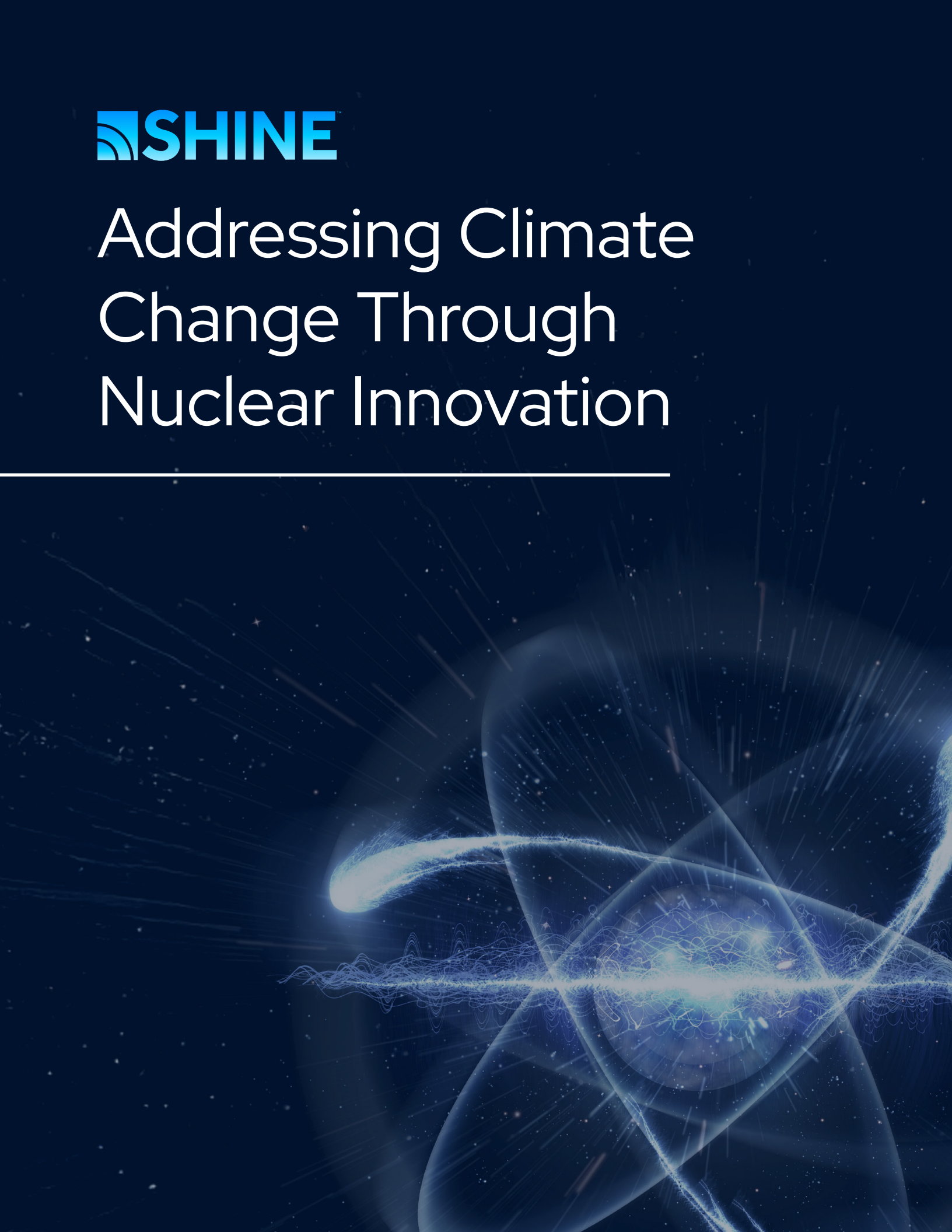
SHINE

Addressing Climate Change Through Nuclear Innovation



Addressing Climate Change Through Nuclear Innovation

SHINE's technical fusion-based approach to producing medical isotopes and recycling nuclear waste has been estimated to reduce, or avoid, more than 40 million tons of CO_2 per year.

Source	CO_2 Emission Reduction / Avoidance
SHINE Technology for Producing Medical Isotopes	4,708 tons CO_2/ year
Opportunity cost of using HFR HALEU for energy production	43,000 tons CO_2/ year
Recycle fissile content from current UNF stockpile (assumed over 30 years)	1.75 million tons CO_2/ year
Recycle fissile content from ongoing UNF generated	1.2 million tons CO_2/year
Enable additional 10% of baseload nuclear (offset gas)	39.7 million tons CO_2/year
Total Potential:	**42.7 million tons CO_2/ year**



SHINE's Chrysalis, Janesville, WI

Executive Summary

Given the gravity of climate change, there has never been a greater need to unlock fusion as a sustainable, carbon-free energy source. However, fusion-based energy production is currently cost-prohibitive, and the realization of economical fusion energy may take decades to achieve. That's why SHINE employs a unique, scalable approach that takes material steps towards avoiding and reducing greenhouse gas emissions.

Producing Medical Isotopes

We are currently constructing a medical isotope facility, Chrysalis, in Janesville, WI, that uses new, innovative and significantly improved nuclear technology to produce life-saving isotopes including molybdenum-99 (Mo-99), iodine-131 (I-131), xenon-133 (Xe-133), and lutetium-177 (Lu-177) among others.

Chrysalis uses our deuteron accelerator and gas target technologies to create D-T fusion, which creates neutrons. The neutrons interact with a liquid uranyl sulfate target solution, generating fission multiplication in a subcritical configuration. Our uranium target solution is prepared using high-assay low enriched uranium (HALEU) with 19.75 percent enrichment. The fission of uranium creates a number of fission by-products, including medical isotopes like Mo-99, I-131, and Xe-133. The liquid uranyl sulfate solution is then processed, and medical isotopes are separated from the partially-fissioned uranium solution. The uranyl sulfate solution is returned to be irradiated again, recycling most of the uranium and producing a new batch of isotopes.

Chrysalis facility meaningfully reduces or avoids greenhouse gas emissions via a number of avenues, including reduction in uranium consumption, reduced transportation, and increased production throughput vs incumbent production processes. Additionally, by recycling our uranium solution, we dramatically decrease the amount of HALEU required for medical isotope production vs. existing production methods.

HALEU supply is limited and is a major concern for new, emerging nuclear fission technologies, like small-modular reactors (SMRs). By reducing the amount of HALEU required for medical isotope production utilizing SHINE's process, we increase the amount of HALEU available for use in other purposes, like electricity generation, further enabling the avoidance of significant greenhouse gas emissions.

Our innovative technology deployed in Chrysalis would reduce greenhouse gas emissions by approximately 50 percent compared to current production processes and saves over 4,000 tons CO_2 emissions per year.



Recycling Nuclear Waste

There are >90,000 metric tons (MT) of used nuclear fuel (UNF) in temporary storage at nuclear power plants across America, and this amount grows by ~2,000 MT/year [1]. This material retains significant energy production potential in the form of unspent uranium and bred plutonium, and therefore represents a large untapped opportunity to recover this fissile material for production of a HALEU alternative for SMRs and mixed-oxide Pu/U (MOX) fuel for light-water reactors (LWRs) and fast reactors.

We are a leading company working to address the nation's UNF disposal challenge by developing a game-changing set of interlinked technologies that reduce the environmental impact of nuclear energy generation through the recycling and ultimately transmutation of UNF. The overall approach will reduce the long-term radiotoxicity of high-level waste, will improve reprocessing economics via value-added

isotope extraction, and will advance technologies to enable fusion energy generation. SHINE is leveraging design, construction, and operational experience gained from commercializing Chrysalis facility to design an end-to-end UNF processing, recycling, and transmutation system.

We are designing a comprehensive aqueous U/Pu co-extraction facility to separate used fuel into U, U/Pu, Np, minor actinides (MA, e.g., Am and Cm), lanthanides, and fission products (FPs). Significant improvements to traditional extraction system design are being incorporated into this process, including targeted valuable isotope recovery, removal of key long-lived isotopes for transmutation, improved in-house commercial grade dedicated equipment, and more efficient systems for handling highly radioactive liquid materials, as informed by Chrysalis.

The use of aqueous recycling of fissile content from UNF significantly reduces the CO2 emissions needed to generate nuclear fuel compared to conventional once-through processes (mining, milling, conversion, and enrichment). These conventional processes represent a large fraction of nuclear power's overall carbon footprint [2]. SHINE assessed the CO2 generation resulting from its planned UNF recycling process. This assessment used historic utility data from similar facilities and used data based on US average CO2 emission to determine total CO2 emissions needed to produce nuclear fuel. The total CO2 emission was found to be **less than 1/10th** of that from comparable processes used today in the once-through fuel cycle. By harvesting the growing stockpile of UNF and displacing the generation of fresh fuel, SHINE can **avoid the emission of over 87 million tons of CO2 over the next 30 years.**

Additional Environmental Benefits

Beyond the reduction of greenhouse gas emissions, our production technology provides a range of other environmental benefits, including the reduction of nuclear waste radioactivity levels, preservation of high assay low enriched uranium (HALEU) resources, and avoidance of orphaned waste.

The systems used in Chrysalis are much smaller consumer of very limited HALEU materials when compared to the current production processes relying on research reactors. Over 10 years, this amounts to over 1 metric ton of HALEU saved. Repurposing these savings to fuel next generation small modular reactors to produce electricity would potentially avoid 43,000 to 47,000 tons of CO2 per year.

Similarly, we believe that addressing the spent fuel challenge that has held back the US nuclear industry for decades will directly lead to more installation of baseload nuclear energy. If closing the fuel cycle results in the adoption of an additional 10% of baseload nuclear power (offsetting natural gas), SHINE's Phase III efforts will result in an additional **avoidance of up to 1.2 billion metric tons of CO2 emissions over 30 years.**

The remaining sections provide a deeper look into the factors considered to reach the above estimates.

Table 1: Opportunity cost of using HFR HALEU for energy production.

HALEU Conserved by SHINE	Thermal SMR energy potential	Electricity potential (33% thermal efficiency)	Potential avoided greenhouse gases [3]	Potential avoided greenhouse gases *per year*
1.1 to 1.2 metric tons every 10 years	100 GWd	871,000,000 to 950,000,000 kWh-e	434,000 to 474,000 tons-CO2	**43,000 to 47,000 tons- CO2**

A Deeper Look – SHINE Reducing Greenhouse Gases While Producing Medical Isotopes

Chrysalis avoids and reduces the anthropogenic emissions of greenhouse gases through several technological innovations. Some of these means of reduction are fundamental to the technology being deployed, while others (such as siting the project in the United States and the use of renewable energy) are deliberate choices of our leadership team.

We have performed a life-cycle estimate of the greenhouse gas emissions from the construction, operation, and decommissioning of the Project, with the exception that the routine radiological wastes during operation of the facility have not yet been estimated at the time of this writing. These emissions are not expected to influence the final results because current reactor technology consumes more uranium and generates more fission products than Chrysalis. Our medical isotope production facility also does not generate high level radioactive waste, such as the standard Mo-99 producer does. All project facility radioactive waste generated is expected to be low level waste.



The estimates of greenhouse gas emissions have revealed the following:

- The reduced air freight shipping of bulk Mo-99 by SHINE should reduce overall life cycle emissions by about 34%.
- The reduced consumption of uranium by our technology is not only an important radiological benefit, but also decreases overall Mo-99 life cycle greenhouse gas emissions by about 18%.
- The enhanced shipping efficiency of domestic production of Mo-99 is largely beneficial to Mo-99 production life cycle emissions, since typically 22% of the European-sourced Mo-99 is estimated to decay before ever reaching the U.S. distribution facilities. This means that the European suppliers must ship 129% more product than SHINE needs to ship to serve the U.S. market. The extra product increases life cycle emissions in all aspects.
- No high level waste is generated in the SHINE process, giving a more clear disposal path and less storage time, which generates greenhouse gas emissions from the electricity consumption. This has not been explicitly estimated yet, but is expected to be a benefit.
- The use of renewable electricity sourcing allows for a reduction of about 15% less greenhouse gas emissions than the standard production technology.

The SHINE facility results in some additional construction and decommissioning emissions. This is primarily due to the use of eight independent irradiation systems, instead of a single reactor containment vessel, leading to more concrete and rebar emissions from initial construction. However, this increases supply reliability for U.S. patients, instead of relying on a single reactor.

The key assumptions for our analysis of greenhouse gas emissions of Chrysalis project include:

- The business-as-usual competitor is the HFR reactor and Curium processing facility in the Netherlands. These two facilities produce

bulk Mo-99 solution, similar to our facility that performs both the irradiation and processing steps in the same building. The HFR / Curium process must then ship Mo-99 destined for the U.S. market via airplane to Missouri, with a total trip duration including customs processing of greater than 24 hours. This results in at least a 22% product loss, necessitating a 129% shipment volume for U.S. customers.

- Six shipments from the Netherlands per week of the Croft SafKeg are made, including six return shipments.
- Fuel for the HFR reactor is HALEU, with five fuel assemblies and one control assembly being replaced each 28-day cycle, with a total mass of 19.75% enriched uranium of 144-159 kg / year. Targets for the HFR reactor amount to another 63-78 kg / year of 19.75% enriched uranium.
- Our uranium losses for six target solution and accelerator systems amount to 39 kg / year of 19.75% enriched uranium.
- HFR / Curium average continuous electrical loading is 1,060 kW, and emissions factors are assumed using the United States average electrical grid carbon intensity.
- The SHINE average continuous electrical loading is 3,196 kW, and we purchase 100% of its electricity during facility operations from renewable electricity purchase agreements. Life cycle emissions for solar and wind power are assumed.
- Concrete and steel inputs for the our Chrysalis facility construction are estimated at 3,400 tons of steel, and 21,250 cubic yards of concrete. Concrete and steel for the HFR plant are estimated at 2,200 tons of steel and 6,100 cubic yards of concrete.
- The HFR facility is only assumed to be 50% dedicated to the production of the 3,000 six-day Curies in the analysis. The other 50% usage is for additional Mo-99, additional medical isotopes, and research and development.

The greenhouse gas emissions estimated from SHINE's scoping study are given in Table 2 below.

Additional environmental benefits beyond direct greenhouse gas emission reductions exist for the our process, as well. These include higher utilization efficiencies of limited HALEU materials, less radioactivity production per medical isotope produced, and much greater certainty in closure of the nuclear life cycle through waste certainty.

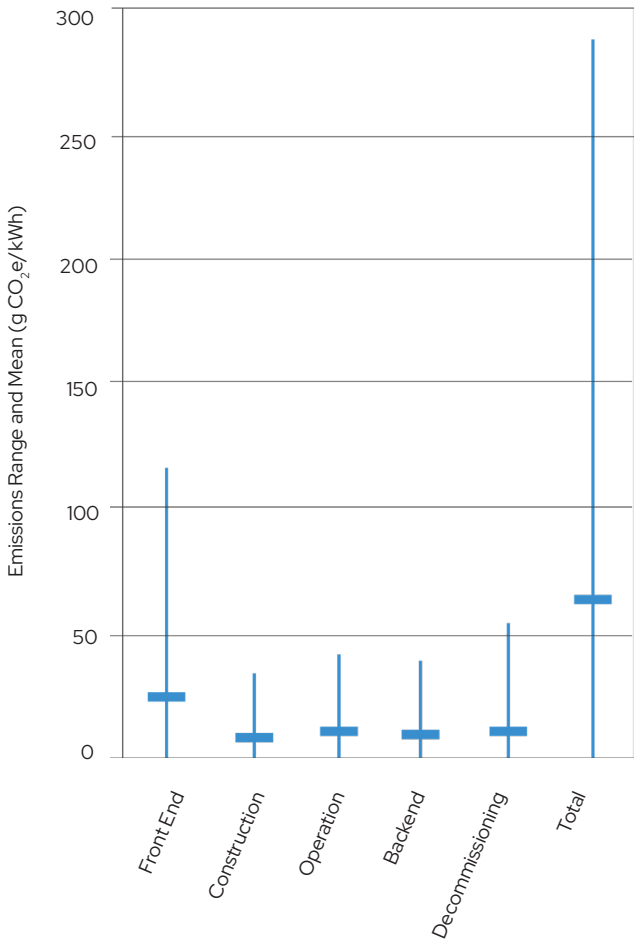
Table 2: Comparison of SHINE and HRF/Curium CO2 Emissions

	SHINE	HFR / Curium
Total per six-day Ci (delivered to U.S. market)	58 lbs CO2 / 6-day Ci	118 lbs CO2 / 6-day Ci
Total for 3,000 six-day Ci/week (delivered to U.S. market)	4,530 tons CO2 / year	9,238 tons CO2 / year

A Deeper Look – SHINE Reducing Greenhouse Gases While Recycling Waste

Many studies have been conducted that assess the life cycle CO2 emissions of the once-through nuclear power cycle. Figure 1 shows ranges and average values for assessed emissions from a 2008 survey paper [4]. This study broke down nuclear energy emissions on a process-by-process basis, allowing a fair comparison to a future state where mining, milling, conversion, and enrichment processes are replaced with an aqueous-based MOX recovery step (closed fuel cycle). From this point forward in the fuel cycle (starting at fuel fabrication), SHINE assumes that the once-through and closed cycles will result in similar CO2 emission profiles.

Figure 1: Range and mean emissions reported from qualified studies for the nuclear fuel cycle [4].



We've performed a simple evaluation of the anticipated CO2 emissions resulting from its planned UNF recycling facility. The starting point for this evaluation is the output of an aqueous recycling plant cost assessment performed by the NRC in 2008 [5]. This assessment estimated a total utility cost for a 200 MT/year aqueous recycling facility to be $9,125 per metric ton of spent fuel processed. Making the conservative assumption that this cost is all attributable to electricity ($0.0653/kWh for industrial customers [6, 7]), this results in 139.7 MWh/MT of electricity consumption. Using average US CO2 production data [8], this further amounts to 54,290 kg of CO2 emission per metric ton of spent fuel being recycled. A more detailed life cycle assessment will be performed in the future to better account for factors such as chemical utilization, but it is anticipated that this will not significantly change the conclusion given the small quantities involved in the process.

The median metric ton of spent fuel in the US started with an enrichment of 3.4% and has a burnup of 40 GWd/MT [9]. This used fuel contains 9.5 kg of plutonium (all isotopes) and 7.0 kg of U-235 (0.74% enriched) that can be harvested to create new MOX fuel. To get a direct comparison to the once-through fuel cycle, this fissile material was used to calculate the amount of spent fuel needed to produce one metric ton of new MOX fuel. The details of this calculation can be found in the compendium spreadsheet, and the net result is that the recovered fissile content from 5.65 metric tons of used nuclear fuel are needed to create one metric ton MOX fuel that has equivalent fissile content of UOX fuel with 3.4% enrichment. This is achieved by using 53.4 kg of Pu and 947 kg of recycled uranium (0.74% enriched).

From the emission data earlier, it is found that 307,000 kg of CO2 are emitted to recycle the 5.65 metric tons of used nuclear fuel. If the resulting MOX fuel operates to a burnup of 40 GWd/MT, it will have produced 317 GWh of electricity. Thus, the CO2 emission resulting from the recycling of UNF contributes 0.97 g CO2/kWh. Compared to median values reported in lifecycle survey literature [10],

producing MOX fuel through recycling results in only 9.3% of the total CO2 from the comparable portions of the once-through fuel cycle (mining, milling, conversion, and enrichment activities (on average) to produce the same mass of UOX fuel.

Using this calculated savings in CO2 emissions, the potential reduction in CO2 emissions via used fuel recycling is summarized in Table 3. These are broken into three facets, 1) savings from recycling the fissile material from the ~90,000 MT of existing UNF, 2) savings from the ongoing recycling of the ~2,000 MT/year of UNF being generated in the US today, and 3) savings from the adoption of an additional 10% of nuclear power plants (offsetting either coal or natural gas [11]). **Over a 30-year timeframe, this represents the avoidance of up to 2.6 billion tons of CO2 emissions.**



Table 3: Summary of CO2 emission reduction potential resulting from aqueous UNF recycling

Source	CO2 Emission Reduction
Recycle fissile content from current UNF stockpile	52.5 million tons CO2
Recycle fissile content from ongoing UNF generated	1.2 million tons CO2/year
Enable additional 10% of baseload nuclear (offset gas)	39.7 million tons CO2/year
Enable additional 10% of baseload nuclear (offset coal)	84.5 million tons CO2/year

References

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