Making Nuclear Renewable

Introduction

There are over 90,000 metric tons (MT) of used nuclear fuel (UNF) in interim storage at nuclear power plants across the U.S [1] (which, if fully recycled just once, could electrify the entire US for at least 8 years). There is no actionable plan for long-term management of this waste, which grows at a rate of 2,000 MT per year and will soon be 6,000 MT/year if recent commitments are met [2]. Without new economically and environmentally viable solutions to advance the state-of-the-art, UNF will continue to hold back the promise of nuclear energy.

The introduction of recycling and transmutation to the back end of the fuel cycle will convert UNF from a waste challenge to a renewable resource and make nuclear energy renewable. The recovery of the U and Pu allows for the production of new fuel which will enhance energy security and reduce the need for new mining, conversion, and enrichment of fresh uranium. In addition, the harvesting of other valuable materials from the UNF stream through a comprehensive UNF recycling program will provide critical resources to global markets. Importantly, the removal of these valuable UNF components will dramatically reduce high-level waste (HLW) volumes that need additional processing or long-term disposal. The addition of an integrated transmutation strategy (such as the one being explored in our recently awarded ARPA-E NEWTON project) will provide a safe, permanent solution to America's UNF challenge by transmuting remaining long-lived waste into much safer forms. Our vision is to eliminate the need for a $100B+ geologic repository and convert the UNF to a truly renewable resource, enabling nuclear fission to become a more realistic solution to climate change.

Our approach to UNF recycling is different than conventional reprocessing efforts. Rather than focusing only on plutonium and uranium, we employ a holistic strategy to recover dozens of valuable isotopes from the waste stream to further reduce the volume of waste and create additional economic potential. We are further differentiated in that we are the only company in the world that has built a facility of this kind in recent decades (Figure 1). Our Chrysalis medical isotope plant required similar design, construction, and licensing characteristics of an end-to-end UNF processing, recycling, and transmutation system. Our experience here positions us to move faster and understand our cost base than other potential competitors.

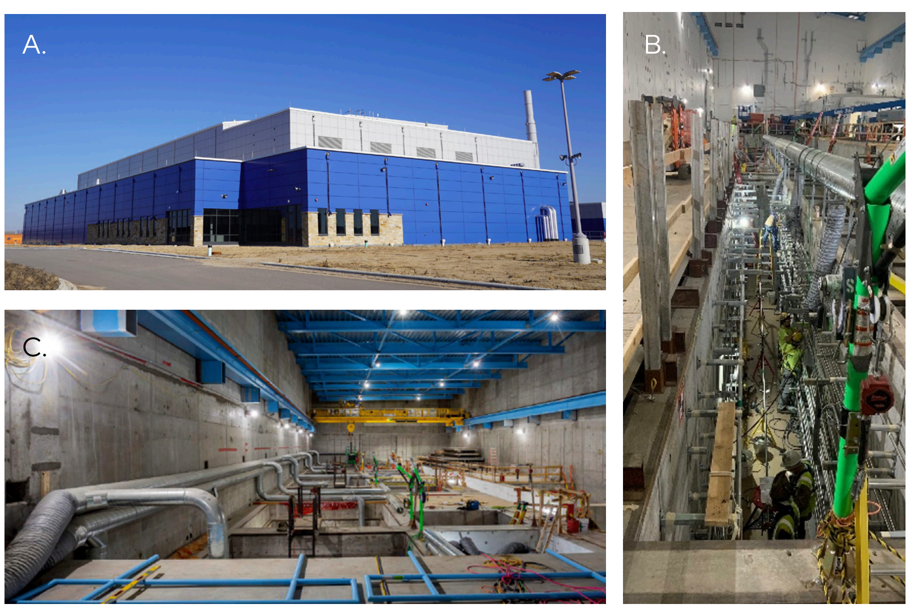

Figure 1: Photos of SHINE's medical isotope production facility (Chrysalis). (A) Exterior, (B) piping and liquid storage, (C) irradiation

Our Technological Approach, Experience, and Team

Our efforts to make nuclear renewable build on our current expertise in plasma physics, particle accelerators, neutron generation, advanced nuclear systems design, manufacturing and operation, radioactive material handling, uranium processing, waste management and construction and project management. We expect our efforts to result in a permanent, cost effective, and environmentally sustainable solution for recycling spent fuel, that supports a sustainable fission energy economy while advancing our pathway to commercial fusion energy.

Figure 2: SHINE and Orano CEO's at the partnership agreement ceremony

We've assembled a coalition of technical and commercial partners to help us achieve these goals. The development of this coalition has accelerated progress towards UNF recycling in the US and has rapidly increased visibility of SHINE's efforts. Key partners with formalized partnership agreements in place include Orano, Argonne National Lab (ANL), Zeno Power Systems, Deep Isolation, and Constellation Energy. Orano is supporting us through technology transfer of recycling technologies from their La Hauge facility in France. We are working with ANL to build an end-to-end lab-scale separation system (CoDCon and ALSEP for technology derisking. Zeno is developing isotope-heated nuclear battery systems and will become a key customer of Sr-90 and Am. Deep Isolation is a key waste disposal partner for the small fraction of waste incidental to reprocessing/transmutation. Finally, Constellation is the largest nuclear electricity utility in the US, has the stated goal of wanting to operate the first plants to burn recycled fuel and will become a key customer. Other collaborators with SHINE currently include Sandia National Labs (SNL), GE-Vernova, the Electric Power Research Institute (EPRI), Pacific Northwest National Lab (PNNL), Idaho National Lab (INL), Oak Ridge National Lab (ORNL), and four top-tier research universities (Texas A&M, UW-Madison, UC-Berkeley, and the University of Alabama at Birmingham).

Supported by partners at Orano and ANL, we are designing a comprehensive U/Pu co-extraction facility to separate spent fuel into U, U/Pu, Np, minor actinides (MA, e.g., Am and Cm), lanthanides, and fission products (FPs). Destruction of Am, Cm, and long-lived fission products via transmutation shifts the current paradigm of recycling to one that actually resolves the issue of having waste that lasts for millions of years. We are already world leaders in developing fusion-based transmutation for the production of medical radioisotopes and are developing a DT driven subcritical MA/FP transmutation unit using next-generation fusion technology.

As depicted in Figure 3, there are significant parallels between our Chrysalis medical isotope production facility (Phase 2) and our planned UNF recycling and transmutation facilities. Both processes include the safe handling and dissolution of uranium, the separation and recovery of valuable materials, and the recycling of uranium. Both also utilize fusion neutron systems as critical process steps. Further, the safety analysis, construction, and licensing strategies overlap significantly, allowing us to leverage experience gained during Phase 2.

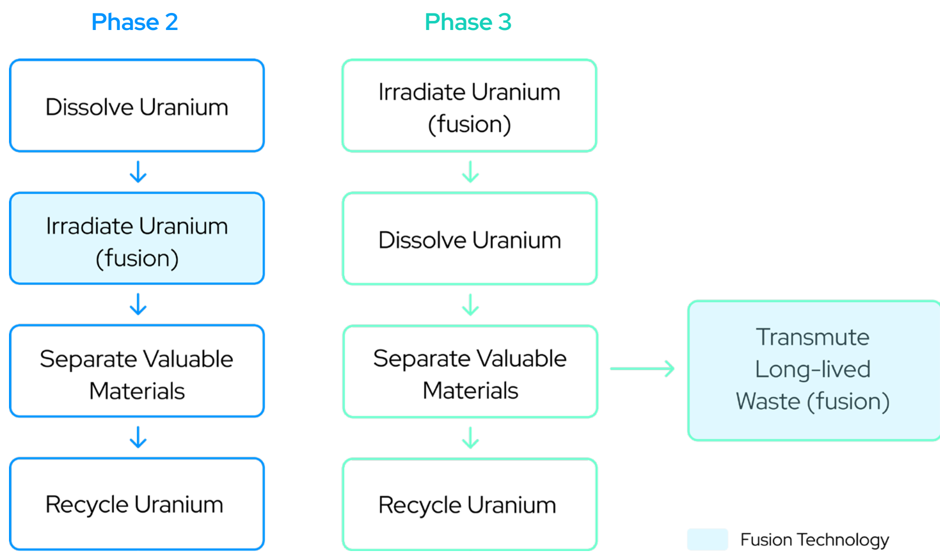

Figure 3: Process comparison for SHINE Phases 2 and 3

Detailed Process Overview

A key objective of our commercialization strategy is to bring UNF recycling with isotope recovery to market by the early 2030s. As such, a recycling process based on liquid-liquid extraction (LLE) methods has been chosen as the core separation strategy. We investigated alternate separation approaches (e.g., pyroprocessing) and concluded that LLE is most likely to be operationally viable within five years, is economically attractive and ecologically safe, and will garner sufficient support from industry stakeholders, investors and the public. The coupling of key improvements in LLE with targeted extraction of radioisotopes and stable elements with commercial value can make this approach to UNF recycling more attractive on a techno-economic basis. When ultimately coupled with transmutation, the holistic recycling/transmutation concept will provide a broad spectrum of valuable isotopes and dramatically reduce waste to be stored on geologic timescales.

A high-level view of the envisioned separation process is provided in Figure 4. The separation process will begin with conventional shearing of fuel rods to expose the fuel pellets. The resultant pellets and hulls will be subjected to a voloxidation process to remove volatile radionuclides from the process stream. This material will then be dissolved in nitric acid, clarified of particulate matter, and moved into a CoDCon [3] separation process to generate U/Pu and U streams. The CoDCon process is a modified version of the PUREX process used in France today and is used to separate the major actinides from the bulk dissolved UNF. A key differentiation from the PUREX process is that Pu is never separated from U which provides increased proliferation resistance. Instead, the CoDCon process was developed to obtain a mixed Pu/U product. The primary output of this step is moved to an ALSEP [4] process to isolate the minor actinides (MA) for transmutation. The MA's represent a significant portion of the remaining used fuel and bring several challenges to high-level waste disposal. Past studies have shown that the separation of minor actinides alone would reduce the total repository volume by up to a factor of seven [5]. Additionally, the lanthanides are segregated in this step, some of which may be value-added products. The raffinate from the ALSEP process is sent to a final fission product capture step, where valuable stable and radioactive elements are harvested. Sr-90 and the platinum group metals (PGMs) are of particular interest for separation due to their value.

Sr-90 is among the major contributors of heat generation in nuclear waste. This property has made Sr-90 notorious for complicating handling of UNF and its storage in deep geological repositories. SHINE has adopted an alternative view on the heat-emitting capabilities of Sr-90. When isolated, it can be an efficient heat source for broad use in space and terrestrially. We've partnered with Zeno Power Systems to convert this waste material to a useful product to be recovered from the UNF. The remaining raffinate (that is not directed towards transmutation) is cemented to be disposed as low- or intermediate-level waste, potentially in deep boreholes co-located at the recycling facility.

After these separations have occurred, DT neutron-based transmutation is expected to be an attractive alternative to disposing of long-lived radioactive waste in a geologic repository (which involves significant economic, environmental, and political challenges). An effective transmutation strategy will reduce the relevant time scales for safe fission product management by transmuting the longest-lived and/or mobile materials into stable isotopes, radioisotopes with significantly shorter half-lives, and/or isotopes that are essentially non-mobile in repository geologies. This is an essential step in a holistic long-term waste management strategy that will significantly reduce and may even eliminate the need for deep geologic storage of spent fuel components by leveraging an intermediate waste storage facility.

We will use DT fusion neutrons to drive a subcritical molten-salt target that is fueled exclusively with MA to fission these MA and additionally transmute other FP placed in the target. The high-energy neutron spectrum has sufficient energy to break up long-lived isotopes into shorter-lived fragments. The resulting transmuted material will be substantially easier and less expensive to store and dispose of in a manner that is commercially, politically, and environmentally viable. Development of the transmutation technology will take advantage of competencies already honed at SHINE including fusion-driven liquid subcritical assembly development, tritium handling, safety/regulatory expertise, and first-of-a-kind large capital equipment nuclear project management.

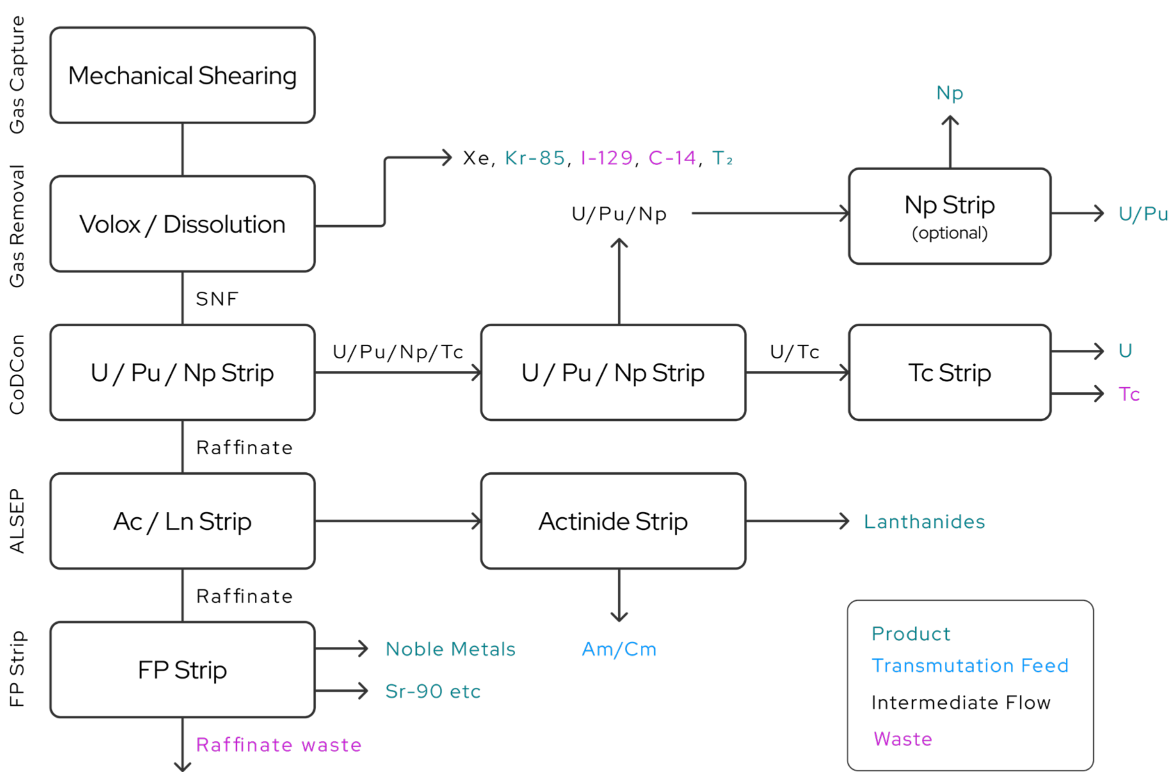

Figure 4: Process flow in SHINE recycling facility

Economic Assessment

In order to make nuclear energy renewable, a service fee on electricity of $10/MW-hr ($0.01/kW-hr) is proposed to be charged to utilities providing clean, reliable baseload nuclear power to the grid. As seen in Figure 5, this service fee will not increase the total levelized cost of electricity to a level that is out of line with existing coal, combined cycle gas, or hydroelectricity. Furthermore, the levelized cost of existing nuclear power, even with a $10/MW-hr service fee to make that nuclear energy truly renewable, will still be significantly less expensive than the levelized costs of constructing new wind or photovoltaic solar energy [6], and a $0.01/kW-hr premium is about half of what is typical for renewable energy. With 800B kWh of electricity generation from nuclear per year in the U.S., a $0.01/kWh-hr service fee would equate to a recurring market size of $8B per year in the US at today's nuclear generation capacity [7]. With 2,000 MT of UNF generated in the US per year, this equates to a $4M/MT of UNF fee. Globally, we expect the TAM is over $30B per year [8]. We expect that nuclear generation capacity will more than double over the next few decades, coinciding with recent pledges to triple nuclear capacity by 2050.

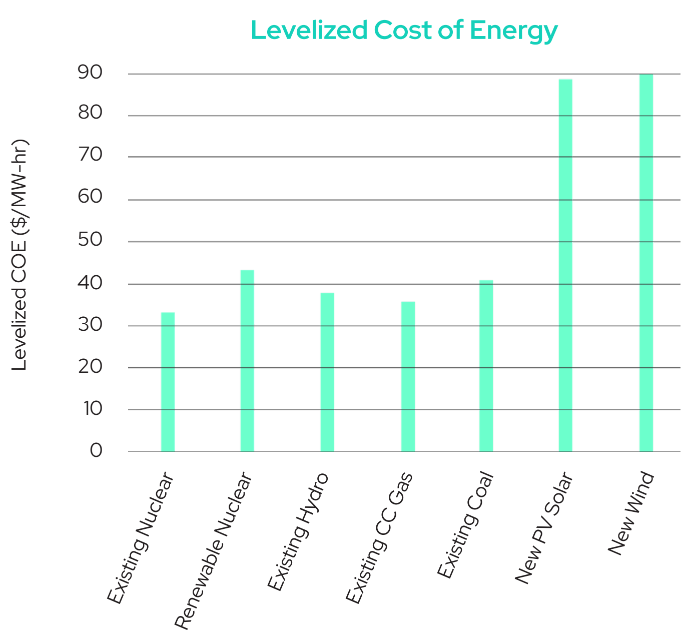

Figure 5: Levilized costs of energy for production options, including renewable nuclear [6]

At modern fuel burnup rates of 50 GWd/MT, the proposed fee equates to $4M/MT of UNF to cover the costs of recycling all the useful fuel constituents, transmutation of targeted problematic isotopes, and permanent disposal of any remaining waste products. Additional sales of recycled materials from the UNF stream increase this topline number. This robust business case will create a sustainable business and also supports US interests by providing new nuclear fuel feedstock and a supply of critical radioactive isotopes and critical stable elements to support domestic needs. We are also developing technologies and strategies to reduce the cost of UNF recycling and to grow the revenue potential by recovering a larger fraction of the available products. Examples of these materials, along with a brief description of their uses, are provided in Table 1.

There is 2,000 MT of UNF generated per year in the US today. We expect that the annual volume of UNF generated in the US will increase in the future as nuclear generation capacity expands. If nuclear generation capacity doubles or triples, in line with recent pledges, the amount of UNF generated in the US would be 4,000-6,000 MT per year. In addition, additional recycling capacity will be required to reduce the US's 90,000 MT backlog that currently exists to a more manageable level of ~25 years backlog equivalent, or 50,000 MT. This could be accomplished with 2,000 MT/year of additional recycling for a 20-year period.

We plan to first construct a pilot facility in the early 2030's that will process 100 MT/year to demonstrate advanced recycling technology at an economically relevant scale. This will be quickly followed by a set of three regional UNF recycling centers totaling a capacity of 2,000 MT/year each that will come online in the mid-to-late 2030's. The transmutation systems rely on further technology development but are anticipated to come online as the volumes of recovered MA and FP accumulate.

If we conservatively estimate that the final payment provided to the nuclear fuel recycler is $0.005/kWh or $2 million per MT recycled, and excluding other revenue stream opportunities, our revenue opportunity in the US would be $12 billion annually, with 6,000 MT per year recycled via our three regional UNF recycling centers. With an expected operating margin of 30%, this would equate to nearly $4 billion in operating income per year, and more than $3 billion of free cash flow generation per year. Upfront capital expenditures for a commercial recycling facility are expected to be approximately 1x annual revenue, or $2 billion per facility.

Source	Reason for Capture
U/Pu	LWR or HALEU fuel
U	LWR fuel (after re-enrichment)
Np-237	Pu-238 production (radio-battery)
Kr-85	Industrial applications
T_2	Fusion fuel
C-14	Agricultural/research applications
Ce, Pr	Industrial applications
Nd	High Temp Superconductors
Cm-244	Radio-battery applications
Am-241	Industrial applications
Ra-226	Medical isotope production
Rh, Ru, Pd	Industrial applications
Sr-90	Radio-battery applications
Y-90	Medical isotope
Cs-137	Industrial applications
Pm-147	Radio-battery applications

Table 1: Recoverable UNF materials of interest, along with their key application

Summary

We are a leading company that has developed game-changing technologies to address the nation's UNF disposal challenge in order to reduce the environmental and economic impact of nuclear energy generation via recycling. Key advantages of our approach include:

- Experience in deploying similar technologies and infrastructure
- A commercial strategy that focuses on recovering as many value-added radioactive and stable isotopes that are commercially interesting
- A technology platform that allows for a holistic solution to waste management including the use of fusion to remediate long-lived waste products

We have expertise in plasma physics, particle accelerators, neutron generation, advanced nuclear systems design, isotope separation, manufacturing and operation, radioactive material handling, uranium processing, and waste management. The ongoing project will result in a permanent, cost effective, and environmentally sustainable solution for recycling and storing used nuclear fuel in the United States and advances a credible, accelerated pathway to commercializing nuclear fusion energy.

SHINE's holistic strategy for effectively managing and recycling nuclear waste streams will remove barriers that have prevented widespread utilization of carbon-free nuclear power. When deployed, this initiative will fundamentally change the nuclear fuel cycle in a way that makes nuclear energy truly renewable. It can be executed in a manner that is consistent with the objectives of all key stakeholders including the U.S. DOE, fuel manufacturers, reactor operators, waste owners, and utilities.

Converting nuclear energy to a renewable source introduces tremendous economic potential and unlocks the key to both a sustainable fission cycle and a value-driven fusion energy case. Through a very minor and sub-typical premium for renewable energy, we will create an economically viable UNF recycling platform including transmutation of residual waste. Our solution solves a significant social issue, making nuclear fission energy renewable, while providing an attractive investment return and business case.

References

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[7] U.S. Department of Energy, 5 Fast Facts About Nuclear Energy, June 2024. Figure derived from US nuclear electricity generation of 775B kWh * $0.01 / kWh = ~$10bn

[8] World Nuclear Association, New Report Highlights Increase in Global Nuclear Reactor Generation & Performance. Figure derived from global nuclear electricity generation of 2600B kWh * $0.01 ~kWh = ~$30bn