY calculates the expected antineutrino trajectory including a
%background effect associated with non-reactor based antineutrino events

%   This function calculates the expected antineutrino trajectory given the
%   MOX core concentration percentage (MOXCorePercent), the measurement
%   duration lifetime in days (timespan), the number of assemblies in the core
%   (TotalAssemblies) which, for purposes of this analysis, was always 193,
%   the fuel assembly volume in cm³ (FuelAssemblyVol), and a background effect
%   (between 0 to 1) associated with non-reactor based antineutrino events
%   (BackgroundPercent)


% Designated Constants--Antineutrino Rate per day converters for each
% isotope
U235_Anti=5.16336E-17;
U238_Anti=7.25345E-17;
Pu239_Anti=3.36024E-17;
Pu241_Anti=4.79755E-17;

% Initiate Testing Procedure

% Measure array length for considered MOX core concentrations array
n=length(MOXCorePercent);

% The measurement duration lifetime variable must allow for 2 additional
% rows to include core composition column and day 0 column
y=zeros((timespan+1),n);
y(1,:)=MOXCorePercent;

    for k=1:n

    % Determine the actual number of MOX and LEU assemblies in core
        MOXAssemblies=round(MOXCorePercent(k)*(0.01)*TotalAssemblies);
        LEUAssemblies=TotalAssemblies-MOXAssemblies;

    % LEU Antineutrino Rate generated per day (for each isotope and total)
    % The referenced file corresponds to the LEU fuel isotopic fission rates
    % for the four considered isotopes: U-235, U-238, Pu-239, and Pu-241
        values=importdata('Data Values/UOX_42.mat');
        U235_AntiLEU=values(:,1)*U235_Anti*FuelAssemblyVol*LEUAssemblies;
        U238_AntiLEU=values(:,2)*U238_Anti*FuelAssemblyVol*LEUAssemblies;
        Pu239_AntiLEU=values(:,3)*Pu239_Anti*FuelAssemblyVol*LEUAssemblies;
        Pu241_AntiLEU=values(:,4)*Pu241_Anti*FuelAssemblyVol*LEUAssemblies;
        LEU_AntiTotal=U235_AntiLEU+U238_AntiLEU+Pu239_AntiLEU+Pu241_AntiLEU;

    % MOX Antineutrino Rate generated per day (for each element and total)
    % The referenced file corresponds to the MOX fuel isotopic fission rates
    % for the four considered isotopes: U-235, U-238, Pu-239, and Pu-241
        values=importdata('Data Values/MOX_43.mat');
        U235_AntiMOX=values(:,1)*U235_Anti*FuelAssemblyVol*MOXAssemblies;
```

```
        U238_AntiMOX=values(:,2)*U238_Anti*FuelAssemblyVol*MOXAssemblies;
        Pu239_AntiMOX=values(:,3)*Pu239_Anti*FuelAssemblyVol*MOXAssemblies;
        Pu241_AntiMOX=values(:,4)*Pu241_Anti*FuelAssemblyVol*MOXAssemblies;
        MOX_AntiTotal=U235_AntiMOX+U238_AntiMOX+Pu239_AntiMOX+Pu241_AntiMOX;

    % Total Antineutrino Rate for Core
        AntiTotal=LEU_AntiTotal+MOX_AntiTotal;

    % Calculate randomized background signal which is expected to follow
    % Poisson statistics as identified by Bernstein et al.
        muBackground=BackgroundPercent*AntiTotal(2);
        stdevBackground=sqrt(muBackground);
        BackgroundLength=length(y);
        Background=zeros(BackgroundLength,1);
        Background=round(normrnd(muBackground,stdevBackground,
                        BackgroundLength,1));

    % Store values in resultant y matrix
        y((2:(timespan+1)),k)=AntiTotal(2:(timespan+1))+
                             Background(2:BackgroundLength);

    end

end
```

B.2.5 t-Test of Evolution Coefficients Function

```
function [ result ] = tTestforCoeff( days, measured, baseline, power, alpha )

%   Performs a t Test for the coefficients of the polynomial regression of the
%   antineutrino measurement evolution as outlined in "Detection of Anomalous
%   Reactor Activity Using Antineutrino Count Evolution over the Course of a
%   Reactor Cycle" by V. Bulaevskaya and A. Bernstein

% In order to compute the vector of standard errors associated with the
% coefficients determined for the polynomial regression of measured data
% perform the following calculation.
[BETAmeasured,SE]=polyfit(days,measured,power);
R=SE.R;
d=(R'*R)\eye(3);
d=diag(d)';
MSEmeasured=(SE.normr^2)/SE.df;
semeasured=sqrt(MSEmeasured*d);

% In order to compute the vector of standard errors associated with the
% coefficients determined for the polynomial regression of baseline data
% perform the following calculation.
[BETAbaseline,SE]=polyfit(days,baseline,power);
R=SE.R;
d=(R'*R)\eye(3);
d=diag(d)';
MSEbaseline=(SE.normr^2)/SE.df;
sebaseline=sqrt(MSEbaseline*d);

% Determine the t test statistic for the following coefficients and their
% associated standard errors
t=(BETAmeasured-BETAbaseline)./sqrt(semeasured.^2+sebaseline.^2);

% Find the length of the time period (i.e. number of counts) so that the
% degrees of freedom can be determined
n=length(days);

% Determine the p-value for the selected data
p=2*(1-tcdf(abs(t),(2*(n-3))));

% If at least one of the null hypotheses is rejected, conclude that the
% observed (measured) evolution deviates SIGNIFICANTLY from that of the
% expected (baseline) data
MINp=min(p);

    if MINp>=alpha
        result=0;
    else
        result=1;
    end

end
```

B.3 Simulators

The following simulators were generated using MATLAB 7.12.0 (R2011a)

B.3.1 ROC t-Test of Fitted Coefficients Simulator

```
%%  ROC t-Test of Fitted Coefficients Simulator
%   This simulator aims to generate the ROC curve for the comparison of a
%   baseline and a measured scenario over a designated number of iterations

%%  Initial values

% 1. Designate the number of iteration cycles for simulation
numiter=100000;
TotalAssemblies=193;

% 2. Designate the measured scenario number of fuel assemblies
MeasuredPercent=100*(M/193);
% M: number of fuel assemblies


% 3. Designate the baseline scenario number of fuel assemblies
BaselinePercent=100*(B/193);
% B: number of fuel assemblies (i.e. 77, 64, 48, 39, & 0)

% 4. Duration Period
TotalDays=494; % Corresponds to the fuel cycle lifetime including day 0

TimePeriodPercent=100*(D/494);
% D: if n is duration period to be analyzed, D=n+1, to include for day 0.
% This equation simply converts the duration period to be analyzed into a
% percentage of the total fuel cycle lifetime

timespan=round(TotalDays*TimePeriodPercent*0.01);
% calculates the duration period to be analyzed (in days) by taking the
% product of two above metrics rounded to nearest integer

days=transpose([0:(timespan-1)]);
% generates a matrix of the duration period to be analyzed

days=days-mean(days);
% in order to eliminate the correlation and instability between the linear
% effect and quadratic effect coefficients, the standard practice, as
% identified by Neter et. al, of redefining the independent variable (time
% duration in days) as a deviation from its mean

% 5. Statistical Testing Threshold
alphaS=0.01*[0.01:0.01:0.1,0.2:0.1:1,2:1:10,20:10:100];
% an array of values corresponding to level of significance threshold,
% alpha, to be used in each iterative step of the statistical testing
% procedure

scale=length(alphaS);
% corresponds to the length of the array alphaS in order to designate the
% number of levels of threshold values to be analyzed in this simulation
```

```
% 6. Fissile Fuel Volume
FuelAssemblyVol=47354.80664;
% Calculated based on the schematics of provided in this work, where the
% fuel assembly is composed of 264 fuel pins with a pin radius of 0.3951 cm
% and length of 365.76 cm

% Additional Constants for Power and Antineutrino Rate Calculations,
% although not needed in this because they are either unnecessary for
% purposes of this simulation or are implemented elsewhere from generated
% functions used in this simulation:

%   Energy/Fission in J
%       U235EnergyPerFission=3.23512E-11; %201.92 MeV
%       U238EnergyPerFission=3.29279E-11; %205.52 MeV
%       Pu239EnergyPerFission=3.36441E-11; %209.99 MeV
%       Pu241EnergyPerFission=3.42225E-11; %213.6 MeV

%   Antineutrino Rate per day converters
%       U235_Anti=5.16336E-17;
%       U238_Anti=7.25345E-17;
%       Pu239_Anti=3.36024E-17;
%       Pu241_Anti=4.79755E-17;

%%  Observed LEU Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   baseline antineutrino measurement evolution given the following inputs
%   designated for this function
BaselineExpected=trajectory(BaselinePercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
BaselineExpectedLength=length(BaselineExpected);

%%  Expected MOX Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   measured antineutrino measurement evolution given the following inputs
%   designated for this function
MeasuredExpected=trajectory(MeasuredPercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
MeasuredExpectedLength=length(MeasuredExpected);

%%  Length of Baseline and Measured Arrays are Equal
%   Simply confirms that the length of the baseline and measured
%   antineutrino measurement evolutions are equal ensuring a proper
%   comparison analysis to generate the ROC curve
if MeasuredExpectedLength==BaselineExpectedLength
    lengthcheck=1;
else
    lengthcheck=0;
end

%%  t-Test of Baseline and Measured Scenarios for ROC Curve Generation

% 1. Initialize arrays that will be used to store the calculated true
% positive (alphaTP), false negative (alphaFN), true negative (alphaTN),
```

```
% and false positive (alphaFP) arrays at the designated level of
% significance
alphaTP=zeros(2,scale);
alphaFN=zeros(2,scale);
alphaTN=zeros(2,scale);
alphaFP=zeros(2,scale);

% 2. Store level of significance values analyzed in the first rows of the
% true positive (alphaTP), false negative (alphaFN), true negative
% (alphaTN), and false positive (alphaFP) arrays
alphaTP(1,:)=alphaS;
alphaFN(1,:)=alphaS;
alphaTN(1,:)=alphaS;
alphaFP(1,:)=alphaS;


% 3. Begin calculating the TP, FN, TN, and FP values at the varying levels
% of significance

for k=1:1:scale

    alpha=alphaS(k);
    % alpha corresponds to the tested level of significance at this
    % iterative loop

    % Initialize TP, FN, TN, and FP variables at the beginning of each
    % iterative loop
    TP=0;
    FN=0;
    TN=0;
    FP=0;

    % Displays a figure corresponding to the progress of the simulation as
    % a percentage of the total number of analyzed levels of significance
    wait=waitbar(k/scale,'Processing Data');

    % At each level of significance, conduct the designated number of
    % iterations (numiter)
    for i=1:numiter


BaselineObserved=expectedcounts(BaselineExpected(2:BaselineExpectedLength));
        % Generate the simulated expected values for the baseline scenario
        % antineutrino evolution


MeasuredObserved=observedcounts(MeasuredExpected(2:MeasuredExpectedLength));
        % Generate the simulated observed values for the measured scenario
        % antineutrino evolution to be used in the TP-FN testing


MeasuredObserved2=observedcounts(BaselineExpected(2:BaselineExpectedLength));
        % Generate the simulated observed values for the baseline scenario
        % antineutrino evolution to be used in the FP-TN testing
```

```
        % True Positive and False Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and measured
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved,BaselineObserved,2,alpha);

        if h==1
            TP=TP+1;
        else
            FN=FN+1;
        end

        %False Positive and True Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and baseline
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved2,BaselineObserved,2,alpha);

        if h==1
            FP=FP+1;
        else
            TN=TN+1;
        end

    end

% Close the wait bar figure generated so that a revised figure can be
% generated upon initiation of the following iterative cycle
close(wait);

% Store the updated TP, FN, FP, and TN values as a fraction of the total
% number of iterations simulated (numiter) in the following matrices
alphaTP(2,k)=TP/numiter;
alphaFN(2,k)=FN/numiter;
alphaFP(2,k)=FP/numiter;
alphaTN(2,k)=TN/numiter;

end

%Plot the FP vs. TP ROC curve
loglog(alphaFP(2,:),alphaTP(2,:),'o');
set(gca,'XTick',(alphaS*100));
set(gca,'YTick',(alphaS*100));
```

B.3.2 ROC t-Test of Fitted Coefficients with Background Simulator

```
%%  ROC t-Test of Fitted Coefficients with Background Simulator
%   This simulator aims to generate the ROC curve for the comparison of a
%   baseline and a measured scenario over a designated number of iterations
%   given a specified background effect associated with non-reactor based
%   antineutrino events

%%  Initial values

% 1. Designate the number of iteration cycles for simulation
numiter=100000;
TotalAssemblies=193;

% 2. Designate the measured scenario number of fuel assemblies
MeasuredPercent=100*(M/193);
% M: number of fuel assemblies


% 3. Designate the baseline scenario number of fuel assemblies
BaselinePercent=100*(B/193);
% B: number of fuel assemblies (i.e. 77, 64, 48, 39, & 0)

% 4. Duration Period
TotalDays=494; % Corresponds to the fuel cycle lifetime including day 0

TimePeriodPercent=100*(D/494);
% D: if n is duration period to be analyzed, D=n+1, to include for day 0.
% This equation simply converts the duration period to be analyzed into a
% percentage of the total fuel cycle lifetime

timespan=round(TotalDays*TimePeriodPercent*0.01);
% calculates the duration period to be analyzed (in days) by taking the
% product of two above metrics rounded to nearest integer

days=transpose([0:(timespan-1)]);
% generates a matrix of the duration period to be analyzed

days=days-mean(days);
% in order to eliminate the correlation and instability between the linear
% effect and quadratic effect coefficients, the standard practice, as
% identified by Neter et. al, of redefining the independent variable (time
% duration in days) as a deviation from its mean

% 5. Statistical Testing Threshold
alphaS=0.01*[0.01:0.01:0.1,0.2:0.1:1,2:1:10,20:10:100];
% an array of values corresponding to level of significance threshold,
% alpha, to be used in each iterative step of the statistical testing
% procedure

scale=length(alphaS);
% corresponds to the length of the array alphaS in order to designate the
% number of levels of threshold values to be analyzed in this simulation

% 6. Fissile Fuel Volume
```

```
FuelAssemblyVol=47354.80664;
% Calculated based on the schematics of provided in this work, where the
% fuel assembly is composed of 264 fuel pins with a pin radius of 0.3951 cm
% and length of 365.76 cm

% Additional Constants for Power and Antineutrino Rate Calculations,
% although not needed in this because they are either unnecessary for
% purposes of this simulation or are implemented elsewhere from generated
% functions used in this simulation:

%   Energy/Fission in J
%       U235EnergyPerFission=3.23512E-11; %201.92 MeV
%       U238EnergyPerFission=3.29279E-11; %205.52 MeV
%       Pu239EnergyPerFission=3.36441E-11; %209.99 MeV
%       Pu241EnergyPerFission=3.42225E-11; %213.6 MeV

%   Antineutrino Rate per day converters
%       U235_Anti=5.16336E-17;
%       U238_Anti=7.25345E-17;
%       Pu239_Anti=3.36024E-17;
%       Pu241_Anti=4.79755E-17;

%%  Observed LEU Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   baseline antineutrino measurement evolution given the following inputs
%   designated for this function
BaselineExpected=trajectoryWbackground(BaselinePercent,timespan,
                                       TotalAssemblies,FuelAssemblyVol,BP);
BaselineExpectedLength=length(BaselineExpected);

%%  Expected MOX Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   measured antineutrino measurement evolution given the following inputs
%   designated for this function
MeasuredExpected=trajectoryWbackground(MeasuredPercent,timespan,
                                       TotalAssemblies,FuelAssemblyVol,BP);
MeasuredExpectedLength=length(MeasuredExpected);

%%  Length of Baseline and Measured Arrays are Equal
%   Simply confirms that the length of the baseline and measured
%   antineutrino measurement evolutions are equal ensuring a proper
%   comparison analysis to generate the ROC curve
if MeasuredExpectedLength==BaselineExpectedLength
    lengthcheck=1;
else
    lengthcheck=0;
end

%%  t-Test of Baseline and Measured Scenarios for ROC Curve Generation

% 1. Initialize arrays that will be used to store the calculated true
% positive (alphaTP), false negative (alphaFN), true negative (alphaTN),
% and false positive (alphaFP) arrays at the designated level of
% significance
```

```
alphaTP=zeros(2,scale);
alphaFN=zeros(2,scale);
alphaTN=zeros(2,scale);
alphaFP=zeros(2,scale);

% 2. Store level of significance values analyzed in the first rows of the
% true positive (alphaTP), false negative (alphaFN), true negative
% (alphaTN), and false positive (alphaFP) arrays
alphaTP(1,:)=alphaS;
alphaFN(1,:)=alphaS;
alphaTN(1,:)=alphaS;
alphaFP(1,:)=alphaS;


% 3. Begin calculating the TP, FN, TN, and FP values at the varying levels
% of significance

for k=1:1:scale

    alpha=alphaS(k);
    % alpha corresponds to the tested level of significance at this
    % iterative loop

    % Initialize TP, FN, TN, and FP variables at the beginning of each
    % iterative loop
    TP=0;
    FN=0;
    TN=0;
    FP=0;

    % Displays a figure corresponding to the progress of the simulation as
    % a percentage of the total number of analyzed levels of significance
    wait=waitbar(k/scale,'Processing Data');

    % At each level of significance, conduct the designated number of
    % iterations (numiter)
    for i=1:numiter


BaselineObserved=expectedcounts(BaselineExpected(2:BaselineExpectedLength));
        % Generate the simulated expected values for the baseline scenario
        % antineutrino evolution


MeasuredObserved=observedcounts(MeasuredExpected(2:MeasuredExpectedLength));
        % Generate the simulated observed values for the measured scenario
        % antineutrino evolution to be used in the TP-FN testing


MeasuredObserved2=observedcounts(BaselineExpected(2:BaselineExpectedLength));
        % Generate the simulated observed values for the baseline scenario
        % antineutrino evolution to be used in the FP-TN testing
```

```
        % True Positive and False Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and measured
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved,BaselineObserved,2,alpha);

        if h==1
            TP=TP+1;
        else
            FN=FN+1;
        end

        %False Positive and True Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and baseline
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved2,BaselineObserved,2,alpha);

        if h==1
            FP=FP+1;
        else
            TN=TN+1;
        end

    end

% Close the wait bar figure generated so that a revised figure can be
% generated upon initiation of the following iterative cycle
close(wait);

% Store the updated TP, FN, FP, and TN values as a fraction of the total
% number of iterations simulated (numiter) in the following matrices
alphaTP(2,k)=TP/numiter;
alphaFN(2,k)=FN/numiter;
alphaFP(2,k)=FP/numiter;
alphaTN(2,k)=TN/numiter;

end

%Plot the FP vs. TP ROC curve
loglog(alphaFP(2,:),alphaTP(2,:),'o');
set(gca,'XTick',(alphaS*100));
set(gca,'YTick',(alphaS*100));
```

B.3.3 Detector Sensitivity Simulator

```
%% Detector Sensitivity Simulator
%  This simulator aims to determine the detector sensitivity by analyzing
%  detector failure over a large number of iterations for designated
%  baseline and a measured scenarios

%% Initial values

% 1. Designate the number of iteration cycles for simulation
numiter=100000;
TotalAssemblies=193;

% 2. Designate the measured scenario bounds to be compared to baseline
% scenario
MinFuelAss=MLOW;
% MLOW: minimum number of MOX fuel assemblies for lowest measured scenario
% bound

IncrementAss=INC;
% INC: incremental assembly number

MaxFuelAss=MHIGH;
%MHIGH: maximum number of MOX fuel assemblies for highest measured
%scenario bound

minmix=100*(MinFuelAss/193);
% This equation simply converts the designated minimum number of MOX fuel
% assemblies into a fraction core concentration

increment=100*(IncrementAss/193);
% This equation simply converts the designated incremental assembly number
% into a fraction core concentration

maxmix=100*(MaxFuelAss/193);
% This equation simply converts the designated maximum number of MOX fuel
% assemblies into a fraction core concentration

scale=((MaxFuelAss-MinFuelAss)/IncrementAss)+1;
% Corresponds to the number of measured scenarios to be compared to the
% baseline scenario as designated by the user input of bounds

% Generate arrays corresponding to the MOX fuel fractional core
% concentration and number of MOX fuel assemblies in core, respectively
MeasuredPercents=[minmix:increment:maxmix];
MeasuredPercentsAss=[MinFuelAss:IncrementAss:MaxFuelAss];

% 3. Designate the baseline scenario number of MOX fuel assemblies
BaselinePercent=100*(B/193);
% B: number of fuel assemblies (i.e. 77, 64, 48, 39, & 0)

% 4. Duration Period
TotalDays=494; % Corresponds to the fuel cycle lifetime including day 0

TimePeriodPercent=100*(D/494);
```

```
% D: if n is duration period to be analyzed, D=n+1, to include for day 0.
% This equation simply converts the duration period to be analyzed into a
% percentage of the total fuel cycle lifetime

timespan=round(TotalDays*TimePeriodPercent*0.01);
% calculates the duration period to be analyzed (in days) by taking the
% product of two above metrics rounded to nearest integer

days=transpose([0:(timespan-1)]);
% generates a matrix of the duration period to be analyzed

days=days-mean(days);
% in order to eliminate the correlation and instability between the linear
% effect and quadratic effect coefficients, the standard practice, as
% identified by Neter et. al, of redefining the independent variable (time
% duration in days) as a deviation from its mean

% 5. Statistical Testing Threshold
alpha=0.01; %designate the threshold value for statistical testing

% 6. Fissile Fuel Volume
FuelAssemblyVol=47354.80664;
% Calculated based on the schematics of provided in this work, where the
% fuel assembly is composed of 264 fuel pins with a pin radius of 0.3951 cm
% and length of 365.76 cm

% Additional Constants for Power and Antineutrino Rate Calculations,
% although not needed in this because they are either unnecessary for
% purposes of this simulation or are implemented elsewhere from generated
% functions used in this simulation:

%   Energy/Fission in J
%       U235EnergyPerFission=3.23512E-11; %201.92 MeV
%       U238EnergyPerFission=3.29279E-11; %205.52 MeV
%       Pu239EnergyPerFission=3.36441E-11; %209.99 MeV
%       Pu241EnergyPerFission=3.42225E-11; %213.6 MeV

%   Antineutrino Rate per day converters
%       U235_Anti=5.16336E-17;
%       U238_Anti=7.25345E-17;
%       Pu239_Anti=3.36024E-17;
%       Pu241_Anti=4.79755E-17;

%%  Observed LEU Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   baseline antineutrino measurement evolution given the following inputs
%   designated for this function
BaselineExpected=trajectory(BaselinePercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
BaselineExpectedLength=length(BaselineExpected);

%%  Expected MOX Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   measured antineutrino measurement evolution given the following inputs
```

```
%   designated for this function
MeasuredExpected=trajectory(MeasuredPercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
MeasuredExpectedLength=length(MeasuredExpected);

%%  Length of Baseline and Measured Arrays are Equal
%   Simply confirms that the length of the baseline and measured
%   antineutrino measurement evolutions are equal ensuring a proper
%   comparison analysis to generate the ROC curve
if MeasuredExpectedLength==BaselineExpectedLength
    lengthcheck=1;
else
    lengthcheck=0;
end

%%  Detector Sensitivity Procedure

% 1. Initialize recorder array that will be used to record the
% measured MOX fuel assembly number as compared to the baseline MOX fuel
% assembly number in order to determine the detector failure for each
% iterative step and recorderFP array that will be used to record the
% result of the t-Test comparison of the baseline MOX fuel assembly number
% measurement to itself
recorder=zeros(numiter,1);
recorderFP=zeros(numiter,1);

% 2. Begin simulation process for detector sensitivity performance
for i=1:numiter

    % Displays a figure corresponding to the progress of the simulation as
    % a percentage of the total number of simulation iterations
    wait=waitbar(i/numiter,'Processing Data');

    BaselineObserved=expectedcounts(BaselineExpected(2:BaselineExpectedLength));
    % Generate the simulated expected values for the baseline scenario
    % antineutrino evolution

    MeasuredObserved2=observedcounts(BaselineExpected(2:BaselineExpectedLength));
    % Generate the simulated observed values for the baseline scenario
    % antineutrino evolution to be used in the FP-TN testing

    recorderFP(i)=tTestforCoeff(days,MeasuredObserved2,BaselineObserved,2,alpha);
    %Record the result of the t-Test for the baseline measurement as
    %compared to itself

    % Perform the t-Test comparison of the antineutrino measurement
    % evolutions produced from the measured MOX fuel assembly number and
    % baseline MOX fuel assembly number, iterating across the entire
    % sample of measured MOX fuel assembly numbers as designated above. The
    % measured MOX fuel assembly number achieved prior to the testing
    % procedures failure will be recorded in the recorder array.
    for k=1:1:scale
```

```
MeasuredObserved=observedcounts(MeasuredExpected(2:MeasuredExpectedLength,k));
        % Generate the simulated observed values for the measured scenario
        % antineutrino evolution to be used in the TP-FN testing

        h=tTestforCoeff(days,MeasuredObserved,BaselineObserved,2,alpha);

        if h==0
            break
        end
        recorder(i)=MeasuredPercentsAss(k);
    end

    % Close the wait bar figure generated so that a revised figure can be
    % generated upon initiation of the following iterative cycle
    close(wait)

end

% Calculate the False Positive Rate (FPR) for the given test statistic
% based on the level of significance value, alpha, designated above.
FPR=sum(recorderFP)/numiter;

% Plot a histogram of the performed data
hist(recorder,MeasuredPercentsAss);
xlabel('Number of Assemblies');
ylabel('Counts');

% Plot a Gaussian fit on the generated histogram
hold on
Multiplier=max(histc(recorder,MeasuredPercentsAss));
STDEV=std(recorder);
xbar=mean(recorder);
y=Multiplier*gaussmf(MeasuredPercentsAss,[STDEV xbar]);
plot(MeasuredPercentsAss,y);
hold off
```

B.3.4 Relative ROC t-Test of Fitted Coefficients Simulator

```
%% Relative ROC t-Test of Fitted Coefficients Simulator
%  This simulator aims to generate the ROC curve for the relative
%  comparison of a baseline and a measured scenario over a designated
%  number of iterations. The start day has also offers the ability to be
%  manipulated in an attempt to strengthen the results of the test
%  comparison

%% Initial values

% 1. Designate the number of iteration cycles for simulation
numiter=100000;
TotalAssemblies=193;

% 2. Designate the measured scenario number of fuel assemblies
MeasuredPercent=100*(M/193);
% M: number of fuel assemblies

% 3. Designate the baseline scenario number of fuel assemblies
BaselinePercent=100*(B/193);
% B: number of fuel assemblies (i.e. 77, 64, 48, 39, & 0)

% 4. Duration Period
TotalDays=494; % Corresponds to the fuel cycle lifetime including day 0

TimePeriodPercent=100*(D/494);
% D: if n is duration period to be analyzed, D=n+1, to include for day 0.
% This equation simply converts the duration period to be analyzed into a
% percentage of the total fuel cycle lifetime

timespan=round(TotalDays*TimePeriodPercent*0.01);
% calculates the duration period to be analyzed (in days) by taking the
% product of two above metrics rounded to nearest integer

days=transpose([0:(timespan-1)]);
% generates a matrix of the duration period to be analyzed

days=days-mean(days);
% in order to eliminate the correlation and instability between the linear
% effect and quadratic effect coefficients, the standard practice, as
% identified by Neter et. al, of redifining the independent variable (time
% duration in days) as a deviation from its mean

startday=TotalDays-SD;
% SD: number of days prior to the end of the cycle/duration period that the
% user would like to begin the test comparison. As stated in the simulator
% definition above, in an attempt to strengthen the results of the test
% comparison, the user can manipulate the start day for the analysis to
% commence based on the notion that by beginning the analysis toward the
% end of the measurement duration period, one can strengthen the result of
% the test comparison by maximizing the difference between the baseline and
% measured antineutrino measurement evolutions

% 5. Statistical Testing Threshold
```

```
alphaS=0.01*[0.01:0.01:0.1,0.2:0.1:1,2:1:10,20:10:100];
% an array of values corresponding to level of significance threshold,
% alpha, to be used in each iterative step of the statistical testing
% procedure

scale=length(alphaS);
% corresponds to the length of the array alphaS in order to designate the
% number of levels of threshold values to be analyzed in this simulation

% 6. Fissile Fuel Volume
FuelAssemblyVol=47354.80664;
% Calculated based on the schematics of provided in this work, where the
% fuel assembly is composed of 264 fuel pins with a pin radius of 0.3951 cm
% and length of 365.76 cm

% Additional Constants for Power and Antineutrino Rate Calculations,
% although not needed in this because they are either unnecessary for
% purposes of this simulation or are implemented elsewhere from generated
% functions used in this simulation:

%   Energy/Fission in J
%       U235EnergyPerFission=3.23512E-11; %201.92 MeV
%       U238EnergyPerFission=3.29279E-11; %205.52 MeV
%       Pu239EnergyPerFission=3.36441E-11; %209.99 MeV
%       Pu241EnergyPerFission=3.42225E-11; %213.6 MeV

%   Antineutrino Rate per day converters
%       U235_Anti=5.16336E-17;
%       U238_Anti=7.25345E-17;
%       Pu239_Anti=3.36024E-17;
%       Pu241_Anti=4.79755E-17;

%%  Observed LEU Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   baseline antineutrino measurement evolution given the following inputs
%   designated for this function
BaselineExpected=trajectory(BaselinePercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
BaselineExpectedLength=length(BaselineExpected);

%%  Expected MOX Values Calculated
%   Calculates and determines the resultant array length of the simulated
%   measured antineutrino measurement evolution given the following inputs
%   designated for this function
MeasuredExpected=trajectory(MeasuredPercent,timespan,TotalAssemblies,
                            FuelAssemblyVol);
MeasuredExpectedLength=length(MeasuredExpected);

%%  Length of Baseline and Measured Arrays are Equal
%   Simply confirms that the length of the baseline and measured
%   antineutrino measurement evolutions are equal ensuring a proper
%   comparison analysis to generate the ROC curve
if MeasuredExpectedLength==BaselineExpectedLength
    lengthcheck=1;
```

```
else
    lengthcheck=0;
end

%%  t-Test of Baseline and Measured Scenarios for ROC Curve Generation

% 1. Initiate arrays that will be used to store the calculated true
% positive (alphaTP), false negative (alphaFN), true negative (alphaTN),
% and false positive (alphaFP) arrays at the designated level of
% significance
alphaTP=zeros(2,scale);
alphaFN=zeros(2,scale);
alphaTN=zeros(2,scale);
alphaFP=zeros(2,scale);

% 2. Store level of significance values analyzed in the first rows of the
% true positive (alphaTP), false negative (alphaFN), true negative
% (alphaTN), and false positive (alphaFP) arrays
alphaTP(1,:)=alphaS;
alphaFN(1,:)=alphaS;
alphaTN(1,:)=alphaS;
alphaFP(1,:)=alphaS;

% 3. Reevaluate days provided the user inputted startday
days=(startday:TotalDays);
days=transpose(days);
days=days-mean(days);

% 3. Begin calculating the TP, FN, TN, and FP values at the varying levels
% of significance

for k=1:1:scale

    alpha=alphaS(k);
    % alpha corresponds to the tested level of significance at this
    % iterative loop

    % Initiate TP, FN, TN, and FP variables at the beginning of each
    % iterative loop
    TP=0;
    FN=0;
    TN=0;
    FP=0;

    % Displays a figure corresponding to the progress of the simulation as
    % a percentage of the total number of analyzed levels of significance
    wait=waitbar(k/scale,'Processing Data');

    % At each level of significance, conduct the designated number of
    % iterations (numiter)
    for i=1:numiter


BaselineObserved=expectedcounts(BaselineExpected(2:BaselineExpectedLength));
```

```
        % Generate the simulated expected values for the baseline scenario
        % antineutrino evolution

        BaselineObserved=BaselineObserved./BaselineObserved(1);
        % Redefine the baseline simulated expected values relative to the
        % measurement collected on the initial day

        BaselineObserved=BaselineObserved(startday:TotalDays);
        % Redefine the given array to just the measured values from the
        % designated start day to the last day of the duration period


MeasuredObserved=observedcounts(MeasuredExpected(2:MeasuredExpectedLength));
        % Generate the simulated observed values for the measured scenario
        % antineutrino evolution to be used in the TP-FN testing

        MeasuredObserved=MeasuredObserved./MeasuredObserved(1);
        % Redefine the measured simulated observed values relative to the
        % measurement collected on the initial day

        MeasuredObserved=MeasuredObserved(startday:TotalDays);
        % Redefine the given array to just the measured values from the
        % designated start day to the last day of the duration period


MeasuredObserved2=observedcounts(BaselineExpected(2:BaselineExpectedLength));
        % Generate the simulated observed values for the baseline scenario
        % antineutrino evolution to be used in the FP-TN testing

        MeasuredObserved2=MeasuredObserved2./MeasuredObserved2(1);
        % Redefine the baseline simulated observed values relative to the
        % measurement collected on the initial day

        MeasuredObserved2=MeasuredObserved2(startday:TotalDays);
        % Redefine the given array to just the measured values from the
        % designated start day to the last day of the duration period

        % True Positive and False Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and measured
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved,BaselineObserved,2,alpha);

        if h==1
            TP=TP+1;
        else
            FN=FN+1;
        end

        %False Positive and True Negative Testing
        %   Conduct a t-Test of the coefficients generated from a
        %   polynomial regression of the baseline expected and baseline
```

```
        %   observed values for the designated level of significance
        h=tTestforCoeff(days,MeasuredObserved2,BaselineObserved,2,alpha);

        if h==1
            FP=FP+1;
        else
            TN=TN+1;
        end

    end

% Close the wait bar figure generated so that a revised figure can be
% generated upon initiation of the following iterative cycle
close(wait);

% Store the updated TP, FN, FP, and TN values as a fraction of the total
% number of iterations simulated (numiter) in the following matrices
alphaTP(2,k)=TP/numiter;
alphaFN(2,k)=FN/numiter;
alphaFP(2,k)=FP/numiter;
alphaTN(2,k)=TN/numiter;

end

%Plot the FP vs. TP ROC curve
loglog(alphaFP(2,:),alphaTP(2,:),'o');
set(gca,'XTick',(alphaS*100));
set(gca,'YTick',(alphaS*100));
```