State of TRISO Fuel Availability in the US

NPRE 480 Mini Project 1

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1 The Problem

The United States (U.S.) has environmental legislation (like the Clean Air Act) that has been around for decades, and is constantly being updated with changing understanding of air pollution and community feedback. These laws are very much alive, and in order to reduce carbon emissions, Illinois adopted the Climate and Equitable Jobs Act (CEJA) [1] in 2021 that targeted zero emissions from the electric power sector by 2030. However, history continues to unfold; while we were writing this, there was a case before the supreme court that challenged the Chevron Deference Doctrine, established in the 70s over this very law, that allowed the newly created Department of Energy to regulate in the gaps of existing regulations.

1.1 Nuclear Fuel Cycle

The nuclear fuel cycle (NFC) describes the plethora steps that nuclear fuel goes through in its life cycle. In Figure 1 we have outlined a simple "once-through" fuel cycle (so called because the fuel goes through the cycle once in its lifetime. Nuclear fuel has the capacity to be reprocessed and recycled into a different fuel type that can produce usable power for several cycles, called a "closed" fuel cycle.

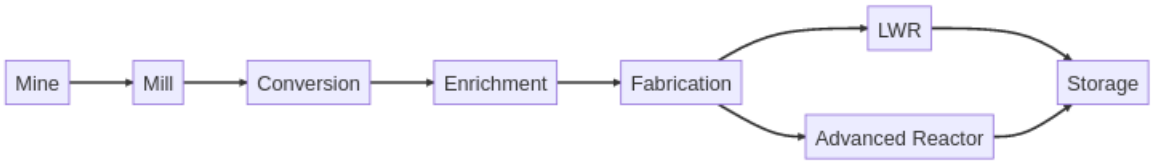


Figure 1: US Once-through Fuel Cycle

In the US, we keep each of these facilities separate in the front-end of the fuel cycle in a "collect and wait" pathway [2]. In lieu of a long or interim solution for the Used Fuel (UF), the back end of the NFC is collocated with the reactors that burn the fuel (with the minor exception of the consolidated storage facility in Morris Illinois. Though nuclear reactors does not produce greenhouse gases during operation, radioactive wastes are generated both at the front end and at the back end of the NFC. Mining and milling will create a large volume of wastes with low radioactivity and depleted uranium will be produced during enrichment. The UF will have a radioactivity of around $10^5 TBq$ per tonne of fuel [3]. Under the current once-through fuel cycle, disposal of the spent fuel is extremely hard because the facility has to last for more than 50,000 years so that decay process can decrease the radioactivity to a reasonable degree. A energy source without fossil fuel is not necessarily clean, because the waste created in both preparation stage and dismantle stage can still be harmful to the environment.

The main steps in the U.S. fuel cycle start with the mining and milling of uranium ore. Where the ore is extracted from the ground, and then uranium is extracted from the ore. Data from the World Nuclear Association (WNA) showed that around two-thirds of the world production of uranium from mines is from Kazakhstan (43%), Canada (15%), and Namibia (11%) [4]. The domestic production of urnaium from mines in the U.S. has dropped significantly for the past ten years: from around 1800 tonnes in 2013 to less than 100 tonnes in 2022.

After the uranium is extracted, a conversion facility transforms it into UO_2 by oxidizing the gasified UF_6. Following deconversion (a process not pictured in Figure 1 as it is commonly combined with the conversion process), the uranium is enriched to a desired concentration of ^{235}U. There are three enrichment processes: gaseous diffusion, gas centrifuge, and laser separation, with gas centrifuge being the most popular method today. Enrichment of uranium is tightly connected

to national defense because highly enriched uranium could be used to produce nuclear weapons. However, there are still some international companies who owns commercial enrichment facilities. Russian company Rosatom has the largest enrichment capacity in the world (27,700,000 SWU/yr), following by Urenco, co-owned by Germany, Netherlands, and United Kingdom (UK), with a capacity of 13,700,000 SWU/yr. Urenco also owns the only civil enrichment plant in the U.S. with a capacity of 4900 SWU/yr [5].

In a fabrication facility, the enriched solid UF_6 will be heated to gaseous form, mix with steam to form UO_2F_2 and with H_2 to form UO_2 powder. The solid UO_2 will then be processed to form fuel pellets, and then to fuel rods that can be used in a reactor [6].

Nuclear reactors can be categorized by moderator and neutron spectrum. For thermal reactors by moderator, there exists water-moderated reactors: two with light water: Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR); and one with heavy water: Heavy Water Reactor (HWR); and graphite-moderated reactors: Gas Cooled Reactor (GCR), Molten Salt Reactor (MSR) and Graphite-moderated Water-cooled Reactor (RMBK). Fast reactors does not have a moderator and can be cooled by liquid metal (Liquid Metal Fast Breeder Reactor (LMFBR)). Among them, the water-cooled reactors: PWR, BWR, HWR, RMBK are more sophisticated whereas the GCR, LMFBR MSR are considered advanced reactors due to their high efficiency and passive safety.

In a typical thermal reactor, U-235 will undergo fission by absorbing a neutron, releasing two fission products and 2-3 fast neutrons. These fast neutrons will be slowed down and become thermal by scattering in the moderator and being absorbed by U-235 again, generating next generation of neutrons. During fission process, U-235 and some U-238 are converted to fission products and Transuranic isotopes (TRU) isotopes, many of them radioactive. For waste manage, the most important isotopes are TRU such as ^{239}Pu with a half life of 24,000 years. These actinides will stay in the waste for more than 100,000 years, posting major difficulty in deposition of UF. Many disposal strategies are proposed: such as geological disposal, seabed disposal, deep hole disposal, space disposal, and waste processing and transmutation. Among these methods, only geological disposal has been implemented by Finland. In technical perspective, the validity of burying spent fuel in a rock bed has been proven, but the political pressure is stopping the U.S. government to implement the geological disposal method.

Alternatively, the reprocessing method will separate the long-lived TRU from the fission products in the spent fuel. The TRU will be transmuted either into higher actinides that decay faster or into fissiles that could be used as a fuel. The reprocessed waste needs to be stored only for several hundred years. However, the cost of reprocessing is so high that this method is also prohibitive currently [7].

For now, U.S. does not have a long-term waste management plan. Yucca Mountain, Nevada was originally chosen to build a geological deposition facility, but was rejected in around 2009. In Finland, a similar geological deposition facility is built on Olkiluoto Island by the company Posiva and will receive first spent fuel in the middle of 2020s [8]. France reprocesses the spent fuel by extracting the plutonium and mixing it with uranium into Mixed OXide fuel (MOX). This process will utilize 96% of the spent fuel. Similar geological deposition method are under development under the CIGEO solution [9].

Closing the fuel cycle with reprocessing could improve the energy security of that country. Compared with fossil fuel, uranium offers a much longer-term electricity supply: nuclear power plants built today could operate for around 60 years. Besides, uranium is available for U.S.: 28% of uranium reserve on earth is in Australia [10], and Europe has abundant capacity to enrich the natural uranium. The uranium will be more available by reprocessing: Through reprocessing, France saved 17% of uranium needed to operate its power plants [9].

1.2 TRISO Fuel

TRi-structural ISOtropic (TRISO) coated fuel particle is a ceramic fuel sphere coated by four layers of carbon. It is widely used in High-Temperature Gas-cooled Reactor (HTGR) because of its excellent performance under high temperature ($700 - 900^{\circ}C$ in HTGR core) and its ability to trap fission products in the particles. This concept was first implemented in the UK for the Dragon Project in the 1950s [11].

A TRISO particle has a total particle diameter of 0.8-1 mm, with the uranium-bearing kernel (usually UO_2 or UCO) taking diameter between 0.35 to 0.6 mm. The kernel is coated by four layers from inside to outside respectively: a porous pyrocarbon buffer providing space for gaseous fission products and fission recoil; a dense, highly isotropic Inner PyroCarbon layer (IPyC) as a deposition surface for SiC layer; a SiC layer to provide structure strength and prison solid fission products; a Outer PyroCarbon layer (OPyC) to protect SiC layer during handling and serves as the bonding surface to graphite matrix. Combining with gaseous helium coolant, this structure eliminated the possibility of hydrogen explosion in high temperature and prevented the fission products from escaping the fuel material.

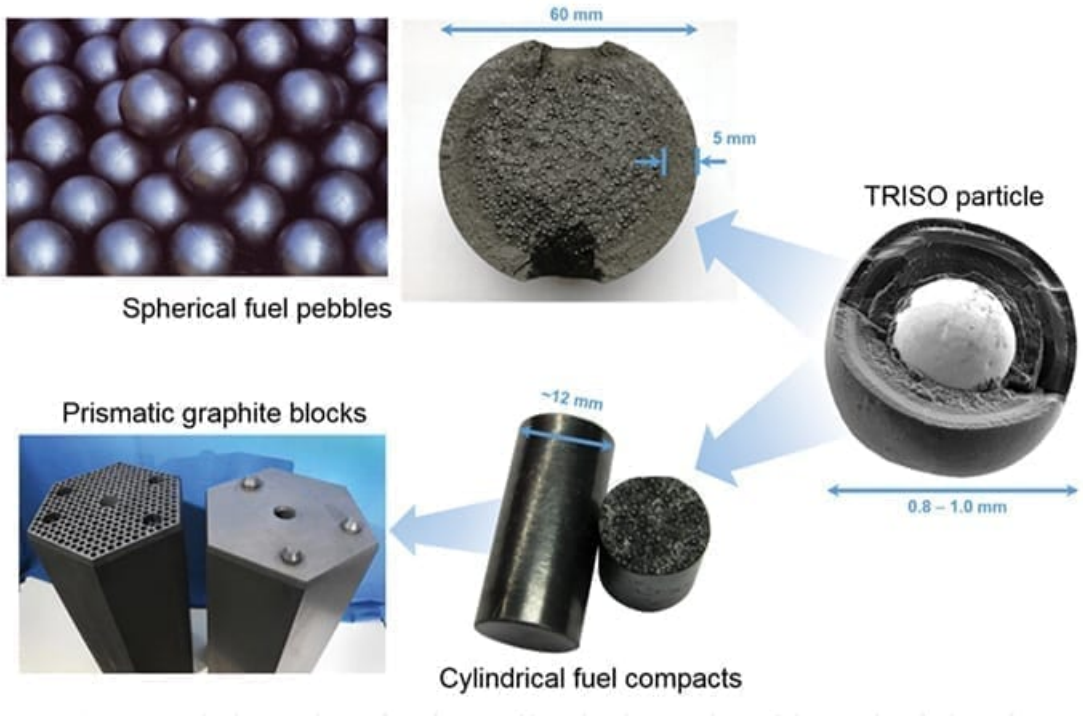


Figure 2: Structure of TRISO Particle

A TRISO-fueld HTGR have different radioactive wastes compared with conventional reactors. CO_2 with radioactive C-14 and other gaseous fission products escaped from the fuel particle will mix with the helium coolant in primary cycle. The solid fission products will stay in the fuel particles as long as the coats are not damaged, which makes reprocessing relatively easier than conventional reactors because the TRISO coating is way more robust than the Zr cladding, ensuring a low failure rate. Serving as the reflector, the irradiated graphite will contribute significantly to the volume of radioactive waste from a HTGR [12].

The most wide-used fabrication method for fuel kernels is the sol-gel process: Actinides will be dissolved in nitric acid. By pumping ammonia, metal oxide will be precipitated and form a gel

sphere, which will become sintered kernel after processing. The coating is applied by the Fluidized-Bed Chemical Vapor Deposition system (FB-CVD): the kernel will be fluidized with a mixture of argon and reactant gases at optimized gas fractions and temperature to deposit the layer. Currently, only two companies own facilities that manufacture TRISO: BWX Technologies, Inc. (BWXT) and Ultra Safe Nuclear Corporation (USNC). As a long-time Department of Defense supplier, BWXT has two factories at Lynchburg, Virginia licensed by U.S. Nuclear Regulatory Commission (NRC) with a total production capability of more than a hundred kg of TRISO [13]. USNC, collaborating with Framatome, opened the first private-funded TRISO facility: the Pilot Fuel Manufacturing facility (PFM) in August, 2022. Located at the East Tennessee Technology Park at Oak Ridge, Tennessee, the facility demonstrated the production of TRISO at scale [14]. In October 13, 2022, X-energy began the construction of the TRISO-X Fuel Fabrication Facility (TF3) also in Oak Ridge, Tenneesse for commercial production of its onw version of TRISO particle: TRISO-X.

2 Scenarios

In many works on energy markets you find their primary metrics are financial based, but we will evaluate several scenarios with separative work units (SWU) and the mass of enriched uranium—a set of metrics more common to fuel cycle analysis—over a series of fuel source scenarios to create a granular look at the issue of TRISO availability.

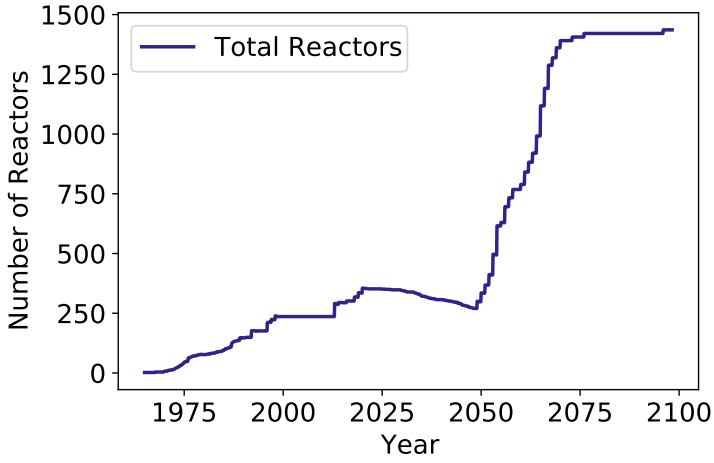


Figure 3: Total number of reactors deployed

In this example, we will look at how locating enrichment facilities overseas impacts our fuel cycle. We will deploy reasonable NFC facilities in the U.S. to isolate the impact of the enrichment location. We will perform a transition analysis from a Light Water Reactor (LWR) fleet to entirely TRISO-fueled reactors that are deployed to meet a constant energy demand as LWRs retire. The deployment, is depicted in Figure 4. This replacement scheme is not historical, as it deploys these reactors, but it does illustrate the relationship between their deployment and the deployment of LWRs, which we may see in countries line China that might look to deploy multiple LWR facilities in the next decade.

In this series of mini projects, we will create a rough understanding of the environmental impacts of a variety of NFC options focused on domestic and international enrichment capabilities. As such, we developed four bounding scenarios that varies the share of domestic enrichment capabilities outlined in 1.

Scenario	% of U.S. Enrichment	% of International Enrichment
Scenario 1	100	0
Scenario 2	60	40
Scenario 3	40	60
Scenario 4	0	100

Table 1: Scenario Summary

2.1 Cyclus and SWU

Cyclus is an agent-based NFC simulator that is incredibly versatile, one of the initial core developers (Professor Katy Huff) likes to say that, "Cyclus can be used to model any process from making a grilled-cheese to international nuclear fuel cycles." The software achieves this versatility through a series of generic archetypes that are primarily transaction based. Over the years, the user community and developers have created a litany of nuclear specific archetypes for everything from proliferation assessment to fuel burnup.

We have referenced SWU several times now without explaining how the measure is derived, so we will rectify that now. SWU, or Separative Work Units, is a ubiquitous measure of effort that goes into producing nuclear fuel. It is simplified as:

$$SWU = Q(C_p C_f) \tag{1}$$

Where:

$$\begin{aligned} SWU &= \text{Separative Work Units [kgSWU]} \\ Q &= \text{ Quantity of material processed [kg]} \\ C_p &= \text{ Enrichment level of the product [\%]} \\ C_f &= \text{ Enrichment level of the feed [\%].} \end{aligned}$$

2.2 Deployment Analysis

In this work we have deployed a "LWR-like" and "Xe-100-like" reactors starting with the currently and previously deployed LWRs. When these reactors retire, either based on history or on an 80-year license, they are replaced by the number of Xe-100-like reactors it takes to generate the amount of energy capacity lost. As the capacity is an order of magnitude smaller in most cases, it is unsurprising that (as LWRs are decommissioned) the number of Xe-100-like reactors explodes.

In the most U.S.-centric vision of the NFC, we can create a scenario with all of the enrichment facilities onshore. As we are not making a distinction between existing international and domestic infrastructure (assuming that it increases as these reactors are deployed), Scenarios 1 and 4 have the same shape. In future parts of this project, we will distinguish them using other metrics (such as emissions from transportation).

Curiously, the 2020-2030 time frame appears to have steady SWU capacity requirements (likely due to the competing deployment and decommissioning of LWR-like and Xe-100-like reactors as the latter deployment begins to ramp up. Unsurprisingly, the overall shape is mirrored in Figure 6.

Similarly, Scenarios 2 and 3 have the same shape, so we have depicted them together with Scenario 2 zoomed in to show the periodic requests for SWU.

We will take a step back from the specific of these NFCs, and remind ourselves why this is important. This part of our semester long project is setting up the environmental impact of the enrichment we would need to replace our fleet of LWRs. In this transition, we are still producing giga-watts of carbon-free energy as depicted in Figure 7.

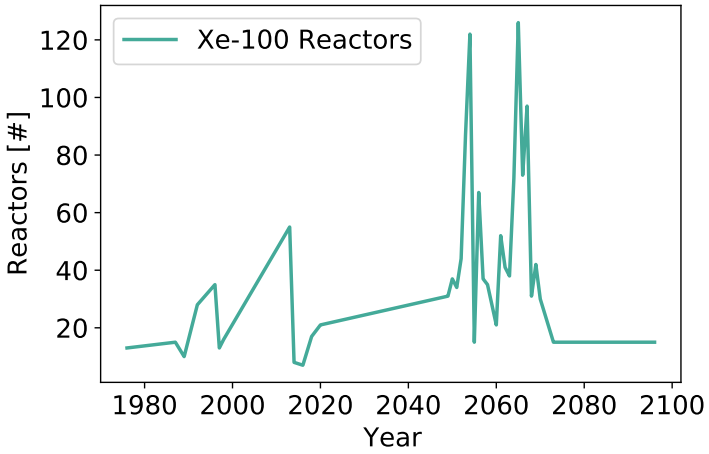


Figure 4: Number of Xe-100-like reactors deployed

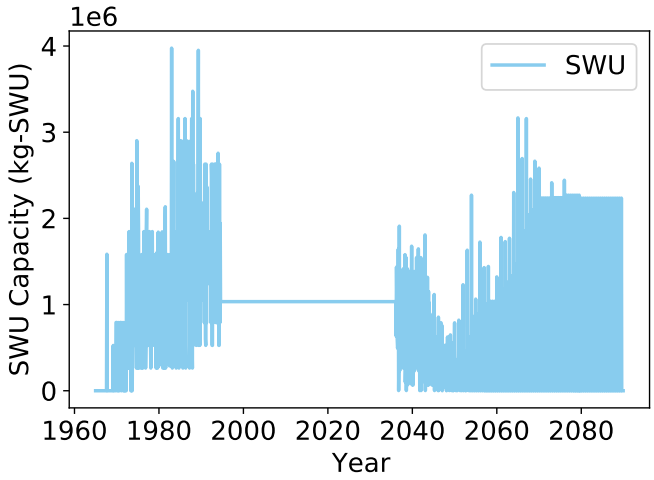
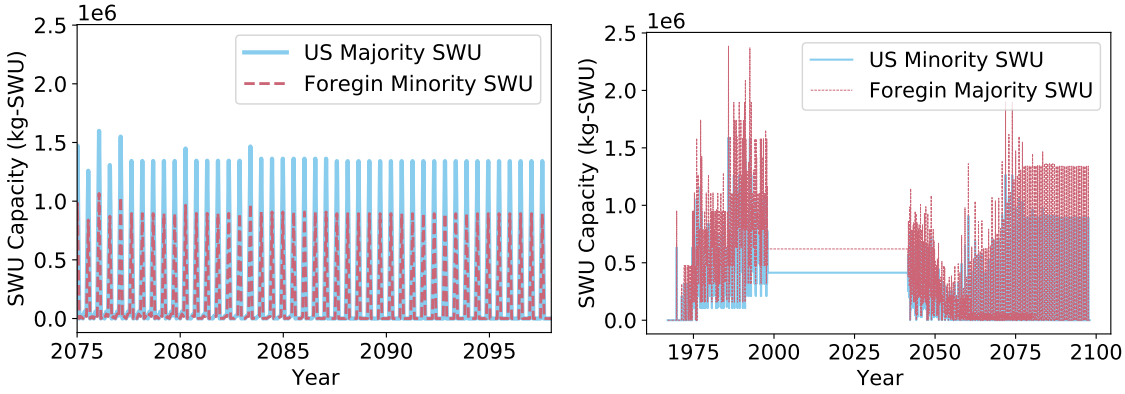


Figure 5: SWU for scenarios 1 and 4

In the next part of this project, we will examine the environmental impacts of collaborative enrichment schemes that members of the National Nuclear Security Administration and Office of Science and Technology Policy have disclosed to us they are considering.



((a)) Scenario 2, Zoomed in

((b)) Scenario 3

Figure 6: Scenarios 2 and 3 have the same form

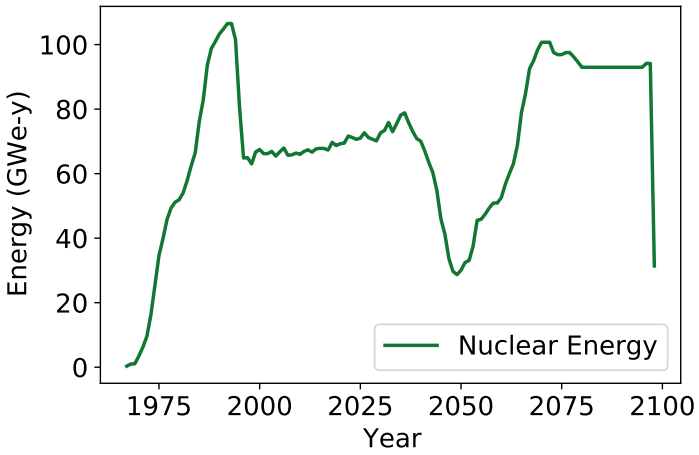


Figure 7: Yearly Energy Production

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Acronyms

BWR Boiling Water Reactor. 2

BWXT BWX Technologies, Inc.. 4

CEJA Climate and Equitable Jobs Act. 1

FB-CVD Fluidized-Bed Chemical Vapor Deposition system. 4

GCR Gas Cooled Reactor. 2

HTGR High-Temperature Gas-cooled Reactor. 3

HWR Heavy Water Reactor. 2

IPyC Inner PyroCarbon layer. 3

LMFBR Liquid Metal Fast Breeder Reactor. 2

LWR Light Water Reactor. 4, 5

MOX Mixed OXide fuel. 2

MSR Molten Salt Reactor. 2

NFC nuclear fuel cycle. 1, 4, 5

NRC U.S. Nuclear Regulatory Commission. 4

OPyC Outer PyroCarbon layer. 3

PFM the Pilot Fuel Manufacturing facility. 4

PWR Pressurized Water Reactor. 2

RMBK Graphite-moderated Water-cooled Reactor. 2

SWU separative work units. 4, 5

TF3 the TRISO-X Fuel Fabrication Facility. 4

TRISO TRi-structural ISOtropic. 3, 4

TRU Transuranic isotopes. 2

U.S. United States. 1, 2, 4, 5

UF Used Fuel. 1, 2

UK United Kingdom. 2, 3

USNC Ultra Safe Nuclear Corporation. 4

WNA the World Nuclear Association. 1