Pyroprocessing: Technical Solution for Spent Fuel Management and Prerequisite for Carbon Neutral Energy Transition

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1. Background

Since President Carter's nuclear policy statement in 1977 [1] deferring indefinitely U.S. commercial reprocessing and recycling of plutonium, a direct disposal of spent nuclear fuel has remained as a *de facto* spent nuclear fuel management policy in the U.S. as imbedded in the Nuclear Waste Policy Act (NWPA) of 1982, amended in 1987. [2]

The NWPA was received enthusiastically by the U.S. utility industry. Utilities would pay a disposal fee of 0.1 cent/kwhr and the entire responsibility for the spent nuclear fuel would be transferred to the federal government. As the cost for the back end of the fuel cycle even at that time was estimated to be several times higher, the 0.1 cent/kwhr disposal fee was a great bargain. The Nuclear Waste Fund Contract embedded in NWPA stipulated the spent nuclear fuel title transfer to take place starting on January 31, 1998, the originally estimated opening date of Yucca Mountain repository. However, this clause went unnoticed in the 1987 amendment, and the utility companies filed lawsuits holding DOE to this date of title transfer. [3] The ensuing court actions and settlements resulted in the spent nuclear fuel storage costs being covered by the Government's judgment funds. Furthermore, the 0.1 cent/kwhr waste fee has also been suspended. [4]

Outside U.S., France, UK, and Japan have continued to pursue commercial reprocessing based on aqueous technology. However, the aqueous reprocessing is complex and expensive; Pu recycling in LWR has very limited fuel value and no economic incentive; and aqueous reprocessing raises proliferation concerns.

Pyroprocessing, on the other hand, is a compact process with much improved economic potential; it recovers all actinides in a single product stream for future use in fast reactors; and it provides safeguards and proliferation-resistant advantages. This paper will explore two very important impacts of pyroprocessing. First, pyroprocessing will provide a technical solution for the spent nuclear fuel management in the near-term. Furthermore, pyroprocessing will enable carbon neutral energy transition based on a fast reactor economy with a hundred-fold increase in uranium resource utilization in the long-term.

2. Pyroprocessing and its Attributes

Pyroprocessing was first utilized in Experimental Breeder Reactor-II (EBR-II) for a complete recycling demonstration. From 1964 through 1969, about 35,000 fuel pins had been

pyroprocessed and refabricated for reloading into EBR-II with a typical turnaround time of 45 days in the Fuel Cycle Facility (FCF), illustrated in Figure 1. [5]

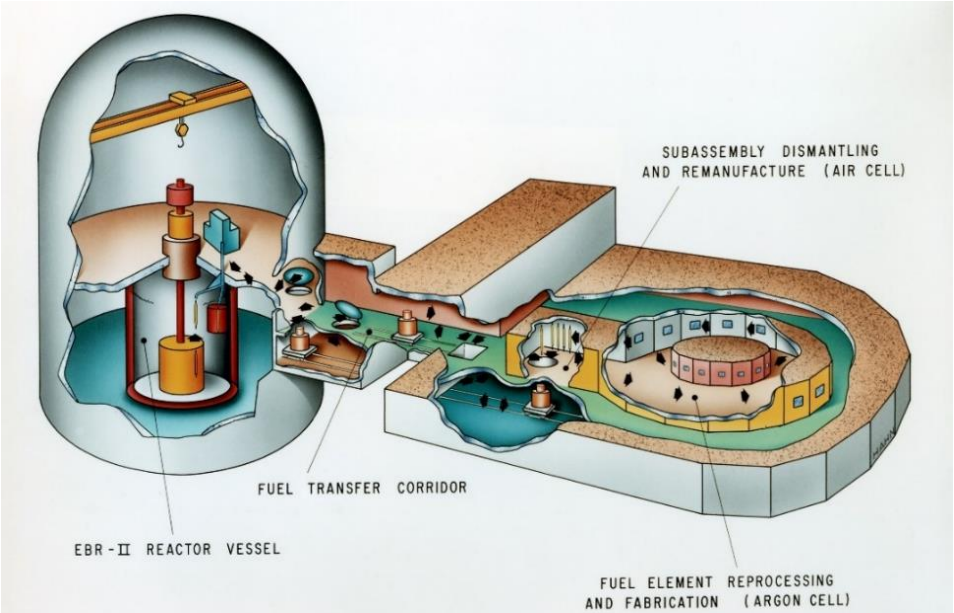

Figure 1. EBR-II and Fuel Cycle Facility

The early pyroprocessing was based on melt-refining, which had two deficiencies: noble metal fission products could not be separated and the actinides buildup in the blanket could not be separated to re-enrich the driver fuel. During the Integral Fast Reactor (IFR) Program carried out at Argonne National Laboratory from 1983 through 1994 [6], an improved pyroprocessing based on elctrorefining was developed, and the mothballed FCF was refurbished with the new electrorefing-based pyroprocessing equipment. Even after the IFR Program was terminated due to anti-nuclear pressures, the refurbished FCF has been utilized to treat the EBR-II spent fuel for disposal purpose. The FCF started spent fuel treatment in 1996 and is still in operation. [7,8]

Pyroprocessing of fast reactor metal fuel was amply demonstrated through the EBR-II spent fuel treatment project. For the LWR application, a front-end process to convert the oxide fuel to metal form is required. The initial process was based on a lithium reduction process, which did not work very well for plutonium. Hence, an electrolytic reduction process was adopted and has been fully demonstrated. [9,10]

Recently, Argonne National Laboratory with support from Merrick & Company developed a conceptual design of a pilot-scale (100 T/yr) pyroprocessing facility for LWR spent fuel as part of Cooperative Research and Development Agreement (CRADA) sponsored by the Landmark Foundation. [11,12] The details on the process flowsheet, process equipment design, process operations, facility design, and cost estimates are presented in Refs. 11 and 12. Therefore, this Section is focused on the attributes of pyroprocessing so that their impact on the spent nuclear fuel management could be comprehended.

Nuclear Waste Lifetime Is Drastically Reduced

The most important attribute of pyroprocessing is that it reduces the effective lifetime of nuclear waste from ~300,000 years to ~300 years. The radiological toxicity (cancer risk if inhaled or ingested) of the light water reactor (LWR) spent fuel constituents is presented in Figure 2, normalized to the radiological toxicity of the uranium ore from which the spent fuel originated. The radiological toxicity of fission products decays rapidly and drops below that of the uranium ore in about 300 years. Transuranic elements (TRU) or actinides, on the other hand, have long half-lives and their radiological toxicity drops below that of the uranium ore in about 300,000 years. In pyroprocessing, essentially all actinides (99.5-99.9%) are removed from the waste streams, reducing the radiological toxicity by a factor of 1,000 or the effective lifetime by the same factor.

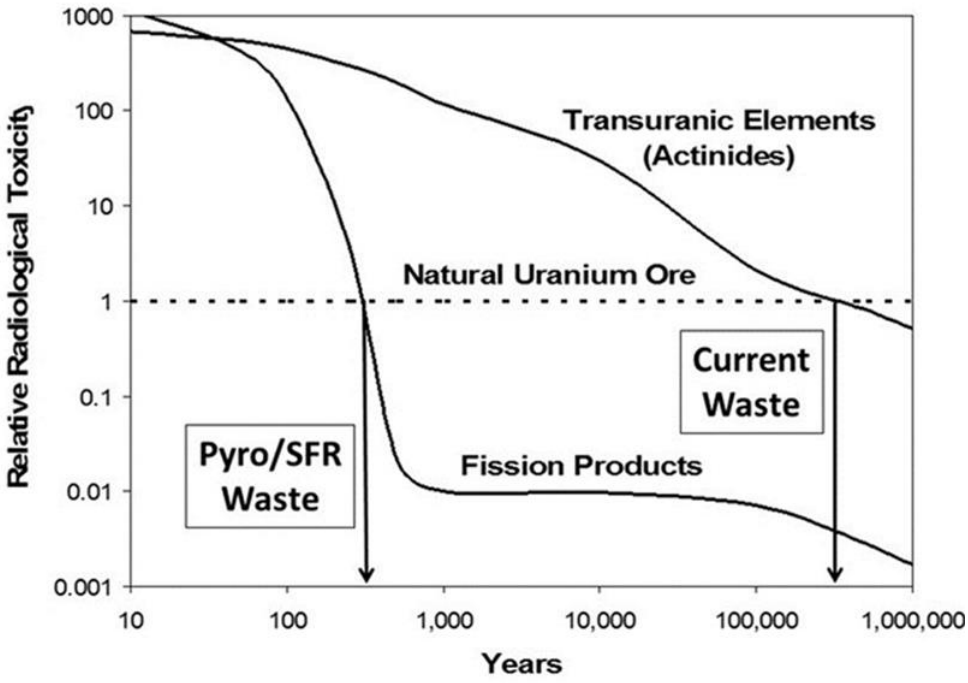

Figure 2. Radiological Toxicity of Spent Fuel Constituents

The degree of dominance of the actinides in long-term radiological risk can be illustrated by normalizing the various components of the radioactive inventory to an easily understood release limits in the original repository standards of 40CFR Part 191, [13] which is no longer applicable, but it is convenient for illustration. Typical LWR spent fuel radioactivity levels at three different time points are presented in Table 1 in terms of these EPA cumulative release limits. (That is to say, the components of the radioactive inventory in spent fuel are divided by the cumulative release limit.) The 10-year activities are dominated by Sr-90 and Cs-137. Decaying with their approximate 30-year half-life, they are gone in 1,000 years. It is obvious that the actinides completely dominate as the source of radioactivity at times even approaching 1,000 years. Because the solubility of actinides in ground water is extremely low, they will not be readily released from the repository. Their toxicity is three orders of magnitude above other contributors shown in Table 1, and that tells the story. If the actinides were removed from the spent fuel, the

EPA standards, whether adopted from old 40CFR Part 191 or new 40CFR Part 197, [14] or whether for 10,000 years or millions of years, could be met on *a priori* basis.

Table 1. LWR spent fuel radioactivity normalized to old EPA cumulative release limits

Radio-nuclide	Activities at 10 yrs	Activities at 1,000 yrs	Activities at 10,000 yrs
Sr-90	60,000	0.0	0.0
Cs-137	90,000	0.0	0.0
I-129	0.3	0.3	0.3
Tc-99	1.4	1.4	1.4
Other F.P.	1,050	5.1	4.4
Actinides	76,000	19,000	4,000

It is important to note that the inventories of Tc-99 and I-129, which are readily dissolvable in ground water and thus considered more likely to be released from the repository, are of the same magnitude as the cumulative release limits. If their entire inventory were released, the release limit (cumulative release limits in the original 40CFR Part 191) could still be met. This is also demonstrated by the total system performance assessments for Yucca Mountain [15] which list the doses from Tc-99 and I-129 equilibrating around 2 mrem/yr, and 0.05 mrem/yr, respectively in the 100,000-year time frame, well below the 15 mrem/yr limit specified in 40CFR Part 197.

Better Repository Space Utilization

Actinides also play a strong role in the thermal design of a repository. In Yucca Mountain Repository design, for example, to limit the far field temperature below water boiling, the thermal load is limited to 0.65-1.42 kW/m in each drift; the drifts are spaced 81 meters apart; and forced ventilation is required for 100-324 years to remove heat. As shown in Figure 3, actinides dominate the long-term heat source in the repository. If actinides are removed, the long-term heat source is eliminated, and more spent fuel can be stored in a given space depending on the repository type. [16]

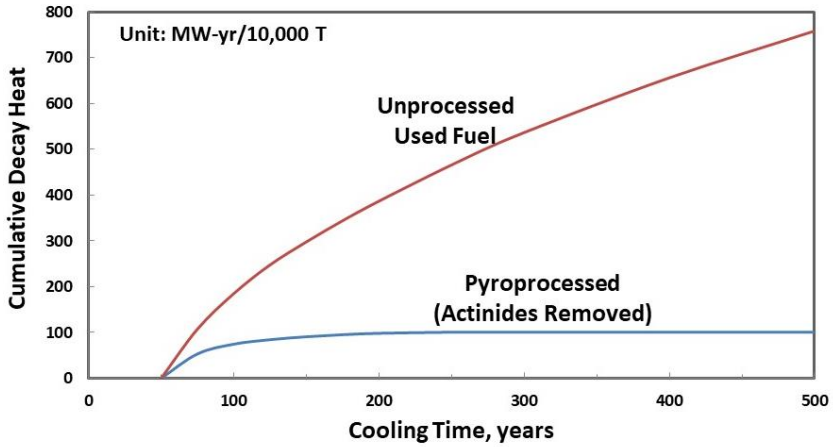

Figure 3. Comparison of long-term heat sources with and without actinides

Pyroprocessing Is Proliferation-Resistant

Electrorefining is intrinsically incapable of producing a pure plutonium product, and plutonium is always recovered in a mixture of the minor actinides (neptunium, americium, curium, etc.), uranium and certain of the fission products. The pyroprocessed actinide mixture has the three properties deleterious to weapons: heat production from the actinides in the mixture, production of spontaneous neutrons, and a high level of gamma radiation. The characteristics of the pyroprocessed actinides are compared with those of weapons grade plutonium and reactor grade plutonium in Table 2. [17]

Table 2. Important Weapons Usability Characteristics

	Weapons Grade Pu	Reactor Grade Pu	Pyroprocessed Actinide Product
Production Method	Low burnup PUREX	High burnup PUREX	High Burnup Electrorefining
Product Composition	Pure Pu 94% Pu-239	Pure Pu 65% Pu-fissile	Pu + MA + U 50% Pu-fissile
Thermal Power watts/kg	2-3	5-10	80-100
Spontaneous neutrons, n/s/g	60	200	300,000
Gamma radiation r/hr at ½ m	0.2	0.2	200

Weapons grade has the high Pu-239 content of weapons-plutonium production, and the high purity as recovered by PUREX processing. Reactor grade is a typical LWR spent fuel, with its greater concentrations of the higher Pu isotopes, as recovered by PUREX reprocessing. Essentially, it is the same as weapons grade except for the isotopic composition. The higher plutonium isotopes give about a factor of three increases in heat production and in spontaneous neutrons, extremely inconvenient but which may not be an insurmountable barrier for use as weapons material, depending on the capabilities of the laboratory designing it.

On the other hand, the pyroprocessed actinides have a heat output a factor of 50 higher than weapons-grade plutonium. Such self-heating can cause real problems with the surrounding high explosives, melting, and perhaps even self-detonation. Spontaneous neutron emission and the gamma radiation level are far above that of weapons or reactor grades – more than 1,000 times greater. Neutron multiplication during the assembly will increase the neutron dose even more. Combined with the gamma radiation, the resulting incapacitating dose of radiation would certainly rule out hands-on weapons production. Heat also tends to throw off small tolerances and stray neutrons interfere with the timing of ignition, key to its effectiveness. For a spontaneous neutron source even 40 times that of the 1945 Trinity test with weapons plutonium, the probability of the expected yield (design yield) would be well less than one percent, with a high probability of yields in the neighborhood of a fizzle. [18]

An Order of Magnitude Improvement in Economics

The project total capital cost estimate for Pilot-Scale (100 T/yr) Pyroprocessing Facility is $398 million. The contingency factors range from 10% to 25% depending on the building type and the maturity of technology and design. The land acquisition cost, if needed, is not included. The operating cost is estimated as $53 million/yr. The details of the capital and operating cost breakdowns are presented in Refs. 11 and 12.

A common perception or myth is that there are economies of scale going from pilot-scale to commercial scale for aqueous reprocessing, but not for pyroprocessing due to batch-type operation, and even further, pyroprocessing is viable for a small throughput but not for large throughput operations.

We investigated a potential approach for scaling the current pilot-scale design up to a commercial-scale facility. We have chosen 400 T/yr facility as an example, but a similar approach can be used to scale up to whatever throughput rate is needed. In our example, there are significant economies of scale achieved at 400 T/yr throughput rate and further economies of scale are expected as scale-up continues.

For simplicity, we assumed the main processing equipment, electrorefiner and electrolytic reducer, remain the same and are duplicated four times. Similarly, the TRU processor, uranium processor, drawdown vessel, and ceramic waste processor are duplicated four times. Some equipment, such as the TRU processor is constrained in size by the criticality safety consideration. Others can be consolidated, but in order to make the materials control and accountancy easier, they are duplicated as the electrorefiner is duplicated.

For the front-end operations, there is flexibility in the equipment utilization. Hence the fuel disassembly station, fuel rod slitter, and hardware waste packaging are replicated three times. Other equipment that can be scaled up easily is duplicated twice. This category includes basket module loader, salt tank, noble metal processor, salt crystallization vessel, waste salt transfer system, and waste packaging.

Having decided on the number of equipment systems, we considered various ways of configuring the processing cells, and adopted a layout where the processing arrangement can be replicated for further scaled up. As compared to the 100 T/yr facility, the hot cell floor area is 1.8 times larger, hence significant economies of scale are achieved. The resulting project total capital cost is $911 million, and the annual operating cost is $90 million/yr for the 400 T/yr facility. The basis for this cost estimate is for a first-of-a-kind and not a follow-on to the 100 T/yr pilot-scale facility. In the latter case, the cost would be further reduced without the first-of-a-kind costs.

If we assume the same approach for a 2,000 T/yr commercial-scale facility, namely the same main process equipment size as the pilot-scale facility and duplicating the number of process equipment, then the capital cost is estimated at $2.4 billion and the operating cost at $208 million/yr. This estimate assumes a first-of-a-kind facility without taking advantage of learning curves or process equipment scale-up potential. Therefore, this estimate should be considered as a conservative estimate. A more detailed engineering should result in a lower cost estimate.

If we assume a fixed charge rate (interests plus capital amortization) of 5%/yr, then the processing costs for the three different facility sizes discussed above are summarized in Table 3.

Table 3. Unit Processing Costs at Various Facility Sizes

Throughput	100 T/yr	400 T/yr	2,000 T/yr
Capital cost, $M	398	911	2,400
Operating cost. $M/yr	53	90	208
Processing cost, $/kg	730	340	160
Equivalent cent/kwhr	0.19	0.09	0.04
Actinide cost, $/kg*	10,200	4,800	2,200

*Equivalent to 20% enriched HALEU

For a commercial-scale facility the processing cost is well below the current waste disposal fee of 0.1 cent/kwhr in the U.S. If pyroprocessed waste form can also save the repository cost, then it is conceivable that both pyroprocessing cost and the disposal cost can be realized within the current waste disposal fee. The total system life cycle cost of the Yucca Mountain repository was last update in 2008 [19] and includes the costs for titanium drip shield to prevent water from the waste packages and Alloy 22 waste packages. For pyroprocessed waste packages, such engineered barriers would not be required, resulting in cost savings. Additional cost savings can be realized since post-closure performance confirmation would not be required. In addition, due to lack of the long-term heat source, more spent fuel equivalent wastes can be placed in a given drift space. Theoretically, much higher savings could be realized [16], but for simplicity we will assume only one half of the emplacement cost would be saved in this analysis.

Table 4. Life Cycle Cost for Yucca Mountain Repository (millions of 2007$) [19]

Cost Element	Costs	Reduction Potential for Pyroprocessed Waste
Engineering, Procurement & Construction (2003-2053)	16,550	Waste package & drip shield fab: 220
Emplacement Operations (2017-2073)	26,730	Waste package & drip shield fab & perf.: 14,260
Monitoring (2074-2123)	10,150	Waste package & drip shield fab & perf.: 8,670
Closure (2124-2133)	1,390	Performance confirmation: 300
Additional Savings		½ of emplacement cost (heat reduction): 15,700
Total	54,820	Total estimated savings: 39,150

In Table 4, the remaining portions of the total system life cycle costs for Yucca Mountain are listed in millions of 2007 dollar. Prior expenditures are not included in Table 4. The remaining life cycle costs amount to $54.82 billion as shown in the second column. Reduction potential for pyroprocessed waste is shown in the third column. The estimated savings amount to $39.15 billion, more than one half of the total life cycle cost.

In Table 3, the recovered actinide cost, equivalent to 20% enriched high assay low enriched uranium (HALEU), is also presented. The 20% enriched HALEU cost at the current uranium ore

cost of \$55/lb U_3O_8 and \$130/SWU is \$11,600/kg. However, no commercial HALEU production capabilities exist today, and the future cost is expected to be even higher. Therefore, the entire cost of a pilot-scale (100 T/yr) facility can be recovered by providing the actinides to advanced reactors requiring HALEU fuel supply.

3. Implications of Pyroprocessing on Spent Fuel Management

In summary, if the LWR spent fuel is pyroprocessed and the recovered actinides are burned in sodium-cooled fast reactors (SFRs), the long-term radiological toxicity is reduced by a factor of 1,000, and the effective lifetime of nuclear waste is reduced from 300,000 years to 300 years. This is by far the most effective and advanced technology, which provides a definitive solution to spent nuclear fuel management:

- Repository is still needed but its siting will be much easier.
- Repository regulatory requirements can be met on *a priori* basis without the source term.
- Costly engineered barriers, such as titanium drip shield, Alloy-22 engineered barrier, and continued monitoring would not be needed, reducing the repository cost.
- Reduced heat load will also result in a further reduction of the repository cost.

The only successfully implemented repositories for direct disposal of spent nuclear fuel are in Sweden and Finland. [20-21] The repository in Sweden illustrated in Figure 4 is based on 500 m deep tunnels in 1.9 billion years old stable bedrock. Finland has a similar geology, and its repository is 520 m deep in granite bedrock. Such stable and vast bedrocks are not available in every country. Pyroprocessed waste would be much easier to dispose in a variety of geologic conditions.

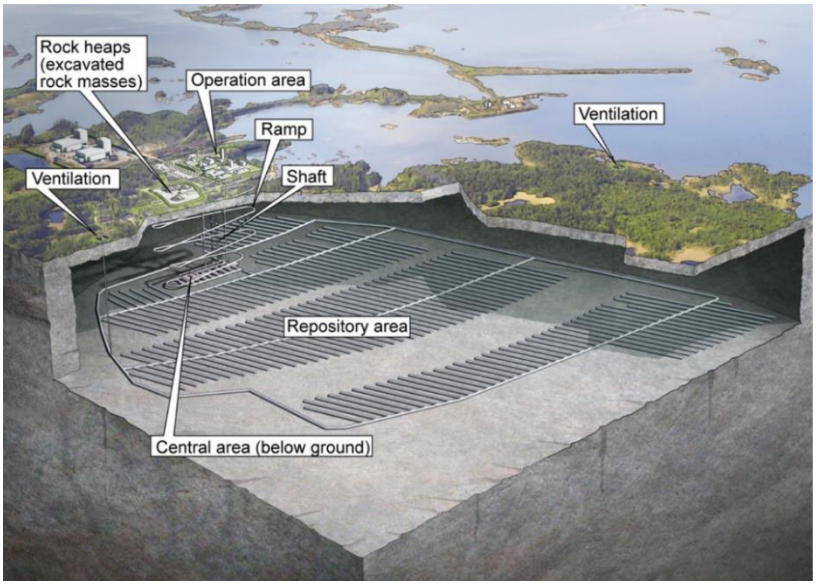

Figure 4. Forsmark Geologic Repository in Sweden

The actinides recovered by pyroprocessing can be effectively burned only in fast reactors. Actinide transmutation, from actinide to non-actinide, or "actinide burning," can be done by fission and by fission only. Neutron capture in the actinides without fission results only in their

evolution to other actinides of ever higher mass, as a rule more and more radioactive. To burn actinides effectively, high-energy neutrons are needed. The transmutation probability, the percentage of neutrons absorbed that cause fission, of typical thermal and fast spectra for the actinide isotopes are compared in Table 5. [6]

Table 5. Transmutation Probabilities (in %)

Isotope	Thermal Spectrum	Fast Spectrum
Np-237	3	27
Pu-238	7	70
Pu-239	63	85
Pu-240	1	55
PU-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242m	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

In a thermal spectrum only a limited number of isotopes fission effectively. If fuel is recycled continuously, higher actinides will continue to build up until they approximately equal the amount of plutonium in the fuel. In a fast spectrum all the isotopes fission substantially and the equilibrium composition is reached with relatively small, quite normal, amounts of higher actinides. The isotopic evolution in thermal recycle is presented in Figure 5. The fissile isotopes, such as Pu-239 and Pu-241 can be burned readily, but fertile isotopes, such as Pu-242 and various americium and curium isotopes, go on building up as burnup progresses. They have no reactivity value in a thermal spectrum and are useless there as fuel.

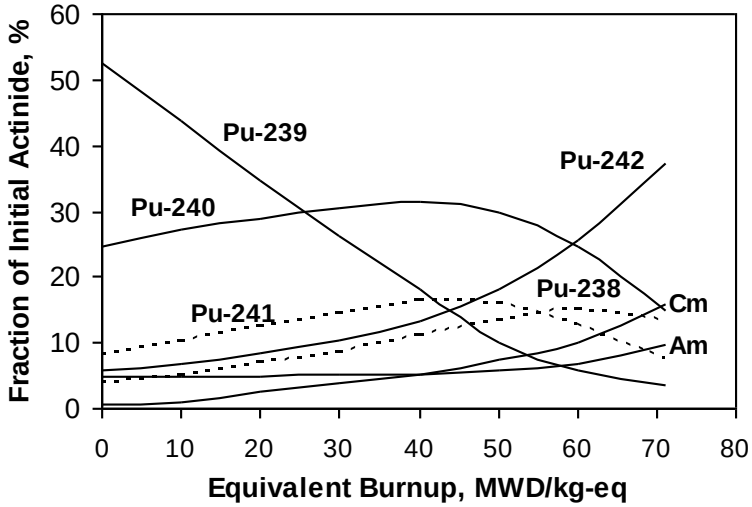

Figure 5. Isotopic Evolution of Actinides in thermal Spectrum [6]

4. Energy Options to Achieve Carbon Neutrality

Worldwide aspirations for a better living standard will exert continued growth of GDP, and hence electrical energy -- multiples of the current consumption in decades and decades to come. Worldwide per capita electricity consumption has been growing linearly over the past 50 years as shown Figure 6 and the world population has also been growing steadily as shown in Figure 7.

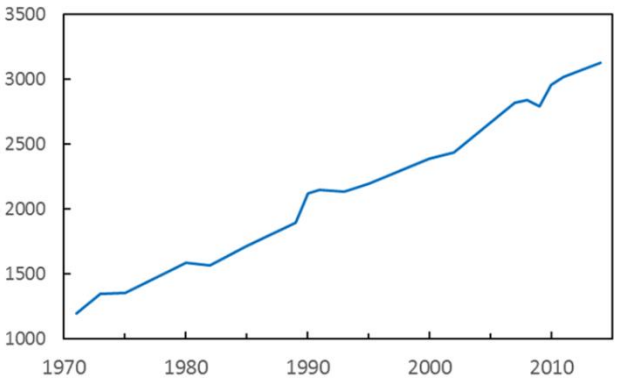

Figure 6. Per Capita Electricity consumption

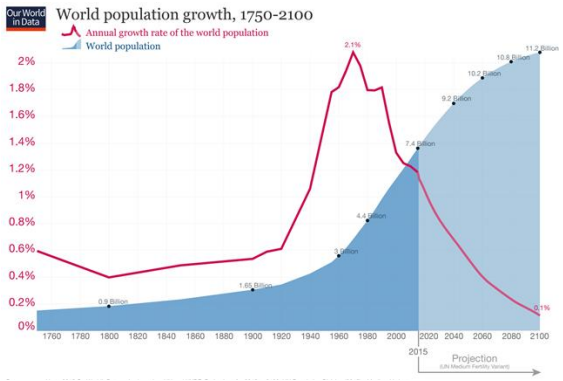

Figure 7. World Population Growth

If we extrapolate the data in Figures 6 and 7, then the total electricity demand in 2050 would be about 1.75 times that of 2020 level. Furthermore, even if we assume the linear growth rate is reduced to 40% of the historical value beyond 2050, the electricity demand in 2100 would be about 2.4 times that of 2020 level.

Given such a high demand for future electricity, which will be further amplified by electrification of transportation, 5G development and so on, we do not have any choice but utilize all energy sources: coal, oil, natural gas, renewables, nuclear and so on. However, only nuclear has capability to deliver multiples of the current consumption level with no greenhouse gases and least amounts of construction commodities and land usages. COP21 Paris Agreement is exerting pressure to replace the fossil energy with carbon-free clean energy options. As shown in Table 6, the fossil energy contributes 63% of electricity and 84% of total energy globally.

Table 6. Global Energy Consumption by Fuel Type (% of Total)

	Electricity	Total Energy
Oil	3.1	33.1
Coal	36.7	27.0
Natural Gas	23.5	24.2
Fossil Subtotal	63.3	84.3
Nuclear	10.4	4.3
Hydro	15.8	6.4
Wind	5.3	2.2
Solar	2.7	1.1
Others*	2.5	1.6

*Geothermal, biomass, wave and tidal.

The hydro-based electricity is almost fully utilized, and hence the burden of achieving carbon neutrality is placed on nuclear or solar/wind renewables. Renewables alone to achieve this goal would require the renewable capacity to expand 8.5 time just to replace the current level of fossil-based electricity. To meet the estimated electricity demand increase by 2050, the renewable capacity has to increase by a factor of 18. Furthermore, to replace the non-electricity fossil energies, the above factors must be tripled.

Such increase is impossible due to inherent limitations of renewables in terms of dilute energy sources, huge amounts of construction commodities relative to nuclear, huge land use requirements and low capacity factors with unpredictable availability. All of these limitations culminate in a very poor ratio of energy returned on invested (EROI). Energy variability mandates energy storage availability, which further reduces the EROI as shown as 'buffered' in the EROI plot shown in Figure 8.

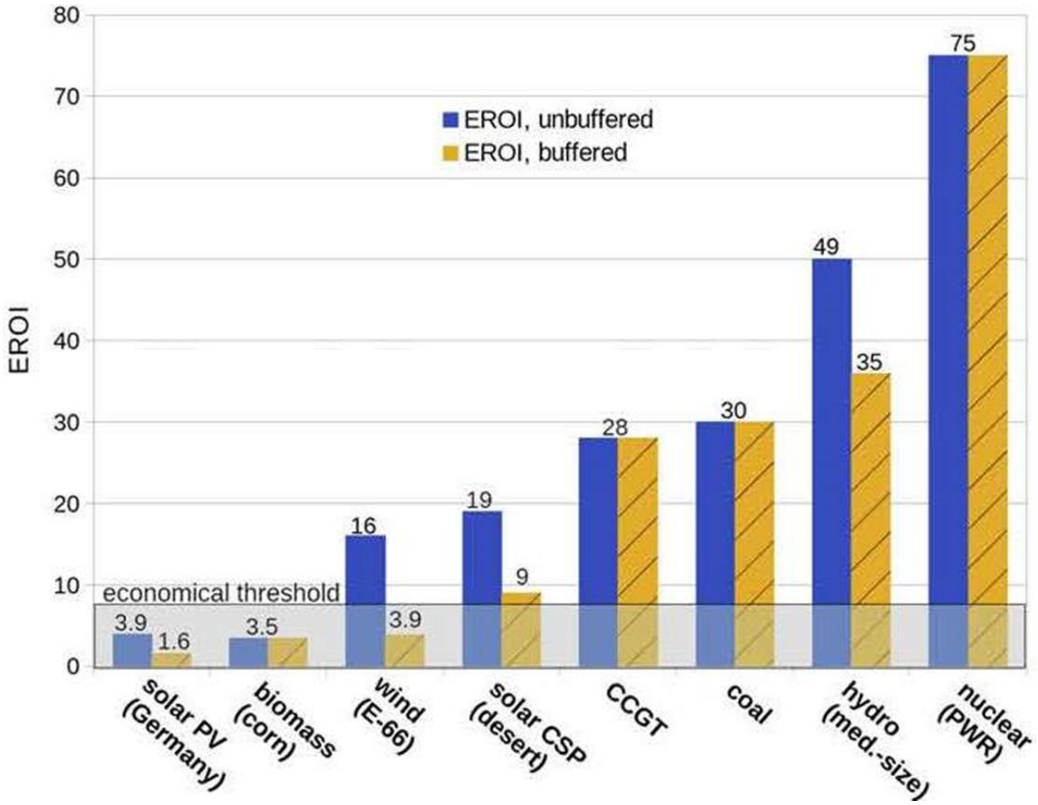

Figure 8. Energy Returned on Invested (EROI) for Various Energy Sources [22]

If we consider the Solar PV case, the EROI ratio is 3.9. If Solar PV becomes the major source of electricity, then it should be able to cope with the variability of electricity generation with time and season, which requires both over capacity and energy storage (buffering). Such buffering further reduces the EROI ratio to 1.6. In Figure 8, the authors assumed 30% over capacity and 10-day storage for the solar PV case. The plant lifetime was assumed to be 25 years for solar PV.

The lead author of Ref. 22 recently updated the EROI ratio for solar PV in German insolation case to 6 for unbuffered and 2 for buffered and the ratio for nuclear to 100. [23] Even with the increased EROI ratio of 2 for solar PV buffered case, the energy payback period is 12.5 years. In

other words, it takes that long to pay back the energy used to construct solar panels and the plant. Following the payback period, net useful energy for the society is generated only for 12.5 years before the plant decommissioning. This is for a single plant case.

If the capacity needs a continuous growth, then the energy payback period will be further increased. We will assume a linear growth of solar PV capacity in the next 50 years, say one unit a year for simplicity. Since the plant lifetime is 25 years, we need to install two units a year after year 25 – one unit to replace the retiring unit and one unit to add capacity. For this case, the resulting cumulative energy generation (in arbitrary unit normalized to the value in year 50) and the net useful energy for the society are shown in Figure 9.

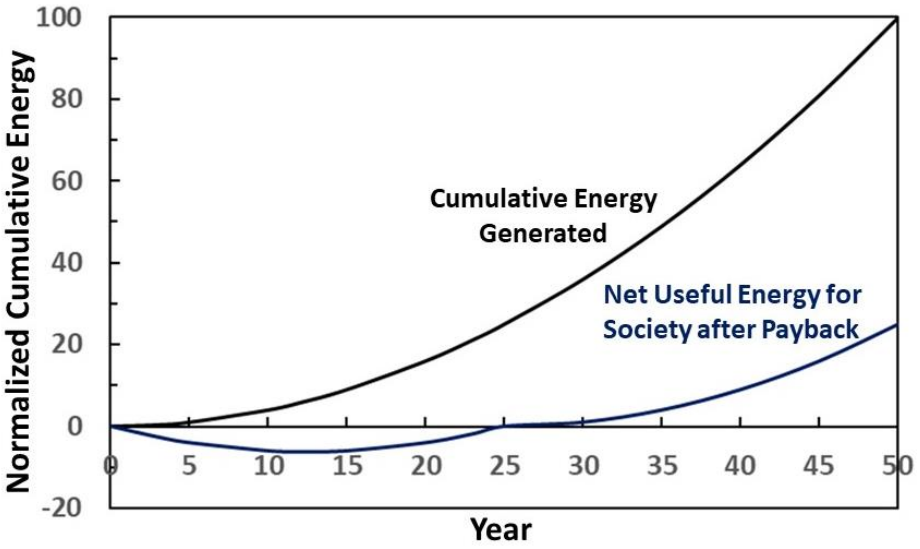

Figure 9. Net Useful Energy for Society for Continuously Growing Solar Capacity

As shown in Figure 9, the payback period is further increased to 25 years. Of the total cumulative generated during the first 50 years, 75% corresponds to the energy used for solar panels and construction, and only 25% is available as net useful energy for the society. This clearly demonstrates that renewables alone cannot sustain the capacity expansion. If the renewable capacity is limited in the range of 10-20% of the total electricity generating capacity, then buffering would not be required and renewables could contribute tangibly toward carbon neutrality goal.

The above analysis on renewables implies that nuclear has to take the burden of supplying 80-90% of the capacity expansion to replace fossil energy sources. Today's commercial reactors utilize only 0.6% of uranium resources. About 11% remaining in spent fuel and about 88% in enrichment tailings are discarded as waste. If today's nuclear capacity of about 400 GWe is all that will be realized, then over 300 years of operation can be supported with the currently estimated uranium resources, and hence nuclear community believes there are plenty of uranium.

However, if nuclear has to replace fossil energies to achieve carbon neutrality, a fast reactor economy is essential, which will increase the uranium resource utilization by more than a hundred-fold. Uranium resource estimates at various times are summarized in Table 7.

Table 7. Uranium Resources (in million tons) [24-26]

	Redbook 2009	Redbook 2018	Redbook 2020
Already Mined	2.410	2.947	3.062
Identified Resources	6.306	7.988	8.071
- Reasonably Assured	4.004	4.815	4.724
- Inferred	2.302	3,173	3.347
Undiscovered Resources	10.401	7.530	7.221
- Prognosticated	2.905	1.698	1.607
- Speculative	7.496	5.832	5.614
Total	19.117	18.465	18.354

Total uranium resource estimates have not increased in the last decade or so. In fact, estimates have a down trend, although as more is mined, undiscovered resources have moved to identified resources category. The period, in years, that can be supported by uranium resources for various growth scenarios is compared in Table 8 between today's commercial reactors and future fast reactors.

Table 8 Period (in years) Supported by Uranium Resources

Scenario	Current Capacity 400 MWe	Replace Fossil 2,800 GWe	80% 2050 Estimate 5,000 GWe
Today's reactors	300	43	24
Future Fast Reactors	43,000	6,100	3,400

A plausible nuclear capacity expansion is presented in Figure 10 and the cumulative uranium requirements in Figure 11, which also illustrates the various categories of uranium resources.

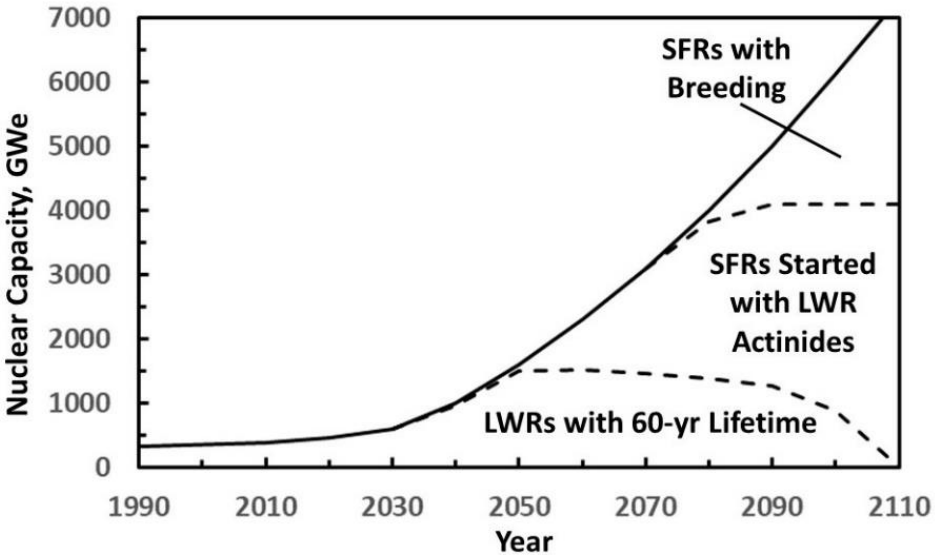

Figure 10. Worldwide Nuclear Capacity Growth Potential

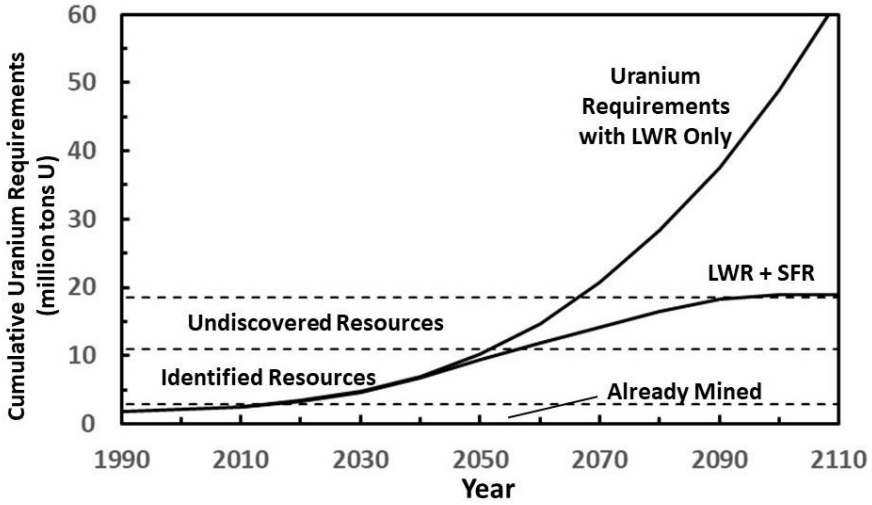

Figure 11. Cumulative Uranium Requirements and Resource Levels

From Figures 10 and 11, it is clear that we need to count on a massive fast reactor deployment in the coming decades. More than 20 fast reactors have been constructed and operated around the world. However, most of them have been shut down and a hiatus continued in the last 20 years or so. However, there is a renewed interest in fast reactors in recent years.

In Russia, BN-600 started operation in 1980 and still in operation. Three BN-800 units were planned in 1980s and the construction of one BN-800 in Beloyarsk was resumed in 2005 and the power operation started in 2016. The 150 MWth/60 MWe MBIR is a multi-purpose fast reactor being constructed at Research Institute for Atomic Reactors to replace BOR-60, and the operation is expected by 2027. Lead-cooled BREST-300 is also under construction.

In India, Fast Breeder Test Reactor (FBTR) has been in operation since 1985. A 500 MWe Prototype Fast Breeder Reactor (PFBR) started construction in 2004 with a goal of 2012 startup, but commercial operation is delayed to October 2022. In China, China Experimental Fast Reactor (CEFR) started operation in 2010. A 600 MWe commercial-scale CFR-600 Unit 1 started construction in 2017 with operation scheduled for 2023. CFR-600 Unit 2 started construction in 2020 with operation scheduled in 2026. In Korea, Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) Project was initiated in 2013 with original plan of construction permit in 2022 and operation by the end of 2028. However, the PGSFR Project was cancelled as part of the nuclear phase-out policy in 2017.

5. Conclusions

Pyroprocessing is an innovative spent fuel reprocessing technology developed during the Integral Fast Reactor (IFR) Program at Argonne National Laboratory and demonstrated through the EBR-II spent fuel treatment project. There is a common perception that pyroprocessing is ideally suited for fast reactor metal fuel treatment but not for the current commercial LWR spent fuel. However, a recent conceptual design of a pilot-scale pyroprocessing facility for LWR spent fuel demonstrates that pyroprocessing facility has a potential for economies of scale as well and the processing cost could be at least an order of magnitude less than the conventional aqueous reprocessing technology.

The most important attribute of pyroprocessing is that all actinides are recovered in a single product stream making it proliferation-resistant and the radiological toxicity of the waste form is reduced by a factor of 1,000. The effective lifetime of nuclear waste is therefore reduced from ~300,000 years to ~300 years, making the permanent repository a much easier task. The regulatory requirements can be met on *a priori* basis without the radioactive source term, and hence locating a repository site becomes much easier. The pyroprocessed waste forms can be disposed in a variety of geologic conditions without any harms to public and environment.

In modern society where almost all consumer products are being recycled, it is unconscionable to simply dispose spent fuel after only 0.6% of uranium resource is used. In order to develop an energy mix to achieve carbon neutrality, a full utilization of uranium resources is crucial for our future generations to enjoy clean energies. Solar and wind renewables should be fully exploited, however due to their inherent limitations, in particular very low ratio of energy return on invested (EROI), their capacities need to be restricted to 10-20% of the total electricity. The balance of ever-expanding electricity demand growth should be satisfied by nuclear energy.

Pyroprocessing allows economically viable recycling of spent fuel, making a full utilization of uranium resources. Actinides recovered from pyroprocessing of LWR spent fuel can be used as fuel for fast reactors. If so, the currently estimated uranium resources alone can support the future nuclear expansion for thousands of years for our future generations.

Pyroprocessing is key to provide a technical solution for the spent fuel management at the same time assuring long-term clean energy potential of nuclear. Immediate priorities should be given to the demonstration projects for a pilot-scale pyroprocessing facility as well as for a next-generation sodium-cooled fast reactor.

References

1. "Nuclear Power Policy," Statement by the President on His Decisions Following a Review of U.S. Policy, April 7, 1977. https://www.nrc.gov/docs/ML1209/ML120960615.pdf
2. "Nuclear Waste Policy Act of 1982," Public Law 97-425: Enacted on January 7, 1983, and Amended as Public Law 100-203 on December 22, 1987.
3. "DOE Settles Storage Bills with Exelon," Nuclear Engineering International, August 1004. https://www.neimagazine.com/news/newsdoe-settles-storage-bills-with-exelon
4. "Court Orders Halt to Nuclear Waste Fee," World Nuclear News, November 20, 2013. https://www.world-nuclear-news.org/WR-Court-orders-halt-to-nuclear-waste-fees-2011134.html
5. Charles E. Stevenson, "The EBR-II Fuel Cycle Story", American Nuclear Society, 1987.
6. C. E. Till and Y. I. Chang, "Plentiful Energy: The Story of the Integral Fast Reactor," CreateSpace, 2011.
7. K. M. Goff, R. W. Benedict, G. M. Teske, and T. J. Johnson, "Production Electrometallurgical Treatment of EBR-II Spent Fuel," Proceedings of the Fifth Topical Meeting on DOE Spent Nuclear Fuel and Fissile Materials Management, Charleston, SC, September 17-20, 2002.
8. D. Vaden, et al., "Engineering-Scale Liquid Cadmium Cathode Experiments," Nucl. Technol., 162, 124, 2008.

9. K. Gourishankar, L. Redey, and M. Williamson, “Electrolytic Reduction of Metal Oxides in Molten Salts,” Light Metals, p. 1075, 2002.
10. S. Herrmann, S. Li and M. Simpson, “Electrolytic Reduction of Spent Light Water Reactor Fuel – Bench-Scale Experiment Results,” Journal of Nuclear Science and Technology (of Japan), 44, 3, pp 361-367, 2007.
11. Y. I. Chang, et al., “Conceptual Design of a Pilot-Scale Pyroprocessing Facility,” Nuclear Technology, 205, pp708-726, May 2019.
12. ANL/NE-Landmark-CRADA-12 Revision 1, “Summary Report: Conceptual Design of a Pilot-Scale Pyroprocessing Facility,” April 10, 2018. https://www.ne.anl.gov/eda/Pilot_Scale_Pyroprocessing_Facility.pdf
13. 40 CFR Part 191, “Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes,” 1985.
14. 40 CFR Part 197, “Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada,” 2008.
15. DOE/RW-0539-1, “Yucca Mountain Science and Engineering Report: Technical Information Supporting Site Recommendation Consideration, Revision 1,” February 2002.
16. R. A. Wigeland, et al., “Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository,” Nuclear Technology, 154, pp 95-106, April 2006.
17. D. L. Goldman, “Some Implications of Using IFR High-Transuranic Plutonium in a Proliferant Nuclear Weapon Program,” LLNL CONDU-94-0199, March 1994.
18. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," Science & Global Security, Vol. 4, 111-128 (1993).
19. DOE/RW-0591, “Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007,” July 2008.
20. SKB, “A repository for nuclear fuel that is placed in 1.9 billion years old rock” https://www.skb.com/future-projects/the-spent-fuel-repository/
21. “Onkalo spent nuclear fuel repository” https://en.wikipedia.org/wiki/Onkalo_spent_nuclear_fuel_repository#:~:text=The%20Onkalo%20spent%20nuclear%20fuel,the%20west%20coast%20of%20Finland.
22. D. Weissbach, et al., “Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants,” Energy Vol. 52, pp. 210-221, April 2013. https://www.sciencedirect.com/science/article/abs/pii/S0360544213000492
23. D. Weissbach, Private Communication, March 21, 2022.
24. “Uranium 2009: Resources, Production and Demand,” A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2010.
25. “Uranium 2018: Resources, Production and Demand,” A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2018.
26. “Uranium 2020: Resources, Production and Demand,” A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2020.