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Zachary Hawari

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THORIUM'S GLOW: LIGHTING THE WAY FOR SAFE, CHEAP ENERGY PRODUCTION

ZACHARY HAWARI[*]

Glenn Seaborg was the Atomic Energy Commission ("AEC") Chairman in 1962. Even then, he marveled at the "almost unlimited amounts of latent energy" in thorium and uranium and the promising solution of using "the fuel in fluid form."[1] This sentiment holds true today. Liquid fluoride thorium reactors ("LFTR")[2] could be safe, clean, and cheap without facilitating the development of nuclear weapons. Even so, civilian nuclear power struggles in an uphill battle for public acceptance. Nuclear proponents must address the legacy of Fukushima and Chernobyl. Critics point to dangers of waste-filled mountains, radioactive clouds, and hazardous elements.[3] States tremble at the prospect of nuclear weapons falling into the hands of terrorists and rogue states. Some, like German Chancellor Angela Merkel, argued we should shut down our nuclear facilities.[4] Many say we should stop expanding and subsidizing the nuclear sector. Others embrace LFTR, an abandoned reactor design, as the path to cheap, virtually limitless energy. LFTR can replace fossil fuels and supplement renewable energy. It may even be the best way to combat modern energy and environmental crises.

Part I addresses what LFTR is and why it is better than traditional nuclear reactors. The first section explains how nuclear reactors work. It then considers some relevant differences between LFTR and conventional nuclear reactors. The second section explores LFTR's advantages

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[*] J.D. Candidate, William & Mary Law School, 2017; B.A. International Affairs, The George Washington University, 2014. The author would like to thank the William & Mary Law School faculty and staff and the *William & Mary Environmental Law and Policy Review* staff for their support. He also greatly appreciates the support and camaraderie of his friends, family, and colleagues.

[1] Robert Hargraves, THORIUM: ENERGY CHEAPER THAN COAL loc. 2401 (2014) (ebook).

[2] LFTR is pronounced "lifter."

[3] *See* Eifion Rees, *Don't Believe the Spin on Thorium Being a 'Greener' Nuclear Option,* THE ECOLOGIST (June 23, 2011), http://www.theecologist.org/News/news_analysis/952238/dont_believe_the_spin_on_thorium_being_a_greener_nuclear_option.html [https://perma.cc/JH3Q-QSAY].

[4] Annika Breidthardt, *German Government Wants Nuclear Exit by 2022 at Latest*, REUTERS (May 30, 2011), http://www.reuters.com/article/germany-nuclear-idUSLDE74T00A20110530 [https://perma.cc/MJ2A-AT56].

in efficiency, waste reduction, fuel availability, proliferation, and safety. As noted in Part II, Cold War politics culminated in the abandonment of thorium and molten salt reactors. The second section of Part II considers and rebuts several common criticisms.

Part III considers how to bring LFTR to fruition and how policy makers could address proliferation crises. The first section calls for an international agency to coordinate state-subsidized nuclear research institutions. The next section argues for a refreshed allocation of energy Research & Development funds focusing on LFTR. The third section considers a hypothetical Iranian deal to highlight the nonproliferation advantages of LFTR. It also offers ways to avoid some of the dangers from the actual Iranian deal.

I. WHAT IS LFTR AND WHAT MAKES IT ATTRACTIVE?

A. The Nuclear Industry Revolves Around Radioactive Elements[5]

1. Nuclear Reactors Produce Heat Through Fission by Bombarding Certain Elements with Neutrons

Nuclear reactors and fossil fuels generate electricity indirectly through the production of heat.[6] That heat creates steam to turn turbines that generate electricity.[7] A nuclear reactor bombards atoms of certain isotopes,[8] such as uranium-233,[9] with neutrons until the atoms split into

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[5] This Note only covers the background nuclear science needed to understand the pitfalls of PWR and advantages of LFTR. For a more detailed explanation of nuclear technology, *see* BRIAN ADE ET AL., U.S. NUCLEAR REGULATORY COMM'N, SAFETY AND REGULATORY ISSUES OF THE THORIUM FUEL CYCLE, 6–11 (2014); Hargraves, *supra* note 1.

[6] *The Nuclear Fuel Cycle*, WORLD NUCLEAR ASS'N (June 2016), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx [https://perma.cc/YFS3-4CCS].

[7] *Id.*

[8] All the atoms of a given element have the same number of protons within their nuclei, but the number of neutrons may differ. *See Glossary*, WORLD NUCLEAR ASS'N (Mar. 2014), http://www.world-nuclear.org/nuclear-basics/glossary.aspx [https://perma.cc/Z4QG-VDJB]. An isotope specifies the atomic mass and accounts for the number of neutrons. Noting the particular isotope can be important. Different isotopes may undergo fission or decay at different rates. Also, some isotopes may be more stable and, hence, more common.

[9] The numbers following an element name or preceding the symbol, e.g., uranium-233 or 233U, refer to the atomic mass of an isotope. The most common isotopes referenced in this Note are thorium-232, uranium-233, -235, and -238, and plutonium-239.

fissile material and heat.[10] In part, controlling this reaction led to the different types of reactors.[11]

2. Nuclear Reactors Can Use Solid Fuel or Liquid/Molten Fuel

a. Pressurized Water Reactors Use Solid Fuel and Cool the Core with Water

Pressurized water reactor ("PWR") is a broad label for the most common type of nuclear reactor, including light water reactors ("LWR") and heavy water reactors ("HWR").[12] Several basic components make up pressurized water reactors.[13] The fuel is usually ceramic pellets of uranium oxide, i.e., solid fuel, placed in fuel rods.[14] The moderator slows the neutrons so that more fission occurs, and the moderator can be water, heavy water, or graphite.[15] Operators insert and withdraw control rods that absorb neutrons to further adjust the rate of fission.[16] The pressure vessel contains these components.[17] Outside the pressure vessel, superheated water and steam turn a turbine to produce electricity.[18] A thick concrete building protects the reactor from the outside world and natural disasters.[19]

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[10] *See Physics of Uranium and Nuclear Energy*, WORLD NUCLEAR ASS'N (Sept. 2014), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/physics-of-nuclear-energy.aspx [https://perma.cc/6YK5-JWJB].

[11] *See Nuclear Power Reactors*, WORLD NUCLEAR ASS'N (Sept. 2014), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx [https://perma.cc/GZ9S-CRVP].

[12] *See id.* In HWR, heavy water (D_2O) replaces the hydrogen in water (H_2O) with deuterium, an isotope of hydrogen with twice the mass. *See* WORLD NUCLEAR ASS'N, *supra* note 8. The use of deuterium helps control neutron absorption and the creation of unproductive elements. *See* WORLD NUCLEAR ASS'N, *supra* note 10.

[13] WORLD NUCLEAR ASS'N, *supra* note 11.

[14] *Id.* When the ceramic pellets overheat and melt, this is referred to as a meltdown. It may be accompanied by a release of radioactive material into the atmosphere and ground water.

[15] *Id.*

[16] *Id.*

[17] *Id.*

[18] *Id.*

[19] *See* WORLD NUCLEAR ASS'N, *supra* note 11. In total, three levels of physical barriers protect the nuclear material: (1) the reactor core, (2) the pressure vessel, and (3) the containment structure. This series of failsafes prevents a catastrophic release of high-pressure steam and contains the radiation in the case of a meltdown.

b. LFTR Uses Thorium Immersed in Molten Salts to Power the Reaction, Contain the Fission Material, and Control the Heat

Thorium is LFTR's primary input, but uranium actually fuels the fission reaction.[20] Thorium is fertile, not fissile, which means it must be converted into a fissile element.[21] Accordingly, thorium-232 is transmuted within a thorium blanket surrounding the core into fissile 233U.[22] The thorium generated 233U is the nuclear fuel for LFTR's fission reaction.[23] An initial investment of plutonium or enriched uranium[24] starts this process, and the uranium and plutonium waste products from PWRs can be used as fuel thereafter.[25] These elements are burned away during the lengthy fission life of LFTR fuel unavailable in PWRs.[26]

But, thorium is only half of what makes LFTR special. LFTR uses molten salt, i.e., liquid fluoride, as a coolant.[27] This allows the reactor to operate without high pressure gasses around the core.[28] One proposed design uses two molten salt systems.[29] The first contains the fissile material and the thorium blanket.[30] The molten salt is chemically processed to remove waste and is used to introduce new thorium.[31] That loop transfers heat to a second loop of clean molten salt.[32] The heat from the non-radioactive loop generates steam and electricity.[33] This eases maintenance and reduces the risk of radioactive contamination.[34]

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[20] *Thorium*, WORLD NUCLEAR ASS'N (Sept. 2015), http://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx [https://perma.cc/T5DT-5NQ7].

[21] *Id.*

[22] *Id.*

[23] *See id.*

[24] Enriched uranium refers to uranium with a higher proportion of 235U to 238U than that of naturally occurring uranium. Enriched uranium may be bred artificially in reactors or naturally occurring uranium may be segregated using centrifuges. *See Uranium Enrichment*, WORLD NUCLEAR ASS'N (May 2016), http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx [https://perma.cc/5CZP-45FF].

[25] Hargraves, *supra* note 1, at loc. 2703.

[26] *Id.* at 6400.

[27] *Id.* at 2599.

[28] *Id.*

[29] *Id.*

[30] *Id.*

[31] Hargraves, *supra* note 1, at loc. 2599.

[32] *Id.*

[33] *Id.* at 2584.

[34] *Id.* 2599.

c. Current Reactors, Such as PWRs, Can Also Use Thorium

This Note claims LFTR is the optimal, long-term solution to nuclear power. More precisely, molten salt reactors that breed fertile nuclear material from thorium are the solution. LFTR is one example. Other molten salt reactors may use chloride salts instead of fluoride salts.[35] That said, several reactor types could use thorium in the interim.

For example, thorium can extend the life cycle of uranium in a modified, once-through LWR.[36] A once-through fuel cycle disposes of the nuclear material after a single use; in contrast, recycled fuel cycles separate the 233U for further production.[37] Recycled fuel coupled with thorium can extend the usefulness of uranium while reducing the production of transuranic species.[38] Alvin Radkowski founded Lightbridge to create thorium fuel rods compatible with current reactors, but the rods never made it to market.[39]

B. LFTR Is More Sustainable, Has More Abundant Resources, Lowers Nuclear Weapon Proliferation Risk, and Is Safer

1. Thorium Is Sustainable in LFTR and Can Extend the Life Span of Uranium in LWRs

Both LFTR and thorium-adapted LWRs last longer and use less nuclear material compared with the uranium-plutonium fuel cycle in PWRs.[40] With reprocessing, a LWR supplemented by thorium could be self-sustaining; in contrast, the uranium-plutonium fuel cycle requires frequent investments of uranium.[41] In LWRs one-third of the initial uranium load must be added every eighteen months to sustain productivity.[42] The DBI thorium reactor proposed by Thorium Power Canada theoretically would require only an additional three percent of its thorium load every

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[35] *See* WORLD NUCLEAR ASS'N, *supra* note 11.

[36] U.S. NUCLEAR REGULATORY COMM'N, *supra* note 5, at 6.

[37] *See id.* The latter may be self-recycling, i.e., for the same reactor, or can be used as fuel in other reactors. *Id.* at 9.

[38] *Id.* at 6.

[39] Hargraves, *supra* note 1, at loc. 2568.

[40] U.S. NUCLEAR REGULATORY COMM'N, *supra* note 5, at 10.

[41] *Id.* at 5.

[42] *Thorium vs. Uranium Fuels*, THORIUM POWER CANADA, INC. (Feb. 5, 2016), http://www.thoriumpowercanada.com/technology/the-fuel/thorium-vs-uranium-fuels [https://perma.cc/DB2W-Q4H2].

eighteen months.[43] This decreases required resources by a factor of ten. Uranium fuel rods in LWRs suffer structural damages caused by heat and radiation, requiring suboptimal replacement.[44] LFTR avoids this waste because molten fuel does not suffer the same structural stresses and can be filtered for waste.[45]

2. LFTR Produces Less Waste per Unit of Energy and Fewer Transuranic Byproducts

First, LFTR produces much less waste.[46] Direct fission or transmutation could destroy transuranic elements, such as plutonium-239, generated in a solid fuel reactor, but the solid fuel must be removed long before this occurs.[47] In liquid fuels, such as in LFTR, transuranic products remain in the core until most undergo fission.[48] Therefore, the waste contains less transuranic material, which means the reactor is more efficient.[49]

The radiotoxicity of the waste produced, particularly 233U, from the thorium-uranium fuel cycle is comparable to uranium-plutonium during the first couple of centuries.[50] However, fewer transuranic products mean thorium waste is ten times less radiotoxic between two hundred to one thousand years.[51] Some isotopes created in LFTR, e.g., 231Pa and 229Th, can result in twice the radiotoxicity after the first millennium and on very long timescales, depending on the type of reactor.[52] This means less waste is produced per kW/hour of electricity than current PWR, and the waste is less harmful during humanly comprehensible timescales.

3. Thorium Is Much More Common than Uranium

At 9.6 parts per million ("ppm"), thorium is three to four times more abundant than uranium, which occurs at 2.7 ppm in the Earth's

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[43] *Id.*
[44] Robert Hargraves & Ralph Moir, *Liquid Fluoride Thorium Reactors*, AM. SCI., July–Aug. 2010, at 305, 308, http://thoriumenergyalliance.com/downloads/American_Scientist_Hargraves.pdf [https://perma.cc/RW52-M29J].
[45] *Id.* at 308.
[46] *Id.*
[47] *Id.*
[48] *Id.*
[49] Hargraves & Moir, *supra* note 44, at 308.
[50] U.S. NUCLEAR REGULATORY COMM'N, *supra* note 5, at 5.
[51] *Id.*
[52] *Id.*

crust.[53] This makes thorium about as common as lead.[54] The amount of economically retrievable thorium is difficult to estimate due to a lack of reliable data.[55] Most estimates are based on uranium and rare earth mineral resources.[56] The industry needs better data, but with improving remote sensing technology and open geographic information systems, this data is easier to obtain and share than ever before. As data improves and thorium is retrieved from rare earth mineral mining waste, the cost of commercially available thorium will fall.

4. Thorium Cannot Be Readily Used in a Nuclear Weapon, and LFTR's Design Discourages Proliferation

LFTR requires an initial fissile investment of plutonium and enriched uranium.[57] LFTR can also use the waste from PWRs as fuel. This would decrease stockpiles of enriched uranium and plutonium, which pose a nuclear proliferation risk.[58] This is true for the same reason LFTR produces less waste: higher burn-up and extended cycle lengths.[59] Whereas the fuel rods in LWRs must be replaced before all the fuel is spent, transuranic elements are destroyed during LFTR's longer fuel cycle.[60]

Admittedly, thorium is converted into 233U. The International Atomic Energy Agency ("IAEA") and United States Nuclear Regulatory Commission ("NRC") rank 233U with plutonium and highly enriched uranium as Category I materials.[61] However, the uranium produced in LFTR is not generally considered suitable for nuclear weapons due to contamination by protactinium, very high temperatures, and extreme radiation.[62]

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[53] *Id.* at 4.

[54] *Element Abundances in the Earth's Crust*, KNOWLEDGEDOOR (Feb. 5, 2016), http://www.knowledgedoor.com/2/elements_handbook/element_abundances_in_the_earth_s_crust.html [https://perma.cc/5EVF-7FRF] (listing the natural abundance elements in the Earth's crust).

[55] BRIAN ADE ET AL., *supra* note 5, at 4.

[56] *Id.*

[57] Hargraves, *supra* note 1, at loc. 2703.

[58] BRIAN ADE ET AL., *supra* note 5, at 5–6.

[59] *Id.*

[60] Hargraves, *supra* note 1, at loc. 2703.

[61] *See Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities*, INT'L ATOMIC ENERGY AGENCY 20 (2011), http://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf [https://perma.cc/4EGN-CRTJ]; *Safeguard Categories of SNM*, U.S. NUCLEAR REGULATORY COMM'N (Feb. 5, 2016), http://www.nrc.gov/security/domestic/mca/snm.html [https://perma.cc/2KGA-ZZ99].

[62] *See* Ralph W. Moir & Edward Teller, *Thorium-Fueled Underground Power Plant Based on Molten Salt Technology*, 151 NUCLEAR TECHNOLOGY 334, 337–38 (2005); U.S. NUCLEAR

LFTR can decrease stockpiles of plutonium and enriched uranium in the long run. But, transportation and storage of these seed materials involve a risk of proliferation. A rogue entity looking to create nuclear weapons could target these stockpiles. Nevertheless, it is unlikely anyone would use LFTR's technology to build a nuclear weapons program. If a state has the plutonium or 235U to start the LFTR reaction, it would be better off using that to build the weapon. Furthermore, the conversion rate to 233U is too slow to facilitate large-scale collection.[63] If a state wants to obtain a nuclear weapon, LFTR is a poor means.

5. LFTR Has Inherent and Passive Safety Features Lacking in PWRs

It may be useful to categorize safety features as "active" and "passive." An active safety feature requires electricity and operator intervention to use, e.g., following proper procedures to shut down a LWR's nuclear reactor.[64] A passive reaction could occur in the absence of both, e.g., a salt plug melting to drain a LFTR's tank.[65] Passive safety features have fewer points of failure than their active counterparts, and thus, are more reliable.[66]

A pressurized water reactor uses water to cool its core.[67] In the event of a power outage, a PWR's facilities have many backups in place to ensure constant cooling.[68] As was made abundantly clear at Fukushima, these "active" failsafes are not always sufficient, especially when a company disregards proper procedure.[69] Due to the nature of solid fuel reactors, the core continues to react after shutdown for a few days.[70] The Fukushima-Daichi reactor was cooling after being properly shutdown,

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REGULATORY COMM'N, *supra* note 5, at 5–6. This quality is considered further in Parts II.B.5 and III.C.

[63] *See* WORLD NUCLEAR ASS'N, *supra* note 20.

[64] *See* INT'L ATOMIC ENERGY AGENCY, *Safety related terms for advanced nuclear plants*, http://www-pub.iaea.org/MTCD/publications/PDF/te_626_web.pdf [https://perma.cc/2A3B-AHV8].

[65] *Id.*

[66] *Id.*

[67] *See* WORLD NUCLEAR ASS'N, *supra* note 11.

[68] George Lerner, *What About Fukushima?*, LIQUID FLUORIDE THORIUM REACTOR (Mar. 19, 2015), http://liquidfluoridethoriumreactor.glerner.com/2015-what-about-fukushima [https://perma.cc/7LVE-6Q88].

[69] *See id.*

[70] *See id.*

yet continued to produce "about 1.5% of their nominal thermal power" when the power failed.[71]

Most likely, the Fukushima-Daichi disaster in 2011 could have been avoided with standard safety protocols and designs.[72] The reactor survived with nothing more than minor damage.[73] Even a minimal amount of electricity would have avoided the meltdown.[74] The backup generators should have been better protected, and the operators should have brought in a spare generator. Instead, the coolant system failed completely, leading to an explosion, meltdown, vessel breach, and radioactive contamination.[75] The Fukushima-Daichi facility was not built to acceptable specifications. The sea walls were inadequate, and the backup generators' placement below sea level allowed the tsunami to flood them.[76] Properly built, maintained, and operated, many other nuclear reactors in the area survived without an issue.[77] For example, the Onagawa reactor was hit harder by the earthquake and tsunami, yet it remained operational.[78]

Passive safety features require little to no human intervention or electricity.[79] LFTR is designed with a "negative temperature coefficient of reactivity."[80] This means the reactor's power quickly drops if its temperature rises above the operating point."[81] In other words, LFTR cools rather than heats up if something goes wrong. Even so, a frozen salt plug would block a pipe leading from the reactor to a containment vessel.[82] If the power failed, the fan cooling the salt plug would stop, allowing it to melt.[83] Unencumbered, the molten salt would drain into a storage tank designed to handle the high temperatures.[84] The excess heat would be

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[71] *Fukushima Accident*, WORLD NUCLEAR ASS'N, http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Fukushima-Accident/ [https://perma.cc/A75Z-ZHU6] (last updated Jan. 2016).

[72] *See* Lerner, *supra* note 68.

[73] *Id.*

[74] *See id.*

[75] *See id.*

[76] *Id.*

[77] *See* Lerner, *supra* note 68.

[78] *Id.*

[79] *See* INT'L ATOMIC ENERGY AGENCY, *supra* note 64.

[80] *See* Kirk Sorensen, *Chernobyl and the Central Role of the Temperature Coefficient* (April 25, 2006), http://energyfromthorium.com/2006/04/25/chernobyl-nuclear-safety-and-the-central-role-of-the-temperature-coefficient/ [https://perma.cc/R8A2-7WYK].

[81] Moir & Teller, *supra* note 62, at 337.

[82] GEORGE LERNER, WHAT IS A LFTR, AND HOW CAN IT BE SO SAFE? loc. 170 (2012) (ebook).

[83] *See id.*

[84] *See id.*

"transferred through heat exchangers that passively carry the heat to the environment aboveground, while retaining the radioactive material belowground."[85] Even if the drainage pipe was damaged, the core would gradually cool in the reactor.[86]

Moreover, the inherent design is less dangerous. The risk of a meltdown is not an issue where the fuel is molten as part of normal operation.[87] As nothing is under pressure, nothing can explosively decompress. Even if the core's containment vessel cracked, the surrounding facility would be designed to contain the heat.[88] As the molten salt solidified, the radioactive elements would be trapped in the facility.[89] Because fluoride salts bind the fuel, there is little risk of contaminating the air or ground water.[90] This results in a reactor capable of containing a disaster without electricity or human intervention.

Of course, nothing can be completely infallible. Productivity disruptions are possible, and liquid fuel may leak. The former can be addressed through diversification of small reactors in many locations.[91] Likely, the worst case scenario of the latter is the loss of the facility, not the city.

II. WHY WAS LFTR ABANDONED?

A. *Specific Historical Considerations from the Cold War Played a Large Role in Thorium's Modern Obscurity*

The cause of LFTR's abandonment is contentious. Supporters argue that states abandoned LFTR because it did not produce plutonium for nuclear weapons.[92] Critics respond that technological barriers and the risk of proliferation doomed LFTR.[93] Either way, scientists have considered thorium for a long time.[94]

The course of nuclear power was set during the Cold War. In 1954, scientists at the Oak Ridge National Laboratory tested the first

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[85] Moir & Teller, *supra* note 62, at 337.
[86] LERNER, *supra* note 82, at loc. 182.
[87] *See* Hargraves & Moir, *supra* note 44, at 310.
[88] *Id.*
[89] *Id.*
[90] Lerner, *supra* note 68.
[91] This would be an example of small modular reactors ("SMR"). Hargraves, *supra* note 1, at loc. 3760.
[92] *See* Hargraves, *supra* note 1, at loc. 2681.
[93] Oliver Tickell, *Promise and Peril of Thorium*, WMD JUNCTION, http://wmdjunction.com/121031_thorium_reactors.htm [https://perma.cc/J2ZM-4525] (last updated Nov. 5, 2012).
[94] *See* Hargraves, *supra* note 1, at loc. 2570.

molten fluoride salt reactor.[95] The reactor was built as part of the aircraft reactor experiment ("ARE").[96] The test was a success and led to the Fireball jet engine reactor.[97] But, it was not meant to be. The invention of practical, in-flight refueling preempted the Fireball project before conclusive testing.[98]

Building on the Fireball project, the Oak Ridge Lab built a molten salt reactor that operated for four years in the 1960s.[99] The experiment simplified the process by separating 233U breeding from the fission reaction, but it proved LFTR as a concept.[100] It could even remove waste materials from the molten salt using a complicated chemical process.[101]

During this period, PWRs were developed to power nuclear submarines. The inventor of the Navy's PWR, Alvin Weinberg "raised concerns about its safety compared to the molten salt reactor."[102] This created a dispute between Wienberg and Milton Shaw, the deputy director of the AEC. Shaw was entrenched in the fast breeder reactor's viability and saw the molten salt reactor as a source of funding.[103] Continuing to argue for LFTR, Weinberg was fired, and LFTR funding ended in 1976.[104] The Nixon administration shifted funding to solid fuel fast breeder reactors that produced 239P faster than LFTR produced 233U.[105] Weinberg later commented, "[LFTR] was a successful technology that was dropped because it was too different from the main lines of reactor development."[106]

Thorium has featured in a few experiments since then. It was again tested during a five year experiment at the Shippingport power reactor from 1977 to 1982.[107] Thorium "produced about 1% more fissile material than it consumed."[108] Germany's pebble bed reactor used thorium between

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[95] *See id.* at 2530.

[96] The military wanted long-range bombers to be able to circle the USSR without landing to refuel. *See id.*

[97] *See id.*

[98] *See id.*

[99] Hargraves, *supra* note 1, at loc. 2583.

[100] *See id.*

[101] *See id.* Further development today would "require deep chemistry expertise" unfamiliar to most modern nuclear engineers. *Id.* at 2694.

[102] *Id.*

[103] This is according to Paul Haubenreich, the former project manager at the Oak Ridge Lab. *See id.*

[104] *See* Hargraves, *supra* note 1, at loc. 3760.

[105] *See id.* at 2681.

[106] *Id.*

[107] *See id.* at 2570.

[108] *Id.*

1983 and 1989.[109] Similar to the Oak Ridge Lab experiment in the 1960s, India has a reactor that separates the breeding and fission processes.[110]

B. *Critics Cite Commercial Infancy, Waste, Insufficient Research and Mining Data, and the Potential for Terror Bombs*

1. Thorium Is Untested on a Commercial Scale

Criticism. Thorium has never been tested on a commercial scale.[111] Even in the lab, LFTR is still theoretical because several key components are missing.[112]

Response. Scientists have researched thorium since the Manhattan Project. Moreover, the molten salt reactor at Oak Ridge Lab operated for five years.[113] As noted above, LFTR's abandonment stems from an inability to produce plutonium for Cold War weapons.[114] Admittedly, for all its potential, LFTR is untested as a commercial means of energy production.[115] But, every untested technology must start somewhere. LFTR is well-founded and worth the risk that some unforeseen barrier will arise to prevent commercial viability.

2. Nuclear Waste Would Skyrocket if LFTR Is Used Commercially

Criticism. If LFTR became a major source of electricity production, the amount of nuclear waste would be multiplied many times over.[116] LFTR's waste may differ from conventional reactors, but it is still hazardous and the half-lives are measured in millennia.[117] Even if LFTR produces less waste, LFTR's alleged cleanliness depends "on digging some pretty deep holes to bury the highly radioactive waste."[118]

Response. If LFTR replaced the current nuclear reactors, nuclear waste would fall.[119] Moreover, non-nuclear waste products could be

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[109] Hargraves, *supra* note 1, at loc. 2570.
[110] *Id.*
[111] *See* Rees, *supra* note 3.
[112] *See id.*
[113] *See* Hargraves, *supra* note 1, at loc. 2530.
[114] *See id.* at 2681.
[115] *See* Rees, *supra* note 3.
[116] *Id.*
[117] *Id.*
[118] *Id.*
[119] *See* Hargraves & Moir, *supra* note 44, at 309.

drastically reduced if LFTR became more popular. These can be poorly contained and dangerous. Fossil fuels pump their negative by-products directly into the atmosphere. The treatment process for solar panels includes a host of toxic chemicals released during production and during the end of life destruction.[120] Wind turbines create dangers for birds, visual interference, and noise pollution.[121] Every choice comes with trade-offs. An increase in nuclear waste comes with a reduction in waste from other areas.

In fairness, even LFTR's nuclear waste poses dangers, and nuclear waste production would increase if LFTR became common enough. Despite what some LFTR advocates argue, substantial reprocessing of nuclear waste would do more harm than good.[122] Worse, regulators seem to have stalled on finding a long-term storage site for nuclear waste.[123] Eventually, that will change. While nuclear waste may require deep holes to contain it, there is something to be said for the security provided by distance.

3. There Is Not Enough Research into Concentrations of Economically Accessible Thorium, Making the Price Uncertain

Criticism. Thorium estimates are based on non-thorium specific searches, e.g., uranium and rare earth minerals.[124] The increase in demand for thorium from hundreds of new reactors would drive up the price.[125] Thorium in nuclear waste is not a solution. Reprocessing is

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[120] *See Environmental Impacts of Solar Power*, UNION OF CONCERNED SCIENTISTS (Mar. 5, 2013), http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-solar-power.html [https://perma.cc/6W6W-L85T].

[121] *See Environmental Impacts of Wind Power*, UNION OF CONCERNED SCIENTISTS (Mar. 5, 2013), http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-wind-power.html [https://perma.cc/R63G-V9FC].

[122] *See Nuclear Reprocessing: Dangerous, Dirty, and Expensive*, UNION OF CONCERNED SCIENTISTS, http://www.ucsusa.org/nuclear-power/nuclear-plant-security/nuclear-reprocessing [https://perma.cc/GH6A-6EAD] (last visited Oct. 24, 2016).

[123] *See The Elusive Permanent Repository*, UNION OF CONCERNED SCIENTISTS, http://www.ucsusa.org/nuclear-power/nuclear-waste/permanent-waste-repository [https://perma.cc/PKE3-ZUJ4] (last visited Oct. 24, 2016).

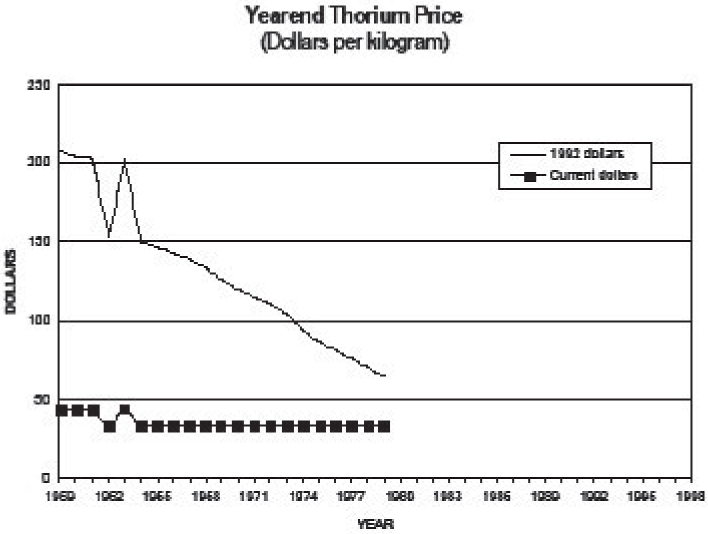
[124] *See generally* Ken Salazar & Suzette M. Kimball, *Thorium Deposits of the United States*, U.S. GEOLOGICAL SURVEY (2009), http://pubs.usgs.gov/circ/1336/pdf/C1336.pdf [https://perma.cc/9NZT-5CHU] (providing "an overview of the significant thorium deposits of the United States" for the next generation of thorium exploration).

[125] *See* K.M.V. JAYARAM, DEP'T OF ATOMIC ENERGY, AN OVERVIEW OF WORLD THORIUM RESOURCES, INCENTIVES FOR FURTHER EXPLORATION AND FORECAST FOR THORIUM REQUIREMENTS IN THE NEAR FUTURE (1987).

expensive, time consuming, and counterproductive because it produces even more waste.[126]

Response. This criticism has some merit. Better surveys are necessary to assess the accessibility of thorium.[127] However, this should not stop LFTR. Exploration is a key aspect of extraction for all mining. Open geographic systems and remote sensing technology make obtaining and sharing this data easier.

The future cost of thorium is difficult to determine. First, waste reprocessing is problematic, and thorium deposits are speculative. Additionally, thorium has never been demanded on a commercial scale.[128] Thorium is as common as lead, but it is radioactive and requires specialized mining and processing.[129] Thorium should cost less than uranium because it is four times more abundant.[130] So, we can guess that the commercial price should fall somewhere between lead and uranium. Economies of scale will reduce extraction costs, making it lean more toward lead. Additionally, less thorium is required in LFTR than uranium in conventional reactors.[131] This means, even if thorium were as expensive as uranium, energy production with thorium would still be cheaper.



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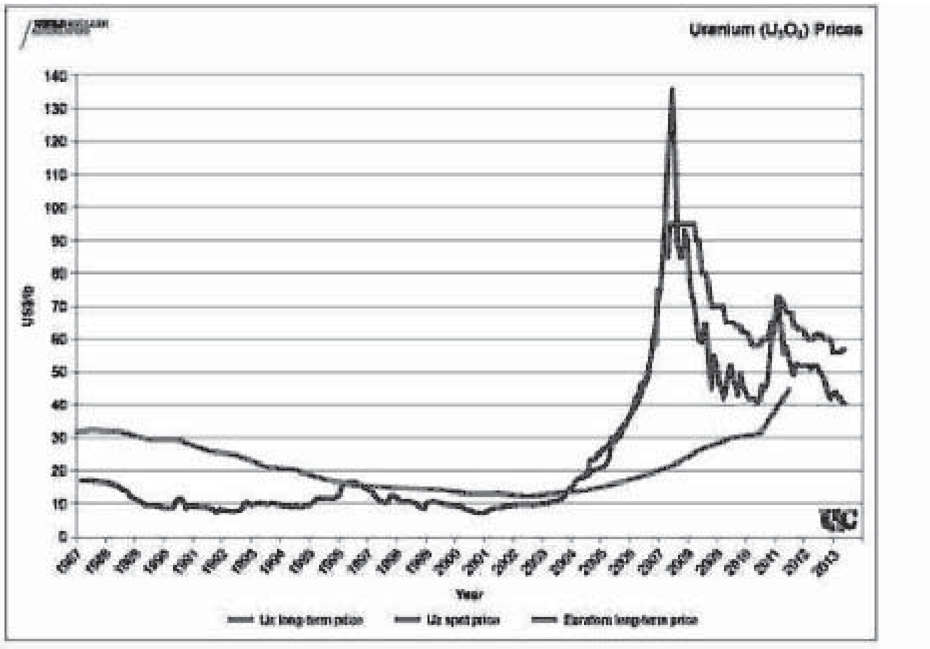
[126] *See Nuclear Reprocessing: Dangerous, Dirty, and Expensive*, *supra* note 122.
[127] *See* Salazar & Kimball, *supra* note 124.
[128] *See* Rees, *supra* note 3.
[129] *See Element Abundances in the Earth's Crust, supra* note 54.
[130] *Id.*
[131] U.S. NUCLEAR REGULATORY COMM'N, *supra* note 5, at 5.



The price of thorium peaked during the early days of experimentation.[132] Demand was relatively high.[133] Since the mid-1960s, thorium prices fell until demand decreased so much that the price lost meaning.[134] Since the 1980s uranium prices have roughly risen but remain volatile.[135] One take away from these trends is that thorium prices can be explained by market forces like any other commodity. The commercial supply of thorium will rise to meet increased demand. Increased supply and economies of scale will drive the price back down. Once on a commercial scale, the long-term cost of energy production using LFTR will decrease, eventually rivaling fossil fuels.

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[132] *See* James B. Hedrick, *Metal Prices in the United States Through 1998*, U.S. DEP'T OF THE INTERIOR & U.S. GEOLOGICAL SURVEY, 155 fig.Yearend Thorium Price (1999), http://minerals.usgs.gov/minerals/pubs/commodity/thorium/690798.pdf [https://perma.cc/M9FC-A3CA]; *Uranium Markets*, WORLD NUCLEAR ASS'N fig.Uranium (U_3O_8)Prices, http://www.world-nuclear.org/info/nuclear-fuel-cycle/uranium-resources/uranium-markets/ [https://perma.cc/9T65-VGJ5] (last updated Feb. 2015).

[133] *See id.*

[134] *See* Hedrick, *supra* note 132.

[135] *See id.*

4. LFTR Would Take Too Long to Implement, and the Nuclear Industry Does Not Support It

Criticism. If the safety and cost claims were true, the nuclear industry would back LFTR. Yet, the nuclear industry does not support thorium or LFTR.[136] LFTR would take too much time and money to bring it to fruition. Either way, as a National Nuclear Laboratory report concluded, the "claims for thorium were 'overstated.'"[137]

Response. The timing of LFTR is primarily a function of priority, not engineering ability. Cross-field researchers built the atomic bomb, which was inconceivable a few decades before, in a very short period of time.[138] With the Manhattan Project's focus and funding, LFTR could be operational within a decade.[139] With reasonable funding, LFTR could be operational within twenty years.[140]

The cost of production per reactor would be cheaper than LWRs thanks to a simpler design associated with liquid fuels, e.g., no need for a complex coolant system to hold high pressure water.[141] However, the current nuclear industry has sunk large costs in PWRs.[142] It has little incentive to invest the capital necessary to convert old facilities or build new facilities. The American government's subsidies are designed to increase profits, not R&D, by reducing taxes.[143] The industry's lack of support does not indicate the lack of a feasible idea so much as a lack of incentives created by sunk costs and subsidies. Moreover, several privately funded projects undermine the claim that the nuclear industry is against LFTR and thorium.[144]

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[136] *See* Rees, *supra* note 3.

[137] *Id.* (citing *The Thorium Fuel Cycle*, UK NATIONAL NUCLEAR LABORATORY (Aug. 2010), http://www.nnl.co.uk/media/1050/nnl__1314092891_thorium_cycle_position_paper.pdf [https://perma.cc/G4AD-V4P6]).

[138] VINCENT C. JONES, MANHATTAN: THE ARMY AND THE ATOMIC BOMB 11–12, 28, 149–50 (1985).

[139] George Lerner, *Manufacturing LFTRs Easier than Other Reactors,* LIQUID FLUORIDE THORIUM REACTOR (Jan. 17, 2012), http://liquidfluoridethoriumreactor.glerner.com/2012-manufacturing-lftrs-easier-than-other-reactors/.

[140] *See id.*

[141] *See id.*

[142] World Nuclear Assoc., *Nuclear Power in the USA*, http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx (last updated Sept. 26, 2016).

[143] Hargraves, *supra* note 1, at loc. 5453.

[144] See *infra* Part III.A for a brief overview of these projects.

5. The 233U Created by LFTR Poses a Proliferation Risk

Criticism. LFTR converts thorium into 233U. This uranium could be extracted from the reactor and used to make a nuclear weapon.[145] A state could harvest large amounts of very pure 233U without alerting the international community.[146]

Response. As previously discussed, LFTR creates 233U from thorium.[147] However, not all uranium is equally suitable for nuclear weapons.[148] Weapons grade uranium, i.e., highly enriched uranium, requires a high proportion of 235U, not 233U.[149] Moreover, LFTR does not convert thorium fast enough to make it an efficient means of 233U breeding without sacrificing energy production.[150] But even if it did, any 233U generated from LFTR is not well suited for a nuclear weapon because it is contaminated with 232U.[151] A state could attach a device to extract protactinium, which is one source of 232U impurities; however, IAEA monitoring would mitigate this risk.[152] To further undermine proliferation attempts, the 233U could be diluted with 238U.[153]

There are inherent barriers in LFTR to retrieving the 233U, e.g., high temperatures and radiation.[154] But, with extreme cost and difficulty, a state could extract pure 233U from LFTR.[155] With modern technology, it may be able to build a new type of nuclear weapon powered by 233U. But, there are much easier and cheaper ways for a state seeking to obtain nuclear weapons. It could divert the 235U it used to start the reactor. LFTR's advantages outweigh the risk that a state may irrationally choose to pursue LFTR to build a nuclear weapon.

III. HOW DO WE GET TO LFTR AND HOW COULD IT SOLVE THE POTENTIAL FOR IRANIAN PROLIFERATION?

Consequences aside, the Manhattan Project was one of the most significant technological undertakings of the 20th century. It required

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[145] Tickell, *supra* note 93.

[146] *Id.*

[147] *See supra* Part I.A.2.b.

[148] Moir & Teller, *supra* note 62, at 337.

[149] SOUTH AFRICA LFTR ENERGY, *Superior Design Advantages Over All Other Nuclear Reactor Designs of LFTR* 7 (n.d.) (considering the nonproliferation attributes of LFTR).

[150] *See* WORLD NUCLEAR ASS'N, *supra* note 20.

[151] *See* SOUTH AFRICA LFTR ENERGY, *supra* note 149, at 7 (explaining three ways 233U could be contaminated by 232U within LFTR).

[152] *See id.*

[153] *See id.*

[154] *See id.*

[155] *See* Tickell, *supra* note 93.

the collaboration of scientists from many different nationalities and academic fields, e.g., nuclear physics, chemistry, and engineering.[156] Even more impressively, this hodgepodge group in the New Mexican desert achieved their goal in a handful of years.[157] It took World War II and the might of the U.S. government to bring these groups together and usher in the era of "big science."[158] Today, we have the luxury of slightly more time, but perhaps the consequences of failure are just as grave. An international approach will be necessary to solve these challenges. States need to create an international agency to organize efforts and shift R&D funding to support LFTR.

A. International Collaboration Would Speed the Process of Achieving LFTR by Reducing Redundancies, Thereby Creating More Efficient Funding

Today's technology allows scientists all over the world to collaborate in a way that the Manhattan Project scientists could scarcely imagine. There are several LFTR projects across the world. India plans an ambitious LFTR and thorium-based nuclear strategy due to scarce uranium deposits and ample sources of thorium.[159] China is perhaps the closest to realizing a thorium reactor with a ten-year deadline.[160] There are also projects in Canada, Denmark, Germany, Japan, Norway, South Africa, the United States, and the United Kingdom.[161]

There has been some collaboration, for example, between the Canada Deuterium Uranium reactor ("CANDU") and the Chinese nuclear

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[156] U. Pitt., *The Manhattan Project*, http://www.pitt.edu/~sdb14/atombomb.html [https://perma.cc/FPR7-B5J3] (last visited Oct. 24, 2016).

[157] F. G. GOSLING, U.S. DEP'T OF ENERGY, *The Manhattan Project: Making the Atomic Bomb*, 64–73 (Jan. 2010), http://energy.gov/sites/prod/files/Manhattan_Project_2010.pdf [https://perma.cc/U3UJ-9YXH].

[158] Charu Anchlia et al., Scientific Networks and The Bomb 3 (May 9, 2011) (unpublished final project, Harvard University Kennedy School of Government) (http://ocw.mit.edu/courses/media-arts-and-sciences/mas-961-networks-complexity-and-its-applications-spring-2011/assignments/MITMAS_961S11_Networkpaper.pdf) [https://perma.cc/2X5T-2XXT].

[159] *See generally* GOV'T OF INDIA, *Long Term Vision of the Department of Atomic Energy*, http://www.nti.org/media/pdfs/26_8.pdf?_=1316719689 (last visited Oct. 24, 2016) (explaining the long-term strategy of India's Department of Atomic Energy) [https://perma.cc/53B7-HBAV].

[160] Ari Phillips, *China's Plan To Develop Totally New Nuclear Fuel Speeds Up*, THINK PROGRESS, Mar. 20, 2014 2:38 PM, https://thinkprogress.org/chinas-plan-to-develop-totally-new-nuclear-fuel-speeds-up-a27a4193675c#.nxyfjbyzf [https://perma.cc/6KRK-2CNB].

[161] *See* INT'L THORIUM ENERGY ORG., *Thorium Energy Report CANDU*, http://www.thoriumenergyworld.com/candu.html [https://perma.cc/58QF-2U65] (last visited Oct. 24, 2016).

agency.[162] Moreover, the Safety Assessment of the Molten Salt Fast Reactor ("SAMOFAR") is a consortium of eleven universities and research laboratories.[163] That said, many of these thorium and LFTR projects collaborate with only one or two partners or within a region.[164] For example, SAMOFAR is primarily a European consortium supported by the European Commission.[165] Notwithstanding these efforts, a collaboration of the international community as a whole could be much more effective. Given the breadth of projects all over the world, many of these projects overlap.

Ideally, an international agency could assign projects addressing different aspects of LFTR research. Institutions could then focus funding on novel technical barriers to LFTR. The agency could work within an existing organization, e.g., through the IAEA or UN, or be formed ad hoc.[166] Here are four key points to the proposed Commission: (1) Commission research is available to all members; (2) the Commission assigns research projects to member states considering economic feasibility, technical specialties, and state requests; (3) only state-operated or state-subsidized institutions conducting nuclear research in a member state are required to participate; and (4) the Commission's mandatory assignments become voluntary after the first commercially viable LFTR prototype goes online.

First, the proposed International Commission on LFTR is a topic-specific international agency dedicated to creating a commercially viable LFTR prototype as quickly, efficiently, and cheaply as possible. By necessity, the research gathered by the Commission would be available to all members. This allows each institution to understand how its assigned project fits within the greater whole. Furthermore, it would allow the members to build upon the completed LFTR prototype with proprietary technology.

Second, some institutions will have the technical knowledge or the financial backing to complete an assignment more efficiently than others. The Commission's Assignment Committee must efficiently allocate assignments across the world. To this end, the Committee would include nuclear physicists, chemists, engineers, and diplomats. States seeking to join the Commission must ensure state-funded programs find a solution to

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[162] *Id.*

[163] *Id.*

[164] *See id.*

[165] *See id.*; SAMOFAR, *Consortium*, http://samofar.eu/consortium/ (last visited Oct. 24, 2016) [https://perma.cc/PXJ6-B6AX].

[166] This proposed international organization will be referred to within this Note as the "International Commission on LFTR" or "Commission."

their assignments. Similarly, private institutions and public institutions from non-member states may opt-in by accepting an assignment from the Committee. The assigned problem is by no means the only project that the institution can research. But, the Commission is only effective so long as its members are willing to contribute to their assignments. It may be most efficient to assign multi-institutional workgroups to address the same issue, e.g., single versus double fluid LFTR systems or mapping thorium deposits. Potential assignments also include how to handle protactinium and graphite core problems.[167]

The Commission would be an opt-in collaborative. The mandatory phase for member states only affects certain state-funded programs. Because this approach is only mandatory for state subsidized research, there is little worry about undermining free competition. The purely private firms would be welcome to contribute to the Commission, but may be hesitant to do so for fear of losing a competitive advantage.

Briefly, it is worth noting that this federalist style system is not the only option. Vertical integration may work as well. This would require member states to contribute money directly to the Commission, and the Commission redistribute the funds as needed. The primary issue with this approach is that states would have to relinquish control.

Finally, the Commission need not last forever. The mandatory assignments become optional upon the completion of the first commercially viable LFTR. It would be sufficient for the collaborative effort to produce a working LFTR prototype, which is available to all Commission institutions, if not the public. Thereafter, it could allow the private market to improve upon these designs. Alternatively, the collaboration could continue as a voluntary agency. Either way, the Commission would combine short-term efficiencies of interstate cooperation while preserving the long-term incentives created by competition.

B. The U.S. and Other States Should Reallocate Energy and Nuclear Subsidies to Support LFTR

The International Energy Agency and Nuclear Energy Agency issued a joint technology roadmap in 2015.[168] One of the key findings is

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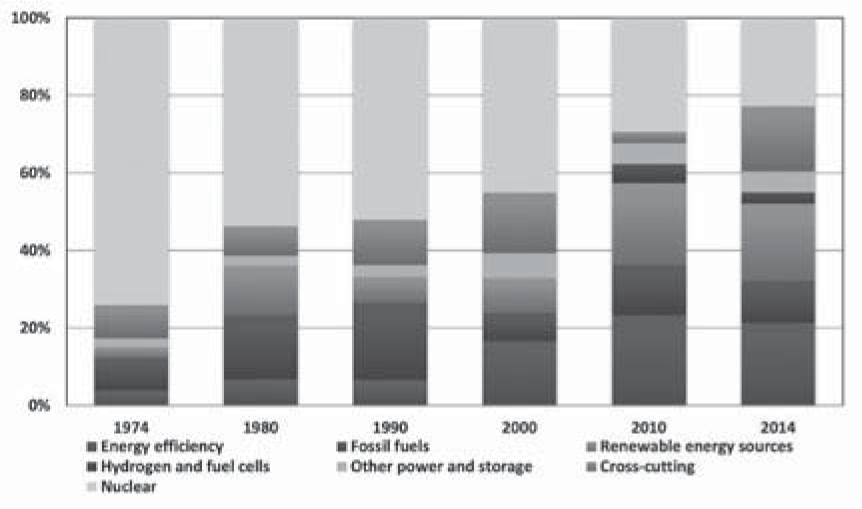
[167] *See* Charles Barton, *What Are The Problems With LFTR Technology?*, THE ENERGY COLLECTIVE (Aug. 29, 2011), http://www.theenergycollective.com/charlesbarton/64177/what-are-problems-lftr-technology [https://perma.cc/X4LW-PRX2].

[168] INT'L ENERGY AGENCY & NUCLEAR ENERGY AGENCY, *Technology Roadmap: Nuclear*

the continued role for governments in nuclear R&D, "especially in the area of nuclear safety, advanced fuel cycles, waste management and innovative designs."[169] This is in response to falling levels of nuclear R&D. Nuclear research, development, and demonstration ("RD&D") has fallen drastically in the past forty years.[170] In 1974, nuclear dominated with 74% of the public energy RD&D budget.[171] By 2014, nuclear RD&D fell to 23%.[172] In contrast, renewables have expanded from 3% to 20%.[173]

Figure 2: IEA Total Public Energy RD&D



My proposed International Commission on LFTR follows the trend within nuclear research of pooling resources in response to decreasing national R&D budgets.[174] In absolute terms, the U.S. has been, and remains, the largest contributor to energy RD&D.[175] However, as a function of GDP per capita, the U.S. makes a much more modest contribution.[176]

Energy 7 (2015), http://www.iea.org/publications/freepublications/publication/Nuclear_RM_2015_FINAL_WEB_Sept_2015_V3.pdf [https://perma.cc/JZ4U-UT5X].

[169] *Id.* at 5.

[170] INT'L ENERGY AGENCY, *Key trends in IEA public energy technology research, development and demonstration (RD&D) budgets* 2, fig.2 (2015), http://wds.iea.org/wds/pdf/IEA_RDD_Factsheet_2015.pdf [https://perma.cc/8XN5-3NUW].

[171] *See id.*

[172] *See id.*

[173] *See id.*

[174] INT'L ENERGY AGENCY & NUCLEAR ENERGY AGENCY, *supra* note 168, at 48.

[175] INT'L ENERGY AGENCY, *supra* note 170, at 2–5.

[176] *See id.*

In 2015, the U.S. Department of Energy selected sixty-eight nuclear R&D projects to fund with over $60 million.[177] Yet, of these selections only a handful are international collaborations.[178] Moreover, very few, if any, of the U.S. nuclear subsidies are directly attributed to thorium or molten salt reactors. Reallocation of subsidies and an international collaboration seems imperative for LFTR to come to market within any reasonable time frame.

C. *The International Community Could Use LFTR in States That Want the Benefits of Nuclear Power but Where Nuclear Proliferation Is a Concern*

For the past several decades, nuclear power has promised cheap, limitless energy. So far this promise has been met with mediocre results. Nevertheless, thirty countries worldwide operated 438 nuclear reactors to produce 10.9% of the world's electricity in 2012.[179] France relies on nuclear power for three-quarters of its electricity.[180] With rising nuclear interest, more states want the benefits of nuclear power.[181] Yet, many worry over the dangers of nuclear technology. If states like Iran were to obtain a nuclear weapon, other states in the region, such as Saudi Arabia and Egypt, may feel sufficiently threatened to start nuclear research as well. It would be all too easy to adapt the infrastructure and knowledge of PWRs to nuclear weapons. This could lead to more nuclear armed states—a dangerous proposition.

President Obama heralded the 2015 Joint Comprehensive Plan of Action between the P5+1,[182] the EU, and Iran as the short- to mid-term solution to Iran's nuclear aspirations.[183] He asserted that Iran cannot build a bomb covertly and that "we have now cut off every single path that Iran could have used to build a bomb."[184] President Obama emphasized in his

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[177] *U.S. Department of Energy Funding for Nuclear R&D*, WORLD NUCLEAR NEWS (June 8, 2015), http://www.world-nuclear-news.org/NN-DOE-funding-for-nuclear-R-and-D-0806157.html [https://perma.cc/9AND-AR25].

[178] *See id.*

[179] *Knowledge Center, World Statistics: Nuclear Energy Around the World*, NUCLEAR ENERGY INSTITUTE (July 2015), http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics [https://perma.cc/5ZTF-4RBQ].

[180] *Id.*

[181] *See id.*

[182] The P5+1 consists of Germany plus the five permanent members of the United Nations Security Council: China, France, Germany, the United Kingdom, and the United States.

[183] Interview by Steve Inskeep with Barack Obama, U.S. President, Whitehouse (Apr. 7, 2015 5:03 AM), http://www.npr.org/2015/04/07/397933577/transcript-president-obamas-full-npr-interview-on-iran-nuclear-deal [https://perma.cc/BWJ5-5FLG].

[184] Barack Obama, U.S. President, Remarks on the Iran Nuclear Deal, 3:20 (Jan. 16, 2016), https://www.whitehouse.gov/issues/foreign-policy/iran-deal [https://perma.cc/L9ER-PM7J].

speech that the breakout time[185] for Iran will increase from three months to over a year.[186] However, the nuclear deal allows Iran to continue enriching uranium, albeit only to the purity suitable for civilian use and with international oversight.[187] Obama conceded that when the deal expires in ten to fifteen years, Iran's breakout time will be very short.[188] He contended that it is better to work with Iran today and know its capabilities for when the deal ends.[189]

The current Iranian deal is fundamentally a delaying tactic. Even assuming (1) the international community can effectively monitor all of Iran and (2) the U.S. and international community would be willing and able to stop Iran, the world is back where it started in fifteen years. At best, Iran will be weeks or months away from breakout. LFTR would address the underlying problem by replacing proliferation prone nuclear reactors with a technology that is proliferation resistant.[190]

An alternative deal based on LFTR would look something like this: within fifteen years Iran must disable three-quarters of its non-LFTR reactors and the remaining within twenty years. Like the actual deal, Iran would be subject to IAEA monitoring.[191] Iran would be encouraged to collaborate with international researchers to create LFTR. Iranian reactors would not be allowed to filter protactinium or take other measures to obtain pure 233U. Furthermore, the energy production of every LFTR facility would be monitored by the IAEA. Presently, Iran must dismantle uranium enrichment facilities and greatly reduce enriched uranium stockpiles in the next few years.[192] The enriched uranium may be held by the IAEA or UN Security Council in trust for Iran. The IAEA will facilitate the sale or return of enriched uranium to Iran to seed new LFTR facilities. This enriched uranium will be subject to a chain of custody by the IAEA and constant monitoring until processed by the reactor.

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[185] The breakout time is the period it would take a state to gather enough nuclear material for a bomb.

[186] Barack Obama, U.S. President, Remarks on the Iran Nuclear Deal, 3:48 (Jan. 16, 2016), https://www.whitehouse.gov/issues/foreign-policy/iran-deal [https://perma.cc/THD2-LZKY].

[187] Eyder Peralta, *6 Things You Should Know About The Iran Nuclear Deal*, NPR (July 14, 2015), http://www.npr.org/sections/thetwo-way/2015/07/14/422920192/6-things-you-should-know-about-the-iran-nuclear-deal [https://perma.cc/8789-H5JR].

[188] Interview by Steve Inskeep with Barack Obama, *supra* note 184.

[189] *Id.*

[190] *See Superior Design Advantages*, *supra* note 149, at 7–11.

[191] *The Iran Nuclear Deal: What You Need to Know about the JCPOA*, WHITE HOUSE 6, https://www.whitehouse.gov/sites/default/files/docs/jcpoa_what_you_need_to_know.pdf [https://perma.cc/V5HD-KFJQ].

[192] Peralta, *supra* note 187.

This would have several immediate effects. First, Iran would be encouraged to work with the international community to create a LFTR prototype. Also, it would change the incentives of the Iranian nuclear program. In fifteen years, all of its PWRs would be dismantled. This would eliminate the need for enrichment facilities. Currently, that infrastructure could produce weapons grade uranium.[193] Instead of an even more dangerous Iran in fifteen years, the breakout time would be substantially longer because it would have to rebuild the enrichment facilities.

Like the actual nuclear deal, the IAEA would monitor the Iranian nuclear program. If Iran were to secretly attach protactinium removal equipment to start syphoning off substantial amounts of pure 233U, it would be obvious to the IAEA. The energy production would plummet. Under the actual deal, IAEA monitoring will become increasingly necessary as the Iranian nuclear program progresses. Under my alternative plan, the IAEA would become less important as the current reactors and enrichment facilities are phased out. The IAEA would only monitor electricity production and facilitate the initial investments of uranium for new LFTR facilities. In this way, Iran would move towards a sustainable nuclear program with reduced risk of proliferation.

CONCLUSION

Under the pressure of global warming, LFTR has the potential for new life. LFTR has been considered and abandoned several times; however, abandonment has been due to preemption, rather than failure.[194] In the 1940s, LFTR could not produce the Bomb. In the 1950s, the Fireball jet engine was preempted by the advent of in-flight fueling.[195] In the 1960s and 1970s, Cold War politics and plutonium reined it in once again.[196] Since then, thorium has resurfaced for an occasional experiment.[197]

LFTR is gaining traction today all over the world from government projects in China[198] and India[199] to private projects, such as Lightbridge and ThorEnergy.[200] Thanks to large thorium deposits and little uranium,

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[193] *Id.*

[194] *See* Hargraves, *supra* note 1, at 2681.

[195] *See id.* at 2530.

[196] *Id.*

[197] *See id.* at 2570.

[198] *Nuclear Power in India*, WORLD NUCLEAR ASS'N, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx [https://perma.cc/H9MJ-MMK9] (last updated Jan. 2016).

[199] Phillips, *supra* note 160.

[200] Hargraves, *supra* note 1, at loc. 2568.

India and Norway are early advocates of thorium.[201] By 2050, India plans to use nuclear energy, including plans for LFTR, for 25% of its electricity.[202] Only time will tell if something comes along to preempt LFTR once again.

That said, thorium used in LFTR could be the solution to fossil fuels and the answer to anti-nuclear advocates. LFTR differs from pressurized water reactors in several material respects. LFTR uses thorium immersed in molten salt at atmospheric pressure.[203] PWRs use solid fuel pellets, which must be cooled by hot, highly pressurized water.[204] LFTR has inherent and passive safety features that do not require operator intervention or electricity.[205] Even "modern" pressurized water reactors harken back to designs from the 1950s.[206] LFTR is not a new idea, but its design can escape the inertia of outdated reactor designs in a way that PWRs cannot.

The United Kingdom's National Nuclear Laboratory ("NNL") is much less optimistic about thorium.[207] The NNL estimates that it is "likely to take 10 to 15 years even with a concerted R&D effort and investment before the thorium fuel cycle could be established in current reactors and much longer for any future reactor systems."[208] Perhaps NNL is correct that thorium would take more than a decade to bring into common usage. However, predicting nuclear technology has been difficult, and technology has exponentially progressed in the last hundred years.

Once U.S. and foreign policymakers appreciate the opportunity, there are several ways they can encourage LFTR. First, like Norway and India, the U.S. has substantial thorium resources that can be exploited. However, mapping and accessibility assessments are sparse. Collecting data and collaborating with the nuclear and mining industries would improve prospects for commercialization. Similarly, several key technologies must be better developed before LFTR can be used on a commercial scale. Many of these technologies are chemistry dominant and would

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[201] *See generally* GOV'T OF INDIA, *supra* note 159; Christ Rhodes, *Thorium Nuclear Power—A Lesson from Norway*, FORBES (Feb. 29, 2012 at 1:07 PM) http://www.forbes.com/sites/energysource/2012/02/29/thorium-nuclear-power-a-lesson-from-norway/#272aa6a0187f.
[202] WORLD NUCLEAR ASS'N, *supra* note 198.
[203] Hargraves, *supra* note 1, at 2599.
[204] WORLD NUCLEAR ASS'N, *supra* note 11.
[205] Lerner, *supra* note 68.
[206] WORLD NUCLEAR ASS'N, *supra* note 11.
[207] *The Thorium Fuel Cycle*, UK NAT'L NUCLEAR LABORATORY (Aug. 2010), http://www.nnl.co.uk/media/1050/nnl__1314092891_thorium_cycle_position_paper.pdf [https://perma.cc/8EC4-8UL4].
[208] *Id.*

require a collaboration between chemists and nuclear engineers. Given the broad scope of international projects, an interstate agency organizing government subsidized research would allow international collaboration to reduce redundancies, make funding more efficient, and move up the LFTR timetable.

Moreover, already existing government subsidies in energy R&D can be reallocated to encourage the nascent LFTR industry in research and construction. Finally, LFTR provides a potential solution for nuclear proliferation in states like Iran. While not absolute, LFTR has inherent barriers to weaponization that make it an inefficient means of production. After seventy years, it is time the U.S. took the back the impetus of nuclear technology and led the world into a more energy efficient future.