LONG-TERM NUCLEAR WASTE FORECASTING FOR LIQUID-FUELED NUCLEAR REACTORS:

A COMPREHENSIVE LONG-TERM ANALYSIS OF LIQUID-FUELED NUCLEAR REACTOR FISSION AND TRANSMUTATION PRODUCTS AND ASSOCIATED ENVIRONMENTAL CONCERNS

By

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Abstract

Nuclear energy doesn't have the best track record when it comes to environmental safety, so when a new technology comes along promising to be the "end all" solution to the worlds energy woes, skepticism is advised. Since the late 1990's, Liquid Fueled Nuclear Reactors [LFNR] have become a more popular topic within the energy science community. Since the early work at Oak Ridge National Laboratory by Alvin Weinberg to the more recent Liquid Fluoride Thorium Reactor [LFTR] designs, the literature has shown the technical viability of LFNR tech. However little analysis into the long-term waste, and how that waste will affect both the Earth and its collective inhabitants. This thesis provides the framework necessary to understand the differences between Solid Fueled Nuclear Reactors [SFNR] and LFNR, from the perspective of waste output. By understanding what comes out the "back end" of a LFNR facility, policy makers can better evaluate the long-term impacts of the technology. As the primary opposition to nuclear energy is the very dangerous, long-lived fission waste generated by nuclear reactors, and the most touted "fact" about LFNR systems is their drastically reduced production of high-level waste and extremely high energy density, it seems prudent to analyze the expected waste output to verify the claim itself. Through detailed examination, this thesis will show that the available data does appear to support the claims being made about LFNR tech and will provide a foundation for future research. This analysis shows LFNR waste mass is in fact as much as 32x less volume than comparative SFNR waste, the volume of long-lived waste produced by LFNR is a lower overall portion of the final waste mass in general, and LFNR facilities would be safer to operate, in terms of "potential catastrophic failure" chance.

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Most importantly, I thank my wife Julie Taylor. I subjected her to countless hours of scientific jargon over dinner and she never left me when I would disappear from “the real world” for days on end during feverish spells of reading article after article to find that ONE thing I couldn’t find. She is an amazing woman and without her standing behind me, I would have never gotten this far.

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2) Introduction

It has become an irrefutable fact that the global community will not meet any realistic carbon reduction targets without a drastic, and relatively rapid, large-scale shift in energy production methods (Olivier, Janssens-Maenhout, Muntean, & Peters, 2013). The recent United Nations Climate Change Conference in Paris saw leading scientists, from around the world and across nearly all academic spectrums, come together in an attempt to create realistic global climate change goals. It has becoming overwhelmingly obvious that the global community will not meet the carbon reduction targets without a drastic, and relatively rapid, large-scale shift in energy production methods. Energy production is the single largest carbon producing industry, with some estimates showing an annual global output in excess of 13.8 billion tons in 2012 (Olivier, Janssens-Maenhout, Muntean, & Peters, 2013). This value represents 40% of the 34.5 billion tons of carbon released globally in 2012, directly from the burning of fossil fuels. The energy market must become an active participant in reducing carbon emissions if any hope of slowing or halting climate change can exist (Baynes, et al., 2015).

Leading thinkers from around the world, including Bill Gates (Conca, 2015; Zhao, Yang, Xiao, & Zhou, 2013), Elon Musk (Musk, 2007), and Taylor Wilson (TEDtalks, 2013), have identified the Liquid-Fueled Nuclear Reactor [LFNR] as a viable candidate for energy dense, low-waste, near-zero carbon output energy production. Bill Gates belief in Molten Salt Reactors [MSR], a type of LFNR technology, led to his decision to expand LFNR research in 2012, after six years of intensive research into the Traveling Wave Reactor [TWR] (Huke, et al., 2015). Ore extraction, processing, and waste processing account for all of the carbon output of LFNR (Herring, MacDonald, Weaver, & Kullberg, 2001). LFNR operate under fundamentally different conditions than traditional Solid Fueled Nuclear Reactors (SFNR). These differences include, but are not limited to; more efficient fuel burnup, reduced volumes of high-level waste, shorter lived waste, and drastically safer operating conditions (Serp J. , et al., 2014).

While standard SFNR utilize solid uranium [U] or plutonium [Pu] ceramic pellets as fuel, LFNR utilize a liquid solvent to dissolve the fissile/fertile isotopes to create a "fuel salt" (Delpech, et al., 2009). Fuel salts offer numerous advantages over solid fissile fuels, the most crucial being a far more efficient burnup ratio (Zhao, Yang, Xiao, & Zhou, 2013). One of the most efficient SFNR ever built, the Fort Saint Vrain High Temperature Reactor [HTR] achieved a burnup of 170 $Gw_{d/t}$ {~18.7%} (Carlson & Ball, 2016). A well designed LFNR style reactor, such as the proposed LFTR, has been projected to achieve burnups as high as 881 $Gw_{d/t}$ {97%} (Ahmad, McClamrock, & Glaser, 2015).

Very little has been published providing thorough analysis regarding exactly what the composition of high-level LFNR waste would be (Ashley, 2012). As with SFNR waste, many questions regarding the waste composition, traits, and sequestration requirements exist. I could locate no comprehensive analysis of LFNR waste, however many claims around the technology have been made through digital media since 2012. To fill this gap, this thesis will provide a comprehensive long-term waste analysis of all fission and transmutation products that created by an LFNR.

First, a brief recap of the history of LFNR technology will provide background information about the technology. Second, a summary of current and future LFNR projects will create framework to relate the urgency of further LFNR research. Third, a brief technical introduction of LFNR technology. Fourth, the chosen model characteristics for this thesis design. Fifth, a detailed summary, by fissile fuel type, including waste product categorization and analysis. Finally, comparisons between LFNR, SFNR, and traditional coal energy cycles will establish a framework in which to differentiate the technologies.

3) History of Liquid Fueled Nuclear Reactors

3.1) Pre 2000

In the earliest days of the Manhattan Project, scientists considered the idea of using a liquid fuel substrate in nuclear reactors, but rejected the concept due to the technological limitations of the era (Rosenthal, Kasten, & Briggs, 1970). Manufacturing technologies at the time were limited, and Liquid Fueled Nuclear Reactors [LFNR] requires extremely specific tolerances to ensure ongoing safe operating conditions. Liquid fuels offer strong negative void coefficients [Appendix 9.1], and as such, can be passively cooled even in the event of a catastrophic system failure (Schludi, 1963). The Air Force turned to Oak Ridge National Laboratory [ORNL] to learn what liquid coolants could meet the unique requirements of liquid fueled reactors (Sorensen, 2014). In 1952, Ray Briant, a chemist at ORNL, had been working on a beryllium-oxide [BeO] moderated sodium [Na]-cooled reactor with solid fuel (Grimes, 1967). Unfortunately, with this configuration, the reactor was unable to maintain long-term operation. The solid fuel pellets failed to handle the incredible heat stresses of the system, designed to maintain a temperature of 1600º F (Grimes, 1967). In addition, because even the slightest exposure to water or water vapor results in a violent thermal reaction, a Na coolant is inherently dangerous to handle (Ashley, 2012).

Briant came up with the idea of combining a liquid salt coolant, which would act as both a coolant and solvent, directly with the fissile fuel and the beryllium moderator [Appendix 9.1] (Sorensen, 2014). The research team eventually realized they could likely use the fluoride of an alkali as the solvent (Sorensen, 2014). At the time, little knowledge regarding fluoride salts had yet been established (Sorensen, 2014).) Briant and his team then converted a small research reactor and tested the viability of a fluoride-cooled core.

The ORNL team learned that the use of a liquid fuel salt created several conditions ideal for a stable long-life nuclear reactor (Engel & Haubenreich, 1970). Gaseous fission products that would normally cause instability within the reactor, such as the nuclear poisons [Appendix 9.1] xenon-137 [^{137}Xe] and krypton-90 [^{90}Kr], could be allowed to off-gas from the fuel mass naturally using the existing pumping action of the reactor (Scott & Eatherly, 1970). The fuel salt could then be subjected to a series of electro-chemical reactions that allowed for the separation of individual elements, and for the removal of fission products and transuranic isotopes from the fuel mass (Delpech, et al., 2009). The fuel salt could also “self-regulate” [Appendix 9.1], due to the specific thermal expansion characteristics of the fuel (Elsheikh, 2013). This expansion reduces the likelihood of a fission reaction while increasing the likelihood of a neutron absorption, resulting in a core that would naturally cool itself when excessive temperatures are reached. Fuel salts would not require the addition of control rods or burnable poisons [Appendix 9.1], further reducing the overall waste mass (Heuer, et al., 2014). Finally, thorium [Th], uranium [U], and plutonium [Pu] form tetrafluorides that are highly stable and will readily dissolve in lithium-beryllium fluoride salt [FLiBe], the ideal solvent for the high temperature environment (Nuttin, et al., 2005).

The ORNL Molten Salt Reactor Experiment [MSRE] research team, led by Physicist Alvin Weinberg, believed the LFNR concept showed great promise (Weinberg & Briant, 1957). The MSRE operated for nearly five years without any major incident, demonstrating that a fluoride salt/fuel combination could work reliably (Engel &

Haubenreich, 1970). The MSRE showed the liquid core to be ideally suited for utilizing fertile ^{232}Th to generate ^{233}U (Rosenthal, Kasten, & Briggs, 1970). The byproducts of a LFNR, regardless of the chosen fuel type, have half-lives measured in decades and centuries, versus millennia (Uhlíř, 2007). This distinction was not lost on the intellectuals within the nuclear research community.

In early 1973, the Nixon administration fired Weinberg, specifically due to his vocal advocacy of the LFNR technology and opposition to the Liquid Metal Fast-Breeder Reactor [LMFBR] (Weinberg A. , 1994). Following Weinberg’s rather public termination, all research into LFNR effectively became blacklisted and Weinberg’s research team moved on to other projects (Sorensen, 2014). The Department of Energy [DOE] and Department of Defense [DOD] cancelled funding for the MSRE project in late 1973, in favor of the Fast Breeder Reactor research (Waltar & Reynolds, 1981). At the time, the LMFBR design was more desirable to the DOD, as ^{239}Pu, a weapons grade fissile isotope, was produced by the LMFBR in relative abundance. (Bauman, et al., 1980). In 1972 ORNL published a technical paper entitled *ORNL-TM-7202* which is now recognized as the “benchmark” for all modern LFNR advancements. This technical paper examined the potential of using a weakly enriched ^{235}U fuel salt, but made no attempt to address reprocessing waste or removal of fission products (Engler, Bauman, & Dearing, 1980).

Scientists at the Kurchatov Institute in the USSR also conducted some research into Molten Salt Reactors [MSR] in the 1970’s (Novikov, 1994). Although the Soviet scientific team never constructed a reactor, they concluded that no physical nor technological obstacles prevented the practical implementation of MSR for commercial power generation (Novikov, 1994). The Soviets abandoned this line of research shortly after the 1986 Chernobyl disaster in response to international outcry against nuclear development (Novikov, 1994).

Britain's Atomic Energy Research Establishment [AERE] conducted MSR research between 1964 and 1973 at its National Laboratories (Martin, 2014). The AERE chose to focus research funds on a lead-cooled MSFR concept using a chloride based salt and plutonium (Martin, 2014). Funding for AERE's MSR research was cut in 1974 after the success a competing development project, the Prototype Fast Reactor [PFR] in Dounreay, UK (Martin, 2014).

Practically no research was conducted into LFNR between 1976 and 2000 (McDowell, 2014). In 2016 Carlo Rubbia, former General Director of the European Organization for Nuclear Research [CERN] stated his belief that the main reason Thorium research was cut in the 1970's is the same reason the technology is so attractive today, LFNR do not produce fissile mass that can be used for weapons production (Rubbia, 2016). As of 2015, the Aircraft Reactor Experiment [ARE] and MSRE are the only molten-salt reactors to have been operated. The lack of research and lack of operating experience has resulted in the development of significant gaps in the body of knowledge regarding liquid fueled nuclear reactors.

3.2) 2000 - Future

Seaborg Technologies, based in Copenhagen, announced in March 2015 an innovative design for a Liquid Fueled Nuclear Reactor [LFNR], “The Wasteburner” or Seaborg Mark II, designed to operate off existing high-level nuclear waste and thorium [Th] (Seaborg Technologies, Unknown). The company aims to use the reactor primarily for high-level radiological waste reduction, with energy production being a side effect of the process.

A Canadian company, Terrestrial Energy Inc., has been developing the Integral Molten Salt Reactor (IMSR) (Terrestrial Energy, Unknown). The IMSR is being designed as a small-scale modular reactor, ranging between 80 and 600 Mw of thermal power. Small-scale modular reactors could be an integral part in future distributed electrical “smart” grids, allowing high-output localized power generation. These distributed grids would drastically reduce the need for infrastructure to distribute power over large areas.

Research conducted by private companies from Japan, Russia, Australia, the United States, Finland, and China have generated renewed interest in LFNR technology in recent years (World Nuclear Association, 2016). The FUJI MSR, a 100-200 Mw LFNR style reactor, is being developed by a consortium of Japanese, US, and Russian scientists (Harper, 2013). The research group estimates it will take 20 years to develop a full-size commercial reactor.

In 2011, the Chinese Academy of Sciences (CAS) announced they too had formally begun a MSR research program (Halper, 2015). The CAS research team is developing both an experimental liquid-fluorine fueled 2 Mw research plant and a 2 Mw pebble-bed solid-thorium/MSR hybrid (Halper, 2015). The estimated completion data of both CAS projects was delayed in 2012 until 2017 (Harper, Completion Date Slips for China's Thorium Molten Salt Reactors, 2012).

Ratan Kumar Sinha, Chairman of the Atomic Energy Commission of India, stated in 2013 the Bhabha Atomic Research Centre [BARC] had successfully tested several molten salt loops [Appendix 9.1] (Jha, 2013). India has a “50-year plan” to convert all of their primary energy infrastructure to ^{232}Th/^{233}U, a proposal that has resulted in significant backlash from the nuclear community (Wong, 2015).

In the private sector, FLiBe Energy founded in 2011 to develop a commercial Liquid Fluorine Thorium Reactor [LFTR] utilizing lithium-beryllium fluoride [FLiBe] salts (FLiBe Energy, Unknown). FLiBe Energy is developing a 20-50 Mw LFTR for use in powering military bases (Waldrop, 2012). Transatomic Power, a startup created by MIT Ph.D. students Leslie Dewan and Mark Massie, with Russ Wilcox of E Ink, is working to develop the Waste-Annihilating Molten Salt Reactor (WAMSR) (Transatomic Power, Unknown). Like the Seaborg Mark II, the WAMSR is designed primarily as a waste-reduction technology, with power generation being a side-effect of the process. Transatomic Power successfully received $2.5 million in venture capital funding in 2015 to fund further development of the WAMSR (Billings, 2015).

The Alvin Weinberg Foundation, a British non-profit dedicated to Thorium energy education and advocacy, was formally launched in the House of Lords in September of 2011 (The Alvin Weinberg Foundation, Unknown). The Evaluation and Viability of Liquid Fuel Fast Reactor System project [EVOL] released its final report in 2014 (Centre National De La Recherche Scientifique, 2014). EVOL examined a number of European MSR concepts [FHR, MOSART, MSFR, & TMSR] and provided assessment of how the EU MSR concepts fit into potential Generation V technology.

While the current state of LFNR can be difficult to assess, due to the very recent and often proprietary nature of the research, it is clear that interest is growing on a global scale, with India, China, Finland, and the United States taking the lead in recent innovations. Citizen scientists such as Kirk Sorenson [Nasa 2000-2010; founder of FLiBe Energy], John Kutsch [Director of Thorium Energy Alliance], Gordon McDowell [Filmmaker], Dr. Kiki Sanford [Science Communicator; Neurophysiologist], Dr. Robert Hargrave [Director of ThorCon Power; Physicist], Dr. Alex Cannara [Programmer; Author], and Dr. Bogdan Maglich [Nuclear Physicist; Inventor] have been participating in LFNR research through private and online research collectives dedicated to advancing and advocating LFNR technology. Several TED talks over the past few years, including those of Elon Musk (Edison Electric Institute, 2015), Bill Gates (TEDTalks, 2010), and young prodigy Taylor Wilson (TEDtalks, 2013), have brought the idea of thorium based LFNR reactors into mainstream scientific discussion.

4) Reactor Characteristics & Chemistry

For the sake of comprehension, information on Solid Fueled Nuclear Reactors [SFNR] has been provided to establish some framework required to understand Liquid Fueled Nuclear Reactors [LFNR].

4.1) Solid Fueled Reactors Core Chemistry

All existing nuclear reactors use a coolant, generally water, flowing past solid-fuel elements within a reactor core to transport heat generated through fission to the steam generator. The steam then powers turbines to generate electricity [Figure 1]. Water possesses a general low thermal capacity, a vaporization point of only 212° F, and a vapor expansion capacity of 1700 to 1, making it a less than ideal coolant for the extremes usually found within the core of a nuclear reactor (Perrow, 2011).

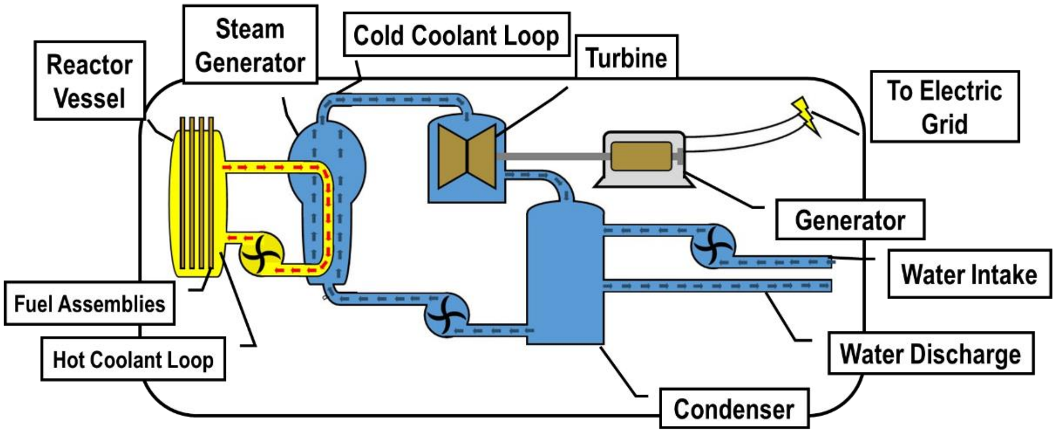

Figure 1 - Solid-Fueled Nuclear Reactor [SFNR] Operational Diagram

Solid fuel bundles are a complicated assembly of ceramic fuel pellets, protective jackets, and physical supports (Shapiro & Fratoni, 2016). Nonporous ceramic material encases the fuel pellets, which can contain Thorium-232 [^{232}Th], Uranium-235 [^{235}U], Uranium-238 [^{238}U], Plutonium-239 [^{239}Pu], and/or Plutonium-241 [^{241}Pu]. Fuel pellets are designed to capture the fission products within the confines of the pellet. These pellets are stacked inside rods wrapped in zirconium alloy cladding, completely sealed at both ends and filled with an inert gas such as helium to improve thermal transfer between the pellets and the cladding (Frost, 2013). The cladding serves as a second barrier to prevent the exchange of fission products between the fissile mass and the coolant. Assembled rods are assembled into fuel bundles, which can vary in exact size/shape depending on reactor design.

Fuel bundles will stay in the reactor core for three to five years before being removed for cooling and eventual sequestration. Upon removal from the reactor core, the fuel bundles contain between 81.3-97.4% unconsumed fuel. Due to the increasing concentration of fission products [Appendix 9.2] within the pellets, the fuel can no longer sustain a chain reaction and therefore cannot be used to generate power efficiently. It can take as long as 12 years for fuel bundles to cool to a temperature at which they can be safely sequestered or reprocessed (Hippel, 2001).

4.2) Liquid Fueled Reactors Core Chemistry

In a Liquid-Fueled Nuclear Reactor [LFNR] the coolant, fuel, and waste are combined in a single fluid (Delpech, et al., 2009). The compound FLiBe, a mixture of lithium fluoride [LiF] and beryllium fluoride [BeF2], has been identified as a viable solvent for this application (Ingersoll, 2005). FLiBe has a melting point of 858° F and a boiling point of 2606° F, allowing the salt to remain a stable liquid at atmospheric pressure (Ingersoll, 2005). It has heat capacity and flow characteristics similar to those of water, allowing existing pump technology to efficiently cycle the fuel mass through the reactor components.

LFNR can utilize ^{232}Th, ^{235}U, ^{238}U, ^{239}Pu, and/or ^{241}Pu as fuel (Nuttin, et al., 2005). Most current research into the technology focus on the ^{232}Th/^{233}U fuel cycle, as the ^{233}U fission cycle results in the creation of very few transuranic isotopes and practically no proliferation-ready isotopes [Appendix 9.3]. A ^{233}U LFNR would require an initial input of around 1-part fissile fuel to 2-parts fertile fuel (Bauman, et al., 1980). The fissile mass, likely, ^{235}U is used to initiate the chain reaction, while the fertile mass, likely ^{232}Th, would steadily be converted to ^{233}Th through transmutation (Delpech, et al., 2009). ^{233}Th, with a half-life of only 22 minutes, decays into protactinium-233 [^{233}Pa] through beta decay [Appendix 9.1] (Brown, Dixon, & Rogers, 1968). The ^{233}Pa, with a half-life of 27 days, will decay to ^{233}U through beta decay. The ^{233}U, a fissile element, eventually replaces the ^{235}U within the initial fuel mass and the reactor becomes self-sustaining, requiring only periodic addition of fertile fuel (Bauman, et al., 1980). Excess ^{233}U can be removed from the reactor and used to initiate other LFNR.

In a single-fluid LFNR, the singular fuel mass would contain the coolant, moderator, fissile fuel, fertile fuel, and fission products. This concept, though technologically easier than a dual-fluid reactor, presents significant long-term challenges. Many of the lanthanide fission products are difficult to chemically separate from Thorium, because of the similarity of their chemical properties (Bauman, et al., 1980).

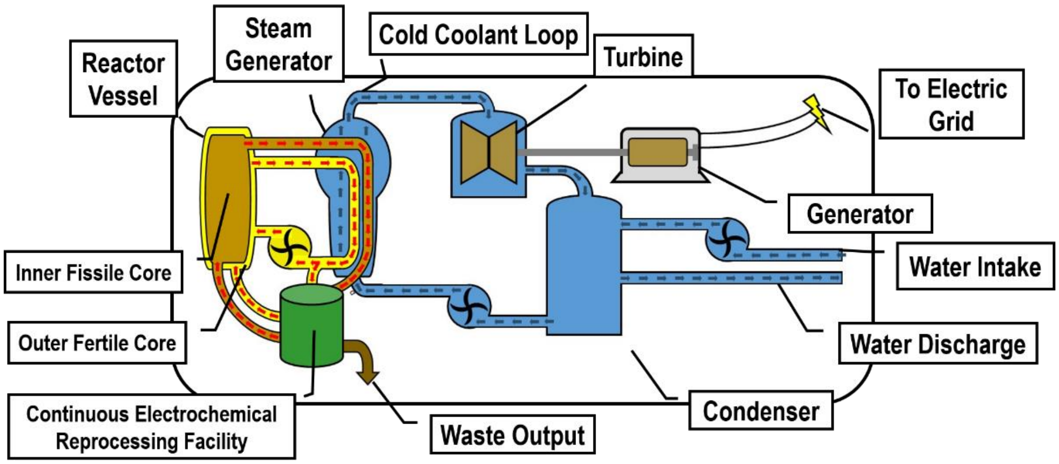

Figure 2 - Liquid-Fueled Nuclear Reactor [LFNR] Operational Diagram

In a dual-fuel LFNR [Figure 2], the core consists of an inner core chamber containing the fissile mass surrounded by an outer core chamber, called the “fertile blanket” (Huke, Armin, et al., 2014). Operators inject ^{232}Th into the outer blanket where it will absorb a neutron to become ^{233}Pa. The ^{233}Pa, now chemically distinct from the fertile ^{232}Th, can be removed from the fertile mass through electrochemical precipitation and allowed to “rest” for around 90 days (Huke, et al., 2015). This resting period allows the ^{233}Pa to fully decay to ^{233}U, which can then be removed as uranium hexafluoride [UF_6] through fluorination. The UF_6 is then reduced uranium tetrafluoride [UF_4], which can be injected into the inner core. Keeping the fission products in the fissile core entirely separate from the outer fertile core drastically increases the long-term efficiency of the reactor (Huke, Armin, et al., 2014).

Regardless of the LFNR design used, the fuel salt runs through a continuous series of electrochemical precipitation reactions while the reactor operates (Delpech, et al., 2009). The continuous removal of individual fission products and reintroduction of unconsumed fissile isotopes ensures the reactor operates at very near 97% burnup (Nuttin, et al., 2005). This process also allows for potentially valuable isotopes, such as those used for advanced scientific research or medical treatments, to be removed and utilized (Chuvilin & Zagryadskii, 2009). For example, a number of the fission products represent significant value for advanced cancer treatments, specifically Bismuth-213 [^{213}Bi] and Technetium-99m [^{99m}Tc] (Knapp, 2012).

In a sense, a well-designed LFNR could be likened more to a factory than a power plant. Electricity production would be just on, of many, products created. Many of the fission products are exceptionally valuable for a wide variety of applications in manufacturing, medical treatments, advanced research, and space travel. The ability to create non-weaponizable ^{238}Pu, currently the most expensive isotope (per gram) on the planet is of extreme interest to any organization that wishes to send any probe or spacecraft beyond the orbit of Mars (Ahmed, McClamrock, & Glaser, 2015). However, individual elements have different handling and storage requirements, and safe operation of the facility would require meeting all of these individual requirements. LFNR plants would likely employ as many chemists and machinists as they would nuclear engineers.

Understanding the full impact of any reactor is incredibly complex. One must consider not only the characteristics of the mass upon removal from the reactor, but a series of decay reactions that will continue to alter the overall waste mass for millennia.

To attempt to create equitable points of comparison, the following model has been created to facilitate examination.

5) Model

To create models that can be compared easily, nearly every isotope present within the waste mass must be examined both individually and as a collective mass. While some fission products are incredible stable, others are violently reactive, explosive, radioactive, highly toxic, and/or pyrophoric. Many are stable under most conditions, but the extreme temperatures utilized by a reactor can allow for seemingly unpredictable behaviors. The following model attempts to combine any and all characteristics that may affect the final waste mass whenever possible. The final analysis, following this section, was generated from the collective data to help the reader understand the incredibly complicated interactions occurring and the complex chemistry of the final waste. Individual variables and rationale are described as necessary.

5.1) Chosen Variables

Element and Isotopic Information collected from CRC Handbook of Chemistry and Physics, 96th Edition (Haynes, 2015). Includes:

- **Atomic Number** – The number of protons within the atomic nuclei of any element.
- **Element Symbol** – As accepted by International Union of Pure and Applied Chemistry [IUPAC]
- **Common Name** – As accepted by IUPAC.
- **Isotope** – Number of protons and neutrons within the atomic nuclei of any element. Most elements have multiple isotopes.
- **Physical State (Gas or Liquid)** – For pure elemental state only.
- **Demand** was determined by a thorough search of peer reviewed papers to identify potentially valuable products. Rated as: No, Sometimes, Yes. All isotopes identified as “Sometimes” or “Yes” will be cited as needed.

Individual isotopic traits were collected from multiple sources. Unless otherwise marked, the information was collected from the CRC Handbook of Chemistry and Physics (Haynes, 2015).

Ratings for the following statistics are: No (no risk) | Sometimes (conditional risk) | Yes (high risk). Includes ratings for each isotope:

- **Reactivity** – How likely is the isotope to react violently with other elements?
- **Explosiveness** – Does the isotope present an explosion hazard under conditions that could exist in a LFNR operation?

- **Pyrophoricity** [Appendix 9.1] – How likely is the isotope to have a pyrophoric reaction?
- **Biological Danger** – Is the isotope toxic or does it represent a specific, non-radiation based hazard to living organisms?
- **Radioactivity** was determined based upon the half-lives of the individual isotope. When possible, radioactivity data was confirmed through peer-reviewed sources, and will be cited as such. All elements whose half-lives are below 345 billion years [3.45E+11] are marked as "radioactive". 345 billion years was chosen as it is 31 times the length of the known universe. 31 half-lives will result in the decay of 99.999999999% of the original mass, leaving less than one billionth of a percent of the original isotope. Any element with a half-life in excess of [3.45E+11] are marked as "observational stable", as little to no decay will occur during any time frame relevant to living organisms.
- **Fissile** and **Fissionable** were recorded as "yes" or "no". In most cases, this data was recorded from the CRC Handbook of Chemistry and Physics, 96th Edition (Haynes, 2015). In cases where the CRC handbook did not provide data, specific citations will be noted.

All isotopes are rated by **Proliferation Threat** based on whether or not the isotope can be used to make a nuclear weapon. In all cases, this was determined through peer reviewed sources, which will be noted when applicable.

All **Half Life**, **Daughter Elements**, and **Decay Modes** were recorded from the International Atomic Energy Agency [IAEA] Nuclear Data Services (IAEA). IAEA half-life data was chosen based on data consistency, frequency of citation in peer reviewed articles, and completeness of data set. Types of Decay are listed as:

α	**Alpha Decay**
β−	**Beta Decay**
CD	**Cluster Decay**
SF	**Spontaneous Fission**
β−β−	**Double Beta Decay**
IT	**Isomeric Transitions**
EC	**Electron Capture**

Likelihood of Creation (of daughter elements) is provided when possible, specific citations will be provided when necessary.

Time to 99.999999999% Decay was calculated by multiplying half-life by 31. “N/A” is used to signify stable elements.

Long term decay yields were calculated using the following values:

30 Days =	8.22E-2	90 Days =	2.47E-1
180 Days =	4.93E-1	1 Year =	1E+0
2 Years =	2E+0	3 Years =	3E+0
5 Years =	5E+0	10 Years =	1E+1
20 Years =	2E+1	30 Years =	3E+1
50 Years =	5E+1	100 Years =	1E+2
500 Years =	5E+2	1,000 Years =	1E+3
5,000 Years =	5E+3	10,000 Years =	1E+4

The fissile isotopes $^{233}\mathbf{U}$, $^{235}\mathbf{U}$, $^{239}\mathbf{Pu}$, and $^{241}\mathbf{Pu}$ were chosen for analysis. These isotopes were chosen based on their ability to sustain a viable chain reaction. Expected fission and transmutation products were grouped into 5 categories based on safe sequestration time periods, as determined by half-life.

The fission waste categories are:

- **Gaseous Products** – All isotopes that can be removed from fuel salts through passive outgassing.
- **Stable Solids** – All stable isotopes, where no radioactive sister isotopes are present (Elements where multiple isotopes can be present and are chemically identical).
- **90 Day Rest Period** – All isotopes that will fully decay ~31($t_{1/2}$) in less than 90 days after removal from the fuel mass.
- **100 Year Rest Period** – All isotopes that will require a 100-year sequestration period to fully decay ~31($t_{1/2}$)
- **Lifetime Entombment** – All isotopes that will require more than 100-year sequestration. 100 years was chosen as the cutoff for this category as the timeframe represents a length of time beyond any currently identified sequestration technology. As such, all products with exceptionally long half-lives and the transuranic isotopes will essentially require permanent entombment.
- **Fuel Mass Transmuted** – The expected percentage of transmutation during fission cycle. Fission/Absorption ratios were recorded from the IAEA Nuclear

Data Services and confirmed through peer reviewed articles (Lammer & Nichols, 2008).

For purposes of clarity within this document, “**Transmuted**” will be used to define “nuclear transmutation through neutron absorption”.

Isotopes created specifically after undergoing fission will be defined as “**Fission Products**”.

Isotopes created through nuclear decay will be defined as “**Decay Products**”.

5.2) Assumptions Made

The following assumptions underlie the model presented for this thesis:

In any case where an element exists within expected fission yields where an isotope of that element is radioactive, all sister isotopes are grouped under the classification of the most dangerous isotope within the set. Because isotopes of the same element possess nearly identical chemical, electrical, and physical properties, any attempted isotopic separation would be expensive, inefficient, and likely would not result in total removal of the dangerous isotopes. In these cases, explanation of potential separation procedures will be given only if any isotope is classified as “in demand”. Generally, this would be due to an isotope being used in research, spaceflight, or medical applications. Otherwise, the assumption that the element will require sequestration until full decay ~31($t_{1/2}$) has occurred.

In cases where an isotopes full decay period exceeds 345 billion years, the isotope is considered “observationally stable”. Though a nearly immeasurable amount of decay will occur during the life of the isotope, the volume would be so minimal as to represent no risk, other than those posed by the chemical traits of the isotope.

In cases where a decay chain may result in an isotope that may transition between solid and gaseous state, or vice-versa, specific gas storage criteria and sequestration durations will be provided.

The generally accepted standard “safe decay time” within the nuclear research community is 25($t_{1/2}$), which will result in the decay of all but one hundred-millionth of a percent of the initial isotope. For this analysis, 31($t_{1/2}$) was chosen, since this represents decay down to one billionth of a percent. Because many of the shorter lived fission products that require under ninety days to decay to a stable isotope, it seems reasonable to simply increase holding time by several weeks to ensure a far more complete decay. In addition, since many of the fission products may have commercial value, there is no reason to risk accidental introduction of potentially damaging radiation into the final saleable product. For all analysis in this thesis, the assumed “safe” decay state of all elements will be $31(t_{1/2})$.

Finally, in all cases for which conflicting data was found during the review of peer reviewed work, the “most dangerous” assumption was always assumed to be true, unless the stated fact is called into question by any subsequent work. This will provide the “worst case scenario” calculation in all cases. While in some cases literature has reported conflicting data, because of the extreme hazard to living organisms presented by radioactive waste, this thesis will always lean towards the “Safest” possible recommendation. In all cases where the possibility of a hazardous event occurring (reaction, explosion, fire hazard, toxicity, and criticality risk [See Appendix 9.1]) exceeds 0.00001%, the risk is considered “yes”. The exception to this assumption occurs when any isotope was identified to possess a given trait only when in a physical state that would not be seen in a LFNR system or subsequent sequestration / use. In such cases, the trait will be marked “no”.

5.3) Other Considerations

This analysis conducted for this thesis does not examine transuranic isotopes heavier than ^{241}Pu. The potential creation of these elements is acknowledged as “transmuted isotopes”. This decision was made based on three facts:

First, because the liquid nature of the fuel salt allows for continuous removal of individual isotopes through electro chemical precipitation, it is very likely that reactors will be designed to extract nearly all ^{238}Pu produced through transmutation. ^{238}Pu is absolutely critical in radioisotopic generators, currently the only viable method of producing power beyond the orbit of Mars, to any human exploration beyond the orbit of Mars [where solar panels can no longer produce enough power] (Hamley, 2016). This trait alone makes ^{238}Pu the most valuable isotope on planet Earth, with an estimated value of $8 million per kilogram (Harvey, 2015). Therefore, very little if any of the fuel mass would likely be allowed to reach a heavier isotopic weight than ^{238}Pu.

Second, several transuranic isotopes created through transmutation are critical for modern devices. For example, all modern ionizing-type smoke detectors and in advanced nuclear batteries incorporate americium-241 [^{241}Am] in very small amounts (Navratil, Schulz, & Seaborg, 1990). Californium-252 [^{252}Cf] is used as a neutron source for initiating nuclear reactors as well as for neutron radiography, which is used to verify the strength of welds and check corrosion levels of metal surfaces (Martin, Knauer, & Balo, 2000). These applications ensure that with proper design, the few transuranic isotopes that would be created would be removed from the fissile mass and used almost immediately.

Third, LFNR style reactors allow for a near total burnup of all transuranic isotopes (which are always fissile/fissionable) (Zhao, Yang, Xiao, & Zhou, 2013). Since overall production of these isotopes would be very low in LFNR systems, any unusable transuranic isotopes created through transmutation could be reinjected into the fissile core for subsequent burnup.

5.4) Considerations

Determining the final compound in which the various isotopes will be extracted and chemically stabilized for use or sequestration is critical. Many of the isotopes created can exist in many compounds, and in the form of gases, liquids, and solids. These final compounds depend on the specific chemistry of each series of reactions, and could vary considerably between individual reactor facilities. This is due to the wide variety of precipitation, catalytic, reduction, and oxidation reactions that could be used to extract individual elements or isotopes. Different facilities may choose differing extraction agents, and as such could alter the final form from perhaps an oxide to a fluoride. Both are chemically stable, but occur due to different electro-chemical processes being utilized by the individual facility.

That said, in most cases the chosen reactions would likely be based primarily on the market cost of the reagents and as such a “most likely choice” can often be assumed. Most isotopes will require some stabilizing prior to market usage, sequestration, or lifetime entombment (Nagasaki & Nakayama, 2015). Depending on the isotope, the actual compound chosen may vary, but it will ideally be a stable compound which is highly resistant to corrosion (Nagasaki & Nakayama, 2015). Some fission products, such as oxygen [O], fluorine [F], carbon [C], iodine [I], and sodium [Na] are highly reactive, and will form compounds very quickly after creation (Kleykamp, 1988). For example, it is unlikely that any fluorine gas created, in the reactor or through nuclear decay, would ever be found as free fluorine (Gouverneur & Seppelt, 2015). When possible, any assumptions as to the “likely” process or outcome will be provided, along with necessary supporting data. It should be noted that this aspect of the analysis is by no means 100% accurate, and has been provided only to create a frame of reference.

For any isotopes in which the ~31($t_{1/2}$) is equal to or below one hour [1.14E-04], the isotope will be treated as "non-existent" in this analysis. These isotopes would never be seen outside of the fuel salt, as they would completely decay before any physical samples could be collected and processed. In these cases, the longer lived daughter products will be acknowledged. Effort has been made to recognize very short-lived, and therefore highly radioactive, products that will be created during sequestration. For many of these very-short lived isotopes, no amount sufficient for analysis has likely ever been created in any usable capacity, and, as such, some gaps in the scientific body of knowledge can exist.

Any fission products created through spontaneous fission are identified by "Various". These fission products can be comprised of any binary or ternary set of isotopes and will follow the same distribution normally exhibited from fission. Spontaneous fission has been effectively ignored for this analysis, as all isotopes capable of spontaneous fission would be returned to the fissile core for burnup.

The "estimated 100% burnup" of 909 $Mw_{d/t}$ was determined by averaging the energy densities of ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu. Actual energy density of individual fuel masses would fluctuate somewhat depending on specific fuel composition and fissile isotopes chosen.

What follows is a summary of the collective data assembled for the above computer model. The Findings section will first explain the primary categories under which all fission products are grouped for this thesis. Next, each fissile fuel type will be examined individually, to provide the necessary framework for understanding the final section. Third, each complete fuel cycle will be examined in full (accounting for all transmutation chains). Finally, a comparison waste analysis of LFNR, SFNR, and traditional coal will show directly how LFNR compares to existing dominant energy technologies.

6) Findings

After completing the data collection phase, the computer model showed that all fission products could be grouped into six categories. These categories were chosen based on isotopic composition, chemical characteristics, and account for all decay chains that will occur within the waste. Therefore, all products within each category will not be subject to potentially dangerous interactions with other products within the category.

After all fission and decay products were categorized, the following categories were chosen for extended explanation based on relevance:

NOTE: Specific isotopic composition will be given in the following section.

Gaseous Products – This category includes all gaseous products created through the fission process. Gaseous fission products will exit the fuel mass naturally through natural off-gassing, and can be collected immediately for a cool-down storage period. The exact mechanism for the removal of gaseous products could vary based on individual Liquid-Fueled Nuclear Reactor [LFNR] design, however it would operate in a similar fashion to existing Solid-Fueled Nuclear Reactor [SFNR] gas removal systems. This cool down period also allows for the very small volume of radioactive decay products created to be safely removed.

While the gaseous fission products are generally stable, a portion of the mass will be ^{135}Xe, which will undergo 31($t_{1/2}$) to ^{135}Cs in approximately 12 days (Allan & Nuttall, 1997). Caesium is highly toxic, pyrophoric, reactive, and radioactive, and as such must be added to in the lifetime entombment mass. Following a 30-day resting period, the remaining mass of Xe and Kr can be sold for industrial manufacturing, as both are in high demand (Herman & Unfried, 2015).

Stable Solids – This category includes all solid-isotopes that:

1. Are not, and will not ever decay into, a gaseous product,
2. Are chemically different from all isotopes present in the fuel/waste mass that are radioactive, or
3. Are not in any way radioactive, and will not require any sequestration period to become stable.

Companies involved in advanced electronics manufacturing and other specialized industries have created a high demand for all stable isotopes created through fission. Though often very little of an individual isotope is created through fission, to eliminate waste these isotopes should be removed in their elemental form or converted to a stable oxide for subsequent distribution.

All isotopes in the stable solids category are chemically distinct from any radioactive isotopes within the waste mass, and as such can be removed through specific series of electrochemical reactions, eliminating the need for excessive reprocessing or cleaning. Most of the stable solids are mildly toxic, but no serious storage hazards exist. It should be noted that ^{113}Cd and ^{115}In are technically radioactive, but are considered observational stable because their half-lives exceed the age of the known universe. As such, the decay that will occur is so slowly it will have no bearing on any foreseeable human civilization.

90 Day Rest Period – This category accounts for ~15% of the total waste mass from the fission process. These isotopes are highly radioactive, with relatively short half-lives, and, as such, require very careful handling and storage. This category includes all solid-isotopes that

1. Are radioactive,
2. Are solid,
3. Will undergo $31(t_{1/2})$ in less than 90 days, from the point of removal from the fuel mass, and/or
4. Are chemically identical to any isotope that meets conditions a, b, and/or c.

While not all of the rhodium [Rh] and iodine [I] isotopes produced are radioactive, the majority [~90%] are highly radioactive. The short half-lived ^{105}Rh (Pierson, 1965), ^{127}Te (Day, Eakins, & Voigt, 1955), and ^{135}I give off significant quantities of Beta particles and associated energies during decay.

The most dangerous isotope in this category, by far, is ^{135}I. ^{135}I is very prone to biological uptake, where it takes residence within the bones and cartilage of the organism (Bustad, 2013). The subsequent beta decay will cause tremendous damage to surrounding living tissues. ^{135}I is one of the isotopes of most concern in the case of an accidental discharge of high-level waste into the environment. In addition, ^{135}I will decay into ^{135}Xe [a gas], which will further decay to ^{135}Cs, a very long-lived radioactive solid. This phase transition from solid → gas → solid makes ^{135}I particularly difficult to store safely. With approximately 80% of this mass undergoing the decay-phase transition process [Solid → Gas → Solid], sequestration of the waste mass requires very specific engineering. The solid mass must rest for at least nine days in a liquid suspension to allow the ^{135}I to decay to ^{135}Xe. Upon its creation, the ^{135}Xe will be removed through natural off-gassing and collected. The ^{135}Xe must rest an additional 12 days to undergo $31a(t_{1/2})$ to decay to ^{135}Cs. The ^{135}Cs must then be added to the lifetime entombment waste mass, and the remaining products can be sold for manufacturing.

After a decay period of 90 days, the remaining mass from this category will be comprised of stable palladium-105 [^{105}Pd] and ^{127}I a. Both of these isotopes are currently in demand in the global marketplace and represent no significant hazards to humans.

100 Year Rest Period – This category was selected based on the volume of material that degrades within the timeframe and the general half-lives of the isotopes within the mass. Though some isotopes decay much sooner, the actual portion of those isotopes to the total mass is very low. The average safe-decay time of this mass is ~72 years. While not as radioactive as isotopes in the "90 days" category, these isotopes are still very dangerous to living organisms. This category includes all solid-isotopes that

1. Are radioactive,
2. Are solid,
3. Will undergo 31 half-lives in between 90 days and 100 years,
4. Are chemically identical to any isotope that meets conditions a, b, and/or c.

All isotopes of promethium [Pm] are highly unstable, and will undergo 31($t_{1/2}$) within 81.5 years.

In fact, all Pm will decay in less than 5 years, with the exception of ^{147}Pm. However, because the isotopes are chemically identical, effective separation of these isotopes can be done only after they have undergone decay. All Pm will decay to Samarium [Sm], and some of that will eventually decay to Neodymium [Nd]. Because Pm, Sm, and Nd are very chemically similar, early elemental separation of the isotopes in this mass is unfeasible. All Sm isotopes can be considered effectively stable, owing to their extremely long half-lives. Both Sm and Nd are in high demand for industrial manufacturing.

The antimony-125 [^{125}Sb] present within the waste mass has a similar decay period to ^{147}Pm, requiring just shy of 85 years to undergo ~31($t_{1/2}$). ^{125}Sb will decay to the metastable element tellurium-125m [^{125m}Te). All ^{125m}Te will undergo isomeric transition within three years, decaying to stable ^{125}Te. Te is in strong demand for a variety of industrial manufacturing processes, ranging from advanced electronic components to vulcanization of rubber for tires (Royal Society of Chemistry, Unknown).

Stable ruthenium-101 [^{101}Ru] comprises nearly two thirds of the Ru mass. The remainder is highly radioactive ^{103}Ru and ^{106}Ru, which require 32 years to undergo ~31($t_{1/2}$). ^{103}Ru will decay to stable rhodium-105 [^{105}Rh], a highly sought after element used in anti-corrosion metal coatings (Royal Society of Chemistry, Unknown). ^{106}Ru will decay to the unstable ^{106}Rh, which will rapidly decay to stable palladium-106 [^{106}Pd].

A 100 year resting period is assumed to ensure that absolutely no radioactive isotopes or dangerous decay products are released. After safe decay, this entire mass is safe for use in industrial manufacturing.

No gaseous products are produced through decay of this portion of the waste mass.

Lifetime Entombment – This category was selected based on the general half-lives of the isotopes within the mass. For all intents and purposes, isotopes in this category will require storage for a timespan longer than the entirety of human existence to date. As such, it has been assumed that waste requiring more than 100 years will effectively require indefinite entombment. Many other nuclear waste analyses, including those used to define current “safe storage standards” for high-level waste, will often divide waste into categories of 500, 1000, 2500, 5000, and 10000 years as well. Given the extreme risk presented by the waste, and the extreme instability of human society in general, this thesis assumes the safest option in these cases will be permanent entombment for all products requiring longer than 100 years to safely decay. This category includes all solid-isotopes that:

1. Are radioactive,
2. Are solid,
3. Will not undergo 31 half-lives in under 100 years,
4. Are chemically identical to any isotope that meets conditions a, b, and/or c.

While caesium-133 [^{133}Cs] is stable, all other isotopes of Cs are not (D'auria, et al., 1978). The very small portion of ^{234}Cs will decay into stable gaseous ^{234}Xenon, which can be vented safely and presents no risks (Alexander, Bennett, Srinivasan, & Manuel, 1968). The remaining mass will eventually decay to stable isotopes of bismuth [Bi], but this will require 935 years. In addition, radioactive caesium will emit gamma rays during decay, requiring strong radiation shielding to prevent risk to living organisms (Ghys, 1960). The ability to emit gamma rays also creates some demand for radioactive caesium for use in irradiating food, as a gamma source neutron spectroscopy, and as a gamma source for some forms of cancer treatment (Bick & Prinz, 2000). Caesium is also highly reactive, pyrophoric, and very toxic to living organisms and must be stored with care.

The technetium -99 [^{99}Tc] within the waste mass is one of the most difficult fission products to deal with (Ojovan & Lee, 2013). Technetium can form anionic compounds easily, making it highly mobile when released into the environment (Dickson, Harsh, Lukens, & Pierce, 2015). Anions are all considered bases as they can accept a H+, making them very reactive and likely to form compounds in aqueous solutions (Sheppard & Thibault, 1990). Most isotopic separation processes utilize the fact that cations are easier to remove through electrochemical processes. Often anionic pertechnetate, the form in which Tc exists during extraction, will be totally unaffected by electrochemical processes (Dickson, Harsh, Lukens, & Pierce, 2015). Tc therefore represents a significant challenge for high-level waste sequestration. The extremely long half-life, penchant for releasing X-rays when decaying, and extreme mobility in the environment, make Tc the prime source for most radiative release from the waste mass after 1000 years (Cohen, 1977).

^{99}Tc is a viable candidate for disposal through transmutation (Tommasi, Delpech, Grouiller, & Zaetta, 1995). By exposing ^{99}Tc to high energy neutrons, such as those produced from a nuclear chain reaction, highly unstable ^{100}Tc can be created through transmutation of ^{99}Tc. ^{100}Tc, with a 31($t_{1/2}$) of 8.27 minutes, will rapidly decay to stable ruthenium-100 [^{100}Ru]. This method of disposal is generally inefficient, given the energy required to generate free neutrons and because the ^{99}Tc must first be extracted from high-level waste, a process currently illegal in many countries (Tommasi, Delpech, Grouiller, & Zaetta, 1995). On the other hand, the use of transmutation for ^{99}Tc disposal would reduce the volume of waste requiring lifetime entombment by 26.5%.

All samarium [Sm] isotopes within the waste mass must be permanently entombed, although only ^{151}Sm is radioactive. Because all Sm isotopes possess identical chemical traits, efficient removal of all ^{151}Sm cannot be ensured. All ^{151}Sm will undergo 31($t_{1/2}$) within 2750 years, decaying to europium-151 [^{151}Eu]. ^{151}Eu, while technically radioactive, can be considered "effectively stable", owing to its half-life exceeding the age of the known universe. ^{151}Eu created by decay cannot be effectively removed, owing to the presence of other radioactive isotopes of Eu within the waste mass.

Like samarium [Sm], all palladium [Pd] isotopes in the waste mass must be permanently entombed due to the presence of ^{107}Pd. ^{107}Pd will undergo 31($t_{1/2}$) in approximately 2 billion years, decaying to stable Silver-107 [^{107}Ag].

Isotopes of europium [Eu] possess the widest variety of half-lives among all fission products. The most radioactive isotope, ^{155}Eu will undergo 31($t_{1/2}$) in 148 years, decaying to stable gadolinium-155 [^{155}Gd]. ^{154}Eu will undergo 31($t_{1/2}$) in 267 years, decaying through beta decay primarily to stable ^{154}Gd. A minute portion [0.02%] will undergo electron capture and decay to stable samarium-154 [^{154}Sm]. ^{153}Eu is stable. ^{152}Eu will undergo 31($t_{1/2}$) in 420 years, decaying to stable ^{152}Sm [72.36%] or “effectively stable” ^{152}Gd [27.64%] through electron capture and beta decay. ^{151}Eu, the longest lived unstable isotope of Eu, can be considered effectively stable with a 31($t_{1/2}$) of 143 quintillion years.

Table 1 - Fuel Isotope Fission / Absorption Ratios

Fuel	Thermal Cross-Section (in Barns)	Likelihood of Fission	
		Fission	Absorption
^{233}U	587 ± 3 *	~ 66.14%	~ 33.86%
^{235}U	693 ± 5 *	~ 72.76%	~ 27.24%
^{239}Pu	1007 ± 8 ‡	~ 93.62%	~ 6.38%
^{241}Pu	1373 ± 11 Θ	~ 98.88%	~ 1.12%

* = (Block, Harvey, & Slaughter, 1960)
‡ = (Safford & Havens, 1961)
Θ = (IAEA, n.d.)

Transmuted Mass – This category covers the portion of the fissile mass that will be transmuted [Appendix 9.1] into heavier elements or isotopes. LFNR’s would allow for all heavier isotopes to be reinserted into the fissile core for further transmutation or burnup. All transmuted isotopes heavier than thorium-232 [^{232}Th], that are not in demand for a specific purpose [such as americium and californium], would be returned to the inner core for eventual burnup.

The likelihood of a fission event occurring upon a neutron collision, as opposed to a neutron absorption resulting in transmutation, increases with isotopic weight [Table 1].

Note that the general availability and volume of pre-fission waste increases exponentially with isotopic weight. Thorianite, the most efficient source of ^{232}Th, the precursor to ^{233}U, yields an average of 12% Th by weight, resulting in ~8.3 tons of pre-fission waste per ton of usable Th (Dunstan & Blake, 1905). The highest uranium bearing ore on Earth, from the Cigar Lake deposit in the Athabasca Basin of Canada, yields 18% raw uranium (Fayek, Janeczek, & Ewing, 1997). ^{235}U only represents 0.72% of the natural uranium, with the remainder comprised of undesirable ^{238}U. To extract a ton of ^{235}U will result in ~1,389 tons of pre-fission waste per ton.

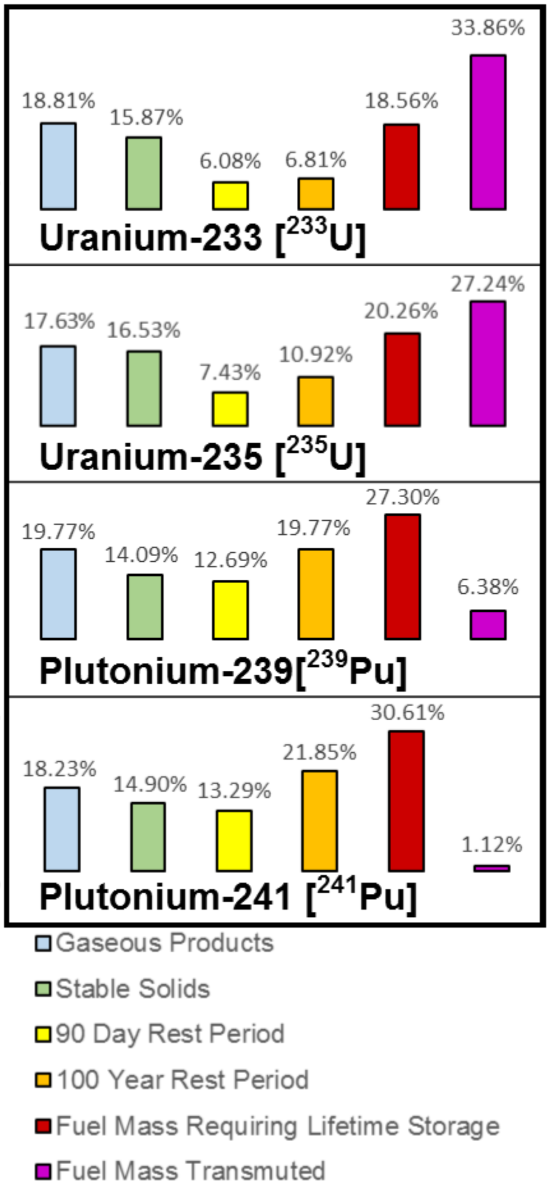

Figure 3 - Simplified Fission Waste Breakdown Comparison

Plutonium-239 [239Pu] is much rarer than uranium in nature, as ^{239}Pu will only exist in miniscule trace amounts naturally on Earth. The process of creating Pu is highly inefficient. Consider that to create Pu, ^{238}U must undergo transmutation by being irradiated with high-energy neutrons. Due to the sheer amount of energy required, this usually occurs inside a nuclear reactor. From most reactor grade fuels containing around 20% ^{235}U, an average yield of around one gram ^{239}Pu will be produced for every 1 Megawatt day of power generated (Edlund, 1975). To produce one ton of ^{239}Pu would requires nearly 1 Terawatt days of power, requiring the fission of ~24.5 tons of fuel. In all, one ton of Pu would produce ~34,000 tons of mining/processing waste, to speak nothing of the highly irradiated fission waste generated in the process.

As a transmutation product of ^{239}Pu, ^{241}Pu is even more rare. With an average absorption rate of only ~6.38%, one ton of ^{241}Pu would produce over 530,000 tons of mining/processing waste and over 15 times the volume of highly irradiated fission waste generated by ^{239}Pu.

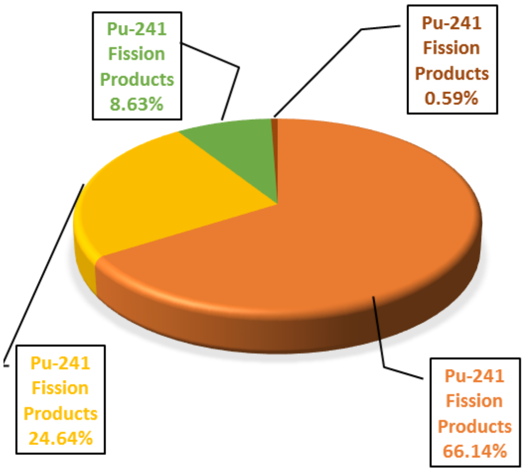

Figure 4 - Uranium-233 [^{233}U] Complete Fission Cycle

Figure 3 shows the general disposition of high-level waste generated within the reactor. It should be noted that Figure 3 shows the general types of waste generated for the fission of each specific fissile isotope. To correctly calculate the composition of a given fuel mass, the fission products of all portions of the fission process must be combined. For example, [Figure 4], ^{233}U fission products account for 66.14% of the total waste mass, 72.76% of the remaining 33.86% [after ^{233}U cycle] of transmuted mass will undergo fission as ^{235}U, 93.62% of that transmuted mass will undergo fission as ^{239}Pu, and so on. It therefore stands to reason that in an “ideal world”, nuclear fission should be conducted with the lightest fissile isotope possible to avoid excessive production of transuranic isotopes. With heavier isotopes, such as ^{241}Pu, yields of transuranic and radioactive isotopes in the final waste mass will be significantly higher.

Since the transuranic waste isotopes are all highly radioactive, frequently pyrophoric, toxic, and will eventually lead to the creation of new highly-radioactive decay products, minimizing production of transuranic isotopes is critical to ensure the long-term environmental safety of a reactor design.

Based on the categories defined above, the following analysis will examine the specific chemistry of each fissile isotope.

6.1) Uranium-233 [^{233}U] Waste Analysis

Of the four viable fissile fuel types shown in Figure 3 above, the ^{233}U fission cycle produces the lowest volume of long-lived radioactive waste. Note that this section only refers to fission products produced directly by ^{233}U fission, and does not include fission products created through subsequent fission of transmuted isotopes. Refer to section 6.5 for complete Liquid-Fueled Nuclear Reactor [LFNR] fuel cycle analysis.

6.1.a) Gaseous

Table 2 - Uranium-233 [^{233}U] Gaseous Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
36	**Kr**	Krypton	83	5.39
54	**Xe**	Xenon	131	19.16
			134	33.49%
			135	6.52%
			136	35.44%

The gaseous products created through the ^{233}U fission cycle represent a total of 18.81% of the waste mass. The waste mass can be reduced immediately by the natural off-gassing of Kr and Xe.

6.1.b) Stable Solids

Table 3 - Uranium-233 [^{233}U] Stable Solid Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
42	**Mo**	Molybdenum	95	40.11%
47	**Ag**	Silver	109	0.25%
48	**Cd**	Cadmium	113	0.08%
49	**In**	Indium	115	0.09%
60	**Nd**	Neodymium	143	37.61%
			145	21.72%
64	**Gd**	Gadolinium	154	>0.00%
			155	>0.00%
			156	0.08%
			157	0.04%
			158	0.01%
66	**Dy**	Dysprosium	160	>0.00%
			161	>0.00%
			162	>0.00%
			163	>0.00%
			164	>0.00%
67	**Ho**	Holmium	165	>0.00%
68	**Er**	Erbium	166	>0.00%
			167	>0.00%

The stable solid fission products created through the ^{233}U fission cycle represent a total of 15.87% of the waste mass. The primary isotopes within the stable solid mass are ^{95}Mo, ^{143}Nd, and ^{145}Nd, comprising 99.4% of the total.

The remaining 0.6% of the stable solids is a mixture of Ag, Cd, In, Gd, Dy, Ho, and Er.

6.1.c) 90 Day Resting Period

Table 4 - Uranium-233 [^{233}U] 90 Day Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
45	Rh	Rhodium	103	>0.00%
			105	8.19%
52	Te	Tellurium	127	1.60%
53	I	Iodine	127	7.54%
			135	82.67%

The fission products created through the ^{233}U fission cycle which will undergo 31($t_{1/2}$) in under 90 days represent a total of 6.08% of the waste mass. The primary isotopes within this mass are ^{105}Rh, ^{127}I, and ^{135}I, comprising 98.4% of the total.

6.1.d) 100 Year Resting Period

Table 5 - Uranium-233 [^{233}U] 100 Year Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
44	**Ru**	Ruthenium	101	46.60%
			103	23.11%
			106	3.62%
51	**Sb**	Antimony	125	1.72%
61	**Pm**	Promethium	147	13.53%
			148	>0.00%
			148m	>0.00%
			149	11.43%

The fission products created through the ^{233}U fission cycle which will undergo 31($t_{1/2}$), between 90 days and 100 years represent a total of 6.81% of the waste mass. The primary isotopes within this mass are those of Ru and Pm, comprising 98.3% of the total.

6.1.e) Lifetime Entombment

Table 6 - Uranium-233 [^{233}U] Lifetime Entombment Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
43	**Tc**	Technetium	99	26.53%
46	**Pd**	Palladium	105	>0.00%
			107	0.62%
			108	0.41%
55	**Cs**	Caesium	133	32.06%
			134	>0.00%
			135	0.03%
			137	36.83%
62	**Sm**	Samarium	147	>0.00%
			148	>0.00%
			149	>0.00%
			150	>0.00%
			151	1.70%
			152	1.15%
63	**Eu**	Europium	151	>0.00%
			152	>0.00%
			153	0.56%
			154	>0.00%
			155	0.12%

The fission products created through the ^{233}U fission cycle which will not undergo 31($t_{1/2}$) in less than 100 years represent a total of 18.56% of the waste mass. The primary isotopes within this mass are those of ^{99}Tc, ^{133}Cs, and ^{137}Cs, comprising 95.4% of the total.

6.2) Uranium-235 [^{235}U] Waste Analysis

Of the four viable fissile fuel types, the ^{235}U is the only isotope that exists in natural ore on Earth. ^{235}U exists as approximately 0.7% of natural ore, and is rarely enriched beyond 20% for energy production. Under normal circumstances, this results in significant transuranic isotope production through transmutation of fertile ^{238}U in the fuel. Isotopes created through transmutation of non-fissile isotopes are not included in this analysis. Also note that this section only refers to fission products produced by ^{235}U fission, and does not include fission products created through subsequent fission of transmuted isotopes. Refer to section 6.5 for complete LFNR fuel cycle analysis.

6.2.a) Gaseous

Table 7 - Uranium-235 [^{235}U] Gaseous Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
36	**Kr**	Krypton	83	3.04%
54	**Xe**	Xenon	131	16.44%
			134	44.51%
			135	1.46%
			136	34.56%

The gaseous products created through the ^{235}U fission cycle represent a total of 17.63% of the waste mass. Collecting the naturally off-gassed Kr and Xe would reduce the waste mass by 1/5th.

6.2.b) Stable Solids

Table 8 - Uranium-235 [^{235}U] Stable Solid Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
42	**Mo**	Molybdenum	95	39.57%
47	**Ag**	Silver	109	0.19%
48	**Cd**	Cadmium	113	0.09%
49	**In**	Indium	115	0.07%
60	**Nd**	Neodymium	143	36.08%
			145	23.84%
64	**Gd**	Gadolinium	154	>0.00%
			155	>0.00%
			156	0.09%
			157	0.04%
			158	0.02%
66	**Dy**	Dysprosium	160	>0.00%
			161	>0.00%
			162	>0.00%
			163	>0.00%
			164	>0.00%
67	**Ho**	Holmium	165	>0.00%
68	**Er**	Erbium	166	>0.00%
			167	>0.00%

The stable solid fission products created through the ^{235}U fission cycle represent a total of 16.53% of the waste mass. The primary isotopes within the stable solid mass are ^{95}Mo, ^{143}Nd, and ^{145}Nd, comprising 99.49% of the total.

The remaining 0.51% of the stable solids are a mixture of Ag, Cd, In, Gd, Dy, Ho, and Er.

6.2.c) 90 Day Resting Period

Table 9 - Uranium-235 [^{235}U] 90 Day Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
45	**Rh**	Rhodium	103	>0.00%
			105	13.14%
52	**Te**	Tellurium	127	0.38%
53	**I**	Iodine	127	1.78%
			135	84.70%

The fission products created through the ^{235}U fission cycle which will undergo 31($t_{1/2}$) in under 90 days represent a total of 7.43% of the waste mass. The primary isotopes within this mass are ^{105}Rh, ^{127}I, and ^{135}I, comprising 99.62% of the total.

6.2.d) 100 Year Resting Period

Table 10 - Uranium-235 [^{235}U] 100 Year Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
44	**Ru**	Ruthenium	101	47.37%
			103	27.80%
			106	3.70%
51	**Sb**	Antimony	125	0.32%
61	**Pm**	Promethium	147	10.90%
			148	>0.00%
			148m	>0.00%
			149	9.91%

The fission products created through the ^{235}U fission cycle which will undergo 31($t_{1/2}$), between 90 days and 100 years represent a total of 10.92% of the waste mass. The primary isotopes within this mass are those of Ru and Pm, comprising 98.3% of the total.

6.2.e) Lifetime Entombment

Table 11 - Uranium-235 [^{235}U] Lifetime Entombment Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
43	**Tc**	Technetium	99	30.31%
46	**Pd**	Palladium	105	>0.00%
			107	0.74%
			108	0.27%
55	**Cs**	Caesium	133	33.05%
			134	>0.00%
			135	>0.00%
			137	31.30%
62	**Sm**	Samarium	147	>0.00%
			148	>0.00%
			149	>0.00%
			150	>0.00%
			151	2.07%
			152	1.32%
63	**Eu**	Europium	151	>0.00%
			152	>0.00%
			153	0.78%
			154	>0.00%
			155	0.16%

The fission products created through the ^{235}U fission cycle which will not undergo $31(t_{1/2})$ in less than 100 years represent a total of 20.26% of the waste mass. The primary isotopes within this mass are those of ^{99}Tc, ^{133}Cs, and ^{137}Cs, comprising 94.66% of the total.

6.3) Plutonium-239 [^{239}Pu] Waste Analysis

^{239}Pu is the lightest transuranic isotope capable of maintaining a fission chain reaction. Since ^{239}Pu is used in high-yield nuclear weapons production, ^{239}Pu has become one of the most highly regulated isotopes on the planet. Global stockpiles of weapons-grade Pu in 2014 were 505±10 tons in 2014 (Glaser & Mian, 2015). These existing ^{239}Pu stockpiles could be utilized in LFNR facilities for energy production, an idea that has been proposed to support global nuclear weapons anti-proliferation (Gat & Engel, 2000). Creation of ^{239}Pu through transmutation of ^{238}U requires vast amounts of energy and produces enormous volumes of high-level waste. From an environmental perspective, Pu is a poor choice for energy production, simple due to the sheer amount of energy that must be consumed simply to create the isotope. Though Pu does in fact release more energy upon undergoing fission, when factoring in the energy required just to make the isotope the resource cost becomes much larger.

Isotopes created through transmutation of non-fissile isotopes are not included in this analysis. It should be noted that this section only refers to fission products produced by ^{239}Pu fission, and does not include fission products created through subsequent fission of transmuted isotopes. Refer to section 6.5 for complete LFNR fuel cycle analysis.

6.3.a) Gaseous

Table 12 - Plutonium-239 [^{239}Pu] Gaseous Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
36	**Kr**	Krypton	83	1.50%
54	**Xe**	Xenon	131	19.51%
			134	38.74%
			135	5.45%
			136	34.80%

The gaseous products created through the ^{239}Pu fission cycle represent a total of 19.77% of the waste mass. This allows for a nearly immediate mass reduction of one-fifth by collection of naturally off-gassing Kr and Xe.

6.3.b) Stable Solids

Table 13 - Plutonium-239 [^{239}Pu] Stable Solid Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
42	**Mo**	Molybdenum	95	34.38%
47	**Ag**	Silver	109	10.41%
48	**Cd**	Cadmium	113	0.58%
49	**In**	Indium	115	0.29%
60	**Nd**	Neodymium	143	31.35%
			145	21.22%
64	**Gd**	Gadolinium	154	>0.00%
			155	>0.00%
			156	0.89%
			157	0.53%
			158	0.30%
66	**Dy**	Dysprosium	160	>0.00%
			161	0.04%
			162	0.02%
			163	0.01%
			164	>0.00%
67	**Ho**	Holmium	165	>0.00%
68	**Er**	Erbium	166	>0.00%
			167	>0.00%

The stable solid fission products created through the ^{239}Pu fission cycle represent a total of 14.09% of the waste mass. The primary isotopes within the stable solid mass are ^{95}Mo, ^{143}Nd, and ^{145}Nd, and ^{109}Ag comprising 97.36% of the total.

The remaining 2.64% of the stable solids are a mixture of Cd, In, Gd, Dy, Ho, and Er.

6.3.c) 90 Day Resting Period

Table 14 - Plutonium-239 [^{239}Pu] 90 Day Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
45	**Rh**	Rhodium	103	>0.00%
			105	44.51%
52	**Te**	Tellurium	127	0.70%
53	**I**	Iodine	127	3.29%
			135	51.50%

The fission products created through the ^{239}Pu fission cycle which will undergo 31($t_{1/2}$) in under 90 days represent a total of 12.69% of the waste mass. The primary isotopes within this mass are ^{105}Rh, ^{127}I, and ^{135}I, comprising 99.3% of the total.

It should be noted that, when compared to fission of U isotopes, ^{239}Pu will produce much more ^{105}Rh and less ^{135}I. As iodine is more prone to biological uptake than ^{150}Rh, this does slightly reduce the risk to living organisms posed from this mass.

6.3.d) 100 Year Resting Period

Table 15 - Plutonium-239 [^{239}Pu] 100 Year Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
44	**Ru**	Ruthenium	101	30.53%
			103	35.36%
			106	22.01%
51	**Sb**	Antimony	125	0.57%
61	**Pm**	Promethium	147	5.37%
			148	>0.00%
			148m	>0.00%
			149	6.16%

The fission products created through the ^{239}Pu fission cycle which will undergo 31($t_{1/2}$), between 90 days and 100 years represent a total of 19.77% of the waste mass. The primary isotopes within this mass are those of Ru, comprising 87.9% of the total.

Note that when compared to fission of U isotopes, ^{239}Pu will produce much more ^{106}Ru.

6.3.e) Lifetime Entombment

Table 16 - Plutonium-239 [^{239}Pu] Lifetime Entombment Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
43	**Tc**	Technetium	99	22.83%
46	**Pd**	Palladium	105	>0.00%
			107	12.19%
			108	7.91%
55	**Cs**	Caesium	133	25.69%
			134	>0.00%
			135	0.05%
			137	24.57%
62	**Sm**	Samarium	147	>0.00%
			148	>0.00%
			149	>0.00%
			150	>0.00%
			151	2.71%
			152	2.12%
63	**Eu**	Europium	151	>0.00%
			152	>0.00%
			153	1.33%
			154	>0.00%
			155	0.61%

Fission products created through the ^{239}Pu fission cycle which will not undergo 31($t_{1/2}$) in less than 100 years represent a total of 27.30% of the waste mass. The primary isotopes within this mass are those of ^{99}Tc, ^{107}Pd, ^{108}Pd, ^{133}Cs, and ^{137}Cs, comprising 93.19% of the total.

6.4) Plutonium-241 [241Pu] Waste Analysis

^{241}Pu is the second-lightest transuranic isotope capable of maintaining a fission chain reaction. Creation of ^{241}Pu through transmutation of ^{238}U is incredibly energy intensive and produces enormous volumes of high-level waste, far more-so than ^{239}Pu, and is rarely a “desired” product within the reactor. Significant global stockpiles of ^{241}Pu exist, the remnants of decades of weapons grade ^{239}Pu production. Most attempts to estimate total global volumes have failed due to the long-time secrecy and often poor record keeping throughout the Cold War. Due to ^{241}Pu’s 14.29-year half-life, significant quantities of americium-241 [^{241}Am] likely exists within these existing waste stockpiles. ^{241}Am is very valuable as a necessary component in many modern smoke detectors and for the construction of micro-scale nuclear batteries. Americium could be extracted from these masses through isotopic separation processes prior to injection in the core, or simply injected into the core to undergo burnup. Because of the ability for a LFNR to achieve very near complete burnup of transuranic isotopes, LFNR facilities could be used to actively eliminate high-level transuranic waste stockpiles, and at the same time produce significant quantities of energy.

Isotopes created through transmutation of non-fissile isotopes are not included in this analysis. Additionally, this section only refers to fission products produced by ^{241}Pu fission, and does not include fission products created through subsequent fission of transmuted isotopes. Refer to section 6.5 for complete LFNR fuel cycle analysis.

6.4.a) Gaseous

Table 17 - Plutonium-241 [^{241}Pu] Gaseous Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
36	**Kr**	Krypton	83	1.10%
54	**Xe**	Xenon	131	17.01%
			134	43.22%
			135	1.24%
			136	37.42%

The gaseous products created through the ^{241}Pu fission cycle represent a total of 18.23% of the waste mass. This allows for a nearly immediate mass reduction of 1/5th by collection of naturally off-gassing Kr and Xe.

6.4.b) Stable Solids

Table 18 - Plutonium-241 [^{241}Pu] Stable Solid Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
42	**Mo**	Molybdenum	95	26.51%
47	**Ag**	Silver	109	17.37%
48	**Cd**	Cadmium	113	1.00%
49	**In**	Indium	115	0.24%
60	**Nd**	Neodymium	143	30.79%
			145	22.01%
64	**Gd**	Gadolinium	154	>0.00%
			155	>0.00%
			156	1.16%
			157	0.91%
			158	0.62%
66	**Dy**	Dysprosium	160	>0.00%
			161	0.06%
			162	>0.00%
			163	>0.00%
			164	>0.00%
67	**Ho**	Holmium	165	>0.00%
68	**Er**	Erbium	166	>0.00%
			167	>0.00%

The stable solid fission products created through the ^{241}Pu fission cycle represent a total of 14.90% of the waste mass. The primary isotopes within the stable solid mass are ^{95}Mo, ^{143}Nd, and ^{145}Nd, and ^{109}Ag comprising 96.68% of the total.

The remaining 3.32% of the stable solids are a mixture of Cd, In, Gd, Dy, Ho, and Er.

6.4.c) 90 Day Resting Period

Table 19 - Plutonium-241 [^{241}Pu] 90 Day Decay Waste Mass

Atomic Number	**Symbol**	**Common Name**	**Isotope**	**% of Mass**
45	**Rh**	Rhodium	103	0.00%
			105	45.91%
52	**Te**	Tellurium	127	0.31%
53	**I**	Iodine	127	1.44%
			135	52.34%

The fission products created through the ^{241}Pu fission cycle which will undergo 31($t_{1/2}$) in under 90 days represent a total of 13.29% of the waste mass. The primary isotopes within this mass are ^{105}Rh, ^{127}I, and ^{135}I, comprising 99.69% of the total.

It should be noted that like ^{239}Pu, when compared to fission of U isotopes, ^{241}Pu will produce much more ^{105}Rh and less ^{135}I. As Iodine is more prone to biological uptake than ^{150}Rh, this does slightly reduce the risk to living organisms posed from this mass.

6.4.d) 100 Year Resting Period

Table 20 - Plutonium-241 [^{241}Pu] 100 Year Decay Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
44	**Ru**	Ruthenium	101	28.52%
			103	31.01%
			106	27.95%
51	**Sb**	Antimony	125	0.21%
61	**Pm**	Promethium	147	5.54%
			148	>0.00%
			148m	>0.00%
			149	6.76%

The fission products created through the ^{241}Pu fission cycle which will undergo 31($t_{1/2}$), between 90 days and 100 years represent a total of 19.77% of the waste mass. The primary isotopes within this mass are those of Ru, comprising 87.48% of the total.

It should be noted that like ^{239}Pu, when compared to fission of uranium isotopes, ^{239}Pu will produce much more ^{106}Ru.

6.4.e) Lifetime Storage

Table 21 - Plutonium-241 [^{241}Pu] Lifetime Storage Waste Mass

Atomic Number	Symbol	Common Name	Isotope	% of Mass
43	**Tc**	Technetium	99	19.60%
46	**Pd**	Palladium	105	>0.00%
			107	15.96%
			108	12.31%
55	**Cs**	Caesium	133	21.97%
			134	>0.00%
			135	>0.00%
			137	22.27%
62	**Sm**	Samarium	147	>0.00%
			148	>0.00%
			149	>0.00%
			150	>0.00%
			151	2.98%
			152	2.34%
63	**Eu**	Europium	151	>0.00%
			152	>0.00%
			153	1.77%
			154	>0.00%
			155	0.79%

The fission products created through the ^{241}Pu fission cycle which will not undergo 31($t_{1/2}$) in less than 100 years represent a total of 30.61% of the waste mass. The primary isotopes within this mass are those of ^{99}Tc, ^{107}Pd, ^{108}Pd, ^{133}Cs, and ^{137}Cs, comprising 92.11% of the total.

6.5) Summary of Sections 6.1 – 6.4

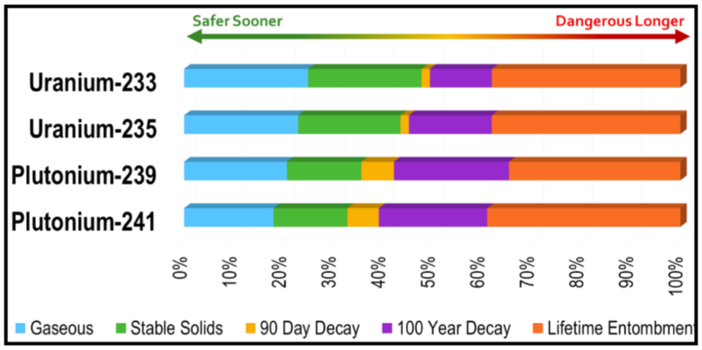

Figure 5 - Side-By-Side Comparison of Fission Products

Figure 5 shows all four fissile fuel options compared side-by side. It should be noted that for the lightest fissile isotope, ^{233}U, results in nearly 45% mass that can be considered "safe" in under 90 days. Conversely ^{241}Pu, the heaviest fissile isotope, produces only 40% mass that can be considered "safe" in 90 days.

This distinction cannot be emphasized enough. While a difference of only 5% may seem insignificant, the fission and decay products present within the 100 year and lifetime entombment masses are among the most dangerous isotopes known by humans. Many of the long lived isotopes, especially technecium-99 [^{99}, antimony-125 [^{125}Sb], tellurium-125m [^{125m}Te), caesium [Cs], and samarium-151 [^{151}Sm] are very easily mobilized through the environment upon release. This contamination can become even faster when the release occurs in or near an aquatic environment.

While many of the fission products within the "stable solids" and "90 day" groups are toxic, and therefore do represent a danger upon environmental release. That said, many of these fission products are in high demand for manufacturing of all sorts of goods, and as such will likely not simply be disposed of. This makes the disposal and/or recycling of these products no different than natural mined elements.

Every single fission product within the "gaseous", "stable solids", and "90 day" categories has high demand for modern manufacturing. So while these masses must be handled carefully initially, after an appropriate “safe resting period” [as required by each individual isotope], they can effectively be considered a resource, versus a waste product. This distinction is important because in a SFNR the same fission products would exist within the spent fuel, but they would be directly combined with the more dangerous isotopes within the fuel pellets. This combined solid state makes effective and safe reprocessing incredibly complicated and dangerous in general. In the LFNR, the elements would be separated from each other, allowing for individual masses to safely decay without risking contamination from longer lived radioisotopes. This drastically reduces the complexity of waste sequestration, reprocessing, and eventual entombment for LFNR waste.

Now, we will examine the complete LFNR waste cycle for each fissile fuel, including all secondary and tertiary fission events.

6.6) Expected LFNR waste output

To determine the waste composition created by a fission reactor the following factors have been defined:

Table 22 - Reactor Burnup Comparisons

Reactor Design	Burnup ~[Gwd/t]	Efficiency (per ton) %
Theoretical Maximum	909	100.0
LFTR	863	95.1
Areva EPR	65	7.2
Westinghouse CAP-1400	59	6.6
Mitsubishi APW	62	6.8
South Korean AP-400	55	6.1
VVER 1200	70	7.7
Hualong One	45	5.0
Areva NP Kerena	65	7.2
Indian AHWR	24	2.6
Indian AHWR-LEU	64	7.0
Chinese HTR-PM	90	9.9
BN-1200	120	13.2
Reduced-Moderation Water Reactor	45	5.0
IRIS	80	8.8
Gidropress VVER-1500	60	6.6
Fort Saint Vrain HTR	170	18.7
Very High-Temperature Reactor	100	11.0
AHTR	156	17.2

Initial Fuel Composition - The ratio of elements that will be dissolved within the fuel salt in the fissile core. For example, in a proposed Liquid Fluorine Thorium Reactor [LFTR], the initial fuel mass would be comprised of FliBe salt with a total of ~2.01% of the fuel mass being comprised of fissile ^{235}U and fertile ^{232}Th. Once the initial volume of ^{235}U has undergone fission, there should be no need for any further addition of fissile fuel, as all necessary fissile fuel would then be supplied by the transmutation of ^{232}Th to ^{233}U. In a traditional uranium fueled Light Water Reactor (LWR), the initial fuel composition would be comprised of, at most, 20% ^{235}U with the remainder being fertile ^{238}U.

Reactor Burnup Ratio - The burnup ratio of the reactor determines the volume of fissile fuel that will undergo fission before no longer being usable within the core. With solid-fueled reactors, burnup is much lower due to the overall inefficiency of fission in solid fuels and the need to remove from the core the growing quantities of nuclear poisons contained within the solid fuel. In LFNR systems, the nuclear poisons are constantly removed from the fuel mass through electrochemical precipitation, and processed as necessary. This allows for a much more complete burnup of the fissile mass than would be possible in any SFNR.

Table 22 shows the reactor burnup ratios of many currently operating and proposed reactor models. All burnup ratios were retrieved from the published literature provided by the manufacturers or public patent records. The burnup ratios provided were derived from published sales literature and other public technical information, and have only been provided to create a frame of reference for analysis. Actual real-world performance may vary from the published literature.

Fission Thermal Spectrum – The operating temperature of a reactor directly affects the efficiency of sustained fission within the reactor. Most SFNR are forced to operate below the ideal thermal range, due to the low vaporization point of the water coolant. A water-cooled SFNR operates at a maximum of 599^{o}F, well below the efficient thermal spectrum, whereas LFNR reactors operate well within the effective thermal range of fission, approximately 1300°F to 1600°F. The higher temperature the core can maintain, the more efficient the burnup of the reactor will be.

The following summary compares the total lifecycle fission outputs for each fissile isotope, based on the analysis provided in sections 6.1 - 6.5. For individual isotopic fission product data, please refer back to sections 6.1 - 6.4. Additional assumptions underlying sections 6.6.a – 6.6.d:

- A FLiBe carrier will be utilized as the fuel carrier (solvent), coolant, and moderator. This salt will contain 34% beryllium fluoride [BeF_2] and 66%

lithium fluoride [^{7}LiF]. FLiBe was chosen due to its extreme chemical stability and imperviousness to radiation. Even when exposed to extreme temperatures and high levels of radiation, FLiBe will not burn, explode, or decompose (Delpech, Cabet, Clim, & Picard, 2010). These traits mean that the FLiBe can be reused for decades, very likely longer than the operating life of the reactor. Note: All ^{6}Li must be removed from the FLiBe prior to use in the reactor, as ^{6}Li is known to produce radioactive tritium [^{4}H] when exposed to neutrons. ^{6}Li exists as approximately ~7.5% of natural lithium.

- The LFNR reactor will utilize a dual-core design to facilitate the most efficient isotopic separation of the waste mass. All fissile, transuranic, actinide, and lanthanide isotopes will be contained to the inner fuel mass until removal and processing.
- The outer core will utilize a constant electrochemical separation process to ensure all protactinium-233 [^{233}Pa] created through transmutation of ^{232}Th is removed from the core before it decays to fissile ^{233}U. ^{233}Pa has a half-life of only 25.6 days and a 31($t_{1/2}$) time of 2.17 years. After a resting period of 25 days to allow ^{233}Pa to decay to ^{233}U. The ^{233}U will be extracted and injected into the inner core.
- The fissile fuel salt mass will be constantly pumped through a series of electrochemical precipitators, ensuring that all fission products and transmuted isotopes are removed from the core before being subjected to further irradiation or being transmute to isotopes heavier than ^{240}Pu.

- All elements within the fuel mass will be separated through electrochemical precipitation when possible (as described in sections 6.1 through 6.4). Separate components of the waste will be processed in the manner most efficient for each specific element, avoiding unwanted chemical reactions whenever possible and ensuring the long-term stability of all dangerous isotopes.
- The LFNR electrical output calculation relies on a combined open-air Brayton-Rankine cycle (Zohuri, McDaniel, & De Oliveira, 2015). The open-air Brayton-Rankine cycle allows for a 46% thermal/electrical conversion efficiency.

6.6.a) ^{233}U LFNR Waste Output

Table 23 - Uranium-233 [^{233}U] Complete Full Cycle Analysis

Fissile Mass	% of Fissile Mass Remaining	Gaseous Mass (%)	Stable Solid Mass (%)	90-Day Decay Mass (%)	100-Year Decay Mass (%)	Lifetime Decay Mass (%)	Transmuted Mass (%)
U-233	100.00	18.81	15.87	6.08	6.81	18.56	33.86
U-235	33.87	17.63	16.53	7.43	10.92	20.26	27.24
Pu-239	9.23	19.77	14.09	12.69	19.77	27.30	6.38
Pu-241	0.59	18.23	14.90	13.29	21.85	30.61	1.12

Utilization of ^{233}U as the primary fissile mass, created through transmutation of fertile ^{232}Th, results in the smallest volume of high-level waste products. Use of ^{233}U as primary fuel will result in 2.7 times less transuranic isotopes than ^{235}U, 10 times less than ^{239}Pu, and 160 times less than ^{241}Pu. Less long lived waste decreases the overall volume of mass that must be safely stored for long periods of time, it also reduces the resources necessary to handle the mass in general. All around, less long-lived waste increases the efficiency of any reactor design. Less fuel required, less waste output, less resources required to handle safe storage, less environmental risk if an accidental release were to occur, and less cost associated with the entire endeavor.

The ^{233}U fission cycle results in the highest volume of gaseous and stable solids of any fissile fuel, allowing for a nearly immediate reduction of the total fuel mass of 47.82%. 6.52% of the mass will be comprised of ^{135}Xe, which will decay to ^{135}Cs in around 72 days. This 6.52% of the gaseous mass must be added to the mass requiring lifetime entombment.

The 90-Day mass will be comprised of 82.67% ^{135}I, which will decay to ^{135}Cs. This 82.67% of the 90-Day mass must be added to the mass requiring lifetime entombment.

Table 24 - Uranium-233 [^{233}U] Post-Fission Cumulative Waste

Gaseous Mass Remaining	Stable Solid Mass Remaining	90-Day Decay Remaining Mass	100-Year Decay Remaining Mass	Lifetime Decay Remaining Mass	Transuranic Remaining Mass
26.71%	22.85%	9.85%	12.46%	28.12%	0.01%
After Adjustment Mass					
24.97%	22.85%	1.71%	12.46%	38.01%	

The transuranic mass will be added to the lifetime decay mass due to high levels of radioactivity and long half-lives. The lifetime mass therefore accounts for a total of 38.01% of the total waste mass.

Assuming a burnup rate equal to a LFTR design of 863.5 $\text{Gw}_{\text{d/t}}$ [95.10%], 4.9% of the fissile mass will remain entirely unchanged. This mass could be reinserted into the fissile fuel mass indefinitely.

It should be noted that 39.72 Terawatt days [Tw_{d}] is equivalent to 5% of the global electrical demand in 2014 (IEA, 2015).

If one were to assume the complete burnup of 100 tons of ^{233}U (which is far more than any singular reactor would require at any one time) after burnup the fissile mass would create:

- 24.97 tons of Stable Gaseous Mass requiring no safe storage period
- 22.85 tons of Stable Solid Mass requiring no safe storage period
- 1.71 tons requiring a 90-Day safe storage period
- 12.46 tons requiring a 100 safe storage period
- 38.01 tons requiring Lifetime Entombment
- 4.9 tons of unchanged ^{233}U fissile mass
- 86.35 Terawatt days [Tw_{d}] of thermal energy
- 39.72 Tw_{d} of electrical energy

6.6.b) ^{235}U LFNR Waste Output

Table 25 - Uranium-235 [^{235}U] Complete Full Cycle Analysis

Fissile Mass	% of Fissile Mass Remaining	Gaseous Mass (%)	Stable Solid Mass (%)	90-Day Decay Mass (%)	100-Year Decay Mass (%)	Lifetime Decay Mass (%)	Transmuted Mass (%)
U-235	100.00	17.63	16.53	7.43	10.92	20.26	27.24
Pu-239	27.24	19.77	14.09	12.69	19.77	27.30	6.38
Pu-241	1.74	18.23	14.90	13.29	21.85	30.61	1.12

Use of ^{235}U as primary fuel will result in 3.74% times less transuranic waste than ^{239}Pu, and 59 times less than ^{241}Pu. ^{235}U can be utilized both without the presence of ^{238}U (as highly enriched U) or as reactor grade uranium (containing up to 95% fertile ^{238}U), the latter producing significantly more high-level waste. This analysis assumes the excess ^{238}U will be removed to prevent excessive transuranic production and reduce the viability of utilizing LFNR for the creation of weapons-grade Pu-239.

Table 26 - Uranium-235 [^{235}U] Post-Fission Cumulative Waste

Gaseous Mass Remaining	Stable Solid Mass Remaining	90-Day Decay Remaining Mass	100-Year Decay Remaining Mass	Lifetime Decay Remaining Mass	Transuranic Remaining Mass
23.33%	20.62%	11.11%	16.68%	28.23%	0.02%
After Adjustment Mass					
22.97%	20.62%	1.70%	16.68%	38.02%	

The ^{235}U fission waste can be quickly reduced by a total fuel mass of 47.82%. 1.46% of the mass will be comprised of ^{135}Xe, which will decay to ^{135}Cs in around 72 days. This 1.46% of the mass must be added to the lifetime entombment mass.

The 90-Day mass will be comprised of 84.7% ^{135}I, which will decay to ^{135}Cs. This 84.7% of the 90-Day mass must be added to the mass requiring lifetime entombment. The transuranic mass will be added to the lifetime decay mass due to high levels of radioactivity and long half-lives. The lifetime mass therefore accounts for a total of 38.02% of the total waste mass.

Assuming burnup rate equal to the LFTR design rate of 863.5 $Gw_{d/t}$ [95.10%], 4.9% of the fissile mass will remain entirely unchanged. This mass could be reinserted into the fissile fuel mass indefinitely with proper reprocessing. Removal of all ^{238}U prior to injection of U into the fissile core is crucial for minimization of overall transuranic production through the transmutation of ^{238}U. Excess ^{238}U could be utilized in the fertile core to generate ^{239}Pu, however the potential for nuclear proliferation makes this option undesirable.

It should be noted that 39.72 Terawatt days [Tw_d] is equivalent to 5% of the global electrical demand in 2014 (IEA, 2015).

If one were to assume the complete burnup of 100 tons of ^{235}U (which is far more than any singular reactor would require at any one time) after burnup the fissile mass would create:

- 22.97 tons of Stable Gaseous Mass requiring no safe storage period
- 20.62 tons of Stable Solid Mass requiring no safe storage period
- 1.70 tons requiring a 90-Day safe storage period
- 16.68 tons requiring a 100 safe storage period
- 38.02 tons requiring Lifetime Entombment
- 4.9 tons of unchanged ^{233}U fissile mass
- 86.35 Terawatt days [TW_d] of thermal energy
- 39.72 TW_d of electrical energy

6.6.c) ^{239}Pu LFNR Waste Output

Table 27 - Plutonium-239 [^{239}Pu] Complete Full Cycle Analysis

Fissile Mass	% of Fissile Mass Remaining	Gaseous Mass (%)	Stable Solid Mass (%)	90-Day Decay Mass (%)	100-Year Decay Mass (%)	Lifetime Decay Mass (%)	Transmuted Mass (%)
Pu-239	100.00%	19.77%	14.09%	12.69%	19.77%	27.30%	6.38%
Pu-241	6.38%	18.23%	14.90%	13.29%	21.85%	30.61%	1.12%

Use of ^{239}Pu as a fissile fuel is generally undesirable, because heavier isotopes are more likely to transmute into heavier transuranic isotopes. The appeal of utilizing ^{239}Pu as a fuel source is the potential for active elimination of existing nuclear weapon stockpiles. Environmentally speaking, the waste volume produced from ^{239}Pu production is significant, though is not included in this section of the analysis.

Table 28 - Plutonium-239 [239Pu] Post-Fission Cumulative Waste

Gaseous Mass Remaining	Stable Solid Mass Remaining	90-Day Decay Remaining Mass	100-Year Decay Remaining Mass	Lifetime Decay Remaining Mass	Transuranic Remaining Mass
20.93%	15.04%	13.54%	21.16%	29.26%	0.07%
After Adjustment Mass					
20.67%	15.04%	6.57%	23.16%	36.56%	

The ^{239}Pu fission waste can be nearly immediate reduced by a total mass of 35.71%. 1.24% of the mass will be comprised of ^{135}Xe, which will decay to ^{135}Cs in around 72 days. This 1.24% of the gaseous mass must be added to the mass requiring lifetime entombment.

The 90-Day mass will be comprised of 51.5% ^{135}I, which will decay to ^{135}Cs. This 51.5% of the 90-Day mass must be added to the mass requiring lifetime entombment. The transuranic mass will be added to the lifetime decay mass due to high levels of radioactivity and long half-lives. The lifetime mass therefore accounts for a total of 36.56% of the total waste mass.

Assuming burnup rate equal to a LFTR design of 863.5 $Gw_{d/t}$ [95.10%], 4.9% of the fissile mass will remain entirely unchanged. This mass could be reinserted into the fissile fuel mass indefinitely with proper reprocessing.

It should be noted that 39.72 Terawatt days [Tw_d] is equivalent to 5% of the global electrical demand in 2014 (IEA, 2015).

If one were to assume the complete burnup of 100 tons of ^{239}Pu (which is far more than any singular reactor would require at any one time) after burnup the fissile mass would create:

- 20.67 tons of Stable Gaseous Mass requiring no safe storage period
- 15.04 tons of Stable Solid Mass requiring no safe storage period
- 6.57 tons requiring a 90-Day safe storage period
- 23.16 tons requiring a 100 safe storage period
- 36.56 tons requiring Lifetime Entombment
- 4.9 tons of unchanged ^{233}U fissile mass
- 86.35 Terawatt days [Tw_d] of thermal energy
- 39.72 Tw_d of electrical energy

6.6.d) ^{241}Pu LFNR Waste Output

Table 29 - Plutonium-241 [^{241}Pu] Complete Full Cycle Analysis

Fissile Mass	% of Fissile Mass Remaining	Gaseous Mass (%)	Stable Solid Mass (%)	90-Day Decay Mass (%)	100-Year Decay Mass (%)	Lifetime Decay Mass (%)	Transmuted Mass (%)
Pu-241	100.00%	18.23%	14.90%	13.29%	21.85%	30.61%	1.12%

^{241}Pu is the most undesirably of all fissile fuel, as heavier isotopes are more likely to transmute into more dangerous transuranic isotopes. The appeal of utilizing ^{241}Pu as a fuel source is the potential for active elimination of existing high-level nuclear waste remaining from past nuclear projects. Environmentally speaking, the waste volume produced from ^{241}Pu production is significant, though is not included in this analysis.

Table 30 - Plutonium-241 [^{241}Pu] Post-Fission Cumulative Waste

Gaseous Mass Remaining	Stable Solid Mass Remaining	90-Day Decay Remaining Mass	100-Year Decay Remaining Mass	Lifetime Decay Remaining Mass	Transuranic Remaining Mass
18.23%	14.90%	13.29%	21.85%	30.61%	1.12%
After Adjustment Mass					
18.00%	14.90%	6.33%	21.85%	38.92%	

The ^{241}Pu fission waste can be nearly immediate reduced by a total mass of 47.82%. 1.24% of the mass will be comprised of ^{135}Xe, which will decay to ^{135}Cs in around 72 days. This 1.24% of the gaseous mass must be added to the mass requiring lifetime entombment.

The 90-Day mass will be comprised of 52.34% ^{135}I, which will decay to ^{135}Cs. This 52.34% of the 90-Day mass must be added to the mass requiring lifetime entombment.

The transuranic mass will be added to the lifetime decay mass due to high levels of radioactivity and long half-lives. The lifetime mass therefore accounts for a total of 38.92% of the total waste mass.

Assuming burnup rate equal to a LFTR design of 863.5 $Gw_{d/t}$ [95.10%], 4.9% of the fissile mass will remain entirely unchanged. This mass could be reinserted into the fissile fuel mass indefinitely with proper reprocessing.

It should be noted that 39.72 Terawatt days [Tw_d] is equivalent to 5% of the global electrical demand in 2014 (IEA, 2015).

If one were to assume the complete burnup of 100 tons of ^{241}Pu (which is far more than any singular reactor would require at any one time) after burnup the fissile mass would create:

- 18.00 tons of Stable Gaseous Mass requiring no safe storage period
- 14.90 tons of Stable Solid Mass requiring no safe storage period
- 6.33 tons requiring a 90-Day safe storage period
- 21.85 tons requiring a 100 safe storage period
- 38.92 tons requiring Lifetime Entombment
- 4.9 tons of unchanged ^{233}U fissile mass
- 86.35 Terawatt days [Tw_d] of thermal energy
- 39.72 Tw_d of electrical energy.

6.7) LFNR/SFNR Comparison

This section is provided solely to provide some context for evaluating LFNR waste production. It is very difficult to directly compare LFNR waste production to that of traditional SFNR. In a LFNR system, all fission products are actively removed from the fuel mass. Removing fission products eliminates the constantly generated nuclear poisons, ensuring the fission chain reaction can be sustained with a minimum of energy loss. This isotopic separation also ensures that all fissile isotopes remain in the core and will not be removed until they are consumed.

In a SFNR, the fission products generally remain trapped within the solid fuel pellets. Trapping these fission products within the solid fuel helps prevent the release of fission products and transuranic elements into the reactor vessel or the environment. Eventually, fission products will be present in high enough quantities to actually inhibit the fission process. This “spent” fuel, generally after 1.5-3 years within the core, must be replaced by fresh fuel. Often as little as 3% of the fissile mass within the fuel mass has been consumed through fission, leaving as much as 97% fuel unconsumed.

For the following assumptions will be made for the following comparison:

- A fuel mix of 5% ^{235}U and 95%^{238}U. This is comparable to modern reactor-grade fuel used in reactors around the world.
- Fuel will be left within the core until the fuel contains 0.9% ^{235}U, 0.6% ^{239}Pu, 0.4% ^{238}Pu/^{240}Pu, and 95% ^{238}U. The remaining 3.1% is comprised of fission products and very small quantities.

- As is the case for most modern spent solid fuel, the fuel mass will not be isotopically separated. Therefore, the entire fuel mass must be permanently entombed.
- Electrical output is based on the assumption that a combined open-air Brayton-Rankine cycle will be utilized (Zohuri, McDaniel and De Oliveira 2015). The open-air Brayton-Rankine cycle allows for a 46% thermal/electrical conversion efficiency.
- The reactor uses pressurized light water as primary coolant.

Based on of 100 tons of ^{235}U, after burnup this theoretical SFNR would create:

- 2439 tons of waste requiring Lifetime Entombment
- 86.35 Terawatt days [Tw_d] of thermal energy
- 39.72 Tw_d of electrical energy

This quick comparison shows even a very efficient uranium fueled SFNR will generate significantly higher volumes of waste requiring Lifetime Entombment. In this example, the theoretical SFNR would generate more than 64 times the mass of high-level waste. In addition, numerous radioactive isotopes are created through neutron irradiation of impurities within the coolant. Neutron bombardment of water also leads to tritium [^{3}H] and carbon [^{14}C] production, both radioactive isotopes capable of forming gaseous and liquid compounds. This irradiated coolant is classified as low-level radioactive waste, as most fission products within the mass will decay in less than 500 years. This additional waste mass has been left out of this comparison since this comparison seeks only to examine the products produced within the core itself. It should be noted that the mass of this reactor-generated low-level waste can be in excess of 45 times the high-level waste mass.

7) Discussion

As outlined in section 3.2, liquid fueled nuclear reactors [LFNR] have become a popular topic in the nuclear science world since renewed interest began in the late 1990's. The data shows that while the volume of dangerous isotopes within LFNR waste mass is significant, the manner in which individual elements can be extracted from the fuel salt greatly reduces the volume of waste requiring long term storage as well as the threat presented by radioactive decay. Long lived unstable isotopes are still produced, but can be separated from the less dangerous fission products and entombed far more easily than can be accomplished with any Solid-Fueled Nuclear Waste [SFNR] waste. The high-level waste reduction of 64 times for ^{235}U fission is very significant: While these high-level wastes still represent very serious threat to living organisms for thousands of years, the drastic reduction in their volume when compared to SFNR is perhaps the strongest advantage the LFNR technology offers.

This analysis shows that from a numbers standpoint, LFNR tech shows incredible promise as a truly near-zero carbon energy source. In a world currently being ravaged by the effects of global climate change, where so much attention is being directed towards the big carbon producing industries, LFNR appears to offer a large-scale solution that could have significant impact on the global carbon output. In addition to the waste analysis within this thesis, existing analysis of the technical operating parameters, show that LFNR offer an unprecedented level of safety for a nuclear reactor. As incidents like Chernobyl and Fukushima have shown, water cooled reactors are inherently dangerous and prone to violent failure. Similar incidents would be impossible from a LFNR style reactor, as the reactor cannot achieve the temperatures required to phase change the fluoride salts from liquid to gaseous state. Combined with very low expansion characteristics, the use of fluoride salts results in operating conditions no more dangerous than a typical coal fired power plant.

As another tool for comparison, consider what the impacts of coal based energy would be. To generate the same energy as 100 tons of ^{233}U would require the combustion of 350 million tons of high-grade anthracite coal. In a modern "clean coal" plant, this mass of coal would result in the release of [but not limited to]:

- 2 Gt (gigatonnes) of Carbon Dioxide [CO2] (~20% current global CO2 output)
- 115, 507 tons of Sulfur Dioxide [SO2]
- 200 Mt of Nitrogen Oxide [NO]
- 122,000 tons of airborne particulates
- 53,000 tons of airborne hydrocarbons
- 175,000 tons of Carbon Monoxide [CO]
- 27.5 tons of Arsenic
- 14 tons of Lead
- 0.5 tons of Cadmium
- 86.35 Terawatt days [Tw_d] of thermal energy
- 39.72 Tw_d of electrical energy

Caveats: LFNR technology shows incredible promise for a world desperately in need of a near-zero carbon high-energy density power source to meet the constantly growing global demand. LFNR technology still requires significant research before large-scale implementation will be viable. The very high temperatures of the reactor core require very specific engineering solutions to ensure components do not degrade or become seriously damaged during ongoing operation, potentially creating a release of dangerous isotopes. Until recently, manufacture of the graphite components was incredibly difficult. Advancements in 3D printing technology may offer a cost effective and reliable manufacturing method for these components (Dalton, 2016).

In addition, with some fissile fuel types, there is a definite risk for potential nuclear proliferation. In the case of the ^{233}U cycle, the natural presence of protactinium with it's half-life of around 25 days effectively "contaminates" the fissile mass, making it unusable for weapons production (Brown, Dixon, & Rogers, 1968). This natural "anti-proliferation" aspect of the ^{233}U is often cited as a reason to support LFNR development (Gat & Engel, 2000).

The inability for the fuel salt mass to enter a "meltdown" state is another clear advantage over SFNR. The natural thermal characteristics give the fuel mass a strong negative void coefficient. Upon overheating, the thermal cross-section of fertile isotopes within the mass will increase, resulting in increased transmutation and decreased fission. This reaction creates a condition often cited as "self-regulating", and is an important safety feature that does not exist within standard SFNR.

A major hindrance to the technology is the general lack of funding for associated research. Research dollars are almost always limited, and similar projects must frequently compete for the limited funds. In addition, the very fact that fissile isotopes are radioactive makes research time consuming, costly, and creates inherent risk to the researchers. This limits the number of researchers with the access to the resources, facilities, and knowledge bases necessary.

While many of the claims about LFNR may be incorrect, or at times highly misleading, the math shows that LFNR does appear to offer the traits to make it a valuable partner in halting or even repairing anthropogenic climate change. In this case, the proof does appear to be in the pudding.

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9) Appendix

9.1) Terminology

Alpha Particle – Governed by the Nuclear Force and Electromagnetic Force. Radiative decay that emits a highly-charged Helium-4 [4H] nucleus. Will result in transmutation to an element 2 protons lighter and 2 less neutrons than the decayed atom. Generally, only seen in heavier isotopes.

Beta Particle – Mediated by the weak force. Radiative decay caused by 1) a neutron within the atomic nucleus gaining a positive charge and creating an electron and electron antineutrino or 2) A proton within the atomic nucleus becoming a neutron, creating a positron and electron neutrino.

Boson – One class of subatomic particles that comprise the universe, the other being Fermions. Bosons can occupy the same space at the same time. A good example of a Boson would be a Photon.

Burnable Poison – Used in some reactors that do not require control rods. Burnable poisons, such as boron or gadolinium, are added to fuel piles to control core flux. Burnable poisons are consumed throughout the operating of a reactor. LFNR do not require burnable poisons.

Burnup – The total volume of mass converted to energy through fission in a nuclear reactor. Burnup is represented as $x = GwD/t$ [Gigawatt Days / Tons of fuel].
Cluster Decay – Rare form of nuclear decay in which an atomic nucleus emits a small number of neutrons and protons, larger than an alpha particle but smaller than a traditional binary fission fragment. Ternary fissions, which are also extraordinarily rare, will also emit fission products of similar size.

Coolant – A substance, generally a liquid or gas, used to transfer heat generated within the reactor core to heat exchangers.

Control Rod – Used in SFNR to control reactor core. Made of elements capable of absorbing neutrons without reacting; such as boron, sliver, indium, and cadmium. Control rods must be physically or mechanically manipulated.

Criticality – All fissile isotopes have a point of "criticality". Criticality is determined by the density, size, shape, enrichment, temperature, and proximity of nearby substances. For example, U-233 has a criticality of mass of 15 kg in a spherical configuration, assuming no surrounding moderators or neutron reflectors which could increase criticality. Therefore, care must be taken to ensure no volume of any fissile or fissionable isotope is allowed to reach a state of criticality. Upon going critical, the fissile mass will begin emitting very strong high levels of gamma rays, X-rays, alpha particles, and beta particles. Many deaths have occurred due to accidentally created criticalities. Worst case scenario (though unlikely), would be fissile mass creating a thermonuclear detonation. The volume of material and specific circumstances for this scenario make it nearly impossible to occur without deliberate intent.

Daughter Isotope – Any isotope that is created through the decay of another isotope.

Decay – The process in which an unstable isotope "ejects" either a neutron, proton, electron, subatomic particles, or radiates energy to become a lighter isotope and eventually become a stable isotope. Decay is measured in "Half-Lives".

Double Beta Decay – Mediated by the Weak Force. Radiative decay caused by 1) Two neutrons within the atomic nucleus gaining a positive charge and creating two positrons and two electrons or 2) Two protons in the atomic nucleus becoming neutrons, creating two neutrinos and two electrons.

Electromagnetic Force - One of the four fundamental forces of nature. The other three being Gravity, Strong Force, and Weak Force. Responsible for most phenomenon in the known universe. At an atomic level, electromagnetic force explains the interactions between positive, negative, and neutral particles.

Element – Classification for individual atoms. Element number is equal to the number of protons in the atomic nucleus.

Fermion – One class of subatomic particles that comprise the universe, the other being Bosons. Fermions are particles that cannot occupy the same space at the same time. Electrons are a good example of a Fermion, as two electron's orbiting an atomic nucleus cannot follow the exact same path or they would collide (if not naturally repelled by their negative charges.)

Fertile – An isotope that can accept a neutron to become a fissile isotope. Fertile isotopes include: Thorium-232, Uranium-234, Uranium-238, Plutonium-238, Plutonium-241.

Fissile – An isotope that can be split by a thermal neutron with enough reliability to sustain a chain reaction, generating energy and fission products. Fissile isotopes include: Uranium-233, Uranium-235, Plutonium-239, and Plutonium-241

Fissionable – An isotope that, though incapable of sustaining a chain reaction, can achieve fission with any type of neutron, even with very low probability. All isotopes heavier than Uranium 233 are fissionable.

Gamma Decay – Release of highly charged ionizing radiation. Very dangerous to living organisms. In nuclear chemistry, all electromagnetic radiation emitted during nuclear decay is referred to as gamma rays, regardless of lower energy threshold. Caused by release of nucleonic binding energy.

Half Life – The amount of time required for 50% of an unstable isotope to decay into a lighter isotope.

Isometric Transition – Radiative decay associated with Gamma Decay. Upon a Gamma emission, there is a chance the gamma ray will excite an electron around the nuclei, in which case the atom will eject a high-energy electron (Internal Conversion). This differs from a Beta Decay, in that the electron is not newly created by the event. Does not result in a change of isotope, but does release gamma radiation. Possible during any gamma decay reaction. Internal conversion does not relate to decrease in atomic mass, and therefore does not result in transmutation directly, but can result in a lighter isotope.

Isotope – Classification for elements that have the same number of protons, but differing number of neutrons. Most elements have several isotopes, however often only a few are stable.

Lanthanides – Elements with atomic numbers between 57 and 71. These elements all share similar chemical traits with Lanthanum, hence their name. Lanthanides are extraordinarily rare in nature, and are involved with no known biological processes. All non-radioactive lanthanides are considered to be of very low toxicity.

Moderator – A medium used to slow fast neutrons generated by fission, converting them to thermal neutrons capable of sustaining a nuclear chain reaction. Common moderators are water, graphite, deuterium oxide, or Beryllium.

Negative Void Coefficient – The likelihood of a reaction increasing or decreasing depending on the presence of voids within the reactor core. This can occur due to coolant loss or other malfunctions within a reactor. A void coefficient of “0.0” is considered stable. Negative void coefficient can be used as a final safety measure, as a strongly negative coefficient will result in a core quickly cooling and ceasing fission upon reactor failure.

Nuclear Poison – aka Neutron Poison. An isotope with a very large neutron absorption cross-section. Presence of nuclear poison within a reactor can reduce efficiency of chain reaction. Common nuclear poisons are: Xenon-135, Samarium-149, Boron, Dysprosium, Europium, Gadolinium, Hafnium, and Iodine.

Nuclear Transmutation – The conversion of one element/isotope to an another element/isotope through neutron absorption or nuclear decay.

Proliferation-Ready – Any isotope that can be used to create nuclear weaponry. U-235, Pu-239, Pu-241 are the most desired weapons grade fissile isotopes. Most other fissile isotopes are too prone to spontaneous fission to be safe for use in bomb cores.

Pyrophoric – Any compound that is likely to spontaneously ignite when exposed to air, and often water. Most metals are pyrophoric when in a state with large exposed surface areas [such as when powdered or sliced thinly].

Salt Loop – A single, sealed system designed to circulate the fuel mass between the core and heat exchangers. A single core reactor would have a 3 loop system (hot-salt loop, cold-salt loop, cold loop). Fissile isotopes and fission products would be isolated to the hot-salt loop. In a dual core reactor (inner fissile core and outer fertile blanket), the primary hot-salt loop would circulate only fluid from the inner core (fissile isotopes and fuel salt) and the secondary hot-salt loop would be used to circulate the outer fertile fuel salt.

Self-Regulate – In nuclear chemistry, “self-regulate” refers to certain reactor configurations that will result in some degree of natural fission regulation without outside manipulation.

Sister Isotope – Isotopes of the same atomic number, and hence the same number of protons.

Spontaneous Fission – A form of fission that can occur without being induced by a neutron. All element larger than 232Th and several unstable actinide fission products can undergo spontaneous fission. Products of spontaneous fission can include any of the isotopes produced through an induced fission, and can be binary or ternary events. However, due to the exceedingly rare occurrence of spontaneous fission, the products can effectively be ignored. What cannot be ignored is the potential for criticality when storing any volume of any concentrated isotope capable of both achieving a fission reaction AND a spontaneous fission reaction.

Strong Force / Strong Interaction / Strong Nuclear Force – One of the four fundamental forces of nature. The other three being Gravity, Electromagnetism, and Weak Force. Strong Force is the most powerful force of the fundamental forces; being around 100 times stronger than electromagnetism, approximately a million times stronger than weak force, and 1038 times stronger than gravity. Strong Force operates only at distances under one femtometer, or approximately the width of one proton. For fission to occur, a neutron must travel within 1 femtometer of the nuclei for Strong Force to bind to the nuclei. This mass change will then induce the effects of the Weak Force, resulting in fission.

Transuranic – All elements larger than Uranium-238. Though transuranic elements may have been created through stellar formation, all are highly radioactive and possess half-lives significantly shorter than the age of the Earth (4.5 Billion years). All transuranic elements no longer exist naturally on Earth, as any that may have once been created have long since decayed. Not all transuranic isotopes are fissile, but all are fissionable.

Weak Force / Weak Interaction / Weak Nuclear Force – One of the four fundamental forces of nature. The other three being Gravity, Electromagnetism, and Strong Force. Weak Force refers to the manner in which subatomic particles (Bosons and Fermions) interact. Weak Force is responsible for all radioactive decay and is crucial in fission itself. Weak force has the smallest range of effect of the fundamental forces. Weak Force always works to arrange the subatomic particles that comprise matter into the most energetically stable configuration possible.

9.2) Fission Product Data [By Isotope]

Table 31 - Fission Product Data

Atomic Number	Symbol	Common Name	Isotope	Gas/Solid (G/S)	Demand	Reactive	Explosive	Pyrophoric	Biologically Dangerous	Radioactive	Fissile?	Fissionable?	Proliferation Threat?	Half Life (years)	Daughter Element	Decay Mode	Likelihood of Creation (%)
6	**C**	Carbon	14	G	**Y**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	5.73E+03	**N-14**	**β−**	100
7	**N**	Nitrogen	14	G	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
8	**O**	Oxygen	20	G	**N**	**Y**	**Y**	**N**	**N**	**Y**	**N**	**N**	**N**	4.28E-07	**F-20**	**β−**	100
9	**F**	Fluorine	20	G	**N**	**Y**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.54E-07	**Ne-20**	**β−**	100
			23	G	**N**	**Y**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	7.07E-08	**Ne-22**	**β−**	86
			23	G	**N**	**Y**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	7.07E-08	**Ne-23**	**β−**	14
10	**Ne**	Neon	20	G	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			22	G	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			23	G	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.18E-06	**Na-23**	**β−**	100
			24	G	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	6.43E-06	**Na-24**	**β−**	100
			25	G	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.91E-08	**Na-25**	**β−**	
			26	G	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	6.25E-09	**Na-25**	**β−**	0.1
			26	G	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	6.25E-09	**Na-26**	**β−**	99.9
11	**Na**	Sodium	23	S	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	STABLE			
			24	S	**Y**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.71E-03	**Mg-24**	**β−**	100
			25	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.87E-06	**Mg-25**	**β−**	
			26	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	3.42E-08	**Mg-26**	**β−**	
12	**Mg**	Magnesium	24	S	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	STABLE			
			25	S	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	STABLE			
			26	S	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	STABLE			
			28	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	2.39E-03	**Al-28**	**β−**	100
			30	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.06E-08	**Al-29**	**β−**	100
			30	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.06E-08	**Al-30**	**β−**	6
13	**Al**	Aluminum	28	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	4.26E-06	**Si-28**	**β−**	100
			29	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.25E-05	**Si-29**	**β−**	
			30	S	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	**N**	**N**	1.14E-07	**Si-30**	**β−**	
14	**Si**	Silicon	28	S	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			29	S	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			30	S	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			32	S	**N**	**Y**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.53E+02	**P-32**	**β−**	

			34	S	**N**	**Y**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	8.78E-08	**P-34**	**β−**	
15	**P**	Phosphorus	32	S	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	3.91E-02	**S-32**	**β−**	
			34	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	3.96E-07	**S-34**	**β−**	
16	**S**	Sulfur	32	S	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			34	S	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
36	**Kr**	Krypton	83	G	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			>0.0
42	**Mo**	Molybdenum	95	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
43	**Tc**	Technetium	99	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	2.11E+05	**Ru-99**	**β−**	100
44	**Ru**	Ruthenium	99	S	**Y**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			101	S	**Y**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			103	S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.08E-01	**Rh-103**	**β−**	100
			106	S	**Y**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.02E+00	**Rh-106**	**β−**	100
45	**Rh**	Rhodium	103	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			105	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	4.04E-03	**Pd-105**	**β−**	100
			106	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	9.45E-07	**Pd-106**	**β−**	100
46	**Pd**	Palladium	105	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			106	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			107	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	6.50E+06	**Ag-107**	**β−**	100
			108	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
47	**Ag**	Silver	107	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			109	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
48	**Cd**	Cadmium	113	S	**Y**	**N**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	8.04E+15	**In-113**	**β−**	100
49	**In**	Indium	113	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			115	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	4.41E+14	**Sn-115**	**β−**	100
50	**Sn**	Tin	115	S	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
51	**Sb**	Antimony	125	S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.76E+00	**Te-125m**	**β−**	100
52	**Te**	Tellurium	125	S	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			125m	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.57E-01	**Te-125**	**IT**	100
			127	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.07E-03	**I-127**	**β−**	100
53	**I**	Iodine	127	S	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			135	S	**N**	**Y**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	7.50E-04	**Xe-135**	**β−**	100
54	**Xe**	Xenon	131	G	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			134	G	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	STABLE			
			135	G	**N**	**Y**	**Y**	**N**	**N**	**Y**	**N**	**N**	**N**	1.04E-03	**Cs-135**	**β−**	100
			136	G	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	2.17E+21			
55	**Cs**	Caesium	133	S	**Y**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			134	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.07E+00	**Ba-134**	**β−**	100
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.07E+00	**Xe-134**	**EC**	<0.1
			135	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.30E+06	**Ba-135**	**β−**	100

			137	S	Y	Y	N	Y	Y	Y	N	N	N	3.02E+01	Ba-137	β−	5
				S	Y	Y	N	Y	Y	Y	N	N	N	3.02E+01	Ba-137m	β−	95
56	Ba	Barium	134	S	Y	Y	N	Y	Y	N	N	N	N	STABLE			
			135	S	Y	Y	N	Y	Y	N	N	N	N	STABLE			
			137	S	Y	Y	N	Y	Y	N	N	N	N	STABLE			
			137m	S	N	Y	N	Y	Y	Y	N	N	N	4.86E-06	Ba-137	IT	100
58	Ce	Cerium	140	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
60	Nd	Neodymium	143	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			144	S	Y	Y	Y	Y	Y	N	N	N	N	2.29E+15	Ce-140	α	100
			145	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
61	Pm	Promethium	147	S	Y	Y	N	N	N	Y	N	N	N	2.62E+00	Sm-147	β−	100
			148	S	N	Y	N	N	N	Y	N	N	N	1.47E-02	Sm-148	β−	100
			148m	S	N	Y	N	N	N	Y	N	N	N	1.13E-01	Sm-148	β−	95
				S	N	Y	N	N	N	Y	N	N	N	1.13E-01	Pm-148	IT	5
			149	S	N	Y	N	N	N	Y	N	N	N	6.06E-03	Sm-149	β−	100
62	Sm	Samarium	147	S	Y	Y	Y	Y	N	Y	N	N	N	1.06E+11	Nd-143	α	100
			148	S	Y	Y	Y	Y	N	Y	N	N	N	7.00E+15	Nd-144	β−	100
			149	S	Y	Y	Y	Y	N	Y	N	N	N	STABLE			
			150	S	Y	Y	Y	Y	N	Y	N	N	N	STABLE			
			151	S	N	Y	Y	Y	N	Y	N	N	N	8.88E+01	Eu-151	β−	100
			152	S	Y	Y	Y	Y	N	Y	N	N	N	STABLE			
			154	S	Y	Y	Y	Y	N	Y	N	N	N	STABLE			
63	Eu	Europium	151	S	N	Y	Y	Y	N	Y	N	N	N	4.62E+18	Pm-147	α	100
			152	S	N	Y	Y	Y	N	Y	N	N	N	1.35E+01	Sm-152	EC/β−	72.4
				S	N	Y	Y	Y	N	Y	N	N	N	1.35E+01	Gd-152	β−	27.6
			153	S	Y	Y	Y	Y	N	N	N	N	N	STABLE			
			154	S	N	Y	Y	Y	N	Y	N	N	N	8.59E+00	Gd-154	β−	100
			154	S	N	Y	Y	Y	N	Y	N	N	N	8.59E+00	Sm-154	EC	>0.1
			155	S	N	Y	Y	Y	N	Y	N	N	N	4.76E+00	Gd-155	β−	100
64	Gd	Gadolinium	152	S	N	Y	Y	Y	Y	Y	N	N	N	1.08E+14	Sm-148	α	100
			154	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			155	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			156	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			157	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			158	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
66	Dy	Dysprosium	160	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			161	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			162	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			163	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			
			164	S	Y	Y	Y	Y	Y	N	N	N	N	STABLE			

67	**Ho**	Holmium	165	S	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
68	**Er**	Erbium	166	S	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			167	S	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
72	**Hf**	Hafnium	186	S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	4.95E-06	**Ta-186**	**β−**	
73	**Ta**	Tantalum	186	S	**N**	**Y**	**Y**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.00E-05	**W-186**	**β−**	
74	**W**	Tungsten	186	S	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
80	**Hg**	Mercury	204	S	**Y**	**Y**	**N**	**N**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			205	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	9.78E-06	**Tl-205**	**β−**	100
			206	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.55E-05	**Hg-205**	**β−**	100
81	**Tl**	Thallium	205	S	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			206	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.99E-06	**Pb-206**	**β−**	100
			207	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	9.08E-06	**Pb-207**	**β−**	100
			209	S	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**N**	**N**	4.11E-06	**Pb-209**	**β−**	
82	**Pb**	Lead	206	S	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			207	S	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			208	S	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	**N**	STABLE			
			209	S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	3.71E-04	**Bi-209**	**β−**	100
			210	S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.22E+01	**Bi-210**	**β−**	100
				S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.22E+01	**Hg-206**	**α**	>0.1
			211	S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	6.87E-05	**Bi-211**	**β−**	100
			212	S	**N**	**N**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.21E-03	**Bi-212**	**β−**	100
83	**Bi**	Bismuth	209	S	**Y**	**N**	**N**	**N**	**N**	**Y***	**N**	**N**	**N**	1.90E+19	**Tl-205**	**α**	100
			210	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.37E-02	**Po-210**	**β−**	
				S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.37E-02	**Tl-206**	**α**	>0.1
			211	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	4.07E-06	**Tl-207**	**α**	99.7
				S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	4.07E-06	**Po-211**	**β−**	0.3
			212	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.15E-04	**Po-212**	**β−**	64.1
				S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.15E-04	**Tl-207**	**α**	35.9
				S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.15E-04	**Po-211**	**β−**	>0.1
			213	S	**Y**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	8.67E-05	**Po-213**	**β−**	97.9
				S	**Y**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	8.67E-05	**Tl-209**	**α**	2.1
			215	S	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**	**N**	1.45E-05	**Po-215**	**β−**	100
84	**Po**	Polonium	210	S	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.79E-01	**Pb-206**	**α**	100
			211	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.64E-08	**Pb-207**	**α**	100
			212	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	9.48E-15	**Pb-208**	**α**	100
			213	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.16E-13	**Pb-209**	**α**	
			214	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	5.21E-12	**Pb-210**	**α**	
			215	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	5.65E-11	**Pb-211**	**α**	100
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	5.65E-11	**At-215**	**β−**	>0.1
			216	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	4.60E-09	**Pb-212**	**α**	

				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	4.60E-09	**Rn-216**	**β−**	>0.1
85	**At**	Astatine	215	S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.17E-12	**Bi-211**	**α**	100
			217	S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.02E-09	**Bi-213**	**α**	100
				S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.02E-09	**Rn-217**	**β−**	>0.1
			219	S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.78E-06	**Bi-215**	**α**	97
				S	**N**	**N**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.78E-06	**Rn-219**	**β−**	3
86	**Rn**	Radon	216	G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.43E-12	**Po-211**	**α**	
			217	G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.71E-11	**Po-213**	**α**	
			218	G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.11E-09	**Po-214**	**α**	
			219	G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.26E-07	**Po-215**	**α**	100
			220	G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.76E-06	**Po-216**	**α**	
				G	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.76E-06	**Ra-220**	**β−**	>0.1
87	**Fr**	Francium	221	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	9.32E-06	**At-217**	**α**	99.9
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	9.32E-06	**Ra-221**	**β−**	0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	9.32E-06	**Tl-207**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	9.32E-06	**C-14**		
			223	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	4.19E-05	**Ra-223**	**β−**	100
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	4.19E-05	**At-219**	**α**	>0.1
88	**Ra**	Radium	220	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	5.68E-10	**Rn-216**	**α**	100
			221	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	8.88E-07	**Rn-217**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	8.88E-07	**Pb-207**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	8.88E-07	**C-14**		
			222	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.21E-06	**Rn-218**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.21E-06	**Pb-208**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.21E-06	**C-14**		
			223	S	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.13E-02	**Pb-209**	**α**	
				S	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.13E-02	**C-14**	**CD**	>0.1
			224	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	9.95E-03	**Rn-220**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	9.95E-03	**Pb-210**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	9.95E-03	**C-14**		
			225	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	4.08E-02	**Ac-225**	**α**	
			226	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.60E+03	**Rn-220**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.60E+03	**Th-226**	**β−β−**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.60E+03	**Pb-212**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	1.60E+03	**C-14**		
			227	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	8.03E-05	**Ac-227**	**β−**	
89	**Ac**	Actinium	225	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.74E-02	**Fr-221**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.74E-02	**Bi-211**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.74E-02	**C-14**		
			227	S	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.18E+01	**Th-227**	**β−**	98.6

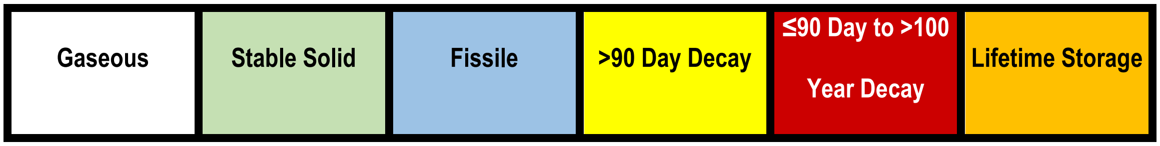
				S	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	2.18E+01	**Fr-223**	**α**	1.4
90	**Th**	Thorium	226	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	5.82E-05	**Ra-222**	**α**	
			227	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	5.12E-02	**Ra-223**	**α**	100
			228	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.91E+00	**Ra-224**	**α**	
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.91E+00	**Pb-208**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	1.91E+00	**O-20**		
			229	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.34E+03	**Ra-225**	**α**	
			230	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.54E+04	**Hg-206**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.54E+04	**Ne-24**		
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.54E+04	**Ra-226**	**α**	
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	7.54E+04	**Various**	**SF**	>0.1
			231	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.91E-03	**Pa-231**	**β−**	
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	2.91E-03	**Ra-227**	**α**	>0.1
			234	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**N**	**N**	6.60E-02	**Pa-234**	**β−**	
91	**Pa**	Protactinium	231	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.28E+04	**Ac-227**	**α**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.28E+04	**Ti-207**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.28E+04	**Ne-24**		
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.28E+04	**Pb-208**	**CD**	>0.1
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	3.28E+04	**F-23**		
			233	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	7.39E-02	**U-233**	**β−**	
			234	S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	7.65E-04	**U-234**	**β−**	
				S	**N**	**Y**	**N**	**N**	**Y**	**Y**	**N**	**N**	**N**	7.65E-04	**Various**	**SF**	>0.1
92	**U**	Uranium	232	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	6.89E+01	**Th-228**	**α**	
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	6.89E+01	**Pb-208**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	6.89E+01	**Ne-24**		
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	6.89E+01	**Hg-204**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	6.89E+01	**Mg-28**		
			233	S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Th-229**		
				S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Pb-209**	**CD**	>0.1
				S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Ne-24**		
				S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Hg-205**	**CD**	>0.1
				S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Mg-28**		
				S	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	1.59E+05	**Various**	**SF**	>0.1
			234	S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Th-230**	**α**	
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Hg-206**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Mg-28**		
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Hf-184**	**CD**	>0.1
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Ne-26**		
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Ne-24**		
				S	**N**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**N**	2.46E+05	**Various**	**SF**	>0.1

			235	S	Y	Y	N	Y	Y	Y	Y	Y	Y	7.04E+08	Th-231	α	
				S	Y	Y	N	Y	Y	Y	Y	Y	Y	7.04E+08	Hf-186	CD	>0.1
				S	Y	Y	N	Y	Y	Y	Y	Y	Y	7.04E+08	Ne-25		
				S	Y	Y	N	Y	Y	Y	Y	Y	Y	7.04E+08	Ne-24		
				S	Y	Y	N	Y	Y	Y	Y	Y	Y	7.04E+08	Various	SF	>0.1
			236	S	N	Y	N	Y	Y	Y	N	Y	N	2.34E+07	Th-232	α	
				S	N	Y	N	Y	Y	Y	N	Y	N	2.34E+07	Various	SF	>0.1
			237	S	N	Y	N	Y	Y	Y	N	Y	N	1.85E-02	Np-237	β−	100
			238	S	N	Y	N	Y	Y	Y	N	Y	N	4.47E+09	Th-234	α	
				S	N	Y	N	Y	Y	Y	N	Y	N	4.47E+09	Pu-238	CD	>0.1
				S	N	Y	N	Y	Y	Y	N	Y	N	4.47E+09	Various	SF	>0.1
			239	S	N	Y	N	Y	Y	Y	N	Y	N	4.46E-05	Np-239	β−	
93	**Np**	Neptunium	237	S	N	Y	N	Y	Y	Y	Y	Y	Y	2.14E+06	Mg-30	CD	>0.1
				S	N	Y	N	Y	Y	Y	Y	Y	Y	2.14E+06	Tl-207		
				S	N	Y	N	Y	Y	Y	Y	Y	Y	2.14E+06	Pa-233	α	
				S	N	Y	N	Y	Y	Y	Y	Y	Y	2.14E+06	Various	SF	>0.1
			238	S	N	Y	N	Y	Y	Y	N	Y	N	5.80E-03	Pu-238	β−	
			239	S	N	Y	N	Y	Y	Y	N	Y	N	6.45E-03	Pu-239	β−	
			240	S	N	Y	N	Y	Y	Y	N	Y	N	1.18E-04	Pu-240	β−	
94	**Pu**	Plutonium	238	S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	U-234	α	
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Hg-206	CD	>0.1
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Si-32		
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Yb-180	CD	>0.1
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Mg-30		
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Mg-28		
				S	Y	Y	Y	Y	Y	Y	N	Y	N	8.77E+01	Various	SF	>0.1
			239	S	N	Y	Y	Y	Y	Y	Y	Y	Y	2.41E+04	U-235	α	
				S	N	Y	Y	Y	Y	Y	Y	Y	Y	2.41E+04	Various	SF	>0.1
			240	S	N	Y	Y	Y	Y	Y	N	Y	N	6.56E+03	U-236	α	
				S	N	Y	Y	Y	Y	Y	N	Y	N	6.56E+03	Hg-206	CD	>0.1
				S	N	Y	Y	Y	Y	Y	N	Y	N	6.56E+03	Si-34		
				S	N	Y	Y	Y	Y	Y	N	Y	N	6.56E+03	Various	SF	>0.1
			241	S	N	Y	Y	Y	Y	Y	Y	Y	N	1.43E+01	AM-241	β−	100
				S	N	Y	Y	Y	Y	Y	Y	Y	N	1.43E+01	U-237	α	>0.1
				S	N	Y	Y	Y	Y	Y	Y	Y	N	1.43E+01	Various	SF	>0.1
			242	S	N	Y	Y	Y	Y	Y	N	Y	N	3.75E+05	U-238	α	
				S	N	Y	Y	Y	Y	Y	N	Y	N	3.75E+05	Various	SF	>0.1

9.3) Fission Product Yields [By Fissile Isotope]

Fission product yield tables have been color-coded for quick-reference.

Color codes are:



Gaseous	Stable Solid	Fissile	>90 Day Decay	≤90 Day to >100 Year Decay	Lifetime Storage

Figure 6 - Color Codes for Fission Product Distribution Figures

9.3.a) Uranium-233 [^{233}U]

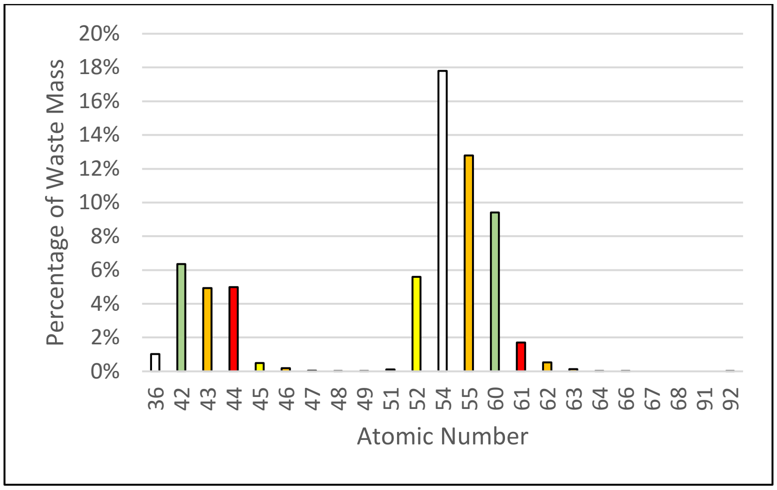


Figure 7 - Uranium-233 [^{233}U] Fission Product Distribution, by Element

9.3.b) Uranium-235 [^{235}U]

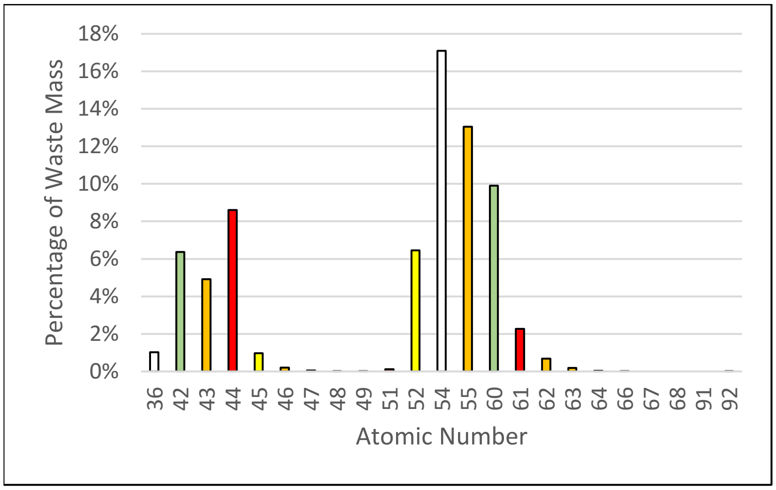


Figure 8 - Uranium-235 [^{235}U] Fission Product Distribution, by Element

9.3.c) Plutonium-239 [^{239}Pu]

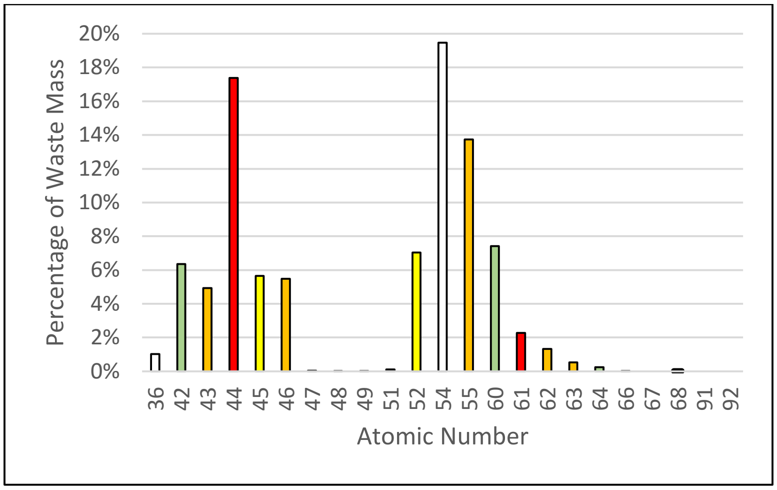


Figure 9 - Plutonium-239 [^{239}Pu] Fission Product Distribution, by Element

9.3.d) Plutonium-241 [^{241}Pu]

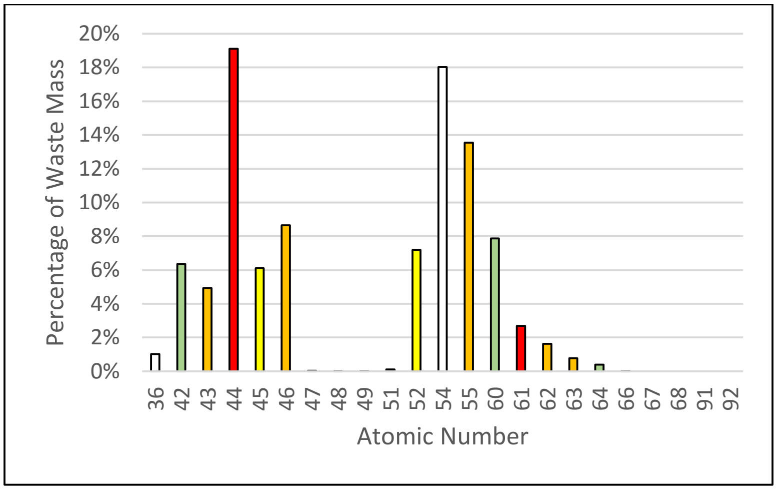


Figure 10 - Plutonium-241 [^{241}Pu] Fission Product Distribution, by Element