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Nuclear Fuel Reprocessing

For the Advanced Nuclear Era

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For the Advanced Nuclear Era

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ABSTRACT

A decision whether to transition to advanced nuclear fuel cycles involving reprocessing will be based on numerous factors such as, among others: policy (e.g., importance of greenhouse gas reduction and maintaining nuclear power as part of the long-term energy mix), economics, regulatory requirements and safeguards/non-proliferation. The purpose of this report is to provide decision makers information regarding: existing and future reprocessing technologies; economic considerations and assumptions; regulations; safeguards and non-proliferation; waste streams requiring disposal and several other factors. The relative importance of these factors to decision making will vary from utility to utility and country to country. Example case studies are provided to gain insight into how a particular utility or country might weight the relative importance of these factors.

Keywords

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EXECUTIVE SUMMARY

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Primary Audience: Utility and national decision makers considering the degree to which to pursue reprocessing

Secondary Audience: Those interested in a high-level review of reprocessing and factors related to reprocessing decision making

KEY RESEARCH QUESTION

Most advanced nuclear fuel cycles involve used fuel reprocessing to a greater or lesser extent to achieve the advantages of those fuel cycles. Reprocessing of commercial used UOX fuel to be converted into MOX fuel for use in existing LWRs has been used in a few countries for several decades. However, there is little experience with use of reprocessing for advanced fuel cycles beyond small-scale pilot facilities at present.

The relative advantages and disadvantages of reprocessing depend on multiple policy, technical, and economic factors that will vary depending on the importance of each of these factors to the particular utility/utilities and country.

RESEARCH OVERVIEW

This report provides an overview of the existing full-scale, commercial used fuel reprocessing technology – PUREX. The discussion of the PUREX reprocessing technology is used as a basis for comparison to the construction and use of new PUREX-like and alternative advanced reprocessing technologies such as pyroprocessing. A survey of the use of reprocessing in key countries along with a survey of past and existing RD&D of advanced reprocessing technologies is provided. The relative importance of waste disposal considerations is discussed, as well. Probably the primary factor for almost all decision making regarding the use of reprocessing is economics – comparing the costs of deploying reprocessing to the economic (and other) benefits of doing so. A review of several economic studies are provided that show different cost versus benefits. A few case studies for utilities/countries with differing levels of technical development, importance of policy factors, and longer-term plans for use of nuclear power are provided to develop insight into how decisions regarding whether, how and which reprocessing technologies should be pursued.

KEY FINDINGS

Economics

Based on the cursory review of specific cost studies for the once-through fuel cycle versus fuel cycles requiring reprocessing, the devil is in the details. Depending on differences in the myriad of economic assumptions made when developing bottom-line cost numbers, one can conclude that the cost fuel cycles requiring reprocessing can be either less than, approximately equal to, or greater than the cost of a once-through fuel cycle. There are several key cost assumptions that drive the final cost numbers such as, but not limited to the cost of: building fast reactors; uranium; building reprocessing facilities and the cost of borrowing money. Two of these particular factors have high uncertainties, but their uncertainties could be reduced with increasing technical and industrial experience: fast reactors and reprocessing facilities.

Several advanced fuel cycles show long-term potential of becoming cost effective and major contributors of net zero energy. RD&D of advanced fuel cycles including those requiring reprocessing in existing or new reprocessing facilities should be supported by current and future nuclear power users. Although initial funding may be more appropriate to be provided at the national level, joint government-nuclear power producer projects should be supported with financial and in-kind resources by the nuclear industry. *It is essential that nuclear power producers remain active in supporting potential advancements to ensure appropriate RD&D – especially for issues regarding FOAK reactors and reprocessing facilities – is being conducted. This requires consistent, long-term nuclear power industry leadership.*

RD&D investment to achieve a full transition to an advanced fuel cycle will need to proceed ahead of all the necessary market conditions existing if such a fuel cycle is to provide a national benefit when needed. This requires foresight and consistent political will.

Need for Existing Used Fuel for Reprocessing

It is unlikely that much of the used fuel already generated would be used for reprocessing unless a reprocessing facility was constructed with capacity significantly larger than needed to match average annual used fuel discharge.

Safeguards

Some organizations think that safeguards issues are more difficult for some advanced fuel cycles. However, others are of the opinion that safeguards issues for advanced fuel cycles are not difficult to address and that almost no materials generated from advanced fuel cycles would be “weapons useable”.

Non-Proliferation

Since avoidance of weapons proliferation is an international goal, RD&D of reprocessing options that do not separate U and Pu should be a high priority, as should research into safeguards by design and other means of preventing diversion of materials.

Regulations

Use of reprocessing requires appropriate regulations and regulatory oversight. The IAEA has developed both a Safety Requirement and a "Specific Safety Guide" for reprocessing facilities that would serve as a good basis for development of national regulations and regulatory guidance, respectively. Some countries, such as the U.S., do not have regulations specifically for reprocessing. In addition to appropriate regulations and implementing guidance, the regulatory body needs knowledgeable staff in reprocessing.

Waste Management

Waste management issues with reprocessed wastes have not been adequately addressed for some advanced reactor types. Many advanced reactor types and their reprocessing wastes still require identification and disposal preparation assessments. Nevertheless, it is anticipated that these waste management issues can be addressed adequately.

WHY THIS MATTERS

Nuclear utilities and countries should continue to evaluate the potential costs and benefits of various advanced fuel cycle technologies. However, a decision to pursue a particular fuel cycle in the longer term will depend strongly on a myriad of policy, economic, technical and logistical factors that will vary from utility to utility or country to country. This report provides insights into the main factors that would govern such decision making.

HOW TO APPLY RESULTS

The user of this report should identify all the factors that are important to the potential use of specific advanced fuel cycles that will likely require reprocessing. These factors will include policy, economic, technical and logistical issues among others. Those interested in even the possibility of future use of reprocessing should cultivate domestic and international opportunities to conduct the necessary RD&D.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Individual utilities/countries should identify all of the factors that would need to be considered in making decisions about whether to pursue advanced fuel cycles requiring reprocessing and if so, what is required to transition to the advanced fuel cycle(s) and reprocessing technology/technologies. Although this report provides a starting point for learning, active participation in domestic and international reprocessing developments is an excellent way of expanding knowledge to support decision making.
- It is essential that nuclear power producers remain active in supporting potential advancements to ensure appropriate RD&D – especially for issues regarding FOAK reactors and reprocessing facilities – is being conducted. This requires consistent, long-term nuclear power industry leadership.

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IMPLEMENTATION CATEGORY: Strategic Long-term

LIST OF ACRONYMS

AFCI	Advanced Fuel Cycle Initiative (U.S.)
AR	Advanced reactor
ARPA-E	Advanced Research Project Agency-Energy (U.S.)
ASTM	American Society for Testing and Materials
BNFL	Formerly British Nuclear Fuels Limited (UK)
BWR	Boiling water reactor
CANDU	Canadian heavy-water pressurized water reactor
CBV	Alternative reprocessing process usually for fuels containing chlorides
CNNC	China National Nuclear Corporation
COEX	Reprocessing process whose product streams are U, U+Pu(+Np)
CURIE	Converting UNF Radioisotopes Into Energy (U.S.)
DOE	U.S. Department of Energy
DUPIC	Depleted Uranium reuse process
EBR	Experimental Breeder Reactor
EdF	Electricité de France
EPRI	Electric Power Research Institute
ERU	Enriched Reprocessed Uranium
EU	European Union
EW	Exempt Waste
FBR	Fast Breeder (or Burner) Reactor
FHR	Fluroide salt-cooled Fast Reactor
FOAK	First-Of-A-Kind
FP	Fission product
FR	Fast reactor
FVM	Alternative reprocessing process usually for fuels containing chlorides
GCR	Gas-cooled graphite-moderated reactor
GHG	Greenhouse gas
GIF	Gen-IV International Forum
GNEP	Global Nuclear Energy Partnership

GTCC	Greater-than-Class-C
GWd/t	Gigawatt-days per metric ton (also GWD/MTU)
GWe/yr	Gigawatt-electricity per year
HALEU	High-Assay Low-Enriched Uranium
HLW	High-level radioactive waste
HTGR	High-temperature gas-cooled reactor
HWR	Heavy-water reactor
IAEA	International Atomic Energy Agency
ICR	Inventory Change Report
IFR	Integral fast reactor
IKMP	Inventory Key Measurement Point
ILW	Intermediate-level radioactive waste
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IIV	Interim Inventory Verificaion
JAEA	Japan Atomic Energy Agency
KAERI	Korean Atomic Energy Research Institute
LLW	Low-level radioactive waste
LMFR	Liquid metal fast reactor
LWR	Light-water reactor
MBA	Material Balance Area
MFFF	MOX Fuel Fabrication Facility
MICANET	Michelangelo Network (European R&D to maintain the nuclear option)
MIT	Massachusetts Institute of Technology
MOX	Mixed oxide fuel (U/PuO_2)
MSR	Molten salt reactor
MTHM	Metric ton of heavy metal
MTIHM	Metric ton of initial heavy metal
MTUNF	Metric ton of UNF
NAS	National Academy of Sciences
NASEM	National Academy of Science, Engineering and Medicine
NEA	Nuclear Energy Agency

NEI	Nuclear Energy Institute
NNSA	National Nuclear Security Administration (U.S.)
NOAK	N^{th}-Of-A-Kind
NPT	Non-Proliferation Treaty
NRC	U.S. Nuclear Regulatory Commission
NUEX	Reprocessing process whose product streams are U, U+Pu(+Np)
O&M	Operations and Maintenance
OPG	Ontario Power Generation (Canada)
PIV	Physical Inventory Verification
PRISM	Pool-type, metal-fueled, sodium-cooled SMR
PUREX	Plutonium Uranium Extraction, reprocessing process separating U and Pu into separate streams
PWR	Pressurized water reactor
PYROX	Pyroprocessing process for oxide fuels
R&D	Research and development
RD&D	Research, development and demonstration
REMIX	Regenerated MIXture of U-Pu Oxides reprocessing process
RepU	Reprocessed uranium
ROK	Republic of Korea
RPP	Rokkasho Reprocessing Plant
SFR	Sodium-cooled Fast Reactor
SMR	Small modular reactor
SSR-W	Soluble Salt Reactor - Wasteburner
TBP	Tri-*n*-butyl phosphate
THORP	Thermal Oxide Reprocessing Plant
TRISO	Tri-structural Isotropic particle fuel
TRL	Technology Reference Level
TRU	Transuranic(s)
TWHe	Terawatt-hours (electric)
UK	United Kingdom
UNF	Used (irradiated) nuclear fuel

UOX	Uranium dioxide (UO_2) fuel
UREX	Reprocessing process whose product streams are U, U+Pu(+Np)
U.S.	United States
VLLW	Very Low-Level Waste
VSLW	Very Short-Lived Waste
WATSS	Waste to Soluble Salt reprocessing process
WNA	World Nuclear Association

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1 INTRODUCTION

Expanding world energy demands and increasing attention to climate change and other environmental concerns are raising interest in low-emission technologies like nuclear energy. At present, the majority of commercial nuclear power is generated in reactors using thermal neutrons to fission primarily U-235, intended to be followed by direct disposal of the spent fuel (a "once through" fuel "cycle"). While a few countries do employ limited reuse of used commercial nuclear fuel (partial recycling, see Chapter 3), these countries are the exception to the once-through fuel "cycle." Expansion of nuclear power that would continue to use a once-through fuel cycle maximizes the need for uranium resources, requires a significant expansion of U-235 enrichment capacity, and maximizes the number of fuel assemblies requiring storage, transportation, and disposal. Currently there are sufficient uranium resources accessible at competitive prices, so there has not been widespread interest in shifting to more advanced fuel cycles employing reprocessing for thermal reactors based solely on economics. As will be discussed, there are multiple reasons in addition to just economic considerations why moving to advanced fuel cycles that employ some degree of irradiated fuel reuse with advanced reactors could become desirable in the next few decades.

Most advanced reactors are designed with higher fuel efficiency, taking advantage of higher initial enrichments, with some intending to consume used fuel materials as they generate power. Some will use the familiar thermal spectrum neutrons, while others will benefit from fast neutrons, which can fission many more isotopes within their fuel. However, resolution of a few main challenges related to fuel will need to be achieved to deploy a new fleet of advanced reactors (EPRI, 2010c):

- Economics that are affected by:
  - Availability of natural uranium (or thorium in a few cases)
  - Waste management needs
  - Reprocessing needs (the primary subject of this report)
  - Cost of RD&D of advanced reactors
- Non-proliferation/security

Arguments for a prominent role for nuclear energy in the future global energy mix often equate sustainable growth in nuclear energy with wider deployment of commercial reprocessing technology as a means to maximize energy extraction from existing uranium and/or thorium resources. For example, a March 2010 survey of U.S. citizens revealed that 79% supported recycling used nuclear fuel. This increased to 85% if it was recommended by a panel of experts (WNA, 2023c).

This report is intended to clarify the role of reprocessing to sustain the expansion of and long-term use for nuclear power. The discussion begins with definition of the term reprocessing and considerations for evaluating reprocessing (Section 1.1 Overview of Reprocessing and Recycling). A summary of major reprocessing facilities worldwide is provided in Appendix A. The status of reprocessing facilities is found in Appendix B.

A key component of this report is to address the question: Why Reprocess? This is introduced in Section 1.4 Why Reprocess? Main Considerations for Choosing Partially- to Fully-Closed Fuel Cycles. Some of the main factors to be considered are addressed in Chapter 7 with example cases in Chapter 8.

Undoubtedly, the most important consideration for potentially adopting an advanced fuel cycle requiring reprocessing is economics. A discussion of economics can be found in Section 7.3 Examples of specific economic analyses are provided in Appendix C.

A more technical description of commercially mature alternatives under development follows, with currently deployed aqueous reprocessing of oxide nuclear fuel from light water reactors (LWRs) used as the principal illustration of key concepts and process elements (Section 2). Existing reprocessing facilities almost exclusively use aqueous processes (see Section 2.3.1). Pyroprocessing is featured as the main alternative to aqueous reprocessing approaches, although its application is widely regarded as being most appropriate for supporting recycle of plutonium in fast spectrum reactors (Section 2.3.2). The discussion broadens with key considerations related to the international approach to reprocessing (Chapter 3). A discussion of major advanced reactor technologies requiring reprocessing can be found in Chapter 4 and Appendix A.

One aspect of all advanced fuel cycles that receives considerable attention are waste management issues – primarily waste streams generated from reprocessing. This is described in Chapter 5. Usually forgotten in the discussion of waste management issues is that at the end of the use of an advanced fuel cycle, the waste remaining in the reactors that will require disposal can be considerable, such as the transuranics that build up in fast reactors. This is discussed in Section 5.4.

Almost all of the advanced fuel cycles and next-generation reprocessing facilities are not technically mature. There is a considerable amount of RD&D occurring throughout the world, which is summarized in Chapter 6.

A common need for all advanced fuel cycles using reprocessing is non-proliferation. A brief discussion of this issue is found in Section 7.2.1. A detailed safeguards example is provided in Appendix D.

Final observations and recommendations are provided in Chapter 9.

1.1 Overview of Reprocessing and Recycling

Commercial reprocessing of used nuclear fuel comprises a series of mechanical and chemical (and/or electrochemical) operations that chemically transform the fuel into distinct process streams, generally with the intent to enable recovery and reuse of fissionable material and transformation of waste into alternative forms. The term "reprocessing" is frequently used interchangeably with the term "recycling." While they are similar, and one may rely on the other, this can create confusion. Reprocessing enables the separation of specific elements from used fuel which allows for those materials' recycling. Recycling encompasses a broader set of fuel cycle technologies, i.e., reactor technology, fuel fabrication technology, (re)enrichment facilities, and other supporting elements that result in usable fuel output from the process. According to the Nuclear Energy Institute (NEI), "*reprocessing extracts reusable constituents from used fuel and recycling incorporates these constituents into new fuel for reuse*" (NEI, 2023). The principal constituents for recycling are the plutonium that was generated during irradiation in the reactor and the leftover uranium (both U-235 and -238). To a lesser extent, some of the minor actinides can also contribute to energy generation in fast reactors.

The reprocessing process does not change the overall radioactivity (distribution and amount of fissile material, fission product, activation product and minor actinide isotopes), but it modifies the form, concentration, and location of that radioactivity (e.g., in a dilute liquid waste stream, a gaseous effluent, a high-level waste to be stabilized in glass followed by geologic disposal, low- and intermediate-level waste requiring shallow land or geologic disposal, or a feedstock for manufacture of new nuclear fuel). Therefore, reprocessing is a means to transition from an open fuel cycle to either a single-recycle (single reprocessing[1]), partially closed[2], or fully closed fuel cycle[3], each of which incrementally increases the utilization of the fuel materials. These different options are illustrated in Figure 1-1 (once-through (solid lines) and single reprocessing (solid and dashed lines[4]) fuel cycles) and Figure 1-2, which depicts partially and fully closed fuel cycles employing fast reactors with reprocessing facilities highlighted in red circles. Fully closed

[1] Single-recycle: reprocessing once to separate nuclides that are fissile in thermal reactors, primarily U-235 and Pu-239/241 in the uranium fuel cycle. The recycled U/Pu for existing light- or heavy-water reactors is converted into mixed oxide fuel (MOX). Spent MOX would be disposed of in a geologic repository.

[2] More than one time through one or more reprocessing facilities (i.e., reprocessing of used MOX in a reprocessing facility to be used in LWRs and/or a separate reprocessing facility to separate radionuclides that are fissile in fast reactors). This can include disposal of fissionable actinide elements.

[3] Continuous reprocessing through fast reactor fuel reprocessing plant(s) with additions of fresh uranium. Therefore, the only waste streams requiring deep geologic disposal would be solidified (typically in glass) fission products except volatiles (e.g., I-129) that would need to be solidified in a manner that avoids high temperatures. A third waste stream would also require disposal that might or might not need to be deep: compacted assembly hardware and cladding.

[4] For single reprocessing of 100% of used fuel the solid line between "Power Station" and "Disposal" in Figure 1-1 would be eliminated.

and potentially partially closed fuel cycles will likely require two separate reprocessing facilities – one for reprocessing of fuel from reactors using thermal neutrons for fission (e.g., LWRs, HWRs, HTGRs), and a second for reprocessing fuel from reactors using fast neutrons for fission (e.g., liquid metal-cooled reactors, molten salt reactors, and others).

It is important to note that *all* fuel cycles still require a combination of shallow land burial for low-level waste (LLW) and geologic disposal for intermediate- and high-level waste (ILW[5] and HLW, respectively (NEI, 2023) for non-fissile material such as fission products, control rods and fuel assembly hulls. Although moving to partially or fully closed fuel cycles will likely reduce the amount of material requiring geologic disposal, even fully closed fuel cycles will still generate waste requiring both shallow land (e.g., LLW) and geologic disposal.

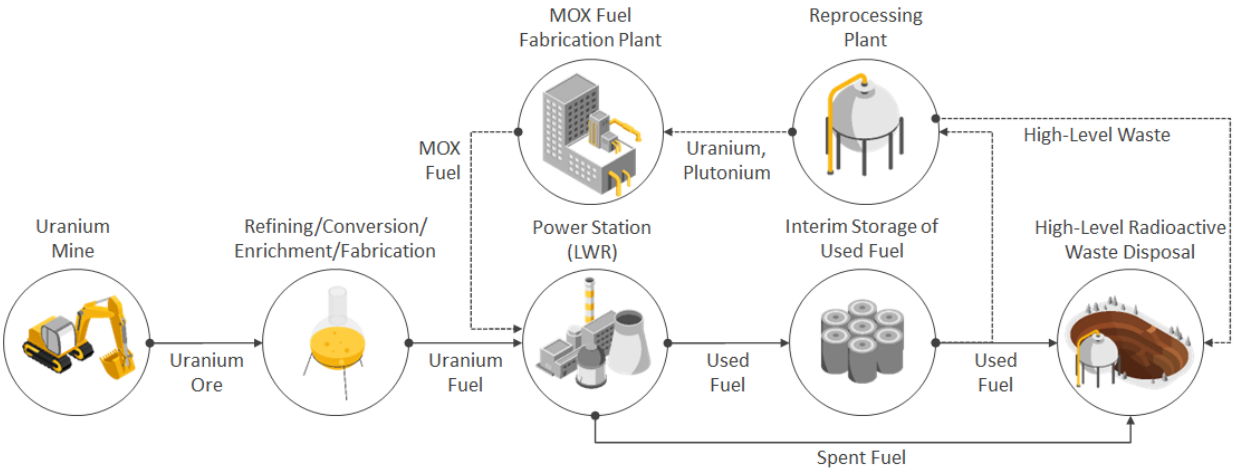

Figure 1-1. Illustration of open nuclear fuel cycle options, once through with solid lines, single-recycle steps added with dashed lines

Key Technical Point

It is important to note that *all* fuel cycles still require a combination of shallow land burial for low-level waste (LLW) and geologic disposal for intermediate- and high-level waste (ILW and HLW, respectively) for non-fissile material such as fission products, control rods and fuel assembly hulls.

[5] In the U.S. and a few other countries, ILW would be either some of Class C and all Greater-Than-Class-C (GTCC) waste.

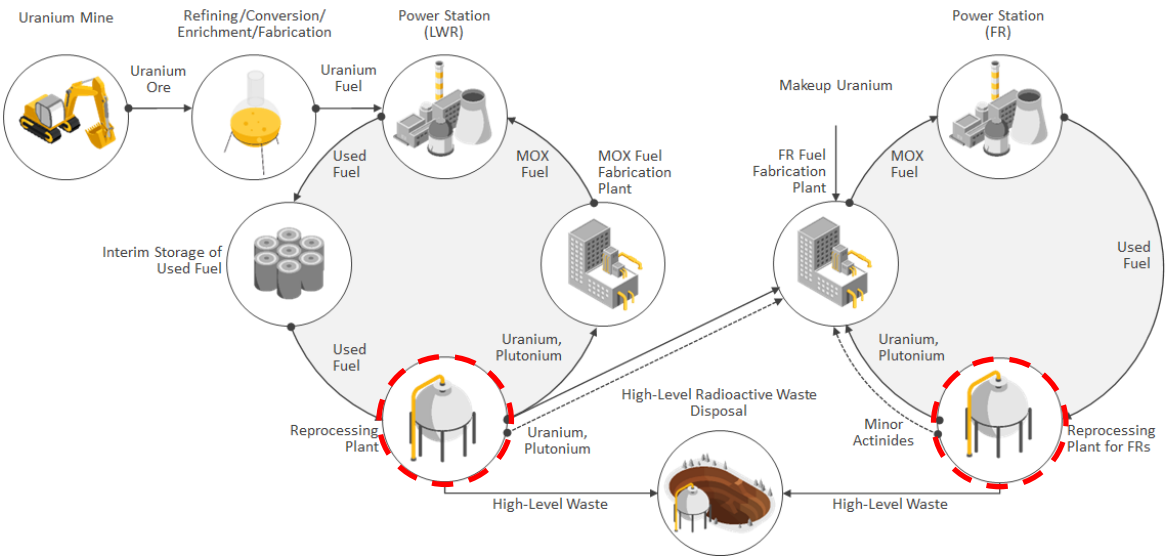

Figure 1-2. Illustration of multiple closed nuclear fuel cycle options. Dashed lines represent the movement of minor actinides. LWR: light-water reactor; MOX: mixed oxide (UO_2/PuO_2) FR: fast reactor

The general path from used fuel to new fuel via reprocessing is shown in Figure 1-3. This includes the so-called "head-end" processing to get used fuel into a form appropriate for the specific separation technology employed, the separation technology itself, and any post-separation processes to transform fuel material(s) appropriate for re-fabrication into new fuel for recycling in reactors.

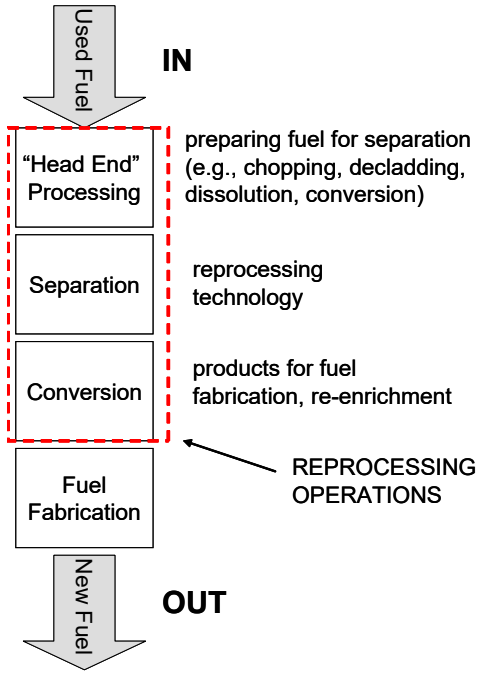

Figure 1-3. General path from used fuel to new fuel via reprocessing

1.2 Existing Reprocessing Facilities

Existing reprocessing facilities worldwide are provided in Table 1-1. Individual reprocessing facilities are discussed in Section 3.2.

Table 1-1. World reprocessing capacity (MTHM per year) [adapted from (NEA, 2020)]

Fuel Type	Facility Location (Name)	Capacity (MHTM)
LWR Fuel	France, La Hague (La Hague)	1700
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)*	800
	Total LWR (approximate)	2100
Other Nuclear Fuels	UK, Sellafield (Magnox)	1500
	India (PHWR, 4 plants)	260
	Total other (approximate)	1760
Total Civil Capacity		3860

*Anticipated start date: 2025

1.3 Advanced Fuel Cycles Requiring Reprocessing

A list of many of the advanced fuel cycles at a laboratory scale through full-scale implementation as of approximately 2006 was compiled by (IAEA, 2008b). Appendix A provides that list.

1.4 Why Reprocess? Main Considerations for Choosing Partially- to Fully-Closed Fuel Cycles

Whether reprocessing might or might not make sense for a utility or country strongly depends on the needs and goals of the specific entity. IAEA (2008b) summarized these major factors:

- Global energy mix and energy policy, current status and prospects for the contribution of nuclear power, and commitment to the reduction of greenhouse gas emissions such as CO_2
- Availability of fissile materials resources
- Nuclear power fleet (number of units, reactor(s) type(s) and fuel cycle technologies implemented, etc.)
- Inventory of radioactive materials (including legacy waste) resulting from past and waste management practices
- Choice and capacity of candidate geologic formations chosen for ultimate disposal
- Public (and political) support for nuclear energy.

These current considerations are drivers for the choice of a national back-end strategy with the following possibilities:

- "Direct Disposal" or "Once-through Fuel Cycle"
- "Storage and Postponed Decision" or "Wait and See Option"
- "Reprocessing and Recycling" or "Closed Fuel Cycle"

There are five key considerations for a closed fuel cycle strategy and R&D on advanced fuel cycles to further improve it:

- Conservation of natural resources
- Optimization of waste management and disposal conditions
- Minimization of environmental impact
- Fuel cycle economics
- Proliferation resistance

Other potential factors could include:

- A desire to become a world leader in reprocessing technology
- Develop reprocessing capacity not only for domestic use, but also to provide reprocessing services to additional customers

The benefits and costs that may influence an entity's interest in reprocessing are summarized briefly here and discussed in more detail in Section 7.1 Benefits.

Benefits:

- Recovery of fissile material leading to reduced demand for natural material leads to the following benefits:
  - Supports expansion of nuclear energy via improved use of existing resources
  - Supports sustainable use of nuclear energy the more closed fuel cycle implemented
  - Supports energy independence if the amount of imported feedstocks can be reduced
  - Reduced demand for uranium (or thorium) ore
- Modifications to waste requiring deep geologic disposal for some fuel cycles using reprocessing[6]:
  - Waste form optimization for all fuel cycles using reprocessing
  - Potential cost reductions compared to a once-through fuel cycle
  - Reduced (but not eliminated) cost for geologic disposal

[6] See Section 5.4 for a discussion of how long it would take fast reactors with reprocessing to reduce the total TRU inventory (waste plus in-reactor). Waste reduction is probably a minor benefit.

- Potential cost reductions depending on the fuel cycle technology chosen
  - Reduction of enrichment services required
  - Reduction to low-level waste (LLW) disposal

Costs:

- Economic costs of building and operating one or more reprocessing facilities
- Economic costs of building and operating advanced nuclear power plants
- Economic cost of ramping up deployment of fuel cycle technologies that require reprocessing
- May require development of appropriate regulations for reprocessing technologies
- Management (storage, transportation and disposal) of reprocessing and advanced fuel cycles wastes (LLW, ILW/GTCC, HLW/Spent fuel)
- In some fuel cycles, additional fissile material security and safeguards

Additional discussion regarding costs is found in Section 7.3 and in Appendix C

Although developed for the United States situation, most of the Nuclear Energy Institute's (NEI's) *Policy Principles for Recycling Used Nuclear Fuel* (NEI, 2023) provides an example to guide the global industry's efforts to advance recycling technologies. The following are excerpts from this proposed policy with minor adaption for globally inclusive terminology:

> **Recycling would not replace the need for disposal in a geologic repository**
>
> - Even in an integrated used fuel management program that includes recycling, a geologic repository would remain necessary because some radioactive byproducts will require permanent disposal.
> - Recycling has the potential to benefit repository development by converting spent fuel into waste forms that are easier to dispose.
> - Co-locating recycling facilities with repository and consolidated interim storage facilities has the potential to provide potential host communities with additional economic benefits.
>
> **Recycling technologies should further clean energy and sustainability goals**
>
> - Recycling has the potential to enhance nuclear generation as a clean, sustainable source of energy by improving resource utilization.
> - The existing inventory of used nuclear fuel contains the energy potential to provide … many additional decades of carbon-free electricity.

Recycling technologies should increase the economic competitiveness of future nuclear reactors

- In the future, it may be more cost effective to produce new fuel with used nuclear feedstock than by beginning with natural uranium—lowering electricity bills, spurring economic growth, and improving energy equity.

Recycling should help improve … energy security

- Recycling, in conjunction with increased domestic uranium production when possible, could enable a long-term strategy to reduce … dependence on imported uranium nuclear fuel.

The [federal government] should support research, development, and demonstration of used nuclear fuel recycling technologies

- Federal investment in recycling technologies can accelerate first-of-a-kind research, development, and demonstration (RD&D).

Recycling technologies should avoid unacceptable proliferation risks

- …[R]ecycling efforts should be guided by best practices established through global experience to date.
- Recycling technologies must be implemented in accordance with strict international safeguards.
- Recycling may result in waste forms that enhance our ability to protect these materials.

The [United States Nuclear Regulatory Commission] (NRC) should license recycling facilities under its current regulations and implement innovative approaches to achieve timely reviews of recycling facilities[7]

- The NRC will need to develop its workforce consistent with the need to license and inspect recycling facilities in the future.
- NRC should learn from its experience licensing the "first-mover" recycling facilities to strengthen its regulatory framework in the future.

[7] Although this is directed at the USA regulator, it would be applicable in many other countries.

2 ELEMENTS OF REPROCESSING FACILITIES

The main purpose of used fuel reprocessing is to separate reusable fuel material from other constituents like those that do not have further energy value (e.g., the fission products (HLW), fuel cladding and other assembly components (ILW or HLW), and LLW/ILW waste streams) or may be deemed undesirable for recycling (e.g., some minor actinides). This reusable fuel material is then input to fuel fabrication processes resulting in reprocessed fuel (like MOX) for further power generation.

2.1 Used LWR Fuel Components to be Reprocessed

In general, for a given amount of power production, the fission product inventory generated is roughly constant for all fuel cycle options, as these are fundamentally derived from the fission process itself in a close to fixed ratio of two fission products per fission (Figure 2-1). If reprocessed, the radionuclides generated by the initial UOX fuel in an LWR that can be reused (i.e., are fissile) in a thermal reactor are: U-235 ("RepU"), Pu-239, and Pu-241.

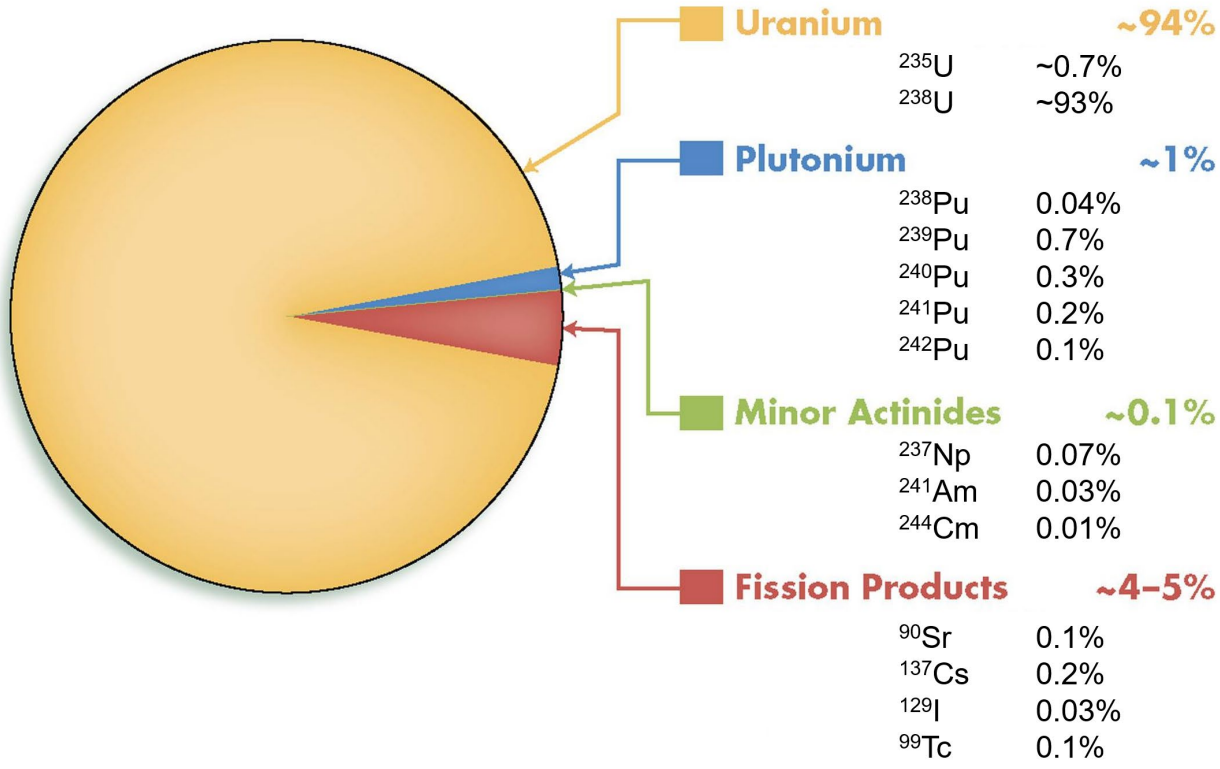

Figure 2-1. Composition of a representative light-water reactor fuel assembly after irradiation to 50 GWd/t burnup (EPRI, 2010c)

2.2 Advantage of Fast Reactors – Fission of U-238 and Other Even-Numbered Actinides

Although reprocessing of LWR and heavy-water reactor (HWR) used fuel back into LWRs or HWRs provides a moderate increase in the use of some actinides (e.g., Pu-239 and Pu-241 (see Figure 2-2), the main advantage of fast reactor technologies is the orders-of-magnitude increase in fission cross-section of U-238. There are also significant increases in fission cross sections in the fast neutron spectrum for other even-numbered actinides such as Pu-238, Pu-240 and Pu-242. The primary advanced fuel cycles employing fast neutrons are liquid metal fast reactors (LMFRs) employing sodium, lead-bismuth and other metal alloys, and molten salt reactors using various chloride or fluoride salts with low melting points and low fast neutron capture cross sections.[8]

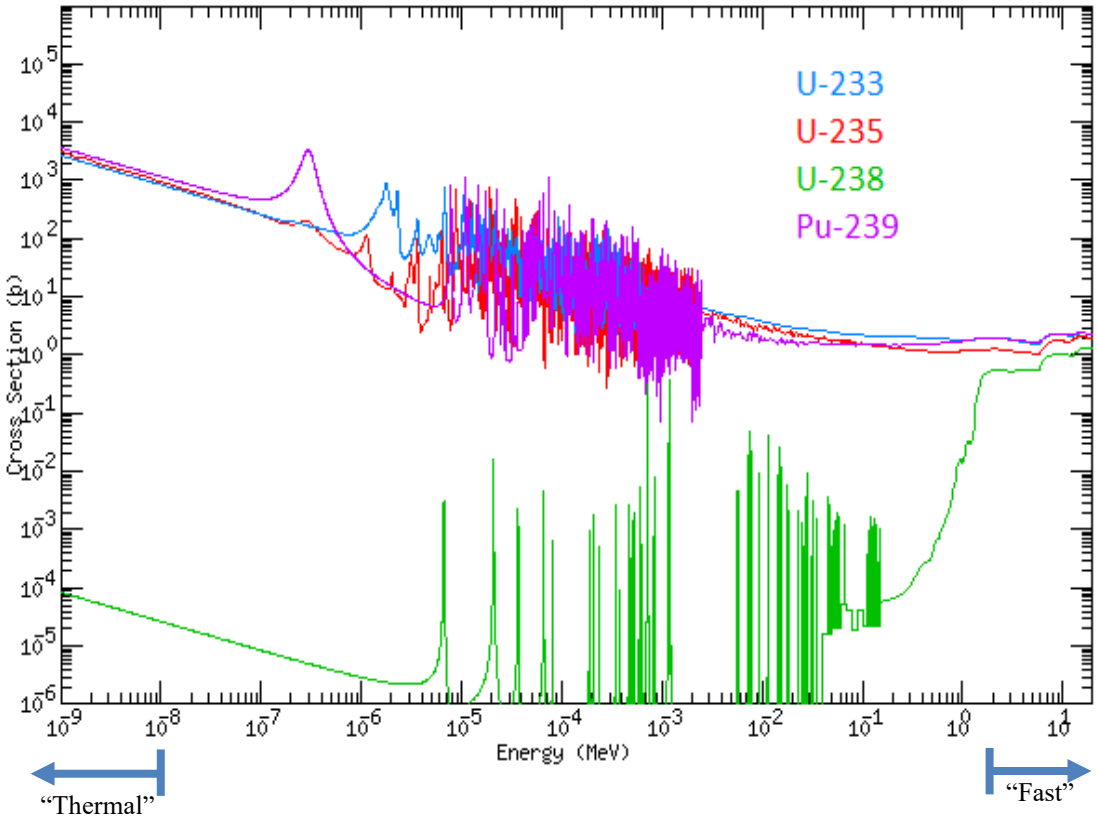

Figure 2-2. Fission cross-section for key radionuclides as a function of neutron energy [downloaded from (Wikimedia Commons, 2017) (Publicly available under a Creative Commons Attribution-Share Alike 4.0 International license)

[8] There are many advanced reactor technologies that would continue to use thermal neutrons (e.g., SMRs, HTGRs, some MSRs) that have other advantages compared to LWRs such as lower up-front capital costs (SMRs and microreactors) or improved thermal efficiency due to higher operating temperatures (e.g., HTGRs and MSRs) (see, e.g., (NASEM, 2023).

2.3 Reprocessing Technologies

Reprocessing can be used mainly for three applications:

- **Recycling of plutonium and uranium in existing light-water reactors (LWRs)**
  LWR fuels are generally manufactured as an oxide-based ceramic, e.g., as uranium oxide (UOX) or uranium-plutonium mixed oxide (MOX) fuels contained in a zirconium-based alloy cladding envelope. Recycling of plutonium and uranium remaining in LWR used fuel has the potential to modestly decrease the demand for natural uranium resources. Savings in demand for natural uranium up to 30% are possible using existing LWR technology (WNA, 2023b). Practical limitations on the benefits of recycling of Pu and U in existing LWRs are imposed by the in-growth of neutron absorbing Pu and U isotopes that cannot be chemically separated from their desirable counterparts. The impact from undesirable U and Pu isotopes can be mitigated by dilution with cleaner material, such as used UOX fuel or other sources of U and Pu. To date, commercial experience with reprocessing of LWR oxide fuel lies exclusively with aqueous/PUREX-based processes (Section 2.3.1 Aqueous Reprocessing - PUREX).
- **Recycling of plutonium and uranium in advanced reactor designs**
  Recycling of plutonium and uranium in some advanced reactors such as in fast reactors (FRs), has the potential to significantly decrease the demand for natural uranium resources. The degree to which FRs maximize nuclear fuel resource utilization depends on the conversion ratio of the reactor technology. A conversion ratio of less than one indicates more fissile material is consumed than is produced; accordingly, such FRs are referred to as "burner" reactors. A conversion ratio greater than one implies more fissile material is produced than is consumed; accordingly, these FRs are referred to as "breeder" reactors. A conversion factor equal to one, break-even mode in which as much fissile material is consumed as is produced.
- **Reprocessing of used fuel for waste management benefit**
  In the short term, the use of reprocessing would reduce the amount of waste to be stored in spent fuel pools, dry storage systems, and geological disposals.[9] More detail is provided in Chapter 5.

While there are several approaches and derived processes, as shown in Table 2-1, aqueous reprocessing and pyroprocessing are the most relevant in terms of their technical and/or commercial maturity, though many alternatives are being pursued, from chloride volatility to crystallization extraction. More information on the dominant technologies is provided in the following sections and in Appendix A.

[9] However, at the very end of the use of an advanced fuel cycle using reprocessing, the remaining fuel in the advanced reactors would be treated as waste. If this waste that would be generated in the future is considered along with operational wastes (primarily arising from reprocessing activities), then the benefit to waste reduction is reduced – potentially considerably. See Section 5.4.

Table 2-1. Summary of major reprocessing technology options

Process	Approach	Process Names	Recycled Streams	Waste Streams
Once-Through (no reprocessing)			None	U+Pu+Np+Am+Cm+FP[a]
Aqueous	Plutonium and Uranium Separation	PUREX	U, Pu	Np+Am+Cm+FP
	Co-extraction of Plutonium and Uranium (Evolutionary PUREX)	Advanced PUREX (UK)	U, U+Pu(+Np)[b]	(Np)+Am+Cm+FP
		COEX™ (AREVA, France)		
		NUEX™ (Energy Solutions, US)		
		UREX (US)		
Electro-Chemical	Pyroprocessing	LiCl-KCl	U, U+Np+Pu+Am+Cm	FP
		NaCl-KCl		
		Fluoride volatility		

[a] FP: fission products as constituents of intact spent nuclear fuel.

[b] Np is included in parenthesis because it could be possibly extracted with some modifications of the PUREX process (e.g., COEX process)

Although this is an example for the PUREX reprocessing technology, Figure 2-3 also depicts the generic diagram for reprocessing technologies discussed in this report, starting with used fuel as the input and fabrication of new fuel as the ultimate output.

Fuel fabrication could be performed at a location other than the reprocessing facility as is done in France. This requires transportation of the fissile material stream from the reprocessing facility to the fuel fabrication facility.

2.3.1 Aqueous Reprocessing – PUREX

Plutonium Uranium Extraction (PUREX) is an aqueous-based solvent extraction process in which an acidic water-based solution (nitric acid for traditional PUREX) containing the constituents of dissolved used fuel is contacted with an immiscible organic liquid stream and subsequently allowed to separate into two distinct phases again. The organic phase comprises tri-*n*-butyl phosphate (TBP), a chemical compound that preferentially binds with dissolved uranium and plutonium but not with fission products and other constituents, diluted to a 20–30% concentration by volume with an organic diluent, typically kerosene or *n*-dodecane, to provide

a desirable process viscosity and density. The separation of the aqueous and organic phases following contact and mixing allows for the separation of U and Pu from the fission products and minor actinides.

The archetypal PUREX process involves the following basic steps as illustrated in Figure 2-3[10]:

- Dissolution of the fuel material in nitric acid
- Separation of uranium and plutonium from fission products and other minor actinides via solvent extraction
- Partitioning of uranium and plutonium into separate product streams
- Purification and conversion of recovered uranium and plutonium into desired physical/chemical forms for use in fuel fabrication

Also shown in Figure 2-3 are important supporting functions related to off-gas and waste management and recovery and regeneration of process reagents (organic solvents and nitric acid).

[10] There are two steps ahead of "fuel preparation" not shown in this figure: (1) Mechanical removal of extraneous metal hardware from the fuel elements; (2) Shearing of fuel rods into short segments, as described in Section 2.3.1.1.

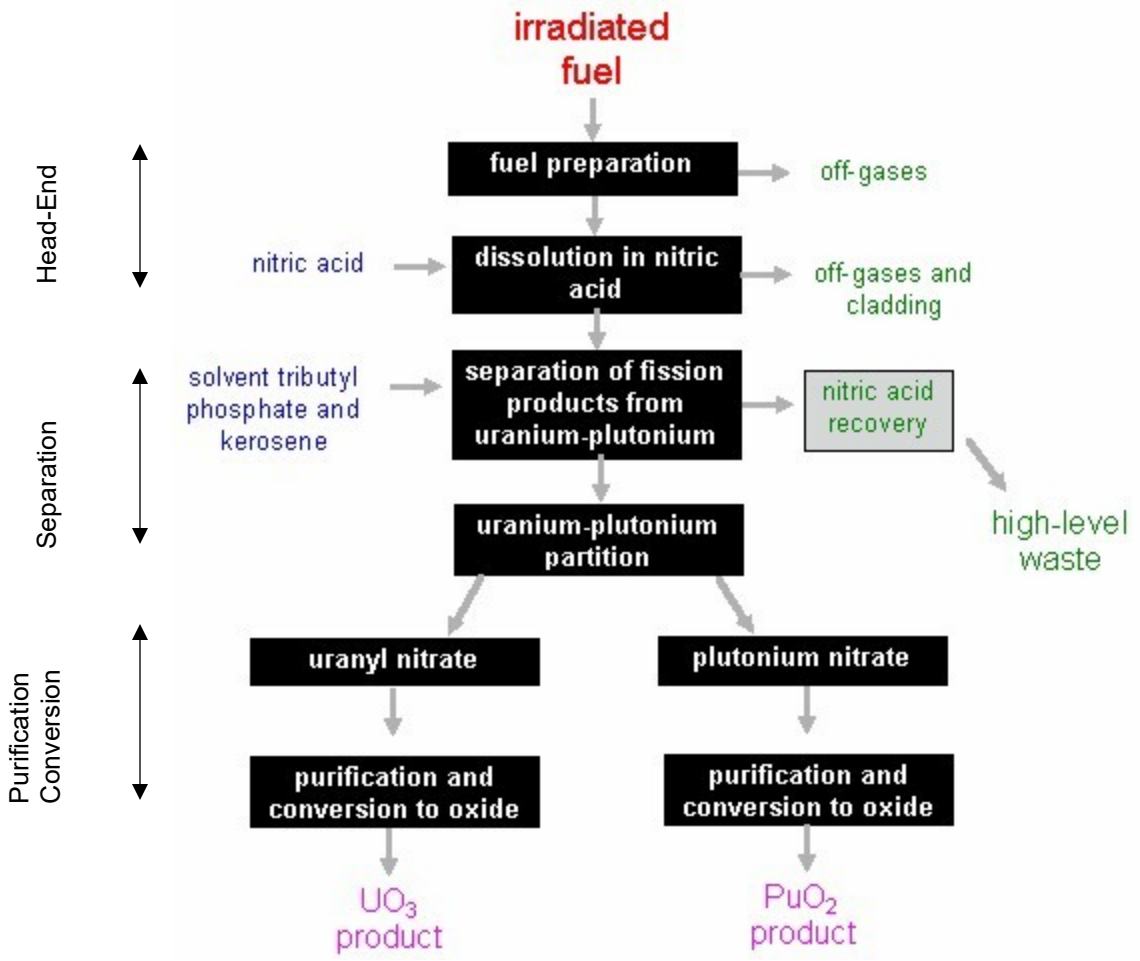

Figure 2-3. Diagrammatic representation of the PUREX process for LWR used fuel reprocessing

2.3.1.1 PUREX Head-End

The head-end phase is defined as the mechanical and chemical operations needed to change intact fuel assemblies into a form suitable for feeding into the chemical separation process segment that follows. Basic head-end steps include:

- Mechanical removal of extraneous metal hardware from fuel assemblies.
- Shearing of fuel rods into short (on the order of 35 mm) segments. A fraction of the volatile fission products escapes into the hot cell exhaust during this operation and is vented to the off-gas treatment system. The sheared cladding hulls are incorporated into the hardware waste.
- Dissolving the fuel material or “meat” in hot, concentrated nitric acid. Most of the fission products in the pellets also dissolve. A fraction of the volatile radioelement inventory, i.e., krypton, xenon, and iodine, is released during this operation and vented to off-gas treatment. Insoluble fission products, primarily noble metal fission products, are added to the metallic waste.

The gaseous and solid waste streams produced require management according to governing regulations and practices:

- Treating the process off-gas to capture volatile materials such as iodine. Although not captured in current (third) generation and older plants, it is likely that other gaseous radionuclides (tritium, ^{85}Kr, and ^{14}C) will be captured and managed for any new commercial reprocessing plant.
- The discarded fuel assembly hardware, empty cladding "hulls" and end pieces, and undissolved solids are packaged for compaction and waste storage or disposal as Intermediate Level Waste (ILW) or greater-than-Class C waste.

A head-end enhancement called voloxidation was the focus of the U.S. DOE and the EU-funded Framework Programme 7 project "ASGARD." Voloxidation involves oxidation of used fuel at temperatures above 400°C to enhance preparation of fuel for subsequent processes by decreasing fuel particle size (Collins, Del Cul, & Moyer, 2011) (INL, 2019) and release of tritium to avoid infiltration into the aqueous system (Jubin, 2023). During this process, uranium dioxide is converted to U_3O_8, resulting in a substantial increase in crystalline volume, destruction of the original ceramic fuel structure, formation of a finely divided powder with high surface area, and separation of fuel material from cladding.

2.3.1.2 PUREX Separation

Solvent extraction is the main technology used to achieve separation in commercial scale reprocessing. A second technology that can be used is ion exchange, although it is generally more appropriate for small quantities of fuel and low concentrations.

The PUREX process, like many other solvent extraction schemes, is currently the most used commercial technology. It takes advantage of the oxidation-reduction chemistry exhibited by the actinides, which provides for predictable, controllable manipulation and separation of elements based on their specific oxidation state. For example, actinides in the +4 and +6 oxidation states, common for Pu and U, respectively, are preferentially extracted into tri-n-butyl phosphate (TBP)/kerosene solvent[11] from moderately concentrated nitric acid solutions while actinides in the +3 oxidation state (americium and curium) and most fission products remain in the aqueous phase. Some fission products (e.g., technetium, zirconium, and ruthenium) and actinides in the +5 oxidation state (such as neptunium) are weakly extracted, depending on solution conditions; consequently, a fraction of certain FPs and Np can be carried in the solvent along with U and Pu (Jubin, 2023) (INL, 2010) (Herbst, Baron, & Nilsson, 2011).

[11] The PUREX solvent is typically a 30% TBP solution diluted in purified kerosene or dodecane.

Developed and deployed as a continuous flow-through process, PUREX extraction of uranium and plutonium is performed using multiple stages to support both high separation efficiencies and high throughputs. This is accomplished by connecting multiple contactor units in series to provide successive mixing of aqueous and organic phases flowing in opposite directions. Solvent extraction consists of the following steps:

- Separation of Pu and U from fission products and other minor actinides by extraction from an aqueous nitric acid solution into the TBP/organic diluent phase.
- Multiple "scrub" steps with varying concentrations of nitric acid solutions for removal of entrained and extracted fission products from the organic phase.
- Stripping of Pu from organic phase by selectively reducing Pu to +3 oxidation state, which leads to its back-extraction into an aqueous nitric acid solution. Any U that back-extracts with the Pu can be re-extracted into fresh solvent (i.e., a U scrub step) and combined with the U-Pu bearing solvent stream. The resulting aqueous Pu stream is ready for subsequent purification and conversion operations.
- Stripping of U from the organic phase with introduction of dilute nitric acid (0.01 M HNO_3) at 50°C. The resulting aqueous U stream (likely bearing some residual Np) is ready for subsequent purification and conversion operations.

2.3.1.3 PUREX Back End - Waste Stream Management

A brief description of what is done with the waste streams from the PUREX process is:

- Assembly end fittings and the fuel rod segments are washed, dried, then compacted prior to disposal
- Volatile fission gas streams are either released to the environment or captured on various media
- The remaining fission products and actinides in liquid streams are precipitated, calcined and then added to a glass melt for eventual disposal

More details of waste stream management are provided in Chapter 5.

2.3.1.4 PUREX Purification/Conversion

Plutonium and uranium from the primary PUREX separation step still contain impurities and are not yet in the final chemical form for subsequent storage or use in fuel fabrication. Accordingly, the two streams typically undergo additional purification or polishing steps to concentrate the product and achieve desired purity[12] and are subsequently converted to a final solid form suitable for storage, transport, and eventual incorporation into new reactor fuel – typically as an oxide powder (Pu and U) or as a nitrate solution (U).

- Purification: Several methods are available for post-separation purification of plutonium and uranium, including ion exchange and cycling through additional solvent extraction steps, which rely on the same principles of separation of impurities from products as the primary separation cycle described above, albeit with some modifications or substitutions of reagents.
- Conversion: As with purification, several methods are available for conversion of Pu or U nitrate solutions to final products, usually an oxide, including thermal denitration (Uranyl nitrate is converted to UO_3 by denitration at elevated temperature) or calcination of loaded ion-exchange resins (Plutonium nitrate is precipitated by oxalate or peroxide and calcined to PuO_2).

At La Hague, once plutonium is stripped from the final solvent phase into an aqueous nitric acid stream, it is precipitated as solid plutonium oxalate, which is filtered, dried, and heated in a furnace to yield plutonium oxide powder. Reprocessed uranium is maintained as a uranyl nitrate solution.

2.3.1.5 Variations of the PUREX Aqueous Process

Additional technologies besides those discussed in the previous paragraphs are also promising for future use. Modifications of the PUREX technology have been developed to optimize the separation of the different components of the fuel, e.g., minor actinides (PNNL, 2012).

2.3.2 Non-Aqueous Reprocessing Technologies (Pyrometallurgical Reprocessing)

Pyrometallurgical reprocessing, commonly referred to as pyroprocessing, represents a second major class of nuclear fuel reprocessing methods. Pyroprocessing of used fuel is based on a mature technology used extensively in the metal refining industry, and it is generally considered well-suited for accommodating metal fuel from fast reactor systems, although it could be applied to other fuels, including UOX (Chang & al., 2019). Pyroprocessing is conducted at high temperatures for oxidation and reduction reactions, involving inorganic molten salts, gases, and liquid metals for process media, either in electrolytic or electrorefining steps (IAEA, 2021b).

[12] For example, a few ASTM product specifications include maximum levels of impurities for nuclear fuel materials (UO_2 and PuO_2 powder) and sintered pellets, including mixed-oxide fuel pellets for fast reactors, e.g., (ASTM, 2004) (ASTM, 2006a) (ASTM, 2006b) (ASTM, 2008).

For nuclear applications, it has been demonstrated at a pilot scale, but it has not yet been deployed on a commercial scale for reprocessing fuel from either LWRs or fast reactors. Only the integral fast reactor (IFR) electrolytic process developed by Argonne National Laboratory has been licensed for use on a large scale and has been used to treat 4.6 tons of used fuel from the Experimental Breeder Reactor-II (EBR-II) (WNA, 2023b).

As the pyroprocessing technologies utilize inorganic chemicals, highly radioactive fuel can be processed without the risk of chemical deterioration, providing an efficient technical barrier to proliferation. Additionally, separation of plutonium from other actinides cannot be easily reached by Pyroprocessing, adding a barrier to technical and physical barrier to proliferation (IAEA, 2021b).

2.3.2.1 Pyroprocessing Head-End

As with any separation process, the head-end activities provide a feed material that is compatible with the separation process. For pyroprocessing, the complexity of the head-end will vary greatly depending on the fuel. For metallic fuels, the headend would consist exclusively of chopping the fuel into small segments, which can then be introduced directly into the electrorefiner as a feed material. Non-metal fuels, especially oxide as it is currently used in LWRs, will require an appropriate head-end treatment to generate a compatible feed material.

A few processes have been demonstrated for conversion of an oxide matrix to a compatible metallic form (Herrmann, Li, and Simpson, 2007):

- Direct pyro-chemical reduction of the oxide fuel matrix by metallic Li (Li^0) in a molten LiCl salt bath at 650°C
- Electrolytic reduction of the oxide fuel matrix in a molten LiCl salt bath seeded with LiO_2 under a voltage applied across electrodes sufficient to convert Li^+ ions to Li^0 at the cathode, which can subsequently reduce U^{4+} to U^0
- Direct electrolytic reduction of U^{4+} to U^0 in a molten LiCl salt bath under a sufficiently high voltage

After appropriate head-end treatment and conversion of non-metallic fuels, pyroprocessing should proceed in a manner indistinguishable from application to metal fuels.

2.3.2.2 Pyroprocessing Separation

Pyroprocessing technology being developed in the U.S. employs an electrorefiner with molten chloride salts (LiCl/KCl eutectic) at temperatures of around 500°C as a solvent for used fuel constituents other than cladding and hardware and other insoluble materials.

To accomplish the desired separation of nuisance constituents (principally fission products) from components to be recycled (uranium, plutonium, and potentially other actinides), the irradiated fuel is immersed in a molten salt bath, which serves as the electrolyte for conducting a charge between the negative electrode (cathode) and positive electrode (anode). The used fuel is attached to an anode, and it is dissolved by the electric current. Uranium and other actinides are then plated on the cathode.

Introduction of different cathodes at the right times allows for separation of bulk uranium from plutonium and other actinides as required for the desired fuel product. The other constituents of the spent fuel either remain undissolved (cladding and noble metal fission products), are driven off as volatile gases (noble gases, iodine, C-14), or preferentially partition into the molten electrolyte medium (cationic and anionic fission products).

2.3.2.3 Pyroprocessing Purification/Conversion

The cathodes containing the desired products from the electrorefiner are processed separately to recover entrained electrolyte salt and cadmium, which can be recycled back into the electrorefiner. The uranium metal collected on the solid cathode can be converted and purified for reuse as a feed for fuel manufacturing or re-enrichment or as a waste form for disposal. The mixed U/TRU metal collected in the liquid cadmium cathode can be sent directly for fabrication of metallic fuels or converted into the desired fuel matrix for fabrication of other fuel types. The extent of product purification required for incorporation into new fuel remains unknown, given the lack of industrial scale experience and lack of a specific end use (e.g., as a metallic fast reactor fuel vs. as LWR UOX).

Fission products (Cs, Sr, Ba, Rb) accumulate in the salt electrolyte as chlorides and can be removed using ion exchange on zeolite columns. The cleaned salt electrolyte can then be returned to the electrorefiner for reuse. The FP-loaded zeolite can be combined with glass frit and vitrified for storage and disposal as High Level Waste (HLW).

2.3.2.4 Potential Benefits and Challenges of Pyroprocessing Technology

Although pyrochemical processing is not yet commercially deployed, it is under active development both in the U.S. and in other countries.[13] Pyrochemical processing is inherently limited to small batch operations so a reprocessing plant with a high throughput, e.g., on the order of 1000 Metric Tons of Initial Heavy Metal (MTIHM) per year, would require a large number of separate pieces of pyroprocessing equipment. In-line process monitoring and material accountancy are more difficult for pyroprocessing than it is for aqueous processes such as PUREX; accordingly, this aspect may prove problematic for nonproliferation and security interests.

[13] A number of countries have active programs investigating pyroprocessing technology; these include Korea, Japan, India, and Russia.

An advantage of pyroprocessing is that most pieces of equipment are small relative to corresponding aqueous reprocessing equipment. Therefore, it may require less hot cell space than the PUREX process, having a correspondingly smaller plant construction cost for a given plant throughput. This would allow construction on the reactor site, creating an enclosed recycling facility. Pyroprocessing technology also does not separate plutonium from uranium and other actinides, intrinsically impeding material diversion for proliferation. Another potential advantage to pyroprocessing is that it is expected to produce a considerably smaller volume of waste per unit throughput than aqueous reprocessing and process reagents are more stable than the organic solvents used in aqueous reprocessing. Some risks are also reduced compared to aqueous processes due to the absence of moderating agents (i.e., water).

2.3.3 Other Reprocessing Techniques

There are other reprocessing options being developed that are at various stages of technology readiness:

- Separate U+Pu all together
- Separate U, Pu+U (small amount of U)
- Separate U, Pu, minor actinides
- Separate U, Pu+Np, Am+Cm
- Separate U, Pu+actinides, certain fission products

Additional technologies besides those discussed in the previous paragraphs are also promising for future use. Modifications of the PUREX technology have been developed to optimize the separation of the different components of the fuel, e.g., minor actinides (PNNL, 2012). Other technologies that use the ability of uranium to form volatile compounds are also gaining attention due to the different fuel forms expected in ARs, such as chloride-based volatility (CBV) and the fluoride volatility method (FVM). These technologies could be especially convenient for designs that employ chlorides and fluorides in their fuels.

The CBV process is based on the principle that at different temperatures different UCl_x volatilization products are produced (ORNL, 1964) which can allow the separation of uranium from transuranics and fission products.

FVM can be performed on fused salt fuels or solid powder fuel, and it is based on the different reactions of uranium and plutonium with fluoride (INL, 2019):

- Uranium forms readily volatile hexafluoride (UF_6)
- Plutonium forms volatile PuF_6 and non-volatile PuF_4

FVM was originally designed for fast breeder reactor fuels, and it is re-gaining attention, as well as the CBV process, due to potential simplifying benefits for AR designs that employ fuel dissolved in molten salt.

2.3.4 Direct Reprocessing Products

Given the lack of experience in most advanced fuel cycle concepts, the details of their waste streams are often poorly known. Furthermore, any new waste streams (i.e., not currently managed in existing industrial reprocessing facilities (e.g., La Hague, Sellafield)) will require more money and time for R&D to deploy appropriate waste stream capture and solidification technologies prior to final disposition (NASEM, 2022).

High-temperature gas-cooled reactors using graphite as a moderator will have larger volumes of waste to address. Options for dispositioning contaminated graphite pebbles or hexagonal blocks include either direct disposal (if adequate disposal volume is available) or dramatically reducing graphite volume. Both options require R&D, although development of volume reduction techniques may require more R&D if release of C-14 to the atmosphere or groundwater is to be avoided. Graphite dust from pebble bed reactors will need to be handled during the decommissioning stage, as well.

Sodium-cooled fast reactors require removing contaminants from the sodium. Although some techniques have been developed, none are at a high enough technical readiness level for industrial use. Some fuel is sodium bonded and is unlikely to be suitable for direct disposal due to sodium's pyrophoricity in the presence of water. Techniques to remove the bonded sodium from such fuel are also not yet technically mature.

Molten salt reactors produce radioactive off-gas and spent fuel waste streams. Both require R&D to convert the streams into waste forms suitable for disposal. Converting the radioactive gases into a solid that is strongly resistant to degradation in the presence of groundwater especially requires a significant amount of work (see Section 2.3.4.2 for more details).

2.3.4.1 New Fuel

The fissile feedstock is converted to the appropriate fuel form, which could be:

- UO_2 or MOX $(U,Pu)O_2$ LWR fuel assemblies[14]. The fabrication process for UOX and MOX is essentially the same.
- U or U/Pu nitride fuel.
- TRISO pellets to be incorporated into graphite pellets or prismatic fuel.
- Metallic fuel for various thermal or fast reactors.
- Liquid fuel (molten salts).

For LWRs, the worldwide fuel fabrication capacity significantly exceeds demand at present. Production capacity as of early 2021 is shown in Table 2-2.

[14] Another option would be an oxide fuel containing Th-232 as a fertile species, which also requires fissile material to supply neutrons to convert the Th-232 to U-233.

Table 2-2. World LWR fuel fabrication capacity, MTHM/yr (WNA, 2021b), WNA ©

WORLD NUCLEAR ASSOCIATION

Table 1: World LWR fuel fabrication capacity, tonnes/yr

	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Brazil	INB	Resende	160	120	400
	CJNF Jianzhong	Yibin	800	800	800
China	CBNF	Baotou	0	0	400
	CNNFC	Baotou	200	200	200
France	Framatome-FBFC	Romans	1800	1400	1400
	Orano	Malvési	Under const.		
Germany	Framatome-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	383	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global Nuclear Fuel – Japan	Kurihama	0	620	630
Kazakhstan	Ulba	Ust Kamenogorsk	0	108	200
Korea	KNFC	Daejeon	700	700	700
Russia	TVEL-MSZ*	Elektrostal	1500	1500	1560
	TVEL-NCCP	Novosibirsk	450	1200	1200
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	787	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	Framatome Inc	Richland	1200	1200	1200
	Global Nuclear Fuel – Americas	Wilmington	1200	1000	1000
	Westinghouse	Columbia	1600	1594	2154
Total			**12,645**	**13,913**	**15,476**

* Includes approx. 220 tHM for RBMK reactors

** Includes approx. 200 tHM for AGR reactors

Source: World Nuclear Association Nuclear Fuel Report 2021, Table 8.2

NB the above figures are about 40% above operational capacities, which meet demand.

Reprocessing of used fuels followed by conversion into new fuels for either thermal or fast reactors requires multiple steps. For example, in PUREX and similar processes using nitric acid, the stream containing the fissile components undergoes purification and conversion prior to being formed into new U/Pu oxide pellets to be used in either thermal or some fast reactors:

- Purification: Additional solvent extraction steps with some modifications or substitutions of reagents.
- Conversion: Several methods are available for conversion of Pu or U nitrate solutions to final products, usually an oxide, including thermal denitration (Uranyl nitrate is converted to UO_3 by denitration at elevated temperature) or calcination of loaded ion-exchange resins (Plutonium nitrate is precipitated by oxalate or peroxide and calcined to PuO_2).

See Section 2.3.2.3 for a description of the pyroprocessing purification and conversion processes.

2.3.4.2 Waste Streams and How They Are Converted to a Disposable Waste Form

PUREX Process

For the PUREX process, there are major aqueous and organic waste. Additional gaseous waste streams are produced during initial fuel segmentation and dissolution in nitric acid. High-, Medium- and Low-Level liquid waste streams are produced. The first cycle extracts the majority of the U and Pu from the nitric acid solution. The remaining solution is HLW that includes the majority of the fission products. Uranium is then partitioned from the plutonium in a second column. Additional extraction and re-extraction steps for both the U and Pu streams creates medium-activity waste streams. Washing of the solvent used in these extraction/re-extraction steps creates LLW streams. All of the waste streams require solidification prior to disposal. HLW is generally dried, calcined, then mixed with glass frit to form a HLW glass. HLW glass has been tailored to have a low leach rate when exposed to water (WNA, 2023b).

The amount of HLW, LLW and GTCC waste produced per metric ton of heavy metal (MTHM) using the PUREX process was estimated in (EPRI, 2014):

- 0.0616 MT HLW liquid per MTHM
- 0.283 MT vitrified HLW per MTHM
- 0.156 m^3 vitrified HLW per MTHM
- 0.190 m^3 Greater-Than-Class-C (GTCC)[15] waste per MTHM
- 8.76 m^3 LLW per MTHM

[15] GTCC is a U.S. Nuclear Regulatory Commission term. Usually, GTCC can be considered one type of "Intermediate-Level" waste – a class used more commonly outside the U.S.

When considering reprocessing for advanced fuel cycles, NEA (2006) estimated the amount of waste generated by waste class for various reprocessing plants. For example, the amount of LILW-SL, LILW-LL and HLW generated by an aqueous reprocessing plant was assumed to be 1.21, 0.8and 0.128 m^3/MTHM, respectively. Similarly, for various pyrochemical reprocessing technologies, the same report estimated ranges for each of the three waste classes to be 0, 2.69 to 2.9 and 0.15 to 0.54 m^3/MTHM, respectively. This report also reports estimates of the amount of waste for the three waste classes for additional fuel cycles using alternative reprocessing technologies. Uncertainties in these numbers are large "…due to the fact that the amount of secondary waste produced depends not only on the technology used, but also on the composition of the spent fuel treated and on the level of optimization in the process" (NEA, 2006).

Pyroprocessing Products

Treatment and waste form options for pyroprocessing technology are described in (INL, 2015) and shown in Figure 2-4. This report was based primarily on research in the United States and the South Korea. The U.S. approach immobilizes spent electrolytic salt containing the fission products into a ceramic waste form while the contaminated cladding hulls and metallic waste are converted into a metallic waste form. The South Korea process is focused on product recycle and minimizing waste volume by segregating fission products from various process streams into separate waste forms. Thus, both salt recycle and fission product loading in the final waste form are higher. Waste minimization is partially accomplished by dechlorinization of the waste salts. There are six major pyroprocessing waste streams: (1) contaminated fuel assembly hardware; (2) fuel cladding; (3) head-end off-gas treatment filters; (4) LiCl salt waste from oxide reduction; (5) metallic waste from electrorefining; and (6) eutectic LiCl-KCl salt waste from drawdown processes.

For off gases, if a high temperature head-end treatment process is used, then an off-gas trapping and solidification process for volatile fission products such as Cs, I and Tc is imperative. In South Korea, the Korean Atomic Energy Research Institute (KAERI) uses a fly ash filter to capture Cs, a silver ion-exchanged zeolite for I and a calcia filter for Tc. Solidification methods for these are still under development. Since I-129 often is the largest contributor to dose rate to humans living downstream of a geologic disposal facility, long-term isolation in a robust waste form is important. At present, the silver ion-exchanged zeolite filters have two major drawbacks: cost, and partial physisorption of iodine that is easily desorbed.

For salt wastes, immobilization directly into glass-bonded sodalite or potentially a tellurite glass is possible.

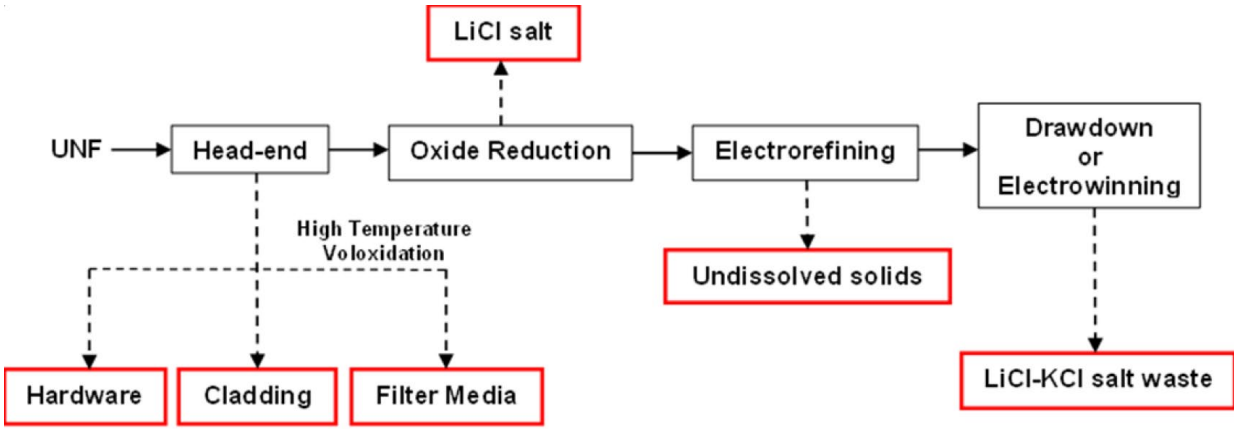

Figure 2-4. Pyroprocessing process diagram showing the six major waste streams (INL, 2015)

3 HISTORY AND CURRENT USE OF REPROCESSING RELATED TO COMMERCIAL POWER PRODUCTION

3.1 History of Reprocessing

Early use of reprocessing was during World War II and in the decade thereafter was almost exclusively for use in producing nuclear weapons material. Later, reprocessing for use in commercial nuclear reactors came to the fore. This section is a brief history of the development of reprocessing.

3.1.1 1940s to 1960s

Initial use of reprocessing occurred in the United States during WWII using pyrochemical and precipitation processes (IAEA, 2008b). Separation methods then changed to hydrometallurgical solvent extraction for plutonium from low burnup uranium reactors (WNA, 2020). Solvent extraction processes were better suited for continuous, remote separation into three streams: uranium, plutonium and fission products plus minor actinides. The early solvent extraction process was optimized for maximum efficiency and evolved into what is called the PUREX process discussed in Section 2 and elsewhere.

The first commercial use of reprocessing was in the 1960s at the EUROCHEMIC plant in Belgium (IAEA, 2008b). The Magnox plant in the UK used the PUREX process and operated from 1964 to 2022 had a processing capacity of 1500 MTHM/yr for the metal Magnox fuel elements in UK nuclear plants (WNA, 2020).

In the United Kingdom, the B205 Magnox Reprocessing Plant began operations to reprocess its Magnox fuel (natural uranium fuel, graphite-moderated, carbon dioxide gas-cooled). Although scheduled to cease operations in 2021 after reprocessing the last of the Magnox fuel (IFPM, 2020) it has continued operations into 2022 (ENS, 2022).

The first reprocessing plant in France was UP1 located in Marcoule. It began operations to reprocess fuel from its gas-cooled natural uranium graphite reactors (GCRs). The plant was shut down in 1998 (NEA, 2008a).

The La Hague UP2-400 reprocessing plant was commissioned in 1966 for military production of plutonium using the PUREX process. In addition to domestic use, it has and still does reprocess commercial UNF for the international market. There are two reprocessing facilities at La Hague, UP2 and UP3 that has a combined processing capability of 1700 MTHM per year. La Hague is still in operation.

3.1.2 1970s

Reprocessing for military purposes was underway by the 1950s. Commercial reprocessing in Russia started in 1977, with two sites dedicated to uranium and plutonium reprocessing: Mining and Chemical Combine (MCC) in Zheleznogorsk and Mayak Production Association in Ozersk. Rosatom announced to fully close the fuel cycle by 2030, while in 2011 only approximately 16% of the Russian used fuel was reprocessed, mainly from VVER–440s, BN-600, research reactors, and naval reactors (WNA, 2021e).

After the 1976 oil crisis, the French La Hague UP2 plant was put into use for reprocessing of commercial UNF. In 1994, the UP2 plant was upgraded from 400 MTHM to 800 MTHM per year (NEA, 2008a).

Starting in 1977, the Japan Atomic Energy Agency operated a 90 MTHM/yr pilot reprocessing plant at Tokai. By the time of its closure in 2014 it had reprocessed 1140 MTHM from some of its BWRs, PWRs as well as its Advanced Thermal Reactor (heavy-water moderated, light-water cooled) (WNA, 2021c).

3.1.3 1980s

By the 1980s, it became clear that development of nuclear energy worldwide would be slower than thought previously in the 1960s and 1970s. Furthermore, implementation of fast reactors was postponed in some countries. Nevertheless, several countries including France (MOX fuel fabrication), India (U recycling in PHWR fuel), Japan (Tokai reprocessing plant), Russia (U recycling in RBMK fuel) and the UK (continued reprocessing of MAGNOX fuel) continued to use and improve PUREX technology (IAEA, 2008b).

In 1989, an additional reprocessing plant at La Hague, UP3 began operation to reprocess foreign UNF. Together, the UP2 and UP3 plants at La Hauge have an annual capacity of 1700 MTHM (NEA, 2008a).

3.1.4 1990s

The Thermal-Oxide Reprocessing Plant (THORP) was commissioned in the UK in 1994 with an annual capacity of 600 MTHM. Approximately 60% of the nuclear feedstock reprocessed at THORP was domestic in origin. The loss of non-UK contracts made THORP economics unfavorable such that the plant closed in 2018. By then THORP had reprocessed over 9000 MTHM from 30 customers in nine countries (WNA, 2021d).

3.1.5 2000 to Present

In China, a pilot reprocessing plant entered hot commissioning in 2010 with the intent to reprocess about 50 MTHM of used fuel (WNA, 2021a).

The Rokkasho reprocessing plant in Japan has been completed, although difficulties with the HLW glass melter and shifting politics in the wake of the 2011 events at Fukushima Daiichi have delayed its operation for over 25 years from the initial plans (EPRI, 2022b).

See Appendix B for information on present and past reprocessing facilities worldwide and the amount of used fuel processed.

3.2 Survey of Reprocessing in Various Countries

The most common reprocessing policies across the globe are either to not reprocess ("once-through" fuel cycle) or "wait and see". For those countries with existing reprocessing facilities, the dominant reprocessing technology in use today is PUREX that separates U and Pu. Use of PUREX in LWRs requires reprocessed uranium (RepU) to be re-enriched whereas plutonium can proceed directly into MOX fabrication. Separation of U and Pu streams resulting in a pure Pu stream is widely considered a proliferation risk.

3.2.1 United States

Reprocessing policy in the United States has undergone multiple shifts. During the 1960s when the majority of LWRs in the U.S. were being designed, it was assumed that reprocessing of used fuel would occur such that the spent fuel pool capacity was limited – on the order of five years of volume.

In the early 1970s a reprocessing plant in South Carolina (Barnwell) was under construction. However, the U.S. Nuclear Regulatory Commission (NRC) required the Barnwell facility be backfitted to some extent such that the cost of completing the facility would be increased. At roughly the same time (1976) the President Ford Administration decided to no longer allow reprocessing for non-proliferation reasons. Although the ban on reprocessing was lifted in the early 1980s in the Reagan Administration, reprocessing was no longer economically competitive with the existing once-through fuel cycle.

In about 1990, the idea that reprocessing could have a benefit for waste disposal was being touted. At the request of the DOE Secretary of Energy, EPRI and the National Research Council were asked to address this potential benefit. EPRI determined that there would be limited benefit to disposal: "The policy would likely incur a large cost penalty, encounter major institutional difficulties, multiply licensing difficulties, and amplify political and public opposition to the nuclear power program as a whole" (EPRI, 1991). The National Research Council (NASEM, 1996) reached a similar conclusion:

- "None of the … system concepts reviewed eliminates the need for a geologic repository. DOE should continue efforts to develop a geologic repository for spent LWR fuel."
- "The current policy of using the once-through fuel cycle for commercial reactors, with disposal of the spent fuel as HLW, should be continued."
- Rather, a U.S. R&D program "should focus on the factors that strongly influence fuel-cycle economics, especially the costs of reprocessing spent LWR fuel, minimization of long-lived radionuclides to secondary wastes in the reprocessing cycle, and on the need to reduce the possible increase in proliferation risks that could result from the commercial use of plutonium in recycled fuels."

In 1993, again due to non-proliferation concerns by setting an example, the Clinton Administration once again shifted back to a reprocessing ban: "The United States does not encourage the civil use of plutonium and does not itself engage in plutonium reprocessing" (White House, 1993). The Administration did commit to meet nuclear cooperative agreements with countries in Western Europe and Japan even though those countries were reprocessing or using reprocessed plutonium (Andrews, 2008). In the early 2000s the G.W. Bush Administration changed the policy again by supporting R&D for the development of advanced reprocessing techniques that would be more resistant to proliferation. The U.S. Department of Energy launched the Advanced Fuel Cycle Initiative (AFCI) followed a few years later by the Global Energy Nuclear Partnership, GNEP (see Section 6.1 for a description of these two programs). However, in 2009, the Obama Administration cancelled the parts of the GNEP program related to development of advanced reprocessing "because it [was] no longer pursuing domestic commercial reprocessing, which was the primary focus of the prior Administration's domestic GNEP program" (DOE, 2009).

WNA (2020) summarized the current state of reprocessing in the U.S.:

> In the USA, no civil reprocessing plants are now operating, though three have been built. The first, a 300 t/yr plant at West Valley, New York, was operated successfully from 1966-72. However, escalating regulation required plant modifications which were deemed uneconomic, and the plant was shut down after treating 650 tonnes of used oxide and metal fuel using the Purex process. The second was a 300 t/yr plant built at Morris, Illinois, incorporating new technology based on the volatility of UF6 which, although proven on a pilot-scale, failed to work successfully in the production plant. It was declared inoperable in 1974. The third was a 1500 t/yr Purex plant at Barnwell, South Carolina, which

was aborted due to a 1977 change in government policy which ruled out all US civilian reprocessing as one facet of US non-proliferation policy. In all, the USA has over 250 plant-years of reprocessing operational experience, the vast majority being at government-operated defence plants since the 1940s.

The U.S. also attempted to construct a MOX fuel fabrication facility to use defense-related plutonium that the U.S. considered excess to defense needs. This MOX Fuel Fabrication Facility (MFFF) had an initial (2002) cost estimate of $1 billion. However, by 2018 with the MFFF still under construction and significantly over budget, DOE cancelled the project (Perry, 2019). The current approach to disposition of excess military Pu is "dilute and dispose" such that no reactor use will be made of this Pu.

The MFFF was designed specifically for military-grade plutonium rather than for commercial-grade plutonium[16]. Had such a facility been successfully completed, it could have led to use of MOX reprocessed from used UOX produced in commercial reactors – once a commercial reprocessing facility was built. Although no such reprocessing facility currently exists in the U.S., the existence of a MOX fabrication facility that could use commercial-grade plutonium could have spurred more interest in a reprocessing facility. Funding for such a mixed-use facility would have needed to come from sources in addition to the NNSA. However, given the large cost increases in the MFFF it is likely that the project would have been canceled anyway.

3.2.2 France Reprocessing

France has taken a very different approach to nuclear power and reprocessing than have other countries such as the United States. The approach in France to pursue nuclear power and reprocessing in a major way was prompted by the Oil Crisis and OPEC Embargo of 1973 (Giraud, 1983). Energy production shifted over the next few decades from about 75 percent dependence on oil to about 75 percent dependence on nuclear energy.

One of the main reasons why France has been so successful in the expansion of nuclear energy and reprocessing is that a single electric utility, Electricité de France (EDF), owns and operates 100% of the nuclear power plants. Furthermore, EDF only operates a handful of different PWR plant types (900 MWe, 1300MWe and 1450MWe) that takes advantage of the benefits of standardization and design re-use.

The La Hague reprocessing plant was commissioned in 1966 for military production of plutonium using the PUREX process. After the 1976 oil crisis, the plant was put into use for the reprocessing of commercial UNF. In addition to domestic use, it has and still does reprocess commercial UNF for the international market. There are two reprocessing facilities at La Hague, UP2 and UP3 that has a combined processing capability of 1700 MTHM per year (Greneche, 2010). La Hague is still in operation albeit at less than 100% capacity. Pu and U are extracted using the PUREX process

[16] Commercial-grade plutonium has higher radiation and thermal source terms than military grade. This would have required a modification of a military-grade plutonium-only MOX fabrication facility.

and are used to fabricate mixed oxide (MOX) fuel. As of 2020, over 35,000 tons of used fuel have been processed, with more than 8,000 MOX fuel assemblies produced to be used in French plants (Morel and Salvatores, 2020). Additional R&D is on-going to demonstrate variations of the PUREX process.

EDF plans to store RepU for up to 250 years, considering it a strategic reserve. As of 2020, La Hague is reprocessing roughly 1100 MTHM of used fuel annually. This produces 11 MT plutonium, which is almost immediately converted to MOX, and 1045 MT RepU for long-term storage as an oxide. EDF has also demonstrated the ability to re-enrich RepU for use in one of EDF's power plants (WNA, 2020).

3.2.3 Canada Reprocessing

The current Canadian policy regarding reprocessing clearly emphasizes non-proliferation:

> Reprocessing, the purpose of which would be to extract fissile material from nuclear fuel waste for further use, is not presently employed in Canada, and so is outside the scope of this Policy; if ever brought forward, the radioactive waste from such a project would fall within the scope of this Policy. Reprocessing in Canada would require consideration of all relevant factors by the federal government prior to its deployment, including ensuring the health, safety and security of people in Canada, and compliance with non-proliferation safeguards and international treaties. The government of Canada remains deeply committed to the 1970 Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which remains the only legally binding global treaty promoting nuclear non-proliferation and disarmament (Government of Canada, 2023).

However, in early 2021, the Ontario Power Generation (OPG) Centre for Canadian Nuclear Sustainabiliy (CCNS) and Moltex Energy announced a collaborative project "to demonstrate the technical viability of recycling used fuel from CANDU reactors" (WNN, 2021). OPG's interest is to "reduce its environmental footprint" via the continued use of nuclear power. Moltex's motivation is for reprocessing to support its WAste To Stable Salt (WATSS) vision. Moltex is developing a Stable Salt Reactor – Wasteburner (SSR-W) that is based on it Stable Salt Reactor technology. Moltex is considering building a SSR-W and a WATSS facility at the Point Lepreau site in New Brunswick with an anticipated start date in the early 2030s (WNN, 2021).

3.2.4 China Reprocessing

China's reprocessing policy is part of its larger nuclear power program with the following goals to achieve a closed fuel cycle (Zhang, 2021):

1. Increase uranium resource utilization
2. Increase energy security
3. Reduce the disposal volume required
4. Minimize waste radiotoxicity
5. Reduce the amount of fuel in reactor spent fuel pools

Commercially, various PWR designs are being used in China. As of late 2015, China estimates it will have 23,500 MTHM of used fuel by 2030 of which 15,000 MTHM will be in dry storage. When China reaches a nuclear power production capacity of 50GWe, it expects to be discharging about 2000 MTHM of used fuel per year.

China considers establishing significant domestic reprocessing capability as important – both for managing its domestic used fuel and for part of its plans to sell reactors abroad. To that end, CNNC Ruineng Technology Co, Ltd was established by the China National Nuclear Corporation (CNNC) in November 2011. This company is to industrialize reprocessing and MOX production as well as management of used fuel.

A pilot reprocessing plant entered hot commissioning in 2010 with the intent to reprocess about 50 MTH/yr. From 2013 to 2015. Another 200 MTHM/yr reprocessing facility is under construction with a planned start date of 2025 (WNA, 2021a).

Initially, an 800 to 1000 MTHM/yr commercial reprocessing plant was to be built using Chinese technology by 2020. However, a series of agreements with Areva (now Orano) were made to construct and operate an 800 MTHM per year reprocessing facility using technology based on the existing La Hague plant. The completion date is targeted for 2030. CNNC will construct the plant with technical input from Areva, and Areva will operate it. As part of an earlier 2015 agreement between CNNC and Areva, the construction cost was estimated to be CHY 100 billion (~USD15.7 billion). In addition, a 3000 MTHM used fuel dry storage facility is to be constructed at the same location. Eventually, the storage capacity may be increased to 6000 MTHM. A MOX production facility might be constructed at the same site. To match anticipated nuclear growth, it is estimated that additional 800 MTHM/yr reprocessing plants will have to be constructed every ten years.

Siting the first production plant has not been without political issues. Initially a site well inland from most of the reactors located in Eastern China was chosen. In 2016, a site in Jiangsu province on the coast was proposed to allow for sea transport of used fuel to the site. However, in August of 2016 public protests resulted in the local government retracting support for that proposal.

In the longer term, use of some reprocessed uranium is also planned for CANDU reactors that are under development. China is also supporting domestic RD&D for a few advanced reactor concepts including HTGR using TRISO fuel, MSR using TRISO fuel, sodium-cooled fast reactor, and thorium molten salt breeder reactor technologies (WNA, 2021a).

3.2.5 India Reprocessing

From the 1950s, India has had a relatively stable strategy for nuclear power in its country that includes the use of reprocessing: (1) use domestic uranium in heavy water reactors using natural uranium; (2) reprocess to use Pu in fast breeder reactors; and use Pu to fuel a thorium fuel cycle to breed U-233. One likely leading reason why India is considering a thorium fuel cycle is that India possesses about one third of the global supply of Th (NASEM, 2022).

At present, only use of U in heavy water reactors has been achieved. India has two reprocessing facilities at Tarapur and Kalpakkam – each with an annual capacity of roughly 100 MTHM. At its ~2021 annual capacity of approximately 115 MTHM per year, India produces about 400 kg Pu per year. The reprocessed Pu could be used for weapons. However, as a result of a 2010 U.S.-India agreement, India plans to build two larger reprocessing facilities that would be placed under IAEA safeguards (WNA, 2023a).

3.2.6 Japan Reprocessing

Japan has been reprocessing its fuel to produce MOX to be used as fresh fuel in some of the reactors in Japan. From 1977 until 2006, a 90 MTHM/yr reprocessing plant was in operation at Tokai Mura. A total of 1140 MTHM of used fuel from BWRs, PWRs and its heavy water-moderated, light water-cooled Advanced Thermal Reactor (WNA, 2021c) (JAEA, n.d.) was reprocessed in this way.

Spent fuel was sent to France and the UK for reprocessing until 1999, when the shipments were discontinued as Japan implemented a plan to reprocess all the fuel domestically. Currently, fuel is stored at plant sites waiting for the completion of a domestic reprocessing plant at Rokkasho. The 800 MTHM/yr Rokkasho plant is based on the technology used at La Hague (Orano) in France. It was initially planned to be completed in 1997, but due to the delays, operation is expected to start in the next few years. As of August 2020, the cost estimate for the complete Rokkasho lifecycle (through decommissioning) had risen to ¥ 13,900 billion ($130 billion) (Nuclear Engineering International, 2020).[17] The startup of the MOX plant is now delayed until 2024 (JNFL, 2022). A geological storage site is planned to start operation in 2035 (EPRI, 2022b).

[17] Japan enacted a Spent Fuel Reprocessing Fund Act in 2016 that includes a plan for funding and implementing used fuel reprocessing (METI, 2016).

Due to the March 2011 event at Fukushima Daiichi, the Japanese government has scaled back its plans for electricity production from nuclear from 30% down to 20-22% by 2030. The government did not, however, abandon its plans for reprocessing 100% of its spent fuel since Pu is considered an asset by the Japanese utilities. NASEM (2022) notes that if Japan were to abandon reprocessing, "the utilities' balance sheets would then have to book spent fuel as a liability, potentially tipping some utilities into bankruptcy unless the government bails them out". Maintaining a reprocessing policy also supports a commitment to communities around nuclear plants and the future Rokkasho reprocessing facility that used fuel would eventually be moved as Japan closes its fuel cycle. However, this step in the fuel cycle is now not anticipated until after 2050 (Toki and Pomper, 2013).

3.2.7 South Korea Reprocessing

South Korea has currently an open fuel cycle. The spent fuel is stored in spent fuel pools waiting for the construction of a centralized interim storage facility, which is planned to be in operation by 2035. In the meantime, R&D is ongoing to demonstrate engineering-scale pyroprocessing to optimize the spent fuel to be stored in the storage facility (IAEA, 2021b). South Korea is one of the leaders in the development of pyroprocessing technology.

3.2.8 Russia Reprocessing

Commercial reprocessing in Russia started in 1977, with two sites dedicated to uranium and plutonium reprocessing: Mining and Chemical Combine (MCC) in Zheleznogorsk and Mayak Production Association in Ozersk. The Ozersk plant that reprocesses oxide fuel has an annual capacity of about 400 MTHM, which has been primarily used for VVER-440 fuel from not only Russia, but also from Hungary and Ukraine. A much larger (ultimately 3000 MTHM per year) plant at Zheleznogorsk is under construction. The first 70 MTHM/yr facility is planned for operation in 2025 with another 800 MTHM planned for 2028 (WNA, 2020). Also located at Zheleznogorsk is a Pilot Demonstration Center to develop advanced reprocessing for both thermal and fast reactors (Nuclear Engineering International, 2017).

Russia also has significant experience operating several sodium-cooled fast reactors:

- BN-350 (350MW_{th}) from 1973 to 1999
- BN-600 (600 MW_e) since 1981
- BN-800 (800 MW_e) since 2015

Rosatom announced to fully close the fuel cycle by 2030, although in 2011 only approximately 16% of the Russian used fuel was reprocessed, mainly from VVER–440s, BN-600, research reactors, and naval reactors (WNA, 2021e). Russia is proceeding with other projects:

- BN-1200 (1200 MW_e) sodium-cooled fast reactor. Construction is planned to start in 2030
- SVBR-100, a lead-bismuth-cooled fast reactor
- Molten salt reactors
- Development of demonstration-scale complex consisting of a 300 MW_e lead-cooled fast reactor fueled by U/Pu nitride. Begun in 2021, this scheduled for completion in 2026-2027 (Podvig, 2021)

A new process for keeping U and Pu together (Regenerated MIXture of U-Pu oxides, REMIX) is being developed in Russia. Uranium-235 levels would be increased by using High-Assay, Low-Enriched Uranium (HALEU, <20% U-235). Pu content would be ~2% resulting in a neutron spectrum similar to that of standard MOX such that reactors using standard MOX could use REMIX without modifications (NASEM, 2022). Six REMIX fuel assemblies have been loaded into a VVER-1000 reactor for five years (Nuclear Engineering International, 2021).

3.2.9 United Kingdom Reprocessing

The United Kingdom has been using reprocessing of spent fuel from Magnox and AGR reactors since the beginning of commercial nuclear power. The fuel has been reprocessed on an industrial scale at the Sellafield site in Cumbria, where approximately 55,000 tons of Magnox spent fuel has been produced since 1964 (NDA, 2014) (WNA, 2021f). The initial 20-year operating life of Sellafield was extended to operate until 2022. In 2020 the government decided to halt reprocessing, and on July 17, 2022, the final feed of used fuel was fed into Sellafield's Magnox Reprocessing Plant. Since then, the spent fuel is stored at Sellafield waiting for geological disposal.

Reprocessing of oxide fuels began a the Thermal Oxide Reprocessing Plant (THORP) that had an annual capacity of 600 MTHM. With THORP's international customers cancelling plans to use THORP for reprocessing, the plant was closed in November 2018 for economic reasons.[18] During THORP's lifetime, more than 9000 MTHM from 30 customers had been reprocessed. The THORP spent fuel pool is still being used to store some AGR spent fuel along with fuel from other reactor types pending final disposal (WNA, 2021d).

The UK has the largest amount of separated plutonium in the world. It has about 140 MT of Pu in storage of which 24 MT is foreign owned (IAEA, 2021a). According to (NASEM, 2022), the UK utilities are not interested in using the Pu in their plants, "because U-based fuels are less expensive and U supplies are relatively abundant."

[18] Approximately 60% of the used fuel reprocessed at THORP was from UK nuclear power.

3.2.10 European Union Policy on Reprocessing

As of the beginning of 2023, the European Parliament added nuclear energy to its "Sustainable Finance Taxonomy." The taxonomy is a classification system to determine whether an economic activity is considered environmentally sustainable to guide private investment. It was concluded that "[t]he criteria for the specific … nuclear activities are in line with EU climate and environmental objectives and aim to help accelerate the shift from solid or liquid fossil fuels … towards a climate-neutral future" (ITA, 2022). However, for an EU member state's nuclear program to be considered sustainable, it must meet three conditions:

1. It must have operational final disposal facilities for very low, low and intermediate radioactive waste
2. It must have plans in place for an operational disposal facility for high-level radioactive waste
3. As of 2025, existing and new build projects must use accident-tolerant fuel, which has been certified and approved by the national regulator

It will be difficult to meet all three conditions for most EU member states. Also of note is that there is no condition related to the use of advanced fuel cycles.

4 MAJOR ADVANCED REACTOR TECHNOLOGIES FOCUSING ON REPROCESSING

The lead time to fully transition to an advanced fuel cycle requiring reprocessing is long. NASEM (2022) determined that the transition could take over 25 years:

> "Most of the advanced reactors, especially the non–light water reactors, will confront significant challenges in meeting commercial deployment by 2050. While at least 10 advanced reactor developers currently aim to deploy their technologies by 2050 in the United States, there are no currently operating fueled prototypes of any of these specific advanced reactor designs in the United States; there are, however, some demonstration and commercial units of similar reactor designs in operation internationally. Moreover, the vast majority of advanced reactors are still in the early design phase [in the U.S.]. Depending on the maturity of the technology, advanced reactor developers face a range of challenges to bringing the proposed technologies to commercialization, including little or no direct operational experience of some designs at engineering scale; the lack of adequate capabilities to develop, test, and qualify advanced fuels and materials; and as a result, the potential considerable time for regulatory approval" (NASEM, 2022).

Advanced technologies that do not require reprocessing, such as SMRs using existing LWR technology, will take less time to deploy. NASEM (NASEM, 2022) also notes that funding for the light-water SMRs (lwSMRs) have benefitted from financial support from the government and private investors for over a decade. Table 4-1 provides a brief summary of advanced reactor technologies and their associated fuel forms.

Table 4-1. Selected advanced reactor technologies and their fuel forms

Reactor Designer	Technology	Reactor Power (MWe)	Fuel Form
BWXT	Defense high-temperature gas-cooled microreactor	1 to 5	UN TRISO
BWXT	Commercial high-temperature gas-cooled microreactor	17	UN TRISO
General Atomics	High-temperature gas-cooled fast reactor	50	UO2 (SiC-SiC Clad)
Terrestrial Energy	Molten salt reactor	392	U-bearing Fluoride Salt
GE Hitachi	lwSMR	300	UO2
Ultra Safe Nuclear Corporation	High-temperature gas-cooled micro-reactor	15	UCO TRISO (SiC Compact)

Table 4-1 (continued). Selected advanced reactor technologies and their fuel forms

Reactor Designer	Technology	Reactor Power (MWe)	Fuel Form
TerraPower	Sodium-cooled fast reactor	345	U-Zr
X-Energy	High-temperature gas-cooled reactor	80	UCO TRISO
NuScale	lwSMR	77	UO2
Westinghouse	Heat-pipe micro-reactor	5	TRISO
Kairos	Fluoride-salt-cooled high-temperature test reactor	35th	UCO TRISO
Holtec	lwSMR	160	UO2
TerraPower	Molten chloride fast reactor	n/a	U-bearing Chloride Salt

The applicability of reprocessing for advanced reactor technologies is generally dependent on the neutron spectrum of the reactor, and the fuel form that reactor is designed to use. All reactors can be operated using fuel developed entirely from raw materials, and all reactors could operate using fuel fabricated from entirely recovered (with much additional processing) feedstocks. Reactors using dissolved fuel will require a degree of fuel processing while operating, sometimes referred to as fuel polishing or conditioning. This can also be combined with reprocessing, but may be separate. As a result, it is generally a design choice to determine the degree to which a reactor system can tolerate the constituents of fuel formed from recovered material.

For thermal spectrum reactors, this design constraint often involves the additional neutron poisons of U-234 and U-236 that build up in small quantities in UNF feedstocks, and are recovered alongside the U-235 and U-238, as well as potential minor actinides in plutonium streams, depending on the separations and purification techniques.

For fast spectrum reactors, essentially all constituents can be tolerated as the minor actinides are consumed over time, but fission products would still ideally be removed from any recovered streams.

Fuel form impacts the ability to be reprocessed. Fuel dissolved in a salt or metal is easiest to recover material from, as they conveniently pair to several separations technologies without a commensurate head-end step to convert the fuel into a different form. Metallic fuel, while requiring some form of shearing, is still able to be conveniently reprocessed with the pyroprocessing techniques. Metal-clad oxides are the industry standard for PUREX reprocessing. TRISO fuel is likely the most difficult to reprocess on a commercial scale, due to the design considerations made for fission product retention. As increasingly durable barriers are placed around the fuel, access to that fuel becomes challenged.

5 WASTE MANAGEMENT ISSUES

Wet storage of used fuel in a pool represents the first step in waste management for the vast majority of reactor technologies in use globally. Wet storage periods vary greatly depending on the fuel cycle and intended use (if any) of the used fuel, pool storage capacity, and the availability of alternative storage or disposal options. Operation of a once-through fuel cycle requires some minimum period of storage in wet or a combination of wet and dry configurations until the fuel meets thermal criteria imposed by an existing disposal system or a disposal system becomes available.

The introduction of reprocessing to the fuel cycle can delay or eliminate disposal of used fuel constituents that are subsequently consumed or destroyed via nuclear reaction (fission or neutron capture) or radioactive decay. For some reactor fuels, reprocessing represents a necessary step in used fuel management in that the original irradiated fuel was unstable in wet storage and warranted prompt reprocessing in order to convert the fuel to a more stable form. This was the case for used fuel from the Magnox reactors in the UK. The oxide fuels used in most reactors today are stable under wet and dry storage conditions, and their direct disposal is widely recognized as a safe and effective permanent disposal option.[19] Accordingly, the incorporation of reprocessing is not required for safe and secure management of most nuclear fuel cycles in use today or envisioned in the near future.

The optimization of waste management is achieved by selectively segregating constituents and creating tailored waste forms to match the set of disposition options. However, the actual net benefit depends heavily on the fuel cycle (especially reactor) technologies in use and the value placed on secondary criteria and outcomes, such as non-financial value of recycling for utilizing residual energy content and perceived virtue (i.e., not based on risk reduction) of not disposing of radioactive waste that can be managed through decay in place or transmutation. Although a permanent disposal solution is needed for some form and some amount of waste from every commercial nuclear fuel cycle, regardless of fuel cycle technology, the use of reprocessing can reduce burdens on that disposal solution. In particular, reprocessing could simplify design by reducing the thermal load of the waste, as well as the waste volume and radioactive source term (though these are both less impactful from a design perspective).

[19] An international scientific consensus exists on deep geologic disposal as the preferred method for permanent disposal of used nuclear fuel and high-level radioactive waste from reprocessing with origins in a 1957 U.S. National Academy of Sciences study (NAS, 1957) (NAS, 2001). Moreover, radioelement solubility, not waste form durability, ultimately controls the release of radionuclides from a deep geologic repository to the environment (NAS, 2011).

On the other hand, it is worth emphasizing that reprocessing of used fuel gives rise to additional waste streams that require appropriate management. Some of the resulting solid radioactive waste streams may not have defined disposal pathways either. Other waste streams, such as noble gases, present additional challenges and may require additional RD&D, particularly under tightening regulatory standards for environmental discharges.

5.1 Waste Classification

IAEA developed six classes of radioactive waste as shown in Figure 5-1. This figure also indicates the type of waste disposal required for each class. Except for Exempt Waste, the other five classes of waste require some sort of disposal depending primarily on their source term (activity), but also somewhat dependent on the half-lives of the waste stream. Section 2.2 of (IAEA, 2009a) provides a description of each class:

> 2.2. In accordance with the approach outlined in the Appendix, six classes of waste are derived and used as the basis for the classification scheme:
>
> (1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
>
> (2) Very short lived waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes.
>
> (3) Very low level waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer lived radionuclides in VLLW are generally very limited.
>
> (4) Low level waste (LLW): Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration.

(5) Intermediate level waste (ILW): Waste that, because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of metres to a few hundred metres.

(6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

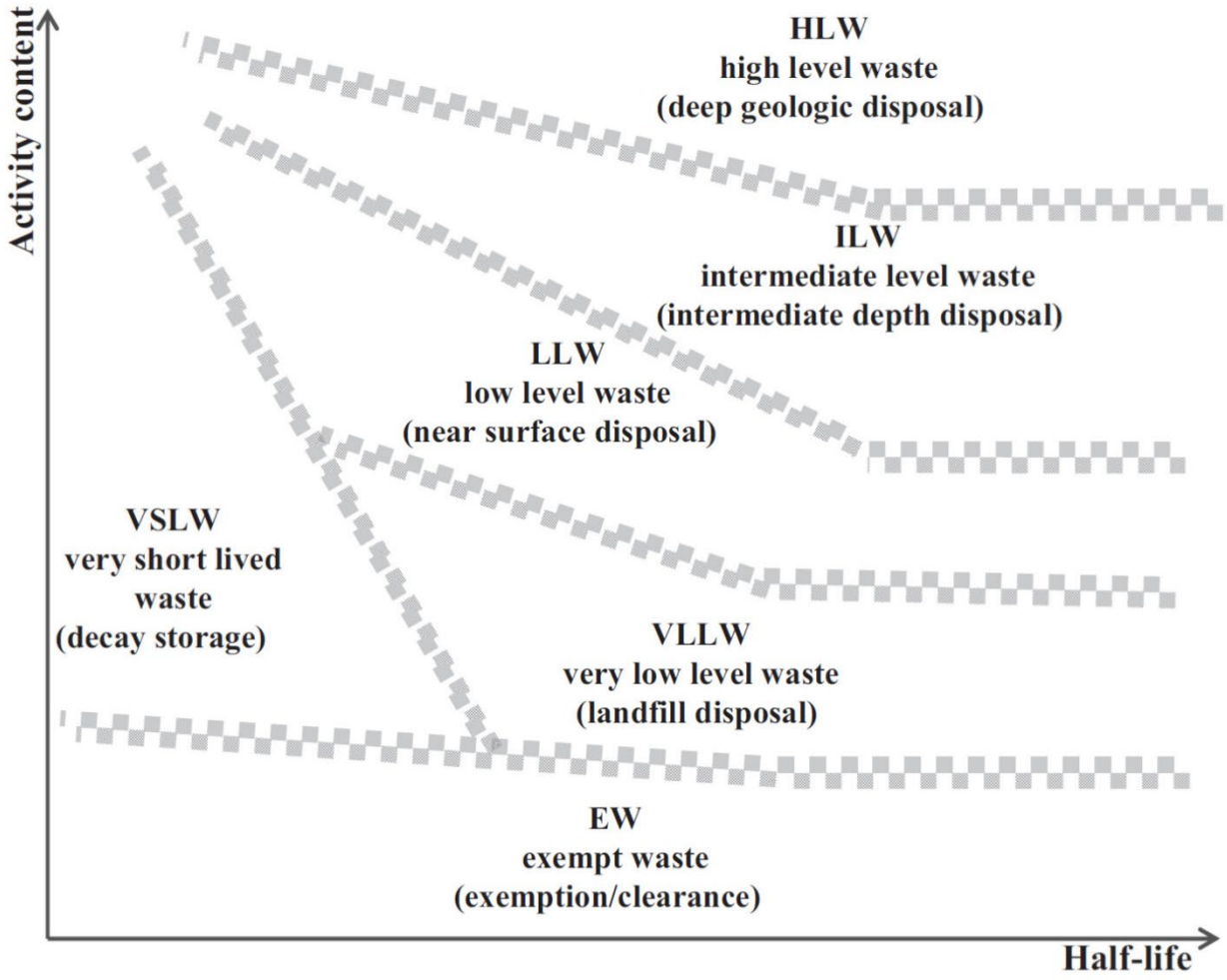

Figure 5-1. Waste classes based on activity content and half-life (IAEA, 2009a)

Examples of waste classification for some waste streams from various fuel cycles:

- VLLW: Mining wastes[20]; some decommissioning wastes
- LLW: Some secondary reprocessing waste streams such as PUREX solvent washing (Figure 2-5); some decommissioning wastes
- ILW: Reprocessing waste streams such as from PUREX secondary extractions (Figure 2-5)
- HLW: Initial aqueous extraction (e.g., PUREX) or electrolytic extraction (e.g., pyroprocessing); volatile fission products; irradiated fuel

The United States classifies wastes differently than IAEA. U.S. regulations do not have EW, VSLW VLLW, and ILW classifications. Both SNF and "IAEA" HLW are classified as HLW in the U.S. Fuel rod cladding hulls are technically not HLW, but are hard to separate from true HLW, so are usually handled as HLW. The U.S. also has classifications for transuranic waste (TRU waste) and Uranium Mining and Mill Tailings. The LLW classification in the U.S. is divided into four sub-classes[21]:

- Class A: Low levels of radiation and heat; no shielding required to protect workers or the public; a rule of thumb is that the Class A wastes should decay to acceptable levels within 100 years.
- Class B: Has higher concentrations of radioactivity than Class A an requires greater isolation and packaging (and shielding for operations) than Class A waste).
- Class C: Requires isolation from the biosphere for 500 years; must be buried at least five meters below the ground surface and must have an engineered barrier (container and grouting).
- Greater than Class C (GTCC): LLW that does not qualify for near-surface burial. This includes transuranics that have half-lives greater than five years and activity greater than 100 mCi/g. As a figure of merit, the IAEA ILW classification is similar to GTCC.

All of the IAEA and U.S. waste streams require solidification prior to disposal.

5.2 Need for Disposal Is Not Eliminated

> "Most importantly, advanced reactors and their associated fuel cycles would not eliminate the requirement for geologic repositories for some radioactive wastes because even advanced reactors will require disposal of radioactive fission products. … The present strategy in the United States of a once-through fuel cycle, if completed, could safely dispose of all spent nuclear fuel from commercial power generation, including fission products and all actinide elements, in a system of one or more deep geologic repositories" (NASEM, 2022).

[20] A small amount of mining wastes may need to be classified as LLW or possibly ILW.

[21] NRC regulation 10 CFR 61.

Every and all fuel cycles operated will generate some quantity of material that is not attractive for use as a feedstock or commodity. While various industries may continue to find uses for fission products that are traditionally considered waste, the need for a disposal solution of some variety will still be required to dispose of the wastes generated that are not recoverable or valuable. There is no economically apparent means of circumventing this necessity.

5.3 Decay Heat Considerations

Total decay heat per GWe-yr was calculated for four advanced reactor fuels in (EPRI, 2022a): sodium-cooled fast reactor (SFR), pebble-bed and prismatic-block high-temperature gas-cooled reactor (HTGR) variants, and a solid-fueled version of the molten salt reactor (MSR)—the fluoride-salt-cooled high-temperature reactors (FHR). For used fuel storage and deep geologic disposal, where most of the decay heat in relevant waste forms will be placed, the main decay time range of interest is between: storage (0 to ~60 years after discharge); disposal (20 to 200 years after discharge). The decay heat per GWe-yr for all the fuel types during the storage period varies by a factor of 2-3; for the disposal period, the highest total decay heat is for PWR fuel (used UOX).

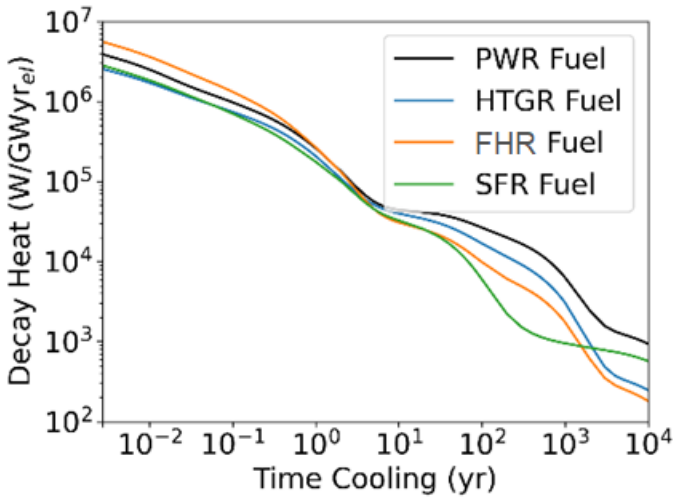

Figure 5-2. Calculated decay heat between advanced reactor types [Figure 7-2 in (EPRI, 2022a)]. PWR: pressurized water reactor (UOX); HTGR: high-temperature, gas-cooled reactor (UCO TRISO); FHR: fluoride salt-cooled high-temperature reactor (UCO TRISO); SFR: sodium-cooled fast reactor (U-Zr)

The total amount of decay heat generated by a particular reactor type is not directly relevant to disposal limitations. More relevant is the amount of decay heat in individual waste containers destined for geologic disposal due to disposal system design temperature limits just outside the waste canisters. The amount of decay heat in a single spent fuel or HLW storage or disposal package is an important factor for those activities. Temperature limits are restricted for all three back-end phases. Temperature limits descend as follows: Storage > Transportation > Disposal. An example of the amount of decay time required to dispose of a canister containing 32 PWR

assemblies containing UOX irradiated to 20, 40 and 60GWd/MTU for various geologies is shown in Figure 5-3. This figure shows that depending on the geology type, a canister containing spent UOX assemblies irradiated to just 40GWd/MTU would take 40, 50, 150 or 200 years for the decay heat to be low enough for direct disposal in unsaturated hard rock, salt, argillite (clay) or crystalline rock, respectively.[22] Thus, much smaller disposal canisters will be required to achieve a reasonable UOX fuel decay time prior to disposal.

An example of the impact of the relative decay heat switching from used UOX irradiated to 50 GWd/MTU in an LWR to MOX generated from a single reprocessing also irradiated to 50 GWd/MTU is shown in Figure 5-3.

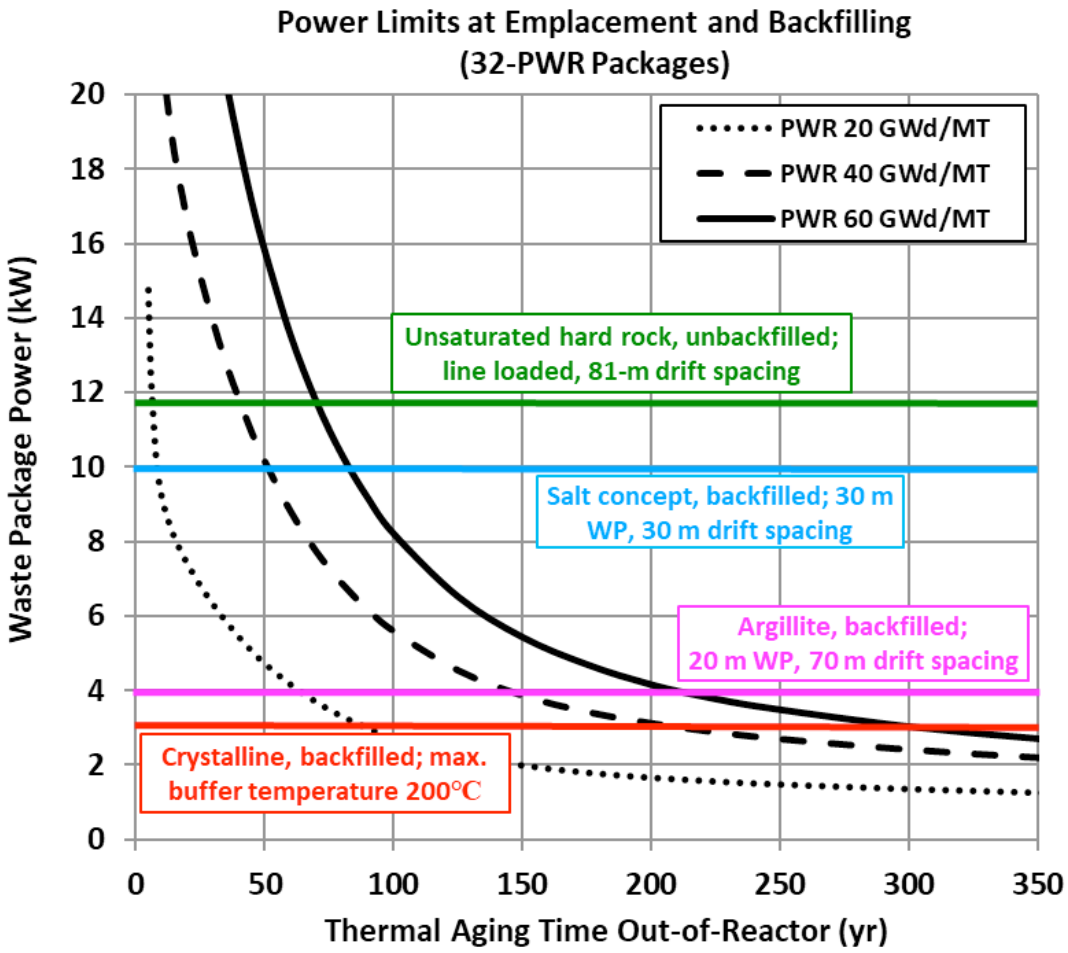

Figure 5-3. Comparison of disposal concept package power limits, with decay curves for 32 PWR fuel assemblies, plotted against time out-of-reactor (SNL, 2021) [after (DOE, 2013)]

[22] The curve labeled "Unsaturated hard rock, unbackfilled; line loaded, 81-m drift spacing" is similar to the candidate disposal facility at Yucca Mountain in the United States.

(EPRI, 2010b) evalutes the decay heat (W/MTHM) for UOX and MOX from the first reprocessing of UOX, respectively, as a function of time. The decay heat for used MOX is approximately three times that for UOX. Thus, the amount of time required for storage, transportation and disposal would increase dramatically for irradiated MOX, or the number of spent MOX assemblies that could be placed in a disposal canister would need to decrease. For example, the number of spent UOX assemblies per disposal canister in the Yucca Mountain repository design would decrease from 24 to approximately eight; the number of spent UOX assemblies per disposal canister for argillite and crystalline repositories would decrease from four to perhaps only one assembly. For the latter case, both the disposal area and the number of disposal canisters would both increase by roughly a factor of three. This would not only increase disposal costs, but could also limit the availability of disposal sites if the area (e.g., acres or hectares) of competent rock of some sites was insufficient for spent MOX disposal. However, used UOX reprocessing followed by conversion to MOX fuel reduces the number of MOX assemblies required for disposal compared to the number of spent UOX assemblies required for disposal. This would partially offset the decay heat prior to disposal penalties from disposal of spent MOX compared to spent UOX.

The fission products Cs-137 and Sr-90 represent the major heat contributors for the first fifty years of storage following offloading. However, with 30-year short half-lives each, decay of Cs-137 and Sr-90 decrease their heat load contribution to less than 50% of the total after 80 years, at which time some of the minor actinides become the dominant heat-producing nuclides (IAEA, 2009c). The heat generated by used fuel and the high-level radioactive waste (HLW) arising due to the minor actinides can vary with the nuclear energy system. Those systems with higher fission and/or conversion efficiencies for heat-generating actinides (e.g., Am-241) have the potential to reduce longer-lived heat-generating inventories under the right conditions.

5.4 Long-Term Radiological Risks from HLW and Disposed Fuel from Advanced Fuel Cycles

> "Radiological risks from disposed waste are dominated by the mobility of long-lived radionuclides and not by the radiotoxicity inventory. … The long-term safety of disposal of actinides in appropriate geologic settings is largely independent of the actinide inventory of the repository, except in the off-normal situation where the geological barrier is bypassed—for instance, by human intrusion. Because the amount of mobile long-lived fission products generated is independent of reactor type, most advanced reactor technologies will have little impact on estimates of long-term repository performance. Key factors for long-term repository performance are the redox conditions of the geochemical environment, waste form stability, groundwater flow rates, and solubility/sorption of radionuclides. A reducing environment is preferred. Advanced reactor technologies will have little or no impact on these factors" (NASEM, 2022).

Individual isotope activities in a HTGR, FHR and SFR-type fuel 200 years after discharge compared to that for PWR fuel are shown in Figure 5-4. For long-term geologic disposal, only a handful of radionuclides matter as the rest will:

- Have such a low activity as to be unimportant
- Have a relatively low half-life compared to the long time scales involved with geologic disposal
- Have a low activity-to-dose conversion factor as to be unimportant
- Move so slowly through the disposal system that they will decay to sufficient extent as to be less important

The dominant radionuclide contributing to very long-term dose rate estimates is usually I-129; in some cases, Tc-99 and Cl-36 also contribute to calculated dose rates. This is because two of these are anionic, which means their sorption onto geologic media is relatively low; Tc-99 is anionic in oxidizing conditions. For the rest of the radionuclides, differences in relative isotopic activities solely with respect to disposal are relatively unimportant.[23] Therefore, comparing I-129 source terms in Figure 5-4, I-129 activities for PWR, HTGR and FHR reactor fuel are similar with I-129 activity from SFR fuel being about eight times higher than PWR fuel. However, it is not SFR fuel itself that would be disposed of. Rather, it would be the HLW from the reprocessed fuel. Nevertheless, the intent of reprocessing any of the fuel types is to transfer as much of the I-129 to a waste stream destined for disposal. Hence, a comparison of I-129 activity in the four types of reactor fuel is useful.

Advocates for some advanced fuel cycles – most of which require reprocessing – often calculate a "radiotoxicity index" for the advanced fuel cycle waste streams compared to spent UOX/MOX from LWRs. This index is calculated by multiplying the isotopic activity in the waste by its dose conversion factor. Usually, the plutonium isotopes contribute the most to this index. Since some of the advanced fuel cycles – particularly those involving reprocessing – specifically target plutonium for removal from waste streams, doing so is considered an advantage for geologic disposal. However, as discussed above, plutonium has a generally low solubility in groundwater and will sorb onto geologic media to such an extent that plutonium almost always contributes little to long-term dose rate estimates. Therefore, radiotoxicity itself is an inappropriate metric for repository performance and risk to the public from waste disposal (Kessler, et al., 2012) (NASEM, 2022).

[23] For shielding, decay heat management and maintaining subcriticality in storage, transportation and reprocessing, additional radionuclides are important.

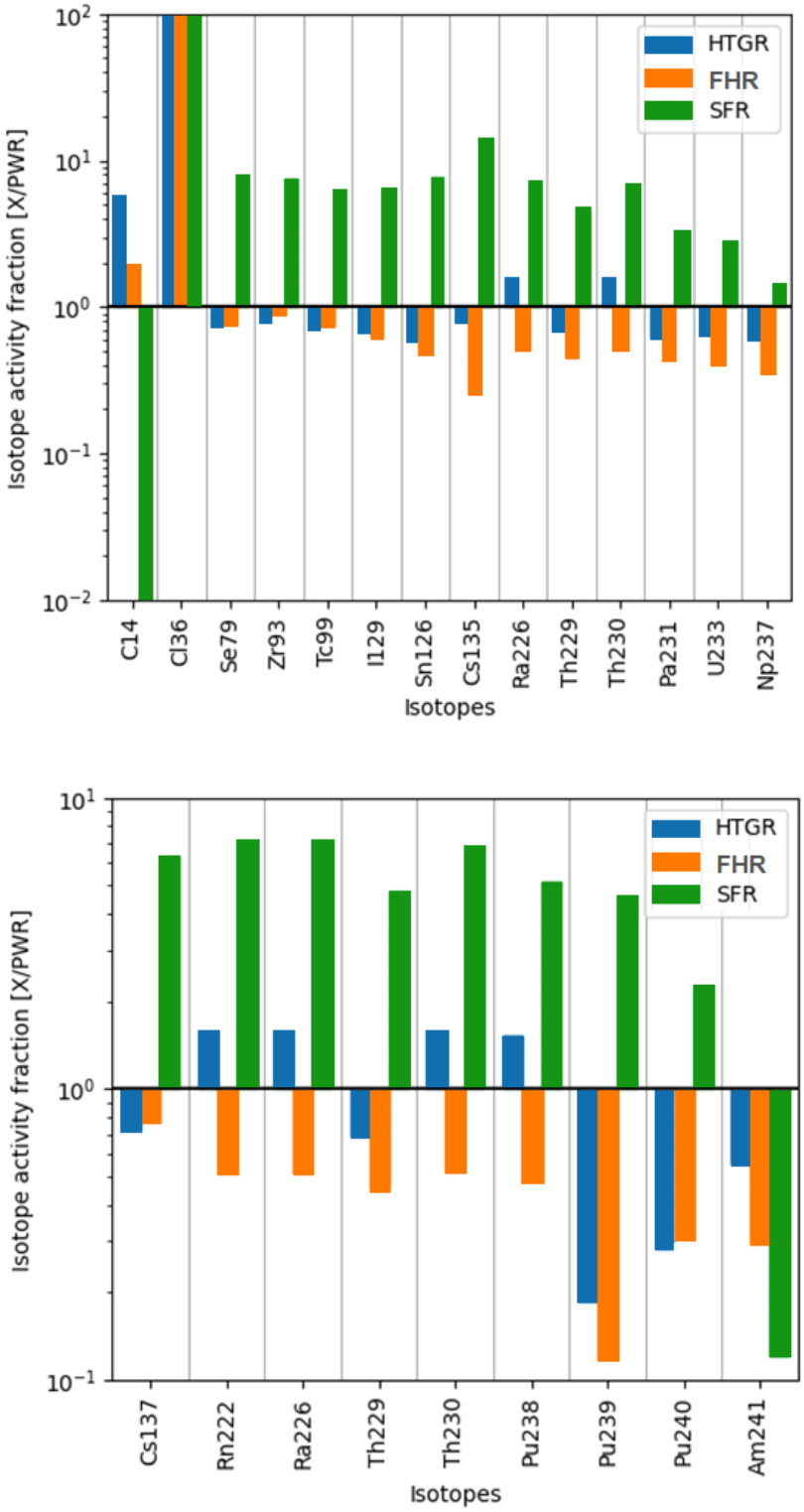

Figure 5-4. Comparison of isotopic composition between three advanced reactors and used PWR fuel after 300 years from reactor discharge [from (EPRI, 2022a). Bars above the centerline represent a relative increase in concentration compared to irradiated PWR fuel, while below represent a relative decrease

IAEA (2008b) notes that significant reductions in discharges to the environment have been achieved by the EU. The La Hague and Sellafield reprocessing plants were contribution about 5% of the industrial radioactive discharges into the North Sea contributing to population dose, whereas oil and gas, and phosphate industrial production were contribution ~35% and 55%, respectively. However, the nuclear industry remains under pressure to further reduce environmental discharges from reprocessing facilities (IAEA, 2008a).

5.5 Buildup of Waste Inventory in Advanced Reactors Eventually Requiring Disposal

Advanced fuel cycles are usually touted as providing for a significant reduction in the amount of waste requiring deep geologic disposal. However, what is usually not taken into account is the inventory of waste that exists in the reactors themselves. Without stating so, if one only considers the waste requiring disposal that is removed from the reactors via normal operations, then one is assuming that the advanced fuel cycle runs at steady state forever.

In reality, one day nuclear power – or at least the particular fuel cycle producing the lower disposal waste stream – will come to an end. At that time, all the waste inventory in the advanced reactors will require disposal, too.

EPRI studied the effect of overall TRU inventory (in-reactor and in disposal) versus time for a fuel cycle involving a mixture of LWRs and fast burner reactors (FBRs) for a zero-growth of installed nuclear capacity scenario in the United States (EPRI, 2008) (Machiels, Massara, and Garzenne, 2009). EPRI assumed a constant installed capacity for an indefinite period of time such that an equilibrium of TRU inventory in the reactors was achieved. Among other goals of the study was to estimate how long it would take for a significant overall reduction in *total* TRU inventory (not just the inventory in the waste, but also that in the reactors) to occur via partial use of FBRs. Table 5-1 shows that the total TRU inventory (both in the waste and in the reactors) for the LWR/FBR fuel cycle compared to a once-through fuel cycle reduces slowly with time. A 50% reduction in TRU inventory would occur after 70 years of the LWR/FBR fuel cycle. To achieve larger reductions in the total TRU inventory, the fuel cycle would need to continue for over 600 and 1300 years to reduce the TRU inventory by 90% and 95%, respectively. Thus, it can be stated that while burner reactors may reduce the TRU inventory destined for disposal while the reactors are in operation, when all the burners are shut down, the total amount of TRU requiring disposal will not be quite so drastically different than in a once-through fuel cycle unless the fast burner fuel cycle is maintained for many centuries. This led EPRI to the conclusion that the waste management benefits of switching to advanced fuel technologies are secondary, and that advanced fuel cycles are not needed for safe disposal of used fuel and high-level waste.

Finally, as discussed in the previous subsection, the mobility of isotopes of a particular element in the disposal system is strongly dependent on its solubility and sorption on geologic media. Essentially all of the TRU elements have low solubility and high sorption in most geologic media. Therefore, reduction of TRU inventory is unimportant with respect to disposal.

Table 5-1. Reduction in TRU inventory as a function of time comparing a LWR/burner to a once-through fuel cycle (Machiels, Massara, and Garzenne, 2009)

Desired TRU Inventory Reduction [%]	Deployment Period to Achieve Inventory Reduction [years]
10	8
25	23
50	70
75	211
90	632
95	1334

Key Technical Point

The waste management benefits of switching to advanced fuel technologies are secondary and that advanced fuel cycles are not needed for safe disposal of used fuel and high-level waste.

6 SURVEY OF U.S. AND INTERNATIONAL RECYCLING AND REPROCESSING R&D ACTIVITIES

6.1 United States RD&D

6.1.1 Advanced Fuel Cycle Initiative (AFCI)

The U.S. desire to avoid separation of Pu from U during reprocessing led to reinitiation of work on used fuel reprocessing R&D in 2002 to develop potential fuel management alternatives. The Advanced Fuel Cycle Initiative (AFCI) program was used by the U.S. Department of Energy to conduct nuclear waste recycling R&D activities. The AFCI program grew out of the Accelerator Transmutation of Waste Program started the 1990s (NASEM, 2022).

DOE (2005) describes the AFCI goals:

> AFCI technology development focuses on reducing the long-term environmental burden of nuclear waste, improving proliferation resistance, and enhancing the use of nuclear fuel resources. The program has one major objective associated with each of these three considerations. The AFCI Program also has a fourth "system management" objective that emphasizes safe and economic nuclear materials management, integrating all of the above considerations (DOE, 2005).

Among other goals for AFCI was to weigh in on whether a second repository would be needed. Part of AFCI activities was to conduct R&D to avoid such a need.[24]

The AFCI considered four fuel cycle strategies:

1. The current once-through strategy used in the U.S. and in most countries.
2. Recycling (via reprocessing and MOX fuel production) into existing thermal reactors. This would require transuranics to go to disposal eventually.
3. Continuous recycle using a combination of thermal and fast reactors. The goal was to minimize TRU requiring disposal.
4. Continuous recycle using solely fast reactors whose goal was to achieve nearly complete use of uranium and TRU.

Of particular relevance is that TRU inventories would be shifted from the waste stream into the reactors themselves. If, in the long term, nuclear energy is replaced by other energy sources, then the fissile material – including TRU – remaining in those final reactors, would require disposal. The actual reduction in TRU inventory depends on the amount of time nuclear energy continues into the future. This is discussed in more detail in Section 5.4 Buildup of Waste Inventory in Advanced Reactors Eventually Requiring Disposal.

[24] Seemingly unrelated to this AFCI effort, DOE has determined that the capacity of the proposed Yucca Mountain disposal site was at least double that of the legal capacity (DOE, 2008).

Global Nuclear Energy Partnership (GNEP)

Initiated in 2007, GNEP was "a comprehensive strategy to increase U.S. and global energy security, encourage clean development around the world, reduce the risk of nuclear proliferation, and improve the environment" (DOE, 2023). The AFCI work was subsumed into the larger GNEP program.

GNEP goals included:

- Reduce America's dependence on foreign sources of fossil fuels and encourage economic growth
- Improve the environment via reduced CO_2 production
- Recycle nuclear fuel using new proliferation-resistant technologies to recover more energy and reduce waste
- Utilize the latest technologies to reduce the risk of nuclear proliferation worldwide

GNEP included a broad implementation strategy:

- A new generation of nuclear power plants in the U.S.
- New recycling technologies
- An aggressive plan to manage spent nuclear fuel in the U.S., including permanent geologic disposal at Yucca Mountain
- Advanced burner reactors
- A Fuel Services program to enable nations to acquire nuclear energy economically while limiting proliferation risks
- Improved nuclear safeguards

The centerpiece of GNEP was that it would work with other nations possessing advanced nuclear technologies to develop new proliferation-resistant recycling technologies in order to produce more energy, reduce waste and minimize proliferation concerns (WNA, 2020). There were 21 member nations participating in GNEP – particularly in the Fuel Services program.

In addition to GNEP goals of reducing dependence on imported fossil fuels and building advanced reactors, GNEP was to develop advanced reprocessing method(s) to avoid separation of Pu from U – starting from the UREX+ process – along with advanced burner reactors (WNA, 2020). To further avoid U/Pu separation, GE Hitachi Nuclear Energy worked to develop a pyroprocessing process to be followed by burning the separated product in their PRISM sodium fast reactor design (NASEM, 2022).

The reprocessing facility envisioned in the core GNEP program would be capable of reprocessing spent fuel from a sodium fast reactor in a "burner" mode (consuming more fissile radionuclides than it produces). DOE envisioned that private industry would operate the sodium-cooled fast

reactors along with the fast reactor fuel production facility and DOE would operate the reprocessing facility. However, the NAS review committee (NASEM, 2008) did not consider the fast tracking of the reactor and processing facilities to full scale deployment as proposed in the GNEP program "credible" without first starting at an engineering scale as the technical and financial risks of jumping straight to full-scale facilities were deemed to be too great.

Regarding the GNEP implementation strategy, a National Academy of Science review of the GNEP program (NASEM, 2008) had the following observations about the program that are relevant to the role of reprocessing:

- "[T]here is no 'silver bullet' that can be built into an enrichment plant or reprocessing plant that can prevent a country from diverting these commercial fuel cycle facilities to non-peaceful use…".
- Regarding the benefits to disposal capacity, "[t]he most significant repository benefits can be achieved by removing the very long-lived minor actinides and recycling them as part of the fuel for fast reactors. To obtain a repository capacity increase ranging from one to two orders of magnitude … it will be necessary to remove and fission through recycle the very long-lived minor actinides." The NAS also notes that additional repository capacity can be achieved by separating the relatively short-lived radionuclides such as Cs-137 and Sr-90 and them storing them until they decay significantly (NASEM, 2008). However, to achieve a significant reduction in these "shorter-lived" radionuclides requires storage times on the order of centuries.
- NAS noted that one of the DOE's GNEP goals was to assure international fuel supply via the U.S. supplying sufficient nuclear fuel cycle services.

In June 2009, the part of the GNEP program involving development of full-scale reprocessing was cancelled in favor of long-term, science-based R&D on advanced fuel cycles and waste management. There was also interest in continuing the Fuel Services program.

Advanced Research Project Agency-Energy (ARPA-E)

In 2007, Congress passed and President G.W. Bush signed into law The America COMPETES Act[25] that authorized the creation of ARPA-E. ARPA-E's mission is to improve economic and energy security of the U.S. Technologies to be funded are to have the following goals:

- Reduce energy imports
- Reduce energy emissions including greenhouse gases
- Improve energy efficiency of all economic sectors

[25] Title 42, Chapter 149, Subchapter XVII of the United States Code as amended by Sec. 5012 of P.L. 110-69 (H.R. 2272), Sec. 904 of P.L. 111-358 (H.R. 5116), and Sec. 10001 of P.L. 116-260 (H.R. 133)

- Provide transformative solutions to improve the management, clean-up and disposal of radioactive waste and spent nuclear fuel
- Improve the resilience, reliability and security of infrastructure to produce, deliver and store energy

The Act also specified that ARPA-E should ensure that the U.S. maintained an international technical lead in developing and deploying advanced energy technologies via:

- Identifying and promoting revolutionary advances in fundamental and applied sciences
- Translating scientific discoveries and cutting-edge inventions into technological innovations
- Accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty

Initial ARPA-E appropriations of $400 million were provided in 2009.

6.2 Survey of U.S. and International Activities to Improve Existing Reprocessing Technologies

6.2.1 Converting UNF Radioisotopes Into Energy (CURIE)

The CURIE Project was initiated within ARPA-E in early 2022 (DOE, 2022a). The purpose of the CURIE project is to support (DOE, 2022b):

> Innovative technologies that enable the secure, economical reprocessing of the nation's LWR UNF could substantially reduce the volume, heat load, and radiotoxicity of waste requiring permanent disposal while providing a valuable and sustainable fuel feedstock for advanced fast reactors. Technical categories identified as the most likely to enable secure, economical reprocessing of UNF to meet these goals include:
>
> - Reprocessing technologies: improvements in preparing UNF assemblies for chemical separations; treatment of gaseous process streams; and separations technologies, such as aqueous separations, pyroprocessing, and fluoride volatility, that significantly reduce waste volumes, improve intrinsic proliferation resistance, and provide AR feedstocks;
> - Integrated monitoring and materials accountancy: improvements in sensor and data fusion technologies that enable accurate and timely accounting of nuclear materials;
> - Facility design and systems analysis: technoeconomic and systems analyses of novel approaches to designing, constructing, and operating reprocessing facilities (e.g., modularization, safeguards-by-design, process intensification), to improve safeguardability, reduce costs, and facilitate siting and licensing of reprocessing facilities.

A total of $48 million in projects related to secure and economic recycle of used fuel were awarded in March 2022 (DOE, 2022a). Another 12 projects were awarded funding by the CURIE program in October 2022 ($38 million total) (DOE, 2022b).

6.3 Survey of U.S. and International Activities to Develop Recycling Activities to Support Advanced Reactor Fuel Cycles

6.3.1 International Projects

IAEA (2008b) summarizes some of the other national and international R&D programs to develop advanced fuel cycles:

- International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)] and the multinational approach (MNA) of the fuel cycle
- GENERATION IV International Forum
- Russian initiative on the creation of multilateral centers for the provision of nuclear fuel cycle services
- R&D undertaken per the French 2006 legislation on the management of spent fuel and nuclear waste
- Fast reactor Cycle Technology development (FaCT) project in Japan

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

Started in 2000 after an IAEA General Conference resolution, one of the "INPRO objectives is to help to ensure that nuclear energy is availble in the twenty-first century in a sustainable manner" (IAEA, 2020). INPRO is proceeding in two phases:

Phase 1: INPRO "developed a methodology for assessing the long-term sustainability of a national or international nuclear energy system. This entailed establishing a set of basic principles pertaining to system sustainability, a set of user requirements in support of each basic principle, and a set of criteria for meeting each user requirement". This work was documented in IAEA-TECDOC-1575/Rev.1 (IAEA, 2008a).

Phase 2: Performance of national and international nuclear energy assessments using the INPRO methodology. Assessments completed by 2009 were published in IAEA-TECDOC-1636 (IAEA, 2009b). Since then, the sustainability assessment component of the INPRO overall methodology was updated (IAEA, 2020).

MICANET (EU)

The objective of Michelangelo Network (MICANET) was "to propose a strategy for the European R&D aimed at keeping the industrial nuclear option open in 21st Century" (European Commission, 2003). Its main goal was to develop the framework for a European

Union partnership with the United States' GEN-IV initiative. The strategy would consider the entire fuel cycle from the front end to final disposal. MICANET were developing criteria for competitiveness and sustainability. Existing R&D facilities across the European Union were compared to the needs defined by MICANET. MICANET and subsequent projects were conducted in the 2002 to 2006 timeframe.

6.3.2 Aqueous Reprocessing Technology R&D as of 2008

The following country-specific aqueous reprocessing R&D as of 2008 was summarized in (IAEA, 2008b).

United Kingdom

- BNFL is developing a de-cladding and dissolution process for direct dissolution of LWR fuel and cladding by contact electrolysis
- BNFL is also investigating conversion of nitrate products from reprocessing using direct thermal denitration

Japan

- Enhancement of the efficiency of material separation and purification, such as:
  - Addition of a crystallization step (JAEA)
  - Direct conversion of nitrates to oxides
  - A study of solvent washing with Butyl Amine compounds

France

- Volume minimization of secondary waste streams (CEA) (e.g. catalytically-mediated denitration of strong nitgric acid solutions)
- Co-extraction of U and Pu maintaining the co-extracted stream into MOX production
- Evolutionary improvement in existing reprocessing capability along with the COEX™ process:
  - Large-capacity reprocessing plant (2000 to 3000 MTHM/yr) such that France could become a "regional center" for reprocessing
  - Co-management of U/Pu streams allowing for new security standards
  - Reprocess a wider range of legacy fuel types including those with a high fissile content
  - Co-locate reprocessing fuel fabrication
  - Reprocessing flexibility (e.g. separation of minor actinides)

Russia

- Direct conversion of nitrates to oxides via plasma chemistry
- Reprocessing optimization, such as:

- Recovery of bulk U followed by U/Pu concentrate for feedstock into fast reactors
- Partitioning fission products and minor actinides followed by solidification in a zirconium matrix
- UNF thermochemical destruction in nitrogen gas, oxidation in NO_2 gas, then extraction from a highly concentrated solution
- UNF thermochemical destruction followed by oxidation and recrystallization, conversion to nitrates to produce concentrated solutions
- U separation via crystallization
- Simultaneous partitioning of U/Pu, TRU, rare earths and Cs/Sr

6.3.3 Non-Aqueous Process R&D as of 2008

The following country-specific aqueous reprocessing processes R&D as of 2008 was summarized in (IAEA, 2008b).

6.3.3.1 Oxide Fuels

Russia

Dimitrovgrad Dry Process (electrowinning): used oxide fuel is powdered, then dissolved in an alkali-chloride mixture (e.g., NaCl-CsCl) at about 630°C. The UO_2 is deposited on the cathode along with noble metal fission products that are subsequently removed by electrolysis. A Cl/O_2 gas is used to form chlorides and oxychlorides of the actinides. The salt is then electrolyzed to remove U/Pu/Np oxides. Electrowinning recovers the minor actinide oxides along with the remaining uranium oxide. The recovered U/Pu/Np oxides are used in new fuel rods.

United States

Work at Argonne National Laboratory: pyroprocessing in a LiCl bath containing 1 wt.% Li_2O all at 650°C. Reduced metals are collected at the cathode. Uranium is recovered in a subsequent electrorefining step. The TRU elements and all but the noble metal fission products are anodically dissolved in the electrorefining process and remain in the LiCl salt. TRU and some of the remaining U is recovered using a liquid cadmium cathode. The oxide fuel reprocessing process (PYROX process) is only at the experimental stage, but shows promise.

South Korea

- Chemical reduction of used UOX fuel using lithium metal. This would decrease the volume of material requiring disposal and could (if allowed in the future) be used in the HYPER partitioning and transmutation system currently under development.
- DUPIC process for use of used fuel from PWRs in CANDUs without chemical processing since lower burnup used PWR fuel contains about 0.6% Pu and 0.9% U-235.

6.3.3.2 Metallic Fuels

United States

Treatment of fast reactor metallic fuels as part of the Integral Fast Reactor development program: fuel pin segments are placed in a LiCl-KCl electrolyte and with a low voltage, the used fuel (except for the noble metal fission products) dissolves in the electrolyte. U is transported to the cathode without much TRU. The TRU can be recovered with the use of a different cathode in a crucible containing cadmium at about 50 vol. percent. The final TRU product is 70% TRU, 30% U and 5% lanthanides. The noble metal fission products are then mixed with the cladding hulls and melted together to form a metallic waste form.

A modified version of the above process is used to reprocess fuel and blanket elements of the Experimental Breeder Reactor II (EBR-II). Given that the process is to be used for waste management, only the uranium is recovered. EBR-II fuel has a U-235 enrichment of 57%, so depeleted uranium is mixed with the reprocessed fuel to achieve an enrichment of less than 20%. TRU and the active metal fission products are left in the electrolyte salt and will be periodically removed and converted into a glass-ceramic waste form. The noble metal fission products are then mixed with the cladding hulls and melted together to form a metallic waste form.

Japan

Similar work as above: actinide/lanthanide extraction in molten chloride and Cd/Bi liquid metal media by electro-deposition and liquid-liquid extraction on UO_2 fuel.

Germany

Similar work with U/Pu extraction.

France

Liquid metal cathodes with reductive extraction processes.

7 EVALUATION OF FACTORS TO BE CONSIDERED WHEN MAKING DECISIONS ABOUT REPROCESSING

7.1 Benefits

7.1.1 Natural Resources Sustainability

Fissile nuclides are necessary to generate nuclear power from fission, and in nature, only U-235 is present in significant amounts, representing 0.71% of the naturally occurring uranium resources. Three additional fissile nuclides, Pu-239, Pu-241 and U-233, can be created in a reactor through neutron capture by the fertile nuclides U-238 and Th-232, respectively, which comprise the bulk of natural uranium (99.28%) and thorium (100%) resources. Thus, U-235, U-238, and Th-232 represent the entirety of terrestrial resources available for all nuclear fuel cycles that rely on fission.

Today, almost all commercial reactors operate with a thermal neutron spectrum: pressurized heavy water reactors, pressurized light water reactors (PWRs), and boiling light water reactors (BWRs). Consequently, they rely primarily on the energy content of U-235 and, to a lesser degree, Pu-239 created from much more abundant U-238 during reactor operation. Therefore, the current nuclear power sector essentially depends on and is limited by the availability of U-235 contained in uranium that can cost-effectively be recovered from available resources (EPRI, 2010c).

Every two years, the IAEA and NEA compile and publish data and estimates on international uranium resources, production, and demand in a report commonly referred to as the “Red Book” (NEA, 2023). The resources are classified based on confidence and knowledge of their existence in traditional economic mineral resources, i.e., Identified Resources and Undiscovered Resources. In addition, other non-traditional sources of uranium can be considered, such as phosphate minerals.

NEA (2023) presents two cases of projections of uranium supply and demand for six permutations of future demand (“High requirements” and “Low requirements”) and uranium for two different production capacities (85% and 100%) based on uranium price (<USD130/kgU and >USD130/kgU). They show that at a uranium price of approximately ~USD130 it is likely that supply and demand will roughly balance through at least 2040.

In terms of natural resource utilization, reprocessing of used UOX fuel and mono-recycling of plutonium as MOX in LWRs provides a 12.5% natural uranium savings. Recycling of reprocessed uranium following purification and re-enrichment (enriched reprocessed uranium or ERU) offers a potential additional natural uranium savings of 9.5%. Additional natural uranium

savings can also be realized through further enrichment of depleted uranium tails. Taken together, these back-end management options have the potential to reduce natural uranium demand by up to a third (EPRI, 2010c).

If the supply of uranium is the primary sustainability concern, then evidence of a continued abundant supply of natural uranium on the world market detracts from motivations to pursue reprocessing for extending uranium supply over the coming decades, i.e., 50–100 years. However, the 10–20% savings potential offered by reprocessing and mono-recycling in LWRs may remain a compelling case for reducing vulnerability to interruptions in external uranium supply. Accordingly, national policies that seek to maximize energy security may trump other important considerations such as economics and waste management.

7.1.2 Waste Reduction

Although the need for disposal cannot be eliminated entirely for any fuel cycle, the introduction of reprocessing to the fuel cycle can reduce and/or delay disposal of used fuel constituents that are subsequently consumed or destroyed via nuclear reaction (fission or neutron capture) or radioactive decay. Section 5.4 discussed the fact that an advanced fuel cycle employing fast burner reactors would need to operate at steady state for multiple centuries before the *total* TRU inventory (waste streams and in the reactors) was markedly decreased compared to a once-through fuel cycle.

7.1.3 Greenhouse Gas (GHG) Emissions Reduction

Nuclear power generates the least amount of CO_2 (eq.) per kW-hr when compared to a variety of alternative energy sources (UNECE, 2021). For nuclear power, the largest proportion of GHGs produced is due to mining operations (over 30%) (UNECE, 2021). Based on a series of assumptions about the evolution of background electricity mixes and industrial processes between 2020 and 2050, nuclear could contribute the greatest reduction in GHGs from electricity production (UNECE, 2021). This remains the case even for coal and natural gas carbon capture technology options. Therefore, if GHG reduction is a major driver, then increased use of nuclear power is a strong option.

7.1.4 National Energy Independence

For countries with limited energy natural resources, use of nuclear power – especially nuclear fuel cycles employing reprocessing to increase the energy availability of natural uranium – could be an attractive option. As discussed elsewhere, some projections of future uranium availability imply that internationally, adequate uranium resources will exist even for many nuclear power growth scenarios. If, however, future uranium resources become limited, then pressure to increase energy extraction via advanced nuclear fuel cycles employing reprocessing will be felt by all countries.

7.2 Challenges

7.2.1 Safeguards and Security

The recovery of residual and in-grown fissile constituents from used fuel also presents nonproliferation and security concerns for their diversion and use in nuclear weapons or an improvised nuclear device by a state or non-state entity. For the uranium-plutonium fuel cycle, the separation of plutonium is generally viewed as undesirable, representing a significant vulnerability for diversion or theft. From this perspective, PUREX and other reprocessing flow sheets that result in complete separation of Pu at some point in the process are frequently dismissed as offering inadequate intrinsic technological barriers to the proliferation/security threat.

An alternative to separation of plutonium as a pure stream is to leave uranium with plutonium during reprocessing. Technologically focused programs and approaches seek to minimize the proliferation and theft risk by favoring certain mixed product streams and facilitating on-stream process monitoring, physical protection, fissile material accountability, and effective administrative controls. However, a DOE-sponsored evaluation found "…only a modest improvement in reducing proliferation risk over existing PUREX technologies, and these modest improvements apply primarily for non-state actors" (BNL, 2009). Additionally, while certain elements of a fuel cycle may offer some benefits in discouraging non-proliferation activities and uses for malicious purposes, these may be offset by the introduction of new challenges and vulnerabilities. For example, when uranium and plutonium are not separated, an additional step in fuel refabrication is required that involves adjustment of the composition of the uranium-plutonium mixture so it is suitable for fuel fabrication.

The constant evolution of alternative proliferation technology routes and security/proliferation threats implies there is no simple technological fix in the near term that will, with confidence, mitigate non-proliferation and security concerns for fuel cycles to be deployed many decades in the future. To be successful, all fuel cycle technologies and options will require effective extrinsic, institutional measures complemented by intrinsic technical fuel cycle attributes and availability of supporting technology (e.g., seals, tracking devices, detectors, and analytical methods).

It should be noted that enrichment technologies and infrastructures are also subject to the same nonproliferation and security concerns as reprocessing facilities. Historically, the cost and scale of enrichment technology needed to produce significant quantities of Highly Enriched Uranium (HEU) provided an effective intrinsic barrier to clandestine development of weapons-grade material. However, continued evolution of existing technology (especially centrifuges) and development of new technologies (e.g., laser-based isotopic enrichment) are reducing the physical size, energy, and feed materials needed to produce HEU. For this reason, non-proliferation and security assessments must consider front-end and back-end fuel cycle technologies in a balanced manner commensurate with the risk they pose.

7.2.1.1 PUREX Safeguards Example (IAEA, 2001)

An example of a safeguards accountancy structure for a PUREX facility reprocessing used LWR fuel (the Rokkasho reprocessing plant, RPP) is found in (IAEA, 2001). See Appendix D for details.

7.2.1.2 Advanced Reactors Safeguards

There are several advanced fuel cycle characteristics that are sufficiently different than LWR technologies, including those using aqueous reprocessing. They can have different mixtures of fissile and non-fissile radionuclides such as:

- High Assay, Low Enriched Uranium (HALEU) that may have U-235 enrichments up to just under 20%
- Different mixtures of plutonium, thorium, U-233 and minor actinides
- The fuel may have a different chemical and physical form than standard UO2 assemblies used in LWRs (e.g., liquid, metal, metal-clad, TRISO)
- Whether the fuel cycles are open or closed (via reprocessing and reuse of some of the separated material)

The National Academy of Science considered non-proliferation implications and security risks for advanced fuel cycles (NASEM, 2022). They note that advanced reactors and their fuel cycles "will have materials that have significantly different characteristics from the current LWR fleet." This would involve potentially new or additional considerations for material accountancy issues with some materials NASEM considered "weapons useable."

The NASEM authors concluded with "findings" and "recommendations" applicable to a U.S. program. The first finding that the NAS committee made regarding the global use of HALEU was that the committee believed it would exacerbate proliferation concerns because the committee considered it a more attractive material for nuclear weapons. Thus, the NAS committee recommended that the appropriate U.S. national organizations should evaluate the proliferation and security risks of the expanded use of HALEU. Also, the committee recommended a similar international effort potentially led by the IAEA.

The second finding was that advanced reactor fuel cycles have a few issues requiring special attention from a safeguards and security perspective. Material accountancy tracking and quantification was considered more difficult molten salt and pebble-bed reactors because unlike solid fuels, these two fuels are mobile, which would require on-line monitoring. Thorium uranium-233 fuel cycles were deemed to have more variants that would require special material tracking considerations. The committee also noted that reprocessing requires monitoring.

Almost all of the advanced fuel cycle safeguards issues are active areas of R&D, or may not pose issues as significant as indicated. In a letter to the NAS, an ANS ad hoc committee disagreed that safeguards issues for advanced fuel cycles were difficult and that some materials would be "weapons useable" (Arndt and Piercy, 2023) showing a differing opinion of the industry.

ANS challenges the positions on nonproliferation taken by NASEM for a variety of reasons. They note that the view of materials being weapons attractive taken by NASEM is primarily based on a single reference using a methodology widely considered by experts within the field to be "a gross over-simplification." The NASEM report assumes that enriched uranium or plutonium can be acquired while downplaying difficulty in using those materials, which can contain many isotopes that are detrimental for the purpose.

There is further disagreement by ANS with NASEM over the characterization of HALEU. The posit by NASEM that HALEU is a direct-use material for producing nuclear weapons as a critical mass for it exists contradicts the IAEA definition, as that critical mass is around 800 kg. This mass would likely be far too large to produce a functional weapon.

The IAEA works to deter the spread of nuclear material through their safeguards oversight. They are conducting a large-scale review of the existing safeguards guidance against the novel attributes of advanced reactors. By leveraging expertise from member nations' work with advanced reactor demonstrations and experiments, this work will incorporate the most up-to-date data into the final determination.

Key Benchmarking Point

Almost all of the advanced fuel cycle safeguards issues are active areas of R&D or may not be likely to pose significantly new issues.

7.2.2 Licensing

7.2.2.1 IAEA Safety Requirements and Recommendations

Internationally, IAEA guidance is sometimes used to form the bases for domestic regulations. The highest level IAEA documents are Safety Fundamentals and Safety Requirements. Safety Guides provide recommendations and guidance on how to comply with the Safety Requirements.

The IAEA Safety Requirement related to reprocessing is IAEA-SSR-4, Safety of Nuclear Fuel Cycle Facilities – Specific Safety Requirements (IAEA, 2017a). This document "applies to nuclear fuel cycle facilities of all types and sizes, including facilities for the processing, refining, conversion, enrichment, and fabrication of fuel, the storage of spent nuclear fuel and the reprocessing of spent nuclear fuel[26], nuclear fuel cycle research and development facilities and supporting ancillary facilities in which radioactive material is handled". The objective of this document is to establish the safety bases (including safety assessments) through requirements for site evaluation, design, construction, commissioning, operation, and preparation for decommissioning.

[26] This includes reprocessing of SNF of breeder materials from thermal and fast reactors.

IAEA has also developed a "Specific Safety Guide" for reprocessing facilities (IAEA, 2017b). The objective of this document is to provide guidance based on IAEA's Member States that will be of use to designers, operators and regulators at all stages of development throughout the facility lifetime. Contents of this document include:

- General safety recommendations
- Site evaluation
- Design
  - General
  - Safety functions
  - Postulated initiating events (internal and external)
  - Instrumentation and control
  - Human factors
  - Safety analysis for:
    - Operations
    - Accident conditions
    - Radioactive waste management including gaseous and liquid discharges
    - Emergency preparedness
  - Construction
  - Commissioning
  - Operation and
  - Decommissioning

There are also appendices that describe "Main Process Routes" (Annex I) and "Structures, Systems and Components Important to Safety" (Annex II in (IAEA, 2017b).

7.2.2.2 U.S. Regulations

In the U.S., 10 CFR Part 50 indirectly includes regulations that could be applied to reprocessing facilities (10 CFR Part 50.2). In this case, a reprocessing facility could be considered a type of "production facility". Appendix F in Part 50 briefly outlines NRC's "Policy Relating to the Siting of Fuel Reprocessing Plants and Related Waste Management Facilities[27]. Among other requirements in this appendix, NRC requires that liquid reprocessing waste be solidified and that the amount of liquid high-level waste on site should be limited to that produced in the last five years.

[27] 35 FR 17533, Nov. 14, 1970, as amended at 36 FR 5411, Mar. 23, 1971; 42 FR 20139, Apr. 18, 1977; 45 FR 14201, Mar. 5, 1980

Amendments to 10 CFR Part 50 to more directly address reprocessing plants were proposed in 1974 (AEC, 1974a) (AEC, 1974b). However, these were never adopted.

In 2007, the U.S. Congress directed the NRC to identify gaps in the existing regulations that indirectly address reprocessing in order to develop a regulatory framework that would directly address reprocessing facilities.

In 2008, two companies announced their intention to license and construct reprocessing facilities. A third company expressed support for the development of reprocessing regulations.

The NRC provided options and resource estimates to the U.S. Congress for updating its reprocessing regulatory framework (NRC, 2013). Although the NRC commissioners instructed NRC staff to develop a reprocessing-specific regulation, development of the regulatory framework was to be limited to one particular regulatory gap – Safety and Risk Assessment Methodologies and Considerations for a Reprocessing Facility.

Although there was some interest by U.S. organizations for NRC to complete a new reprocessing-specific regulation, in 2021, NRC discontinued its efforts based on "limited interest expressed or expected from potential applicants for reprocessing facilities in the near-term use of reprocessed spent fuel." (NRC, 2023) NRC concluded that the cost of developing a new regulation was not justified and that existing regulations would suffice in the nearer term.

7.2.3 Criticality Management

The IAEA safety requirement (IAEA, 2017a) and guide (IAEA, 2017b) for reprocessing facilities include provisions for nuclear criticality safety. Criticality safety for reprocessing plants using aqueous chemical processes, such as the PUREX process, is more challenging than for non-aqueous methods such as pyroprocessing. The overall safety requirement during operation is (IAEA, 2017a) that "[a]ll operations with fissile material shall be carried out to maintain and adequate margin of subcriticality, under operational states and conditions that are referred to as credible abnormal conditions or conditions included in the design basis." Monitoring and surveillance programs are required to ensure there is no accumulation of fissile material that could become critical. Appropriate limits shall be set. Section 9.85 of (IAEA, 2017a) identifies four conditions or procedures that have a potential for criticality:

- Accidental transfer of two batches of fissile material instead of just one (double batching)
- Transfer or temporary movement of fissile material during operational states
- Fissile material that is not directly monitored must be placed into containers specifically designed for the particular purpose
- All procedures must adhere to safety requirements both at the sending and receiving areas

Section 9 of (IAEA, 2017a) also includes requirements for enriched uranium and MOX fabrication, uranium enrichment and conversion facilities and other fuel processing facilities.

Additional details for implementation of (IAEA, 2017a) is found in Sections 7.46 through 7.53 in the Specific Safety Guide (IAEA, 2017b).

7.2.4 Impact on an Existing LWR Fleet Including System Complexity

Transitioning from an LWR reactor fleet using a once-through fuel cycle to a fuel cycle requiring reprocessing has been considered by many, such as (MIT, 2011) and (NASEM, 2023) A realistic transition period to a "steady state" advanced fuel cycle will take many decades to achieve[28].

A National Academy of Sciences report, Laying the Foundation for New and Advanced Nuclear Reactors in the United States (NASEM, 2023) addresses the factors to consider in transitioning to a fuel cycle using advanced reactors – most of which require reprocessing. In addition to technology gaps of various sizes, the report addresses several common and less frequently considered issues:

- The evolving electricity system and the potential role of advanced reactors, such as:
  - The general competitiveness of nuclear power
  - Changing customer expectations
  - Electricity grid issues (supply and demand, implications for reliability and resilience)
  - Pricing and electricity regulatory reform
- Economics, such as:
  - Entry barriers
  - Advanced reactor cost drivers
  - Public-private partnerships
  - Demonstration programs
  - DOE efforts to support technical development
  - Commercialization
- Nuclear power's potential to play a broader role in the future energy system
- Project management and construction
- Lack of clarity of existing regulations
- Social acceptance
- Safeguards
- Nuclear exports and international competition

[28] For example, in the (MIT, 2011) study, the amount of time to fully transition could be 50 to 100 years. NASEM (2023) notes that "most advanced reactors will not complete demonstration until the 2030s".

7.2.5 Storage, Transportation and Disposal

As discussed elsewhere, storing, transporting, and disposing of waste streams will need to be considered for those advanced fuel cycles for which the waste streams are different than those for the once-through fuel cycle. Wastes from aqueous reprocessing are already managed routinely. The higher decay heat and radioactivity of used MOX compared to UNF can be accommodated during storage and transportation by using smaller containers. Section 5.3 discussed the more problematic issue of spent MOX disposal due to its higher decay heat. Examples of other waste management issues that can be managed with proper consideration are: pyrophoricity of sodium-coated metallic fuel; potentially larger volumes of graphite waste; and conversion and solidification of molten salts.

The only potential challenges for disposal of volatile fission product wastes released during reprocessing are to develop solidification methods – particularly for I-129 due to its very long half-life and its high solubility and mobility in groundwater and C-14 for largely the same reasons. More robust waste forms have yet to be developed for iodine (see Section 2.3.4.2) and C-14 such that existing methods of disposition of these two radionuclides can all be considered "dilute and disperse".

As discussed in Section 5.5, reduction of waste streams containing actinides requiring deep geologic disposal can be achieved in the short term.[29] However, over the lifetime of the fuel cycle, the amount of time required to achieve a significant reduction in TRU inventory in the entire fuel cycle (including buildup of TRU in the advance reactors) will take centuries.

7.3 Economics: Is the Long-Term Benefit Worth the Up-Front Cost?

There have been many studies investigating the economics of various advanced fuel cycles – most of which include reprocessing of some kind, such as: (BCG, 2006) (EPRI, 2009) (EPRI, 2010b) (MIT, 2011) (ETI, 2018) (EPRI, 2019) to name a few. Depending on the assumptions made and the fuel cycles considered (once-through to near-fully-closed with, for example, fast reactors) it is possible to conclude that reprocessing with or without advanced fuel cycles is highly uneconomic to economic enough to transition to over the longer run. It also depends on one's perspective.

- Most common perspective: cost of reprocessing and production and use of fuel using reprocessed fissile material compared to main avoided or reduced costs, such as:
  - Lower natural uranium demand
  - Reduced (but never eliminated) geologic disposal need
  - Potential long-term reduced enrichment need

[29] The amount of fission products requiring disposal is not greatly different between the existing once-through fuel cycle using LWRs and advanced fuel cycles.

- Fraction of the back-end cost contribution to total electricity production costs (relatively small compared to reactor construction costs for all major fuel cycles).
- Who will fund long-term RD&D to transition to one or more sustainable advanced fuel cycles (e.g., government, private or public/private partnerships). Transition times are likely to be on the order of several decades.
- Semi-qualitative to qualitative factors become especially important if the relative cost of fuel cycles requiring reprocessing is not much higher than the once-through scenario:
  - Importance of energy independence (e.g., Japan, France, South Korea, many others)
  - Desired contribution to greenhouse gas emission reduction (requires "strong" desire to surmount near-term (perhaps to ~2050) cost hurdles to achieve a long-term, consistent increase of the share of nuclear to overall energy production)
  - Unwillingness to dispose of used nuclear fuel with theoretical future energy potential
  - What is almost never considered is whether a reduced disposal need or changes to the types of waste to be disposed will make siting, licensing and construction any easier
  - Feasibility of a multi-national approach to nuclear energy production and waste disposal
  - Essential for any fuel cycle: Existence of a robust domestic or international nuclear energy production capability upon which to rely to make the transition(s) to advanced fuel cycle(s) requiring reprocessing

A few economic studies are presented below. Additional examples of economic analyses are found in Appendix C.

7.3.1 Comparison of the Nominal Costs for Four Fuel Cycles in the EPRI Analyses

For the EPRI cost analyses discussed above, nominal costs for the four fuel cycles discussed above were compared (EPRI, 2010b). The four fuel cycles considered were:

- Fuel Cycle 1: Once-through
- Fuel Cycle 2: Single recycle of used UOX fuel converted into MOX fuel to be used in PWRs
- Fuel Cycle 3: Multiple recycles of used UOX and used MOX fuels to be converted into MOX fuels appropriate for a combination of PWRs and fast reactors
- Fuel Cycle 4: Multiple recycles using exclusively fast reactors

A comparison of costs using all nominal values as input is shown in Figure 7-1. Overall fuel cycle costs at equilibrium for Fuel Cycle 4 are 39% lower than for the once-through cycle (Fuel Cycle 1). For Fuel Cycle 4, although the reprocessing costs are the highest for the four fuel cycles, front end costs are very small and waste management costs are about half that of the once-through fuel cycle.

Fuel cycle costs are most sensitive to the range of potential uranium and reprocessing/fuel fabrication costs. Relatively low uranium and high reprocessing/fuel fabrication costs will make the once-through fuel cycle the most economic. Conversely, relatively high uranium but low reprocessing/fabrication costs will make the more advanced fuel cycles more economic.

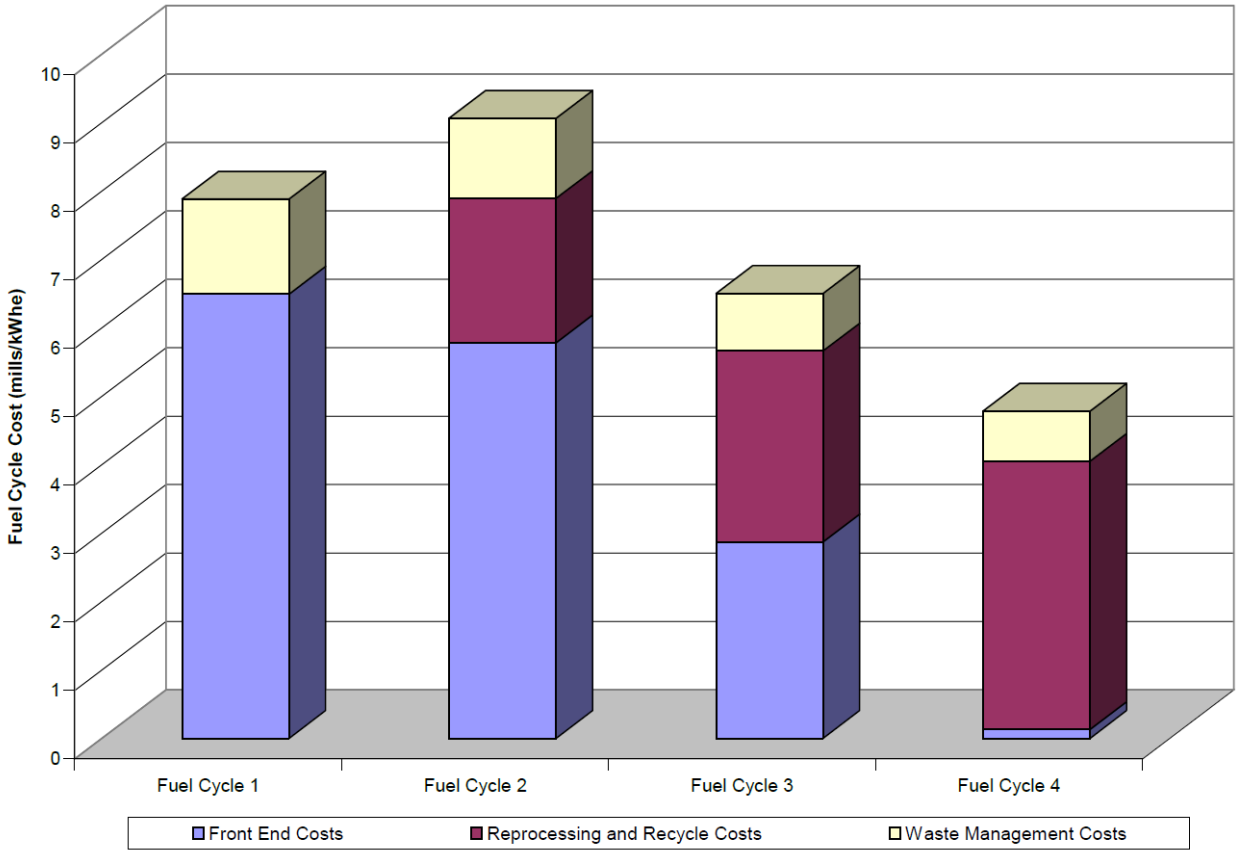

Figure 7-1. Comparison of overall fuel cycle costs using nominal unit costs for fuel cycles 1 through 4 [Figure 5-1 in (EPRI, 2010b)]

EPRI studied the breakeven points for the cost of uranium versus the cost of the three different fuel cycles (EPRI, 2009) (EPRI, 2010b) as shown in Figure 7-2: (1) once-through; (2) Pu single recycling in PWRs using the PUREX process; and (3) Pu multirecyling in fast reactors using and advanced PUREX process. This figure suggests that the price of UO_2 would need to increase to approximately $500/kgHM for the cost of a single recycle of used UOX converted to MOX for LWRs to achieve breakeven. It would take the use of fast reactors to make some advanced fuel cycles more competitive with the once-through fuel cycle. However, the analyses summarized in Figure 7-1 and Figure 7-2 have excluded reactor capital costs. If the capital costs for fast reactors are higher than those for LWRs, then it is not clear if even an advanced fuel cycle employing fast reactors would be economically competitive.

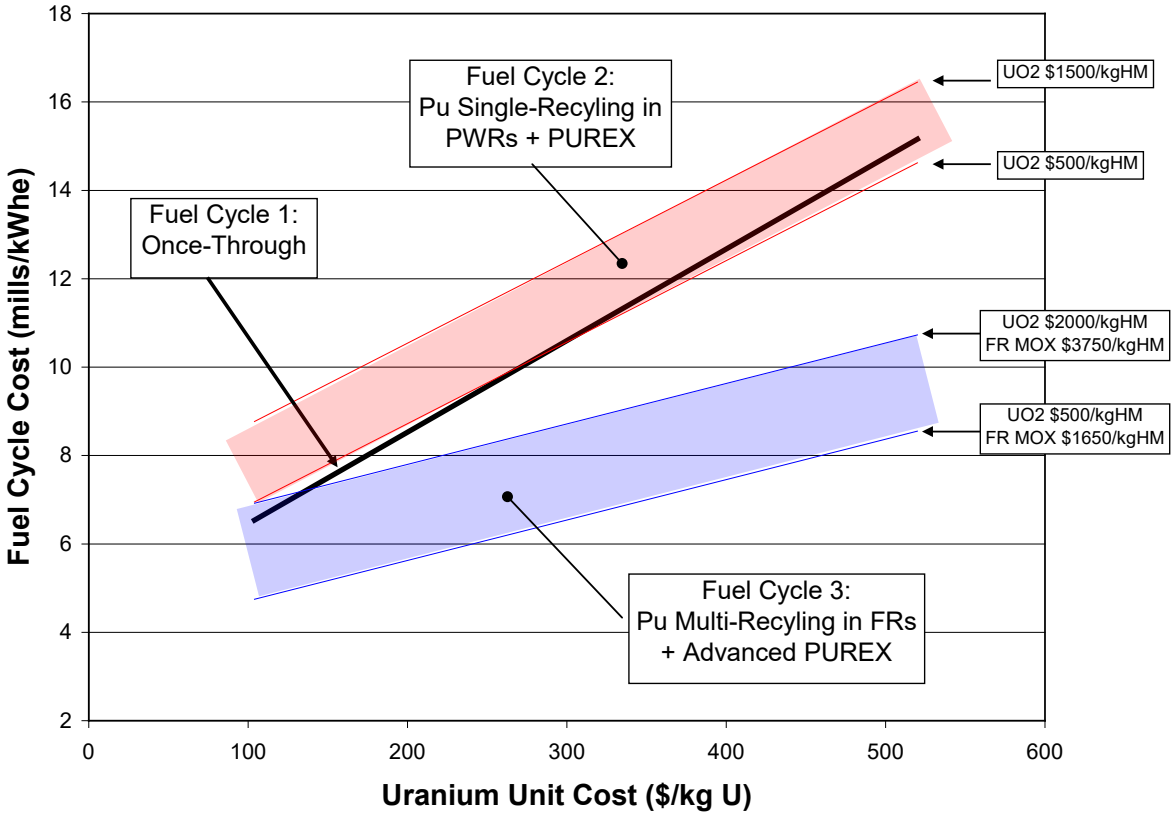

Figure 7-2. EPRI equilibrium modeling of fuel cycle costs using the OECD/NEA SMAFS model adapted from (EPRI, 2009) (EPRI, 2010b). NOTE: capital costs for reactors are not included.

The NEA 2022 "Red Book" for uranium supply and demand (NEA, 2023) implies that supply and demand can be met through at least 2040 at a uranium price of approximately USD130/kgU. Comparing that uranium price to Figure 7-1 and Figure 7-2 supports the general conclusion made in (EPRI, 2009) and (EPRI, 2010b) that the future price of uranium should be low enough such that only if a transition to a mostly closed fuel cycle (multiple recycle of U/Pu/minor actinides) using fast reactors has already been achieved could a near-fully closed fuel cycle be economical. The NEA (2023) uranium supply versus cost projections along with the EPRI analyses imply that a single reprocessing of used UOX to generate MOX for LWRs would remain uneconomical.

Key Technical Point

The future price of uranium should be low enough such that only if a transition to a mostly closed fuel cycle (multiple recycle of U/Pu/minor actinides) using fast reactors *has already been achieved* could a near-fully closed fuel cycle be economical.

7.3.2 MIT Breakeven Cost Analysis (MIT, 2011)

In its report, *The Future of the Nuclear Fuel Cycle* (MIT, 2011), MIT predicted that for a once-through fuel cycle, the uranium price by 2050 for its "medium case" of prices would be $114/kg and $118/kg for a 1% and 4% nuclear power growth scenario, respectively (constant 2008 dollars); by 2100, MIT (2011) predicted those prices would rise to $125/kg and $139/kg, respectively, which is consistent with the implications of (NEA, 2023) as shown in Figure 7-1. Thus, MIT concluded that "There is no shortage of uranium resources that might constrain future commitments to build new nuclear plants for much of this century at least. … The benefits to resource extension and to waste management of limited recycling in LWRs using mixed oxide fuel as is being done in some countries are minimal" (MIT, 2011).

Therefore, MIT (2011) recommended:

> For the next several decades, a once through fuel cycle using light water reactors (LWRs) is the preferred economic option for the U.S. and is likely to be the dominant feature of the nuclear energy system in the U.S. and elsewhere for much of this century. Improvements in light-water reactor designs to increase the efficiency of fuel resource utilization and reduce the cost of future reactor plants should be a principal research and development focus (MIT, 2011).

The conclusion about the continuation of the once-through fuel cycle was echoed by the National Academy of Sciences and Engineering in its report *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors* (NASEM, 2022), among others. However, both of these organizations along with many others advocate continued RD&D in advanced fuel cycles to gain enough experience to make a better determination whether transitioning to a more advanced fuel cycle will make economic sense eventually.

7.3.3 Cost Challenges

Given that reprocessing may not yet be economical, what action could a country take *now* regarding reprocessing? The early July 2023 uranium price of $56.2/lb ($123.6/kg) can be compared to some of the break-even cost estimates based on assumptions about the cost of reprocessing and production of fuel using reprocessed materials. For example, EPRI (EPRI, 2009) (EPRI, 2010b) concludes that for a single reprocessing of used UOX to be converted into a one-time MOX use in a LWR, the cost of uranium needs to be at least about $300/kg if the cost of

reprocessing is $500/kgHM (EPRI, 2009), which is the low end of EPRI's estimate of reprocessing costs; for the high end of the (EPRI, 2009) reprocessing cost range, uranium prices would need to be in the upper hundreds of dollars per kg for breakeven to occur. BCG (2006) estimated the breakeven uranium price of $31/lb ($68/kg) for an assumed reprocessing cost of $520/kg. Therefore, BCG (2006) concluded that existing uranium prices were high enough to justify reprocessing. For a fully closed fuel cycle, the (EPRI, 2010b) analysis concluded that a fully closed fuel cycle would be less expensive than a once-through fuel cycle for a uranium price well below $100/kgU – again meaning that the existing price of uranium is high enough to justify a fully closed fuel cycle.

What has been neglected in all of the studies reviewed above is the cost of transitioning to an advanced fuel cycle. France and Russia do have commercial reprocessing, so they have passed the first of many hurdles. Furthermore, Russia is operating a handful of fast reactors. However, most countries use a once-through fuel cycle, so they would be starting from the beginning.

A question that can be asked is: even if the current price of uranium is lower than some current estimates of that required to make reprocessing into LWR MOX and/or FR-MOX (or other fast reactor fuel types) more economic than the once-through cycle, when does it make sense to start "spending ahead" to make the transition perhaps before long-term economics are fully favorable?[30]

The National Academies of Sciences (NASEM, 2023) developed a report, Laying the Foundation for New and Advanced Nuclear Reactors in the United States. A major issue the NAS addressed was economic viability of any nuclear project:

> [S]ignificant costs are required for closing the fuel cycle, the most difficult to surmount being the large and sustained investments in fuel cycle infrastructure (reprocessing and fuel fabrication facilities, non–light water advanced reactors, geologic repository needed for all disposal options) that does not currently exist in the United States (reprocessing and fuel fabrication facilities, non–light water advanced reactors, geologic repository needed for all disposal options). Furthermore, for any advanced reactor and associated nuclear fuel cycle to be deployed, additional proliferation, security, and safety risks will need to be addressed and managed.
>
> With these factors in mind, there is a need to confront various risks associated with the commercialization of advanced nuclear projects, and the future landscape in which they may play a role. Fundamentally, the projects must convincingly and honestly demonstrate that they can compete in a marketplace in which there are

[30] "Favorable" fuel cycle economics after fuel transition to an advanced fuel cycle would be high uranium prices and low reprocessing/fuel fabrication prices.

alternatives. For deployment in the United States, they must demonstrate a pathway to overcome the concerns that legitimately arise from the historical cost and schedule performance of previously built reactors (NASEM, 2022).

NASEM (2003), stated the following about investor risk for advanced reactors (and their supporting fuel cycle technologies):

> An investor contemplating an investment in the commercial deployment of an advanced reactor must evaluate a range of different risks:
>
> **Technology Risk.** The demonstration of an advanced technology is anticipated to serve to retire most of the technical risks associated with that technology. Modifications could introduce new technical risks, and experience with the reactor over time may reveal new risks.
>
> **Commercialization Risk.** Even after a reassuring demonstration, there are challenges associated with commercial deployment, such as overcoming the project management cost and schedule delays that have plagued nuclear construction in the United States and Europe; establishing supply chains for fuel, parts, and components of sufficient quality, volume, and price; developing a sufficient order book to justify the establishment of a manufacturing facility; and ensuring the availability and cost of the necessary skilled workforce both for construction and operations. Commercial success may depend as well on international marketing.
>
> **Revenue Risk.** The economic assessment must include an assessment of the revenue over the life of operations. There may be significant uncertainty in anticipated revenues over time, including risks that arise from competing technologies or from regulatory or policy changes.
>
> **Regulatory Risk.** The operator must obtain a license from the NRC after a thorough evaluation of both general and site-specific issues. While the design may be certified, there may be project-specific risks associated with NRC inspections, tests, analyses and acceptance criteria (ITAAC), or expensive backfits to deal with safety issues that arise during operations. Constraints arising from regulatory requirements will affect business plans, such as the plans for reduced staffing or to provide process heat to adjacent commercial users. Moreover, operation may require permits and rights-of-way from state and local governments.
>
> **Infrastructure Risk.** The success of a project may depend on the availability and cost of necessary infrastructure, such as the availability of transmission lines.
>
> **Financing Risk.** The success of the project is dependent on access to equity and debt markets and the terms by which such financing is available, such as interest rates on debt. Financing is affected by the availability, extent, and reliability of incentives for commercial deployment, such as government loan guarantees or tax incentives.

> **Reputational Risk.** The investor must assess whether involvement in a nuclear project will pose a reputational risk with the investment community, shareholders, regulators, or other key stakeholders.
>
> **Contract Risk.** If nuclear vendors and EPC contractors are unwilling to offer contracts to buyers that cover (or at least share) completion risk, buyers may see other non-nuclear generation options as less risky. Knowing who will bear the risk if a project cannot be completed for whatever reason, especially for FOAK units, is essential.

NASEM (2023) also recommends that a consortium be created to pursue construction and ensure the availability of skilled personnel. An alternative would be to implement a «long-term business relationship, preferably an equity partnership such as a joint venture, or a consortium, with a qualified engineering, procurement, and contruction firm experienece in the nuclear industry».

Regarding whether the U.S. should proceed with advanced fuel cycles including reprocessing, the NAS (NASEM, 2022) concluded:

> Continued use of the once-through fuel cycle for the existing U.S. light water reactor (LWR) fleet has several merits: (1) lower cost compared with any fuel cycle that involves reprocessing and recycling, (2) a reliable international market for nuclear fuel services from multiple suppliers (although that could be disrupted by international crises, such as war)4; (3) compatibility with the projected available uranium resources; (4) well-understood proliferation resistance of the entire fuel cycle; and (5) theft resistance of spent nuclear fuel (NASEM, 2022).

(ETI, 2018) provides some common characteristics of low- versus high-cost nuclear projects. Of note, the largest impact to project success appeared to be having a near-complete design prior to the start of construction. A subjective tally of characteristics of a new reprocessing facility in various countries could be:

Low-Cost Plants:

- Highly productive labor will exist in a few countries, whereas low-cost labor would be less common.
- The degree of detailed construction planning prior to starting construction will likely be country-specific.
- NOAK design is unlikely to exist even in countries with existing reprocessing facilities since plant upgrades (e.g., modifications to the PUREX process; use of different or additional equipment). Evolutionary rather than revolutionary design changes should be less expensive.

High-Cost Plants:

- Lack of completed design before construction is started could be common – especially if it is a FOAK plant.
- Major regulatory interventions during construction could occur in countries in which regulations are not fully developed and clear, or a cumbersome review process exists.
- FOAK design will be the most likely scenario in all countries to a greater or lesser extent. Exceptions could be a long-term policy involving periodic construction of additional reprocessing facilities.
- Litigation between project participants, if it occurs, could be highly costly in terms of any financial settlements, but mostly in terms of potentially lengthy delays during plant construction. One conclusion that could be inferred is that the fewer the number of project participants, the lower the likelihood of litigation.
- Significant delays and rework required due to supply chain issues is a high risk since almost no major reprocessing equipment is off-the-shelf. If no qualified suppliers exist, this will increase delays and cost.
- Long construction schedule: only the most construction-efficient countries could avoid this.
- Relatively high labor rates and low productivity: given most countries that would consider construction of a reprocessing plant would likely have high labor rates, this would increase cost. Productivity will also vary among countries and is also dependent on other external factors: maturity of regulations and regulatory oversight; quality of construction management; supply chain issues.
- Insufficient oversight by owner: the sufficiency of oversight is likely to correlate with the owner's experience with existing reprocessing facilities along with the clarity of regulations or regulatory guidance and completeness of the plant design.

However, once nuclear plants are operational and their construction costs represent "sunk" costs, recurring fuel cycle costs, including reprocessing, become much more significant, as do operation and maintenance (O&M) costs.[31]

[31] The cost of the Rokkasho reprocessing plant in Japan has increased significantly over the course of the project and now exceeds $27 billion (Forbes, 2011), up from the original $6.9 billion estimate. Construction of a new aqueous reprocessing plant is estimated to cost in the $15–20 billion range for an 800 metric tons heavy metal (MTHM) per year facility. Operation and maintenance costs are estimated at $500 million per year (Bunn, Holdren, Fetter, & van der Zwaan, 2015) (Tabuko, 2008) (INL, 2021a). This equates to an operations and maintenance cost (i.e., excludes debt retirement) of $625/kg.

7.4 Is All Existing Used Fuel Worth Reprocessing?

There is a general feeling in much of the nuclear industry that in addition to used fuel that will be produced in the future, all or nearly all the existing used fuel should be reprocessed rather than directly disposed of. In 2012, Oak Ridge National Laboratory performed an assessment of the value of used nuclear fuel that had been generated in commercial nuclear power reactors (~70,150 MTHM as of 2011) (ORNL, 2012). The authors concluded that:

> "…up to ~1700 MTHM of existing commercial UNF should be considered for retention to support research, development, and demonstration (RD&D) needs and national security interests. The 70,150 MTHM includes commercial (~67,600 MTHM), highly enriched uranium (HEU) (~50 MTHM), and DOE-owned (~2500 MTHM) UNF. The remainder, ~68,450 MTHM (both DOE-owned and commercial UNF) or **~98% of the total current inventory by mass, can proceed to permanent disposal without the need to ensure retrievability for reuse or research purposes**. … This assessment does not assume any decision about future fuel cycle options or preclude any potential options, including those with potential recycling of commercial UNF, since **the ~2000 MTHM that is generated annually could provide the feedstock needed for deployment of alternative fuel cycles**; for example, by 2030 an additional ~40,000 MTHM of commercial UNF will have been generated." [emphasis added]

Thus, essentially all the *existing* used fuel (as of at least 2011) can be disposed of based on the goals determined by the authors. Those authors considered various characteristics of the used fuel, such as: isotopic compositions (e.g., fissile and non-fissile content), physical and material characteristics that impact recycling and/or disposal facility design and operations (e.g., accessibility of material, diversity of material, condition of material, and material hazards), national security materials strategy, and current and projected RD&D needs to support UNF management and alternative fuel cycle development. Assuming the current U.S. discharge rate of about 2000 MTHM per year remains constant and a 2000 MTHM per year reprocessing facility requiring five years of cooling prior to disposal becomes available in 2030 (the earliest date the authors believe is possible), then "a portion of the discharged UNF would not need to be retained to support this facility until 2025" (ORNL, 2012). Based on the assumption of a 2000 MTHM per year reprocessing facility becoming available in 2030, the proportion of used fuel, by decade, that should be either disposed of or retained is shown in Figure 7-3. Prior to 2010, 98% of all discharged fuel can be directly disposed; by 2040 essentially all discharged fuel could be recycled in a 2000 MTHM per year reprocessing facility.

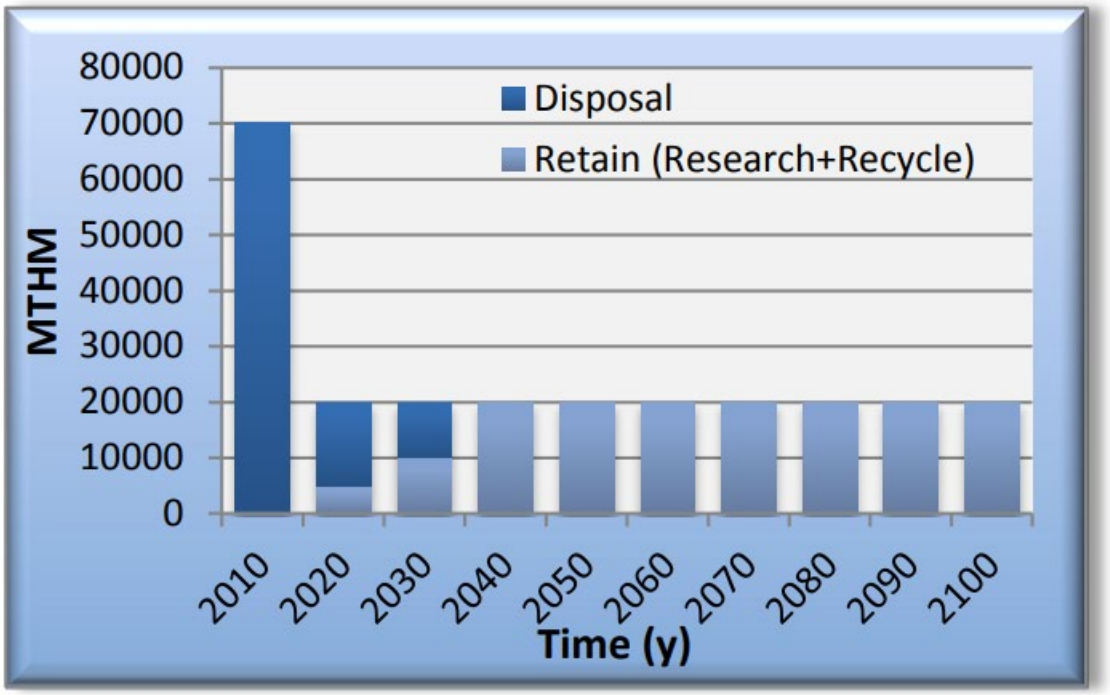

Figure 7-3. Categorization of UNF assuming current discharge rate (~2000 MTHM/yr) and recycling beginning in 2030. [from (ORNL, 2012)]

Although Figure 7-3 is just one example of a future in which reprocessing is used in the U.S., it illustrates the point the authors of ORNL (2012) made that disposal of the vast majority of existing used fuel "will not adversely impact deployment of an alternative fuel cycle in the future, even for a recycle fuel cycle." A 2000 MTHM per year reprocessing facility size assumed in ORNL (2012) is larger than even the La Hague facility which has a capacity of 1700 MTHM per year. Hence, the initial capital cost would be high even if existing PUREX technology were adopted. Furthermore, a 2000 MTHM per year reprocessing facility to be built in a country with no or decades-old commercial used nuclear fuel reprocessing experience would require significant lead time for siting, design, licensing[32] and construction activities. It could be appropriate for *some* of the used fuel generated five to perhaps ten years before reprocessing facility operation to be saved for reprocessing. If the authors' assumption in (ORNL, 2012) that it would take a minimum of nearly two decades (2012 to 2030) is reasonable, then as of the time this report is released (late 2023), this would mean that the vast majority of used fuel could be disposed of up until about 2033 to 2038 while still enabling "steady-state" reprocessing.

[32] Licensing may also require development of appropriate regulations for a reprocessing facility if existing regulations are not suitable or desirable.

A Boston Consulting Group economic study summarized in Appendix C (BCG, 2006) assumed an even larger reprocessing facility than that assumed by (ORNL, 2012) – 2500 MTHM/yr. Because such a large reprocessing facility was assumed, BCG (2006) could assume that previously-generated UNF would be used to some extent, which affected the amount of spent nuclear fuel storage, transportation and disposal required.

The analyses in (ORNL, 2012) was performed for the U.S. situation, which is the largest annual generator of commercial used nuclear fuel. A reprocessing facility this large would be appropriate for the United States that is expected to discharge 2000 MTHM per year. For countries that discharge less from their reactors per year, the reprocessing facility could be smaller – assuming the facility would be sized solely for domestic needs. Also, if a country already has existing, relevant licensing and construction experience with a reprocessing facility similar in design to the proposed reprocessing facility, the lead time could be shorter.

Key Benchmarking Point

Reprocessing of a significant portion of existing used fuel is not necessary to enable the adoption of reprocessing technology, based on the annual output of fuel from most reactor fleets.

8 SCENARIOS FOR WHICH REPROCESSING MIGHT OR MIGHT NOT MAKE SENSE: EXAMPLE CASE STUDIES

IAEA (2008b) recognized that whether a particular country chooses to use an advanced fuel cycle will be dependent on multiple factors. To better illustrate how these differences could result in different choices about the use of advanced fuel cycles, a set of example case studies have been developed. Table 8-1 lists factors that could influence whether a particular country or utility would choose to transition to an advanced fuel cycle. Individual cases, presented after Table 8-1, are based on differences in the existence or importance of these factors to a particular country/utility are explored to provide insight about how the particular factors can result in different desires to proceed with a transition to an advanced fuel cycle. For all cases it is assumed that fuel cycle economics and non-proliferation are important and that none of the countries have adequate natural uranium resources to supply 100% of their uranium needs to carry out a once-through fuel cycle.

Table 8-1. Factors influencing the choice to use an advanced fuel cycle involving reprocessing – case studies

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Existing and Future Nuclear Power Conditions						
Existing UOX reprocessing and MOX fabrication facilities		X	X			
Global energy mix: nuclear to remain significant	X	X	X		X	
Global energy mix: reduce nuclear in the future		X		X		
Global energy mix: introduce and maintain nuclear						X
Domestic fissile resources available			X			
Existing nuclear fleet: all LWRs/HWRs	X	X		X	X	X
Existing nuclear fleet: LWR/advanced			X			
Existing installed capacity >50GWe	X	X				
Existing installed capacity 10 to 50GWe			X	X	X	
Existing installed capacity <10GWe						X
Future nuclear fleet: all LWRs	X	X				X

Table 8-1 (continued). Factors influencing the choice to use an advanced fuel cycle involving reprocessing – case studies

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Future nuclear fleet: LWRs/advanced			X		X	
Future nuclear fleet: mix to fully close fuel cycle		X		X		
Waste inventory: large	X	X	X	X		
Waste inventory: small					X	X
Geologic disposal: diverse options, large capacity	X	X	X			
Geologic disposal: minimal options or small capacity				X	X	X
Public support for nuclear: high		X	X			X
Public support for nuclear: moderate	X			X	X	
Significant domestic nuclear R&D facilities exist	X	X	X	X	X	
Factors considered important:						
Conservation of nuclear resources		X		X	X	X
Waste requiring geologic disposal reduction		X		X	X	X
Minimization of environmental impact (greenhouse gas reduction)	X	X		X	X	X
Fuel cycle economics	X	X	X	X	X	X
Proliferation resistance	X	X	X	X	X	X
Become a world leader in reprocessing technology	X	X	X		X	
Reprocessing capacity for use by multiple non-domestic utilities and countries		X	X			

A few details of the some of the factors in this table:

- Fuel cycle economics includes all aspects of costs to transition to an advanced fuel cycle:
  - RD&D to advance reprocessing and advanced reactor technologies to an industrial scale
  - Facility design, licensing, construction, operation and decommissioning
  - Waste management
  - Near-term and anticipated uranium supply costs
- Existing UOX reprocessing and MOX fabrication facilities: it is assumed that those countries/utilities that have such facilities already have the necessary infrastructure, regulatory process and workforce to support the infrastructure. It is assumed that all other countries have little to no infrastructure, no or immature regulations and essentially no trained workforce.
- Domestic fissile resources available: the resources are adequate to provide fuel for 100% of the existing and planned reactors.
- Geologic disposal:
  - Diverse options: multiple types of geology amenable to disposal. In addition, it is assumed these strata are at reasonable depths
  - Capacity: promising geologies are large enough to hold the anticipated amount of waste to be generated over the fuel cycle lifetime(s)
- Conservation of nuclear resources: desire to minimize the need for fresh U/Th.
- Reprocessing capacity for use by multiple non-domestic utilities and countries: the country or utility intends to reprocess not only its own used fuel but also that of other countries/utilities for profit. Waste products from reprocessing will be returned to the country of origin.

Case 1: This country/utility has a large nuclear program of LWRs using a once-through fuel cycle fuel with UOX produced from fresh U. It has an intention to maintain nuclear power as an important part of its energy mix into the future. The current waste inventory is already large. There are some uranium natural resources in the country, but not enough to fully supply the existing and planned future reactors. This country and its nuclear utilities assume that uranium prices will not dramatically increase for many years and that access to fresh uranium will not become constrained. Historically, this country has investigated a wide range of advanced reactor types and a few advanced fuel cycles, but rarely beyond a pilot test facility. Low- to medium-TRL R&D is being conducted with some governmental funding for FOAK advanced reactor technology demonstrations. Nationally, there has been both defense and commercial reprocessing experience, but both were long enough ago such that most of the skilled labor no longer exists. Furthermore, there are no reprocessing-specific regulations in place.

There are significant geologic disposal technical options – some of which have been investigated, but also significant political opposition to disposal such that at present, the country's geologic disposal program is stalled.

Case 1 options:

- Maintain a once-through fuel cycle for the foreseeable future.
- In the event of the need for more rapid nuclear expansion or consistently higher fresh U prices than anticipated, RD&D programs to develop advanced reactor technology and reprocessing processes that do not separate U from Pu are justifiable.
- With sufficient resources via government-private cost sharing, this country could retain and potentially increase its international leadership in advanced fuel cycles and reprocessing even if no full-scale advanced reactors or reprocessing facilities are built in the near future.
- International RD&D agreements including multi-national funding could accomplish full-scale FOAK facilities.
- Reprocessing-specific regulations should be put in place to guide RD&D.

Case 2: This country/utility has a large program of LWRs, a PUREX reprocessing plant larger than needed for purely domestic use and a facility to produce MOX for LWRs. A significant fraction of the LWRs are burning MOX. The reprocessing facility has demonstrated the capability to reprocess used MOX although the current plan for used MOX is to store it for future potential use. Furthermore, the country is exporting its PUREX technology. There are almost no domestic natural U resources, which is the main reason why the country/utility embarked upon partial recycling. It does not assume stable uranium prices and that access to fresh uranium will not become constrained. Historically, this country has investigated a wide range of advanced reactor types and a few advanced fuel cycles. Fast reactor technology at full scale was in use for several years but then shut down for economic reasons. Low- to moderate-TRL R&D is being conducted with some governmental funding for FOAK advanced reactor technology demonstrations. Nationally, there has been both defense and commercial reprocessing experience, such that most of the skilled labor already exists. Furthermore, there are reprocessing-specific regulations in place. The country also has a significant amount of HLW already in storage. There are adequate geologic disposal technical options – some of which have been investigated and one of which is nearing the license application stage for disposal of HLW glass. This country is already a world leader in reprocessing and its continued RD&D in this area makes it a logical point for commercial and R&D opportunities.

Case 2 options:

- Given that a reprocessing facility already exists, continued operation for reprocessing used UOX and conversion to MOX for use in LWRs is sensible.
- It is also sensible to store once-burned used MOX until such time as it is economically feasible to reprocess it for use in, for example, fast reactors.[33] As long as sufficient, long-term storage capacity for used MOX can be made available, this decision can be delayed.
- In the event of the need for more rapid nuclear expansion or consistently higher fresh U prices than anticipated, RD&D programs to develop advanced reactor technology and reprocessing processes that do not separate U from Pu are justifiable and are already underway.
- With sufficient resources via government-private cost sharing, this country will retain and potentially increase its international leadership in advanced fuel cycles and reprocessing.
- International RD&D agreements including multi-national funding could accomplish full-scale FOAK facilities.

Case 3: This country is very rapidly expanding its use of nuclear power, thereby outstripping its domestic supply of uranium. There may be concern about partial loss of access to international natural uranium supplies. It already has plans to expand its small-scale reprocessing facilities to a larger scale. It also has various stages of RD&D activities on advanced fuel cycles. The rapid expansion of nuclear power will mean a rapid increase in the amount of waste requiring disposal. This country has significant geologic disposal options and is exploring at least two sites at this time. This country is destined to become a world leader in advanced fuel cycles due to its rapid ramp-up of nuclear power and its investment in future technology.

Case 3 options:

- In the near term, continuing with a once-through fuel cycle is a strong option.
- With sufficient resources via government-private cost sharing, this country will retain and potentially increase its international leadership in advanced fuel cycles and reprocessing.
- Given the country's general interest in commercial exports, it is likely that building a reprocessing facility of a size greater than its future domestic needs is a likely option.
- International RD&D agreements including multi-national funding could accomplish full-scale FOAK facilities.

[33] Given the relatively high decay heat of used MOX compared to used UOX and the reduced capability of a potential geology to reject decay heat, used MOX probably cannot be disposed of economically at present. Additional decay time prior to direct disposal might be needed.

Case 4: This country has no natural uranium resources. Although this country has reduced its nuclear fleet, there may be interest in expanding it again first by putting some of its existing, shuttered plants back online. Given this country's interest in energy independence, it will be essential to develop advanced fuel cycles if nuclear power is to remain an option. This country has had experience in reprocessing already: at present, it has a relatively small reprocessing facility in operation with a second, much larger facility nearing completion. Converting some of its existing nuclear plants to burn MOX is the next logical step. It also ran a small fast reactor for several years. Availability of domestic disposal could be challenging due to limited appropriate geology and significant public opposition.

Case 4 options:

- In the near term, continuing with primarily a once-through fuel cycle is a strong option.
- If the larger reprocessing plant is completed, then it makes sense to use it – initially to produce MOX for use in LWRs.
- If use of nuclear power continues to be part of the country's energy mix and the desire for energy independence remains strong, then work toward a more fully closed fuel cycle should proceed now given the long lead time to commercial deployment.
- Maintaining adequate used UOX and used MOX storage capability is essential given the long lead time before a geologic disposal facility becomes available.
- International RD&D agreements including multi-national funding could accomplish full-scale FOAK facilities.

Case 5: This country has a moderately sized nuclear program with a combination of LWRs and HWRs that have been in operation for a few decades. Like Case 4, it also has no natural uranium resources. Energy independence is also a major goal for this country. However, it has no reprocessing capability due to an international agreement although it is continuing to conduct R&D at the laboratory scale on advanced reprocessing technology. At present, its only option for an advanced fuel cycle is using used LWR fuel in its HWRs and is proceeding with low TRL work at this time (modified DUPIC). It has a near-surface disposal facility for LLW/ILW, but deep geologic disposal for HLW is decades away. The most significant issue for its entire nuclear power program at the moment is that the available used fuel storage space is nearly full and the utility has not been given the approval to proceed with construction of additional storage space.

Case 5 options:

- For the foreseeable future, this country must continue with a once-though fuel cycle. It will require a change in international agreements to allow reprocessing with advanced fuel cycles.
- Continued RD&D on a modified DUPIC process for some reuse of used LWR fuel is a reasonable approach.
- If reprocessing is to be used, it must be at an international facility along with MOX (or other fuel using U/Pu) fabrication.
- This country will likely require approval for additional used fuel storage space or reactors will need to be shut down.

Case 6: This country has a relatively small nuclear program using LWRs. It has no domestic uranium supply and almost no disposal geology options. It has no reprocessing program per international agreements. R&D is minimal. At the national policy level, three options for ultimate used fuel disposition are being considered: (1) direct disposal of used UOX within the country; (2) disposal of UOX in another country; and (3) sending its used UOX for reprocessing without taking back the HLW.

Case 6 options:

- For the foreseeable future, this country must continue with a once-though fuel cycle. It will require a change in international agreements to allow reprocessing with advanced fuel cycles.
- Although decades of effort on the subject have not met with success, this country should pursue development of an international disposal facility.
- Use of a foreign reprocessing and MOX (or other U/Pu fuel) fabrication facility should be pursued along with the possibility of not taking back the HLW.
- International agreements for R&D on reprocessing should be established – if for no other reason than to develop some domestic reprocessing know-how.

Finally, all cases would benefit from the existence of an international government-industry consortium to carry out the large amount of RD&D required to fully transition to an advanced fuel cycle. The consortium could also be tasked with developing domestic skills for design, licensing (both regulation and implementation), construction, operation and decommissioning of advanced reactors and reprocessing facilities. It could also have the responsibility to develop waste management options useable in the consortium countries.

9 OBSERVATIONS AND RECOMMENDATIONS

9.1 Economics

Based on the cursory review of specific cost studies for the once-through fuel cycle versus fuel cycles requiring reprocessing, it can be seen that devil is in the details. Depending on differences in the myriad of economic assumptions made when developing bottom-line cost numbers, one can conclude that the cost fuel cycles requiring reprocessing can be either less than, approximately equal to, or greater than the cost of a once-through fuel cycle. There are several key cost assumptions that drive the final cost numbers such as, but not limited to the cost of: building fast reactors; uranium; building reprocessing facilities; geologic disposal; and the cost of borrowing money. Three of these particular factors have high uncertainties, but their uncertainties could be reduced with increasing technical and industrial experience: fast reactors, geologic disposal and reprocessing facilities.

It is anticipated that adequate natural uranium resources to support continuation and modest expansion of nuclear power worldwide will be adequate for many decades to come. Therefore, those nations with *existing* reprocessing technologies and reactors capable of using reprocessed fuel are in the best position to continue use of reprocessed fuel. *At present*, for existing reactors without access to reprocessed fuel, there is little incentive to initiate a reprocessing program. This could and potentially should change in the future.

Some fraction of the *existing* irradiated fuel removed from reactors potentially will likely be worth reprocessing in the future. For that fraction, the fuel could remain in storage until such time that it becomes evident that it is worthwhile to reprocess (when advanced reactors and their fuel cycles (including reprocessing) are at a sufficient technology readiness level and economics become favorable). The incremental cost of continued storage of potentially valuable irradiated fuel could be low compared to the value of the energy resource in this fuel. A fraction of the *existing* irradiated fuel will likely never be worth reprocessing and could be disposed of, assuming nuclear capacity is constant or growing. For some advanced fuel cycles requiring or having an option for reprocessing, essentially all of the irradiated fuel from at least the first few fuel cycles will be worth reprocessing.

What has been neglected in most economic studies is the cost of transitioning to an advanced fuel cycle. France and Russia do have commercial reprocessing, so they have passed the first of many hurdles. Furthermore, Russia is operating a handful of fast reactors. However, most countries use a once-through fuel cycle, so they would be starting from the beginning.

RD&D investment to achieve a full transition to an advanced fuel cycle will need to proceed ahead of all the necessary market conditions existing if such a fuel cycle is to provide a national benefit when needed. This requires foresight and consistent political will.

Several advanced fuel cycles show long-term potential of becoming cost effective and major contributors of net zero energy. RD&D of advanced fuel cycles including those requiring reprocessing in existing or new reprocessing facilities should be supported by current and future nuclear power users. Although initial funding may be more appropriate to be provided at the national level, joint government-nuclear power producer projects should be supported with financial and in-kind resources by the nuclear industry. *It is essential that nuclear power producers remain active in supporting potential advancements to ensure appropriate RD&D – especially for issues regarding FOAK reactors and reprocessing facilities – is being conducted. This requires consistent, long-term nuclear power industry leadership.*

All countries – large and small – would benefit from the existence of an international government-industry consortium to carry out the large amount of RD&D required to fully transition to an advanced fuel cycle. The consortium could also be tasked with various additional responsibilities, like developing domestic skills for design, licensing (both regulation and implementation), construction, operation and decommissioning of advanced reactors and reprocessing facilities. It could also have the responsibility to develop waste management options useable in the consortium countries.

9.2 Need for Existing Used Fuel for Reprocessing

The analyses in (ORNL, 2012) was performed for the U.S. situation, which is the largest annual generator of commercial used nuclear fuel. A reprocessing facility this large would be appropriate for the United States that is expected to discharge 2000 MTHM per year. For countries that discharge less from their reactors per year, the reprocessing facility could be smaller – assuming the facility would be sized solely for domestic needs. Also, if a country already has existing, relevant licensing and construction experience with a reprocessing facility similar in design to the proposed reprocessing facility, the lead time could be shorter. In the near term, continuing with a once-through fuel cycle is a strong option.

It is unlikely that much of the used fuel already generated would be used for reprocessing unless a reprocessing facility was constructed with capacity significantly larger than needed to match average annual used fuel discharge. If adequate geologic disposal options are available, it would make economic sense to directly dispose of a significant portion of the existing used fuel, if that option is or becomes available.

9.3 Safeguards

NASEM (2022) thinks that safeguards issues are more difficult for some advanced fuel cycles. Examples of more difficult issues are material accountancy for pebble bed and molten salt reactors rather than stationary fuels. Th/U-233 cycles need safeguards development because of the large number of variants in their systems. However, in a letter to the NAS, an ANS ad hoc committee disagreed that safeguards issues for advanced fuel cycles were difficult and that some materials would be “weapons useable” (Arndt and Piercy, 2023).

9.4 Regulations

Use of reprocessing requires appropriate regulations and regulatory oversight. The IAEA has developed both a Safety Requirement (IAEA, 2017a) and a "Specific Safety Guide" (IAEA, 2017b) for reprocessing facilities that would serves as a good basis for development of national regulations and regulatory guidance, respectively. Some countries, such as the U.S., do not have regulations specifically for reprocessing. In addition to appropriate regulations and implementing guidance, the regulatory body needs knowledgeable staff in reprocessing.

9.5 Non-Proliferation

Since avoidance of weapons proliferation is an international goal, RD&D of reprocessing options that do not separate U and Pu should be a high priority, as should research into safeguards by design and other means of preventing diversion of materials.

9.6 Waste Management

Waste management issues with reprocessed wastes have not been adequately addressed for some advanced reactor types. Many advanced reactor types and their reprocessing wastes still require identification and disposal preparation assessments. Nevertheless, it is anticipated that these waste management issues can be addressed adequately. If reduction in the volume of waste requiring disposal is important, most advanced fuel cycles will have less waste to dispose of. Long-term geologic disposal requirements are not significantly different between a once-through and advanced fuel cycles. Therefore, disposal reduction should not be among the primary reasons to switch to an advanced fuel cycle.

A frequently stated benefit of fuel cycles using reprocessing is a reduction in wastes requiring deep geologic disposal. As discussed in Section 5.4 Buildup of Waste Inventory in Advanced Reactors Eventually Requiring Disposal, reduction of waste streams containing actinides requiring deep geologic disposal can be achieved in the short term.[34] However, over the lifetime of the fuel cycle, the amount of time required to achieve a significant reduction in TRU inventory in the entire fuel cycle (including buildup of TRU in the advance reactors) will take centuries. Therefore, EPRI concludes there is little disposal benefit from adopting advanced fuel cycles that cannot be maintained on the order of centuries.

[34] The amount of fission products requiring disposal is not greatly different between the existing once-through fuel cycle using LWRs and advanced fuel cycles.

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A SUMMARY OF MAJOR INTERNATIONAL REPROCESSING FACILITIES

The following table is reproduced from Table 8 in (INL, 2021b).

Country	Facility Name	Dates of Operation	Production Scale	Fuels Reprocessed
China	Lanzhou Nuclear Fuel Complex.	2010 to present.	Pilot Plant 10 to 20 MT/y.	
	Gansu Nuclear Technology Industrial Park.	Under development.	200 MT/y.	
	Reprocessing Plant. Based on Orano technology. Site location TBD.	Under development. Target early 2030s.	800 MT/y.	LWR fuels.
France	Marcoule UP1.	1958 to 1976.	900 MT/y Military.	GGR.
		1976 to 1993.	Military and civilian.	
		1993 to 1997.	Civilian.	
	LaHague UP2.	1966 to 1976.	800 MT/y.	GGR.
	LaHague UP2-400.	1976 to 2004.	400 MT/y.	LWR and GGR.
	LaHague UP2-800.	1994 to present.	800 MT/y.	LWR.
	LaHague UP3.	1989 to present.	800 MT/y.	LWR, MOX, RR.
Germany	Karlsruhe Reprocessing Plant.	1971 to 1990.	Pilot Plant 35 MT/y.	LWR.
	Wackersdorf Nuclear Reprocessing Plant.	Under development 1982 to 1988. Abandoned.	350 MT/y.	LWR.
India, Trombay, Bhabha Atomic Research Centre (BARC)	Uranium Thorium Separation Facility (UTSF).	2002 to present.	THOREX Pilot Plant.	ThO2 irradiated in CIRUS reactor.
	Power Reactor Thoria Reprocessing Facility (PRTRF).	2015 to present.	THOREX Pilot Plant.	ThO2 irradiated in Dhruva PHWR reactor.
	Plutonium Reprocessing Plant (PRP).	1964 to 1973.	PUREX 30 MT/y.	CIRUS reactor fuel. Al-clad metallic NU.

Country	Facility Name	Dates of Operation	Production Scale	Fuels Reprocessed
	PRP (refurbished).	1983 to present.	PUREX 60 MT/y.	Dhruva PHWR fuel. Al-clad metallic NU.
India, Kalpakkam, Indira Gandhi Centre for Atomic Research (IGCAR)	Kalpakkam Atomic Reprocessing Plant (KARP).	1996 to 2003 2009 to present.	PUREX 100 MT/y.	Madras Atomic Power Station (MAPS) PHWR fuel.
	KARP Expansion Project PReFRe-3A.	Under development.	PUREX.	
	Lead Mini Cell Facility.	2002 to present.	Pilot Plant.	Fast Breeder Test Reactor (FBTR) U/Pu carbide fuel.
	Compact Reprocessing Facility for Advanced Fuels (CORAL).	2003 to present.	Pilot Plant 12 kg/y.	FBTR U/Pu carbide fuel.
	Demonstration Fast Reactor Plant (DFRP).	Under development.	Demonstration Plant 100 to 500 kg/y.	FBTR and Prototype Fast Breeder Reactor (PFBR) fuels.
	Fast Reactor Fuel Reprocessing Plant (FRFRP).	Under development.	14 MT/y.	PFBR fuels.
India, Tarapur, Bhabha Atomic Research Centre (BARC)	Tarapur Plutonium Pant.	1964 to 1974.	PUREX 30 MT/y.	CIRUS reactor fuel. Al-clad metallic NU.
	Tarapur Plutonium Pant (Refurbished).	1984 to 1997.	PUREX 50 MT/y.	CIRUS and Dhruva reactor fuels. Al-clad metallic NU.
	Power Reactor Fuel Reprocessing Plant – 1 (PReFRe-1).	1979 to present.	100 MT/y.	MAPS and Rajasthan Atomic Power Station (RAPS) PHWR fuels.
	Power Reactor Fuel Reprocessing Plant – 2 (PReFRe-2).	2011 to present.	100 MT/y.	MAPS and RAPS PHWR fuels.
	Integrated Nuclear Recycle Plant (IP-1).	Under development.	600 MT/y.	

Country	Facility Name	Dates of Operation	Production Scale	Fuels Reprocessed
Japan	Tokai Reprocessing Plant.	1977 to 2009.	100 MT/y.	LWR, MOX.
	Rokkasho Nuclear Fuel Cycle Facility.	Target 2021.	800 MT/y.	LWR, MOX.
Russia, Production Association Mayak (PO Mayak), Ozersk (Formerly Chelyabinsk-65)	Defense Radiochemical Facility, Plant B (a.k.a., Plant 24).	1948 to early 1960s (Shutdown as Plant BB was brought online.).		Spent fuels from plutonium production reactors.
	Defense Radiochemical Facility, Plant BB (a.k.a., Plant 35).	1959 to 1987.		Spent fuels from plutonium production reactors.
	RT-1 Reprocessing Facility (Incorporating parts of Plant B).	1977 to 2016.	400 MT/y.	VVER-440, BN, and Naval fuels.
	RT-1 Reprocessing Facility (Refurbished).	2016 to early 2030s (To be shut down as RT-2 comes online.).	400 MT/y.	VVER, RBMK, BN, and Naval fuels.
Russia, Siberia Chemical Enterprise (SCE), Seversk, (Formerly Tomsk-7)	Radiochemical Works (RCW) Unit 15 (Contained two reprocessing lines.).	1961 to 1994 1962 to 1994.	6,000 MT/y.	Spent fuels from plutonium production reactors.
	Pilot Demonstration Power Complex (PDPC) Nitride Fuel Plant KEU-2.	Under development. Target 2024.	5 MT/y.	BREST-300 mixed nitride fuels.
Russia, Zheleznogorsk (Formerly Krasnoyarsk-26)	Defense Radiochemical Facility.	1953 to 1995.	3,000 MT/y.	Spent fuels from plutonium production reactors.
	RT-2 Reprocessing Facility.	Under development. Target 2025.	1,000 to 1,500 MT/y.	VVER, RBMK, BN and fuels.
	Pilot Demonstration Centre (PDC).	2015 to present.	10 to 250 MT/y as capacity is increased.	VVER and BN fuels.

Country	Facility Name	Dates of Operation	Production Scale	Fuels Reprocessed
United Kingdom, Sellafield	B204 Reprocessing Plant.	1952 to 1964.	300 to 750 MT/y.	Windscale Pile, MAGNOX.
	B204 Head-End Plant (Head-end to B205.).	1969 to 1972.		LWR.
	B205 (aka MAGNOX) Reprocessing Plant.	1964 to 2020.	Military and civilian. 1,500 MT/y.	MAGNOX.
	Thermal Oxide Reprocessing Plant (THORP).	1994 to 2018.	1,200 MT/y.	AGR, LWR.

B REPROCESSING PLANT STATUS (AS OF THE END OF 2006)

From Spent Fuel Reprocessing Options, IAEA-TECDOC-1587, © IAEA, 2008, Table I-1, status as of the end of 2006:

I-1. PAST, CURRENT AND PLANNED REPROCESSING CAPACITY IN THE WORLD (tHM/year)

Country	Site	Plant		Operation		Capacity	
				Start	Shut-down	Present	Future
Belgium	MOL	Eurochemic	LWR	1966	1975		
China	Jiuquan	RPP	LWR	?			25
	Lanzhou		LWR	2020			800
France	Marcoule	APM	FBR	1988	1996		
	Marcoule	UP1	GCR	1958	1997		
	La Hague	UP2	LWR	1967		1000	1000*
	La Hague	UP3	LWR	1990		1000	1000*
Germany	Karlsruhe	WAK	LWR	1971	1990		
India	Trombay	PP	Research	1964		60	60
	Tarapur	PREFRE 1	PHWR	1974		100	100
	Kalpakkam	PREFRE 2	PHWR	1998		100	100
	Kalpakkam	PREFRE 3A	PHWR	2010			150
	Tarapur	PREFRE 3B	PHWR	2012			150
Japan	Tokai-mura	JAEA TRP	LWR	1977		90	90
	Rokkasho-mura	JNFL RRP	LWR	2007		800	
Russian Fed.	Chelyabinsk	RT1	WWER-440, BN-350, BN-600 RR	1977		400	400
	Krasnoyarsk	RT2	WWER-1000	2025			1500
		Demonstrative facilties	VVER-1000 RBMK	2013			50÷ 100
UK	Sellafield	B205	GCR	1967	2012	1 500	
	Sellafield	Thorp	LWR/AGR	1994		900	1 000
	Dounreay	UKAEA RP	FBR	1980	2001		
USA	West Valley	NFS	LWR	1966	1972		
	Hanford	Rockwell	U metal	1956	1989		
	Savannah River	SR	U metal	1954	1989		
	Idaho Falls	R	U-Al alloy	1959	1992		
Total Capacity						5950	6 525

* 1000tHM for each plant with a cumulated maximum of 1700 tHM for the La Hague site

From Spent Fuel Reprocessing Options, IAEA-TECDOC-1587, © IAEA, 2008, Table I-2:

I-2. CUMULATIVE AMOUNTS OF CIVIL REPROCESSED SPENT FUEL (tHM, the end of 2006)

Country	Site	Plant	Fuel Type				
			GCR	LWR	FBR	MOX	TOTAL
Belgium	Mol	Eurochemic[a]	19[b]	86			105
France	Marcoule	UP1	18 000[c]				18 000
	La Hague	UP2/UP3		22 450	100	150	22 700
Germany	Karlsruhe	WAK[a]		180			180
India	Trombay	PP					
	Tarapur	Prefre-1					
Japan	Tokai-mura	TRP		1 000		18	1 018
Russian Fed.	Chelyabinsk	RT-1		3 550	450		4 000
UK	Sellafield	B205	42 000[e]				42 000
	Sellafield	Thorp		5 800[f]			5 800
	Dounreay	UKAEA RP			14		14
USA	West Valley	NFS[a]		194			194
TOTAL			60 019	33 260	564	168	94 011

[a] Closed facility [b] CANDU, GCR and other [c] UNGG [d] Spent fuel from Fugen [e] Magnox
[e] LWR/AGR

Table 10-1. Reprocessing at La Hague for foreign customers (end of 2009) [adapted from (Greneche, Reprocessing and Recycling of Used Nuclear Fuels: The French Feedback Experience and International Aspects, 2010)]

Country	HLW Remains in France [MTHM]	HLW Returned to the Country of Origin [MTHM]
The Netherlands	79	247
Belgium	40	631
Switzerland	70	701
Japan	151	2793
Germany	172	5311

C FUEL CYCLE ECONOMIC ANALYSIS STUDIES

This appendix provides a sampling of comparative economic analyses for several fuel cycles:

1. Once-through.
2. Single reprocessing of used UOX converting the reprocessed uranium and plutonium into MOX to be used in LWRs.
3. Multiple reprocessing with reprocessed fissile material in a combination of LWR MOX and fast reactor MOX (FR-MOX).
4. Near fully closed: many reprocessing cycles reinserting reprocessed fast reactor fuel back into fast reactors. The fast reactors would use not only uranium and plutonium, but also most of the transuranics, as well (e.g., Am, Pu, Cm).

Not all of the sample studies that follow consider all four fuel cycles.

C.1 Cost of Reprocessing in France

A 2000 report to the French prime minister, "Economic Forecast Study of the Nuclear Power Option" (Charpin, Dessus, & Pellat, 2000), developed costs for electricity generated by nuclear power in France based on six scenarios shown in Table 10-1.

Table 10-1. Scenarios used to consider economic costs of alternative fuel cycles [adapted from (Charpin, Dessus, & Pellat, 2000)]

Reactor Service Life (years, average)	41	45
Reprocessing ends in 2010	**Scenario 1**	**Scenario 4**
Single-use reprocessing, partial used UOX use (20 LWR reactors using MOX)	**Scenario 2**	**Scenario 5**
Single-use reprocessing, full used UOX use (28 LWR reactors using MOX)	**Scenario 3**	**Scenario 6**

The economic study also included many other assumptions that are not reported here.

The bottom-line results were reported in terms of the mean cost of electricity per kW-hr (Table 10-2). Compared to the cost of the scenarios for which it is assume reprocessing stopes in 2010, the cost of electricity for the two scenarios using 100% reprocessing is 1% higher, which is certainly within the range of uncertainty. Although the authors specifically state that the results should be used with "caution", it seems reasonable to conclude that there is no significant difference in cost with or without the use of reprocessing for the scenario of reprocessing of used nuclear fuel for use in LWR reactors.

Table 10-2. Mean cost of electricity for six nuclear power scenarios in France relative to Scenario 1 [adapted from (Charpin, Dessus, & Pellat, 2000)]

Scenario	Mean Cost of Electricity per KW-hr Relative to Scenario 1
1	1.000
2	1.005
3	1.010
4	0.992
5	0.950
6	0.956

C.2 Boston Consulting Group Cost Study (BCG, 2006)

Perhaps the most optimistic cost study of the use of reprocessing was performed by the Boston Consulting Group (BCG) (BCG, 2006). BCG's study was funded by AREVA (now Cogema, operator of the La Hague reprocessing facility in France) for the United States market comparing the economics of the once-through scenario versus reprocessing and use of MOX in existing LWRs and – eventually – fast reactors (i.e., fully transitioned to an advanced fuel cycle) (BCG, 2006). The study assumed used UOX fuel from existing LWRs would be reprocessed and converted to MOX fuel to be used in LWRs. Used MOX fuel would be generated at a rate of 300 MHM per year and would be stored until such time as fast reactors came online.

A potentially significant advantage BCG had was access to proprietary economic data for La Hague; such data have been unavailable for most economic studies.

BCG (2006) determined the net cost of recycling by evaluating the costs of reprocessing, MOX fuel fabrication, disposal costs for HLW and compacted waste and transportation, and credits for the value of MOX and reprocessed uranium-based fuels. The reprocessing facility annual throughput was assumed to be 2500 MTHM per year, compared to the throughput of La Hague of 1700 MTHM per year and the Rokkasho plant nearing completion (800 MTHM per year). Also, this exceeds the existing annual used fuel generation rate in the U.S. of approximately 2000 MTHM.

The BCG (2006) report concluded that the undiscounted total life-cycle cost for a fuel cycle that has already fully transitioned to use of MOX fuel would be $113 billion compared to a cost range of $124 billion to $130 billion for a once-through cycle with spent UOX sent to Yucca Mountain. BCG (2006) estimated that the cost of implementing reprocessing followed by the

one-time use of MOX is between -$50/kg and +$100/kg (-10% to +20% of the total recycling strategy cost).[35]

The report lists several benefits from the fully transitioned scenario:

- It eliminates the need for a second repository by reducing the volume of waste but only by assuming the legal capacity of Yucca Mountain is increased from 70,000 MTHM to 120,000 MTHM[36].
- Younger (reactor discharge within three years), hotter fuel would be taken first thereby relieving decay heat issues for spent fuel pools.
- Use of existing technology "with appropriate modifications" such as the use of a reprocessing facility using the COEX process that does not generate a pure plutonium stream versus the PUREX process used at La Hague that does generate a pure plutonium stream.
- Provides experience for an operational transition to future technology developments such as advanced fuel cycles and fast reactors.
- Notes that reprocessing costs are independent of uranium prices and enrichment costs.

BCG (2006) included several assumptions that tended to minimize the relative cost of using a fuel cycle requiring reprocessing compared to a once-through fuel cycle:

- A relatively high increase in the use of nuclear power in the U.S.[37].
- A relatively low cost of money (3% per year) that would be more typical of a government-owned facility.
- Increasingly higher uranium prices going forward.
- The reprocessing facility would have a throughput of 2500 MTHM/yr.
- The reprocessing facility would become available in 2020[38] All used fuel generated after 2020 would be reprocessed.

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[35] Note that this cost estimate range is ten times lower than that assumed in (EPRI, 2009): $500 to $1500/kg. Furthermore, the EPRI (2009) cost estimate was based on use of the existing PUREX process, whereas the BCG (2006) study assumed a COEX process that has not yet been used at an industrial scale.

[36] Technically, the Yucca Mountain site is capable of being expanded to significantly higher than that (EPRI, 2007a) (DOE, 2008).

[37] Presumably, lower nuclear power growth rates would decrease the value of transitioning to a fuel cycle using MOX fuel in LWRs. Also, over the next decade, it is more likely that the number of nuclear power plants in the U.S. will decrease slightly.

[38] Based on the assumed used UOX production rate of 2000 MTHM/yr and a reprocessing rate of 2500 MTHM/yr, BCG (2006) determined that 40% of the existing used UOX fuel in existence in 2020 would be able to be recycled.

- The reprocessing plant would be able to keep up with a higher degree of nuclear power production until about 2070.
- The Yucca Mountain site would be allowed to dispose of the equivalent of 120,000 MTHM compared to the existing legal limit of 70,000 MTHM (of which 63,000 MTHM is assumed to be from commercial nuclear power with the remaining from defense-related activities).
- None of the used MOX would be disposed of[39]; used MOX would be saved for some time in the future when the authors assumed a fully-developed fast reactor fleet would be available to use part of the reprocessed used MOX as fuel. This assumption lowers its disposal cost estimate by an unknown, but potentially significant amount.
- The reprocessing plant has a 50-year lifetime (may or may not be optimistic).

C.3 EPRI 2009 Cost Study (EPRI, 2009)

The economics of reprocessing is generally not considered as the main reason to implement reprocessing for the current LWR operating fleet. However, in the future AR market and considering that certain designs are being developed to take advantage of the energy that currently resides in the spent fuel, the economics of reprocessing could become more convenient. EPRI (2009) evaluated the economics of reprocessing for the current fleet. The cost of nuclear fuel and fuel cycle services comprise a relatively minor fraction of the overall cost of nuclear generated electricity, i.e., typically less than 20% (Figure 10-1) if capital and O&M costs are included, and the costs associated with back-end fuel cycle services, including reprocessing and disposal, represent an even smaller fraction, i.e., <5%.

[39] The authors state that "[d]isposal of used MOX in Yucca Mountain is not considered a viable option because it would almost entirely eliminate the repository optimization benefits gained through densification" (BCG, 2006).

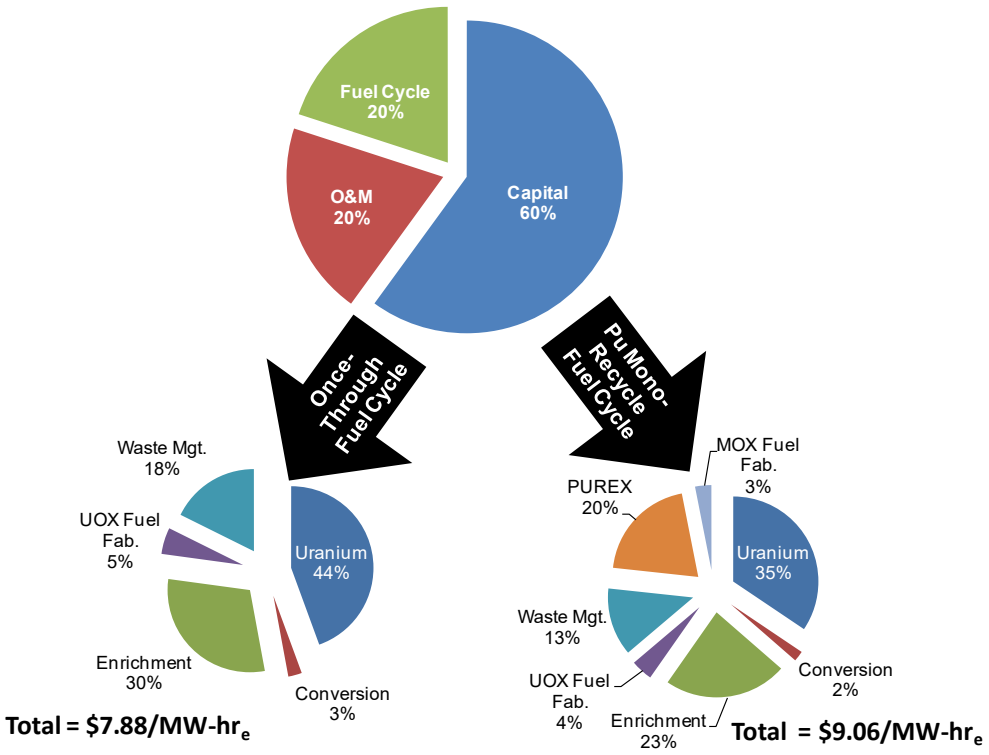

Figure 10-1. General cost breakdown for nuclear electricity and fuel cycle cost breakdown for once-through and Pu mono-recycle (Data from (EPRI, 2009), Table 3-3)

C.4 EPRI 2010 Cost Study (EPRI, 2010c)

EPRI has performed fuel cycle cost comparisons for a range of options, and (EPRI, 2009) includes results for the comparison between the once-through and Pu mono-recycle fuel cycles[40]. The results underscore that costs for the two fuel cycles are most sensitive to the price of uranium and reprocessing services. Ultimately, reprocessing of used UOX fuel for single recycle as MOX in LWRs appears competitive as long as natural U costs are high compared to current prices (e.g., higher than $400/kg)[41] and the reprocessing costs are kept low (e.g., below $1000/kgHM[42]).

[40] Under both once-through and Pu mono-recycling scenarios, direct disposal of used UOX and MOX are required.

[41] As of early July 2003, the price of natural uranium was about $120/kgHM.

[42] Kg of heavy metal

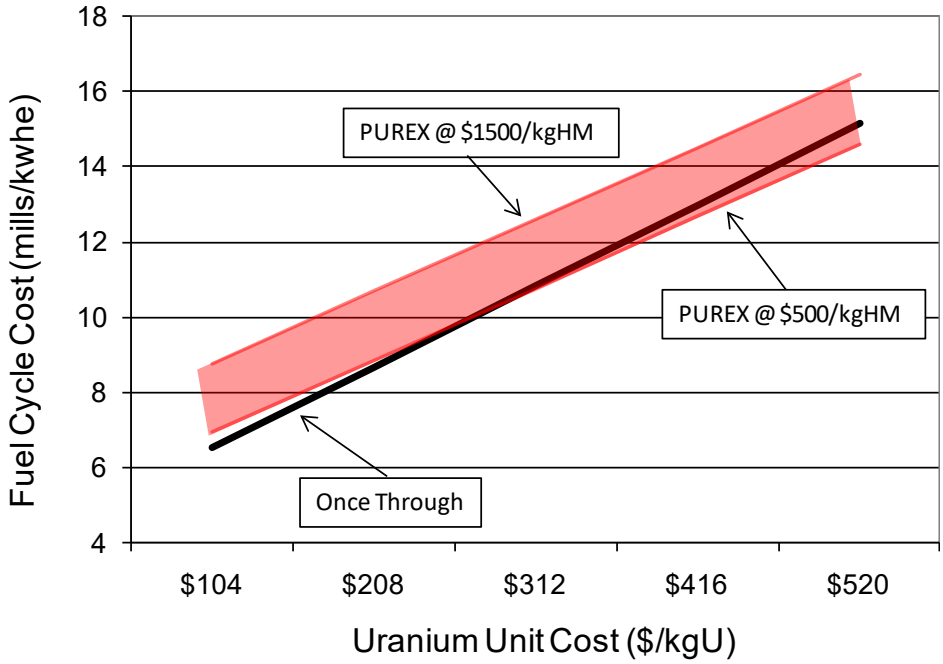

Figure 10-2. Comparison of once-through and Pu mono-recycling fuel cycle costs as a function of uranium ore concentrate and PUREX reprocessing costs adapted from (EPRI, 2009)

Mono-recycling of Pu in LWRs can be expected to reduce front-end fuel cycle costs (given the savings in natural uranium and enrichment) and some waste management costs; however, if these savings do not offset increases due to PUREX reprocessing services and MOX fuel fabrication, then the overall back-end and fuel cycle costs will increase. Conversely, the corresponding decrease in reliance on the front-end further decreases sensitivity of nuclear electricity costs to the price of natural uranium and enrichment.

C.5 Harvard 2005 Cost Study (Bunn, Holdren, Fetter, & van der Zwaan, 2015)

The Harvard study compared costs of a once-through cycle to two cases; (1) cost of reprocessing to produce MOX for a single use in LWRs; and (2) cost of reprocessing and fabrication and use of fuel in fast reactors (Bunn, Holdren, Fetter, & van der Zwaan, 2015). Some of the authors' conclusions are:

- Case 1 compared to once-through[43]:

[43] 2005 dollars

  - Assuming a reprocessing price of $1000/kg HM[44] and with other central estimates for key fuel cycle parameters in their study, the breakeven price for uranium would be $370/kg.
  - A uranium price of $50/kg U and reprocessing and recycling price of $1000/kg HM would increase the cost of nuclear electricity by 1.3 mill/kW-hr, which is more than 80% higher for waste management (including credits and charges for recovered plutonium and uranium).
- Case 2 compared to once-through:
  - Using central cost parameters, reprocessing in conjunction with fast reactors will not be economically competitive until uranium costs exceed $340/kg U. This assumes the capital costs for fast reactors is higher than LWRs by $200/kWe.
  - For a uranium price of $50/kg, the cost of reprocessing in conjunction with fast reactors would be about 7 mill/kW-h higher than for the once-through scenario.

The authors note that the above numbers are conservative since some costs were neglected.

C.6 EPRI 2010 Cost Study Comparing a Once-Through to Plutonium Recycling in Fast Reactors (EPRI, 2010b)

This report describes a parametric study of "equilibrium"[45] fuel cycle costs comparing a once-through fuel cycle with a fuel cycle involving multiple recycling of plutonium and then use in a combination of LWRs and fast reactors (Figure 10-3). It compares fuel cycle costs using variations of uranium costs, advanced PUREX reprocessing and use of MOX fuel in a combination of LWRs (MOX) and fast reactors (FR-MOX) including fuel fabrication. Parameters investigated were: costs of uranium, uranium enrichment, advanced PUREX reprocessing services (for both UO_2 and FR-MOX fuels) and UO_2 and FR-MOX fuel fabrication. Of note is that the cost of fast reactor construction and operation compared to similar PWR costs was not considered.

[44] Lower than their central estimate of $1500/kg HM

[45] Assumes the nuclear industry has already fully transitioned to the new fuel cycle such that NOAK fast reactors are constructed and operated. Thus, this neglects startup and transition costs such as FOAK facilities.

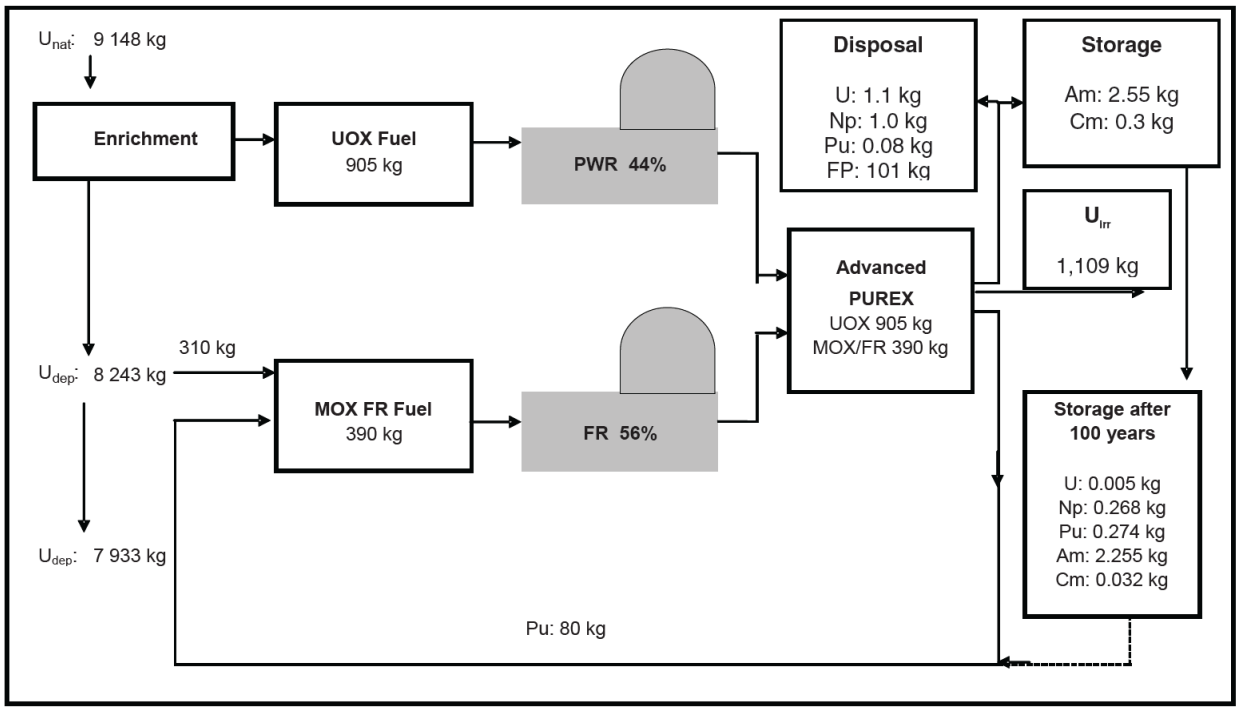

Figure 10-3. Multiple plutonium recycling using MOX fuel in fast reactors – mass flow assumptions per terawatt-hour-electric (TWhe). "PWR 44%" and "FR 56%" refer to the fraction of total energy supplied by PWRs using fresh UO2 and FRs using FR-MOX fuel, respectively. [(EPRI, 2010b) Figure 1-2]

The model used the Steady-State Analysis Model for Advanced Fuel Cycles Schemes (SMAFS) computer modeling code (EPRI, 2007b) for the two fuel cycles includes the following data input parameters:

- Unit cost parameters associated with fuel cycle costs include:
  - Front-end fuel cycle (natural uranium, conversion, enrichment, fuel fabrication).
  - SNF transport and storage for all fuel types to be transported and stored.
  - Reprocessing (advanced PUREX) of UO2 and FR-MOX fuel.
  - Dry storage, packaging and long-term storage for all fuel types considered. Long-term
  - Storage costs for materials such as depleted uranium (DU), and reprocessed uranium
  - Reprocessed uranium (REPU).
  - Waste disposal, including short-lived (SL) and long-lived (LL), low and intermediate level waste [LILW], and SNF and HLW.
- Waste generation parameters associated with:
  - Front-end of the fuel cycle (enrichment and fuel fabrication).
  - Reactor operation: LILW-SL, LILW-LL, and SNF.

- Advanced PUREX reprocessing: LILW-SL, LILW-LL, and HLW.

Variations in unit parameters were labeled “nominal value” (NV), “lower bound” (LB) and “upper bound” (UB). Nominal values for waste managment costs were calculated to be 1.39 and 0.84 mills/kWhe for the once-through and PWR and PWR/fast reactor fuel cycles, respectively. Total fuel cycle costs (mills/kWhe) were calculated to be 7.88 and 6.50 for the once-through and PWR and PWR/fast reactor fuel cycles, respectively.

As for almost all other cost studies, variations in uranium and reprocessing costs are the main drivers in the cost of fuel cycles – excluding NOAK reactor construction and operations costs.

> *Assuming the nominal fuel cycle costs described in this report, EPRI calculates that the overall fuel cycle costs associated with multiple FR-MOX recycles in fast reactors are 21% lower than the nominal fuel cycle costs for the once-through fuel cycle.*
>
> *However, the fuel cycle costs associated with multiple FR-MOX recycles in FRs are not yet proven. In other words, there are large uncertainties for the costs associated with the advanced PUREX reprocessing of UO_2 and FR-MOX fuels and for the fabrication of FR-MOX fuel. … Thus, the costs associated with these advanced fuel cycle schemes should be regarded as highly uncertain at this time (EPRI, 2010b)*

Bearing in mind uncertainties, another conclusion from this study is that transitioning to a fuel cycle involving a combination of PWRs and fast reactors that could both burn MOX may be worth the up-front transition costs to realize the long-term cost benefit.

C.7 EPRI Cost Study for a Fully Closed Fuel Cycle (EPRI, 2010b)

In a manner similar to its two previous studies discussed above, EPRI conducted another cost comparison between a once-through fuel cycle and a “fully closed” fuel cycle using Advanced PUREX reprocessing to recycle FR-MOX fuel multiple times for continued use solely in fast reactors (Figure 10-4) (EPRI, 2010b). In addition to recycle of uranium and plutonium, minor actinides are also assumed to be separated and recycled for use. Using the same SMAFS code used previously (EPRI, 2007b), EPRI assumed the fuel cycle employing multiple recycle of fast reactor fuel was at equilibrium (full transition to this advanced fuel cycle has already occurred)[46] and the conversion ratio for the fast reactors is 1, meaning the amount of fissile material produced equals the fissile material consumed. No fuel would be directly disposed in this fuel cycle – only HLW from reprocessing.

In addition to the parameters that were varied in previous EPRI studies discussed above, a few other indicators of interest were tracked:

[46] Regarding equilibrium, EPRI (2010b) states: “It should be noted that establishing equilibrium conditions may require decades or more and the real fuel cycles are not typically in equilibrium.”

- Reduction of transuranics (TRU) in the waste, referred to as “TRU Loss.” This indicator is dependent on the number of times the used fuel is recycled
- A few indicators of interest for geologic disposal:
  - Activity of HLW after 1000 years
  - Decay heat of HLW after 50 and 200 years since decay heat limits are set for various types of disposal geologies;
  - Volume of waste to be disposed, which provides an indication of how much disposal capacity is required.

For the nominal case, EPRI (2010b) calculated that the cost for the once-through and fully closed fuel cycle using reprocessing of fast reactor fuel is 7.88 and 4.78 Mills/kWhe, respectively. Waste management costs for the once-through fuel cycle were found to be 90% higher due to a reduced need for HLW storage, transportation and disposal for the advanced fuel cycle case. Thus, if the costs are at the nominal value, transitioning to a fully closed fuel cycle might make economic sense over the very long run. However, again, the primary factors influencing costs are the price of uranium and the cost of Advanced PUREX reprocessing. If the uranium cost is at the lower bound set in the model, pursuing this advanced fuel cycle may not be worthwhile. Furthermore, there are large uncertainties in the cost estimate for the advance fuel cycle due to lack of experience.

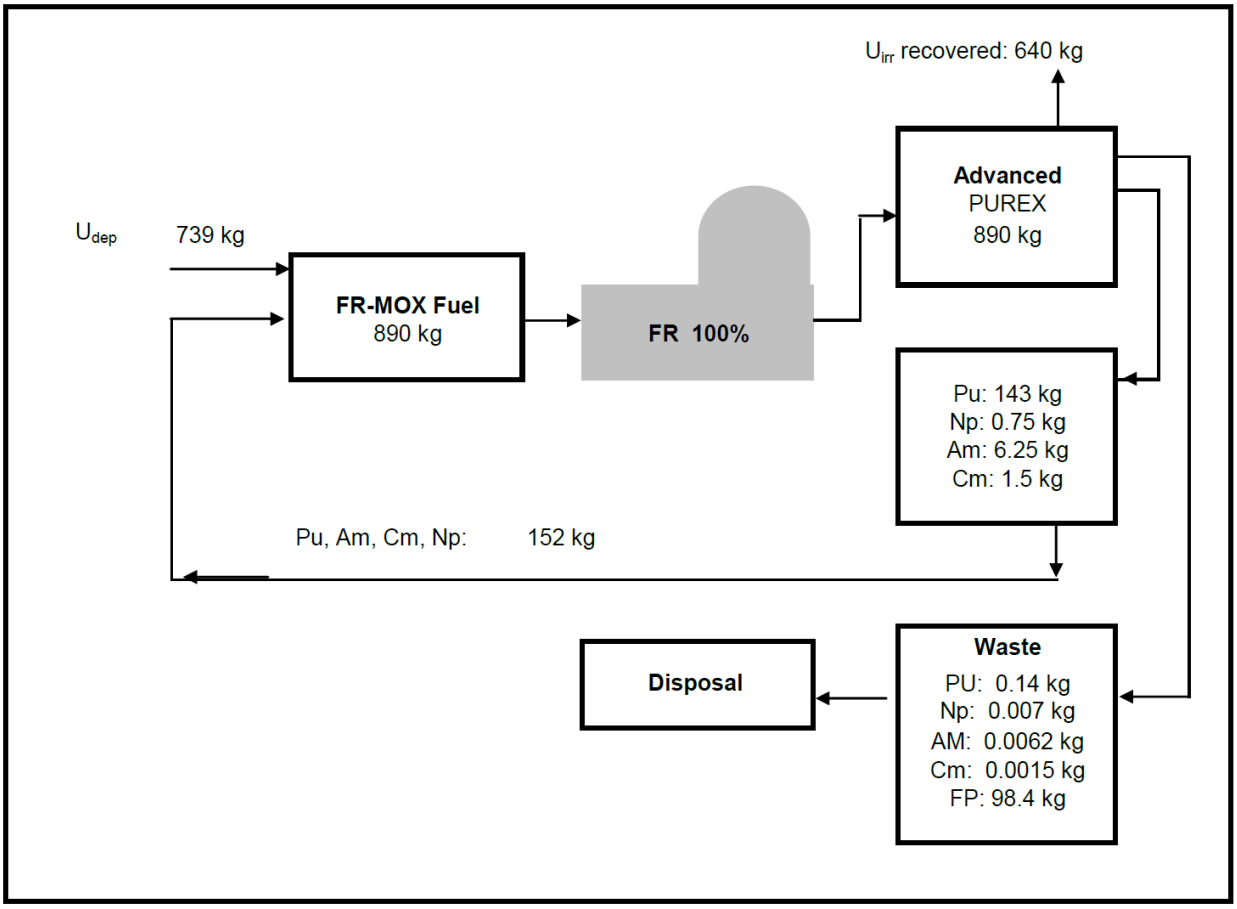

Figure 10-4. Fully closed fast reactor fuel cycle involving multi-recycling of plutonium and minor actinides – mass flow assumptions per TWHe. FP: fission products [taken from Figure 1-2 in (EPRI, 2010b)]

C.8 Cost Comparisons of Once- and Twice-Through Fuel Cycles Rodriquez-Penalonga and Moratilla Soria (2017)

Rodriquez-Penalonga and Moratilla Soria (2017) summarized the history of estimated once-through and twice-through (PUREX-reprocessed plutonium used a single time as MOX in an LWR) from eight fuel cycle economic studies, shown in Figure 10-5. An additional study discussed above, (EPRI, 2009), determined that the cost of electricity for the once-through and single MOX recycle in an LWR was 7.88 and 9.06 mill/kWhr, respectively. These numbers were added to Figure 10-5.

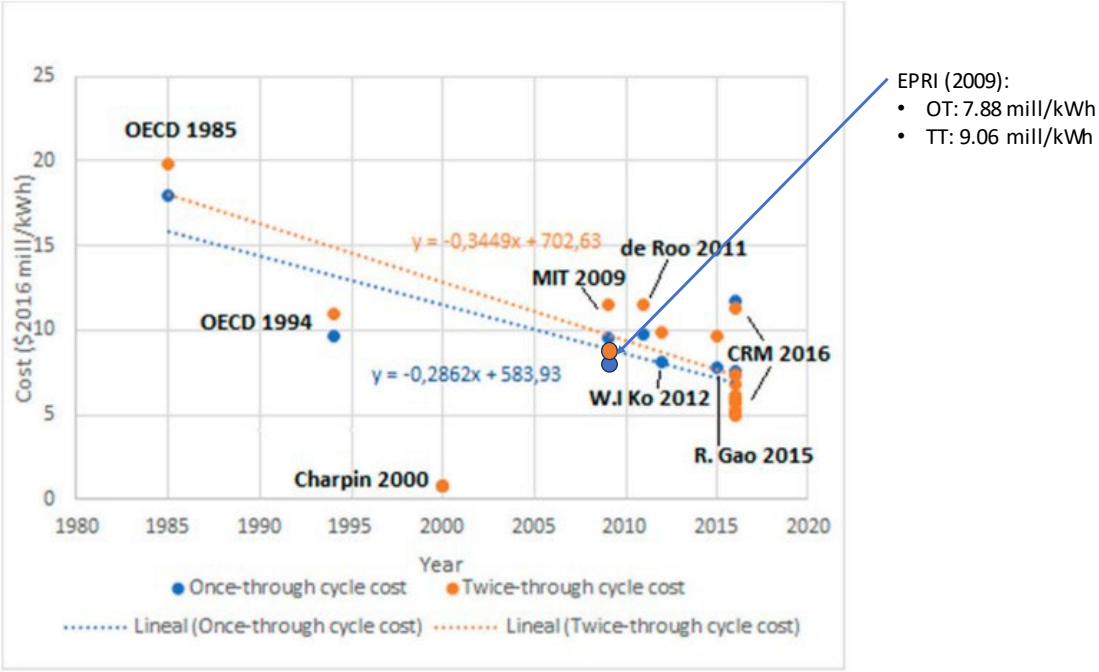

Figure 10-5. Evolution of once-through and single recycle of MOX in LWRs fuel cycle costs ($2016 mill/kWh). Compiled from eight economic studies [adapted from Rodriguez-Penalonga & Moratilla Soria, 2017 with (EPRI, 2009) data added]

Cost estimates in USD mill/kWhr for the two fuel cycles decrease with time until approximately 2009. Cost estimates from 2009 through 2016 included in the study result in the following ranges:

Fuel Cycle	Low	High
Once-Through	8	12
Twice-Through (single MOX use in LWR)	5	12

Seven of the nine studies calculated that the single recycle electricity cost was higher than the once-through cost. Two studies determined the opposite. The relatively wide range in fuel cycle costs is attributable to the range of assumptions made in each study. It should also be reiterated that the uncertainty in the single recycle fuel cycle cost is relatively high compared to the once-through fuel cycle costs for which there is considerably more experience.

Also from the same paper, (Rodriguez-Penalonga & Moratilla Soria, 2017), the authors compared the history of deep geologic repository (DGR) and reprocessing costs from six sources. Figure 10-6 shows the general trend upward in DGR cost estimate and a general trend downward in reprocessing costs. Figure 10-5 and Figure 10-6 together suggest that the economic conditions to support at least some advanced fuel cycles is trending in a favorable direction. However, there is no clear trend in uranium prices, which is a key factor in reprocessing economics.

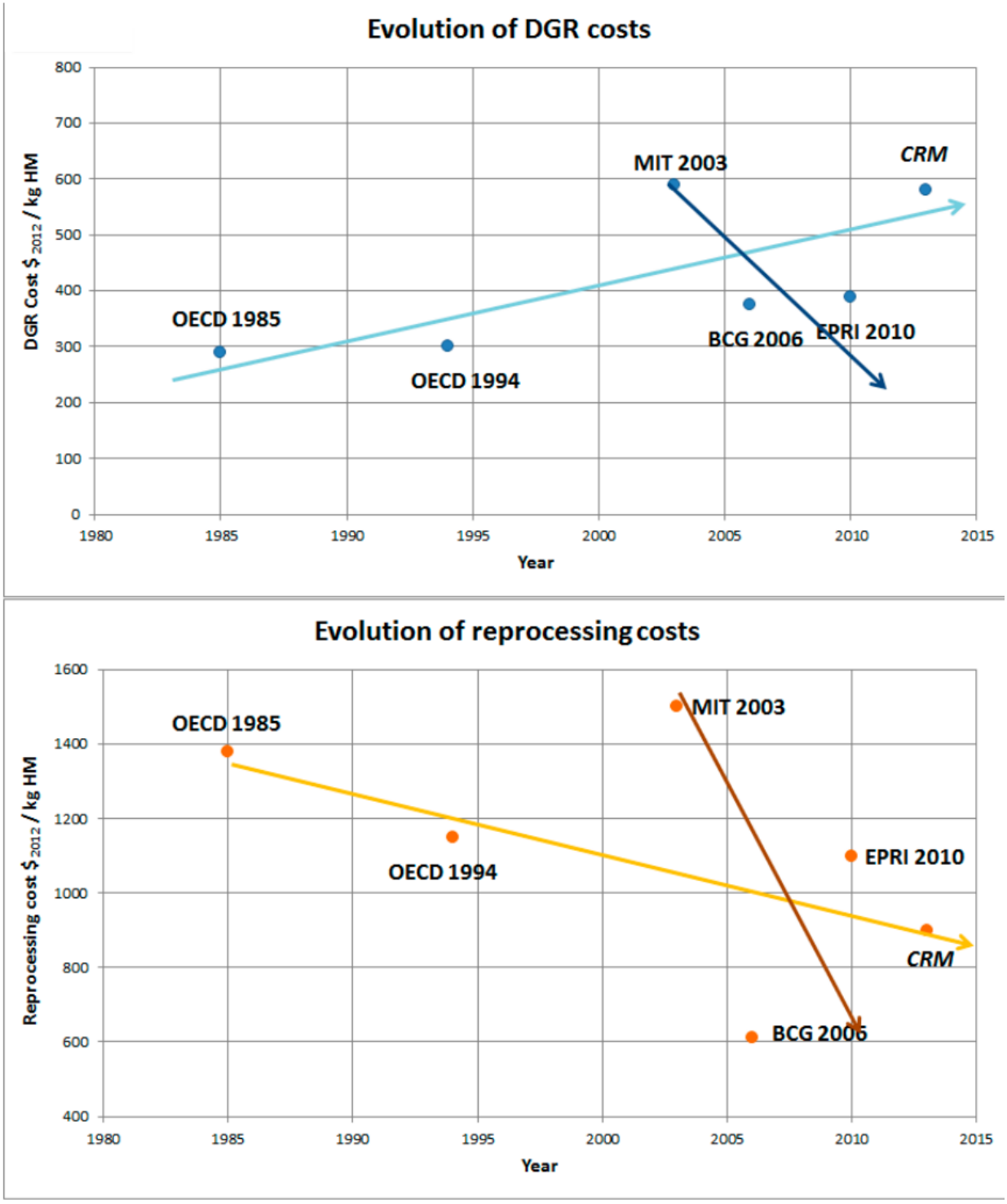

Figure 10-6. Evolution of deep geological repository (DGR) and reprocessing costs [from Rodriguez-Penalonga & Moratilla Soria, 2017)]

However, as with all economic forecasts, past behavior is not a guarantor of future cost estimates. If switching to an advanced fuel cycle is to be done solely by industry, the nexus of

economic conditions to support a fuel cycle involving reprocessing needs to exist for long enough that utilities and their investors are willing to take the risk to proceed all the way to full implementation (NOAK advanced reactors and potentially reprocessing facilities). However, by the time market signals become consistent enough, the need for advanced fuel cycles would be near-immediate. Thus, it would be best to have an advanced fuel cycle well on its way to full implementation (e.g. TRL-8 or -9) ahead of 100% favorable economics. In all likelihood, this will only happen with government support.

C.9 Observation on the Relative Costs of the Once-Through Fuel Cycle versus Fuel Cycles Using Reprocessing

Based on the cursory review of specific cost studies for the once-through fuel cycle versus fuel cycles requiring reprocessing, it can be seen that devil is in the details. Depending on differences in the myriad of economic assumptions made when developing bottom-line cost numbers, one can conclude that the cost fuel cycles requiring reprocessing can be either less than, approximately equal to, or greater than the cost of a once-through fuel cycle. There are several key cost assumptions that drive the final cost numbers such as, but not limited to the cost of: building fast reactors; uranium; building reprocessing facilities; geologic disposal; and the cost of borrowing money. Three of these particular factors have high uncertainties, but their uncertainties could be reduced with increasing technical and industrial experience: fast reactors, geologic disposal and reprocessing facilities.

D SAFEGUARDS EXAMPLE (IAEA, 2001)

The importance of ensuring any reprocessing facility to have a high level of safeguards to minimize the possibility of fissile material diversion is universal. A reprocessing facility requires multiple monitoring and material accountability systems throughout the plant – from the point at which used fuel enters until every fissile material and waste stream leaves the facility. An example of materials accountancy is provided in this appendix. The example is from the Rokkasho Reprocessing Plant (RPP) in Japan that is nearing completion.

The basic accountancy system for RRP is shown in Figure 10-7. The RRP is divided into five major Material Balance Areas (MBAs). Within each MBA, there are Inventory Key Measurement Points (IKMPs) that are based on the types of materials requiring measurement and the verification approach to be applied. The IKMPs provide input to Interim Inventory Verification (IIV) systems to provide timely inventory verifications. They also feed into the Physical Inventory Verification (PIV) system. There are Flow Key Measurement Points (FKMPs) for all nuclear material streams that cross between MBAs. All of this information flows into an Inventory Change Report (ICR) that "will be verified as required" (IAEA, 2001).

In addition, there are Other Strategic Points (OSPs) within individual MBAs for verification of material flows.

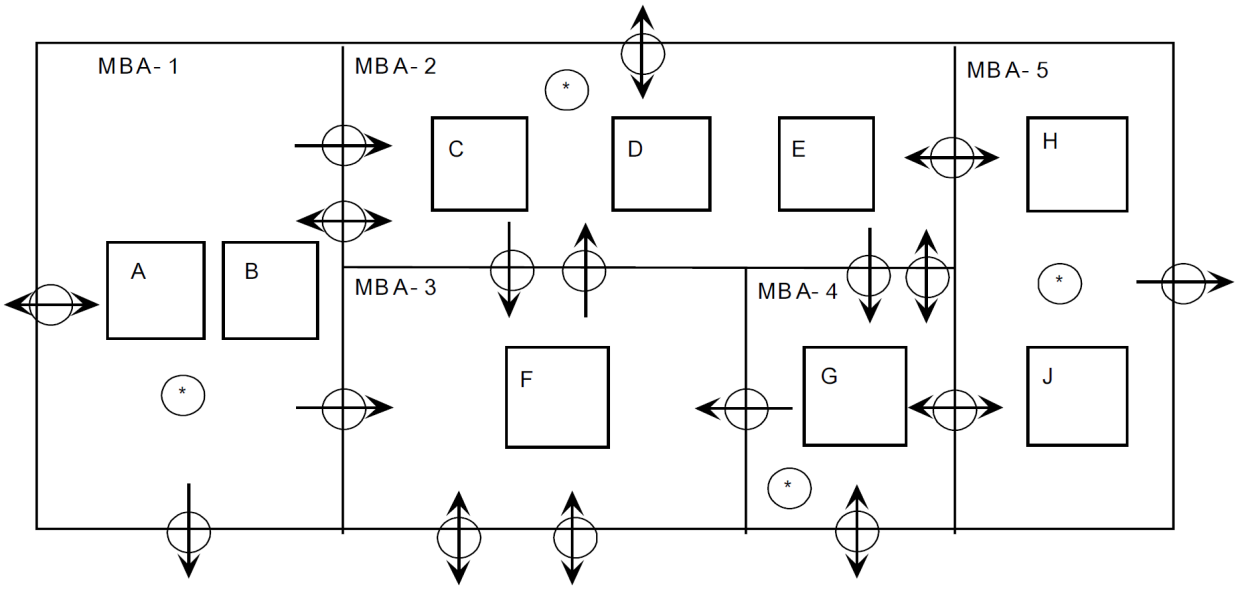

Figure 10-7. Rokkasho safeguards monitoring areas (IAEA, 2001)

The following is a brief description of the MBAs and IKMPs:

MBA-1: Spent fuel receipt and storage area, Head-end area
- **IKMP A:** Spent fuel receipt and storage area
- **IKMP B:** Head-end area

MBA-2: Main process area (including U conversion and laboratories)
- **IKMP C:** Nuclear material in main process area
- **IKMP D:** Nuclear material in the analytical laboratory
- **IKMP E:** Nuclear material in the U conversion area

MBA-3: Waste treatment and storage area
- **IKMP F:** Nuclear material in the waste treatment and storage area

MBA-4: MOX conversion area
- **IKMP G:** Nuclear material in the MOX conversion area

MBA-5: Product storage area
- **IKMP H:** UO3 product material in the storage area
- **IKMP J:** MOX product material in the storage area

*** :** Nuclear Loss
MBA: Material Balance Area
IKMP: Inventory Key Measurement Point

Verification methods and procedures have been developed for all flow and inventory points throughout the facility. Unattended measurement systems are installed as possible and will be controlled by the IAEA Inspectorate. Samples of solutions will be taken from the majority of the vessels using automated sampling systems. These are sent to an on-site laboratory that will be jointly monitored by the IAEA and the relevant Japanese authority.

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PROGRAM

Used Fuel and High-Level Waste Management, P41.03.01

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