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Waste Stream Analyses for Nuclear Fuel Cycles

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Idaho National Laboratory

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SUMMARY

A high-level study was performed in Fiscal Year 2009 for the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) Advanced Fuel Cycle Initiative (AFCI) to provide information for a range of nuclear fuel cycle options (Wigeland 2009). At that time, some fuel cycle options could not be adequately evaluated since they were not well defined and lacked sufficient information. As a result, five families of these fuel cycle options are being studied during Fiscal Year 2010 by the Systems Analysis Campaign for the DOE NE Fuel Cycle Research and Development (FCRD) program.

The analysis of these fuel cycles also requires an evaluation of potential waste streams for each option. The objective of this waste stream study is to obtain information about these waste streams that can be used to:

- Describe the quality and completeness of the data
- Describe (as practical) waste streams arising from each option
- Identify waste stream similarities and differences (discriminators) for the different options.

The waste stream study relied on the results of the five fuel cycle option studies done separately by the Systems Analysis Campaign. These five potential fuel cycle options are based on the following reactor concepts, which are described in more detail in interim status reports for these studies:

- Advanced Once-Through reactor concepts (Once-Through) (Taiwo 2010a)
- Fission-Fusion Hybrid (FFH) reactor concepts (Halsey 2010)
- High Temperature Gas Reactor (HTGR) (Piet 2010)
- Molten Salt Reactor (MSR) (Gehin 2010)
- Thorium/U-233 Fueled Light Water Reactor (Th/U-233) (Taiwo 2010b)

Waste Streams from the Fuel Cycle Options

Table S-1 summarizes the radioactive waste streams identified for the different analyzed options. Several waste streams (fuel fabrication wastes, reactor core structure materials, and cladding and fuel structure materials) would be radioactive due to contamination with radioactive fuel components, fission products, or activation products. This radioactivity will affect their recyclability and impact disposal requirements. Front-end radioactive wastes from mining and enrichment are listed for completeness. Amounts and concentrations of radioactive materials in these waste streams are expected to be much less than in used fuel, but the amounts of these wastes will vary for some of the fuel cycle options – for example, some options do not require U fuel enrichment, so depleted uranium would be eliminated in those options.

Noble gases (mainly xenon and krypton-85), iodine-137, carbon-14, and tritium are grouped together in the table as “gaseous fission products (FPs).” Gaseous FPs would evolve from all reprocessing options, and would be separately captured and immobilized in separate waste forms designed for the chemistry and to meet the disposal requirements for each of these gases, even though they are grouped together in the table.

Semivolatile and nonvolatile FPs can be separately captured and immobilized in separate waste forms, if desired, in some fuel cycle options. In other fuel cycle options, these FPs are more readily separated from recycled fuel in a single waste stream and immobilized in a single waste form.

Table S-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010.

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	Comments
Advanced Once-Through reactor concepts														
1	Ultra Long Life Fast Reactor (ULFR)	Mod. Open	Aqueous, Echem	Y	Y	Y	N	N	N	N		N	Y	
2	CANDLE	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
3	Fast Mixed spectrum reactor (FMSR)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	Same as CANDLE.
4a	Traveling Wave Reactor (TWR)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
4b	Traveling Wave Reactor (TWR)	Mod. Open	Melt refining	Y	Y	Y	N	Y	Y	Y	Y		Y	Melt refining, being a less efficient separations process, will result in actinide contamination in FP waste streams.
5a	Energy Multiplier Module (EM^2)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
5b	Energy Multiplier Module (EM^2)	Mod. Open	DUPIC	Y	Y	Y	N	Y	Y	N	N	N	Y	DUPIC chops but does not heat or dissolve SNF. In this DUPIC variant, cladding and gaseous FP are removed and disposed.

Notes:

1. Echem = electrochemical
2. LWR = light water reactor
3. CANDLE = Constant Axial shape of Neutron flux, nuclide density and power shape During Life of Energy production
4. Mod. Open = modified open cycle
5. DUPIC = Direct Use of spent PWR fuel In CANDU
6. SNF = spent nuclear fuel
7. CANDU = CANada Deuterium Uranium reactor

Table S-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010 (continued).

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	Comments
Fusion-Fission Hybrid (FFH) reactor														
1	CFNS coupled with FFTS waste burner	Full Recycle	Aqueous, Echem	N	N	Y	Y	Y	Y	Y		N	N	Burns waste from LWR used fuel reprocessing, multirecycle. Assumes the U mining/enrichment is attributed to the LWRs.
2a	Fission Suppressed Breeder (FSB) fissile fuel factory	Full Recycle	On-line	N	N	N	Y	Y	Y	Y		N	N	Assumes DU fuel, and wastes from U mining/enrichment is attributed to other reactors that need EU. Many variations are possible depending on U or Th fuel, and how bred U/TRU is cycled in other reactors.
2b	Fission Suppressed Breeder (FSB) fissile fuel factory	Full Recycle	On-line	Y	N	N	Y	Y	Y	Y		N	N	Assume Th fueled, so wastes from Th mining are included in this analysis.
3a	Laser Inertial Fusion Energy (LIFE) Once-Through deep burn concept	Once-Through	---	Y	N	N	Y	N	N	N		N	Y	This Once-Through variant assumes that gaseous FPs are retained in the fuel.
3b	Laser Inertial Fusion Energy (LIFE) Once-Through deep burn concept	Mod. Open	On-line	Y	N	N	Y	Y	Y	N		N	Y	This Mod. Open variant assumes that gaseous FPs are released from the fuel, captured, and disposed; and some cladding/fuel structure is discarded.

Notes:

1. CFNS = Compact Fusion Neutron Source fusion driver
2. FFTS = Fission Fusion Transmutation System
3. DU = depleted uranium
4. EU = enriched uranium
5. TRU = transuranic

Table S-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010 (continued).

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	Comments
High Temperature Gas Reactor (HTGR)														
1a	Once-Through HTGR	Once Through	---	Y	Y	Y	Y	N	N	N		N	Y	A TRISO fuel particle that retains gaseous FPs is assumed.
1b	Once-Through HTGR	Once Through	---	Y	Y	Y	Y	N	Y	N		N	Y	BISO fuel is assumed that vents gaseous FPs.
2	Minimal fuel treatment HTGR	Mod. Open	AIROX	N	N	Y	Y	Y	Y	Y			Y	Recycles LWR used fuel; limited separations; attribute U mining/enrichment to LWRs.
3	Single recycle in HTGR	Mod. Open	Aqueous or Echem	N	N	Y	Y	Y	Y	Y		N	Y	1st reactor could be LWR or HTGR; full separations.
4	Sustained recycle with HTGRs only	Full Recycle	Aqueous or Echem	N	N	Y	Y	Y	Y	Y		N	N	Full separations.
Molten Salt Reactor (MSR)														
1	Two-fluid Th MSR	Full Recycle	On-line	Y	N	N	Y	N	Y	Y		N	N	Full separations.
2	Single-fluid Molten Salt Breeder Reactor (MSBR)	Mod. Open or Full Recycle	On-line	Y	N	N	Y	N	Y	Y		N	N	Full separations.
3	Single-fluid Denatured Molten Salt Breeder Reactor (DMSBR)	Once Through	---	Y	Y	N	Y	N	Y	Y	N	N	Y	U238 is used for denaturing; sparging to remove gaseous and noble FP.
Thorium/U-233 Fueled Light Water Reactors (Th/U-233)														
1	Th/U233 fuel multirecycle in current PWRs	Full Recycle	Aqueous or Echem	Y	N	Y	N	Y	Y	Y		N	N	No U used after initial startup.

Notes:

1. AIROX = Atomics International Reduction Oxidation
2. Full Recycle systems maximize actinide utilization. Once-Through and Modified Open systems will have disposed actinides in spent fuel or in separated waste streams from reprocessing.
3. All fuel cycles may have about the same amounts of FP per unit of energy produced. Designs to transmute some FP exist; the FFH waste burner is the only one included in this analysis.
4. Most of the fuel cycle options are insufficiently defined to specify types and amounts of wastes from fuel fabrication, reactor cores, and cladding/fuel structure.
5. Wastes produced to provide starting fissile material, and reactor decommissioning wastes after closure, exist but are not included here. Fabrication facility, reactor operation, and separations facility operations and maintenance LLW can be significant but are not included here. Reactor core wastes include metallic and non-metallic core structures, moderators, and reflectors that must be periodically discarded and replaced. Fuel structure and cladding includes fuel assemblies, support structures, inert components of IMFs, coatings on particles and pebbles, and molten salts.

Advanced Once-Through Reactor Concepts

Advanced Once-Through fuel cycle concepts are designed to achieve higher U utilization than is typical for UOX-fueled LWRs, and avoid reprocessing used fuel. Several AOT variations exist; five have been included in the AOT study (Taiwo 2010). All of these variations use enriched U fuel, and so will generate front-end radioactive wastes from U mining and enrichment. All five use fast reactors and use either fuel shuffling or separate zones that contain fissile and fertile isotopes, so that larger amounts of both the fissile and fertile isotopes are eventually burned. The fertile material is either natural or depleted U; the starting fissile material is either transuranic (TRU) material separated and recycled from LWR used fuel, or EU; and fissile material for continued operation after a startup time period is either bred in the AOT reactor, or else obtained from recycled used LWR fuel.

Once-Through fuel cycle concepts do not produce waste streams from separating used fuel (because no reprocessing is done), and only produce spent fuel that is direct-disposed. These spent fuels will contain gaseous and other fission products and un-burned actinides. They will have high short-term radiolytic heat generation and high initial radiotoxicity because of high levels of FPs in the spent fuel, because higher fuel burnup results in higher levels of FPs. But long-term heat generation and radiotoxicity should be relatively lower, because the expected levels of long-lived TRU should be relatively lower.

Two variations included in the AOT analyses illustrate how such concepts as the Traveling Wave Reactor (TWR) and the Energy Multiplier Module (EM^2) can also include limited recycling designed to further increase uranium utilization and better utilize residual TRU, while still minimizing potential proliferation concerns that can occur for full recycling options. In these variations, melt refining or other limited recycling technologies may be able to remove enough FPs from used fuel to enable the remaining fuel material to be recycled to a reactor; or the used fuel may be chopped and packaged into a fuel bundle for a CANada Deuterium Uranium (CANDU) reactor, without any chemical reprocessing, in a DUPIC (Direct Use of spent PWR fuel In CANDU) recycle process. Both of these variants will cause some evolution of gaseous FPs (in DUPIC) and evolution of a wider range of gaseous, semivolatile, and relatively non-volatile FPs (in melt refining), also likely contaminated with relatively smaller amounts of actinides. These variations will result in the evolution of some waste streams from the reprocessing operations, and cause these fuel cycle concepts to be more appropriately described as Modified Open rather than Once-Through options.

Fusion-Fission Hybrid

Waste streams from FFH concepts are not well qualified or quantified because no FFH systems currently exist and their technical maturity is in early stages. However, the FFH options in this study can result in radioactive waste scenarios that are unique compared to other fuel cycle options. Specific waste streams that may be more unique to FFH options compared to other fuel cycle options include:

- Tritium contamination and/or losses
- Heavily irradiated beryllium metal
- Salt processing wastes including tritium and beryllium contamination
- Structural components activated by high energy neutrons

Three FFH options have been addressed in the FFH study (Halsey 2010). The dedicated FFH waste burner is designed to reduce the waste disposal challenges from the larger LWR energy production fleet, primarily through elimination of most actinides from the waste. Its actinide burning efficiency is expected to be high enough that it is likely that amounts of MA that are eventually discarded will be mainly limited to used fuel processing losses in both the LWR recycle and the FFH recycle. It is also

possible to transmute significant portions of long-lived fission products if deemed desirable – at a cost in neutron economy in the FFH burner.

The Fission Suppressed Breeder (FSB) fissile fuel factory seeks to produce minimal high-level radioactive waste (HLW) via suppression of fission in the breeding blanket. Fission products may be removed in online salt processing or left to accumulate in the blanket. The largest amounts of radioactive wastes may result from how the fissile material produced in the FFH fissile factory is used, in Once-Through, Modified Open, or Full Recycle options. Potential waste streams from two different FSB options (based on whether depleted uranium (DU) or thorium is used as the fuel) are included in this analysis.

The Laser Inertial Fusion Energy (LIFE) Once-Through deep burn option seeks to minimize TRU sent to waste by pushing the burn-down phase as far as needed to meet waste management objectives. Waste quantities are minimized through maximum energy extraction from the fissionable resource. With higher resource utilization, the fission product levels will also be higher (in rough proportion with the resource utilization and fuel burnup). The spent fuel would have fission product concentrations much higher than is typical in LWR used fuel, which must be considered in packaging, storage, and disposal facility heat management.

High Temperature Gas Reactor

High temperature gas reactor options reviewed in this study illustrate a range of potential Once-Through, Modified Open, and Full Recycle categories and include those that would use a range of Tristructural-isotropic (TRISO) and Bistructural-isotopic (BISO) U, TRU, and mixed oxide (MOX) fuels. The different fuel cycle categories and different potential fuels imply different potential radioactive waste streams and compositions. Radioactive waste streams in HTGR concepts that are not common in most other fuel cycle options include:

- Graphite blocks from reactor cores
- SiC and C (or other material) coatings separated from fuel particles and pebbles during recycle
- Discarded spent fuel in Once-Through cases (particles or pebbles coated with durable SiC and C (or other material) coatings.

A few waste management issues are unique to HTGR options. The graphite block moderator material could be a relatively large-mass radioactive waste stream compared to other HTGR radioactive waste streams, unless the graphite material can be recycled. Analyses and planning have been done to determine how to best recycle this material. In addition, the coatings on fuel particles and pebbles, designed for durability and toughness, present a challenge during reprocessing. These coatings also represent a large-mass waste stream in fuel recycling options.

Molten Salt Reactor

MSR variations can include different fuels (enriched uranium [EU] or Th), single or two-fluid molten salt designs, or operation with or without on-line reprocessing. These variations result in variations in potential types and amounts of waste streams which are not common to most other fuel cycle options, including:

- No cladding
- Graphite blocks from reactor cores

- Spent molten salt fuel in the Once-Through Denatured Molten Salt Breeder Reactor (DMSBR) case.

The continuous online separations in all MSR recycle options and the continuous gaseous and noble metal sparging in the Once-Through option enable higher burnup than in other non-MSR options because of the removal of FP poisons and the lack of cladding that can degrade over time under high burnup conditions. So, like other high burnup options, levels of FPs produced during MSR operation and collected in waste streams separated during online reprocessing will be relatively high, in proportion with the fuel burnup; but unlike other cases, levels of fissile materials and TRU in the fuel need not be high, since levels of FP poisons can be continuously maintained at lower levels than would occur in other high-burnup fuels.

Waste streams containing semivolatile and nonvolatile FPs separated during on-line reprocessing can be quite concentrated, and can contain amounts of salt waste, and so will require consideration of heat generation and waste loadings during subsequent handling and management.

Thorium/Uranium-233 Multirecycle in Pressurized Water Reactor

The Th-fueled Pressurized Water Reactor (PWR) multirecycle fuel cycle avoids uranium enrichment because it uses Th fuel in normal operation. The long-term heat and radiotoxicity of waste streams from the Th233/U-233 fuel cycle are less compared to the U-238/Pu-239 fuel cycle, because smaller amounts of TRU elements are produced. Still, other isotopes including Pa-231, Th-229, and U-230 are produced which must be included in waste radiotoxicity and proliferation risk analyses.

Irradiated THO2-based fuels contain U-232, which has strong gamma emitting daughters Bi212 and Tl208, and which aids in proliferation mitigation but causes remote, shielded, and automated reprocessing and refabrication. However, proliferation risk considerations should not be minimized. U-233 is fissile and could be misused. One possible proliferation-mitigating solution, denaturing the fuel with U-238, increases the normally undesirable production of TRU elements. In addition, proliferation risk will continue to exist from separations processes needed for multirecycle that could produce recycle streams that are candidates for misuse.

Results and Conclusions

Results and conclusions include:

- Families of several fuel cycle options cross-cut across the Once-Through, Modified Open, and Full Recycle strategies.
- Limited fuel reprocessing such as DUPIC, AIROX, or melt refining will generate some radioactive wastes including fuel cladding and structure materials, gaseous fission products, and (in some cases) semivolatile fission products. Limited fuel reprocessing will likely result in less efficient separations of waste FPs from recyclable actinides, resulting in waste FP contamination in recycled actinide streams and TRU contamination in waste FP streams.
- Fission product contamination of recycled fuel, and the presence of TRU elements, will cause recycled fuel handling and fabrication operations to be remote operations inside shielded hot cells.
- TRU contamination in some waste streams will cause those streams, which otherwise might meet LLW Class C limits, to require disposition as GTCC LLW.

- The amounts of radioactive non-fuel wastes from reactor core structures and fuel cladding and structure materials for some fuel cycle options can be large compared to the used fuel waste streams. Some analyses have been done to evaluate how to recycle these relatively large waste streams.

- High-burnup used fuels will have high concentrations of high-heat-generating and high-radiotoxicity isotopes, that may cause lower waste loadings in waste forms and in geological repositories to stay within expected thermal and radiotoxicity limits.

- Full Recycle options can significantly lower short and long-term radiotoxicity and heat generation compared to some Once-Through and Modified Open options, because of the transmutation of high-radiotoxicity, high-heat, long-lived TRU isotopes.

The quality and completeness of data available to date for the fuel cycle options is insufficient to perform quantitative radioactive waste analyses using recommended metrics. This study has been limited thus far to qualitative analyses of waste streams from the candidate fuel cycle options, because quantitative data for wastes from the front end, fuel fabrication, reactor core structure, and used fuel for these options is generally not yet available. These data gaps exist for most of the fuel cycle options evaluated in this study. At the time such data are available, these additional waste stream analyses can be done:

- Mass, volume, and compositions of different radioactive waste streams

- Mass, volume, and waste loading of waste forms for the different waste streams

- Radiotoxicity and heat generation of the radioactive wastes

The mass, volume, composition, radiotoxicity, and heat generation for the waste streams and waste forms can be normalized to the amount of thermal or electric energy produced for the different options.

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ACRONYMS

AFCI	Advanced Fuel Cycle Initiative program
ACZ	Active Control Zone
AIROX	Atomics International Reduction Oxidation
ANL	Argonne National Laboratory
AOT	Advanced Once-Through
BISO	Bistructural-isotopic fuel coating, a predecessor coating to TRISO. The nuclear fuel kernel surrounded by a porous carbon layer (next to the fuel for gas expansion volume) and a dense SiC layer.
BNL	Brookhaven National Laboratory
BWR	Boiling water reactor, a type of LWR
CANDLE	Constant Axial shape of Neutron flux, nuclide density and power shape During Life of Energy production
CANDU	CANada Deuterium Uranium
CFNS	Compact Fusion Neutron Source fusion driver
DMSBR	Denatured Molten Salt Breeder Reactor
DOE	United States Department of Energy
DU	Depleted Uranium
DUPIC	Direct Use of spent PWR fuel In CANDU
Echem	Electrochemical separations
EM^2	Energy Multiplier Module
EU	Enriched Uranium
FCRD	Fuel Cycle Research and Development
FCZ	Fixed Control Zone
FFTS	Fission Fusion Transmutation System
FLIBE	Fluorine-lithium-beryllium salt
FMSR	Fast Mixed Spectrum Reactor
FFH	Fusion-Fission Hybrid
\GNEP	Global Nuclear Energy Program
GTCC	Greater-than-Class-C
HEU	High Enriched Uranium

HLW	High-level waste
HM	Heavy metal
HTGR	High Temperature Gas Reactor, one of the Generation IV concepts
IMF	Inert matrix fuel
INL	Idaho National Laboratory
LEU	Low Enriched Uranium
LLW	Low-level waste
LWR	Light water cooled reactor
MA	Minor actinides: actinide elements other than U or Pu, typically Np, Am, Cm
MOX	Mixed Oxide
MSBR	Molten Salt Breeder Reactor
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
MT	Metric ton
MTIHM	Metric ton of initial heavy metal (fissionable material)
NbC	Niobium carbide
NGNP	Next Generation Nuclear Plant
NRC	United States Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
P&T	Partitioning and transmutation
PIE	Post Irradiation Examination
PBR	Pebble Bed Reactor, a variant of the HTGR
PMBR	Pebble Bed Modular Reactor (South Africa, canceled)
PWR	Pressurized Water Reactor
RU	Recycled uranium
SNF	Spent nuclear fuel
TRISO	Tristructural-isotropic, a type of micro fuel particle containing an oxide or oxycarbide kernel or fuel meat, surrounded by four layers of three isotropic materials - porous buffer layer of carbon, inner layer of dense pyrolytic carbon, ceramic layer of silicon carbide, and outer layer of dense pyrolytic carbon
TRU	Transuranic elements, e.g., Pu, Np, Am, Cm (or Np, Pu, Am, Cm, Bk, and Cf)
TWR	Traveling Wave Reactor

UCO	Uranium oxycarbide, a mixture of uranium dioxide (UO_2) and uranium carbide (UC) particles
ULFR	Ultra Long Life Fast Reactor
UNF	Used Nuclear Fuel
UOX	Uranium oxide
UREX	Uranium extraction, aqueous separation method for U-based fuels

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1. INTRODUCTION

A high-level study was performed in Fiscal Year 2009 for the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) Advanced Fuel Cycle Initiative (AFCI) to provide information for a range of potential nuclear fuel cycle options (Wigeland 2009). At that time, several potential fuel cycle option families could not be adequately evaluated because they were not well defined and lacked sufficient information for analysis. As a result, five of these potential fuel cycle option families are being studied during Fiscal Year 2010 by the Systems Analysis Campaign for DOE NE Fuel Cycle Research and Development (FCRD).

The analysis of these fuel cycles includes a high level evaluation of potential waste streams for each of the fuel cycle options. This report presents the results of this waste stream study.

1.1 Relevance of Radioactive Waste Streams for Nuclear Fuel Cycles

The disposition of radioactive wastes, and perceptions of the dangers of radioactive wastes, are among the greatest potential barriers to the future continuance and growth of nuclear power generation in the United States and the rest of the world. For example, Figure 1-1 shows that 14 states in the U.S. currently have legislated moratoria on new nuclear power plants, or other related restrictions, largely based on radioactive waste issues (Blake 2006, Djokic 2009, Soelberg 2009).

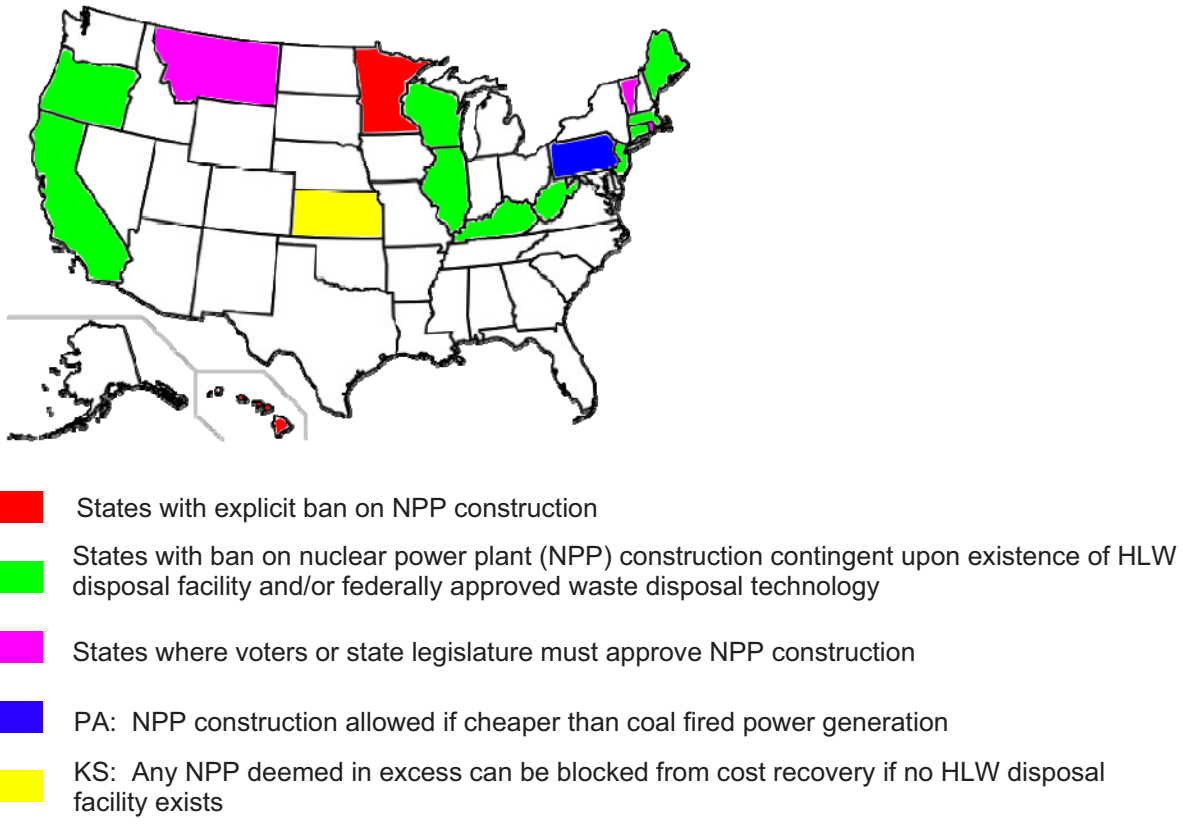

Figure 1-1. States in the U.S. that currently have legislation against nuclear power.

1.2 Objective and Scope of the Waste Stream Study

The objective of the waste stream study is to obtain and analyze information about waste streams for the selected fuel cycle options that can be used to:

- Describe the quality and completeness of the data
- Describe (as practical) waste streams arising from each option
- Identify waste stream similarities and differences (discriminators) for the different options

The waste stream study relies in large part on the results of the five fuel cycle option studies being performed during FY-2010 by the Systems Analysis Campaign. These five potential fuel cycle options are based on the following reactor concepts, which are described in more detail in interim status reports for these studies:

- Advanced Once-Through reactor concepts (Once-Through or AOT) (Taiwo 2010a)
- Fusion-Fission Hybrid (FFH) (Halsey 2010)
- High Temperature Gas Reactor (HTGR) (Piet 2010)
- Molten Salt Reactor (MSR) (Gehin 2010)
- Thorium/U-233 Fueled Light Water Reactors (Th/U-233) (Taiwo 2010b).

2. FUEL CYCLE OPTIONS UNDER EVALUATION

Each of the fuel cycle options being evaluated during FY2010 by the Systems Analysis Campaign consists of a "family" of variations in objectives, fuels, and reactors designs within each concept.

Each example fuel cycle option can be categorized based on the three general fuel cycle strategies now being advanced by DOE for future consideration and development. These categories are shown in Figure 2-1 (DOE 2010) and summarized as:

- Once-Through: Systems where nuclear fuel is prepared, used in a single reactor cycle and directly disposed of without re-use.
- Modified Open: Systems where nuclear fuel may reused directly, reconditioned, physically modified for re-use, separated for reuse of some components, etc. where a combination of separated wastes and used fuel may be disposed.
- Full Recycle: Systems where nuclear fuel is fully recycled with the intent to extract maximum energy content and minimize the processing wastes to be disposed with no intent to direct-dispose used fuel.

Table 2-1 summarizes the families of concepts reported in the interim status reports to date. These variations illustrate the range and types of concepts within each of the fuel cycle option families. This table is not intended to include all possible concepts within each of these families. The features described in this table include claims by proponents, for which information is often insufficient to verify, because of early stages of technology development and demonstration. The reference documents for the five fuel cycle families (Gehin 2010, Halsey 2010, Piet 2010, and Taiwo 2010a and 2010b) provide more detail about the different options.

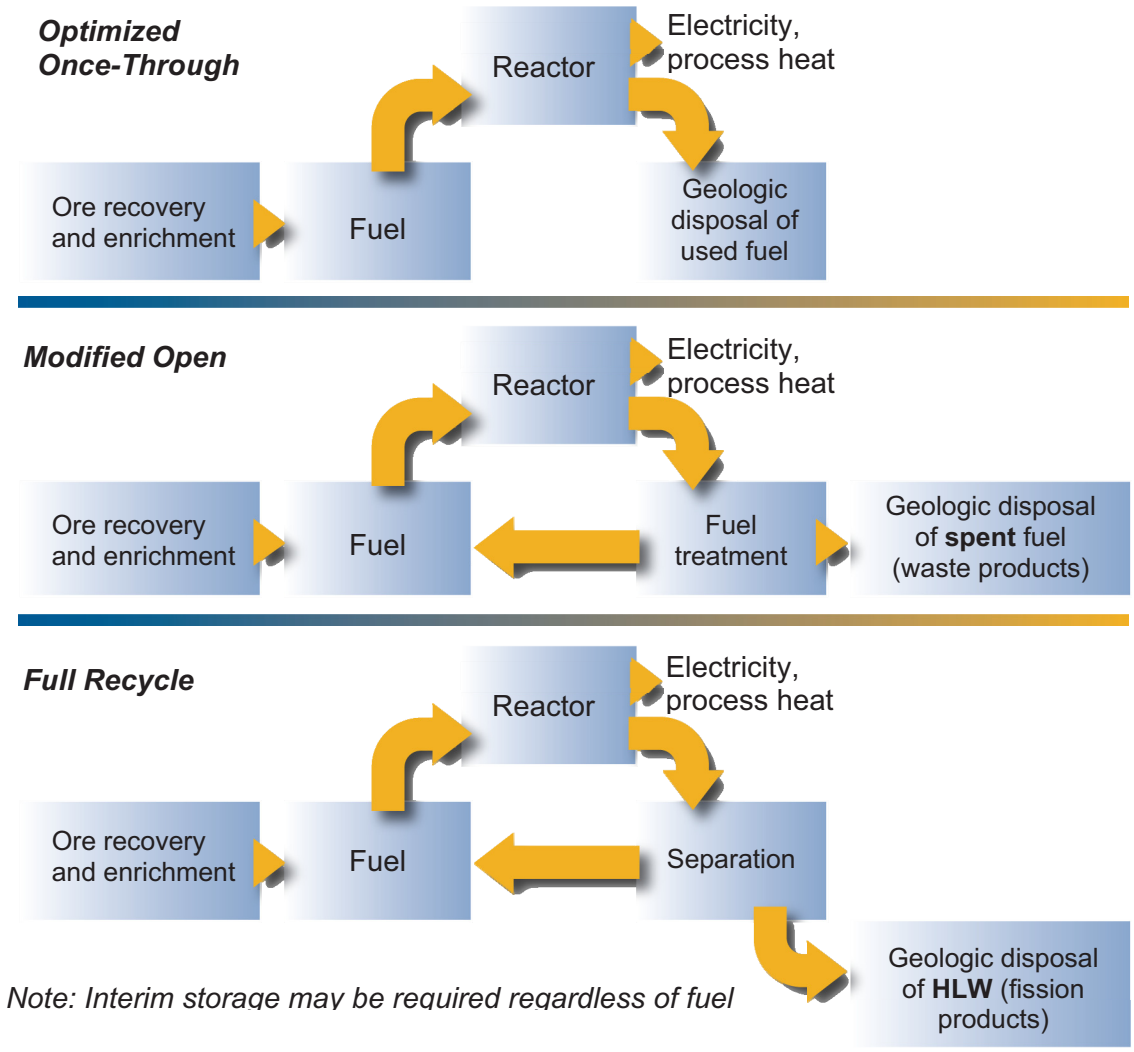

Figure 2-1. General nuclear fuel cycle categories (DOE 2010).

Figures 2-2 through 2-18 are high-level block diagrams of these fuel cycle families. This table and these figures highlight features of each of the fuel cycle options and families. These diagrams show, at a high level, features of the fuel cycle options in this analysis. Some discussion of these options, with respect to their impact on radioactive waste streams, is summarized in Section 3.

Table 2-1. Families of potential fuel cycle options being studied during Fiscal Year 2010.

Fuel cycle option and family		Goal(s)	Reactor	Fuel	Overall breeding ratio	Cycle length, years	Features and comments
Advanced Once-Through reactor concepts. Advanced Once-Through concepts are fast reactor-based to achieve higher U utilization than can be obtained in LWRs, while avoiding multiple recycling of used fuel. Variations include limited separations to further increase U utilization and burn TRU. These variations are Modified Open Cycle options.							
1	Ultra Long Life Fast Reactor (ULFR)	High U utilization. Long-life Once-Through reactor.	Fast	Annular Driver: EU-10Mo metal Inner & annular blanket: Natural U-10Mo metal	1.08	44 (49 yrs w/ 90% capa-city factor)	Driver fuel: EU; blanket fuel: natural U; spent ULFR fuel is disposed. Long-life by derating power density, annular core. Potential capital and operating cost reductions, lower proliferation risk. Unresolved questions: Ultimate U utilization?
2	CANDLE	High U utilization ~28%. Long-life Once-Through reactor.	Fast	Starter zone: 10.3% enriched U-Zr metal Co-axial blanket: DU-Zr metal Outer reflector: DU	1.20	>60 yrs up to ~200 yrs	No refueling, once through. Can burn all DU resulting from enriching the U in the starter zone. The active burn zone moves axially with time. Unresolved questions: (1) no workable fuel design exists at the current time; (2) the potential reactor difficulties control due to the tall core; (3) Core active zone cooling feasibility considering pressure drop of the long length core.
3	Fast Mixed Spectrum Reactor (FMSR)	High U utilization.	Fast and thermal zones. Breed and burn.	Core driver: Initially 9.2% enriched U; then 3.4% fissile U bred in the blanket Annular blankets (thermal zones): DU	1.29	1.5 yr w/ 90% capa-city factor	Fissile content is bred in thermal blanket zone. Be is moderator. Elements with bred fissile content are shuffled from the inner annular blanket to fast driver core, core elements are discharged at up to 256 GWd/t burnup, and fresh DU fuel elements are added to the outer blanket annulus. Unresolved issues: Cladding that can tolerate the high fluence does not exist at this time. This and other issues (reactor physics, thermal hydraulics, fuels, and materials) need to be resolved before this design is feasible.
4	Traveling Wave Reactor (TWR)	Avoid reprocessing. High U utilization, up to 40x higher than current LWRs with limited multi-reprocessing.	Fast breed and burn	Active Control Zone (ACZ): fissile fuel assemblies (EU in initial charge) or bred in DU-Zr assemblies. Fixed Control Zone (FCZ): DU-Zr fertile fuel assemblies	1.20	40	No external refueling. Fuel shuffling between stationary breed and burn zones. High Burnup fuel shuffled to core periphery. Limited fuel reprocessing using melt refining is under consideration to enable fuel burnup ~15% per pass to increase to ~50% in multiple passes
5	Energy Multiplier Module (EM^2)	Avoid reprocessing. Higher U utilization, 3-5x current LWRs. Use DU and UNF wastes.	Fast breed and burn	Starter section: Conversion section:	1.1	>30	Factory-built, modular plants for better economics, underground siting for low proliferation risk. He gas cooled high temperature (850°C) fast reactor with SiC composite cladding. Fuel burnup = mass of starter, so end-of-life waste = waste component of initial fueling, so no further growth of nuclear waste inventory; re-use used EM^2 fuel recycled using variant of DUPIC process, avoiding wet chemistry separations. In DUPIC the fuel rods are chopped, cladding and gaseous FPs are removed to some extent, and solid FPs remain in the recycled fuel. Allows more time for developing/deploying closed fuel cycle. Unresolved questions: Fuel and FP behavior, SiC composites, separations, manufacturing.

Table 2-1. Families of potential fuel cycle options being studied during Fiscal Year 2010 (continued).

	Fuel cycle option and family	Goal(s)	Reactor	Fuel	Overall breeding ratio	Cycle length, years	Features
Fusion-Fission Hybrid (FFH). FFH system concepts are based on using a thermonuclear fusion driver as the source of neutrons that are then used in fission fertile isotopes, Different FFH concepts vary based on the proposed method of controlling fusion, and on the FFH system objective – to burn radioactive wastes, breed more fissile fuel, or produce power. FFH technology maturity depends on the maturity of the fusion driver, none of which yet exist. Once fusion is demonstrated, the complexities of combining fusion and fission technologies must be solved before FFH systems are viable. Materials of construction that can tolerate the high energy fluxes and temperatures need to be solved.							
1	CFNS coupled with FFTS	Transmute even-atomic-number, difficult-to-transmute TRU isotopes. Increase U utilization compared to other fuel cycles. Produce energy.	Thermal FFTS	Driver: Li^6-Ti Subcritical FFTS blanket: 75% TRU-Zr metal, Na coolant			**Waste burner.** CFNS fusion driver coupled with a FFTS waste burning blanket. CFNS is a tokomak with diverter for high energy density plasma, using a Pb neutron multiplier and solid Li^6-Ti tritium breeding material. LWR UNF is reprocessed to recycle fissile TRU (~75% of total TRU in LWR UNF) into LWR inert matrix fuel; remaining fertile even-atomic number TRU is transmuted in FFTS. Liquid Na coolant. 45-60% TRU transmutation per pass, 400-500 GWd/MTIHM burnup. Support ratio on the order of 15:1 (LWR thermal : FFTS thermal).
2	Fission Suppressed Breeder (FSB)	Produce fissile material (U-233 or Pu-239) for fission reactors. Produce energy.	Thermal (Be pebble modera-tor)	Driver: Li^6-Ti Blanket: Molten Th-FLIBE or DU-FLIBE			**Fissile Fuel Factory.** A large mirror or tokomak fusion driver, coupled with a FLIBE molten salt fuel circulating in the helium cooled blanket. Tritium is bred from Li^6 in the molten salt. Th in the molten salt converts to Pa-233, which decays to fissile U-233 for reactor fuel. DU in the molten salt converts to Np-239 and then to Pu-239 and other TRU elements for reactor fuel. Molten salt flows from the reactor blanket to remote online processing to remove the Pa-233 and/or Np239 to suppress undesirable fission of these isotopes. U-232 (with high heat and strong gamma emission) can be produced to minimize proliferation potential. One FSB could support 5-10 fission reactors, or larger numbers of near-break-even MSRs that use U-233 as initial fuel.
3	Laser Inertial Fusion Energy (LIFE) concept	Generate energy from fission of fissile material produced from fertile material. High U or Th utilization, ~99%. No enrichment or reprocessing.		Driver: Diode-pumped solid-state laser, DT targets. Fission blanket: DU pebble bed, cooled by FLIBE.		40	**Once-Through Deep Burn.** The laser delivers power to the cryogenic DT targets; 15-25 fusion gain, producing 10^{20} n/sec. Behind first W-clad wall are Be pebbles to multiply and slow neutrons, cooled by molten Pb-Li. Fission power is produced from natural U pebbles circulating in FLIBE cooling media, transferred to a secondary molten salt loop for Brayton cycle electricity generation. Other fuels are possible. Issues: Replacement of W-clad first wall every 5-20 yrs due to neutron damage; development of fission fuel for extreme burnup and aggressive environment. Variations include pebble designs (porous U ceramic, hollow sphere of oxycarbide fuel in oxide dispersion of ferritic steel; “refabrication” (remote online processing) if needed; other drivers.

Table 2-1. Families of potential fuel cycle options being studied during Fiscal Year 2010 (continued).

	Fuel cycle option and family	Goal(s)	Reactor	Fuel	Overall breeding ratio	Cycle length, years	Features
High Temperature Gas Reactor (HTGR) (thermal reactors only; gas-cooled fast reactors such as EM^2 are covered under advanced once through concepts). For all HTGR concepts: High operating temperature enables higher thermal efficiency compared to other reactor designs, but challenges materials of construction forcing use of non-metallic or non-ferrous materials such as graphite, SiC, pyrolytic C, diamond, fluorinated Si, Mg, etc. These materials present different separations and waste disposition challenges. The reactor design can include prismatic core with fuel particles in channels or rods, or slowly moving bed of pebbles made of fuel particles. Prismatic cores require occasional replacement and recycle or disposal. Particles and pebbles durable coatings are analogous to cladding in LWR fuel elements. TRISO particles are designed for durability suited for Once-Through options, but less suited for recycle options. BISO particles are suited for releasing volatile FPs during reactor operation, releasing pressure, but are less durable in long-term operation, and are more suited for recycle options.							
1	Once-Through HTGR	Energy production for electricity or process heat.	Thermal (Graphite moderator)	More robust: TRISO Less robust but vents volatile FPs: BISO; UCO	<1		One irradiation of uranium-based fuel in an HTGR, the used fuel is disposed. Possible fuel compositions: UOX or UCO. This option is evaluated in the interim HTGR report (Piet 2010) but will not be further studied in FY2010.
2	Minimal fuel treatment HTGR	Recycle LWR or HTGR used fuel once, minimal separations. Energy production for electricity or process heat.		More robust: TRISO Less robust but vents volatile FPs: BISO; Impure U-TRU oxycarbide			Irradiation of recycled U and TRU from LWR or HTGR in an HTGR. Minimal fuel treatment implies a separations process such as AIROX, during which more volatile and reactive FPs are separated from the recycled material, and the recycled material contains not only UTRU but also amounts of less volatile/reactive FP impurities that are not easily separated from the U/TRU during the minimal separations process. The used HTGR fuel is disposed.
3	Single recycle in HTGR	Recycle LWR or HTGR used fuel once, full separations. Energy production for electricity or process heat.		More robust: TRISO Less robust but vents volatile FPs: BISO; TRU oxycarbide			Irradiation of recycled TRU from LWR or HTGR in an HTGR with full separation of the LWR or HTGR used fuel. This is analogous to the uranium-free Inert Matrix Fuel (IMF) option in LWRs but is typically called “deep burn” by advocates. The used fuel is disposed after a single pass in the HTGR. Full separations enables HTGR fuel with fewer impurities and presumably higher burnup in HTGR, compared to a minimal separations process used in Option 2 above. Recovered U (RU) is put into indefinite storage.
4	Sustained recycle with HTGRs only	Same as Single Recycle (Option 3 above), but with repeated recycle, higher U utilization, and no used fuel direct disposal.		MOX-TRU			Repeated recycle of TRU and some RU separated from previous used fuel. Analogous to repeated recycle of LWR-MOX or heterogeneous assemblies of LWR-IMF and LWR-UOX pins; either of which can be recycled indefinitely if reactor safety limits such as void coefficient are met and fissile support is provided during subsequent recycles. Used fuel is never disposed. Only FPs are disposed. DU and excess RU are put into indefinite storage.
5	Sustained recycle in HTGR and fast reactors	Same as Sustained Recycle in HTGRs (Option 4 above), but with higher U utilization.		MOX-TRU (HTGR); IMF (FR)			After TRU fuel is used 1-2x in an HTGR, residual TRU is separated and used in fast reactors. Analogous to 2-tier recycling in the former GNEP program. Used fuel is never disposed. Only FPs are disposed. DU and excess RU are put into indefinite storage, but unlike sustained recycle in HTGRs only, the RU and DU could be used in fast breeder reactors. This option is evaluated in interim HTGR report (Piet 2010) but will not be further studied in FY2010.
6	Complete recycle						Repeated recycle of TRU and RU from previous used fuel. Only FPs are disposed. We find no evidence that this is possible in a thermal spectrum HTGR, but this fuel cycle is the intent of the related Gas Cooled Fast Reactor (GFR); beyond the scope of this assessment.

Table 2-1. Families of potential fuel cycle options being studied during Fiscal Year 2010 (continued).

	Fuel cycle option and family	Goal(s)	Reactor	Fuel	Overall breeding ratio	Cycle length, years	Features
Molten Salt Reactor (MSR). In MSRs, the fuel fertile and fissile elements are dissolved in molten fluoride salts, so no fuel fabrication is required, an advantage over reactor designs that require fuel fabrication and cladding that degrades with irradiation. Fuel processing can be continuous and on-line, limiting buildup of FP poisons in the reactor at any time. Fissile U-233 bred from natural Th can be the fuel. MSRs have the inherent self-limiting safety feature of a negative void coefficient - if the core heats up, thermal expansion of salt in the core reduces the fissile inventory (and therefore power levels), passively cooling the core, reducing chance of a "core melt-down." In addition, freeze-plugs set to melt at a target temperature can be used to drain molten salt to critically-safe storage tanks should core temperatures exceed the temperature limit. As a breeder reactor, the MSR can burn all actinides with ½ lives between 20-10,000 years.							
1	Two-fluid Th MSR	Breed U-233 from Th. Generate energy from U-233 fission.	Epi-thermal	Fissile core: U-233 in molten salt; Fertile annular blanket: Th in molten salt	>1		On-line chemical processing is done for both the blanket and core salts, to remove FPs and transfer U-233 bred from Th in the blanket to the core. Th is transmuted in the blanket to Pa-233. Pa-233 must be allowed to decay (27.4 day ½ life) outside the reactor to prevent its fission (or the MSR becomes a converter, not a breeder). Outside of the reactor the Pa-233 decays to U-233, which is separated from the blanket salt using fluoride volatility, and added to the core salt. Materials corrosion concerns result from the high operating temperatures and corrosive salts. Corrosion-resistant materials for salt piping limits the current viability of the two fluid design. Blanket salt on-line processing: (a) Bi separator removes Pa-233 for decay storage to U-233 outside reactor, (b) fluorinate U-233 to volatilize UF6 to cold trap, where UF6 condenses, ready to transfer to core salt or to other reactor. Core salt on-line processing: (a) decay cool 1-2 days, (b) He sparging to remove gaseous FPs for capture and disposal or release, (c) fluorinate U to volatilize UF6 to cold trap, where UF6 condenses, (d) U-free salt is vacuum distilled to volatilize re-useable salts from less volatile FP salts, (e) recycled UF6 and new U-233F6 are reduced to UF4 and combined with cleaned distilled salts for recycle to core, (f) captured FPs are treated to final waste form and disposed. Other variations in separations processes can include salt removal and batch processing, etc.
2	Single-fluid Molten Salt Breeder Reactor (MSBR)	Breed U-233 from Th. Generate energy from U-233 fission.	Epi-thermal		1.06		Breed U-233 from Th by (a) tuning the spectrum in the central region of the reaction chamber to fission fissile fuel components, and (b) moderating and limiting the spectrum to produce thermal absorption within the fertile isotopes in the outer regions. Graphite is used as reflector material, and must be replaced periodically due to radiation damage. The MSBR design includes 4 loops.
3	Single-fluid Denatured Molten Salt Breeder Reactor (DMSBR)	Breed U-233 from Th. Generate energy from U-233 fission. Avoid online chemical processing.				30	No online chemical processing is needed because (a) Th is added to the initial loading and allowed to decline over the life of the reactor, and (b) enriched U is added as needed to maintain criticality. U-238 is added as needed to maintain all uranium in a denatured state. Gaseous FPs and noble metals are removed from the fuel salt through gas sparging and plate out (noble metals Nb, Mo, Tc, Ru, Hr, and others are not soluble in fluoride salts).

Table 2-1. Families of potential fuel cycle options being studied during Fiscal Year 2010 (continued).

	Fuel cycle option and family	Goal(s)	Reactor	Fuel	Overall breeding ratio	Cycle length, years	Features
Thorium/U-233 Fueled Light Water Reactors (Th/U-233). Variations of Th fueled LWRs include Once-Through and multi-recycle options. The option described in this document is a multi-recycle option that, after a starting fuel of fissile material, uses no additional fissile material besides the U-233 bred from Th-232 in the reactor. This may not be possible without some additional fissile material addition.							
1	Th/U233 fuel multirecycle in current PWRs	Energy production for electricity or process heat.	Thermal	Th/U233	>1	1.5	Breeding ratio only slightly >1, requiring no external fissile material except for original core. These may be required: (a) Fuel shuffling, (b) heterogeneous seed and blanket fuel, and (c) higher temperature sintering during Th fuel fabrication due to high ThO2 melting point. ThO2-based MOX fuels require HF for dissolution during aqueous separations. HF causes corrosion of stainless steel, mitigated using Al nitrate. The long-term heat and radiotoxicity of waste streams from the Th233/U-233 fuel cycle are less compared to the U-238/Pu-239 fuel cycle, because smaller amounts of TRU elements are produced. Still, other isotopes including Pa-231, Th-229, and U-230 are produced which must be included in waste radiotoxicity analyses. Irradiated THO2-based fuels contain U-232, which has strong gamma emitting daughters Bi212 and Tl208, aiding in proliferation mitigation but causing remote, shielded, and automated reprocessing and refabrication. Proliferation risk considerations should not be minimized. U-233 is fissile and could be miss-used. Denaturing the fuel with U-238 increases production of TRU elements. Separations processes needed for multirecycle could produce multiple recycle streams that are subject to proliferation risk.

Notes:

1. The features described in this table include claims by proponents, for which information is often insufficient to verify, because of early stages of technology development and demonstration. In some cases, capabilities of key components are not currently available to make the concept practical or even possible. Please refer to the reference documents for these five fuel cycle families (Gehin 2010, Halsey 2010, Piet 2010, and Taiwo 2010a and 2010b) for more detail about the different options.
2. CANDLE = Constant Axial Shape of Neutron flux, nuclide density and power shape During Life of Energy production
3. CFNS couple with FFTS = Compact Fusion Neutron Source fusion driver, coupled with the Fission Fusion Transmutation System as a waste burning blanket
4. DU = Depleted Uranium
5. EU = Enriched Uranium
6. FLIBE = Fluorine-lithium-beryllium salt
7. FP = fission product
8. IMF = inert matrix fuel
9. LWR = light water reactor
10. MA = minor actinide(s)
11. MOX = mixed oxide
12. TRU = Transuranic
13 UCO = uranium oxycarbide

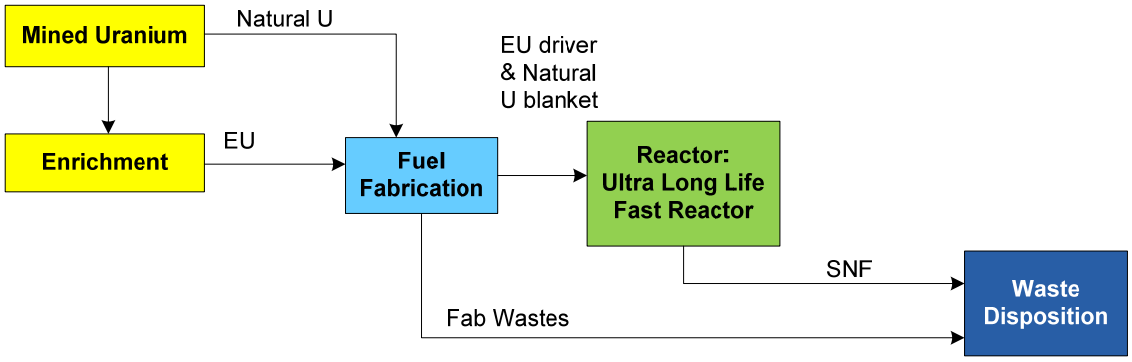

Figure 2-2. Advanced Once-Through Ultra Long Life Fast Reactor (ULFR).

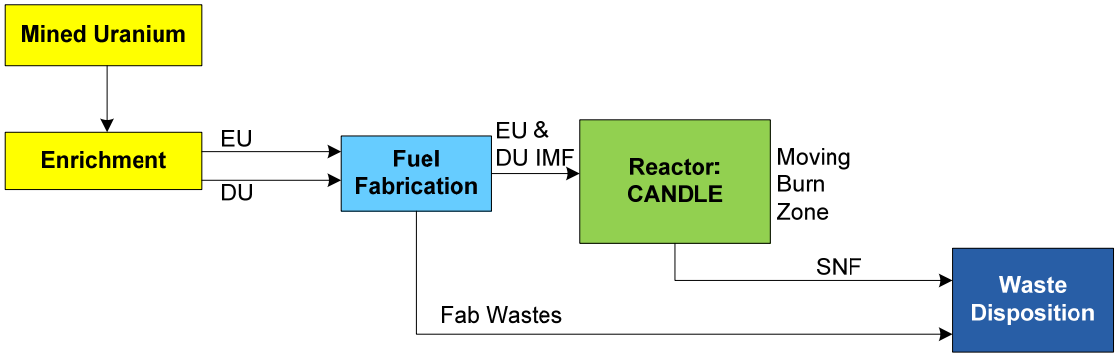

Figure 2-3. Advanced Once-Through CANDLE reactor.

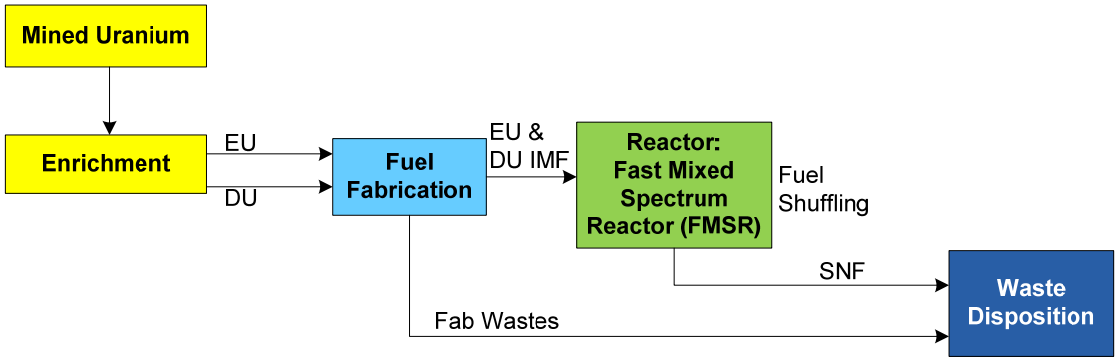

Figure 2-4. Advanced Once-Through Fast Mixed Spectrum Reactor (FMSR).

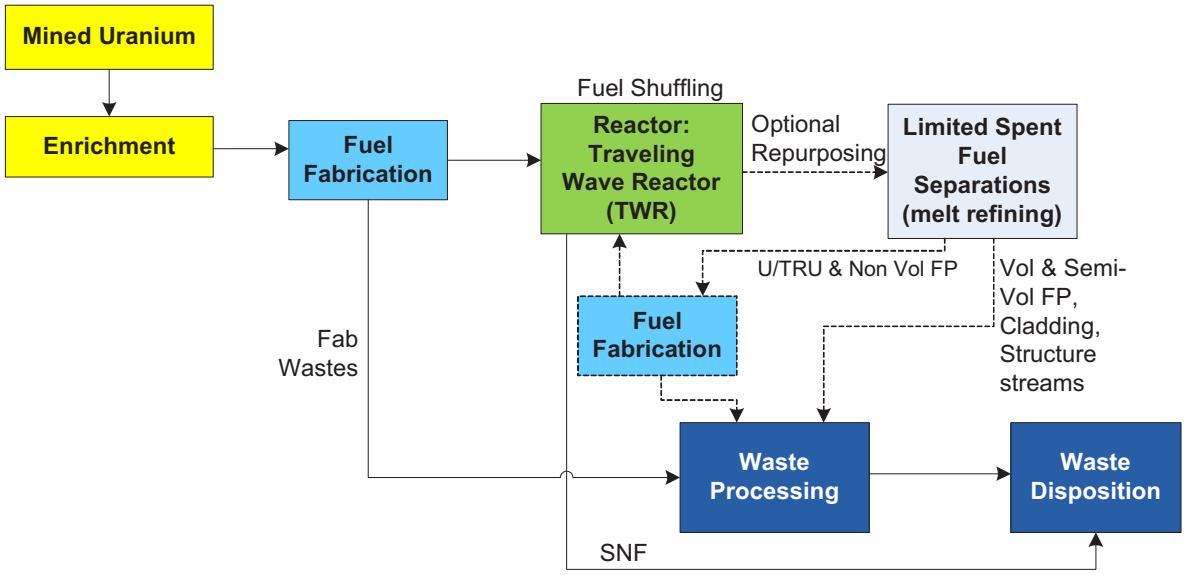

Figure 2-5. Advanced Once-Through Traveling Wave Reactor (TWR).

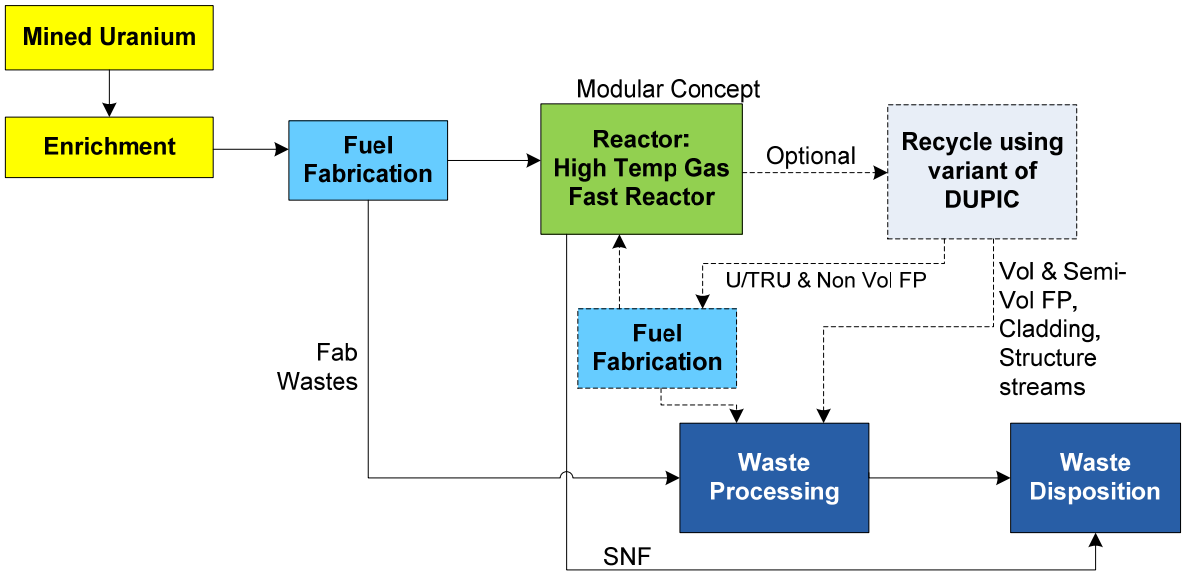

Figure 2-6. Advanced Once-Through Energy Multiplier Module (EM^2).

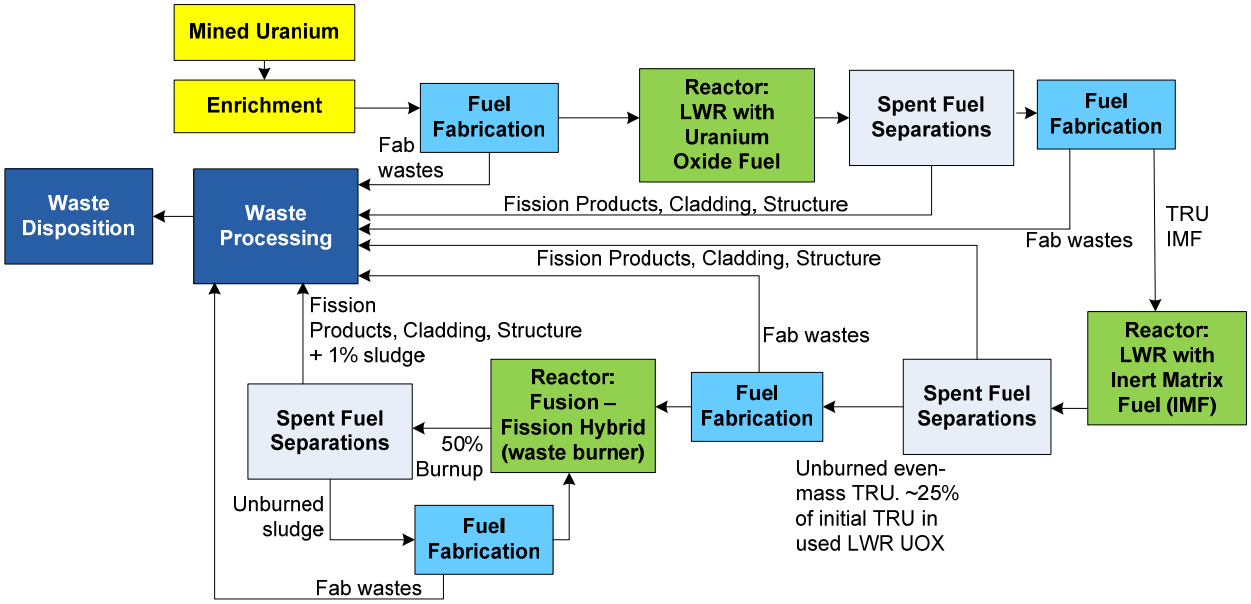

Figure 2-7. Fusion-Fission Hybrid (FFH) CFNS coupled with FFTS waste burner.

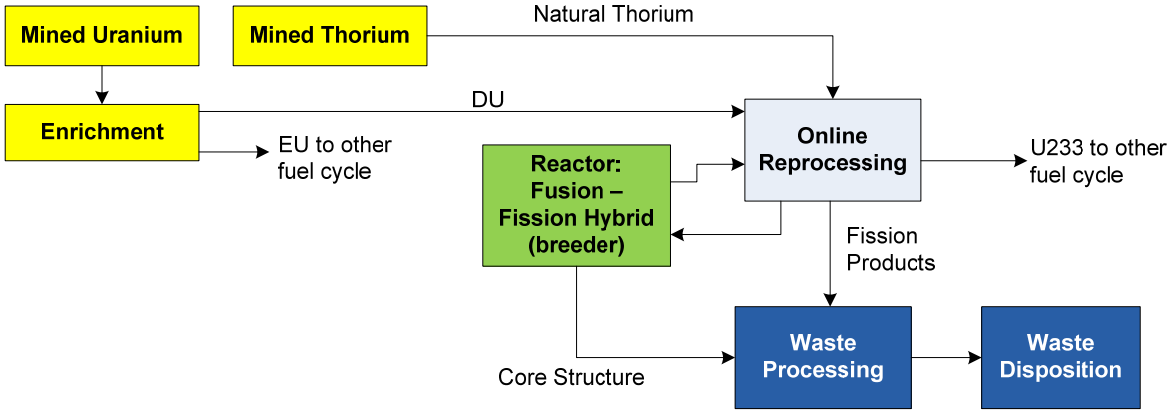

Figure 2-8. FFH Fission Suppressed Breeder (FSB) fissile fuel factory.

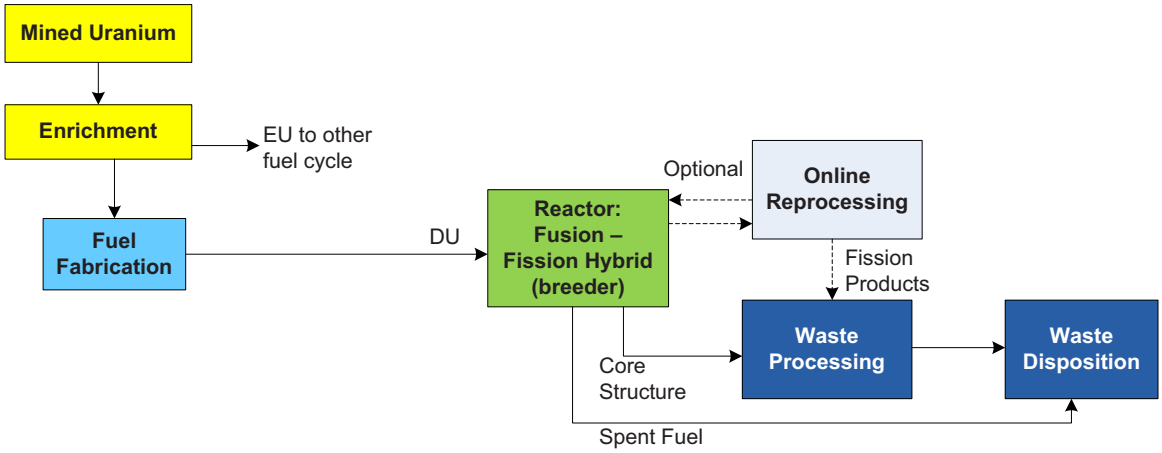

Figure 2-9. FFH Laser Inertial Fusion Energy (LIFE) Once-Through deep burn concept.

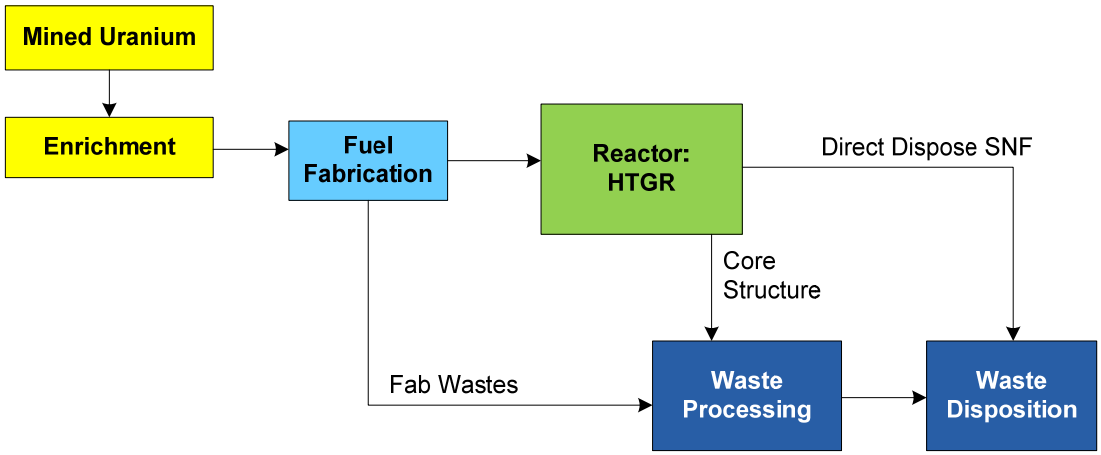

Figure 2-10. Once-Through HTGR (not to be further studied in FY2010).

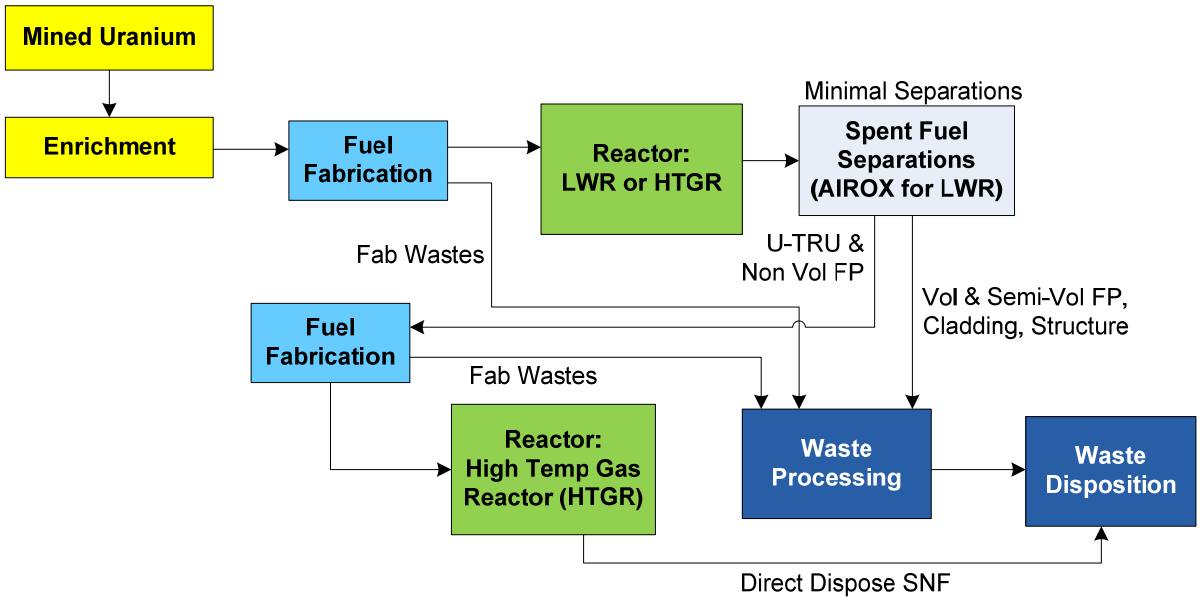

Figure 2-11. Minimal fuel treatment HTGR.

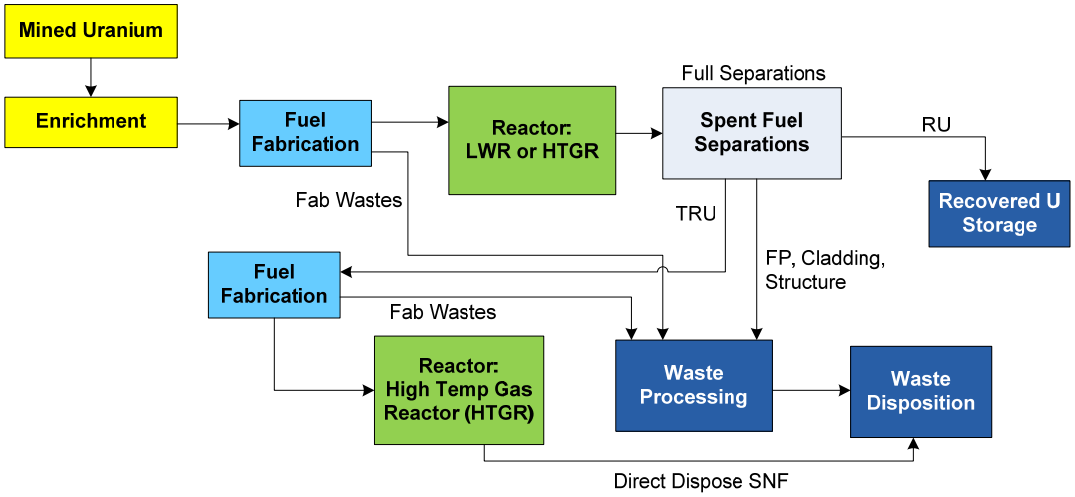

Figure 2-12. Single recycle in HTGR.

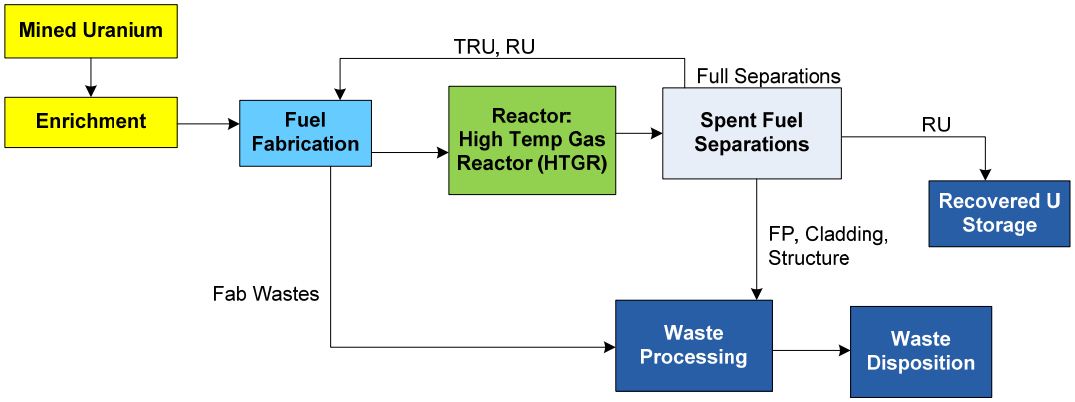

Figure 2-13. Sustained recycle with HTGRs only.

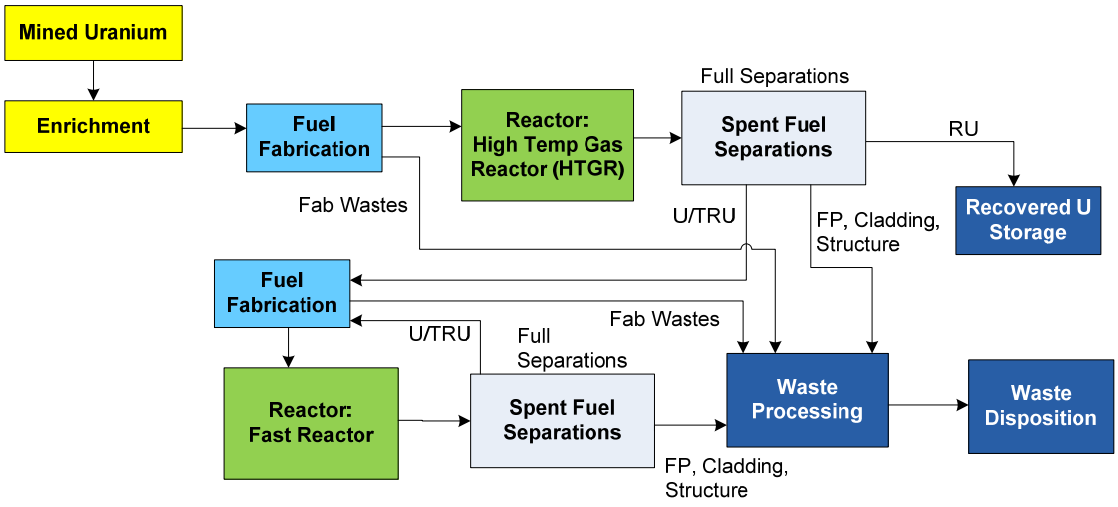

Figure 2-14. Sustained recycle in HTGR and fast reactors.

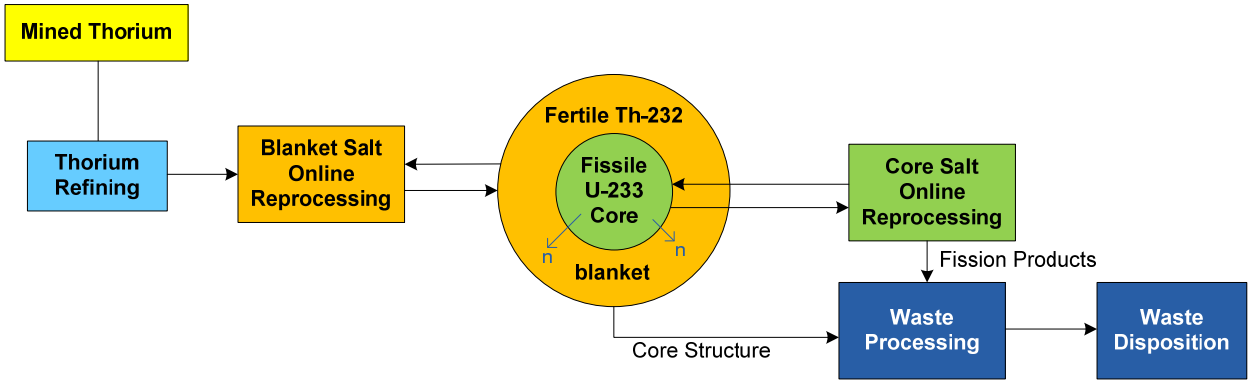

Figure 2-15. Two-fluid Th MSR (Gehin 2010).

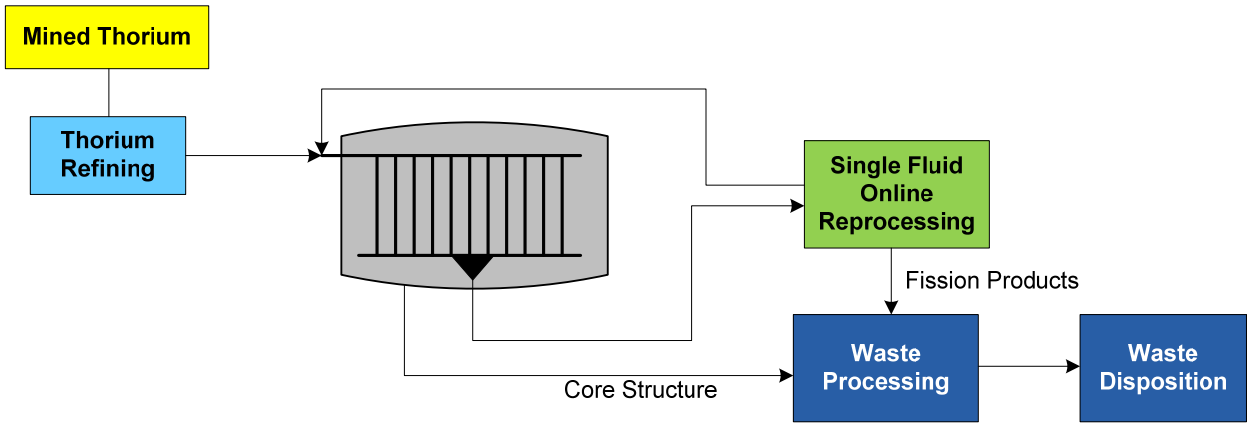

Figure 2-16. Single-fluid Molten Salt Breeder Reactor (MSBR).

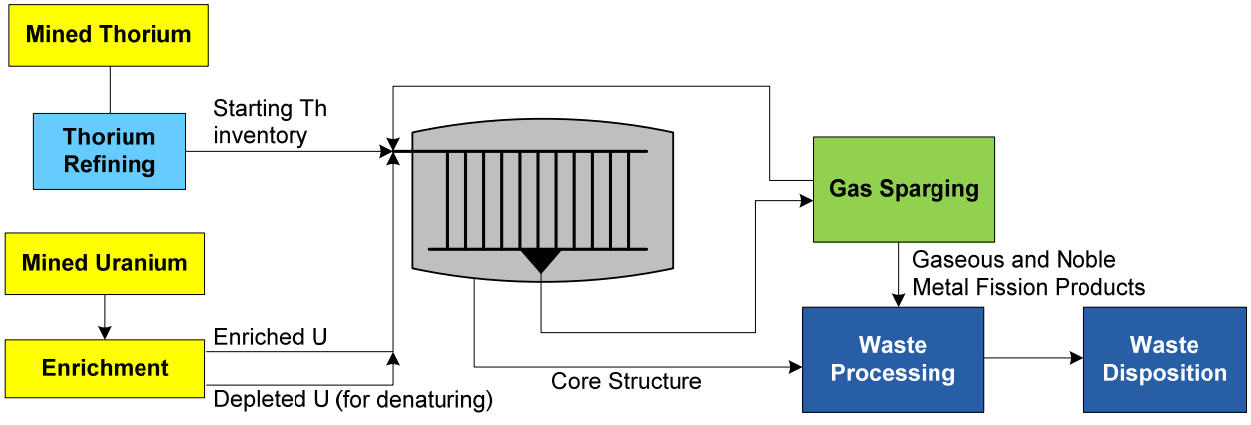

Figure 2-17. Single-fluid Denatured Molten Salt Breeder Reactor (DMSBR).

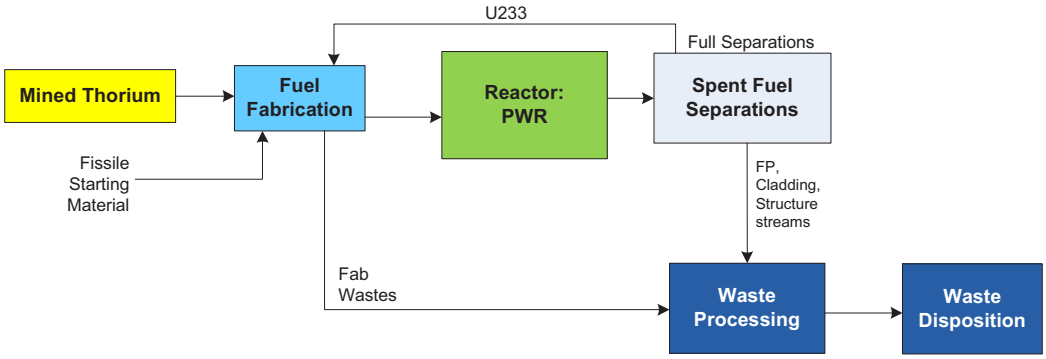

Figure 2-18. Th/U233 fuel multirecycle in current PWRs.

3. RADIOACTIVE WASTE STREAMS FOR FUEL CYCLE OPTIONS

These general fuel cycle categories portray the highest level variations in how used fuel and waste from reprocessing used fuel is handled:

- The Once-Through category is based on direct disposal of used fuel in a geological repository after it leaves the reactor, without any re-use of the used fuel. No disposal of high level waste (HLW) resulting from used fuel separation is done, because no used fuel is reprocessed.
- The Modified Open category allows for re-use of used fuel, but still includes eventual direct disposal of used fuel. The re-use could consist of taking used fuel from one reactor and placing it into another reactor, with or without reconditioning, separation of certain components, or other modifications. Fuel components not re-used, and eventually spent fuel that is not used, is disposed. Spent fuel and fuel components that are not re-used are disposed.
- The Full Recycle category includes separation of used fuel into waste and recycle components; recycle components are made into new reactor fuel, and waste components are disposed. No direct disposal of used fuel is assumed.

3.1 Radioactive Waste Stream Types

Radioactive waste streams that can occur in one or more of these fuel cycle categories, regardless of fuel or reactor type and operation, include:

- Front end radioactive wastes from uranium mining and enrichment that are mainly operations and maintenance wastes, and are typically regulated as low-level wastes. The amounts and types of these wastes can vary because some fuel cycle options do not necessarily include uranium enrichment, and some fuel cycles based on thorium do not necessarily use uranium. These waste streams are mentioned in this report for completeness and perspective, although the relative amounts and concentrations of radioactive contaminants in these waste streams are less than those in the used fuel.
- Radioactive wastes from fuel fabrication. Fuel fabrication for different fuel cycle options can include processing (a) natural, low enriched, or high enriched uranium (NU, LEU, or HEU), (b) thorium, (c) combinations of relatively pure (contaminant-free) recycled uranium (RU), transuranic (TRU) elements, or minor actinides (MA), or (d) RU, TRU, or MA that also contains

fission product (FP) contaminants at concentrations higher than are now accepted in typical oxide, mixed oxide (MOX), or inert matrix fuels (IMF), or other current fuel types.

- Waste reactor core structures. Current commercial light water reactors (LWRs) can include metal hardware that could be removed from used nuclear fuel assemblies prior to direct disposal or reprocessing. Reactors that use other core or fuel structures such as Be, graphite, SiC, or carbon-carbon composites would generate these other types of wastes. To the extent practical, core structure materials could be recycled (especially the large amounts of graphite expected in HTGR reactors). Used core structure materials are radioactive due to contamination with radioactive fuel components, fission products, or activation products. This radioactivity will affect the recyclability of used core materials and impact disposal requirements.

- Cladding materials and fuel structure. Current LWRs use metal-clad fuel elements (mainly Zircaloy and less common, stainless steel). Some prior, current, and future reactor designs use fuels with other types of metal cladding (such as Mg alloys), non-metallic cladding (such as graphite, pyrolytic carbon, and SiC), inert metal such as Zr alloyed in IMF, or molten salts in which fertile and fissile fuels are dissolved. Direct-disposed spent nuclear fuel (SNF) will include these cladding and fuel structure materials. Waste streams containing fuel structure and cladding materials that are separated from recycled used fuel materials are likely for any fuel cycle option.

- Gaseous fission products (mainly noble gases Xe and Kr, iodine, carbon-14, and tritium). Fuel cycle options in both Modified Open cycle and Full Recycle categories, and even some Once-Through options, will result in gaseous fission products released from the fuel either in the reactor or during post-reactor reprocessing. These gaseous fission products must be captured and properly disposed according to regulatory requirements. Although frequently grouped together for discussion purposes, Xe and Kr, iodine, C14, and H3 are managed separately in most fuel cycle scenarios, according to their separate chemical and radiological behaviors and regulatory requirements.

- Semivolatile fission products (including Group 1, Group 2, transition metals, and many nonmetals in the periodic table). Limited separations such as AIROX and melt refining, that could occur in Modified Open Cycle options, and full separations such as aqueous and electrochemical separations, will result in waste streams that contain these fission products. AIROX and melt refining that rely on volatility to separate these fission products from recyclable fuel materials can theoretically enable separate capture and disposition of semivolatile FPs. UREX separations can also enable separation of Group 1 and Group 2 FPs from other fission products, making possible separate waste forms and dispositions if desired and if regulatorily allowed. All of these fission products must be immobilized and disposed according to regulatory requirements.

- Nonvolatile fission products, actinides, and lanthanide wastes. When actinides are not included in recycled fuel streams, then they can become wastes in combination with or separated from fission products. The partitioning of actinides, lanthanides, and other fission products depends on the separations process. AIROX and melt refining could leave some amounts of nonvolatile FPs with the actinides that are recycled. Likewise, these partial separations processes are known to inefficiently separate actinides from waste streams, leaving a portion of actinides as contaminants in FP waste streams. Full separations such as UREX+1A options can more efficiently separate the actinides for recycle, and separate lanthanides, Tc, and Group 1-2, isotopes from other fission products for disposal depending on their chemistry, desired waste forms, heat, radiotoxicity, or longevity.

3.2 Radioactive Waste Streams

Table 3-1 summarizes the radioactive waste streams that would arise for the different fuel cycle options. The following sections provide additional detail for each option.

Waste streams identified here would require immobilization and disposal according to policy and regulatory requirements. Some waste streams that are not considered to meet the definition of HLW may be dispositioned as Greater-than-Class-C (GTCC) LLW if the radioactive content exceeds Class C LLW limits. Other waste streams that would meet the definition of HLW would require disposition as HLW in a geologic repository.

Several waste streams shown in the table (from fuel fabrication, reactor core structure, and cladding and fuel structure) are expected to be radioactive due to contamination with radioactive fuel components, fission products, or activation products. This radioactivity will affect the recyclability of used core materials and impact disposal requirements.

For simplicity in the table, some waste streams such as noble gases, iodine, C14, and H3 are grouped into a single column, although we expect that these gaseous FPs would evolve from essentially all separations process and would be separately captured and separately immobilized in separate waste forms. In some fuel cycle options, semivolatile and nonvolatile FPs can be separately captured and immobilized in separate waste forms, if desired; in other fuel cycle options, these FPs are more readily separated from recycled fuel in a single waste stream and immobilized in a single waste form. In partial separations, these FP streams can be contaminated with actinides when FP-actinide separations are not as efficient as expected in full separations.

3.2.1 Advanced Once-Through Reactor Concepts

Advanced Once-Through (AOT) reactor concepts are designed to achieve higher U utilization than is typical for UOX-fueled LWRs, and avoid full used fuel separations. Several AOT variations exist; five have been included in the AOT study (Taiwo 2010). All of these variations use enriched U fuel, and so will generate front-end radioactive wastes from U mining and enrichment. All five use fast reactors and use either fuel shuffling or separate zones that contain fissile and fertile isotopes, so that both the fissile and fertile isotopes are eventually burned. The fertile material is either natural or depleted U; the starting fissile material is EU; and fissile material for continued operation after a startup time period is fissile material bred in the AOT reactor.

Fuel cycle concepts strictly limited to Once-Through fuel do not produce waste streams from separating used fuel, and only produce spent fuel that is direct-disposed. (Several variations, however, have been included in the discussion of AOT concepts.) These spent fuels will contain gaseous and other fission products and un-burned actinides. They will have high short-term radiolytic heat generation and high initial radiotoxicity because of high levels of FPs in the spent fuel, because higher fuel burnup results in higher levels of FPs. But long-term heat generation and radiotoxicity should be relatively lower, because the expected levels of long-lived TRU should be relatively lower.

Table 3-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010.

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	Comments
Advanced Once-Through reactor concepts														
1	Ultra Long Life Fast Reactor (ULFR)	Once Through	---	Y	Y	Y	N	N	N	N		N	Y	
2	CANDLE	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
3	Fast Mixed spectrum reactor (FMSR)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	Same as CANDLE.
4a	Traveling Wave Reactor (TWR)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
4b	Traveling Wave Reactor (TWR)	Mod. Open	Melt refining	Y	Y	Y	N	Y	Y	Y	Y		Y	Melt refining, being a less efficient separations process, will result in actinide contamination in FP waste streams.
5a	Energy Multiplier Module (EM^2)	Once Through	---	Y	Y	Y	N	N	N	N	N	N	Y	
5b	Energy Multiplier Module (EM^2)	Mod. Open	DUPIC	Y	Y	Y	N	Y	Y	N	N	N	Y	DUPIC chops but does not heat or dissolve SNF. In this DUPIC variant, cladding and gaseous FP are removed and disposed.

Notes:

1. Echem = electrochemical
2. LWR = light water reactor
3. CANDLE = Constant Axial shape of Neutron flux, nuclide density and power shape During Life of Energy production
4. Mod. Open = modified open cycle
5. DUPIC = Direct Use of spent PWR fuel In CANDU]
6. SNF = spent nuclear fuel
7. CANDU = CANada Deuterium Uranium reactor

Table 3-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010 (continued).

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										Comments
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	
Fusion-Fission Hybrid (FFH) reactor														
1	CFNS coupled with FFTS waste burner	Full Recycle	Aqueous, Echem	N	N	Y	Y	Y	Y	Y		N	N	Burns waste from LWR used fuel reprocessing, multirecycle. Assumes the U mining/enrichment is attributed to the LWRs.
2a	Fission Suppressed Breeder (FSB) fissile fuel factory	Full Recycle	On-line	N	N	N	Y	Y	Y	Y		N	N	Assumes DU fuel, and wastes from U mining/enrichment is attributed to other reactors that need EU. Many variations are possible depending on U or Th fuel, and how bred U/TRU is cycled in other reactors.
2b	Fission Suppressed Breeder (FSB) fissile fuel factory	Full Recycle	On-line	Y	N	N	Y	Y	Y	Y		N	N	Assume Th fueled, so wastes from Th mining are included in this analysis.
3a	Laser Inertial Fusion Energy (LIFE) Once-Through deep burn concept	Once-Through	---	Y	N	N	Y	N	N	N		N	Y	This Once-Through variant assumes that gaseous FPs are retained in the fuel.
3b	Laser Inertial Fusion Energy (LIFE) Once-Through deep burn concept	Mod. Open	On-line	Y	N	N	Y	Y	Y	N		N	Y	This Mod. Open variant assumes that gaseous FPs are released from the fuel, captured, and disposed; and some cladding/fuel structure is discarded.

Notes:

1. CFNS = Compact Fusion Neutron Source fusion driver
2. FFTS = Fission Fusion Transmutation System
3. DU = depleted uranium
4. EU = enriched uranium
5. TRU = transuranic

Table 3-1. Radioactive waste streams expected from potential fuel cycle options being studied during Fiscal Year 2010 (continued).

Fuel cycle option and family		Fuel cycle category	Candidate separation process	Radioactive waste streams [yes (Y) = expected, no (N) = not expected] for that fuel cycle option										Comments
				U/Th mining	U enrich-ment	Fuel fabrication	Core structure	Cladding and fuel structure	Gaseous FPs	Semi-volatile FPs	Non-volatile FPs	Acti-nides	Spent fuel assemblies, particles, pins	
High Temperature Gas Reactor (HTGR)														
1a	Once-Through HTGR	Once Through	---	Y	Y	Y	Y	N	N	N		N	Y	A TRISO fuel particle that retains gaseous FPs is assumed.
1b	Once-Through HTGR	Once Through	---	Y	Y	Y	Y	N	Y	N		N	Y	BISO fuel is assumed that vents gaseous FPs.
2	Minimal fuel treatment HTGR	Mod. Open	AIROX	N	N	Y	Y	Y	Y	Y			Y	Recycles LWR used fuel; limited separations; attribute U mining/enrichment to LWRs.
3	Single recycle in HTGR	Mod. Open	Aqueous or Echem	N	N	Y	Y	Y	Y	Y		N	Y	1st reactor could be LWR or HTGR; full separations.
4	Sustained recycle with HTGRs only	Full Recycle	Aqueous or Echem	N	N	Y	Y	Y	Y	Y		N	N	Full separations.
Molten Salt Reactor (MSR)														
1	Two-fluid Th MSR	Full Recycle	On-line	Y	N	N	Y	N	Y	Y		N	N	Full separations.
2	Single-fluid Molten Salt Breeder Reactor (MSBR)	Mod. Open or Full Recycle	On-line	Y	N	N	Y	N	Y	Y		N	N	Full separations.
3	Single-fluid Denatured Molten Salt Breeder Reactor (DMSBR)	Once Through	---	Y	Y	N	Y	N	Y	Y	N	N	Y	U238 is used for denaturing; sparging to remove gaseous and noble FP.
Thorium/U-233 Fueled Light Water Reactors (Th/U-233)														
1	Th/U233 fuel multirecycle in current PWRs	Full Recycle	Aqueous or Echem	Y	N	Y	N	Y	Y	Y		N	N	No U used after initial startup.

Notes:

1. AIROX = Atomics International Reduction Oxidation
2. Full Recycle systems maximize actinide utilization. Once-Through and Modified Open systems will have disposed actinides in spent fuel or in separated waste streams from reprocessing.
3. All fuel cycles may have about the same amounts of FP per unit of energy produced. Designs to transmute some FP exist; the FFH waste burner is the only one included in this analysis.
4. Most of the fuel cycle options are insufficiently defined to specify types and amounts of wastes from fuel fabrication, reactor cores, and cladding/fuel structure.
5. Wastes produced to provide starting fissile material, and reactor decommissioning wastes after closure, exist but are not included here. Fabrication facility, reactor operation, and separations facility operations and maintenance LLW can be significant but are not included here. Reactor core wastes include metallic and non-metallic core structures, moderators, and reflectors that must be periodically discarded and replaced. Fuel structure and cladding includes fuel assemblies, support structures, inert components of IMFs, coatings on particles and pebbles, and molten salts.

Two variations included in the AOT analyses illustrate how such concepts as the Traveling Wave Reactor (TWR) and the Energy Multiplier Module (EM^2) can also include limited recycling designed to further increase uranium utilization and better utilize residual TRU, while still minimizing potential proliferation concerns that can occur for full recycling options. In these variations, melt refining or other limited recycling technologies may be able to remove enough FPs from used fuel to enable the remaining fuel material to be recycled to a reactor; or the used fuel may be chopped and packaged into a fuel bundle for a CANada Deuterium Uranium (CANDU) reactor, without any chemical reprocessing, in a DUPIC (Direct Use of spent PWR fuel In CANDU) recycle process. Both of these variants will cause some evolution of gaseous FPs (in DUPIC) and evolution of a wider range of gaseous, semivolatile, and relatively non-volatile FPs (melt refining), also likely contaminated with relatively smaller amounts of actinides. These variations will result in the evolution of some waste streams from the reprocessing operations, and cause these fuel cycle concepts to be more appropriately described as Modified Open rather than Once-Through options.

3.2.2 Fusion-Fission Hybrid

Waste streams from FFH system concepts are not well qualified or quantified because no FFH systems currently exist and their technical maturity is in early stages. However, the FFH options in this study can result in radioactive waste scenarios that are unique compared to other fuel cycle options.

The dedicated FFH waste burner is designed to reduce the waste disposal challenges from the larger LWR energy production fleet, primarily through elimination of most actinides from the waste. Its actinide burning efficiency is expected to be high enough that it is likely that amounts of MA that are eventually discarded will be mainly due to used fuel processing losses in both the LWR recycle and the FFH recycle. It is also possible to transmute significant portions of long-lived fission products if deemed desirable – at a cost in neutron economy in the FFH burner.

The FFH fissile factory seeks to produce minimal high-level radioactive waste (HLW) via suppression of fission in the breeding blanket. What fission products are produced may be removed in the salt processing or left to accumulate in the blanket. The largest amounts of radioactive wastes may result from how the fissile material produced in the FFH fissile factory is used. Two possible bounding limits for amounts of these "secondary" radioactive wastes are:

- Use of FFH bred U-233 as initial fissile to start a Th-fueled MSR with near-breakeven conversion ratio. This fuel cycle would send separated fission products to waste disposal with only processing losses of Th and U, with little higher actinides.

- Use of a blended U-Th cycle in the FFH breeder, and a blended Once-Through U-Pu cycle in LWRs. This would send used fuel to disposal with a mixture of TRU and fission products.

The FFH deep burn option seeks to minimize TRU sent to waste by pushing the burn-down phase as far as needed to meet waste management objectives. The waste is envisioned to be a robust intact fuel form containing primarily fission products. Waste quantities are minimized through maximum energy extraction from the fissionable resource. At nearly complete burn, LIFE would produce about 20 times more energy per ton of fuel than Once-Through LWRs. The spent fuel, however, would have fission product concentrations much higher than is typical in LWR used fuel, which must be considered in packaging, storage, and disposal facility heat management.

When used FFH fuels are reprocessed, then the full range of potential waste streams is possible. In addition, exotic core structure and fuel cladding materials including tungsten, beryllium, silicon, and carbon materials may be required in some designs. Some of these may need to be periodically discarded

and replaced to maintain core integrity in high radiation energy and temperature environments. Levels of waste or leaked H3 are expected to be higher than for thermal reactors because of the formation of H3 from Li6 in FFH designs.

Specific waste streams that may be more unique to FFH options compared to other fuel cycle options include:

- tritium contamination and/or losses
- heavily irradiated beryllium metal
- Salt processing wastes including tritium and beryllium contamination
- structural components activated by high energy neutrons

3.2.3 High Temperature Gas Reactor

Radioactive waste streams from HTGR fuel cycles include:

- Wastes from front-end U and/or Th mining and U enrichment (for those cases that use EU)
- Fuel fabrication
- Graphite blocks from reactor cores
- SiC and C (or other material) coatings separated from fuel particles and pebbles during recycle
- Gaseous FPs in all cases except a Once-Through TRISO case
- Other FPs in all Modified Open and Full Recycle cases
- Some amount of discarded actinides in cases that use minimal separations processes that do not efficiently separate actinides from fission products
- Discarded spent fuel in Once-Through cases (particles or pebbles coated with durable SiC and C (or other material) coatings.

The amounts of FPs will increase in proportion to the fuel burnup, regardless of HTGR case; the amounts of TRU will also increase in proportion with fuel burnup, unless TRU is recycled and burned.

A few waste management issues are unique to HTGR options. The graphite block moderator material could be a relatively large-mass radioactive waste stream compared to other HTGR radioactive waste streams, unless the graphite material can be recycled. Analyses and planning have been done to determine how to best recycle this material. In addition, the coatings on fuel particles and pebbles, designed for durability and toughness, present a challenge during reprocessing. These coatings also represent a large-mass waste stream in fuel recycling options.

3.2.4 Molten Salt Reactor

MSR variations can include different fuels (EU or Th), single or two-fluid designs, or operation with or without on-line reprocessing. These variations result in variations in potential types and amounts of waste streams, which could include:

- Wastes from front-end U and/or Th mining and U enrichment (for those cases that use EU)
- Graphite blocks from reactor cores
- Gaseous FPs in all cases

- Other FPs in all cases (except the Once-Through DMSBR would still retain nonvolatile FPs in the molten salt fuel
- Spent molten salt fuel in the DMSBR case.

The continuous online separations in all MSR recycle options and the continuous gaseous and noble metal sparging in the Once-Through option enables higher burnup than in other non-MSR options because of the removal of FP poisons and the lack of cladding that can degrade over time under high burnup conditions. So, like other high burnup options, levels of FPs produced during MSR operation and collected in waste streams separated during online reprocessing will be relatively high, but unlike other cases, levels of fissile materials and TRU in used fuel need not be high, since low levels of FP poisons can be continuously maintained.

Waste streams containing semivolatile and nonvolatile FPs separated during on-line reprocessing can be quite concentrated, and can contain amounts of salt waste, and so will require consideration of heat generation and waste loadings during subsequent handling and management.

3.2.5 Thorium/Uranium-233 Multirecycle in Pressurized Water Reactor

The Th-fueled Pressurized Water Reactor (PWR) multirecycle fuel cycle will result in a variety of waste streams radioactive wastes including:

- Wastes from front-end Th mining and refining (but not enrichment)
- Fuel fabrication
- Cladding and fuel structure
- Gaseous and other FPs

The long-term heat and radiotoxicity of waste streams from the Th233/U-233 fuel cycle are less compared to the U-238/Pu-239 fuel cycle, because smaller amounts of TRU elements are produced. Still, other isotopes including Pa-231, Th-229, and U-230 are produced which must be included in waste radiotoxicity analyses.

Irradiated THO2-based fuels contain U-232, which has strong gamma emitting daughters Bi212 and Tl208, and which aids in proliferation mitigation but causes remote, shielded, and automated reprocessing and refabrication.

Proliferation risk considerations should not be minimized. U-233 is fissile and could be misused. Denaturing the fuel with U-238 increases production of TRU elements. Separations processes needed for multirecycle could produce multiple recycle streams that are subject to proliferation risk.

4. Waste Management Metrics and Fuel Cycle Analyses

All of the fuel cycle options under evaluation will result in the generation of radioactive wastes from front end fuel mining and preparation, fuel fabrication, reactor core structure materials, discarded spent fuel assemblies, and/or separated waste streams from used fuel reprocessing. The basic radioactive waste management objective is to “reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials” (Dixon 2009). The recommended metrics are as follows (Dixon 2009):

- Quantity of actinides in high level waste for disposal, normalized per unit of energy produced

- Decay heat of waste at the time of waste form creation, normalized per unit of energy produced
- Radiotoxicity of disposed high level waste at 10,000 and 1,000,000 years, normalized per unit of energy produced
- Estimated dose for disposed high level waste, normalized per unit of energy produced
- Mass of initial heavy metal in waste disposed (all waste types), normalized per unit of energy produced
- Packaged volume of waste disposed (all waste types), normalized per unit of energy produced
- The packaged volume of material to be stored, normalized per unit of energy produced.

With data on the amounts and properties of waste streams that evolve from the different fuel cycle options, we can evaluate these options with respect to some but not all of these metrics. We can document the quantity of actinides, the decay heat and radiotoxicity, and mass of initial heavy metal.

We can also predict waste forms and waste loadings, volumes, and masses of those waste forms. We can guess at waste packages that might be compatible to the different waste forms, and estimate using those guesses the numbers, volumes, and masses of those waste packages. But to guess at waste packages would presume selection from current transportation, storage, and disposal options that are not necessary designed or optimized for these future fuel cycle options. Converting waste stream mass data to waste forms, and converting the waste form data to packaged waste data, risks introducing artifacts in the analyses based on current waste policies and regulations and not directly tied to the characteristics of the waste itself.

We can normalize the estimated waste values to unit of energy produced (either thermal or electrical), which seems to be the simplest and fairest way to analyze the environmental burden of radioactive waste generated by different fuel cycle options.

We cannot, at this time, estimate dose from disposed wastes, without presuming a specific disposal site and without detailed analysis about waste behavior in that disposal site.

Specific used fuel properties are not yet available for the five fuel cycle option families, so a quantitative analysis of the different options using waste management metrics listed above is not yet possible. The following sections show a few general, qualitative analyses that have been included in this report in lieu of specific, quantitative analyses.

4.1 Fission Product Yield for Different Fuel Cycle Strategies

Nuclear fission results in the production of undesirable fission products that increasingly interfere with the fission process as their concentrations increase. A quantitative analysis of the different options using waste management metrics listed above is not yet possible. Meanwhile, a qualitative evaluation may be done to show, in general terms, relative amounts of thermal fission product yield for different actinides, which are used in different fuel cycle options. Figure 4-1 shows a first-order comparison of thermal fission yield for different actinide isotopes, and indicates that:

- In overview for thermal fission, the FP yields for the highest-yield isotopes are similar for two U isotopes, Np237, and four Pu isotopes. For any thermal reactor that uses U, Th, Pu, or Np as the fuel, the fission product yield, at least for most of the fission products produced in the greatest amounts, is similar. The amounts of these major fission products may not vary significantly for different thermal fission reactors, when normalized to a similar fuel burnup basis.

- For FPs with atomic masses <92, between 100-128, and >150: there is some variation, ranging between less than a factor of 10 up to about a factor of over 10^5. The greatest variation occurs for atomic masses >160.

- But, for most of the highest-yield FPs, which are between about 92-102 and 130-150, the variation in thermal fission yield is less than a factor of 10. The greatest variation for high-yield FPs is for those between 102-110, when the yield of FPs from U233 and U235 fission ranges over 10x lower than the yield from the Np239 and Pu239, Pu240, Pu241, and Pu242 fission. And, for masses between 88-92, the FP yield for Np237 and Pu239 is up to about 1/4 of the yield from U233 and U235.

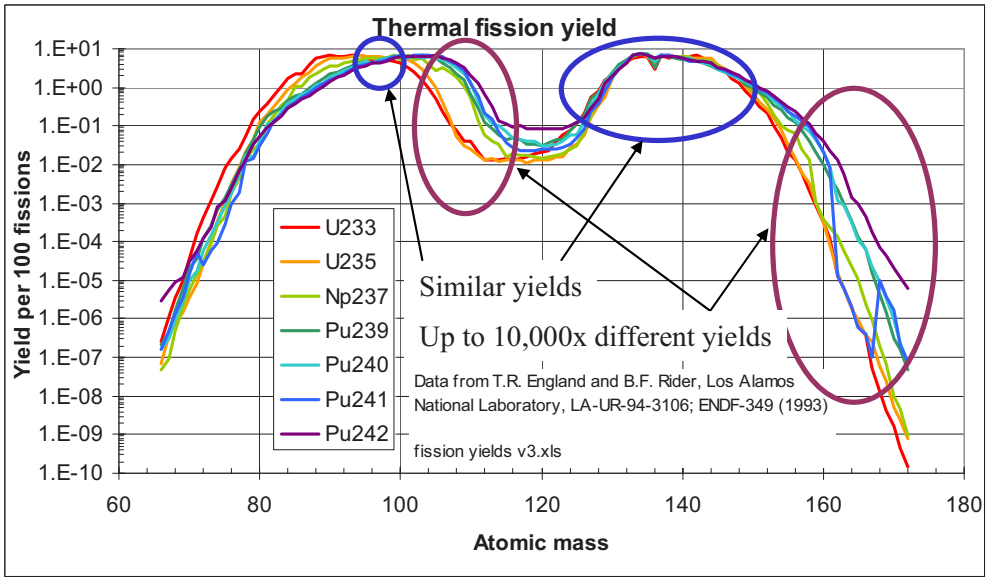

Figure 4-1. Fission product yield for thermal fission from fissile U, Np, and Pu isotopes.

4.2 Used Fuel Radiotoxicity and Decay Heat

Used fuel radiotoxicity and decay heat can be quantitatively analyzed when used fuel compositions and masses for the specific fuel cycle options are available. Meanwhile, results of some prior waste stream studies for some similar fuel cycle cases can be used to generally describe waste radiotoxicity and decay heat over time for some Once-Through, 1-recycle (Modified Open), and Full Recycle fuel cycle strategies.

Figure 4-2 shows the radiotoxicity of waste for many different fuel cycle cases. Of the four cases in this figure, three use a thermal reactor and one uses a fast reactor. Both thermal and fast reactors are included in Once-Through options in the waste stream study. However, the fast reactor case in this figure may not adequately represent any of the advanced fast reactor options in the waste stream study.

- Once through LWR-UOX at 51 MWth-day/kg-fuel burnup

- Once through LWR-UOX at 100 MWth-day/kg-fuel burnup

- Once through HTGR-UOX at 102 MWth-day/kg-fuel burnup - note that we would prefer to have a more recent calculation for 178.5 MWth-day/kg-fuel burnup, but for now we use a 2005 Argonne National Laboratory (ANL) early Next Generation Nuclear Plant (NGNP) calculation

- Once through CR=0.50 fast reactor (148 MWTh-day/kg-fuel burnup) fed by 29% enriched uranium.

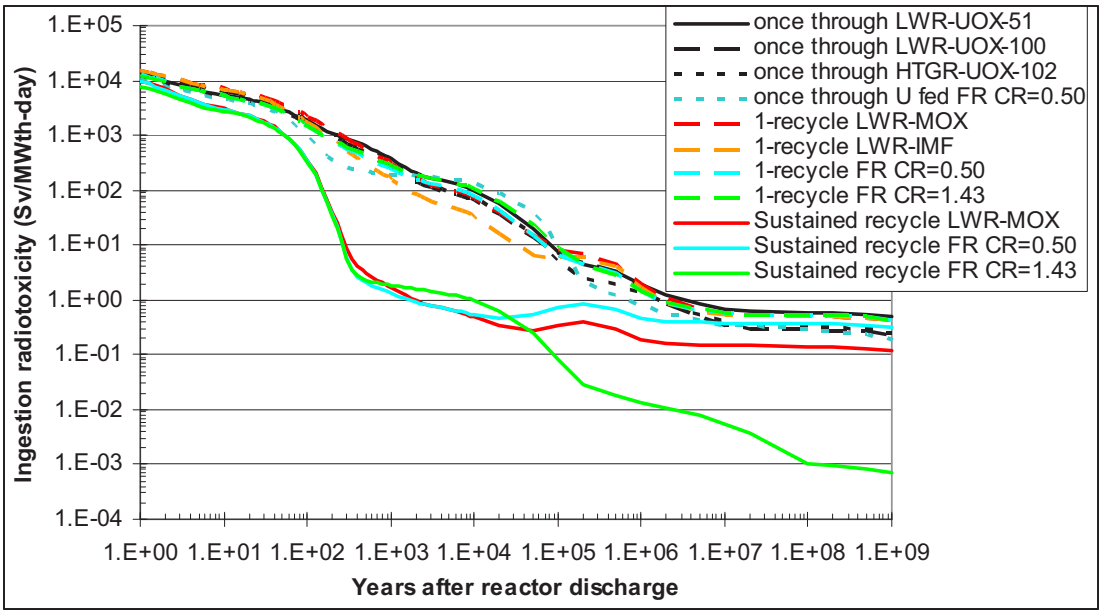

Figure 4-2. Radiotoxicity for a wide range of fuel cycles.

Four 1-recycle cases in this figure are Modified Open Cycle cases. Two of these include recycling used fuel in fast reactors; the other two recycle used fuel in thermal reactors. Recycling in both thermal and factors is included in the Modified Open Cycle cases in the waste stream study.

- 1-recycle LWR-MOX-TRU (50 MWth-day/kg-fuel) fed by LWR-UOX-51
- 1-recycle LWR-UOX/IMF-TRU (554 MWth-day/kg-fuel) fed by LWR-UOX-51
- 1-recycle FR-metal-TRU (CR=1.50, 132 MWth-day/kg-fuel) fed by LWR-UOX-51
- 1-recycle FR-metal-TRU (CR=1.43, 37 MWth-day/kg-fuel) fed by LWR-UOX-51.

Three Full Recycle cases are included in this figure, in both thermal and fast reactors. Recycling in both thermal and factors is included in the Full Recycle cases in the waste stream study.

- Sustained recycle LWR-MOX-TRU, fed by LWR-UOX-51
- Sustained recycle FR-metal-TRU (CR=1.50, 132 MWth-day/kg-fuel) fed by LWR-UOX-51
- Sustained recycle FR-metal-TRU (CR=1.43, 37 MWth-day/kg-fuel) fed by LWR-UOX-51.

All once through cases use enriched uranium fuel. All recycle cases include all of the transuranics. Except for the fast breeder case, all recycle cases include the appropriate mixture of LWR-UOX and any excess recovered uranium, separation losses at 0.1% of TRU, and are normalized to energy recovered from the fuels (MWth-day).

In general terms, and without trying to evaluate any specific fuel cycle option, this figure indicates that:

- Full Recycle options - whether fast breeder, fast burner, or thermal – result in substantially lower short term (out to 1,000 years) and long term (from 1,000 to 1 million years and beyond) radiotoxicity.
- A fast breeder Full Recycle option might result in lower radiotoxicity compared to the other two Full Recycle options only after ~100,000 years; this is due to the decoupling of that case from LWR-UOX. At around ~10,000 years, the breeder case has higher radiotoxicity because there is relatively more Pu239 in that system.
- 1-recycle (Modified Open) options, whether thermal or fast reactor, do not significantly decrease radiotoxicity compared to current Once-Through thermal cases, unless they can achieve significantly more burnup of TRU than in the 1-recycle cases in this figure.
- Some Once-Through cases don't vary significantly, whether thermal or fast, LWR or HTGR (using the old HTGR data). This may not be true for the Advanced Once-Through cases in the waste stream study, if those cases can achieve significantly more burnup of TRU than in the Once-Through cases in this figure.

More detailed analyses show that the lower radiotoxicity achieved by Full Recycle options results from the more significant burning of highly radiotoxic and high longevity TRU, compared to other cases in this figure. It is yet to be seen how waste radiotoxicity of the Once-Through, Modified Open, and Full Recycle fuel cycle options of this study compare.

Figure 4-3 shows heat emission for the same fuel cycle cases. The trends are similar to those for radiotoxicity, for the same reasons.

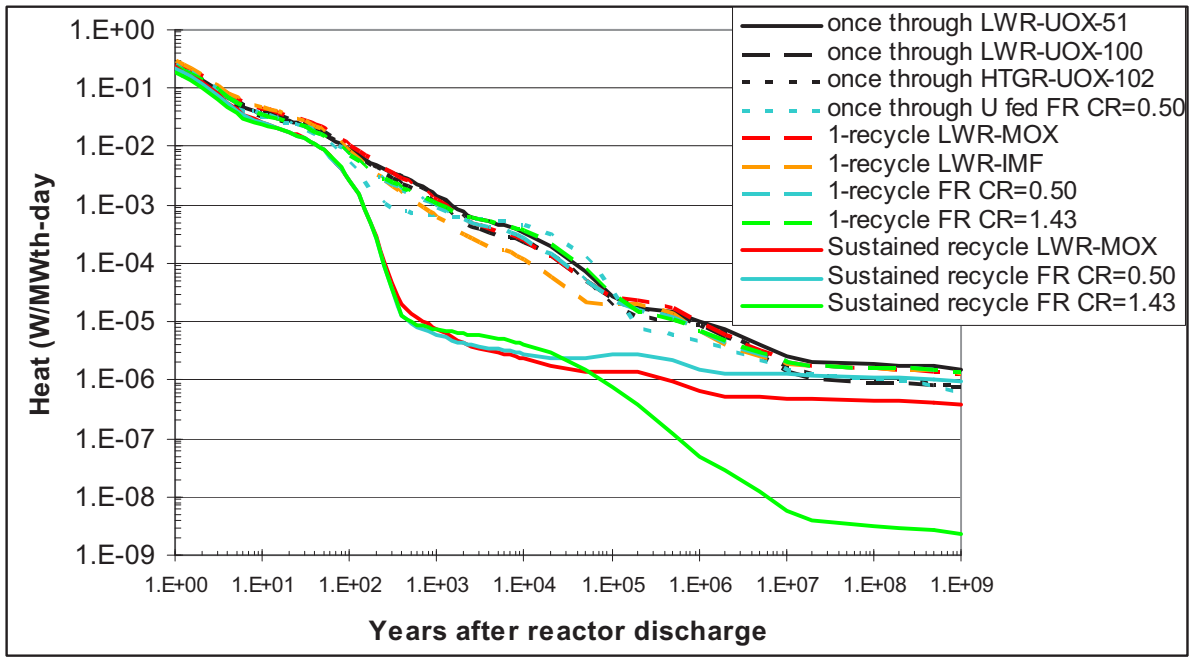

Figure 4-3. Heat for a wide range of fuel cycles.

5. RESULTS AND CONCLUSIONS

A high-level study was performed in Fiscal Year 2009 for the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) Advanced Fuel Cycle Initiative (AFCI) to provide information for a range of potential nuclear fuel cycle options (Wigeland 2009). At that time, several potential fuel cycle options could not be adequately evaluated because they were not well defined and lacked sufficient information for analysis. As a result, five of these potential fuel cycle options are being studied during Fiscal Year 2010 by the Systems Analysis Campaign for DOE NE Fuel Cycle Research and Development (FCRD).

The analysis of these fuel cycles includes a high level evaluation of potential waste streams for each of the fuel cycle options. The objective of the waste stream study is to obtain and interpret information about waste streams for the selected fuel cycle options that can be used to:

- Describe quality and completeness of the data
- Describe (as practical) waste streams arising from each option
- Find waste stream similarities and differences (discriminators) for the different options.

The waste stream study relied on the results of the five fuel cycle option studies being performed during FY-2010 by the Systems Analysis Campaign. These five potential fuel cycle options are based on the following reactor concepts, which are described in more detail in interim status reports for these studies:

- Advanced Once-Through reactor concepts (Once-Through or AOT) (Taiwo 2010a)
- Fusion-Fission Hybrid (FFH) (Halsey 2010)
- High Temperature Gas Reactor (HTGR) (Piet 2010)
- Molten Salt Reactor (MSR) (Gehin 2010)
- Thorium/U-233 Fueled Light Water Reactors (Th/U-233) (Taiwo 2010b).

Results and conclusions of this study include:

- Families of several fuel cycle options cross-cut across the Once-Through, Modified Open, and Full Recycle strategies.
- Limited fuel reprocessing such as DUPIC, AIROX, or melt refining will generate some radioactive wastes including fuel cladding and structure materials, gaseous fission products, and (in some cases) semivolatile fission products. Limited fuel reprocessing will likely result in less efficient separations of waste FPs from recyclable actinides, resulting in waste FP contamination in recycled actinide streams and TRU contamination in waste FP streams.
- Fission product contamination of recycled fuel, and the presence of TRU elements, will cause recycle fuel handling and fabrication operations to be remote operations inside shielded hot cells.
- TRU contamination in some waste streams will cause those streams, which otherwise might meet LLW Class C limits, to require disposition as GTCC LLW.
- The amounts of radioactive non-fuel wastes from reactor core structures and fuel cladding and structure materials for some fuel cycle options can be large compared to the used fuel waste streams. Some analyses have been done to evaluate how to recycle these relatively large waste streams.

- High-burnup used fuels will have high concentrations of high-heat-generating and high-radiotoxicity isotopes, that may cause lower waste loadings in waste forms and in geological repositories to stay within expected thermal and radiotoxicity limits.
- Full Recycle options can significantly lower short and long-term radiotoxicity and heat generation compared to some Once-Through and Modified Open options, because of the transmutation of high-radiotoxicity, high-heat, long-lived TRU isotopes.

The quality and completeness of data available to date for the fuel cycle options is insufficient to perform quantitative radioactive waste analyses using recommended metrics. This study has been limited thus far to qualitative analyses of waste streams from the candidate fuel cycle options, because quantitative data for wastes from the front end, fuel fabrication, reactor core structure, and used fuel for these options is generally not yet available. These data gaps exist for most of the fuel cycle options evaluated in this study. At the time such data are available, these additional waste stream analyses can be done:

- Mass, volume, and compositions of different radioactive waste streams
- Mass, volume, and waste loading of waste forms for the different waste streams
- Radiotoxicity and heat generation of the radioactive wastes

The mass, volume, composition, radiotoxicity, and heat generation for the waste streams and waste forms can be normalized to the amount of thermal or electric energy produced for the different options.

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