Seattle Journal of Technology, Environmental & Innovation Law

Volume 12
Issue 1 *Issue 12 (2022)*

Article 3

1-19-2022

Uranium 233: The Nuclear Superfuel No One is Using

Maris Hanson
Seattle University School of Law

Uranium 233: The Nuclear Superfuel No One is Using

Cover Page Footnote

Juris Doctor candidate 2022, shareholder in Flibe energy. With thanks to Glenn Seaborg, and Alvin Weinberg for paving the way, Kirk Sorensen for his tireless efforts to realize the potential of U233, and my control rod, David.

Uranium 233: The Nuclear Superfuel No One is Using

By Maris Hanson[*]

I. INTRODUCTION

Energy and water are the two most fundamental building blocks of life.[1] With these building blocks, humanity can produce virtually every other product: from the food we eat, to the houses we live in, and the clothes we wear.[2] Energy significantly increases our quality of life through advancements, such as refrigerators, washing machines, dishwashers, transportation, heating, air conditioning, phones, and the internet.[3] However, access to energy is not equal between nations, and the world will need to increase energy production substantially to continue advancing and improve the living conditions in developing nations.[4] Currently, the United States (U.S.) primarily uses fossil fuels to produce energy.[5] This usage is a concern because burning fossil fuels release carbon dioxide, a greenhouse gas, which contributes to climate change.[6] Climate change has many noticeable effects, including the

[*] Juris Doctor candidate 2022, shareholder in Flibe energy. With thanks to Glenn Seaborg, and Alvin Weinberg for paving the way, Kirk Sorensen for his tireless efforts to realize the potential of U233, and my control rod, David.

[1] Ron Smith, *Water and Energy Limiting Factors*, FARM PROGRESS (Dec. 29, 2008), https://www.farmprogress.com/management/water-and-energy-limiting-factors [https://perma.cc/L74T-2X4Q].

[2] Debora Rodrigues, *Water, Energy, Food – Increasingly Everything is Connected*, FORBES (Sep. 15, 2016), https://www.forbes.com/sites/uhenergy/2016/09/15/water-energy-food-increasingly-everything-is-connected/?sh=6ca02c0e2af4, [https://perma.cc/7DCU-7E6X].

[3] Cesar Pasten & J. Carlos Santamarina, Energy and Quality of Life, Energy Policy, 49 ENERGY POLICY 468, 469 (2012), [https://perma.cc/ZE5A-H658].

[4] *Id*. at 473-74.

[5] *U.S. Energy Facts Explained*, U.S. ENERGY INFORMATION ADMINISTRATION, https://www.eia.gov/energyexplained/us-energy-facts/ (last visited Oct. 19, 2021) [https://perma.cc/LFF5-GM5S].

[6] *The Causes of Climate Change*, NASA, https://climate.nasa.gov/causes/ (last visited Oct. 19, 2021) [https://perma.cc/SYN4-FM3X].

rising sea level from melting ice caps and increasing evaporation of freshwater.[7]

Clean energy alternatives like solar, wind, and geothermal power are popular topics and have been extensively treated in other works.[8] These clean energy sources help to raise the quality of life worldwide by reducing greenhouse gas emissions because they do not release carbon dioxide into the atmosphere.[9] For example, clean energy can produce abundant freshwater, thus preserving one of the fundamental resources needed to sustain life.[10] This freshwater can sustain life by providing drinking water and making agriculture possible, but freshwater is limited and desalinization needs a more efficient and clean energy source to be viable.[11] Energy and filters are fifty percent of the reverse osmosis cost, while electrolytic and evaporative desalinization technologies cost even more energy.[12]

Additionally, technology exists to extract carbon from seawater, and because the ocean absorbs carbon from the atmosphere removing carbon from seawater will pull carbon out of the atmosphere.[13] Scientists can turn this collected carbon into hydrocarbon chains, supplying fuel and replacing gasoline.[14] The extracted carbon fuel can be stored, burned for net-zero impact, or linked into longer hydrocarbons to make oil or plastics.[15] However, this solution only makes sense with a portable energy source that produces less carbon than it extracts.[16] Considering the breadth and impact of the climate crisis, it would be irresponsible not to explore all possible solutions to climate change. This article does not intend to suggest that we limit exploration of any clean energy sources. Rather this article encourages the consideration of an additional solution that can be pursued in tandem with those efforts: nuclear energy.

---

[7] *Id.*

[8] *See generally, U.S. Energy Facts Explained*, U.S. ENERGY INFORMATION ADMINISTRATION, https://www.eia.gov/todayinenergy/index.php?tg=%20renewable (last visited Oct. 19, 2021) [https://perma.cc/8WFB-SUDZ] (list of articles on renewable energy).

[9] Bret Kugelmass, *Want to Stop Climate Change? Embrace the Nuclear Option*, USA TODAY (Jan. 22, 2020), https://www.usatoday.com/story/opinion/2020/01/22/climate-change-solution-nuclear-energy-our-best-hope-column/2821183001/ [https://perma.cc/9HJ9-GGDR]. [https://perma.cc/9HJ9-GGDR].

[10] Ron Smith, *supra* note 1.

[11] *See* Temple Fennell, *How Energy Efficient Technologies Can Help Us Solve the Global Clean Water Crisis*, RENEWABLE ENERGY MAG. (Oct. 13, 2020), https://www.renewableenergymagazine.com/panorama/how-energyefficient-technologies-can-help-us-solve-20201013 [https://perma.cc/YE5B-UMQ7] (Detailing that energy constrains water solutions and suggesting technology be developed to lower the energy cost of solutions).

[12] SA Avlonitis, *Operational water cost and productivity improvements for small-size RO desalination plants*, 142 DESALINATION 295, 296 (2002) [https://perma.cc/4ZM2-SQ2U] (comparing the actual and theoretic energy costs for distillation vs. reverse osmosis methods of desalination resulting in a cost of between 12.6 and 15.2 kWh/m^3).

[13] Holli Riebeek, *The Ocean's Carbon Balance*, NASA (Jul. 1, 2008), https://earthobservatory.nasa.gov/features/OceanCarbon [https://perma.cc/F88G-WSWG].

[14] Don Wilmott *Fuel from Seawater?What's the Catch?* SMITHSONIAN MAG. (Dec. 16, 2014), https://www.smithsonianmag.com/innovation/fuel-seawater-whats-catch-180953623/ [https://perma.cc/FE3S-9AN6].

[15] *Id.*

[16] *See generally* Bob Marcotte, *Low-cost Catalyst Helps Turn Seawater Into Fuel at Scale*, SCI. DAILY (Jul. 15, 2020), https://www.sciencedaily.com/releases/2020/07/200715123120.htm [https://perma.cc/8CAR-BE8J].

Nuclear power plants generate energy by splitting atoms and harnessing the energy they release.[17] Nuclear power generates more power per square mile than solar and wind and more power per kilogram of fuel than coal or natural gas.[18] Nuclear power does not release carbon dioxide into the atmosphere, and so it is considered clean energy.[19] With its high energy density and the lack of greenhouse gas emissions, nuclear energy has great potential as the source of clean, constant energy to reap the benefits mentioned above.[20] However, not all nuclear power is equally beneficial.

Uranium 233 (U233) deserves special consideration in nuclear fuel regulations due to its proliferation resistance, safer waste profile, renewability, and beneficial byproducts as compared to Uranium 235 (U235) and Plutonium (Pu).[21] At a bare minimum, the Nuclear Regulatory Commission (NRC) should include U233 in the regulatory materials it creates.[22] For example, the NRC should include a description of a closed loop U233 fuel cycle on its website, which now only includes a description of the fuel cycle of U235.[23] The NRC should also review current regulations and consider how they would apply to an in situ U233 fuel cycle, where the fuel is created and burned in the same reactor. These changes would facilitate the adoption of a nuclear energy technology that could provide ample clean energy for the U.S and be shared more freely with developing nations. Wider use of U233 would increase energy output without greenhouse gas emissions, and innovators could use this abundant, clean energy to power the technological solutions to climate change.

One possible barrier to the development of a closed loop U233 fuel cycle is the current definition of reprocessing. The most efficient reactor design using U233 requires the extraction of various fission byproducts from a continuously cycling fluid fuel.[24] The U.S. does not license fuel reprocessing for commercial use in the U.S. due to nuclear weapon

---

[17] *Nuclear 101: How do Nuclear Reactors Work*?, OFF. OF NUCLEAR ENERGY, https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work (last visited Oct. 19, 2021) [https://perma.cc/PK4C-6ZZF].

[18] Laurence William, *Why should we go nuclear?*, ANGEL J. (May. 11, 2016), https://anglejournal.com/article/2016-05-why-nuclear/#:~:text=Nuclear%20power%20is%20in%20a,kg%20of%20U235%20per%20day. [https://perma.cc/N6PR-Y53W].

[19] *Id.*

[20] *Id.*

[21] Uranium 233 is a nuclear isotope of Uranium with 2 fewer neutrons than Uranium 235. *See generally*, Video Interview with Kirk Sorensen, Chief Technologist, Flibe Energy, Oct. 5, 2021. For this article, proliferation resistance means not easily used as weapons material. The term is a complex one that is used in many contexts. *See generally*, Larry R. Avens, William D. Stanbro & P. Gary Eller, *What Actually is Meant by "proliferation resistance" in Discussion of Advanced Nuclear Fuel Cycles*, LOS ALAMOS NAT'L LAB'Y (Jul. 18, 2004), https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-04-4193 [https://perma.cc/NP4U-YF56].

[22] *About NRC*, UNITED STATES NUCLEAR REGULATORY COMMISSION,, https://www.nrc.gov/about-nrc.html (last visited Oct. 19, 2021) [https://perma.cc/6FQB-6HHU] (The NRC is an independent agency in charge of regulating and licensing civilian nuclear material use).

[23] *Stages of the Nuclear Fuel Cycle*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/materials/fuel-cycle-fac/stages-fuel-cycle.html (last visited Oct. 19, 2021) [https://perma.cc/6XKH-LEZQ].

[24] Video Interview with Kirk Sorensen, *supra* note 21.

proliferation concerns.[25] As a result, any process determined to be "reprocessing" faces a high regulatory hurdle.[26] The NRC glossary defines reprocessing as "[t]he processing of reactor fuel to separate the unused fissionable material from waste material. Reprocessing extracts isotopes from spent nuclear fuel so they can be used again as reactor fuel." The NRC should clarify this definition to exclude chemical reprocessing done within the reactor's radiation cell necessary for fluid fuel reactors. Additionally, the NRC should interpret this definition to allow the change of spent solid fuel to liquid fuel, which innovators could use to kick start the U233 fuel cycle, reducing current waste stores by more than half and generating energy in the process.[27] The NRC should explicitly allow this interpretation to reduce current nuclear waste.

Finally, Congress should stop the irreversible dilution of current U233 for long-term waste storage.[28] This harmful process is known as down blending and makes the existing stockpile of this superfuel irretrievable.[29] While Congress previously saw U233 as waste, companies can use U233 as fuel in advanced reactor designs if Congress stops the down blending.[30]

This article will provide basic nuclear information, such as the difference between thermal and fast reactors, the basics of a standard pressurized water reactor, and the creation of nuclear waste. This article will also discuss nuclear concerns and the benefits of U233 as a fuel source. The discussion will focus on the benefits of U233, particularly in a fluid fuel cycle such as the proposed liquid floride thorium reactor (LFTR pronounced lifter) and give examples of other proposed advanced reactors. The article will also describe the current regulatory scheme, or lack thereof, regarding U233 and suggest essential changes to encourage and include U233 and liquid fuel reactors on the NRC website. Finally, this article will also suggest solutions to the challenges of nuclear waste storage in the U.S. and provide concrete steps to preserve the existing U233.

---

[25] *Reprocessing*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/materials/reprocessing.html (last visited Oct. 19, 2021) [https://perma.cc/AK95-M89T].

[26] In March 2021 the NRC issued a notice that it was halting rulemaking activity that would have created regulations for a fuel reprocessing facility. Annette L. Vietti-Cook, *Spent Fuel Reprocessing*, NUCLEAR REGULATORY COMMISSION (2021), https://www.nrc.gov/docs/ML2030/ML20301A389.pdf [https://perma.cc/F73G-44Y5].

[27] Video Interview with Kirk Sorensen, *supra* note 21.

[28] *See Upgrades Prepare Way for Oak Ridge to Process Remaining Uranium-233*, OFFICE OF ENVIRONMENTAL MANAGEMENT,, https://www.energy.gov/em/articles/upgrades-prepare-way-oak-ridge-process-remaining-uranium-233#:~:text=OAK%20RIDGE%2C%20Tenn.&text=Stored%20in%20the%20world's%20oldest,It%20did%20not%20prove%20viable.&text=A%20Building%202026%20hot%20cell%20before%20crews%20remove%20old%20equipment. (last visited Oct. 19, 2021) [https://perma.cc/V75R-LTMC].

[29] John Huitari, *DOE Disposing of Uranium-233 Waste*, OAKRIDGE TODAY (Aug. 27, 2017), https://oakridgetoday.com/2017/08/27/doe-program-disposing-uranium-233-waste-stored-ornl/ [https://perma.cc/V37P-59TN]. Daughter products are the smaller atoms created by the splitting of a larger atom. *See* Glenn T. Seaborg, *infra* note 60.

[30] Video Interview with Kirk Sorensen, *supra* note 21.

II. BACKGROUND: BASIC NUCLEAR INFORMATION

Three particles make up atoms: protons, neutrons, and electrons.[31] The number of protons determine the atomic number, or which element from the periodic table, of any particular atom. The number of protons and neutrons added together determines the isotopic number.[32] The same element can have different isotopes, such as Uranium 232, 233, 235, and 238, but they all react chemically in an identical way.[33] An imbalance in the number of protons and neutrons makes an atom unstable and prone to transmutation through radioactive decay.[34]

A. Radioactivity and Decay

Radioactive or nuclear decay can happen in three ways: alpha, beta, and gamma decay.[35] Alpha decay is the emission of two protons and two neutrons (a helium atom), which lowers the atomic number by two, moving the atom down the periodic table of elements by two and reducing the isotopic number by four.[36] Beta-decay is the emission of an electron and the transmutation of a neutron into a proton.[37] This process moves an element up the periodic table of elements by one, while keeping the same isotopic number.[38] Gamma decay is the emission of a photon from the nucleus of an atom that lowers the atom's energy state but does not affect either the atomic or isotopic number of the atom.[39] Gamma decay occurs when an atomic nucleus is in an excited state.[40] This excited state can be caused by previous alpha decay, beta decay, or a collision with a free neutron.[41] In a free neutron collision, the neutron bounces off the atom, imparting energy and leaving the atom in an excited state resolved by the emission of a high-energy photon called a gamma ray.[42]

---

[31] Roberta C. Barbalace, *Anatomy of the Atom*, ENVIRONMENTALCHEMISTRY.COM (Dec., 1998), https://environmentalchemistry.com/yogi/periodic/atom_anatomy.html [https://perma.cc/W4VQ-VFW5].
[32] *Id.*
[33] *See id.*
[34] Protons are positively charged particles and neutrons are neutrally charged particles. The positive charges of protons repel each other, and without an equal number of neutrons to dilute the repulsion and hold the nucleus together the atom is prone to split or eject particles. *RadTown Radioactive Atom: Teacher Information*, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, https://www.epa.gov/radtown/radtown-radioactive-atom-teacher-information (last visited Oct. 19, 2021) [https://perma.cc/HQC2-WY97].
[35] *Radioactive Decay*, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, https://www.epa.gov/radiation/radioactive-decay (last visited Oct. 19, 2021) [https://perma.cc/AU92-KCSA].
[36] John O. Rasmussen, *Radioactivity*, BRITANNICA (Aug. 23, 1998), https://www.britannica.com/science/radioactivity#ref48273 [https://perma.cc/W4VQ-VFW5].
[37] *Id.*
[38] *Id.*
[39] *Id.*
[40] *Id.*
[41] *Id.*
[42] *Id.*

B. Neutron interactions: A Game of Probabilities

Neutron interaction is a game of probabilities.[43] A neutron interacts with an atom in three possible ways: collision, capture, or fission.[44] More energetic neutrons have a lower chance of interacting with anything.[45] Each element and isotope has a different chance of an interaction occurring.[46] Many elements, like oxygen, have virtually no chance of neutron interaction.[47]

When an atom deflects a neutron, scientists call it a collision. During the collision the neutron will impart some energy to the atom and lose speed.[48] Elements with a high chance of collision, but a low chance of absorption or fission, are excellent at slowing down high-energy neutrons.[49] Such materials moderate the neutron and scientists call them moderators.[50] Hydrogen (in water) and carbon (in graphite) are two examples of excellent neutron moderators.[51]

Nuclear transmutation occurs when an atom absorbs a neutron during an interaction with another atom.[52] Scientists call this process neutron capture or absorption. Absorption changes the isotope, increasing the isotopic number by one, normally creating an imbalance between protons and neutrons.[53] Generally, this imbalance causes the atom to become unstable and begins a chain of nuclear decay.[54] The atom will emit alpha or beta particles, stepping up and down the periodic table until a stable configuration is reached.[55] Scientists call this process radioactive decay. The series of elements an atom transmutes into until reaches stability they call the decay chain.[56] When a decay chain includes semi-stable fissionable isotopes, scientists call the source material fertile. Thorium-232 and U238 are both fertile and can transmute into U233 and Pu respectively.[57]

In sufficiently large atoms, the neutron absorption can cause the nucleus to split. Scientists call this process fission.[58] Fission releases a large amount of energy, some free neutrons, and two atoms from an array of possible smaller atoms.[59] Scientists call these two smaller atoms

---

[43] P PHIL M. RINARD ET AL, *PASSIVE NONDESTRUCTIVE ASSAY OF NUCLEAR MATERIALS* 357 (Doug Reilly et al. eds., 1991).
[44] *Id.* at 359.
[45] *Id*. at 361-362.
[46] *Id*. at 364. Video Interview with, Parker Okabe, PhD, Project Manager, Flibe Energy (November 5, 2021).
[47] Rinard, *supra* note 43, at 362-63.
[48] *Id*. at 360.
[49] *Id*. at 370.
[50] *Id*.
[51] *Id*. at 368-69
[52]*Id*. at 359.
[53] *RadTown Radioactive Atom: Teacher Information*, *supra* note 34.
[54] *Id*.
[55] *Radioactive Decay*, *supra* note 35
[56] *Id*.
[57] *RadTown Radioactive Atom: Teacher Information*, *supra* note 34.
[58] Rinard, *supra* note 43, at 359-61.
[59] *Id*.

daughter products.[60] While it is impossible to predict which two isotopes will form from any single fission event, scientists can predict the overall percentage of different daughter products from a large number of fission events based on the original atom's size.[61] Scientists use the same statistical methodology with coin flips where they cannot predict whether heads or tails will result on any given coin flip, but can say with confidence that roughly 500 heads and 500 tails will result from 1,000 coin flips.[62]

C. Thermal vs. Fast Neutrons: Changing the Rules of the Game

Most free neutrons leave an atom in a highly energized state, either through fission or a particle accelerator.[63] These highly energized neutrons are said to be in the "fast spectrum."[64] When materials such as water (specifically the hydrogen in water) or graphite moderate these fast neutrons, they slow until they have an energy level similar to the material moderating them.[65] These slowed neutrons are in an energetic equilibrium with their environment and scientists call them "thermal" neutrons because they have the same temperature as the atoms around them.[66] Slower neutrons are always more likely to interact with other atoms.[67]

Whether a neutron is fast or thermal affects the energy of subsequent collisions and the rate of collision.[68] Faster neutrons collide with other atoms less frequently but with more energy.[69] This means that fission by fast neutrons will generally release more free neutrons than fission caused by thermal neutrons.[70] However, due to the smaller chance of interaction for each atom within the fast spectrum neutron, reactors need more fuel to maintain the same rate of reactions.[71]

D. Reactors, Fuel, and Nuclear Waste: Harnessing the Reactions

Reactors control and contain neutron collisions and use the heat generated by these reactions to generate energy.[72] Reactors consist of a

[60] *See*, Glenn T. Seaborg, *History of Met Lab Section C-I: May 1945 to May 1946*, U.S. DEP'T OF ENERGY OFF. OF SCI. AND TECH. INFORMATION, 1, 165 (June 1, 1980), https://www.osti.gov/servlets/purl/5063798 [https://perma.cc/2M9X-YL85] Video interview with Parker Okabe interview, *supra* note 46.

[61] See generally, *supra* note 60 at 411-12, Seaborg Papers, detailing how samples were bombarded with neutrons to induce fission and then the material was separated into distinct elements to count which daughter products resulted.

[62] Rinard, *supra* note 43, at 375-76.

[63] *Id*. at 358. Video interview with Parker Okabe interview, *supra* note 46.

[64] Rinard, *supra* note 43, at 358.

[65] *See Id*. at 371.

[66] *Neutron Energy*, NUCLEAR-POWER.NET, https://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/fundamental-particles/neutron/neutron-energy/ [https://perma.cc/DME3-SLY6].

[67] Rinard, *supra* note 43, at 363.

[68] *Id*. at 358.

[69] *Id*. at 367. Video interview with Parker Okabe interview, *supra* note 46.

[70] *Physics of Uranium and Nuclear Energy*, WORLD NUCLEAR ASS'N, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/physics-of-nuclear-energy.aspx [https://perma.cc/3J2Z-B5DE].

[71] Video Interview with Kirk Sorensen, *supra* note 21.

[72] Office of Nuclear Energy, *supra* note 20.

core, biological shielding, and various supporting auxiliary services.[73] Reactors can operate using either fast or thermal spectrum neutrons. Due to the increased fuel requirements of fast spectrum reactors and other efficiency concerns, power generating reactors universally operate with moderated neutrons in the thermal spectrum.[74] The core of a reactor contains the fuel and the moderator.[75] Spontaneous fission introduces neutrons into the core, and then by adjusting the geometric arrangement of the fuel in relation to the moderator, nuclear technicians can increase, decrease or maintain the reaction. Scientists call the change in reaction rate criticality.[76] Supercritical reactions increase in rate, subcritical reactions decreasing in rate, and critical reactions maintain a balanced rate.[77] Standard practice places the fuel and moderator in a supercritical arrangement and inserts "control rods" of neutron absorbing material to regulate the reaction rate in line with energy demand and other operational requirements.[78]

The collision of neutrons with atoms transfers energy; this energy can eject neutrons or split the atom into two lesser elements.[79] All these reactions release energy, eventually expressed as heat.[80] This heat boils water in the reactor, which creates steam, turning turbines to generate electricity.[81] The difference between using nuclear fuel and fossil fuels is the source of the heat and the waste generated.[82] With fossil fuels, burning (or oxidizing) the carbon generates heat, releasing carbon dioxide (CO_2) and other chemicals into the air.[83] In a nuclear reactor, the fission of fuel and subsequent decay of the daughter products create heat.[84] However, many of these unstable daughter products are dangerously radioactive and need to be contained for an extended period of time.[85] Fission can create a variety of elements as a result of the subsequent decay chains.[86] Reactor sites must store these elements safely and continually remove heat until the radioactivity decreases and the waste becomes thermally stable.[87]

---

[73] *Id.* Video interview with Parker Okabe interview, *supra* note 46.
[74] Video Interview with Kirk Sorensen, *supra* note 21.
[75] *Id.*
[76] *What is Criticality*, MIT NSE NUCLEAR INFO. HUB, https://mitnse.com/2011/03/18/what-is-criticality/ [https://perma.cc/U8W6-Z672].
[77] *Id.*
[78] *Id.*
[79] Rinard, *supra* note 43, at 361.
[80] Office of Nuclear Energy, *supra* note 17.
[81] *Id.*
[82] John Papiewski, *The Differences Between Nuclear Power & Fossil Fuel-Burning Power Plants*, SCIENCING, https://sciencing.com/differences-between-nuclear-power-fossil-fuelburning-power-plants-21387.html [https://perma.cc/4MSJ-MDAS].
[83] *Id.*
[84] Office of Nuclear Energy, *supra* note 17. Video interview with Parker Okabe interview, *supra* note 46.
[85] Seaborg, *supra* note 60 at 165, Video Interview with Kirk Sorensen, *supra* note 21.
[86] *See generally* Seaborg, *supra* note 60, detailing the original research in determining the daughter products from naturally fissile fuels.
[87] *Backgrounder on Radioactive Waste*, U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html [https://perma.cc/HMT3-U88P]. Video interview with Parker Okabe interview, *supra* note 47.

The NRC classifies radioactive waste into different levels: high, medium, and low.[88] They consider spent fuel high-level waste.[89] They have not currently approved any site to store high-level radioactive waste.[90] All high-level radioactive waste is either spent fuel or waste separated from spent fuel.[91] Companies currently store high-level waste at reactor sites, whether the reactor is still functioning or not, because there is nowhere to move the spent fuel.[92] First, they cool spent fuel in a pool of water, and then after at least a year, but often ten years, they move the spent fuel out of the pools and into storage units called dry casks.[93] Dry casks are steel containers filled with inert gas and sealed with the radioactive waste inside, and then covered in concrete.[94] These casks are licensed for forty years, but the NRC can inspect and recertify them for another forty years.[95]

D. Fuel Sources, Enrichment, and Breeding: Playing the Game on a Neutron Budget

Only three known isotopes have enough propensity to fission for use as fuel in a nuclear reactor: U233, U235, and Pu239.[96] Of these, only U235 occurs naturally.[97] U233 and Pu239 no longer exist in natural deposits and require naturally occurring fertile precursors, Th232 and U238 to transmute from neutron capture, a process known as breeding.[98]

U235 makes up roughly 0.71% (or 7.100 parts per million) of all uranium ore, with U238 making up the difference.[99] To sustain fission reactions, scientists need to enrich U235.[100] Enrichment is a process that increases the concentration of a desired isotope.[101] U235 needs a density of about three to five percent before it can sustain fission.[102] For enrichment, scientists first convert U235 into a fluoride gas and then spin that fluoride gas in a centrifuge.[103] U235 has a lower mass by three atomic units than its more abundant relative U238.[104] U238's greater

---

88 *Radioactive Waste Management*, WORLD NUCLEAR ASS'N, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx [https://perma.cc/6UR9-H277].
89 United States Nuclear Regulatory Commission, *supra* note 87.
90 *Id.*
91 *Id.*
92 *Id.*
93 *Spent Fuel Pools,* U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/waste/spent-fuel-storage/pools.html, [https://perma.cc/4W2W-TQAL], United States Nuclear Regulatory Commission, *supra* note 88.
94 *See* United States Nuclear Regulatory Commission, *supra* note 87. Interview with Parker Okabe interview, *supra* note 46.
95 *Id.*
96 *Special Nuclear Material,* U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/materials/sp-nucmaterials.html [https://perma.cc/FX73-BGUD].
97 *Id.* Interview with Parker Okabe interview, *supra* note 46.
98 Video Interview with Kirk Sorensen, *supra* note 21.
99 *Uranium Enrichmen*t, U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html [https://perma.cc/K49B-Q9YJ].
100 *Id.*
101 *See Id.*
102 *Id.*
103 *Id.*
104 *Id.*

mass tends to react more to the spinning and ends up in greater concentrations in the outside layer allowing separation from the lighter innermost material.[105] Repeating this process will eventually result in a greater concentration of U235.[106]

Th232 can breed U233 through neutron capture.[107] Th232 exists in the continental crust, the rock layer under the soil, and the shallow seabed.[108] All rare earth mines consider Th232 a waste product and it generates disposal costs for mine operators.[109] Each cubic meter of continental crust yields sufficient Th232 to generate a U.S. household's energy needs for a year after breeding it into U233.[110]

When U238 captures a neutron it transmutes into U239 which undergoes beta decay to become Pu239.[111] Since all U235 fuel will consist of a majority of U238, Pu239 will accumulate in any U235 reactor.[112] If these plutonium atoms remain in a reactor's neutron field, subsequent interactions will cause them either to fission or capture a neutron to become Pu240.[113] As an important note, sustainable breeding of any nuclear fuel requires a minimum of two free neutrons per fission: one to cause the next fission reaction and one to transmute the fertile atom.[114] U235 and Pu239 only satisfy this two neutron requirement when fissioned with fast neutrons since thermal reactions average less than two neutrons per release.[115] U233 is the only fissile material that averages more than two neutrons when fissioned by thermal neutrons; this remarkable property justifies calling U233 the nuclear superfuel.[116] U233 is the only fuel that can sustainably breed more fuel than it burns while operating in the thermal spectrum instead of the fast spectrum.[117]

E. Society's Concerns Regarding Nuclear Energy: Proliferation, Waste, and Meltdown

Society's concerns over the hazards of nuclear energy prevented the realization of the promised lower cost and greater availability of energy. Like the three types of nuclear fuel, society has three major concerns that impede the fulfillment of nuclear energy's promises. Weapons proliferation, nuclear waste management, and catastrophic

---

105 *Id.*
106 *Id.*
107 *Special Nuclear Materials*, U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/materials/sp-nucmaterials.html [https://perma.cc/Y667-ARF8].
108 *See Continental Crust*, SCI. DAILY, https://www.sciencedaily.com/terms/continental_crust.htm [https://perma.cc/ZQL4-AJ8J].
109 Video Interview with Kirk Sorensen, *supra* note 21.
110 *Id.*
111 Interview with Parker Okabe, *supra* note 46.
112 United States Nuclear Regulatory Commission, *supra* note 99. Interview with Parker Okabe, *supra* note 46.
113 United States Nuclear Regulatory Commission, *supra* note 107. Interview with Parker Okabe, *supra* note 46.
114 Video Interview with Kirk Sorensen, *supra* note 21.
115 *Id.*
116 *Id.*
117 *Id.* (U233 releases approximately 2.3 neutrons per fission in the thermal spectrum).

reactor failures such as Chernobyl and Fukushima Daiichi created political and social obstacles to adopting nuclear power.[118]

The history of nuclear research requires some contextual awareness of the weapons development programs of World War II and the Cold War. The designers of the first functioning nuclear reactors in the world had a singular purpose: to provide the fissile materials required to build atomic weapons.[119] Countries have used both U235 and Pu239 to build atomic weapons.[120] This article will not address the engineering challenges associated with the weaponization of nuclear materials. However, every country to demonstrate nuclear weapons capability chose not to pursue U233.[121] Early knowledge of the radiological properties of U233 came from national efforts to examine its feasibility as a replacement for weaponized Plutonium.[122] The research showed then, as it does today, that U233 is an intrinsically flawed weapons material because of its unavoidable contamination with trace amounts of U232 and the gamma rays emitted by this element's decay chain.[123]

Nuclear fission creates radioactive nuclear waste, but not all waste is equally impactful or environmentally hazardous.[124] Counterintuitively, the most intensely radioactive nuclear wastes are the safest and least impactful to the environment because they quickly become inert.[125] The transuranic family harms the environment the most because they require tens of thousands of years of secure storage before becoming safe.[126] The properties of nuclear fuel and reactor design cause the creation of transuranic waste.[127] Because fuel choice and reactor design are inextricably linked, they cannot be analyzed independently. Proposed thermal reactors based on U233 will outperform similar designs using U235 or Pu239 due to the greater propensity of U233 to fission in the thermal spectrum.[128]

The broadest concern in any discussion of nuclear energy is operational safety.[129] This issue has nothing to do with fuel choice but depends entirely on the reactor's design. The primary risk of modern reactors is the choice of water as both moderator and primary coolant, which requires pressure to keep that water liquid.[130]

---

[118] *See generally*, Benjamin K. Sovacool and Christopher Cooper, *Nuclear Nonsense: Why Nuclear Power is No Answer to Climate Change and the World's Post-Kyoto Energy Challenges*, 33 WM. & MARY Envtl. L. & Pol'y Rev. 1 (2008).

[119] *See* Seaborg Papers supra note 60 at 495, Video Interview with Kirk Sorensen, *supra* note 21.

[120] Geoff Brumfiel, *Become A Nuclear Superpower...In Ten Steps,* BBC FUTURE (Nov. 18, 2014), https://www.bbc.com/future/article/20120607-nuclear-weapons-in-ten-steps [https://perma.cc/DF5L-JWE5].

[121] Video Interview with Kirk Sorensen, *supra* note 21.

[122] *Id.*, Seaborg, *supra* note 60.

[123] Kirk Sorensen, Thorium Research in the Manhattan Project Era, 101 (2014) (Master's Thesis, Univ. of Tenn.) (on file with author).

[124] U.S. NUCLEAR REGUL. COMM'N, *supra* note 87.

[125] *Id*.

[126] *Id*.

[127] *See Id*.

[128] Seaborg, *supra* note 60, Video Interview with Kirk Sorensen, *supra* note 21. Interview with Parker Okabe, *supra* note 46.

[129] *See generally*, Sovacool & Cooper, *supra* note 118.

[130] Gordon McDowell, *Kirk Sorensen @ PROTOSPACE on Liquid Fluoride Thorium Reactors*, YouTube (June 2, 2011). at 1:10. [https://perma.cc/CYG7-HRB2].

Reactor designers can entirely avoid these operational risks by using U233 as a fuel in an innovative fluid-fueled molten-salt reactor design such as the LFTR.[131] Molten salt reactors do not require pressure, so the hydrogen-steam explosions like Chernobyl are not a possibility. As a result, reactors utilizing these innovative designs offer clean, abundant energy to solve the energy and environmental crises.

While U233 has many advantages over U235 and Pu239, it must still overcome the negative public perceptions of nuclear power. Due to significant public concern over nuclear power, the government heavily regulates all nuclear power. The NRC and other agencies tailor nuclear power regulations to U235 and Pu239.[132] The NRC also designs these regulations for pressurized water reactors.[133] The traditional pressurized water reactors have a decades-long monopoly on the market, which gives them a significant advantage in an already challenging industry.[134] However, U233 has such significant advantages that it justifies special consideration in regulations.

F. Benefits of U233 as a Fuel Source

U233 is the ideal nuclear fuel source because it can sustainably breed in thermal spectrum reactors, it produces a minuscule amount of transuranic waste, and, it intrinsically resists weaponization.[135] Today, nuclear power predominately uses U235, a naturally occurring element in light water reactors.[136] While this type of nuclear power is carbon-friendly, it has some disadvantages not shared by U233. While U235 occurs naturally and Pu239 can breed from U238, each element requires a fast-spectrum reactor to sustainably breed more fuel than it burns. Th232 breeds U233, and is far more plentiful than U235 or U238.[137] One cubic meter of the continental crust contains the Thorium needed to supply a U.S. household's energy needs for a year.[138]

In addition, U235 and Plutonium generate greater amounts of dangerous waste than U233.[139] The most problematic byproduct of nuclear reactors is a type of radioactive waste called transuranic.[140]

---

[131] Video Interview with Kirk Sorensen, *supra* note 21.
[132] *See, Chairman Christopher T. Hanson Remarks at the United States Nuclear Industry Council Advanced Reactor Summit,* U.S. NUCLEAR REGUL. COMM'N (March 23, 2021), https://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2021/s-21-005.pdf.
[133] *See Id.*
[134] Video Interview with Kirk Sorensen, *supra* note 21.
[135] *Id.*
[136] *Nuclear Fuel Explained,* U.S. ENERGY INFO. ADMIN., https://www.eia.gov/energyexplained/nuclear/the-nuclear-fuel-cycle.php (last visited Feb. 4, 2021) [https://perma.cc/W55G-SF72].
[137] *New Developments in Uranium Exploration, Resources, Production and Demand: Proceedings of a Technical Committee Meeting Jointly Organized by the International Atomic Energy Agency and the Nuclear Energy Agency of the OECD and Held in Vienna, 26-19 August 1991* 104 (1992), https://inis.iaea.org/collection/NCLCollectionStore/_Public/23/086/23086140.pdf?r=1 [https://perma.cc/R9WB-5M8H], Interview with Parker Okabe, *supra* note 46.
[138] Video Interview with Kirk Sorensen, *supra* note 21.
[139] *Id.*
[140] WORLD NUCLEAR ASSOCIATION *supra* note 90 (saying High Level Waste (HLW) has both long-lived (10,000 or more years) and short-lived components (less than 10,000 years), depending on the length of time it will take for the radioactivity of particular radionuclides to decrease to levels that are considered non-

Transuranic waste consists of elements with an atomic number greater than 92.[141] These elements do not occur naturally and cause harm because of their high radioactivity and longevity.[142] Transuranic waste also decays slowly, which makes it the most environmentally harmful nuclear waste.[143] In comparison, U233 produces exponentially less transuranic radioactive waste. [144]

Not only does U233 create less transuranic waste, it also resists nuclear weapon proliferation in two ways. First, it produces less Plutonium than U235-based fuel.[145] The U233 fuel cycle produces far less Plutonium because the fuel does not contain U238.[146] Unlike U235 which contains over 95% U238 and relies on the production of Plutonium to continue the fission reactions, the neutrons released by U233 fission interact with Thorium to produce more U233.[147] While U233 reactors will produce a small amount of Plutonium as a byproduct, they will produce far less Plutonium than current reactors.[148] Second, U233 resists nuclear weapons proliferation because U233 includes U232. This mixture of isotopes resists proliferation because U232 is less stable than U233. U233 has a half-life of 68.9 years compared to U232 at 160,000 years.[149] U232 decays through the emission of strong gamma rays, which makes it easier to locate and requires more transportation precautions.[150] Currently, scientists cannot separate U232 from U233. While theoretically scientists can separate U232 from U233 by separating their precursors in the reactor, they have not yet achieved this

---

hazardous for people and the surrounding environment. If generally short-lived fission products can be separated from long-lived actinides, this distinction becomes important in management and disposal of HLW.

[141] *What is Transuranic Radioactive Waste?*, U.S. ENV'T PROT. AGENCY, https://www.epa.gov/radiation/what-transuranic-radioactive-waste (last visited Nov. 8, 2020) [https://perma.cc/5CPH-54EX].

[142] *Id*.

[143] WORLD NUCLEAR ASSOCIATION *supra* note 89 (explaining waste storage for Long lived Intermediate Waste and HLW.) Interview with Parker Okabe, *supra* note 46.

[144] Video Interview with Kirk Sorensen, *supra* note 21.

[145] For this article, proliferation resistance means not easily used as weapons material. The term is a complex one that is used in many contexts. *See generally*, Larry Avens et al, *What Actually is Meant by "Proliferation Resistance" in Discussions of Advanced Nuclear Fuel Cycles?*, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-04-4193 [https://perma.cc/NP4U-YF56]

see also What is Plutonium?, U.S. NUCLEAR REGUL. COMM'N, https://www.nrc.gov/reading-rm/basic-ref/students/science-101/what-is-plutonium.html [https://perma.cc/6Q7S-7E6G]. Interview with Parker Okabe, *supra* note 46.

[146] Special Nuclear Materials, *supra* note 107. Interview with Parker Okabe, *supra* note 46.

[147] *Status Report – LFTR: Advances in Small Modular Reactor Tech. Dev. (2016)*, INT'L ATOMIC ENERGY AGENCY, 3 (2016), https://aris.iaea.org/PDF/LFTR.pdf [https://perma.cc/7SS9-WGN3]. Interview with Parker Okabe, *supra* note 46.

[148] Video Interview with Kirk Sorensen, *supra* note 21.

[149] *Id. See* K.A. Pradeep Kumar, et al, *Advances in Gamma Radiation Detection Systems for Emergency Radiation Monitoring*, 52 Nuclear Engineering and Tech. 10, 1 introduction, [https://perma.cc/Q7NF-9EYW].

[150] K.A. Pradeep Kumar, et al, *Advances in Gamma Radiation Detection Systems for Emergency Radiation Monitoring*, Nuclear Engineering and Technology vol. 52 issue 10 pg 1 (Oct. 2020), https://www.sciencedirect.com/science/article/pii/S1738573319304425 [https://perma.cc/Q7NF-9EYW]. Interview with Parker Okabe, *supra* note 46.

separation.[151] For these reasons, U233 has a fundamentally different risk profile from U235 and Plutonium for weapons proliferation.[152]

Furthermore, the U233 fuel cycle produces beneficial byproducts.[153] Bismuth 213 and Actinium 225 are some of these products. Researchers seek after these rare isotopes for study in targeted alpha therapy that treats diffuse cancers like leukemia. [154]

Additionally, U233 has more benefits when used in a LFTR.[155] Virtually all nuclear power currently comes from pressurized water reactors.[156] These reactors use solid fuel submerged in water for cooling and moderation of fission reactions.[157] This water requires pressure to stay liquid at the high temperatures found in the reactor core.[158] As seen at Chernobyl, hydrogen-steam explosions historically cause the most harm of nuclear disasters. [159] The LFTR uses U233 as a liquid fuel with no water and so does not require pressurized containment, which makes such explosions impossible.[160]

In addition to avoiding hydrogen-steam explosions and other pressure-failure disasters, the LFTR has additional passive safety mechanisms.[161] The liquid fuel in the LFTR consists of a fluoride salt that circulates through the reactor core.[162] After the liquid fuel leaves the reactor it passes through a pipe with a hole leading to a drainage tank.[163] Blowers cool the pipe and the hole in the pipe so when the molten salt hits the blowers, a frozen plug forms, allowing the salt to complete the

---

[151] *See* Video Interview with Kirk Sorensen, *supra* note 22. Jungmin Kang and Frank N. von Hippel, *U-232 and the Proliferation Resistance of U-233 in Spent Fuel*, 9 Science and Global Security 1, 1 (2001) https://fissilematerials.org/library/sgs09kang.pdf.

[152] *See* U.S. DEPT. OF ENERGY, LRL INTEREST IN U-233 (1966), https://digital.library.unt.edu/ark:/67531/metadc720752/m2/1/high_res_d/79078.pdf [https://perma.cc/38QP-Q5ZS] (declassified Hanford Historical document showing interest in clean U-233 for weapons).

[153] *Nuclear Forensics: A Scientific Search Problem*, NUCLEAR FORENSIC SEARCH PROJECT (last visited Nov. 8, 2020), https://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html [https://perma.cc/M789-7TT8] (showing the decay chain for Np-237, a parent of U-233); Seaborg, *supra* note 61, at 121 (reporting results of original experiment determining decay chain of U-233).

[154] D. Scheinberg, *Actinium-225 and Bismuth-213 Alpha Particle Immunotherapy of Cancer,* INT'L ATOMIC ENERGY AGENCY (2014), https://www.osti.gov/etdeweb/biblio/22270180 [https://perma.cc/JH9Y-9DKX] (reporting positive results for phase 2 monoclonal antibody targeted alpha therapy study and citing scarcity of Bismuth-213 as a major obstacle). Frank Bruchertseifer et al., *Targeted Alpha Therapy with Bismuth-213 and Actinium-225: Meeting Future Demand*, 62 Journal of Labelled Compounds [https://onlinelibrary.wiley.com/doi/abs/10.1002/jlcr.3792] (describing recent positive clinical experience and discussing ways to increase the production of the isotopes).

[155] Liquid Flouride Thorium Reactor.

[156] *See generally* Sovacool & Cooper, *supra* note 118.

[157] *Pressurized Water Reactors*, UNITED STATES NUCLEAR REGULATORY COMMISSION (Jan. 15, 2015), https://www.nrc.gov/reactors/pwrs.html [https://perma.cc/83QV-9VN4].

[158] *Id.*

[159] *Chernobyl Accident 1986*, WORLD NUCLEAR ASS'N (May 2021), https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx [https://perma.cc/MVP4-KFLN].

[160] INT'L ATOMIC ENERGY AGENCY, *supra* note 147, at 2.

[161] *Id.*

[162] Caroline Delbert, *This Molten Salt Reactor is the Next Big Thing in Nuclear,* POPULAR MECHANICS (Oct. 19, 2020), https://www.popularmechanics.com/science/energy/a34386186/molten-salt-reactor-new-design-nuclear-waste/ [https://perma.cc/U8G6-76MZ].

[163] M. Richardson *Development of Freeze Valve for use in the MSRE* OAK RIDGE NAT'L LAB'Y (1962), 5-6 http://moltensalt.org/references/static/downloads/pdf/ORNL-TM-0128.pdf [https://perma.cc/5JRN-J2JX] [https://perma.cc/5JRN-J2JX]].

path to circulate back into the core.[164] Unlike many standard safety features that require intervention to begin, these blowers rely on power to continue.[165] In a disaster with loss of power, the plug melts, draining the fuel into a separate tank, which ends the fission reactions.[166] Alternatively, the operators can safely cut power at any time and the fuel will drain away ending fission.[167] This process makes the LFTR walk-away safe in a disaster, a feature shared by no other reactor design in the world.[168]

The LFTR naturally follows power loads, meaning operators do not need to exert active control to regulate criticality.[169] As the temperature increases, the fuel expands, which means more space between atoms and fewer reactions. As the fuel cools, it contracts, which increases reactions, so the fission rate naturally regulates itself. This process contrasts with modern electric power and nuclear plants, which require active control to adjust the power load and face limits in the frequency and rate of adjustment.[170]

G. Counterarguments to U233

U233 has successfully fueld a reactor.[171] However, the U.S. never built the Molten Salt Breeder Reactor because the U.S. chose to focus on U235 reactors to stockpile Pu239 for weapons use.[172] This means that Thorium did not run extensively in any non-experimental reactors and that U233 has significantly fewer hours of operation reactors than other fuels.[173] Pressurized Water Reactors have years of uptime providing operational information and data to study.[174] However, U233 successfully fueled a reactor and is garnering more interest worldwide.[175] For example, China is working on a liquid fueled Thorium reactor and Russia is doing research using U233 as a fuel in Russian reactors.[176]

---

[164] Caroline Delbert, *supra* note 162.
[165] *Id.*
[166] *Id.*
[167] Interview with Parker Okabe, *supra* note 46.
[168] *See* Caroline Delbert, *supra* note 162.
[169] McDowell video of Kirk Sorensen, *supra* note 130 at 58:25 – 59:00,
[170] *Technical and Economic Aspects of Load Following with Nuclear Power Plants,* NUCLEAR ENERGY AGENCY, 20 (2011), https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf [https://perma.cc/WXG2-48ZK]. *Base Load vs. Load Follow,* NUCLEAR-POWER.COM, https://www.nuclear-power.com/nuclear-power/reactor-physics/reactor-operation/normal-operation-reactor-control/base-load-vs-load-follow/ [https://perma.cc/Y8KT-RP3N].
[171] Video Interview with Kirk Sorensen, *supra* note 21.
[172] *Id*., Interview with Parker Okabe, *supra* note 46.
[173] Video Interview with Kirk Sorensen, *supra* note 21.
[174] *Id*.
[175] *Id*.
[176] A.A. Hassan et al., *Investigation of Using U233 in Thorium Base Instead of Conventional Fuel in Russian BWR by SERPENT Code,* J Phys: Conf. Ser. 1689 012031 (2020), https://iopscience.iop.org/article/10.1088/1742-6596/1689/1/012031/pdf; Smirti Mallapaty, *China Prepares to Test Thorium-fuelled Nuclear Reactor,* NATURE (Sept. 9, 2021), https://www.nature.com/articles/d41586-021-02459-w.R.

Because U233 will contain U232, a hard gamma emitter, storage and transport will require new controls and safety measures.[177] Although no designs predict that U233 or U232 will leave the reactor after startup and initial fuel loading, regulations will need to cover transportation and storage of U233.[178] Gamma rays penetrate more than any other form of radiation and so require the most shielding.[179] However, the NRC already has analogous controls in place for nuclear waste and U233 would not require stronger controls than nuclear waste so the NRC could easily adapt these controls.[180] Additionally, the lower transuranic waste profile should offset any additional fuel handling cost since these costs would replace any current nuclear waste storage and transport outlays.[181]

The minimal benefits of U233 in a pressurized water reactor means that the relatively smaller gains have not overcome the inertia of U235 as the predominant fuel.[182] However, even in pressurized water reactors, simulations show that U233 produces less transuranic waste and outperforms U235.[183]

Inertia, operational comfort, and supply are the largest factors preventing adoption of U233.[184] The NRC and other agencies have created an entrenched and robust regulatory regime structured around the legacy technology of U235 and pressurized water reactors.[185] To overcome this inertia, U233 must conquer the fear of change coupled with fear of the unknown. This fear of the unknown mostly manifests through safety concerns and projecting old failure scenarios onto new technology.[186] Companies must also grapple with a sunk cost fallacy because the significant investments made in pressurized water reactors that make it difficult for energy companies to adopt new methods.[187]

H. Pressurized Water Reactors and Solid Fuels

Pressurized Water Reactors (PWRs) are the predominant nuclear reactors today.[188] PWRs burn fuel for energy in the thermal spectrum.[189] PWRs use fabricated solid rods for fuel, and use water as both a coolant and moderator to slow down the fast neutrons.[190] To effectively generate power, the reactor must operate at temperatures exceeding 300 degrees Celsius.[191] This high temperature requires extreme pressure to keep the water liquid, roughly 70 times sea level pressure, to prevent the water

---

[177] Video Interview with Kirk Sorensen, *supra* note 21.
[178] *Id*., Interview with Parker Okabe, *supra* note 46.
[179] Video Interview with Kirk Sorensen, *supra* note 21; Interview with Parker Okabe, *supra* note 46.
[180] Video Interview with Kirk Sorensen, *supra* note 21.
[181] *Id*.
[182] Hassan et al, *supra* note 176, at 2; Interview with Parker Okabe, *supra* note 46.
[183] Hassan et al, *supra* note 176, at 2; Interview with Parker Okabe, *supra* note 46.
[184] Video Interview with Kirk Sorensen, *supra* note 21.
[185] *Id*.
[186] *Id*.
[187] *Id*., M. Richardson, *supra* note 162.
[188] *See* NUCLEAR REGULATORY COMMISSION, Pressurized Water Reactors, *supra*, note 156.
[189] *See id*.
[190] *See id*.
[191] Gordon McDowell, *Thorium 2017*, YouTube (July 23, 2017). at 1:40. [https://perma.cc/QK6Q-AAWA].

from turning into steam.[192] This pressure places huge stress on the materials of the reactor, particularly as the reactor increases in size.[193] Loss of pressure creates the most catastrophic failure for light water reactors.[194] With loss of pressure, the liquid water will flash to steam.[195] This change increases the volume of the water by 1,000.[196] Critically, the steam also loses the ability to cool the fuel rods.[197] Luckily, fission stops without liquid water to moderate the neutrons.[198] However, the unstable daughter products trapped in the fuel rod continue to release energetic particles.[199] Scientists call this energy decay heat.[200] The steam or gaseous water absorbs the heat which starts to separate the hydrogen from the oxygen.[201] The hydrogen and oxygen react with each other enough to recombine with an enormous amount of energy because of the high concentrations.[202] This steam explosion is thought to be the biggest problem with the disaster at Chernobyl.[203]

For safety reasons, engineers must design a pressurized water reactor to contain the liquid moderator.[204] They must also leave enough radiation-shielded space to contain the even greater volume of gas that would be created by a loss of pressure.[205] The fuel and the moderator together make up the reactor core.[206] The biologically shielded part of the reactor, including the core, coolant, and support subsystems, is known as the reactor cell and is sealed to contain the radiation from fission reactions.[207] The reactor cell must include enough space to contain any gas created by a loss of pressure.[208] Light water reactors face the design challenge of containing heat to convert into energy and then quickly converting to reject heat in case of an emergency.[209]

The solid fuel used in pressurized water reactors traps fission daughter products inside the fuel rod's cladding or case.[210] Xenon absorbs huge amounts of neutrons making it especially problematic for reactors because those neutrons directly effect the criticality of the reactor. As a gas, xenon exerts pressure, which cracks the cladding of the fuel rod.[211]

---

[192]*Id.*
[193] *See id.;* Interview with Parker Okabe, *supra* note 46.
[194] McDowell video, *Thorium 2017*, *supra* note 191.
[195] *Id.*
[196] *Id.*
[197] *Id.*
[198] *Id.*
[199] *Id.*
[200] *Id.*; Interview with Parker Okabe, *supra* note 46.
[201] McDowell video of Kirk Sorensen, *supra* note 130.
[202] McDowell video, *Thorium 2017*, *supra* note 191.
[203] *Id.*; Interview with Parker Okabe, *supra* note 46.
[204] *See* NUCLEAR REGULATORY COMMISSION, Pressurized Water Reactors, *supra*, note 157.
[205] *See id.*
[206] *See id.*; INTERNATIONAL ATOMIC ENERGY AGENCY, *supra* note 147, at 3.
[207] Support subsystems include control rods, control rod springs and pumps. Control rods are rods that aggressively absorb neutrons to slow down the reaction rate and are used to control the rate of fission. INTERNATIONAL ATOMIC ENERGY AGENCY, *supra* note 147, at 3. Interview with Parker Okabe, *supra* note 47.
[208] NUCLEAR REGULATORY COMMISSION, Pressurized Water Reactors, *supra* note 147.
[209] Video Interview with Kirk Sorensen, *supra* note 21.
[210] Sovacool & Cooper, *supra* note 118 at 73.
[211] *Id.*

This cracking means that reactors only consume approximately 5% of fissile material before needing to exchange the fuel rods.[212] Companies must discard the remaining 95% of the fuel as high-level nuclear waste because the United States does not allow reprocessing of fuel.[213] This article discusses potential proliferation concerns and reasons for this ban under the current regulatory structure.

I. Advantages of LFTR Reactors

Companies have proposed several advanced reactors that improve on pressurized water reactors. The LFTR uses U233 as a fuel in a thermal reactor.[214] Instead of solid fuel and a liquid moderator, the LFTR uses a liquid fuel in molten salt with a solid graphite moderator.[215] This liquid state allows the fuel to continuously recirculate using far more of the fissionable material and not just 5%.[216] The molten salt does not require pressure since it remains liquid in an 850-degree range compared to the 100-degree range where water remains liquid.[217] This design also requires less space for the LFTR because the radiation cell does not need to contain enough volume for both liquid and gas states.[218]

Additionally, liquid fuel means that operators can remove xenon and other fission daughter products on-site without the need to reprocess and remanufacture a fuel rod.[219] Xenon and other gases can bubble out of the liquid for collection.[220] Because operators extract waste products from the fuel, instead of extracting waste along with fuel because of the breakdown of the fuel rod cladding, the concentrated waste products make the fuel use far more efficient.[221] This waste concentration means the LFTR will produce far less waste than a pressurized water reactor producing the same amount of energy.[222] The LFTR will not only greatly reduce overall waste, but produces a much smaller amount of transuranic waste because it uses Thorium and U233, not U235 and U238.[223] Also, U233 fissions in nine out of ten reactions, compared to two out of three reactions for Plutonium.[224] This means that only one of ten collisions results in transmutation to U234. In comparison, one of three collisions with Pu239 transmutes to Pu240 creating transuranic waste.[225] This

[212] *Id.* at 51.
[213] *Id.*
[214] INTERNATIONAL ATOMIC ENERGY AGENCY, *supra* note 147, at 2.
[215] *Id.*
[216] *See id.*
[217] McDowell video, *Thorium 2017*, *supra* note 191.
[218] INTERNATIONAL ATOMIC ENERGY AGENCY, *supra* note 147, at 5.
[219] *See id.* at 6-7.
[220] *Id.*
[221] *See id.* at 9, McDowell video, *Thorium 2017*, *supra* note 191.
[222] McDowell video, *Thorium 2017*, *supra* note 191.
[223] Interview with Parker Okabe, *supra* note 46.
[224] Nuclear Data Center at KAERI (Dec. 7, 2021), https://atom.kaeri.re.kr/nuchart/getEvaf.jsp?mat=9222&lib=endfb8.0 (showing the cross-section data for U233)
[225] Nuclear Data Center at KAERI (Dec. 7, 2021), https://atom.kaeri.re.kr/nuchart/getEvaf.jsp?mat=9437&lib=endfb8.0 (showing the cross-section data for Pu239)

greater efficiency results in relatively cleaner, shorter-lived waste from the LFTR compared to PWRs.[226]

Another advantage of LFTR over PWRs includes the frozen plug, the passive fail-safe design described in the introduction.[227] This design increases safety on two fronts. First, it changes the paradigm from requiring energy for safety measures to requiring a small amount of energy for normal operation. The interruption of that energy triggers safety measures.[228] Second, because the design uses a separate drain tank and reactor core, no single area has to both retain heat, and then quickly dump heat.[229] This feature overcomes the design challenges mentioned above with PWRs. By moving all the fuel safely to a separate location to reject, the LFTR can manage heat far more effectively and avoid many more disasters than PWRs.[230]

Other companies are also developing innovative reactor designs. The NRC has approved the NuScale Modular Reactor.[231] Companies build this PWR in pieces, but it faces the same problems as current PWRs. Another company, Elysium, has proposed a Fast Molten salt reactor.[232] This reactor has many of the advantages of a liquid fuel cycle and avoids the drawbacks of PWRs; however, they plan to burn Plutonium from current nuclear waste, which means they do not capitalize on U233's advantages as a fuel.[233]

III. CURRENT REGULATORY STRUCTURE

The law treats isotopes differently depending on their properties. Title 1 of the Atomic Energy Act defines "special nuclear material" as Pu239, U235, and U233.[234] The act classifies these isotopes based on the fissile properties of its members.[235] All three isotopes fission; U235 occurs naturally, and U233 like Plutonium 239 needs to breed in a reactor.[236]

The act defines "source material" as any material with Uranium or Thorium in concentrations greater than 0.05%.[237] Source material can absorb a neutron to become fissile material.[238] Thorium 232 absorbs a neutron to become U233, and U238 becomes Pu239 in the same way.[239]

---

226 INTERNATIONAL ATOMIC ENERGY AGENCY, *supra* note 147, at 2.
227 *Id*. at 2, 8.
228 *Id*. at 3.
229 *Id*.
230 *See id.*
231 Dave Levitan, *First U.S. Small Reactor Design is Approved*, Scientific American (Sept. 9, 2020), https://www.scientificamerican.com/article/first-u-s-small-nuclear-reactor-design-is-approved/ [https://perma.cc/DJW8-YLYG].
232 Caroline Delbert, *supra* note 162.
233 *Id*.
234 42 USCS §2014(aa)
235 UNITED STATES NUCLEAR REGULATORY COMMISSION, Special Nuclear Material, *supra*, note 98.
236 *Id*.
237 UNITED STATES NUCLEAR REGULATORY COMMISSION, *Source Material* (Last updated July 6, 2020), https://www.nrc.gov/materials/srcmaterial.html [https://perma.cc/3ZCJ-P5GE].
238 *Id*..
239 *Id*. Video Interview with Kirk Sorensen, *supra* note 21.

U235 makes up a small percentage of naturally occurring Uranium with the rest being U238, not a fissile material.[240] The U.S. pursued U235 for energy because it produced Plutonium, a preferred weapons material.[241] One out of every twelve fissile reactions with Pu239 produces Pu240, the first transuranic. [242] U235 produces exponentially less transuranic waste than Plutonium.[243] However, the Thorium and U233 fuel cycle produces even less transuranic waste and is more proliferation resistant than both U235 and Plutonium.[244]

The NRC built the current regulatory system for PWRs and the U235 fuel cycle.[245] This makes sense because the U.S. currently favors PWRs; nevertheless, applying these regulations to licensing the LFTR and other advanced reactor designs presents unique challenges. The Code of Federal Regulations (CFR) contains the current licenses for a U.S. nuclear plant.[246] The CFR details a three-part process consisting of a license application, a safety review, and an environmental review.[247] The NRC made some adjustments to encourage advanced reactor designs.[248] For example, in an article it outlines a flexible regulatory and review process that can accommodate a wide range of reactor designs.[249] The NRC also provides a roadmap to help alternative (non-PWR) reactors understand how the regulation process applies to them.[250] Additionally, the NRC posted a case study using the Molten Salt Reactor Experiment from 1964 to demonstrate how the regulation applies to an advanced reactor design.[251] These steps help alternative and advanced reactors; however, the NRC can and should do more to facilitate a migration to U233 as the primary nuclear fuel for the United States.

As a start, the NRC could publicly recognize the value of U233 through grants or awards, encouraging migration to U233 as a fuel source. For example, the Advanced Reactor Demonstration Program, run by the Department of Energy (DOE), provided ten matching grants to

---

[240] UNITED STATES NUCLEAR REGULATORY COMMISSION, Uranium Enrichment, *supra*, note 99.
[241] *Id*. Interview with Parker Okabe, *supra* note 46.
[242] Transuranic elements have an atomic mass greater than 239. They are man-made, long-lived with half-lives greater than 10,000 years, and they are highly radioactive, making them the most problematic category of nuclear waste. *What is Transuranic Radioactive Waste?, supra* note 141; Interview with Parker Okabe, *supra* note 46.
[243] Interview with Parker Okabe, *supra* note 46.
[244] Video Interview with Kirk Sorensen, *supra* note 21.
[245] *Stages of the Nuclear Fuel Cycle*, *supra* note 23 (referring to the U235 as "*the* fuel cycle" emphasis added).
[246] 10 C.F.R § 50.1 (1998).
[247] *New Reactor Licensing Process*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/images/reactors/new-reactor-licensing-process.gif [https://perma.cc/6XNQ-HG42]. 10 C.F.R. § 52.1 (2019).
[248] *Advanced Reactors (non-LWR designs*), UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/reactors/new-reactors/advanced.html [https://perma.cc/P5YF-RAET].
[249] *Flexible Licensing Processes for Advanced Reactors*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/reactors/new-reactors/advanced.html#flexLearn [https://perma.cc/B9XH-A926].
[250] *A Regulatory Review Roadmap for Non-Light Water Reactors*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/docs/ML1731/ML17312B567.pdf [https://perma.cc/83SQ-986X], Interview with Parker Okabe, *supra* note 46.
[251] *Molten Salt Reactor Case Study*, UNITED STATES NUCLEAR REGULATORY COMMISSION (Sept. 4, 2019), https://www.nrc.gov/docs/ML1924/ML19249B632.pdf [https://perma.cc/D3NA-M8SQ].

promote advanced reactors' development in 2020.[252] In October 2020, the first two awards went to U235 fueled reactors.[253] In December 2020, three more awards went to two different modular reactor designs using U235 as a fuel and operating in the fast spectrum.[254] Another five awards also went to U235 fuel designs, two using small pebble fuel instead of the traditional fuel rods, and a third using U235 in liquid fuel form in a fast reactor.[255] While these innovations improve on traditional PWR designs, none use U233, despite its proliferation resistance and lower waste profile.

As previously noted, the NRC defines reprocessing as "[t]he processing of reactor fuel to separate the unused fissionable material from waste material. Reprocessing extracts isotopes from spent nuclear fuel so they can be used again as reactor fuel."[256] Reprocessing is not practiced in the U.S. due to concerns about proliferation.[257] Currently Japan, China, Russia, and several European countries reprocess fuel.[258] President Gerald Ford temporarily halted reprocessing in the United States in November 1976 and President Jimmy Carter announced a policy that indefinitely deferred reprocessing in the US on April 7, 1977.[259] Although President Ronald Reagan lifted that ban in 1981, the NRC has not enacted any regulations allowing reprocessing.[260] Furthermore, the rulemaking to consider reprocessing facilities was discontinued on March 19, 2021.[261]

Reprocessing raises nuclear weapon proliferation concerns but without reprocessing, spent fuel remains waste.[262] With reprocessing, fabricators can recover the fuel to power more efficient advanced

---

[252] *Advanced Reactor Design Program*, UNITED STATE DEPARTMENT OF ENERGY, https://www.energy.gov/ne/advanced-reactor-demonstration-program [https://perma.cc/4EL2-XVMY].

[253] Rita Baranwal, *It's Time for the United States to Demonstrate Advanced Reactors*, UNITED STATE DEPARTMENT OF ENERGY (Oct. 14, 2020), https://www.energy.gov/ne/articles/its-time-united-states-demonstrate-advanced-reactors [https://perma.cc/YZ74-TYVG], Interview with Parker Okabe, *supra* note 47.

[254] *Energy Department's Advanced Reactor Demonstration Program Awards $20 million for Advanced Reactor Concepts,* OFFICE OF NUCLEAR ENERGY (Dec. 22, 2020), https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-20-million-advanced [https://perma.cc/RD8V-G98B], Interview with Parker Okabe, *supra* note 46.

[255] *Energy Department's Advanced Reactor Demonstration Program Awards $30 Million in Initial Funding for Risk Reduction Projects*, OFFICE OF NUCLEAR ENERGY (Dec. 16, 2020), https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-30-million-initial [https://perma.cc/BV2X-JERY], Interview with Parker Okabe, *supra* note 46.

[256] *Id. Fuel reprocessing (recycling)*, NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/reading-rm/basic-ref/glossary/fuel-reprocessing-recycling.html [https://perma.cc/M4YP-KHA5].

[257] Annemarie Wall, *Going Nowhere in the Nuke of Time: Breach of the Yucca Contract, Nuclear Waste Policy Act Fallout and Shelter in Private Interim Storage*, 12 ALB. L. ENVTL. OUTLOOK J. 138, 154-55 (2007).

[258] *Processing of Used Nuclear Fuel*, WORLD NUCLEAR ASSOCIATION, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx#ECSArticleLink2 [https://perma.cc/4WT9-775B].

[259] David Rossin *U.S. Policy on Spent Fuel Reprocessing: The Issues*, FRONTLINE, https://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/rossin.html [https://perma.cc/C87R-7VWD]

[260] Timothy Gardner, *U.S. Nuclear Power Industry Group Sees Reprocessing as Potential Waste Fix*, REUTERS (NOV. 16, 2020), https://www.reuters.com/article/idUSL1N2I2322 [https://perma.cc/4XCV-2TN6].

[261] Margaret Doane, *Discontinuation of Rulemaking for Spent Fuel Reprocessing*, UNITED STATES NUCLEAR REGULATORY COMMISSION (Mar. 5, 2021), https://www.nrc.gov/docs/ML2030/ML20301A388.pdf.

[262] *Processing of Used Nuclear Fuel*, *supra* note 258.

reactors, as many other countries currently do.[263] The main concern with reprocessing regards the potential of the extracted material for weapons use.[264] If the chemical treatment of the fuel remains inside the radiation envelope, like in U233 liquid-fueled reactors, the fuel never leaves the reactor, resulting in no proliferation.[265] Additionally, the fuel inside the biological shielding is more secure than fuel transported between facilities because the radiation and heat levels inside the shielding are lethal.[266]

The Department of Energy (DOE) is currently losing lawsuits and paying judgments to nuclear plants due to its failure to provide permanent nuclear waste storage.[267] The Nuclear Waste Policy Act of 1982 (NWPA) gives the DOE the responsibility to build and operate a high-level nuclear waste repository.[268] Further, it provides guidance and authorization for the Nuclear Regulatory Commission to evaluate and license the site, subject to Environmental Protection Agency (EPA) approval.[269] Later amendments to the NWPA require the DOE to evaluate Yucca Mountain, Nevada, for the repository unless authorized by Congress to evaluate another site.[270] The pending Nuclear Waste Policy Amendments Act of 2019 would have allowed the NRC to approve an interim site to consolidate waste until a final repository is created.[271] However, this Act expired in January at the end of the 116th congressional session.[272] As of August 2021, no member of Congress has introduced a similar bill.

The DOE's ongoing failure to provide a high-level nuclear waste repository puts it in ongoing breach of contract and creates liability for damages to the utilities operating nuclear power plants.[273] From 1998, when the duty to provide a repository commenced, through 2018, the government has paid $7.4 billion in damages for failing to take possession of the spent on-site with the reactor that produced it.[274] As of December 2020, two sites have applied to be consolidated interim

---

263 *Id.*
264 *Id.*
265 Video Interview with Kirk Sorensen, *supra* note 21.
266 *Id.*, Interview with Parker Okabe, *supra* note 476
267 *Nuclear Waste Storage Sites in the United States*, CONGRESSIONAL RESEARCH SERVICE (Apr. 13, 2020) https://sgp.fas.org/crs/nuke/IF11201.pdf, [https://perma.cc/W2FJ-RBXK].
268 42 USC §10101, et seq. *Summary of the Nuclear Waste Policy Act*, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, https://www.epa.gov/laws-regulations/summary-nuclear-waste-policy-act#:~:text=(1982),of%20state%20and%20federal%20governments. [https://perma.cc/Q765-DLNN].
269 *Summary of the Nuclear Waste Policy Act*, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, https://www.epa.gov/laws-regulations/summary-nuclear-waste-policy-act#:~:text=(1982),of%20state%20and%20federal%20governments.
270 *Id.*
271 Nuclear Waste Policy Amendments Act of 2019, H.R. 2699, 116th Cong. (2019). Nuclear Waste Policy Amendments Act of 2019, S. 2917 116th Cong. (2019).
272 *Id.*
273 Sys. Fuels, Inc. v. United States, 66 Fed. Cl. 722, 735, (2005). Indiana Mich. Power Co. v. DOE, 88 F.3d 1272.
274 *Id.*

storage sites with the Nuclear Regulatory Commission: one in Texas in 2016, the other in New Mexico in 2017.[275]

A. Proposed Regulatory Changes

Agencies can make several changes to regulations that would safeguard proliferation concerns and streamline the use of U233 in power. First, the Nuclear Regulatory Commission should include U233 and liquid fuel cycles with other reactor designs in the Licensing Modernization Project, and review the regulations as applied to a Thorium/U233 cycle.[276] Second, the NRC or Congress should clarify that chemical processing inside the reactor cell does not qualify as "reprocessing." Third, The NRC or Congress should clarify that changing spent fuel from oxide to fluoride does not qualify as reprocessing, thus allowing advanced reactors to utilize spent fuel in more efficient reactors, and reducing the overall amount of waste. Fourth, the NRC should approve the consolidated interim site requests and give priority to proposed sites with advanced reactors that will use the waste as fuel. This approval will save the government millions of dollars owed in ongoing damages due to its failure to provide a high-level waste repository. Fifth, The DOE should include reactors using U233 as fuel the next time it awards grants like the Advanced Reactor Design Program. Last, to accelerate the migration to U233 as the preferred fuel cycle, Congress needs to stop the irreversible down blending of current U233 stores.[277]

B. Include U233 in the Licensing Modernization Project

While the Licensing Modernization Project considers several different designs in its updating of regulations, no guidelines require it to consider different fuel types or materials.[278] A possible explanation lies in the mission, stated as "industry led and agency supported."[279] Southern Company pledged to financially back the project and no clear definition exists for "industry."[280] If the Licensing Modernization Project only includes existing operators and companies in the modernization, the regulations will naturally skew toward protecting current interests and models instead of future innovation.

As they review the regulations, the NRC should consider how different fuels will affect the risk model and whether the regulation only

---

[275] *Consolidated Interim Storage Facilities, (CISF)*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/waste/spent-fuel-storage/cis.html [https://perma.cc/6H49-7E8K].
[276] *Stages of the Nuclear Fuel Cycle*, *supra* note 26; *Chairman Christopher T. Hanson Remarks at the United States Nuclear Industry Council Advanced Reactor Summit*, *supra* note 132.
[277] *Upgrades Prepare Way for Oak Ridge to Process Remaining Uranium-233*, OFFICE OF ENVIRONMENTAL MANAGEMENT (Jan. 21, 2020), [https://perma.cc/V75R-LTMC].
[278] CFR 10 §§50 and 52.
[279] *Stages of the Nuclear Fuel Cycle*, *supra* note 26; *Chairman Christopher T. Hanson Remarks at the United States Nuclear Industry Council Advanced Reactor Summit*, *supra* note 132.
[280] *NRC Approves New Approach to Streamline Advance Reactor Licensing Process*, OFFICE OF NUCLEAR ENERGY (July 9, 2020), https://www.energy.gov/ne/articles/nrc-approves-new-approach-streamline-advanced-reactor-licensing-process [https://perma.cc/P849-TX9S].

applies to certain kinds of fuels. For example, all fuel types will require radiation shielding and radioactive waste provisions. However, the NRC should not require pressurized containment and proof of structural integrity at the high pounds per square inch required by light water reactors for liquid fuel cycles not operating under high pressure.[281] U233 will require more radiation shielding than U235 and Plutonium, but will not have fuel rods to submerge in pools for years as part of its waste disposal.[282] U233 will also need fewer transport controls on its source material because Thorium does not fission naturally and so presents a lower proliferation risk.[283] Evaluating the regulations with U233 and a liquid fuel cycle in mind will even the playing field for U233 and U235 reactors.

C. Include the U233 Fuel Cycle on the NRC Website

In addition to the proposed changes detailed above, the NRC should update its website to publicly signal approval of U233. The NRC website presents a wealth of information regarding nuclear regulations and nuclear power. However, when it describes the fuel cycle, it only illustrates the U235 fuel cycle.[284] The website describes the mining and enrichment of Uranium with no mention of Thorium.[285] Additionally, when discussing fuel fabrication, it only mentions solid fuel.[286] As part of its mission to educate, the NRC should either add the Thorium/U233 fuel cycle onto the current pages or create additional pages explaining the U233 fuel cycle. The NRC should also do this for liquid fuel versus solid fuel. These changes would signal that the NRC recognizes U233 as a nuclear fuel. It would also signal an equal playing field where the two fuels are both acknowledged. An equal playing field could send an encouraging message to innovators that the NRC will consider advanced designs using U233 and liquid fuel as an alternative to U235 and solid fuel.

D. Clarify the Definition of Reprocessing to Exclude Treatment of Liquid Fuel and Conversion of Spent Solid Fuel to Liquid Fuel

Reprocessing extracts isotopes from spent nuclear fuel so they can reenter reactors as fuel."[287] The Nuclear Regulatory Commission's current definition of reprocessing states that "the processing of reactor fuel separates unused fissionable material from waste material."[288] One possible interpretation of this definition excludes the chemical treatment

[281] Video Interview with Kirk Sorensen, *supra* note 21.
[282] *Id*.
[283] *Id*., Interview with Parker Okabe, *supra* note 46.
[284] *Stages of the Nuclear Fuel Cycle*, *supra* note 23.
[285] *Id*.
[286] *Fuel Fabrication*, UNITED STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/materials/fuel-cycle-fac/fuel-fab.html [https://perma.cc/XYL4-6JEK].
[287] *Id*., Interview with Parker Okabe, *supra* note 46.
[288] *Fuel Reprocessing (recycling)*, United STATES NUCLEAR REGULATORY COMMISSION, https://www.nrc.gov/reading-rm/basic-ref/glossary/fuel-reprocessing-recycling.html [https://perma.cc/XK24-6PHH].

of liquid fuel and the conversion of solid oxide fuel to liquid fluoride fuel. The NRC could adopt a simplified definition as "the removal of fissile material from waste."[289] This wording clearly excludes the LFTR and other similar liquid fuel cycles from the definition of reprocessing. Alternatively, the NRC can define "spent fuel" as a fuel that has been removed from the reactor cell of a reactor.

As explained above, the liquid fuel cycle can cycle continuously through the reactor core; however, this would become less and less efficient without removing the waste. Chemically extracting the waste from the fuel is important for the optimal performance of a liquid fuel cycle. This process is substantially different from the above definition of reprocessing because the fuel is not "spent" but active at the time of treatment; the fuel is inside the reactor at the time of processing and not in a separate facility, and the waste, and not the isotopes are extracted.[290]

Liquid fuel cycles include separation of fissionable material from waste material as part of the closed cycle process.[291] While liquid fuel cycle applicants will argue that they do not extract "isotopes from spent nuclear fuel" but rather extract waste from active nuclear fuel, the NRC should clarify this ambiguity to specifically allow liquid fuel cycles.[292] Additionally, liquid fuel cycle applicants can argue that they do not extract "isotopes" but rather waste. The NRC should clarify that any separation of isotopes from waste done inside the reactor cell does not fall under the definition of reprocessing. Alternatively, the NRC could define "spent nuclear fuel" as a fuel already outside the reactor.

In addition to allowing the more efficient liquid fuel reactors, clarifying the definition of reprocessing could pave the way for reactors to run on current spent fuel and nuclear waste. The NRC should clarify that separation of fuel from waste outside the reactor cell meets the definition of reprocessing, not the transfer of fuel from oxide or solid state to a liquid fluoride state. In this case, no separation of isotopes from the waste needs to occur, but operators can chemically treat the fuel to move from the solid oxide form into liquid or gas. Like the processing done as part of the liquid fuel cycle, applicants can argue that this falls within current regulations. Additionally, to facilitate the use of spent fuel without prior separation, the NRC should allow the consolidation of drycasks which store this spent fuel, as the article will discuss in the next section.

Not only does clarifying the definition of reprocessing allow for innovation, but it also preserves the purpose of the policy. Presidents banned reprocessing to guard againt nuclear weapons proliferation. However in the two processes described above no isotopically pure

[289] *Processing of Used Nuclear Fuel*, *supra* note 258.
[290] Video Interview with Kirk Sorensen, *supra* note 21.
[291] Sameer Surampalli, *Is Thorium the Fuel of the future to Revitalize Nuclear?* POWER ENGINEERING (Aug. 13, 2019) https://www.power-eng.com/nuclear/reactors/is-thorium-the-fuel-of-the-future-to-revitalize-nuclear/#gref [https://perma.cc/MP5H-8W4V].
[292] *Fuel Reprocessing (recycling)*, *supra* note 288.

fissile materials leave the reactor, and no transportation occurs so nuclear proliferation risks do not increase.[293]

E. Allow Consolidation of Waste

Congress should reintroduce and pass the 2019 Nuclear Waste Policy Amendment Act, allowing for the creation of consolidated interim storage. The NRC should approve the applications for consolidated interim storage, giving preference to any site with plans to use the waste safely. These sites will save the government millions of dollars in breach of contract judgments and reduce the amount of high-level waste ultimately destined for long-term storage.[294] Ideally, the companies will use the waste to transmute Thorium into U233 and, in the process, produce much more energy than that already extracted from the fuel.[295] Even without use in an advanced reactor, simply licensing a site will save the government money by obviating the need to pay judgments to current nuclear plant operators.

F. Include U233 Designs in the Programs like the Advanced Reactor Design Program

Although the Advanced Reactor Design Program did not grant any awards to reactors using U233 as fuel, the DOE should remedy this in future programs. It should offer this program again, or one like it, with grants awarded to promote the use of U233 due to its decreased proliferation risk, lower waste profile, and more plentiful source material.

G. Stop the Down Blending of Existing U233

Lastly, Congress should immediately stop the practice of down blending existing U233 and preserve it to harvest the beneficial by-products and to preserve it for use as fuel. Down blending reduces the concentration of U233 so that it can go to a long-term storage facility.[296] Several ways exist to achieve this, but it usually involves mixing the material with low-density Uranium increasing the waste volume and diluting it.[297] Because contractors mix the low-density Uranium with other elements it becomes cost prohibitive and technologically difficult to isolate the U233 or the beneficial daughter products such as Actinium

---

[293] Video Interview with Kirk Sorensen, *supra* note 21.

[294] *Contract Liability Arising from the Nuclear Waste Policy Act (NWPA) of 1982*, EVERYCSRREPORT.COM (Feb. 1, 2012), https://www.everycrsreport.com [https://perma.cc/27SV-ME87]. Written in February of 2012, this report states that over 78 claims have been filed since 1998 costing the government over 2 billion in damages. *Civilian Nuclear Waste Disposal*, PROJECT ON GOVERNMENT SECRECY (last updated Sept. 17, 2021), [https://fas.org/sgp/crs/misc/RL33461.pdf]. Last updated in December of 2018 puts the total damages paid at 6.9 billion. However, the breach is ongoing, so damages claims continue to grow.

[295] Solid fuel rods can only burn 5% of the fuel meaning that 95% remains to be burnt. Sovacool & Cooper, *supra* note 118 at 51.

[296] *DOE Disposing of Uranium-233 Waste Stored at ORNL*, OAKRIDGE TODAY (Aug 27, 2017), https://oakridgetoday.com/2017/08/27/doe-program-disposing-uranium-233-waste-stored-ornl/ [https://perma.cc/V37P-59TN].

[297] *Id.*

and Bismuth and their precursors.[298] Medical researchers desperately seek for Actinium and Bismuth to continue targeted alpha therapy cancer studies.[299] Down blending makes it impossible or cost-prohibitive to recover the U233 and the Actinium and Bismuth.[300]

IV. CONCLUSION

The greater efficiency and safety of U233 can make clean, abundant energy a reality. Nuclear energy produces more energy per square mile and kilogram of fuel than any other energy source. This can help reverse climate change and raise the quality of life because it will take enormous amounts of energy to achieve these goals and the world will only achieve these goals if the energy does not release more carbon dioxide into the atmosphere. Not all nuclear energy is equal. U233, in a liquid fuel cycle, can provide energy while reducing or eliminating many of the concerns with traditional nuclear reactors in several ways.

First, U233 presents less of a proliferation risk than U235 and Plutonium because of U232 contamination. Second, the U233 fuel cycle produces less waste overall, and less of the longest-lived waste than other fuel cycles. Third, U233 comes from Thorium, a ubiquitous and abundant resource, unlike U235 which is relatively scarce. Fourth, U233 is the only fuel that breeds in the thermal spectrum, meaning reactors require less fuel to sustain criticality and companies only need one reactor instead of a breeder reactor and a burn reactor. Finally, the liquid fuel cycle eliminates the risk of steam explosions and failures from the stress exerted by pressure in traditional reactors. The liquid fuel cycle also has additional passive safety features that further reduce the likelihood of nuclear disasters.

The NRC designed the current regulatory structure for pressurized water reactors and so the regulations do not easily apply to U233 and liquid fuel cycles. The NRC is updating the regulations, but the updates will need to consider U233 and liquid fuel cycles. The NRC should also include U233 and liquid fuel cycles in its educational materials and approve nuclear waste consolidation sites. Additionally, the NRC should clarify the definition of fuel reprocessing to specifically exclude treatment of fuel to remove waste in the liquid fuel cycle and the transition of fuel from solid to liquid. These steps are a start, but the government should support the use of U233 with grants. Additionally, Congress or the DOE should stop the down blending of existing U233. It is time to use this superfuel to fulfill the long-delayed promise of earth's most abundant source of energy.

---

[298] Glenn T. Seaborg, *infra* note 61 (U233 daughter product chart). Video Interview with Kirk Sorensen, *supra* note 21.
[299] Video Interview with Kirk Sorensen, *supra* note 21. Interview with Parker Okabe, *supra* note 46.
[300] Video Interview with Kirk Sorensen, *supra* note 21. Interview with Parker Okabe, *supra* note 46.