

Energy Return on Investment from Recycling Nuclear Fuel

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1.0 INTRODUCTION

Energy Return on Investment (EROI) is defined as the ratio of final energy produced to final energy invested (or consumed) in the process. Final energy is defined as energy in forms readily usable by consumers, such as gallons of gasoline, megawatt-hours of electrical energy, or cubic feet of natural gas. All forms of final energy are derived from an energy resource, such as oil in the ground. The resource must be extracted and processed in some way to convert it into final energy, such as gasoline. These extraction and processing actions themselves require investment (or consumption) of energy. Of course, the final energy produced from the resource should be many times greater than the final energy invested in the extraction and processing actions.

This report presents an evaluation of the EROI from recycling an initial batch of 800 t/y of used nuclear fuel (UNF) through a Recycle Center under a number of different fuel cycle scenarios. The study assumed that apart from the original 800 t of UNF only depleted uranium was available as a feed. Therefore for each subsequent scenario only fuel that was derived from the previous fuel cycle scenario was considered. The scenarios represent a good cross section of the options available and the results contained in this paper and associated appendices will allow for other fuel cycle options to be considered.

Scenario 1: Produce both plutonium-uranium mixed oxide (MOX) fuel and reprocessed uranium (RepU) fuel for use in existing light water reactors (LWRs) (One-Pass Recycle Option).

Scenario 2: Recycle of the used MOX and RepU UNF from Scenario 1 for use in LWRs again, a Two-Pass Recycle Option. In this scenario, the fissile material is used three times: once as fresh fuel in an LWR and twice more as recycled fuel in LWRs.

Scenario 3: Operation of sodium fast reactors (SFRs) to obtain additional energy from the used nuclear fuel available after Scenario 1 considering 3 different conversion ratios (CRs) for the core operation namely CR of 0.3 (Burner), a CR of 1 (Neutral) and a CR of 1.2 (Breeder). In this scenario, the fissile material is used three times: once as fresh fuel in an LWR, once as recycled fuel in an LWR, and finally as recycled fuel in an SFR.

This report does not include any discussion of the once-through (open) fuel cycle and is not a comparison with the once-through fuel cycle. Calculations of the EROI of the once-through fuel cycle have been presented by other entities (example: World Nuclear Association [1]). Thus, this report does not include any estimates of the energy consumption during natural uranium (NatU) mining, ore processing, enrichment, etc. Instead, this report considers the energy resource to be the used nuclear fuel from LWRs. It is assumed that the acquisition of this resource requires no additional energy investment at all because it is currently stored at existing LWRs.

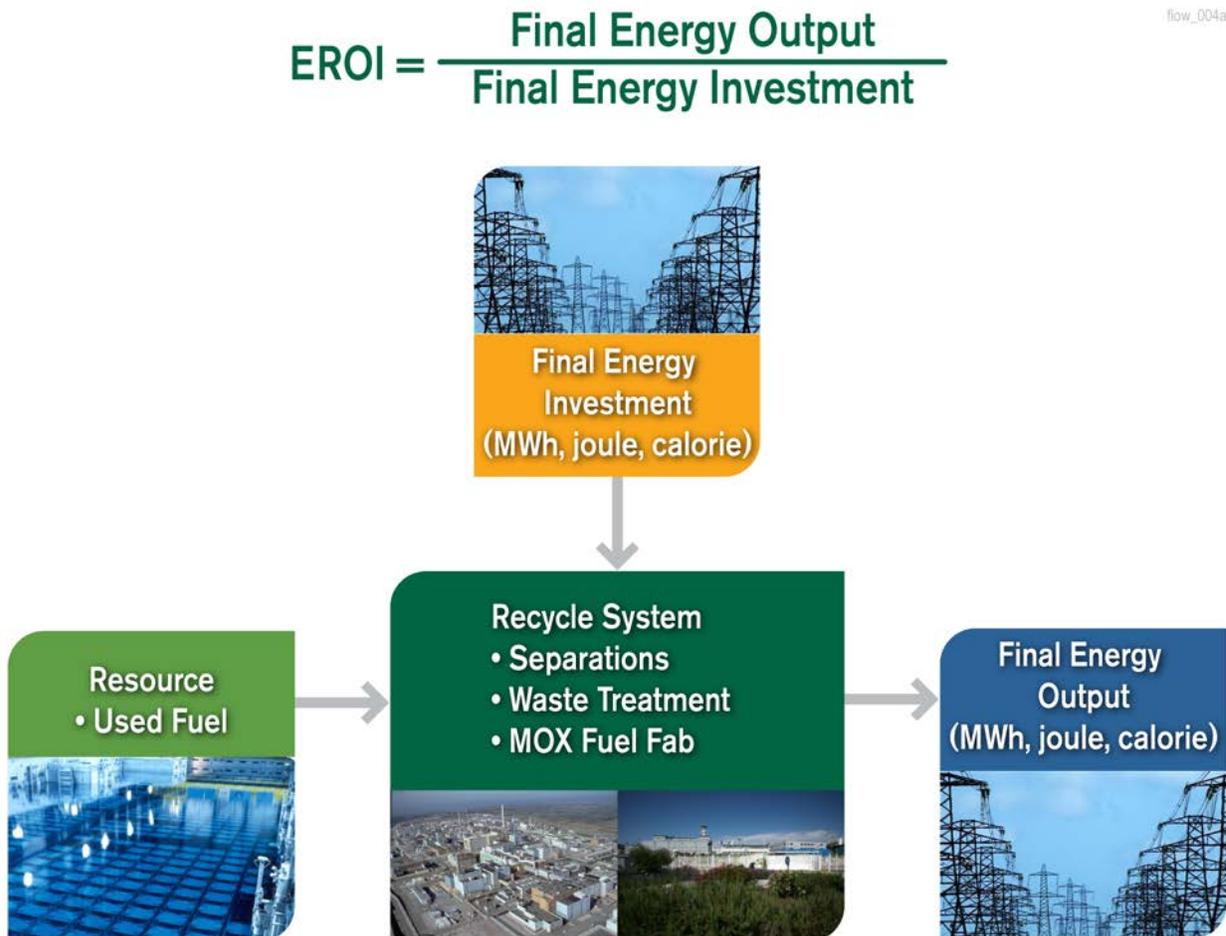
For completeness the report estimates the energy that would be required to build and decommission any of the facilities that are specifically required to extract energy from the UNF. This includes the recycling facilities, specific RepU Facilities and the SFR. It does not include the construction and dismantlement of LWRs.

2.0 ENERGY RETURN ON INVESTMENT FOR THE ONE PASS RECYCLE SCENARIO

Figure 1 provides a graphic illustration of the EROI concept for the one-pass recycle option. In this calculation, the final energy produced is defined as the electrical energy produced (to the grid) from loading the recycled MOX and RepU fuel in existing operating LWRs. The final energy invested (or consumed) is defined as the electrical energy and thermal energy (natural gas) that is invested (or consumed) in operating the following facilities:

- Recycle Center Facilities
 - Recycling Plant (including associated waste treatment facilities)
 - MOX Fuel Fabrication Plant
- RepU Processing Facilities
 - Conversion to UO_3
 - Conversion to UF_6
 - Conversion to U_3O_8
 - Electrolysis
 - Enrichment of RepU
 - Conversion to UO_2 and RepU Fuel Fabrication Facility

Figure 1. EROI Concept (One-Pass Recycle Option)



The Recycle Center is sized to process 800 metric tons of heavy metal of used nuclear fuel (UNF) per year (800 tHM/y). The energy consumption for an 800 tHM/y Recycle Center is extrapolated from actual operational data of similar recycling facilities in France (La Hague Recycling Plant and MELOX MOX Fuel Fabrication Plant).

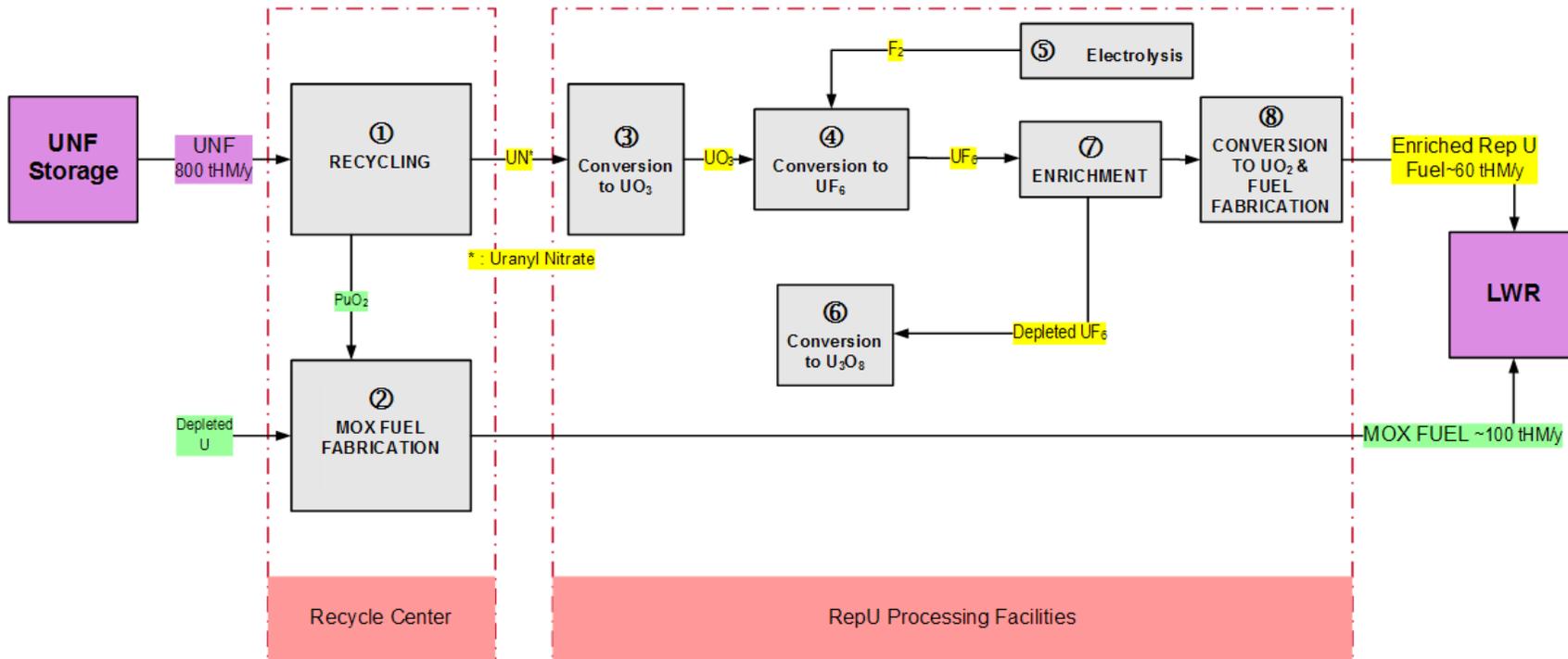
3.0 KEY ASSUMPTIONS

This section describes the key assumptions used in the EROI evaluation.

3.1 FUEL CYCLE

The EROI calculation is based on the fuel cycle shown in Figure 2. The material flow is based on the PUREX recycling technology currently in use at the LaHague Recycling Plant.

Figure 2. LWR Used Nuclear Fuel Cycle (One-Pass Recycle Option)



In this fuel cycle scenario, the plutonium is recovered from the UNF and used to fabricate MOX fuel and the recovered uranium is converted, enriched, and fabricated into RepU fuel. The final energy output is electrical energy produced (to the grid) from loading the MOX and RepU fuel into operating LWR's. The main facilities in this figure are numbered from 1 through 8. These facility numbers will be used in Sections 3.0 and 4.0 to describe the functions of the facilities and to tabulate their final energy investments (consumptions).

A description of the two large boxes shown in Figure 2 is provided below:

Recycle Center: This box shows the facilities that are associated with the Recycle Center this analysis assumes will be constructed in the United States to recycle LWR used nuclear fuel. The Recycle Center facilities should be located on the same site due to process considerations, safety and security (no transportation of Pu powder between facilities), and operational cost considerations (waste management, etc.). Additional information on these facilities is discussed in Section 4.0 (Key Recycling Facilities) and Section 5.0 (Final Energy Consumption Data) of this report.

RepU Processing Facilities: This box shows the facilities associated with processing the RepU fuel recovered from the recycling of the LWR used nuclear fuel in the Recycle Center. This analysis assumes that some of the RepU fuel processes are performed in RepU "dedicated" facilities while other RepU fuel processes will be integrated into "existing" natural uranium (NatU) facilities. The dedicated conversion facilities are required to prevent contamination of the UOx lines with U²³².

The list below identifies the different processes associated with recovery, conversion, and fabricating RepU fuel and the associated type of facility ("dedicated" or "existing") in which the process will be located.

- "Dedicated" Facilities
 - Conversion to UO₃ (Box 3 in Figure 2)
 - Conversion to UF₆ (Box 4 in Figure 2)
 - Conversion to U₃O₈ (Box 6 in Figure 2)
- "Existing" Facilities
 - Electrolysis (Box 5 in Figure 2)
 - Enrichment (Box 7 in Figure 2)
 - Conversion to UO₂ & Fuel Fabrication (Box 8 in Figure 2)

The RepU Processing Facilities do not have to be collocated with the Recycle Center. Additional information on these facilities is discussed in Section 3.0 (Key Recycling Facilities) and Section 4.0 (Final Energy Consumption Data) of this report.

3.2 THE ENERGY RESOURCE: USED NUCLEAR FUEL

The energy resource is assumed to be used UOx fuel that was burned in LWRs (box labeled UNF Storage on the left side of Figure 2). It is intended to represent an average of the U.S. reactor fleet. The discharge burn-up is assumed to be 50 GWD/t. This is a batch-average burn-up, with some fuel assemblies having a higher burn-up and some having a lower burn-up. The initial enrichment required to achieve this burn-up is assumed to be 4.1 % U²³⁵. These two assumptions, along with a cooling time of 4 years, yield the plutonium isotopic composition, or plutonium quality assumed to exist in the used nuclear fuel. This is the starting point, or the energy resource, for this EROI calculation.

3.3 MOX AND REPU FUEL TO BE FABRICATED

The MOX and RepU fuel to be produced in these facilities is assumed to contain sufficient fissile material to achieve a discharge burn-up which is the same as the UOx fuel, or 50 GWD/t. These assumptions are summarized in Table 1. The MOX fuel is composed of the plutonium recovered from the recycled LWR used nuclear fuel. This plutonium is converted to an oxide and is mixed with fresh uranium tails material with an assumed composition of 0.25 % U^{235} left over from the enriching of fresh natural uranium used to manufacture fresh UOx. The amount of plutonium is 9.6 weight-percent of the total heavy metal in the MOX fuel.

The uranium in the UNF is the resource for the RepU fuel. This material is assumed to have a nominal enrichment of 0.76 weight-percent. After it is separated from the UNF, this material must be enriched to about 5 weight-percent to achieve the same 50 GWD/t discharge burn-up as the initial fresh UOx fuel.

3.4 RECYCLE CENTER REFERENCE SIZE

The assumed capacity of the reference Recycle Center is 800 tHM/y. The Recycle Center includes both the aqueous recycling facilities for UNF uranium oxide (UOx) and the associated waste treatment.

3.5 FABRICATION PLANTS (MOX/REPU) SIZE

The fuel fabrication facilities are sized to match the product (Pu/RepU) from the 800 tHM/y Recycle Center. The Recycle Center produces LWR MOX fuel while the RepU fuel is produced in a UOx fuel fabrication facility. The MOX fuel contains the plutonium from the recycled LWR used nuclear fuel and the RepU fuel contains the uranium which has been enriched from the average assumed discharge enrichment of approximately 0.76 % U^{235} to an enrichment of about 5 %.

3.6 EXCLUSIONS

Only energy consumption parameters that have significant impact on EROI calculation are included in this evaluation. The following energy consumption parameters are excluded:

- Transportation of used nuclear fuel elements to the Recycle Center
- Transportation of workers
- Manufacturing and transportation of fuel cladding
- Transportation of small quantity of depleted uranium used in MOX fabrication
- Manufacturing and transportation of reagents

The EROI evaluation does not consider normalization of climate conditions for heating and cooling of a Recycle Center located in the United States since a specific site for the Recycle Center has not been identified. The energy used for heating and cooling of the Recycle Center facilities in France is included in the actual plant energy usage data contained in this report. The climate in France in the vicinity of the La Hague and MELOX Plants is considered a moderate climate.

Table 1. Summary of Key Assumptions

Parameter	Assumed Value
<i>UOx Fuel</i>	
UOx Initial Enrichment	4.1 % U ²³⁵
UOx Discharge Burnup	50 GWD/t
Cooling Time Before Recycling	4 years
<i>MOX Fuel</i>	
Recycle Center Capacity	800 tHM/y
MOX produced	100 t/y
Pu throughput	9.6 t/y
Percent Pu in heavy metal	9.60%
Enrichment of uranium in MOX fuel	0.25 % U235
MOX Discharge Burnup	50 GWD/t
<i>RepU Fuel</i>	
RepU produced	748 t/y
Percent of U ²³⁵ in RepU	0.76%
RepU Fuel Produced	59 t/y
RepU Fuel Enrichment	~5 % U235
RepU Discharge Burnup	50 GWD/t

4.0 KEY RECYCLING FACILITIES

The key facilities considered in the EROI evaluation include the Recycle Center (Recycling Plant and MOX Fuel Fabrication Plant) and the RepU Processing Facilities (RepU Conversion Facilities, Electrolysis Facility, RepU Enrichment Facility, and RepU Fuel Fabrication Facility). Each of these facilities is described in this section.

4.1 RECYCLING PLANT

The Recycling Plant (Box 1 in Figure 2) receives the UNF UOx fuel, removes the end pieces and metal clad, dissolves the spent UOx fuel pellets, and separates the uranium and plutonium from the fission products and other actinides. The fission products and minor actinide waste stream is also stabilized in this facility.

The Recycling Plant includes a number of operations, which are described below.

4.1.1 FUEL RECEIPT & STORAGE (FRS) FACILITY

The function of the FRS Facility is to receive casks containing UNF, conduct cask maintenance, and transfer the UNF using either dry or wet fuel unloading techniques to a storage pool.

4.1.2 SHEARING/DISSOLUTION/COMPACTION FACILITY

Fuel assemblies are taken from the storage pool and transferred into the shearing machine. The UNF is cut into rod sections that are transferred to the dissolver. The end pieces and empty rod sections (hulls) are cleaned and size reduced by compaction.

4.1.3 SEPARATION/PURIFICATION/CONCENTRATION FACILITY

The separation and purification process is based upon countercurrent liquid-liquid extractions. The solvent used is TBP diluted in dodecane diluent.

4.1.4 FISSION PRODUCT VITRIFICATION FACILITY

The purpose of the vitrification unit is to prepare solutions for the vitrification process, and to incorporate the High Active Liquid Waste (HALW) and undissolved fines into a glass matrix using a cold crucible melter. The glass is poured into canisters which are sent to the appropriate storage facility.

4.1.5 HIGH ACTIVE SOLID WASTE STORAGE FACILITY

Compacted waste canister storage is designed for the interim storage of the compacted waste canisters from compaction unit.

4.1.6 LIQUID AND SOLID WASTE TREATMENT FACILITY

This facility is dedicated to the treatment of the liquid and solid wastes generated in the plant. In the liquid waste treatment area, the main function is liquid waste decontamination by concentration and evaporation.

4.2 MOX FUEL FABRICATION PLANT

The MOX Fuel Fabrication Plant (Box 2 in Figure 2) takes the plutonium product of the Recycling Plant and produces MOX fuel assemblies. The facility contains process equipment in glove boxes inside process cells dedicated to the LWR MOX fuel fabrication and associated storage areas. The process mixes the PuO₂ powder and uranium oxides with recycled scrap powder to form MOX fuel pellets. The pellets are loaded into fuel rods, which are then assembled into (U, Pu) fuel assemblies for use in LWRs.

The fabrication of MOX fuel is similar to that of uranium oxide fuels. It is performed in the following phases:

- Mixing the powders
- Sintering
- Grinding
- Graining (inserting pellets into zirconium rods)
- Assembly (final stage – inserting rods into metal structures to form fuel assemblies for loading into LWRs).

It is important to note that the current design constraints on the LWR MOX Fuel Fabrication Plant restrict the concentration of Pu in the fabrication process to less than 12.5 weight-percent.

4.3 REPU CONVERSION FACILITIES

The RepU Conversion Facilities (Boxes 3, 4, and 6 in Figure 2) converts the oxide of the recycled uranium into a fluoride so that it can be enriched. After enrichment, the depleted material is converted to U_3O_8 in a RepU plant. These facilities are dedicated RepU facilities in order to avoid contamination of the UOx lines with the U^{232} isotope in the RepU. U^{232} has several short-lived decay products, including Tl^{208} , which emits a very strong gamma-ray with an energy level of 3.4MeV.

4.4 ELECTROLYSIS FACILITY

In the Electrolysis Facility (Box 5 in Figure 2) gaseous fluorine is produced by using electrolytic cells, which contain molten potassium bifluoride and anhydrous hydrogen fluoride. An electrical current passes through the cell and dissociates the anhydrous hydrogen fluoride into hydrogen and fluorine. Cell temperature is maintained by internal water cooling. The electrolysis process will be performed in existing NatU facilities.

4.5 REPU ENRICHMENT FACILITY

The RepU Enrichment Facility (Box 7 in Figure 2) takes the reprocessed uranium, which has a U^{235} enrichment in the region of 0.76%, and enriches it to about 5%. The enrichment is accomplished in existing NatU Enrichment Facilities, but will have a dedicated line for RepU enrichment. This evaluation assumes the enrichment facility uses the centrifuge process rather than the more energy intensive diffusion process. The input to the process is low-enriched uranium hexafluoride. The enrichment process concentrates the lighter isotopes of uranium, including the U_{234} , U^{235} , and U^{236} in the U^{238} . This enriched material is then used in the manufacture of the fuel pellets. The bulk of the material is left with a lower enrichment than it started with and is sent to a waste storage facility.

4.6 REPU FUEL FABRICATION FACILITY

This evaluation assumes that an existing LWR Fuel Fabrication Facility (Box 8 in Figure 2) converts the UF_6 to UO_2 and produces the RepU fuel assemblies. The fuel fabrication is accomplished in existing NatU fuel fabrication facilities, but will contain process equipment dedicated to the LWR RepU fuel fabrication and associated storage areas. Due to the decay products of the U_{232} in the RepU, some of the process equipment is placed behind shielding to reduce worker doses. No glove boxes or hot cells are required. The RepU fuel fabrication process involves manufacturing RepU fuel pellets, loading the pellets into the fuel rods, and assembling the fuel rods to form the fuel assemblies. The steps in the manufacture of the pellets are similar to those described in Section 3.2 for the MOX fuel.

5.0 FINAL ENERGY CONSUMPTION DATA

The final energy consumed in the operation of the Recycle Center is extrapolated from actual energy consumption data from operating Recycling Plant (La Hague) and MOX Fabrication Plant (MELOX) in France. These facilities have the highest energy consumption in a Recycle Center (approximately 90% of the total energy consumption associated with operating Recycle Center and associated RepU Facilities). Energy consumption for the RepU Conversion, Enrichment, and Fabrication facilities is based on a combination of actual facility operational data as well as engineering analysis of future facilities that AREVA is currently building or planning to build. The actual energy consumption data and the method used to extrapolate to the reference 800 tHM/y plant are described in this section. The estimated energy consumption of each facility for the 800 tHM/y plant is summarized in Table 2.

5.1 ESTIMATED ENERGY TO OPERATE THE 800 tHM/Y RECYCLE FACILITIES

Table 2 below provides the energy consumption data for the operational facilities in France, as well as the normalized energy consumption estimates for an 800 tHM/y Recycle Center.

The process/analysis associated with determining the energy consumption of the different Recycle Center facilities, as well as the normalization of the operating facilities the 800 tHM/y reference facility, is discussed in the following sections.

Table 2. Annual Energy Consumption (Recycle Center & RepU Facilities)

ALL YEARLY FIGURES	RECYCLING ①	MOX FUEL FABRICATION ②	RepU CHEMICAL PROCESSING conversion to UF ₆ ③+④+⑤, conversion to U ₃ O ₈ ⑥	RepU ENRICHMENT ⑦	RepU FUEL FABRICATION ⑧	TOTAL
Reference Plant	La Hague	MELOX	Project EPICURE*	GB II	FBFC ROMANS	
Reference Throughput	1015 tHM (2006)	130 tHM (average 2003-2009)	* See Note 1 below.	* See Note 1 below.	869 tU/y (average 2005-2008)	
Reference Energy Consumption	690 GWh	43 GWh			41 GWh	
Incl. Electricity	378	38			31	
Incl. Thermal	312	5			11	
EROI Study Throughput	800 tHM	100 tHM	748 tHM	748 tHM	59 tHM	
Estimated Energy Consumption (GWh)	416	43	36	15	3	513
Incl. Electricity	220	38	21	15	2	296
Incl. Thermal	196	5	15		1	217
% of Total Estimated Consumption	81.1%	8.4%	7.0%	2.9%	0.6%	

Note 1: AREVA does not currently operate equivalent facilities nor access to actual operation energy consumption date. The estimated energy consumption for these facilities is based on detailed design / operational studies for new AREVA facilities currently under development:

- * EPICURE - AREVA RepU Conversion Facility
- * George Besse II (GBII) - AREVA Enrichment Facility

5.2 RECYCLE CENTER

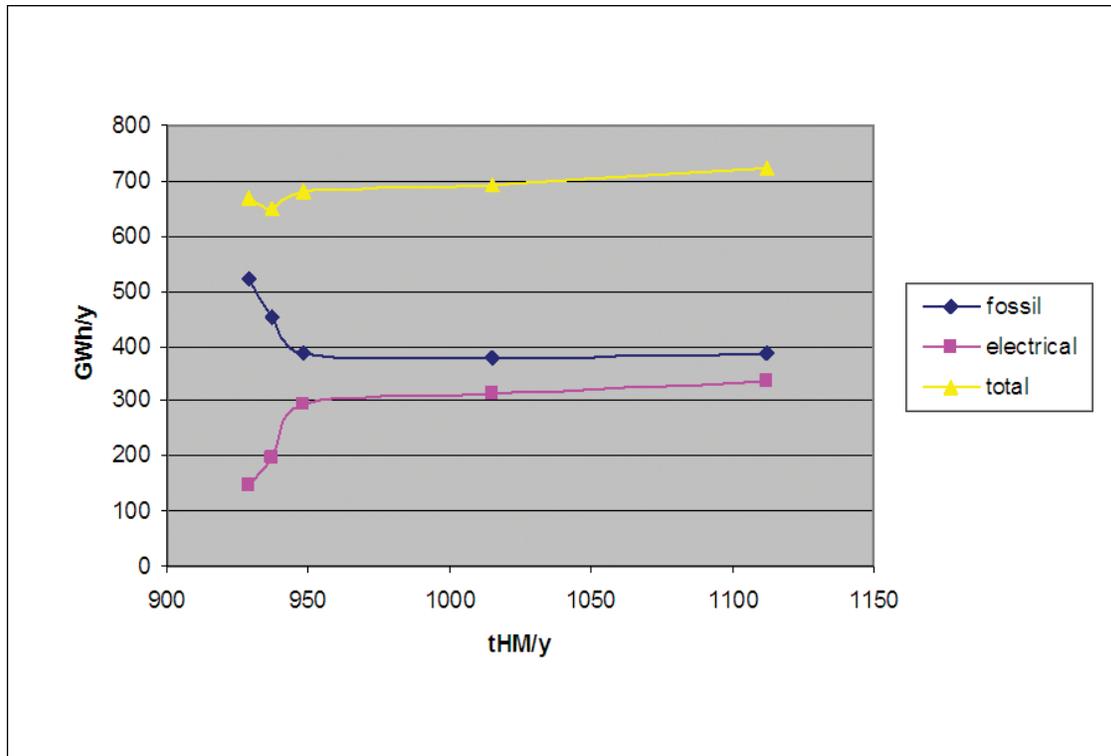
5.2.1 RECYCLING PLANT

This section presents the energy consumption of the Recycling Plant (Box 1 of Figure 2). The energy necessary to recycle 800 tHM/y of UNF is based on actual energy usage data from AREVA's La Hague Plant that has a throughput capacity of 1,600 tHM/y (note: La Hague has two operational lines designed for recycling 800 tHM/y each).

La Hague Energy Consumption Data

Figure 3 and Table 3 provide the La Hague Plant's energy consumption data [3] for years 2004 to 2009 (note: latest available information data/Figure 3 only shows 5 data points since data for years 2004 and 2005 are nearly the same throughput).

Figure 3. LA Hague Plant Energy Consumption vs. Throughput



As shown in Table 3, the overall energy consumption is not significantly different from one year to another, and roughly correlates with the throughput. The evolution within the last two years (2008 and 2009) of the energy distribution (fossil fuel vs. electricity) derives from the replacement of steam generators from fuel oil type to electrical type. The thermal energy from fossil fuels is used primarily to heat facilities and operate limited plant components.

Table 3. LA Hague Energy Consumption vs. Throughput

	2004	2005	2006	2007	2008	2009
Recycled UNF (tHM/y)	1100	1112	1015	948	937	929
Electricity Consumption (GWh/y)	399	386	378	387	425	521
Thermal Energy Consumption (GWh/y)	334	336	312	292	198	148
Total (GWh/y)	733	722	690	679	623	669

In the EROI calculation, the energy consumption for 2006 is used as representative of typical operation of the La Hague Plant in terms of both throughput and typical climate conditions. In addition, precise distributions of the energy consumption between the following systems for La Hague plant (including associated waste treatment plants) are available:

- Process,
- Ventilation,
- Utilities,
- Heating,
- Lighting,
- Monitoring,
- Others (transportation, energy losses, etc.)

Energy Calculation for the 800 tHM/y Reference Plant

The La Hague plant is composed of two plants: UP3 and UP2-800 which are designed for each to process a maximum of 800 tHM/y. The reference 800 tHM/y Recycle Center is therefore comparable to one of these two plants. However, the treated throughput of La Hague plant is lower than the design throughput of 1600 tHM/y, so the energy consumption factor cannot be simply extrapolated from the La Hague operational data.

For parts of the La Hague plant, the energy consumption is dependent on the size the plant (ventilation, heating, lighting, monitoring, etc.), whereas energy consumption for other parts of the plant depend on the treated throughput of UNF (process, utilities).

For each of the plant systems listed above, either a volume factor (VF) or a throughput factor (TF) is applied as follows:

The volume factor corresponds to the sum of the volumes of the main process buildings of the reference 800 tHM/y plant (which are the main contributors to the energy consumption) divided by the sum of the volumes of the main process buildings of La Hague plant (UP3 + UP2-800). The assumption was made in this calculation that the other buildings (storage pools, control rooms, etc) will contribute in the same proportion.

The individual buildings associated with the reference 800 tHM/y plant and the La Hague plant is described in Reference [2].

The result of this calculation gives a volume factor equal to: $VF = 42\%$.

The VF factor is applied to the following energy consumptions:

- Ventilation,
- Heating,
- Lighting,
- Monitoring,
- Others

The throughput factor is calculated on the basis of the assumed annual throughput of the 800 tHM/y plant compared to La Hague throughput in 2006. The throughput factor is equal to:

$$TF = 800/1015 = 78.8\%$$

In this calculation, the throughput factor is rounded up to: TF= 80%

The TF is applied to the following energy consumptions:

- Process
- Utilities

Table 4 provides the estimated energy consumption of the reference 800 tHM/y Recycling Plant based on applying the VF (42%) and the TF (80%) to the associated Recycle Plant systems/processes.

Table 4. Estimated Energy Consumption (800 tHM/y Recycling Plant)

	La Hague 2006	800tHM/y Recycling Plant
Recycled UNF (tHM/y)	1015	800
Electricity Consumption (GWh/y)	378	220
Thermal Energy Consumption (GWh/y)	312	196
Total Energy Consumption (GWh/y)	690	416

Efforts are continuing to reduce energy consumption in La Hague plant. In addition, internal AREVA studies indicate that an optimized design of a new plant should lead to further reduction in operational energy consumption.

As discussed previously, a new 800 tHM/y Recycle Plant energy consumption will also be dependent on the selected site location (geographical location and climatic characteristics).

Estimated energy consumption for reference 800 tHM/y Recycle Plant: 416 GWh/y (81% of total energy consumption of Recycle Center & RepU Facilities)

5.2.2 MOX FUEL FABRICATION PLANT

This section presents the energy consumption of the MOX Fuel Fabrication Plant (Box 2 in Figure 2).

MELOX Energy Consumption Data

Table 5 shows the annual energy consumption and associated MOX fuel fabrication throughput for the MELOX Plant for years 2004 through 2009 [4]:

Table 5. MELOX Energy Consumption vs. Fuel Fabrication Throughput

	2004	2005	2006	2007	2008	2009
Fabricated MOX Fuel (tHM/y)	122	145	145	125	126	134
Electricity Consumption (GWh/y)	37	36.6	37.6	38.5	38.1	38.5
Thermal Energy Consumption (GWh/y)	6.4	5.9	5.7	4.8	5.6	3.6
Total (GWh/y)	43.4	42.5	43.3	43.3	43.7	42.1

As shown in Table 5, the electrical energy consumption is very stable from one year to another. The energy consumption is primarily dependent on the design of the building (ventilation, cooling) since the process equipment used to fabricate the MOX fuel is constantly maintained under operational conditions.

The fossil fuel (thermal energy) consumption, which is primarily used to heat the buildings, varies according to the yearly climatic conditions. This is reflected in the thermal energy consumption for years 2007 and 2009 in which the meteorological conditions were unusually mild which resulted in lower thermal energy consumption.

Energy Calculation for the 800 tHM/y Reference Plant

The associated MOX Fuel Fabrication Plant for the referenced 800 tHM/y Recycle Center is composed of one building with a yearly manufacturing capacity of 100 tHM/y MOX Fuel. Since a conceptual layout of a 100 tHM/y MOX Fabrication Plant is not available (building size, equipment layout, etc.), this EROI analysis is based on the actual energy consumption data for the MELOX plant – total energy consumption of approximately 43 GWh/y. This is a conservative assumption since the MELOX energy consumption data correlates with MOX fabrication capacity between 122 tHM/y and 145 tHM/y. This assumption will not significantly impact the EROI calculation since the MOX Fabrication Plant energy consumption only represents approximately 8 % of the total energy consumption for the Recycle Center.

Estimated energy consumption for 100 tHM/y MOX Fuel Fabrication Plant is 43 GWh/y (8% of total consumption of Recycle Center & RepU Facilities)

5.3 REPU FACILITIES

Energy Consumption Data

The energy consumption estimates related to RepU facilities are based on a combination of actual energy consumption data and results from actual process studies for facilities currently under development by AREVA. Operational energy consumption data is available for RepU fuel fabrication and is used in this EROI calculation. At the current time, AREVA does not operate or have access to actual energy consumption data for the RepU Conversion and Enrichment facilities. AREVA is currently designing/constructing equivalent RepU Conversion and Enrichment facilities in France.

- EPICURE – AREVA RepU Conversion Facility (currently in design/construction phase)
- Georges Besse II (GB II) – AREVA Centrifuge Enrichment Facility (currently ramping-up operations)

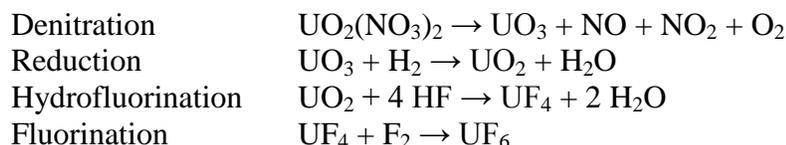
The energy consumption estimates provided below for the RepU Conversion and Enrichment facilities are based on the AREVA EPICURE and GB II energy consumption process studies correlated to the actual size of the RepU facilities to support a 800 tHM/y Recycle Center.

5.3.1 REPU CONVERSION FACILITIES

This section presents the energy consumption of the RepU Conversion facilities (Boxes 3, 4, 5, and 6 in Figure 2) as well as the denitration process that is located in the Recycling Plant (Box 1 in Figure 2). The estimated energy consumption for the RepU Conversion facilities given below is based on engineering process studies performed by AREVA associated with the development of the EPICURE RepU Conversion Facility. Below is a general description of the chemical process and the energy consumption estimate based on the AREVA studies (adjusted to account for facility size difference).

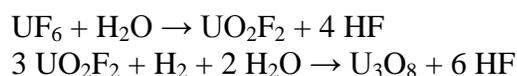
General Description – Chemical Process

Uranyl nitrate (UO₂(NO₃)₂) is converted to uranium hexafluoride (UF₆) for use in enrichment operations. The main chemical transformations are:



Hydrofluorination to UF₄ and fluorination to UF₆ are the most energy consuming steps. Fluorination to UF₆ is achieved by contact of fluorine gas (F₂) with UF₄. Fluorine is produced on site by electrolysis.

An additional energy consuming step is the incorporation of depleted uranium hexafluoride (DUF₆) defluorination to uranium oxide (U₃O₈) according to the following equations:



Energy Estimate for the RepU Conversion Facilities

The estimated energy consumption for entire RepU chemical conversion process (fluorine production, fluorination to UF₆, defluorination of DUF₆) is approximately 36 GWh/y (21 GWh/y electrical + 15 GWh/y thermal).

This estimate includes process energy consumption for all the RepU Conversion Facilities and the denitration process. Utility (HVAC) energy consumption is also included for all the RepU Conversion Facilities, except for the following processes.

- The denitration utility energy consumption is included in the 800 tHM/y Recycling Plant (Box 1 in Figure 2) energy calculation
- The electrolysis utility energy consumption is included in the Conversion & Fuel Fabrication Plant (Box 8 in Figure 2) energy calculation

Estimated energy consumption for RepU chemical processing: 36 GWh/y (7% of total consumption of Recycle Center & RepU Facilities)

5.3.2 REPU ENRICHMENT

This section presents the energy consumption for enriching the RepU in a NatU enrichment facility (Box 7 in Figure 2).

Energy Consumption Data

The following energy consumption estimate is based on energy requirements for enriching the RepU from the reference 800 tHM/y Recycle Center in a centrifuge enrichment facility. Operational energy consumption data for the RepU Enrichment Facility (centrifuge technology) is not available within the AREVA Group. The estimated energy consumption for the RepU Enrichment given below is based on engineering process studies performed by AREVA associated with the design & startup of the Georges Besse II Enrichment Plant (centrifuge technology).

Energy Calculation for Enriching the RepU from the Recycle Center

This analysis assumes that the enrichment of the U₂₃₅ content of UF₆ from 0.76 % to 5 % is performed in an existing NatU enrichment plant using centrifuge technology. Enrichment of 748 tU/y would require a separate work unit of 0.34x10⁶ SWU/y and would yield 58.5 tU/y of enriched RepU and 689.5 tU/y

of 0.4 % depleted RepU.¹ Only the electrical needs have been estimated as the thermal needs are almost negligible compared to the electrical ones [5].

The calculation for determining the required SWU is described in the following paragraphs.

A generalized enrichment element can be treated as a “black box” into which flows material of a certain isotopic composition and out of which flow two streams, one containing a higher percentage and the other a lower percentage of the desired isotope than was present in the feed stream.

Separative Work per Unit (SWU) is calculated according to the following equation:

$$SWU=[P*V(xp)+W*V(xw)-F*V(xf)]*T \text{ (Formula 1)}$$

T = time

The symbols F, P, and W denote feed, product, and tails flow rates and are usually expressed in units such as kilograms per second (kg/s).

$V(x_i)=(2^{x_i}-1)*\ln[x_i/(1-x_i)]$, where the symbols xp, xw, and xf refer to the percentage composition in numbers of molecules of the desired isotope (U^{235}) in the respective flow stream.

The 800 tHM/y Recycle Center yields an annual flow rate of F=748 tU with xf=0.76%. The selected enrichments for Product and Tails are 5% (xp) and 0.4% (xw), respectively.

Product and Tails annual flow rates are calculated by mass balance on U^{235} :

$$P=58.5 \text{ tU and } W=689.5 \text{ tU}$$

By applying Formula 1 with T=1 year, the required SWU is calculated as 0.34x10⁶ SWUs.

Based on the results of the GB II process studies, the energy consumption for enriching the RepU from a 800 tHM/y Recycle Center is 45 kWh/SWU. As calculated previously, the RepU enrichment will require approximately 0.34x10⁶ SWU which results in an annual enrichment facility energy consumption of 15 GWh (0.34x10⁶ SWU x 45 kWh/SWU). This estimate is in good agreement with published estimates for centrifuge technology. Table 6 shows the reference consumption data published in the URENCO sustainability reports.

Table 6. URENCO Enrichment Consumption Data

Year	kWh/SWU
2006	42
2007	40
2008	39
2009	37

Estimated energy consumption for RepU enrichment: 15 GWh/y (3% of total consumption of Recycle Center & RepU Facilities)

¹ The separative work unit (SWU) carries units of mass and quantifies the degree of isotopic separation achieved. It is proportional to the feed mass as well as the energy requirement.

5.3.3 RepU FUEL FABRICATION

This section presents the energy consumption for fabricating the RepU fuel in a NatU fuel fabrication facility (Box 8 in Figure 2).

Energy Consumption Data

Table 7 provides the direct energy consumption for UO₂ production at the FBFC ROMANS [7]. The average energy consumption from 2005 to 2008 for average UO₂ production of 865 tU/y (average) is:

- Electricity – 30.8 GWh/y
- Natural gas – 10.6 GWh/y

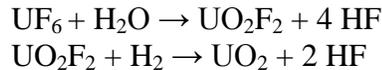
Table 7. FBFC Romans Energy Consumption vs. Fabricated UO₂ Throughput

	2005	2006	2007	2008
UO ₂ (tU/y)	920	869	819	855
Electricity consumption (GWh/y)	30.1	30.4	31.7	31.1
Natural gas consumption (GWh/y)	12.5	8.4	10.8	10.8
Total (GWh/y)	42.6	38.8	42.5	41.9

Energy Calculation for Fuel Fabrication in an Existing NatU Plant

The energy consumption for a fuel fabrication plant to support the reference 800 tHM/y Recycle Center was calculated based the energy requirements for the FBFC plant. The required electrical and thermal energy in GWh/tU at FBFC was calculated and applied to a 58.5 tU/y RepU fuel fabrication.

A bottom-up calculation of the electrical needs based on chemical engineering assessments was also performed. The process incorporates both chemical and physical processing. Uranium hexafluoride is hydrolyzed and reduced to UO₂ powder according to the following equations:



The powder is then pelletized, sintered and loaded into fuel rods and assemblies. The most substantial energy consumption steps are hydrolysis, reduction and sintering.

On the basis of the FBFC ROMANS operational data for electrical consumption, the energy requirements for production of 58.5 tU/y is 2.1 GWh/y. To verify this energy consumption value, a bottom-up calculation gives an electrical energy requirement of 2 GWh/y and confirms this calculation.

Similarly, on the basis of the FBFC ROMANS operational data, the natural gas consumption for the 58.5 tU/y is 0.7 GWh/y. The natural gas is used primarily to heat facilities and operate limited plant components and is independent of product throughput.

Estimated energy consumption for enriched RepU fuel fabrication: 3 GWh/y (<1% of total consumption of Recycle Center & RepU Facilities)

5.4 ENERGY INVESTMENT SUMMARY

Table 8 summarizes the energy investment for both the Recycle Center (Recycling Plant and MOX Fuel Fabrication Plant) as well as the additional energy investment associated with the RepU facilities.

Table 8. Summary of Energy Investment During Operations

Facility	Energy Consumption (GWh/y)
Recycling Plant (Box 1 of Figure 2)	416
MOX Fuel Fabrication Plant (Box 2 of Figure 2)	43
Total Recycle Center (MOX Fuel Only)	459
RepU Conversion Facility (Boxes 3, 4, 5, and 6 of Figure 2)	36
RepU Enrichment Facility (Box 7 of Figure 2)	15
RepU Fuel Fabrication Facility (Box 8 of Figure 2)	3
Additional Incremental Energy Investment Due to RepU Fuel	54
TOTAL ENERGY INVESTMENT – Both MOX (Recycle Center) + RepU Fuel	513

5.5 ENERGY REQUIRED TO CONSTRUCT AND DECOMMISSION RECYCLING FACILITIES

An estimate of the energy consumed during the construction and decommissioning of the recycling facilities depicted in figure 2 is summarized in Table 10 below supported by detailed calculations in Appendix A of this report. Construction energy calculations assumed a facility design similar to La Hague, but scaled to process 800 tHM/y. Decommissioning calculations were based upon published information from the West Valley Demonstration Project and the numbers should be considered as being very conservative in nature since they include numbers for waste specific to the West Valley Site that would not be found in a future recycling facility.

The energy consumed during the construction phase includes the energy used:

- The production of the principal raw construction materials.
- Refinement of those materials into useful forms.
- Transportation.
- Installation of the materials as part of the construction of the facilities.
- The energy consumed during the dismantling phase includes the energy used.
- Decommissioning and dismantling the facilities.
- Transportation and disposal of the contaminated materials.

Energy consumption analysis only considered primary processes that are expected to be significant contributors to the total energy consumed during the construction and decommissioning phases of the Recycling Center Facilities and the RepU “Dedicated” Facilities.

Energy consumption for the extraction, transportation and manufacture of the building/equipment items is based on industry publications and experience from URS , and provides a reasonable approximation for use in determining the energy required to construct and dismantle the Recycling Center and the RepU “Dedicated” Facilities.

Table 9. Summary of Energy Consumed, by Phase, Area and Type

	Construction Phase				Decommissioning Phase		
	Concrete GWh	Metallic Elements GWh	Reinforcing Steel GWh	Excavation GWh	Electricity GWh	Natural Gas GWh	Diesel GWh
Recycle Center Facilities	210.74	236.41	439.19	20.36	5198	9122	2479
RepU Processing Facilities	5.37	7.10	11.19	0.35	132	232	63
Total	216.11	243.52	450.38	20.71	5331	9355	2542

Total Energy consumed is approximately 18,000 GWh. If the recycling facilities are assumed to have an operating life of 50 years this will equate to an annual energy investment of 360 GWh/y.

6.0 FINAL ENERGY OUTPUT

Both the MOX and the enriched RepU fuel are assumed to be loaded into existing LWRs. The 800 tHM/y Recycle Center will recover 100 t/y of MOX fuel and 59 t/y of RepU fuel. The thermal energy produced by the recycled fuel is the amount of each type of fuel multiplied by the discharge burn-up. The final energy produced is defined as electrical energy (energy provided to the grid). Typical net efficiency value for nuclear plants is 33% (conversion of thermal energy to net electrical power available to the grid after deducting the electrical power required to operate the plant). Table 9 provides a summary of the energy (thermal and electrical energy) extracted from MOX and RepU fuel on an annual basis for an 800 tHM/y Recycle Center.

Table 10. Summary of Annual Energy Produced

Fuel Type	Tons/year	Burn-up, GWD/t	Thermal Energy, GWh/y	Electrical Energy, GWh/y
MOX	100	50	120,000 ⁽¹⁾	39,600 ⁽²⁾
REPU	59	50	70,800	23,400
Total	159		190,800	63,000

⁽¹⁾ Thermal Energy Calculation: $100 \text{ t} \times 50 \text{ GWD/t} \times 24 \text{ h/D} = 120,000 \text{ GWh/y}$

⁽²⁾ Electrical Energy Calculation: $120,000 \text{ GWh/y} \times 0.33 = 39,600 \text{ GWh/y}$

7.0 EROI SUMMARY FOR ONE PASS RECYCLE SYSTEM

Table 11 summarizes the EROI calculations for the operation of the Recycle Center and associated RepU facilities during the One Pass Scenario.

Table 11. EROI Calculations

Fuel Type	Final Energy Produced (GWh/y) (ref. Table 10)	Final Energy Invested (GWh/y) (ref. Tables 8 & 9)	EROI = Final Energy Produced ÷ Final Energy Invested
MOX Only	39,600	459	86
RepU Addition	23,400	54	433
Total MOX + RepU	63,000	513	123
Construction and Decommissioning	N/A	360*	N/A
Total MOX + RepU + Construction And Decommissioning	63,000	873	72

*Energy investment related to construction and decommissioning of the recycling facilities has been calculated as 360 GWh per year assuming a 50 year lifetime.

8.0 TWO PASS RECYCLE OPTION

This section summarizes the results from Appendix B which considers the energy requirements and energy return for recycling of the used MOX and RepU, manufacturing it into new fuel and returning it for an additional irradiation in an LWR. To bound the number of times the used MOX and RepU can be recycled and placed back into an LWR it was determined that the characteristics of any new fuel manufactured must have similar performance in the reactor when compared to fresh UOx or the U/Pu content must stay within the current design parameters or regulations for fuel manufacture or shipment. The results of the study in Appendix B are shown in Table 12 below. Based upon the assumption that the used MOX and RepU from the one-pass system will form the basis for the feed to the recycle center an allowance must be made for the construction and decommissioning energy associated with recycling this material. 159 t UNF/800 t capacity x 360 (energy construction and D&D) = 72 GWh/y

The total energy return for the combined One Pass and Two Pass Recycle Systems are presented in Table 13.

Table 12. Energy Consumed and Produced for the Two-Pass Recycle Option

Fuel Type	Final Energy Produced, GWh/y Ref. Appendix B, Table 3	Final Energy Consumed, GWh/y Ref. Appendix B, Table 2
MOX Only	19,800	76.9
RepU Total	4,250	37.7
Construction and Decommissioning Associated with second pass.	N/A	72
Total	24,050	186.6

Table 13. Complete Energy Return on Investment for Two-Pass Recycle

Fuel Type	Final Energy Produced (GWh/y) (ref. Tables 11 & 12, Appendix B)	Final Energy Invested (GWh/y) (ref. Tables 11 & 12, Appendix B)	EROI = Final Energy Produced ÷ Final Energy Invested
One-Pass Recycle (Total MOX + RepU + Construction and Decommissioning)	63000	873	72
Two Pass Recycle	24,050	186.15	Not Applicable
Total	87,050	1059.15	82

*Energy investment related to construction and decommission of the recycling facilities has been calculated as 360 GWh per year assuming a 50 year lifetime

9.0 RECYCLE OF THE USED FUEL FROM THE ONE-PASS RECYCLE SYSTEM INTO A SODIUM FAST REACTOR

This section summarizes the results from Appendix C which considers the energy requirements and energy return for recycling of the used MOX and RepU from the One Pass Recycle System. Thus, before the material gets to this point, it has already been burned in LWRs two times. All of the subsequent recycles would be conducted in 1100 MWe Sodium Fast Reactors (SFR) that are designed to consume 11.24 t/y of Pu. Three conversion ratios were considered to give representative results of various possible fuel cycles. This is not a complete listing because there are many more possible fuel cycles that involve SFRs.

- CR < 1, (0.3) Burner reactor used to manage the Pu with only one pass through the SFR. The energy consumed and produced are shown in Table 14.
- CR ≈ 1, Break even reactor with the reactor producing as much Pu as it consumes. The results are shown in Table 15 for the initial pass through the SFR and each additional pass through the SFR.
- CR > 1 (1.2 Breeder reactor that produces additional Pu each cycle that is then manufactured into LWR MOX , to be burned one more time in LWRs. The results are shown in Table 16.

It should be noted that for a SFR to come to equilibrium on the Pu content in the fuel can take 9 to 10 passes through the reactor followed by recycle. Based upon AREVA's experience it is typical that the Pu loading in the fuel will increase by approximately 40% between the first and the ninth cycle. Appendix C details the results of this equilibrium cycle for each of the conversion ratios considered.

Table 14. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycles for Burner SFR with CR <1

SFR Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Number of SFR Required	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y
One SFR Burn	30.8	25.6*	2.3	68	16,700	94

*Each SFR consumes 11.24 t/y of Pu

Table 15. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycles for Break Even SFR CR ≈1

SFR Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Number of SFR's Required	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y
One SFR Burn	16.35	48.4*	4.3	100	46,400	104
Each Additional Burn	22.7	48.4*	4.3	100	46,400	46.0

*Each SFR consumes 11.24 t/y of Pu

Table 16. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycles for Breeder SFR CR >1

SFR Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Number of SFR's Required	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y
One SFR Burn	16.35	48.4*	4.3	100	55,100 ¹	105.5
Each Additional Burn	22.7	48.4*	4.3	100	55,500 ²	68.5

*Each SFR consumes 11.24 t/y of Pu

1 Includes energy produced from UOx blankets.

2 Includes energy produced from LWR MOX.

9.1 ENERGY REQUIRED TO BUILD AND DECOMMISSION SODIUM FAST REACTOR

This section summarizes the calculations presented in Appendix D that estimate the energy consumed during the construction and decommissioning of a Generation IV Sodium Fast Reactor (SFR), Table 17. The calculations consider the energy consumed during the construction phase that includes the production of the principal raw construction materials, refinement of those materials into useful forms and installation of the materials as part of the construction of the SFR. The energy consumed during the dismantling phase that includes, decommissioning a SFR including dismantling and disposal of the contaminated materials.

The energy consumption for the extraction, transportation and manufacture of the building materials -- concrete and reinforcing bars and subsequent decommissioning is based on industry publications and engineering experience, and provides a reasonable approximation for use in determining the energy required to construct and dismantle a SFR.

Table 17. Summary of Energy Consumed During Construction and Decommissioning of a SFR.

	Construction Phase		Decommissioning Phase		
	Concrete GWh/Mwe	Reinforcing Steel GWh/Mwe	Electricity GWh/Mwe	Natural Gas GWh/Mwe	Diesel GWh/Mwe
Energy for 1100 MWe Reactor	40	198	138	241	66

The total energy for construction and decommissioning of each 1100 MWe reactor required is

$$40 + 198 + 138 + 241 + 66 = 683 \text{ GWh per reactor}$$

Total Energy consumed is approximately 683 GWh for each 1100 MWe SFR required. If the SFR has an assumed operating life of 50 years this will equate to an annual increase in the energy consumption during operation of the SFR of 14 GWh/y per reactor. The energy required to construct and decommission the SFR's required for each scenario is presented in Table 18. Total energy consumed for D&D and construction is the sum of the number of reactors multiplied by the energy for construction and D&D of one reactor.

For CR <1, there are 2.3 reactors required * 14 = 33 GWh/y for this scenario for a year.

Table 18. Energy Required to Construct and Decommission SFR's

SFR Fuel Cycle	Number of SFRs Required	Energy Consumed to Construct and Decommission GWh/y	Energy Consumed During Operations, GWh/y	Total Energy Consumed GWh/y
CR <1, One SFR Burn	2.3	33	94	127
CR = 1, One SFR Burn	4.3	60	104	164
CR = 1, One Additional Burn	4.3	60	46	106
CR >1, One SFR Burn	4.3	60	105.5	165.5
CR >1, One Additional Burn	4.3	60	68.5	128.5

9.2 TOTAL ENERGY RETURN ON INVESTMENT FOR THREE SFR RECYCLE SCENARIOS.

Table 19 below details the EROI calculation for the One-Pass Recycle MOX and RepU cycle with subsequent recycle through the SFR for the 3 conversion ratio designs of SFR considered.

Table 19. Complete EROI Calculations for SFR Scenarios Considered in Report

Fuel Cycle	Final Energy Produced (GWh/y)	Final Energy Invested (GWh/y)	EROI = Final Energy Produced ÷ Final Energy Invested
One-Pass Recycle (LWRs Only)	63,000	873	72
One SFR Burn with CR<1	16,700	127	Not Applicable
One-Pass Recycle + One SFR Burn with CR <1	79,700	1,000	80
One SFR Burn with CR=1	46,400	164	Not Applicable
One-Pass Recycle + One SFR Burn with CR = 1	109,400	1037	105
Each Additional SFR Burn with CR = 1	46,400	106	Not Applicable
One-Pass Recycle + Two SFR Burns with CR = 1	155,800	1,143	136
One SFR Burn with CR>1	55,100	165.5	Not Applicable
One-Pass Recycle + One SFR Burn with CR >1	126,000	1,038	109
Each Additional SFR Burn with CR >1	55,500	128.5	Not Applicable
One-Pass Recycle + Two SFR Burns with CR >1	168,600	1,166.5	144

10.0 CONCLUSIONS

The energy return on investment has been calculated for a number of fuel cycle scenarios and was based upon recycling of 800tHM of used UO_x fuel that had been discharged from LWRs. No fresh material other than depleted uranium was added into any fuel cycle considered. The results are presented in Figure 4 below.

The use of the SFR for recycling UNF and extracting additional energy from the fuel offers many potential scenarios that could be considered, this report considers only a few options. However the calculations and results presented in the report and the appendices would allow additional calculations to be conducted for other scenarios.

The EROI is a useful figure of merit when considering future fuel cycles. As with any calculation the assumptions will drive the answers. In this report, where possible, the calculations have been based upon current engineering practices and real data. In areas where there was less data available a conservative engineering judgment was made and documented.

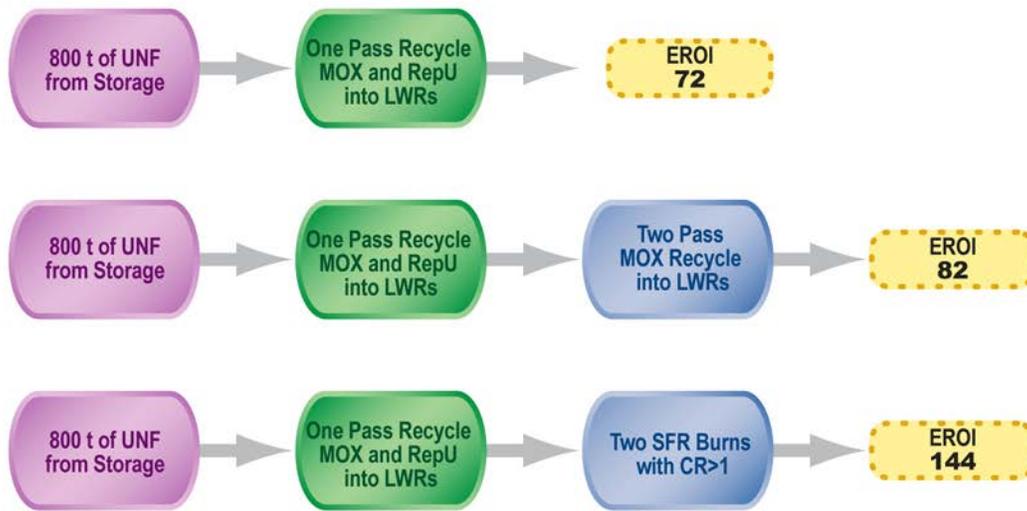
Figure 4 below depicts the EROI for varying fuel cycle scenarios. The One-Pass Recycle System, in which MOX and RepU are recycled back into LWRs, yields an EROI of 72. An additional recycle of the used MOX and RepU increases the EROI up to 80. The introduction of SFRs, however, would raise the possibility of a much higher EROI. One option would take the MOX from the One-Pass Recycle System and recycle it through a SFR twice, which would increase the EROI of the fuel cycle to 144.

One of the main drivers affecting the EROI calculation was the efficiency of the reactor system to convert the fuel to electrical energy. In the case of the LWR this was assumed to be 33% and for the SFR 40%. Fuel burn-up was set at current industry values for LWRs and at reasonable levels for the SFR. It is important to realize that the fuel burn-up and change out is driven by other factors within the reactor system such as scheduled maintenances and the requirement for zero fuel failure. Unduly high fuel burn-ups were considered unlikely to be achievable.

The EROI for the SFR has been capped for the purpose of this study after 2 cycles. Subsequent recycle of the used SFR fuel will increase the EROI. However there has never been any industrial scale multi recycle of SFR fuel conducted. For the fuel in the SFR to come to equilibrium can take 9 to 10 cycles through the reactor and subsequent recycle. There will be increasing process losses and associated degradation in the isotopics of the Pu used in the fuel. At each stage the Pu content will increase and by cycle 9 or 10 can be 40% higher than the original Pu content in cycle 1. The calculations associated with the equilibrium fuel cycle for the SFR are presented in Appendix C of this report.

It is recommended that future work should consider a way to use the EROI as one of the figures of merit when considering future fuel cycles.

Figure 4. Results of Energy Return on Investment for Scenarios Considered in This Report.



11.0 REFERENCES

1. World Nuclear Association, Energy Analysis of Power Systems (www.world-nuclear.org/info/inf11.html).
2. CFTC Conceptual Design Studies Final Report – AREVA Report Number: RPT 3000285.
3. Rapport environnemental, social et societal, AREVA NC établissement de La Hague années 2006 à 2009.
4. Rapport environnemental, social et societal, AREVA établissement de MELOX années 2006 à 2009.
5. Measures of the Environmental Footprint of the Front End of the Nuclear Fuel Cycle, E. Schneider, B.W. Carlsen, E. Tavriles, August 2010, NL/EXT-10-20652, FCRD-SYSA-2010-000104.
6. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. M. Lenzen, 2008, Energy Conversion and Management 49, 2178-2199.
7. Rapport environnemental, social et societal, établissement FBFC Romans année 2008.

Appendix A

EROI – Construction and Dismantling of Recycle Center and RepU Dedicated Facilities

INTRODUCTION

This appendix provides an estimate of the energy consumed during the construction and decommissioning of an 800 tHM/yr Used Nuclear Fuel (UNF) Recycle Center, which comprises of the Recycling Center Facilities and the RepU “Dedicated” Facilities.

The energy consumed during the construction phase includes the energy used:

- The production of the principle raw construction materials.
- Refinement of those materials into useful forms.
- Transportation
- Installation of the materials as part of the construction of the facilities

The energy consumed during the dismantling phase includes the energy used:

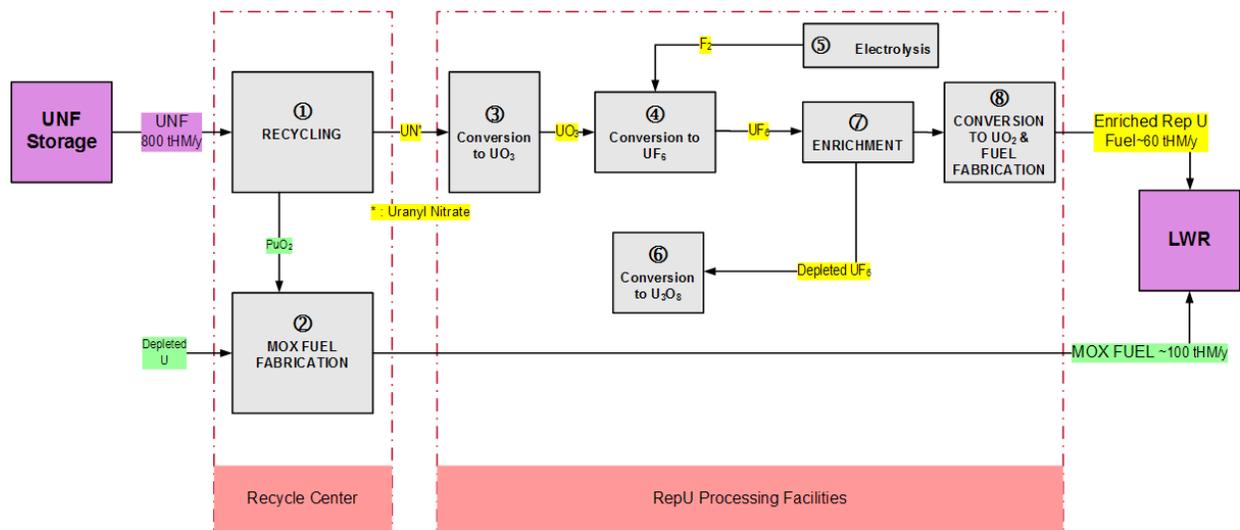
- Decommissioning and dismantling the facilities.
- Transportation and disposal of the contaminated materials.

Energy consumption analysis will only consider primary processes that are expected to be significant contributors to the total energy consumed during the construction and decommissioning phase of the Recycling Center Facilities and the RepU “Dedicated” Facilities.

Energy consumption for the extraction, transportation and manufacture of the building\equipment items is based on industry publications and experience from URS , and provides a reasonable approximation for use in determining the energy required to construct and dismantle the Recycling Center and the RepU “Dedicated” Facilities.

The Energy Return on Investment (EROI) calculation is based on the Fuel Cycle diagram shown in, Figure 1:

Figure 1. Used Nuclear Fuel Recycle System



The Used Nuclear Fuel Recycle System includes:

- Recycling Plant (Box 1 in Fig. 1)
 - The recycle facility is assumed to be sized at 800tHM/y.
 - Fuel Receipt and Storage Facility (FRS)
 - Shearing/Dissolution/Compaction Facility (SDC)
 - Separation/Purification/Concentration Facility (SPC)
 - Fission Product Vitrification Facility (FPV)
 - High Active Solid Waste Storage (HSS)
 - Waste Treatment Facility (WTF)
 - Administration, Utilities and Reagents Facility (AUR)
- MOX Fuel Fabrication Facility (Box 2 in Fig. 1)
 - MOX Fuel Fabrication Facility (MFFF)
- RepU Processing Facilities (Box 3, 4 and 6 in Fig. 1)
 - RepU “Dedicated” Facilities

KEY ASSUMPTIONS

The following Key Assumptions and Metrics are used:

- Approximately 1/3 of the building volumes is underground
- Reinforcement steel is provided at 150 kg per cubic meter of concrete
- Cableway is ~2.5 kg per linear meter
- 38.6 MJ per liter of diesel
- 35.0 MJ per liter of gasoline
- 37.5 MJ per Cubic Meter of Natural Gas

ENERGY CONSUMPTION

Summary of Energy Consumed

Table 1. Summary of Energy Consumed, by Phase, Area and Type

	Construction				Decommissioning		
	Concrete GWh	Metallic Elements GWh	Reinforcing Steel GWh	Excavation GWh	Electricity GWh	Natural Gas GWh	Diesel GWh
Recycle Center Facilities	210.74	236.41	439.19	1.38	5198	9122	2479
RepU Processing Facilities	5.37	7.10	11.19	0.02	132	232	63
Total	216.11	243.52	450.38	1.40	5331	9355	2542

The data used for the decommissioning estimates for the recycling facility were scaled from the published data for the decommissioning of the West Valley Demonstration Project (WVDP). The WVDP decommissioning scope did include more than the decommissioning of the recycle center facilities. As such the energy consumption data for decommissioning is very conservative and a degree of caution should be used for the data presented.

Construction Materials Considered

The following materials/work processes are included in the analysis:

- 4000 psi concrete: Foundations, buildings
 - Raw material production and transportation
 - Batch-plant operations
 - Transportation and installation
- Metallic Elements: rebar, pipe, structural members, equipment, sheet product
 - Raw material production and transportation
 - Mill operations and transportation
 - Secondary mills and fabrication
 - Transportation and installation
- Earthwork
 - Excavation and backfill

Construction Material Takeoffs

The estimate of material quantities to construct the 800 tHM/yr Recycling Center Facilities and the RepU “Dedicated” Facilities were provided by the engineering division of AREVA (SGN). The estimates are based on actual decommissioning studies for AREVA’s La Hague Recycling Plant and MELOX MOX Fuel Fabrication Plant, as well as detailed studies AREVA performed as part of the Global Nuclear Energy Partnership (GNEP) Program. The material quantities in this report have been scaled to represent the referenced 800 tHM/yr Recycle Center.

For each of the above Facilities, the quantity of concrete estimated for the foundations and buildings are reflected in Table 2. In addition to the concrete, an estimate for the mass of metallic elements are provided and reported in Table 3. Based on the provided metric of 150 kg of reinforcing steel per cubic meter of concrete, additional metallic quantities can be defined, in Table 4. Finally, the total site excavated volume for the entire area is provided at 756,967 cubic meters for the Recycle Center Facilities and 12,900 cubic meters for the RepU Processing Facilities.

Table 2. Building Dimensions and Provided Quantities for Concrete in each Facility

Facility		Building	Building Dimensions Area x H m ² x m	Building Concrete Cubic Meters	Foundation Concrete Cubic Meters	
Recycle Center Facilities	Recycling Plant	FRS	Cask Park	0	8,000	
			Cask Receipt	1250 x 30	Metal Building	1,250
			Cask Maintenance	1500 x 30	17,500	1,500
			Docking/Unloading/Dry Transfer	3016 x 27	0	3,016
			Cask Tilting	480 x 21	20,964	480
			Fuel Wet Transfer	1350 x 30	6,075	1,350
			Pool	2300 x 33	19,000	4,400
		SDC	Shear, Dissolution, Compaction	4145 x 40	46,297	6,218
			Clarification Accountability	1080 x 40	11,692	1,620
		SPC	Separation, Purification, Concentration	5625 x 38	52,402	8,438
		FPV	FP/Fines Storage	2322 x 25	16,835	3,483
			Vitrification	3960 x 44	42,640	3,960
		HSS	Compacted Waste Storage	29288 m3	13,447	1,739
			Vitrified Waste Storage	77803 m3	16,800	4,200
		WTF	Liquid Waste Treatment	900 x 26	14,063	2,250
			Solid Waste Treatment	6750 x 15	15,840	3,600
			Waste Drum Storage	2250 x 25	14,563	2,242
		AUR	Utilities Production and Reagents	7200 x 11	21,000	5,600
			Administration, Change Rooms	2242 x 25	5,513	1,838
		MOX	MOX	U/Pu Conversion	5600 x 25	7,020
	MOX fuel fabrication			2450 x 15	25,312	6,750
	RepU Processing Facilities	RepU "Dedicated" Facilities	Chemical Processing Facilities	41000 m3	9,450	1,760
			Recycle Center Facilities		366,963	73,014
		RepU Processing Facilities		9,450	1,760	
		Total		376,413	74,774	

Table 3. Quantities of Metallic Components by Facility

Facility	High Active Cells				Low Active Cells				
	Equipment tonnes	Pipes tonnes	Liner, Drip Trays tonnes	Heavy Steel tonnes	Equipment tonnes	Pipes tonnes	Framework Tonnes	Handling Equipment tonnes	Cableway tonnes
FRS	1439	702	369	108	909	156	580	857	55
SDC	2558	355	126	949	553	151	143	145	94
SPC	2105	1069	99	879	143	33	175	97	40
FPV	855	234	65	755	362	69	132	261	84
HSS	62	0	0	0	122	20	297	155	36
WTF	1055	479	34	317	305	121	199	237	40
AUR	0	0	0	0	839	109	190	10	33
MOX	1849	77	9	51	2320	251	82	72	112
REPU	298	88	21	92	167	27	54	55	15
Recycle Center Facilities	9923	2916	702	3059	5553	910	1798	1834	494
RepU Processing Facilities	298	88	21	92	167	27	54	55	14
Total	10221	3004	723	3151	5720	937	1852	1889	508

Table 4. Reinforcing Steel, at 150 kg per Cubic Meter of Installed Concrete

Facility	Building	Building Re-Bar Tonnes	Foundation Re-bar Tonnes
FRS	Cask Park	0	1,200
	Cask Receipt	0	188
	Cask Maintenance	2,625	225
	Docking/Unloading/Dry Transfer	0	452
	Cask Tilting	3,145	72
	Fuel Wet Transfer	911	203
	Pool	2,850	660
SDC	Shear, Dissolution, Compaction	6,945	933
	Clarification Accountability	1,754	243
SPC	Separation, Purification, Concentration	7,860	1,266
	FP/Fines Storage	2,525	522
FPV	Vitrification	6,396	594
HSS	Compacted Waste Storage	2,017	261
	Vitrified Waste Storage	2,520	630
WTF	Liquid Waste Treatment	2,109	338
	Solid Waste Treatment	2,376	540
	Waste Drum Storage	2,184	336
AUR	Utilities Production and Reagents	3,150	840
	Administration, Change Rooms	827	276
MOX	U/Pu Conversion	1,053	162
	MOX fuel fabrication	3,797	1,013
RepU "Dedicated" Facilities	Chemical Processing Facilities	1,418	264
Recycle Center Facilities		55,044	10,952
RepU Processing Facilities		1,418	264
Total		56,462	11,216

1.0 CONSTRUCTION ENERGY CONSUMED-METRICS

1.1.1 CONCRETE PRODUCTION AND INSTALLATION

Several research reports produced by the Athena Institute were utilized to provide an estimate of the energy required to produce, transport and install concrete 1, 2, and 3. The research was conducted for Canadian producers and users, but was broken into regions. Only the more densely populated regions (West and East Coast) were used to determine an aggregate metric. The Central and Prairie regions were not included due to exceedingly high transportation costs, and were considered inconsistent with the average U.S. population density. The breakdown of the energy consumed is identified in Table 5.

Table 5. Production and Transportation Energy Requirements of Concrete GJ per Cubic Meter

Extraction	Transportation	Processing	Transportation between batch plant and site and placement	Total Placed
0.089	0.074	1.549	0.012	1.724

Table 6 identifies that the bulk of the energy (89% in this analysis) required to produce and place concrete lies in the processing. However, upon determination of the final site location, it may be necessary to recalculate the transportation energy. Note the batch plant distance in this case is set at 10 km from the site.

1.1.2 METALLIC PRODUCTION AND INSTALLATION

Due to the energy intense nature of the production of metal, there are a number of studies on which to draw metrics⁴, shown in Table 6.

Table 6. Energy per Step in Metallic Production by Metallic Elements, GJ per Tonne

Metallic Elements	Extraction	Extraction Transportation	Processing	Primary Mill	Finishing Mill	Transportation to Site and Installation	Total Installed
Plate-Liner Sheets Cableway	2.59	0.63	18.83	4.27	1.00	0.63	27.95
Steel (rod) - rebar	2.59	0.63	18.83	1.28	0.00	0.63	23.96
Tubing (pipes)	2.59	0.63	18.83	4.27	2.31	0.63	29.26
Heavy Beams	2.59	0.63	18.83	4.27	3.04	0.63	29.98
Framework (Joists)	2.59	0.63	18.83	4.27	1.72	0.63	28.67
Fasteners	2.59	0.63	18.83	1.28	8.96	0.63	32.91
Equipment*	2.59	0.63	18.83	4.27	6.00	0.63	32.95

*Values for the “Equipment” conformation were not included in the referenced reports, but are assumed values based on the complexity of the reported conformations.

Note that the processing energy is again the bulk of the energy. In this case, the average processing energy is a cross section of both BOF (Blast Oxygen Furnace) type plants and EAF (Electric Arc Furnace). The average for the studies identified for BOF plants was ~19 GJ per tonne, and the energy for EAF plants is closer to 8 GJ per tonne. The industry is moving to the more efficient EAF process, but is still dominated by BOF facilities. Note also that the transportation to site is the same as the extraction transportation. This is due to the assumption that the averages established for the transportation of the raw materials, will extend to the average distance required to transport the finished product to the site from the mill. Note there was no specific correlation between the reported metallic elements and all of the categories established in the SGN information. In particular, “Equipment” and “Handling Equipment”. Considering the complexity of the reported metallic elements, an assumption was made with respect to the “Finishing Mill” energy requirements.

Excavation

The final metric established is the energy required to excavate for the foundations. Nearly 1/3 of each building is located underground, making the excavation portion of the project more significant than may be for other projects. There is limited published data for excavation energy requirements. However, the U.S. Department of Transportation utilizes a metric to adjust fixed price contracts for fluctuations in fuel prices⁵, and publish these in gallons per cubic yard excavated (Table 7). Fuel usage factors for all excavation items include mobilization, clearing and grubbing, excavating, hauling, compacting and preparing the subgrade. Note the quantities described are for both diesel and gasoline and are to be taken in combination (diesel in equipment, and gasoline in support vehicles).

Table 7. Fuel Usage by Excavation Type, Gallons of Fuel per Cubic Yard

Excavation Type	Diesel			Gasoline		
	Low	Avg.	High	Low	Avg	High
Earth	0.27	0.29	0.30	0.11	0.15	0.21
Rock	0.37	0.39	0.42	0.17	0.18	0.22
Other	0.33	0.35	0.38	0.15	0.16	0.18

By utilizing the following conversions, the energy per cubic meter is determined, shown in Table:

- 38.6 MJ per liter of diesel
- 35.0 MJ per liter of gasoline

Table 8. Excavation Energy Per Cubic Meter, MJ

Excavation Type	Diesel			Gasoline		
	Low	Avg.	High	Low	Avg	High
Earth	3.60	3.87	4.00	1.33	1.81	2.54
Rock	4.94	5.20	5.60	2.06	2.18	2.66
Other	4.40	4.67	5.07	1.81	1.94	2.18

The average combined value of 6.55 MJ per cubic meter for the 3 excavation types will be used for this study.

CONSTRUCTION ENERGY CONSUMED – RESULTS

Table 9. Energy Requirements for Installation of Concrete

Facility	Building Concrete GWh	Foundation Concrete GWh	Total Concrete GWh
Recycle Center Facilities	176	35	211
RepU Processing Facilities	5	1	5
Total	180	36	216

Table 10. Energy Requirements for Fabrication and Installation of Rebar

Facility	Building Re-Bar GWh	Foundation Re-bar GWh	Total Re-bar GWh
Recycle Center Facilities	366	73	439
RepU Processing Facilities	9	2	11
Total	376	75	450

Table 11. Energy Requirements for Fabrication and Installation of Various Metallic Components

Facility	High Active Cells				Low Active Cells				
	Equipment GWh	Pipes GWh	Lining, Drip Trays GWh	Heavy Steel GWh	Equipment GWh	Pipes GWh	Framework GWh	Handling Equipment GWh	Cableway GWh
Recycle Center Facilities	90.45	23.70	5.45	25.48	50.82	7.40	15.34	14.60	3.83
RepU Processing Facilities	2.73	0.72	0.16	0.77	1.53	0.22	0.43	0.44	0.11
Total	93.18	24.42	5.61	26.24	52.35	7.62	15.77	15.04	3.95

Table 12. Energy Requirements for Excavation

Facility	Excavation GWh
Recycle Center Facilities	20.36
RepU Processing Facilities	0.35
Total	20.71

DECOMMISSIONING MATERIALS CONSIDERED AND QUANTITY ESTIMATION

In 1996, DOE submitted a preliminary Environmental Impact Statement (EIS) for the West Valley Demonstration Project⁶, a former fuel reprocessing and vitrification facility. This EIS was updated in 2007 and listed quantities of material to be decommissioned, and the energy requirements to complete the decommissioning, transportation and complete disposal. Key quantities identified in the EIS include:

- Cubic meters of concrete
- Tonnes of steel
- Cubic meters of soil
- Other Non-Hazardous

These identified quantities were utilized to scale the estimated energy requirements for the Recycling Center Facilities and RepU “Dedicated” Facilities decommissioning. The ratio of the total quantity of concrete between the WVDP and the three areas identified, were used to estimate the quantities of the soil and “Other non-hazardous”.

- Recycle Center Facilities: $439,977/61,280 = 7.18$
- RepU Processing Facilities: $11,210/61,280 = 0.18$

The key quantities identified (concrete and steel) and the estimated quantities (soil and other non-hazardous) are identified in Table 12.

Table 13. Key Quantities for Determining Decommissioning Energy Requirements.

Facility	Concrete Cubic Meters	Steel Tonnes	Soil Cubic Meters	Other Non-Hazardous Cubic Meters
West Valley Demonstration Project	61280	23800	1107000	140000
Recycle Center Facilities	439,977	93,274	7948018	1005169
RepU Processing Facilities	11,210	2,498	202504	25610

DECOMMISSIONING ENERGY CONSUMED – METRICS

The EIS includes the electricity, natural gas and diesel fuel expected to be used to decommission the WVDP. These quantities are factored by the key quantities ratio determined above to estimate the quantities required for the Used Nuclear Fuel Recycling Center.

Table 14. Utility Requirements for Decommissioning

Facility	Electricity MW-Hrs	Natural Gas Cubic Meters	Diesel Liters
West Valley Demonstration Project	724,000	121,971,000	32,204,000
Recycle Center Facilities	5198162	875,725,109	231,217,678
RepU Processing Facilities	132442	22,312,254	5,891,104

Converting these quantities to energy, utilizing the following conversions:

- 3600 MJ per MW-Hr
- 37.5 MJ per Cubic Meter of Natural Gas
- 38.6 MJ per Liter of Diesel

DECOMMISSIONING ENERGY CONSUMED - RESULTS

Table 15. Utility Requirements for Decommissioning

Facility	Electricity GWh	Natural Gas GWh	Diesel GWh
West Valley Demonstration Project	724.0	1,270.5	345.3
Recycle Center Facilities	5,198.2	9,122.1	2,479.2
RepU Processing Facilities	132.4	232.4	63.2

Figure 2. Distribution of Estimated Energy Requirements of the Recycling Center Facilities during Construction – GWh

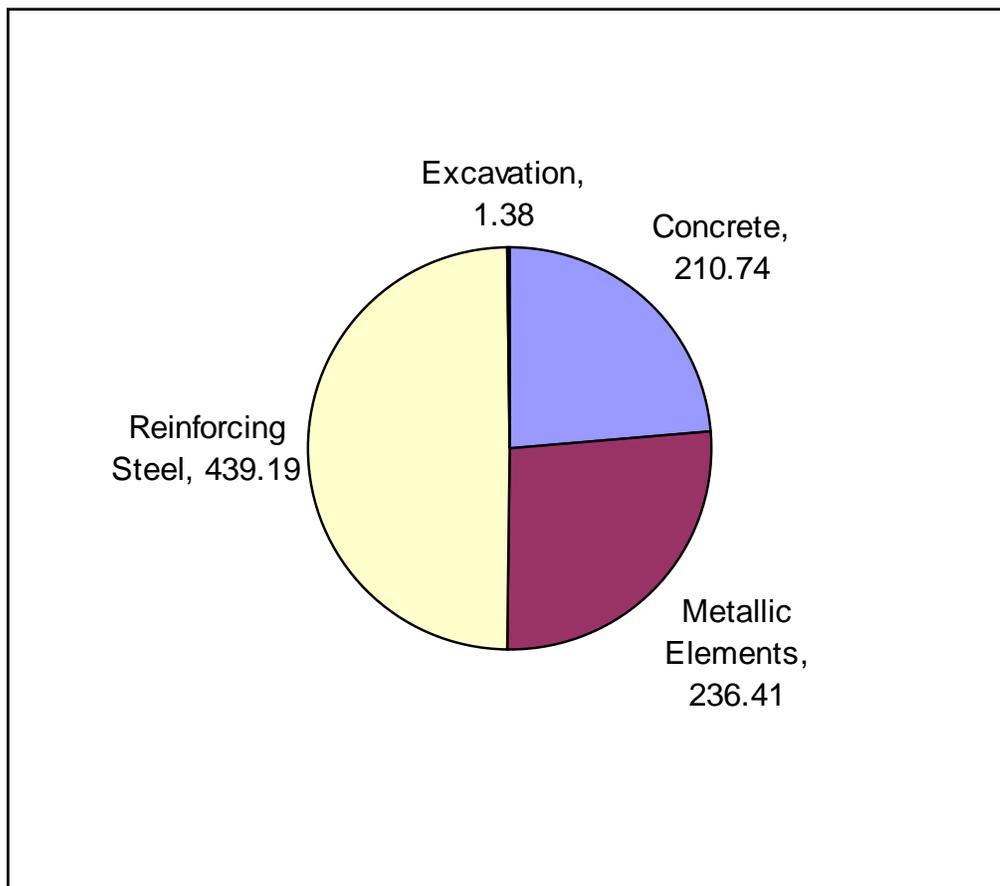


Figure 3. Distribution of Estimated Energy Requirements of the RepU Facilities during Construction – GWh

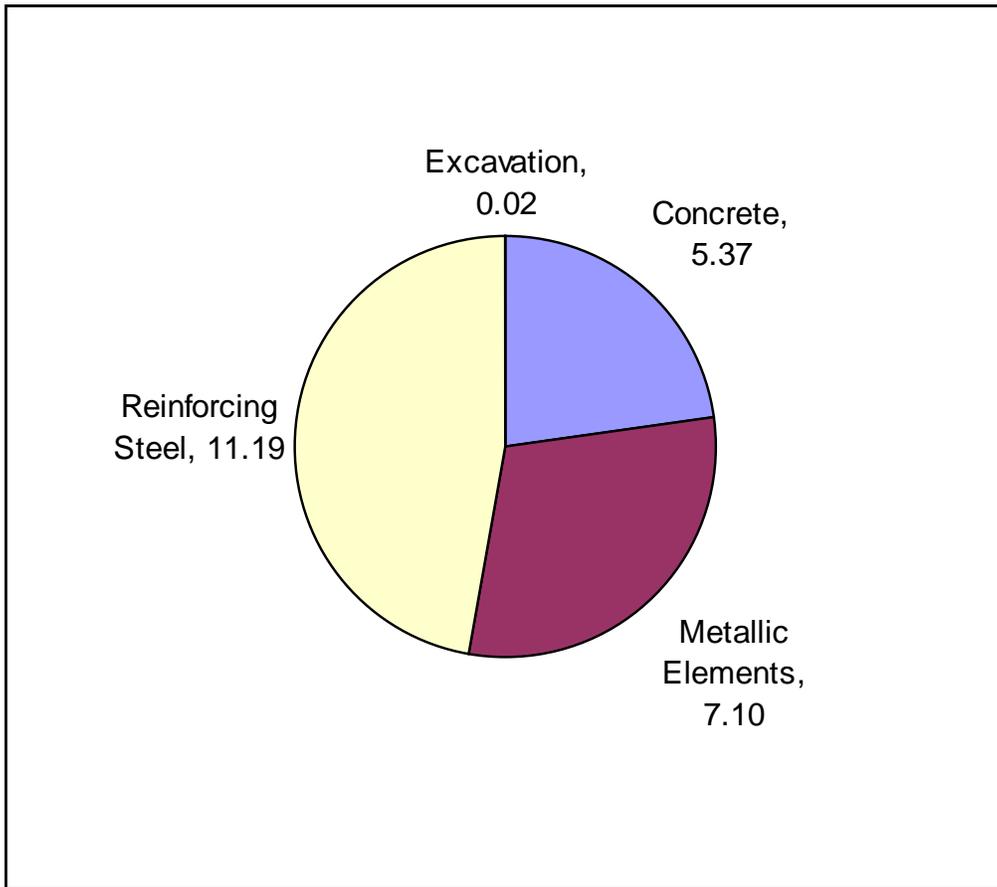


Figure 4. Distribution of Estimated Energy Requirements of the Recycling Center Facilities during Decommissioning – GWh

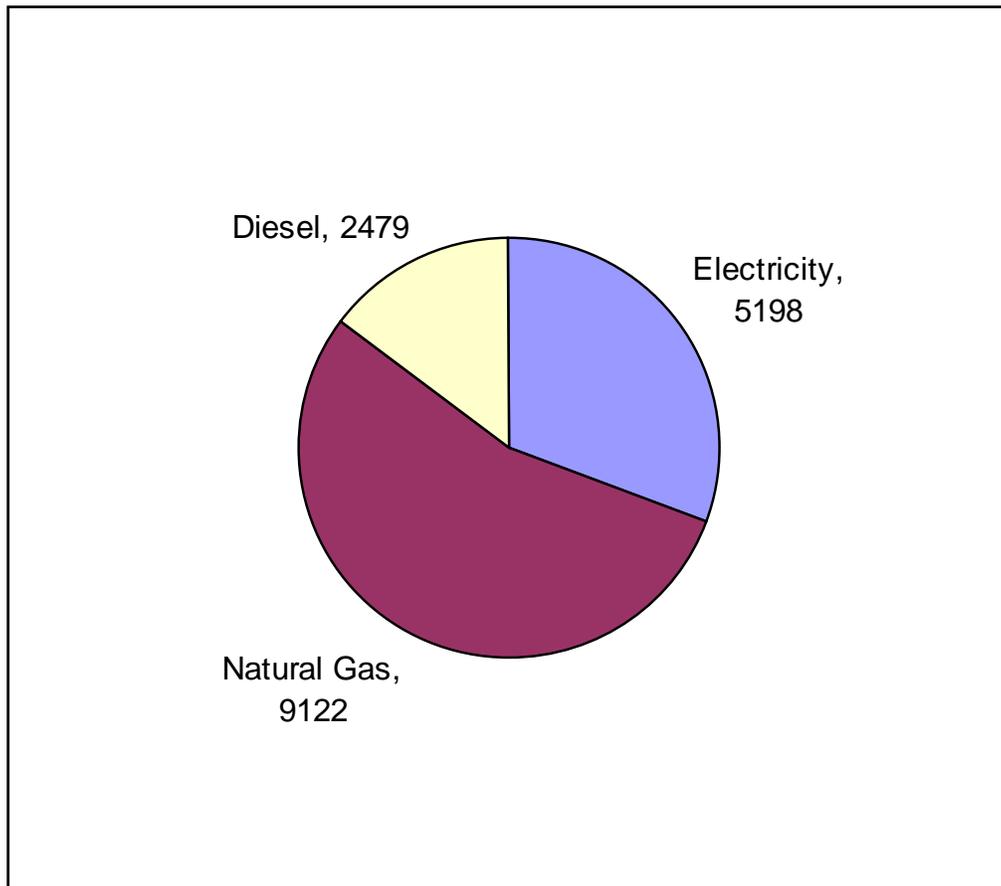


Figure 5. Distribution of Estimated Energy Requirements of the Recycling Center Facilities during Decommissioning – GWh

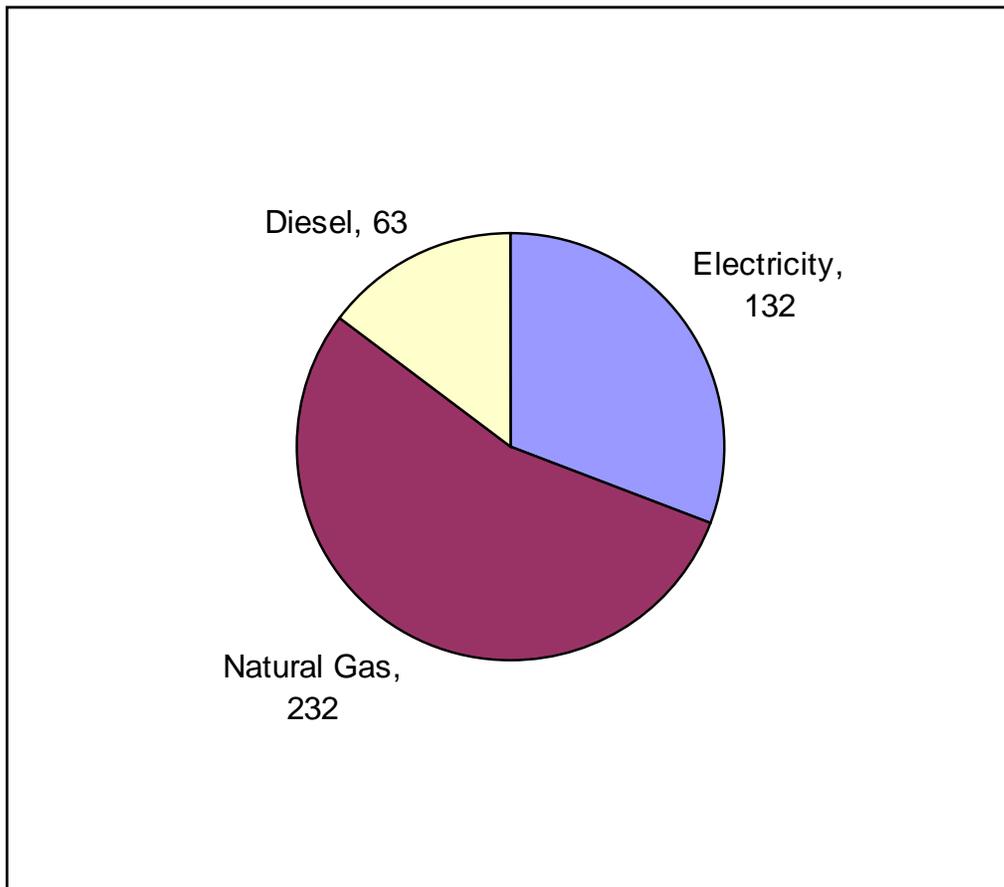


Figure 6. Distribution of Estimated Energy Requirements of the Recycling Center Facilities during Construction and Decommissioning – GWh

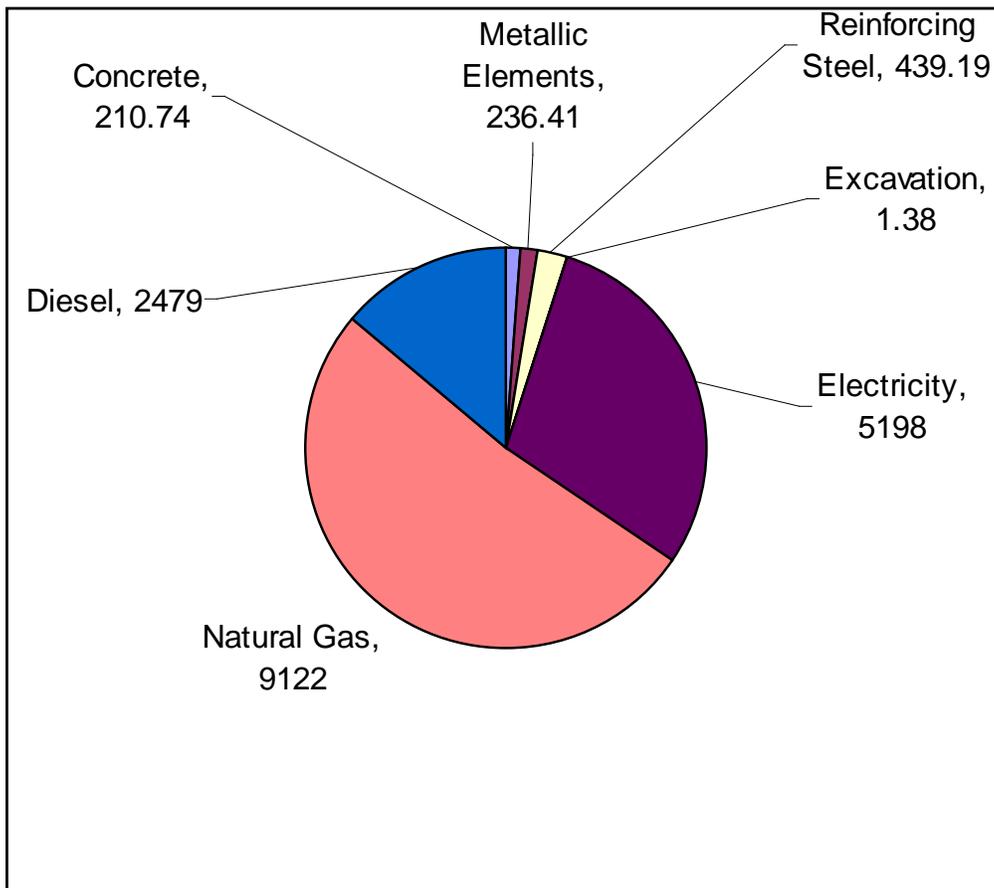


Figure 7. Distribution of Estimated Energy Requirements of the RepU Facilities during Construction and Decommissioning – GWh

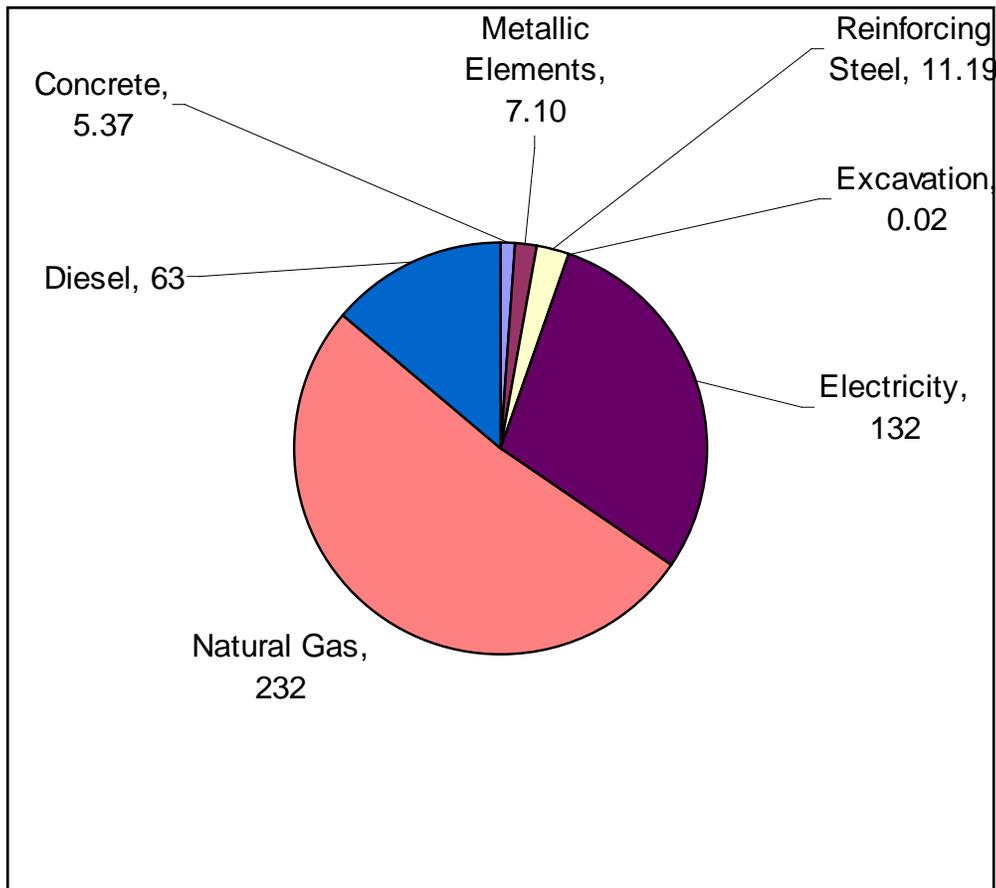
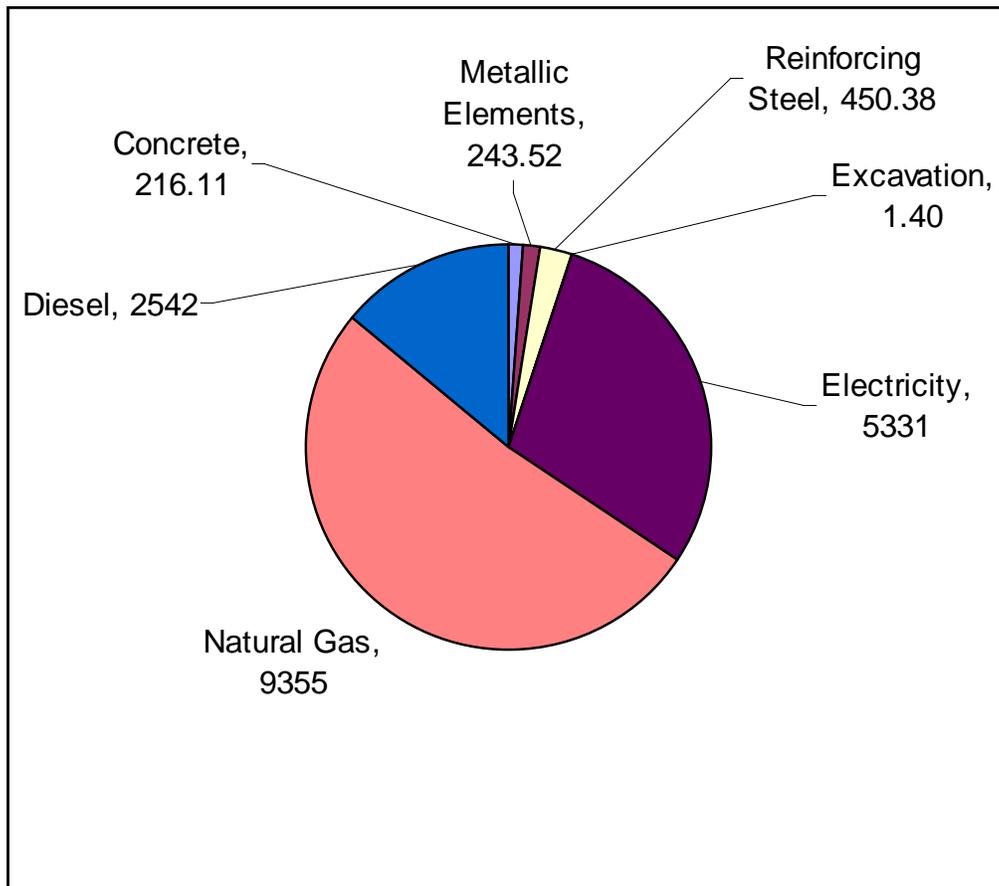


Figure 8. Distribution of Estimated Energy Requirements of the RepU Facilities during Construction and Decommissioning – GWh



REFERENCES

1. ATHENA INSTITUTE CEMENT AND STRUCTURAL CONCRETE PRODUCTS: LIFE CYCLE INVENTORY UPDATE #2 – 2005, OTTOWA.
2. CEMENT AND STRUCTURAL CONCRETE PRODUCTS: LIFE CYCLE INVENTORY UPDATE, PREPARED BY VENTA, GLASER & ASSOCIATES, OTTAWA, CANADA, OCTOBER 1999.
3. RAW MATERIAL BALANCES, ENERGY PROFILES AND ENVIRONMENTAL UNIT FACTOR ESTIMATES: CEMENT AND STRUCTURAL CONCRETE PRODUCTS, PREPARED BY CANADA CENTRE FOR MINERAL & ENERGY TECHNOLOGY AND RADIAN CANADA INC., OTTAWA, CANADA, OCTOBER 1993.
4. ATHENA INSTITUTE, CRADLE TO GATE LIFE CYCLE ANALYSIS INVENTORY: CANADIAN AND US STEEL PRODUCTION BY TYPE, MARKUS ENGINEERING RESOURCES, MARCH 2002.
5. U.S. DEPARTMENT OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION, DEVELOPMENT AND USE OF PRICE ADJUSTMENT CONTRACT PROVISIONS, DATE: DECEMBER 10, 1980:
[HTTP://WWW.FHWA.DOT.GOV/PROGRAMADMIN/CONTRACTS/TA50803.CFM](http://www.fhwa.dot.gov/programadmin/contracts/TA50803.cfm) – ACCESSED 5/1/11.
6. FINAL ENVIRONMENTAL IMPACT STATEMENT FOR DECOMMISSIONING AND/OR LONG-TERM STEWARDSHIP AT THE WEST VALLEY DEMONSTRATION PROJECT AND WESTERN NEW YORK NUCLEAR SERVICE CENTER – TABLES 4-3, 4-61.

Appendix B

Two-Pass Recycle System

1.0 INTRODUCTION

In the main body of the report, Energy Return on Investment (EROI) was calculated for the Mixed Oxide (MOX) and Reprocessed Uranium (RepU) fuel fabricated from the recycling of used Light Water Reactor (LWR) Uranium Oxide (UOx) fuel. This appendix details the calculations related to the useful energy that can be extracted from the used MOX and RepU fuel if it goes through additional recycling, fuel fabrication and subsequent irradiation in an LWR. To bound the number of times the used MOX and RepU can be recycled and placed back into an LWR it was determined that the characteristics of any new fuel manufactured must have similar behavioral performance in the reactor when compared to fresh UOx or the U/Pu content must stay within the current design parameters or regulations for fuel manufacture or shipment.

For the purpose of this study it is assumed that the fuel cycle facilities described in Section 2 of the main body of the report, and depicted in Figure 1 are capable of recycling used MOX and RepU and that no new fuel cycle facility is required. Recycling of large quantities of used MOX has been demonstrated by AREVA at LaHague on a scale of the order of tens of tonnes of material per year. A complete mass balance for the One-Pass and Two-Pass Recycle Systems are depicted in Figure 2.

2.0 KEY ASSUMPTIONS

- The existing fuel cycle facilities used for the recycling of UOx fuel would be adequate for the recycle of used MOX and RepU and the subsequent manufacture of new MOX and RepU fuel assemblies.
- Any fuel assembly that was produced by recycling must have the same operational characteristics in a reactor as a standard fresh UOx fuel assembly design.
- The isotopic concentration of Pu or U of any fuel assembly produced by recycle must be within the current operating design margins for current fuel cycle facilities.
 - Less than 5% enrichment for uranium based fuel.
 - Less than 12.5% Pu content for MOX fuel
- No blending of fresh UOx was considered to offset the isotopes of the second pass MOX or RepU.
- The time taken to recycle used MOX and RepU is approximately the same as the time taken to recycle UOx fuel.
- Pu loss associated with undissolved solids is assumed to be negligible for the purpose of this study.

2.1 Two-Pass Recycle MOX

Two-Pass Recycle MOX for the purpose of this report is defined as the MOX fuel that can be produced from the recycling of used MOX. This material has already been irradiated in an LWR two times, once as fresh fuel and once as MOX fuel. After its second pass through the recycle system, it will be burned a third time in an LWR.

The 100 t/y of used one-pass MOX fuel when recycled would produce 7.2 t/y of Pu for the second pass through the recycle system. At the maximum allowed manufacturing facility design loading of 12.5% Pu in the heavy metal, this would allow the production of approximately 58 t/y of MOX fuel for the second pass.

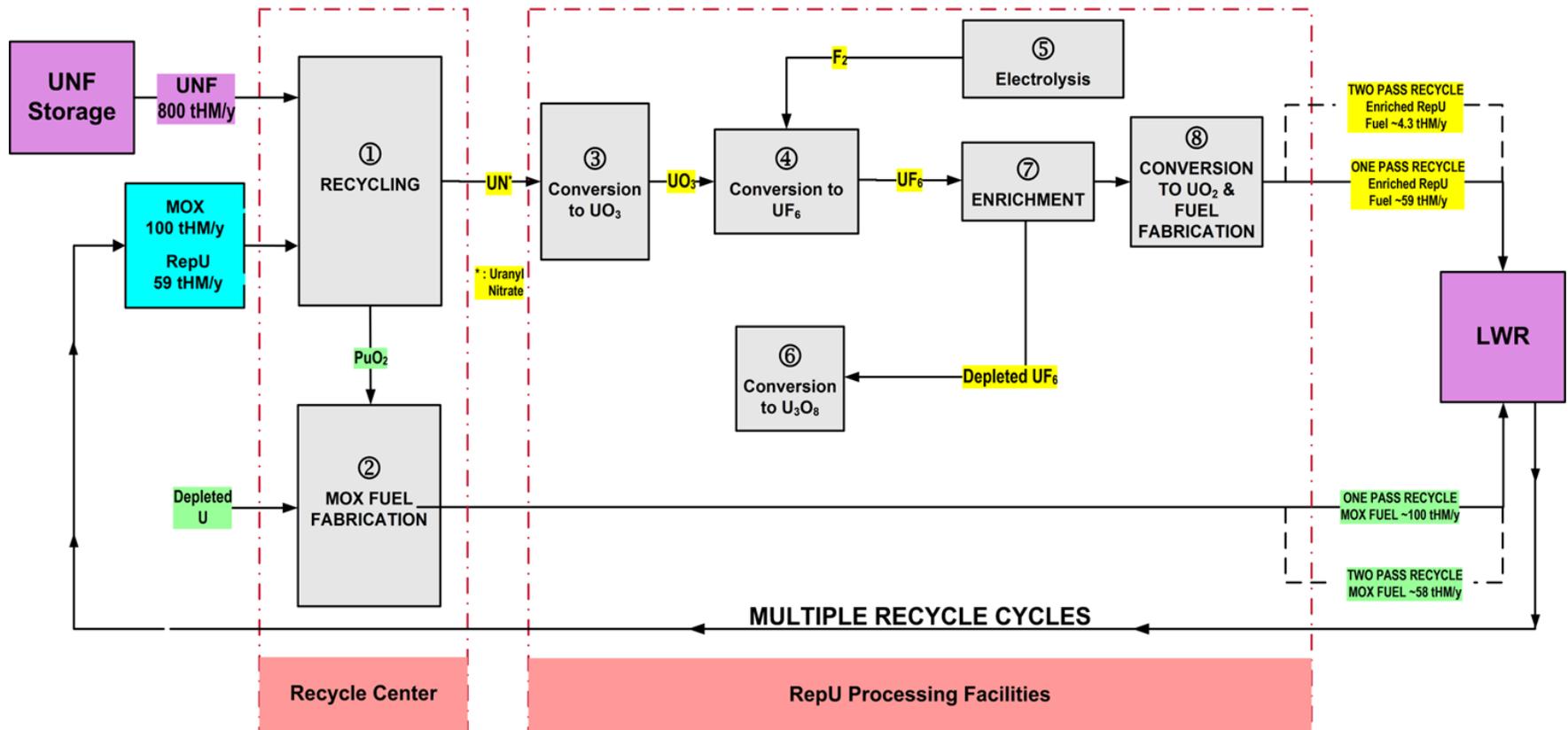
The Pu obtained from recycling one-pass MOX will have less fissile content. Therefore two-pass MOX would only produce 43 GWD/t of thermal energy when placed in the LWR.

The irradiation of Pu in an LWR results in a build-up of non-fissile isotopes of Pu, which are not subsequently separated from the fissile Pu during the recycling of the used MOX. In order to manufacture new fuel from this one-pass Pu that has similar characteristics to the behavior of current UO_x fuel in an LWR, the loading of Pu has to be increased to compensate for the non-fissile Pu present.

Previously modeled [1] One-Pass and Two-Pass LWR MOX fuel recycle systems were used as a basis for estimating the achievable discharge burn-up of the Two-Pass MOX recycle system. The first cycle used a Pu loading of 9.6% Pu in the heavy metal to achieve a discharge burn-up of 50 GWD/t. The second cycle would require a loading of 14.4% to achieve the same burn-up. In a MOX fuel fabrication plant the current design limit for Pu loading in a fuel assembly is 12.5%. This operational limit of 12.5% for the Pu was used in the analysis presented here. Therefore, the discharge burn-up was decreased in proportion to the loading to derive the estimated $(12.5/14.4) \times 50 = 43$ GWD/t burn-up.

In the absence of blending in fresh Pu into the head end of the recycling plant through the recycling of mixed batches of MOX and UO_x fuel, recycling of batches of MOX fuel assemblies on their own can really only be conducted once. If the Pu is irradiated additional times, the limited amount of fissile material will not provide sufficient reactivity to allow it to be used in a fuel assembly for a LWR that behaves in the same manner as current UO_x fuel. The discharge burn-up for the two-pass irradiation is reduced from 50 GWD/t to 43 GWD/t. Further irradiation with discharge burn-ups lower than this may not be economical and therefore this possibility is not considered.

Figure 1. Recycle of Used LWR Fuel in the Two-Pass Recycle System



2.2 Two-Pass RepU

Two-Pass RepU for the purpose of this report is defined as the RepU fuel that can be produced from the recycling of used RepU. This material has already been irradiated in an LWR two times, once as fresh fuel and once as RepU fuel. After its second pass through the recycle system, it will be burned a third time in an LWR.

The 59 t/y of used Once-Through RepU fuel contains about 93.5% uranium with an enrichment of 0.76 weight-percent U-235. This RepU is enriched to the present manufacturing, transport, and handling limit of 5%. This produces $(59 * 0.935) * (0.0076 - 0.004) / (0.050 - 0.004) = 4.3$ t/y with a RepU tails enrichment of 0.4%. With the increased U-236 content from the first pass through the recycle system, this fuel can achieve an estimated burn-up in the region of 40 GWD/t.

Each irradiation cycle results in a build-up of U-236. The increasing amount of U-236, a non-fissile isotope, will require an increasingly higher U-235 enrichment to compensate and produce the required excess reactivity to achieve the necessary discharge burn-up in an LWR. The first irradiation of RepU requires an increase in enrichment of about 0.9 w/o U-235, putting the fuel at 5% enrichment. The second irradiation would require an even higher enrichment of about 6% to achieve the same discharge burn-up of 50 GWD/t. Since the current limit for fuel transportation, manufacturing, handling, and storage is 5%, the enrichment for the two-pass RepU is set to 5% enrichment and the achievable discharge burn-up is estimated by the amount of fissile burned. This yields a discharge burnup for two-pass recycled RepU at 5 w/o of 50. $x (5.0 - 0.76) / (6.0 - 0.76) = 40$ GWD/t.

A limiting factor for RepU is the fact that each subsequent recycle only produces a fraction of the fuel of the previous one due to the enrichment process. This quickly yields a small quantity of RepU which is economically unattractive to handle. For example, the initial 800 tonnes of UNF provides 59 tonnes of enriched RepU for the One-Pass RepU irradiation. The 59 tonnes of irradiated One-Pass RepU only yields about 4.3 tonnes of enriched RepU for the Two-Pass RepU irradiation. The third pass RepU irradiation will not have enough RepU fuel to fill a fuel assembly. Therefore, no further RepU recycling is considered.

It should also be noted that following the first pass through the recycle system, the RepU will contain approximately 0.7 t of Pu that can be used to produce 7.3 t of MOX fuel with 9.6% Pu content. Due to the isotopics of the Pu recovered this MOX fuel can reach burn-ups of 50GWD/t.

These assumptions are summarized in Table 1.

Table 1. Summary of Key Assumptions for the Two-Pass Recycle System

Parameter	Assumed Value
LWR Thermal Efficiency	33%
<u>MOX Recycle</u>	
MOX recycled from First Pass Recycle	100 t/y
MOX produced for Second Pass Recycle	58 t/y
Pu in Two-Pass fuel	7.2 t/y
Percent of Pu in Heavy Metal	12.5%
Enrichment of uranium in MOX fuel	0.25 w/o U-235 for U-tails 0.76 w/o U-235 for RepU
Discharge Burn-up of MOX Two-Pass fuel	43 GWD/t
<u>RepU Recycle</u>	
RepU recycle from First Pass Recycle	59 t/y
RepU fuel produced for Second Pass Recycle	4.3 t/y
Percent of U-235 in RepU	0.76%
Percent of U-235 in RepU tails	0.4%
RepU Fuel Enrichment	5 w/o U-235
Discharge Burn-up of RepU Two-Pass fuel	40 GWD/t
MOX fuel produced	7.3 t/y
Percent of Pu in Heavy Metal	9.6%
Enrichment of uranium in MOX fuel	0.25 w/o U-235 for U-tails 0.76 w/o U-235 for RepU
Discharge burnup of MOX Two-Pass fuel	50 GWD/t

3.0 ENERGY CONSUMPTION

The key Recycling Center facilities include the recycling facility, the MOX fuel manufacturing facility, the RepU conversion facility, the RepU enrichment facility, and the RepU fuel fabrication facility. These facilities are described in the main body of the Report. The energy consumed recycling both MOX and RepU are taken from Table 7 in the main body of the report and are summarized in Table 2.

Table 2. Summary of Annual Energy Consumption of the Two-Pass Recycle System

	One-Pass Recycle System (from Main Body of Report)		Energy Per Tonne (GWh/t)	Two-Pass Recycle System	
	Fuel Recycled (t/y)	Energy Consumption (GWh/y)		Tonnes Recycled or Fabricated	Energy Consumption (GWh/y)
Recycle Center (Box 1 in Figure 2)	800	416	0.520	100	52.0
MOX Fabrication (Box 2 in Figure 2)	100	43	0.430	58	24.9
RepU Recycle (Recovers U and Pu) (Box 1 in Figure 2)	800	416	0.520	59	30.7
RepU Conv., Enr., & Fabrication (Boxes 3 – 8 in Figure 2)	59	54	0.915	4.3	3.9
MOX (Pu from RepU) Fabrication (Box 2 in Figure 2)	100	43	0.430	7.3	3.1

The operational energy costs to recycle the 100 t/y of One-Pass MOX and the 59 t/y of One-Pass RepU are derived from the data for a facility with a nominal recycling capacity of 800 tUNF per year. Since the facilities work on a batch process the energy required to recycle the MOX and RepU batches can be approximated based upon the ratio of the recycle batch size compared to the initial 800tHM/y figures. Similarly the energy required to fabricate the Two-Pass MOX fuel is estimated based upon the fabrication batch size ratio, as shown in Table 2. The energy to convert, enrich, and fabricate the RepU is approximated based on ratioing the energy for the 59t of RepU. This is a good approximation since the initial, final, and tails enrichments are the same for both cases.

Please note in the mass of used RepU and used MOX are combined to make a single batch of material to process through the recycle facility and the calculation above reflects this combination of RepU and MOX.

For example the energy required to recycle 100 tHM MOX is $(100/800)*416=52$ GWh/y

4.0 ENERGY PRODUCTION

Both the MOX and the enriched RepU fuel are assumed to be loaded into existing LWRs. The Recycle Center, with a capacity of 800 tHM/y, will recover approximately 100 t/y of MOX fuel and 59 t/y of RepU fuel for the first pass through the recycle system. The thermal energy produced by the recycled fuel is the amount of each type of fuel multiplied by the fuel’s discharge burn-up, and this energy is converted to electrical energy that is sent to the electric grid. The overall reactor plant efficiency is assumed to be 33%. The net electrical energy produced per year is provided in Table 3.

Table 3. Summary of Annual Energy Produced in the Two-Pass Recycle System

Fuel Type	t/y	Burn-up, GWD/t	Thermal Energy, GWh/y	Electrical Energy, GWh/y
MOX	58	43	59,900	19,800
RepU-UOx	4.3	40	4,130	1,360
RepU-MOX	7.3	50	8,760	2,890
Total	69.6	----	72,790	24,000

5.0 SUMMARY

Table 4 presents the calculation of the Energy Return on Investment for the Two-Pass Recycle System, using both MOX and RepU fuel. It should be noted that these numbers are comparable to those presented in the main body of this Report in that both sets of figures consider only the energy consumed in operations and do not include the energy required to construct and decommission the facilities.

The mass flow and energy balance for both the MOX and RepU options are also depicted in Figure 2.

Table 4. EROI Calculation for Twice-Through Cycles

Fuel Type	Final Energy Produced, GWh/y (ref. Table 3)	Final Energy Consumed, GWh/y (ref. Table 2)	EROI = Final Energy Produced ÷ Final Energy Consumed
MOX Only	19,800	76.9	257*
RepU Total	4,250	37.7	113*
Total	24,000	114.6	210*

**The EROI calculation in this table does not include the energy consumed or produced by earlier recycle of the original 800 tHM of UOx Fuel used to produce the original feed material for this fuel cycle.

6.0 REFERENCE

1. Technical Report 39 – Core Design to Optimize Minor Actinide Burning, AREVA, RPT-30001162-000, April 2009.

Appendix C

Sodium Fast Reactor Recycle

1.0 INTRODUCTION

In the main body of the report, Energy Return on Investment (EROI) was calculated for the Mixed Oxide (MOX) and Reprocessed Uranium (RepU) fuel fabricated from the recycling of used Light Water Reactor (LWR) Uranium Oxide (UOx) fuel that was placed back into an LWR for a further irradiation, One-Pass. Appendix A of this report conducted additional calculations that estimated the additional useful energy that could be extracted by further recycling of the used LWR MOX and LWR RepU fuel for a second time, Two-Pass, in an LWR. Recycling of the UNF for a third cycle was determined not to be practical in an LWR system based on the engineering requirements.

This appendix describes the calculations related to the useful energy that can be extracted from the used MOX and RepU fuel following the first irradiation cycle in an LWR with subsequent recycles being conducted in a sodium fast reactor (SFR). The calculations presented assume varying conversion ratio's (CR) in the SFR core and in the case of the breeder reactor, recycle of the excess Pu produced back into available LWR's.

For the purpose of this study it is assumed that the fuel cycle facilities described in Section 2 of the main body of the report, and depicted in Figure 1 are capable of recycling used fast reactor fuel and that no new fuel cycle facility is required. Recycling of large quantities of used fast reactor fuel has been demonstrated by AREVA at LaHague on a scale of the order of tens of tonnes of material per year.

2.0 KEY ASSUMPTIONS

- All reactor core calculations are based upon an SFR of 1100 MWe generating capacity consuming approximately 11.24 t/y of Pu. The number of SFR's will vary based on the scenario considered.
- The fuel cycles facilities for the SFR will be the same facilities used for LWR recycle.
 - The recycle facility will be the same for the LWR UOx, RepU, LWR MOX and SFR MOX.
 - The recycle facility is assumed to be sized at 800tHM/y.
- It is assumed that the SFR and recycling facility will be collocated on the same site. No off site shipment of fuel.
- For the case where the conversion ratio of the SFR is greater than 1, (Breeder reactor) NO additional SFR's will be required to manage the Pu produced each cycle by the SFR. The additional Pu produced will be utilized as LWR MOX into the existing LWR's. For one pass only in an LWR.
- Energy required to manufacture SFR MOX will be approximately the same as LWR MOX manufacture.
- The isotopic concentration of Pu for SFR MOX fuel assembly produced is relaxed so the facility can operate above 12.5% Pu concentration.
- Time taken to recycle used SFR MOX is approximately the same as the time taken to recycle UOx, RepU and MOX fuel.
- Pu loss associated with un-dissolved solids during multiple recycle of SFR MOX or process losses during recycling of the SFR MOX is assumed to be negligible for the purpose of this study.
- Conversion ratios and maximum fuel burn-ups for the SFR were chosen based on engineering expectations for realistic values.
- SFR UOx manufacture has been assumed to be approximately the same as RepU manufacture as no enrichment is required.

2.1 BASIS OF MASS FLOW FOR PU AVAILABLE FOR SFR MOX RECYCLE

The recycle facility is sized to process 800 metric tHM/y of spent LWR UNF per year. The initial calculations in the body of the main report showed that recycling 800 tHM of UOx fuel will produce 100 t/y of MOX fuel and 59 t/y of RepU fuel which is then irradiated in an LWR. This 159 t of used MOX and used RepU contains approximately 7.9 t of Pu following the irradiation cycle. This evaluation assumes that the, 7.9 t/y of Pu is recycled and manufactured into MOX fuel for a fast reactor.

2.2 FAST REACTOR CONVERSION RATIO

The major factor influencing the fast reactor fuel cycles is the conversion ratio (CR).

The CR is the Pu production in the SFR reactor core divided by the Pu consumption in the reactor core.

For the purpose of this report the following fuel cycle were considered.

- CR < 1, Burner reactor
- CR ≈ 1, Break even reactor
- CR > 1 Breeder reactor.

For each CR, both a One-Pass fuel cycle and a subsequent fuel recycle were examined. It should be noted that for a SFR to come to equilibrium on the Pu content in the fuel can take 9 to 10 passes through the reactor followed by recycle. Based upon AREVA's experience it is typical that the Pu loading in the fuel will increase by approximately 40% between the first and the ninth cycle.

The following sub-sections discuss the parameters assumed for each CR.

2.2.1 CR < 1:-PU BURNER

This fuel cycle represents a fast reactor core design that overall consumes more Pu during operations compared to the amount that of Pu it produces, that it would be used as an "actinide burner". A CR of ≈ 0.3 [1] is selected to represent this class of fuel cycle. While this is not the smallest possible CR, it is one that can be achieved in production. The basis for this fuel cycle is an advanced actinide burner reactor with an assumed fuel burn-up of 100 GWD/t.

The target burn-up for the reactor core is 100 GWd/t. Due to the design of the core for a reactor with a CR<1 using target blankets the maximum burn-up achieved during the first pass in AREVA's experience will be in the range of 68 GWd/t average across the core.

The Pu discharged from the fast reactor can be sent to a repository (One-Pass cycle) or recycled and additional energy extracted. For the multi-cycle option, a feed of recycled MOX fuel produced from LWR UOx spent fuel is still required to replenish the Pu consumed in order to sustain a constant annual energy production. Both of these options are presented in Figure 1.

Subsequent cycles of this design of burner reactor eventually reach fuel burn-ups of 76 GWd/t., (Cycle 9). This higher burn-up is a result of the slightly higher Pu loading in each subsequent fuel cycle compared to the previous. It should be noted that the purpose of this reactor is to destroy Pu. This takes place by either fissioning it or by transmuting it to another isotope. Efficient use of the fissile material was not an objective of the design.

2.2.2 CR ≈ 1:-BREAK EVEN

This fuel produces as much Pu as it consumes and can therefore sustain itself with no additional Pu from recycle of UNF from LWR's. A fast reactor with this conversion ratio requires a feed of fast reactor MOX fuel with approximately 16 %Pu in the heavy metal [2] for the One-Pass cycle. To achieve multiple

recycle of the SFR used MOX the Pu content will have to be increased with each subsequent cycle to compensate for the reduction in fissile Pu. For optimum performance an assumed fuel burn-up of 100 GWD/t has been assumed. The mass balance for this cycle is presented in Figure 2.

2.2.3 CR > 1:-BREEDER REACTORS

This fuel cycle represents using a fast reactor core design that produces significantly more Pu than it consumes. It is similar to the cycle for a fast reactor with $CR \approx 1$ except that it produces sufficient surplus Pu that it can also sustain LWR MOX cycles or be used to provide fuel for additional SFR's. for the purpose of this study it is assumed that only one pass through an LWR will be conducted. A CR of 1.2 was selected to represent this class of fuel cycle. While this is not the largest possible CR, it is one that is realistic from an engineering perspective. This fuel cycle will require a small feed of tails uranium as feedstock for the additional targets which produce additional Pu. A fast reactor with this conversion ratio requires a feed of fast reactor MOX fuel with 16% Pu in the heavy metal [2] for the One-Pass cycle. A multi-cycle fuel cycle is estimated. It should be noted that by cycle 9 the feed Pu loading will need to be increased to approximately 22.7% Pu to compensate for the reduction in fissile Pu loaded into the fuel. For optimum performance of this fuel cycle a fuel burn-up of 100 GWD/t has been assumed for the driver fuel and a burnup of 12.7 GWD/t for the blankets.

One of the characteristics of this fuel cycle is that it produces a stream of MOX fuel for use in an LWR. The energy extracted from the LWR fuel is considered as an option. The mass balance for a once through and multiple recycle are presented in Figure's 3 and 4.

3.0 ENERGY CONSUMPTION DATA

As per previous calculations in the main body of the report the energy consumption data for the SFR fuel cycle facilities are based on the ratio of the size of the batch of material divided by the design basis throughput of the facility. The basis for energy consumption is summarized in Table 1.

Table 1. Fuel Processing Energy Consumption Bases

	Facility Throughput, t/y	Energy Consumption, GWhe/y	Unit Energy Consumption, GWhe/t
Used UOx Recycling	800	416	0.52
MOX Fuel Fabrication	100	43	0.43
Fast Reactor UOX Blankets Fabrication (Based on RepU Fabrication Facility)	59	3	0.051

For the SFR with a $CR > 1$ axial and radial blankets of UOx will be required. This blanket material contains no Pu and is therefore not MOX fuel. The energy consumed to produce the MOX and UOx fuel is based on the following assumptions.

1. The recycle of the used UOx and used MOX will require the same energy per tHM of feed material as the 800tHM/y recycling facility, 416 GWh/y for 800 t/y.
2. The MOX fuel fabrication will require 43 GWh/y for 100 t/y of MOX fuel fabricated. This energy consumption is applied to both fast reactor MOX fuel and LWR MOX fuel since they both require the special manufacturing considerations pertinent to Pu fuel.

3. The UOx fuel for fast reactor radial and axial blankets does not contain Pu and therefore the fabrication and fabrication energy consumption of this fuel will be similar to that of RepU fuel. This fuel is not enriched and therefore will not require conversion and enrichment. The fabrication is therefore requires 3 GWh/y for each 59 t/y produced.
4. The thermal efficiency of the LWR is assumed to be 33%. The thermal efficiency of the SFR is assumed to be 40%. This is due to the higher operating temperature of the fast reactor compared to the LWR.
5. The axial blanket fuel fabrication energy consumption will be included with the MOX fuel fabrication energy consumption. This is because the material will be located in the same MOX fuel assembly rods with the Pu bearing material in the center of each rod and the UOx material placed above and below.
6. For the multiple recycle options there are numerous scenarios that can be considered particularly in the case where the CR > 1. The scenario considered in this report is LWR MOX to SFR MOX for first cycle. Fuel is then recycled with excess Pu manufactured into one pass LWR MOX that is not recycled.
7. The energy consumed for multiple recycle is an approximation based upon the assumptions that have been carried through-out this calculation in this report.

4.0 ENERGY PRODUCTION

The Recycle Center will recover 7.9t of Pu in the 100 t/y of used MOX fuel and the 59 t/y of used RepU fuel. The thermal energy produced by the recycled fuel is the amount of each type of fuel multiplied by the discharge burnup. The energy is provided as electrical energy provided to the electric grid. The overall plant efficiency is assumed to be 40% for the fast reactor and 33% for the LWR. The net electrical energy produced per year is provided in Tables 2, 3, and 4.

Table 2. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycles for Burner SFR with CR<1

Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y	EROI*
One-Pass	30.8	25.6	68	16,700	94	177*

*The EROI calculation in this table does not include the energy consumed or produced by earlier recycle of the original 800 tHM of UOx Fuel used to produce the original feed material for this fuel cycle.

Energy Produced $25.6 \times 68 \times 24 \times 0.4 = 16,700$ GWhe/y

Energy Consumed One Pass

Energy Consumed Recycle Used MOX and RepU $(100+59) \times 416/800 = 83$ GWhe/y

Energy Consumed to manufacture SFR MOX $25.6 \times 43/100 = 11$ GWhe/y

Total Energy Consumed 83+ 11= 94 GWhe/y

Table 3. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycles
 for Break Even SFR CR ≈1

Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y	EROI*
One-Pass	16.35	48.4	100	46,400	104	446*
Multi-Cycle	22.7	48.4	100	46,400	46.0	1000*

*The EROI calculation in this table does not include the energy consumed or produced by earlier recycle of the original 800 tHM of UOx Fuel used to produce the original feed material for this fuel cycle.

Energy Produced per cycle $48.4 \times 100 \times 24 \times 0.4 = 46,400$ GWhe/y

Energy Consumed One Pass

Energy Consumed Recycle Used MOX and RepU $(100+59) \times 416/800 = 83$ GWhe/y

Energy Consumed to manufacture SFR MOX $48.4 \times 43/100 = 21$ GWhe/y

Total Energy Consumed for one pass $83 + 21 = 104$ GWhe/y

Approximate Energy Consumed for each subsequent Recycle

Energy Consumed for each subsequent recycle $48.4 \times 416/800 = 25$ GWhe/y

Energy Consumed to manufacture SFR MOX $48.4 \times 43/100 = 21$ GWhe/y

Total Energy Consumed for subsequent recycle $25 + 21 = 46$ GWhe/y

Table 4. Summary of Annual Energy Produced and Consumed in Fast Reactor Fuel Cycle
 for Breeder SFR CR>1

Fuel Cycle	% Pu In SFR MOX	Fuel Throughput, t/y	Discharge Burnup, GWD/t	Energy Produced, GWhe/y	Energy Consumed, GWhe/y	EROI*
ONE-PASS RECYCLE ENERGY						
SFR MOX	16.35	48.4	100	46,500	104	
SFR UOx	0.0	29.5	12.7	3,600	1.5	
Total				50,100	105.5	474*
MULTI-CYCLE RECYCLE ENERGY						
SFR MOX	22.7	48.4	100	46,500	46	
SFR UOx	0.0	29.5	12.7	3,600	16.5	
LWR MOX	9.6	13.7	50	5,400	6	
Total				55,500	68.5	791*

*The EROI calculation in this table does not include the energy consumed or produced by earlier recycle of the original 800 tHM of UOx Fuel used to produce the original feed material for this fuel cycle.

One Pass Energy Produced

$48.4 \times 100 \times 24 \times 0.4 = 46,500$ GWhe/y (SFR)

$29.5 \times 12.7 \times 24 \times 0.4 = 3,600$ GWhe/y (SFR)

Total $46,500 + 3,600 = 50,100$ GWhe/y

One Pass Energy Consumed

Energy Consumed Recycle Used MOX and RepU $(100+59) \times 416/800 = 83$ GWhe/y

Energy Consumed to manufacture SFR MOX $48.4 \times 43/100 = 21$ GWhe/y

Energy Consumed to manufacture SFR UOx (RepU) $29.5 \times 3/59 = 1.5$ GWhe/y

Total $83 + 21 + 1.5 = 105.5$ GWhe/y

Multiple Recycle

Approximate Energy Produced for each subsequent Recycle

$48.4 \times 100 \times 24 \times 0.4 = 46,500$ GWhe/y (SFR MOX)

$29.5 \times 12.7 \times 24 \times 0.4 = 3,600$ GWhe/y (SFR UOx)

$13.7 \times 13.7 \times 50 \times 0.33 = 5,400$ GWhe/y (LWR MOX)

Total $46,500 + 3,600 + 5,400 = 55,500$ GWhe/y

Approximate Energy Consumed for each subsequent Recycle

Energy Consumed for each subsequent recycle SFR MOX $48.4 \times 416/800 = 25$ GWhe/y

Energy Consumed to manufacture SFR MOX $48.4 \times 43/100 = 21$ GWhe/y

Energy Consumed for UOx Recycle $29.5 \times 416/800 = 15$ GWhe/y

Energy Consumed for SFR UOx (Based on RepU) $29.5 \times 3/59 = 1.5$ GWhe/y

Energy Consumed for LWR MOX Manufacture $13.7 \times 43/100 = 6$ GWhe/y

Energy consumed for LWR MOX Recycl Assumed once through only

Total Energy Consumed for subsequent recycle $25 + 21 + 15 + 1.5 + 6 = 68.5$ GWhe/y

5.0 SUMMARY

Table 3 presents the data which is the basis for calculation of the Energy Return on Investment for the Two-Pass use of used MOX and RepU fuel and also the EROI for each fuel cycle. It should be noted that these numbers are on the same basis as those presented in the main report in that they are based on energy consumed in operations and do not include the energy required to construct and decommission the facilities.

Figures 1 through 4 depict the heavy metal mass flow and energy consumption and production. Figure 1 show the one-pass and multi-pass cycles for fast reactors with a $CR < 1$. Figure 2 shows the one-pass and multi-pass cycles for fast reactors with a $CR \sim 1$. Figure 3 shows the one-pass cycle for fast reactors with a $CR > 1$. Figure 4 shows the multi-pass cycle for fast reactors with a $CR > 1$.

In general, higher EROI values are obtained for fuel cycles that recycle only spent fuel that contains higher concentrations of Pu. Fuels such as spent UOx contain much lower concentrations of Pu and therefore, require more recycling, and more feed material in order to obtain a given amount of Pu. This increases the energy consumed and reduces the EROI.

6.0 REFERENCES

1. AREVA. *Technical Report*, RPT-3001161-000 April 30, 2009.
2. D. Verrier. *RE: Question to Support Study in US for DOE*. AREVA SAS, March 31, 2011. Email.

Figure 1. One-Pass and Multi-Pass Cycles for Fast Reactors with a CR < 1

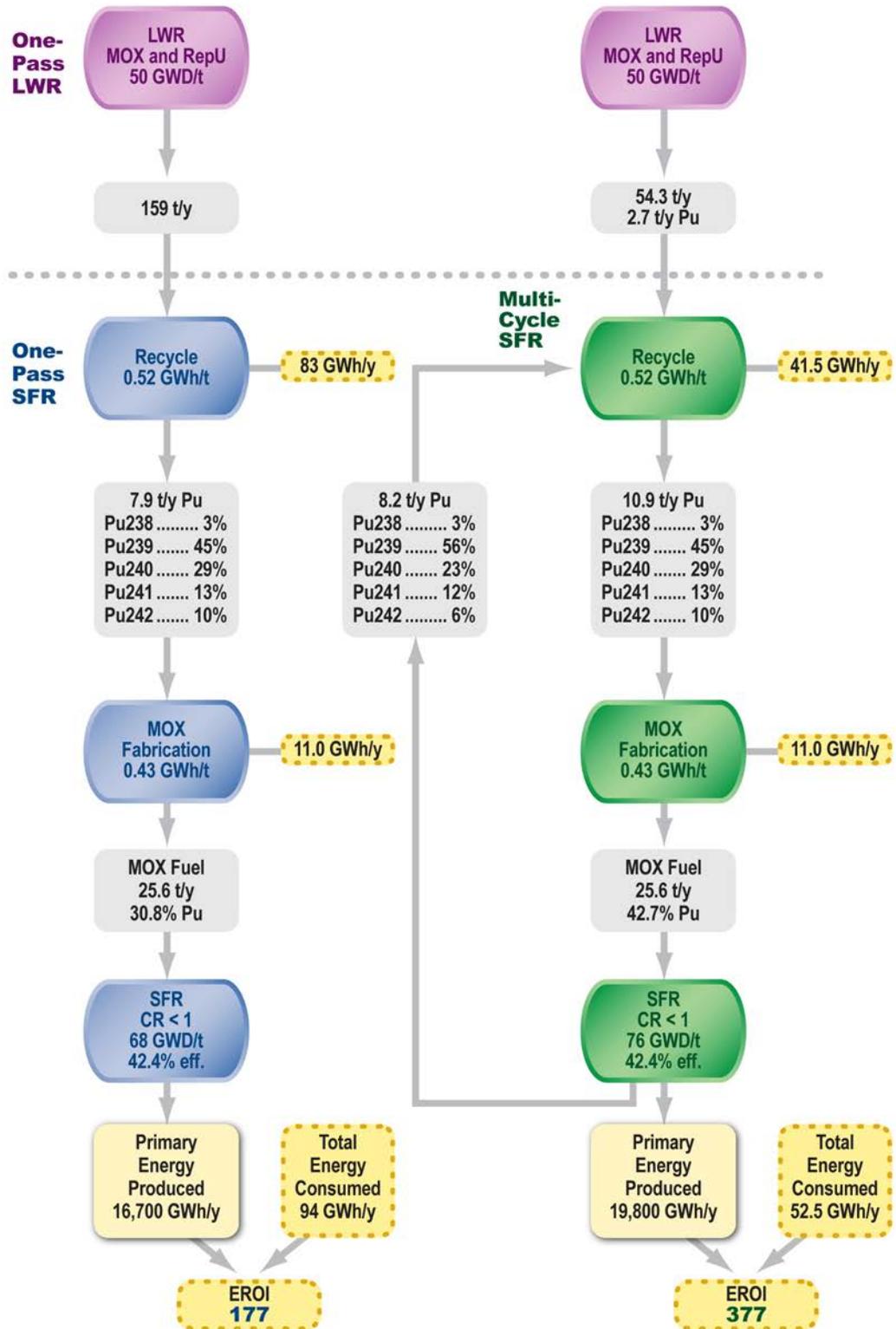


Figure 2. One-Pass and Multi-Pass Cycles for Fast Reactors with a CR ≈1

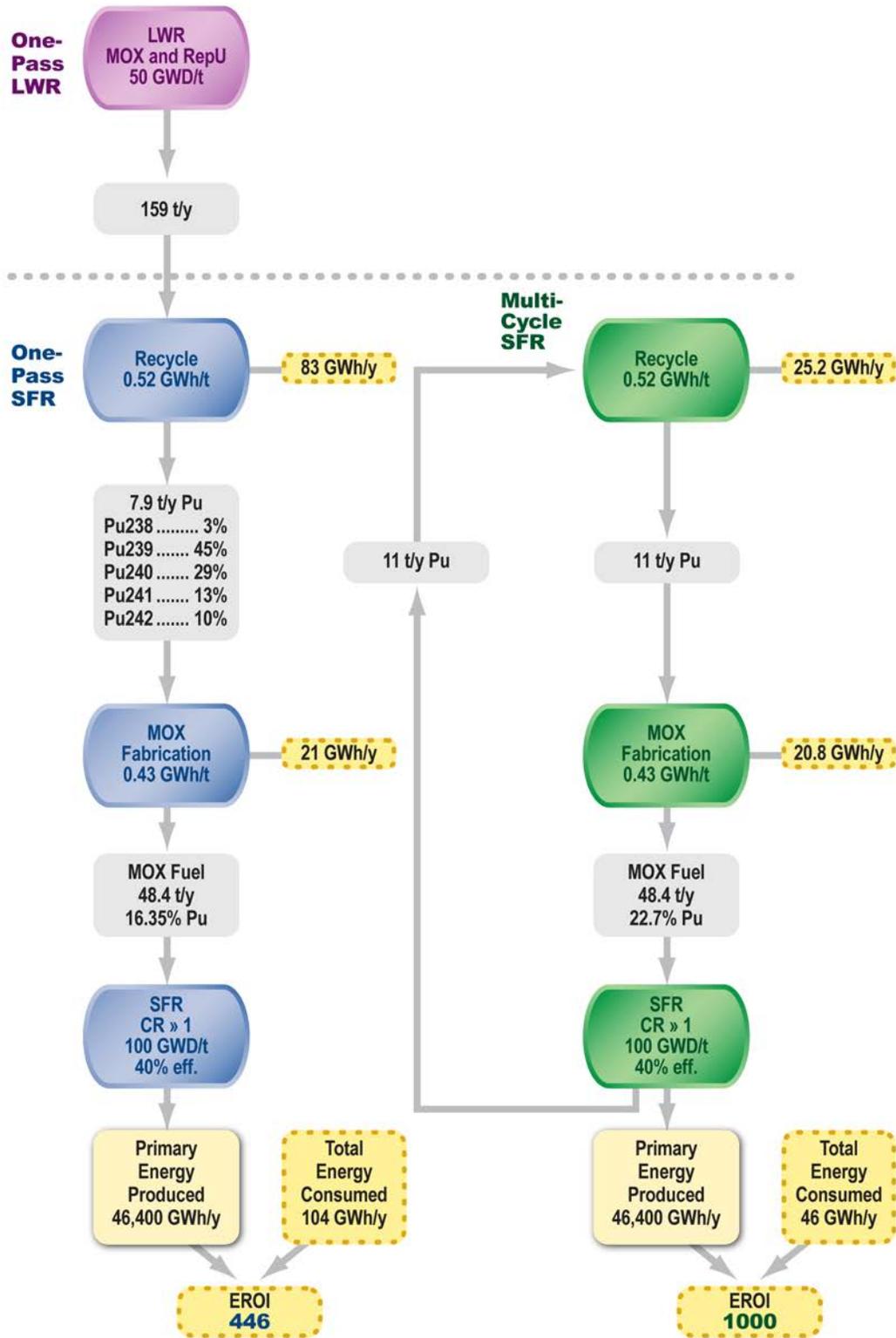


Figure 3. One-Pass Cycle for Fast Reactors with a CR > 1

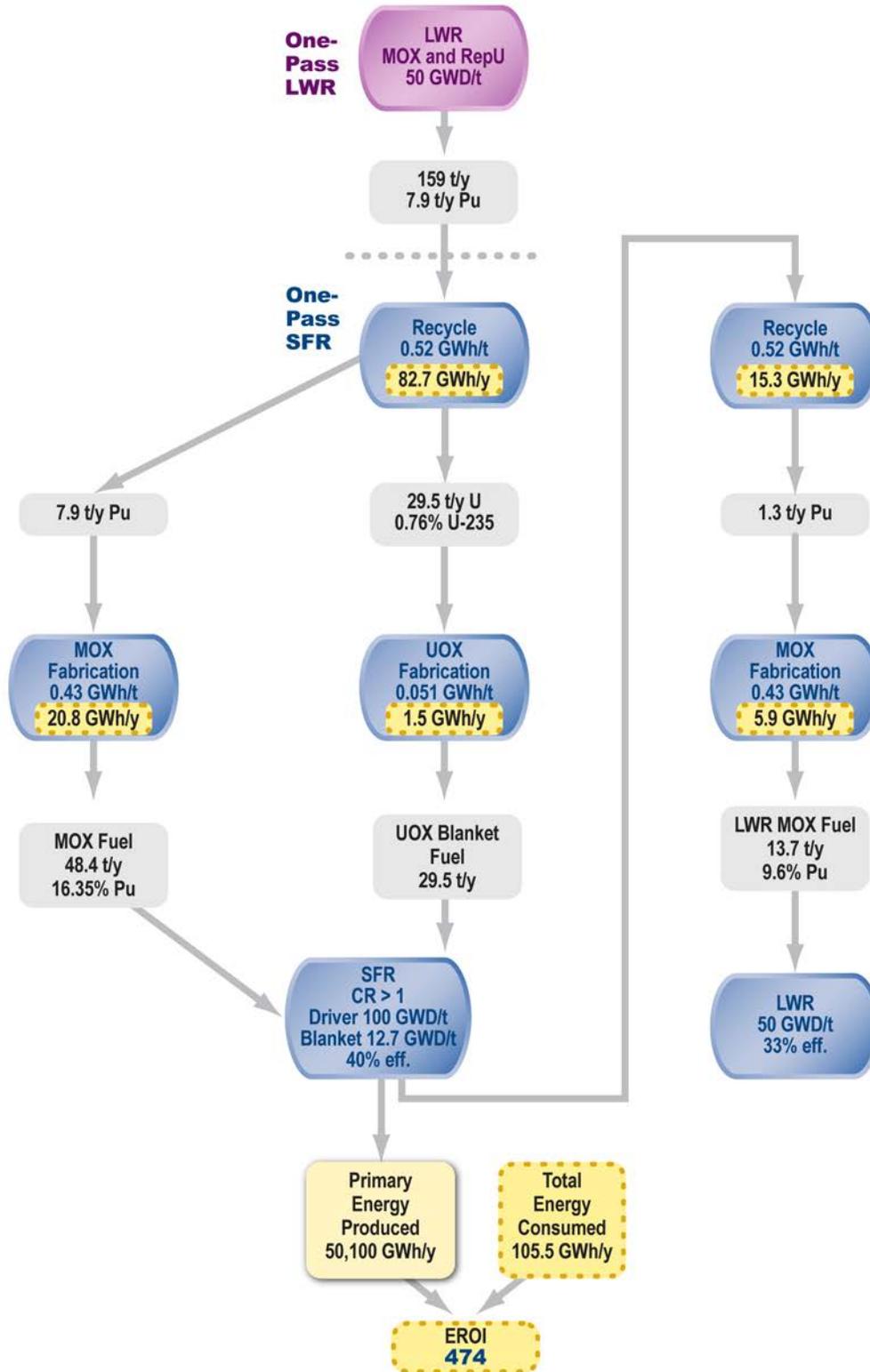
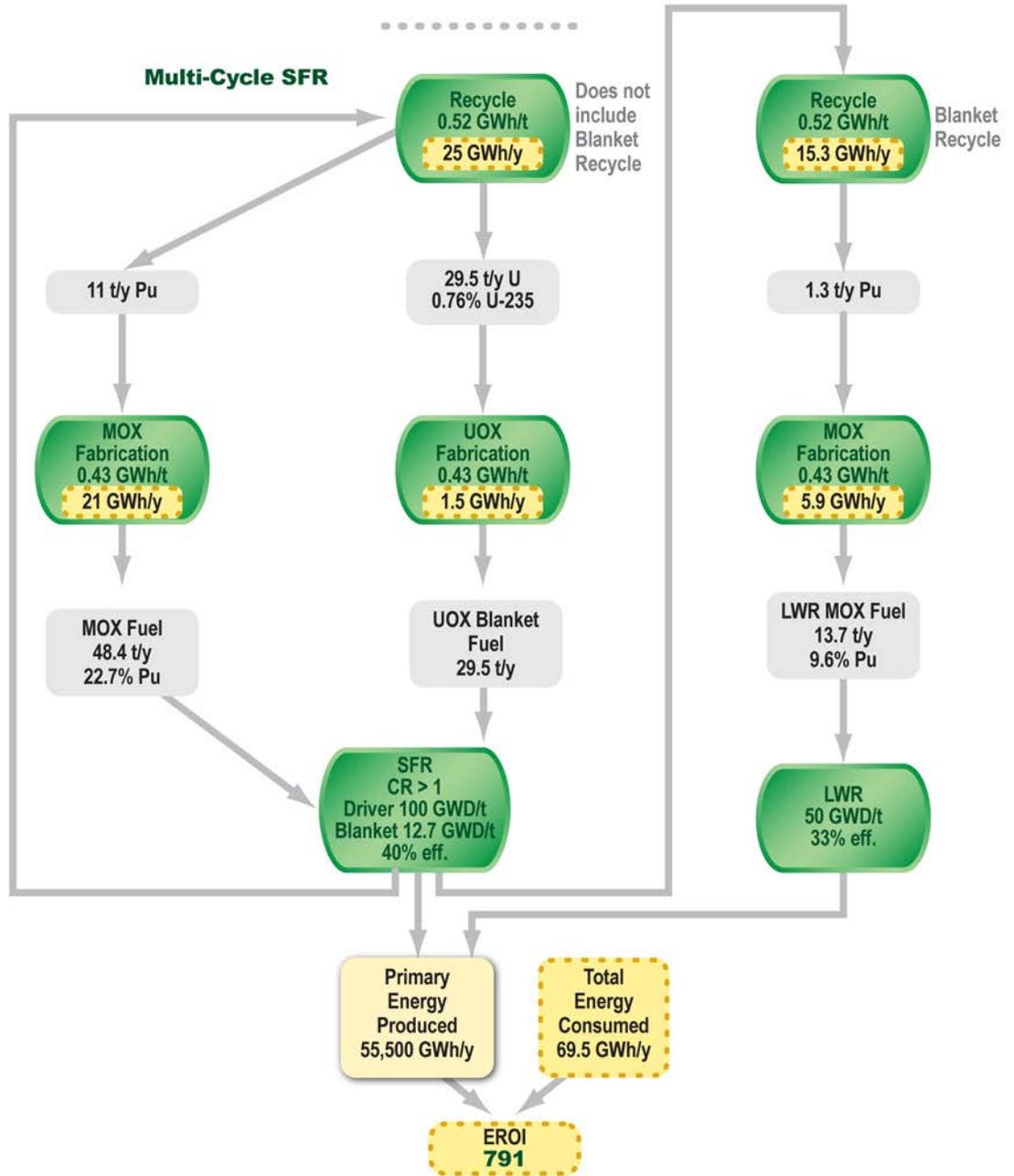


Figure 4. Multi-Pass Cycle for Fast Reactors with a CR > 1



Appendix D

Energy Required to Construct and Decommission a Sodium Fast Reactor

1.0 INTRODUCTION

This appendix provides an estimate of the final energy consumed during the construction and decommissioning of a Generation IV Sodium Fast Reactor (SFR).

- The energy consumed during the construction phase includes the production of the principle raw construction materials, refinement of those materials into useful forms and installation of the materials as part of the construction of the SFR.
- The energy consumed during the dismantling phase includes, decommissioning a SFR including dismantling and disposal of the contaminated materials.

Energy consumption analysis will only consider primary processes that are expected to be significant contributors to the total energy consumed during the construction and decommissioning phase of the SFR.

Energy consumption for the extraction, transportation and manufacture of the building materials – concrete and reinforcing bars and subsequent decommissioning is based on industry publications and in house experience, and provides a reasonable approximation for use in determining the energy required to construct and dismantle a SFR.

2.0 SUMMARY OF ENERGY CONSUMED

Table 1. Summary of Energy Consumed, by Phase and Type

	Construction		Decommissioning		
	Concrete GWh/Mwe	Reinforcing Steel GWh/Mwe	Electricity GWh/Mwe	Natural Gas GWh/Mwe	Diesel GWh/Mwe
Nominal Values	0.0364	0.1797	0.1251	0.2195	0.0596
1100 MWe	40	198	138	241	66

Total Energy for construction and Decommissioning for each 1100 SFR

$$40 + 198 + 138 + 241 + 66 = 682 \text{ GWh per reactor}$$

Construction Materials Considered

For the purposes of this study the Sodium Fast Reactor (SFR) considered in the scenarios was sized at approximately 1100 GWe. Table 2 contains published¹ information on the relative concrete volume and steel weight for seven types of reactors. It also contains the following information from the World Nuclear Organization².

- Sizewell B: 1188 MWe, 520,000 m³ concrete (438 m³/MWe), 65,000 t rebar (55 t/MWe);
- AP1000: 1100 MWe, <100,000 m³ concrete (90 m³/MWe), <12,000 t rebar (11 t/MWe).

Table 2. Material Quantities vs Reactor Type

Reactor Type	Power Level	Building Volume, cu-m/MWe	Concrete Volume, cu-m/MWe	Steel Weight, Tonnes/MWe
1970s PWR	1000	340	75	37
1970s BWR	1000	390	88	41
EPR	1600	400	130	44
ABWR	1380	450	140	46
ESBWR	1500	320	69	33
GT-MHR	286	410	76	27
AHTR-IT	1235	150	42	16
Sizewell	1188		440	55
P1000	1117		90	11

This data is expressed in terms of units per MWe. It should also be noted that there is a large amount of uncertainty in some of the estimates and therefore the data is only good to one or two significant digits.

Plotting the data reveals no real trend with reactor size for either concrete volume or steel weight. However it can be expected that the non-pressurized, SFR's, would have a lower concrete volumes and steel weights than other reactor designs. This is due to their low operating pressure, which avoids the use of thick pressure vessels and piping, and also avoids the necessity of large makeup tanks and vapor suppression for accident mitigation.

Construction Material Takeoffs

The quantities of concrete, excavation and weight of steel for a nominal 1100 MWe SFR were estimated after considering the information for several reactor types¹, including Light water reactors (LWRs) and gas-cooled reactors. The following quantities were selected so that the energy costs for construction and decommissioning can be provided per MWe.

- Concrete 76 m³ per MWe
- Steel 27 Tons per MWe

Construction Energy Consumed-Metrics

The following materials/work processes are included in the analysis:

- 4000 psi concrete (typical): Foundations, buildings
 - Raw material production and transportation
 - Batch-plant operations
 - Transportation and installation
- Metallic Components: Rebar
 - Raw material production and transportation
 - Mill operations and transportation
 - Fabrication
 - Transportation and installation

1.1.1 CONCRETE PRODUCTION AND INSTALLATION

Several research reports produced by the Athena Institute were utilized to provide an estimate of the energy required to produce, transport and place concrete^{3, 4, and 5}. The research was conducted for

Canadian producers and users, but was broken into regions. Only the more densely populated regions (West and East Coast) were used to determine an aggregate metric. The Central and Prairie regions were not included due to exceedingly high transportation costs, and were considered inconsistent with the average U.S. population density. The breakdown of the energy consumed is identified in Table 3.

Table 3. Production and Transportation Energy Requirements of Concrete GJ per Cubic Meter

Extraction	Transportation	Processing	Transportation between batch plant and site and placement	Total Placed
0.089	0.074	1.549	0.012	1.724

Table 3 makes it fairly clear that the bulk of the energy (89% in this analysis) required to produce and place concrete lies in the processing. However, once the location of the site is determined, it may be necessary to re-calculate the transportation energy. Note the batch plant distance in this case is set at 10 km from the site.

Metallic Production and Installation

Due to the energy intense nature of the production of metal, there are a number of studies on which to draw metrics⁶, shown in Table 4.

Table 4. Energy per Step in Metallic Production by end Conformation, GJ per Tonne

Metallic Elements	Extraction	Extraction Transportation	Processing	Primary Mill	Finishing Mill	Transportation to Site and Installation	Total Installed
Steel (rod) – rebar	2.59	0.63	18.83	1.28	0.00	0.63	23.96

Note that the processing energy is again the bulk of the energy. In this case, the average processing energy is a cross section of both BOF (Blast Oxygen Furnace) type plants and EAF (Electric Arc Furnace). The average for the studies identified for BOF plants was ~19 GJ per tonne, and the energy for EAF plants is closer to 8 GJ per tonne. The industry is moving to the more efficient EAF process, but is still dominated by BOF facilities. Note also that the transportation to site is the same as the extraction transportation. This is due to the assumption that the averages established for the transportation of the raw materials, will extend to the average distance required to transport the finished product to the site from the mill.

Construction Energy Consumed – Results

Table 5. Energy Requirements for Instalation of Concrete

	Concrete GWh/Mwe
SFR	0.0364

Table 6. Energy Requirements for Fabrication and Instalation of Rebar

	Reinforcing Steel GWh/Mwe
SFR	0.1797

Decommissioning Materials Considered and Quantity Estimation

In 1996, DOE submitted a preliminary Environmental Impact Statement (EIS) for the West Valley Demonstration Project⁸, a former fuel reprocessing and vitrification facility. This EIS was updated in 2007 and listed quantities of material to be decommissioned, and the energy requirements to complete the decommissioning, transportation and complete disposal. Key quantities identified in the EIS include

- Cubic meters of concrete
- Tonnes of steel
- Cubic meters of soil
- Other Non-Hazardous

These identified quantities were utilized to scale the estimated energy requirements for the SFR. The ratio of the total quantity of concrete between the WVDP and the three areas identified, were used to estimate the quantities of the soil and “Other non-hazardous” materials.

- Ratio of WVDP Concrete Volumes to SFR Concrete Volumes on a per MWe basis
 - $76/61280 = 0.000173$

The key quantities identified (concrete and steel) and the estimated quantities (soil and other non-hazardous) are identified in Table 7.

Table 7. Key Quantities for Determining Decommissioning Energy Requirements.

Facility	Concrete Cubic Meters/MWe	Steel Tonnes/MWe	Soil Cubic Meters/MWe	Other Non-Hazardous Cubic Meters/MWe
SFR	76	27	1373	24

Decommissioning Energy Consumed - Metrics

The EIS includes the electricity, natural gas and diesel fuel expected to be used to decommission the WVDP. These quantities are factored by the key quantities ratio determined above to estimate the quantities required for the SFR.

Table 8. Utility Requirements for Decommissioning

Facility	Electricity MW-Hrs/MWe	Natural Gas Cubic Meters/MWe	Diesel Liters/MWe
SFR	125	21,069	5,563

Converting these quantities to energy, utilizing the following conversions:

- 3600 MJ per MW-Hr
- 37.5 MJ per Cubic Meter of Natural Gas
- 38.6 MJ per Liter of Diesel

Decommissioning Energy Consumed - Results

Table 9. Utility Requirements for Decommissioning

Facility	Electricity GWh/MWe	Natural Gas GWh/MWe	Diesel GWh/MWe
West Valley Demonstration Project	0.1251	0.2195	0.0596

Figure 1. Distribution of Estimated Energy Requirements of the SFR During Construction (GWh/MWe)

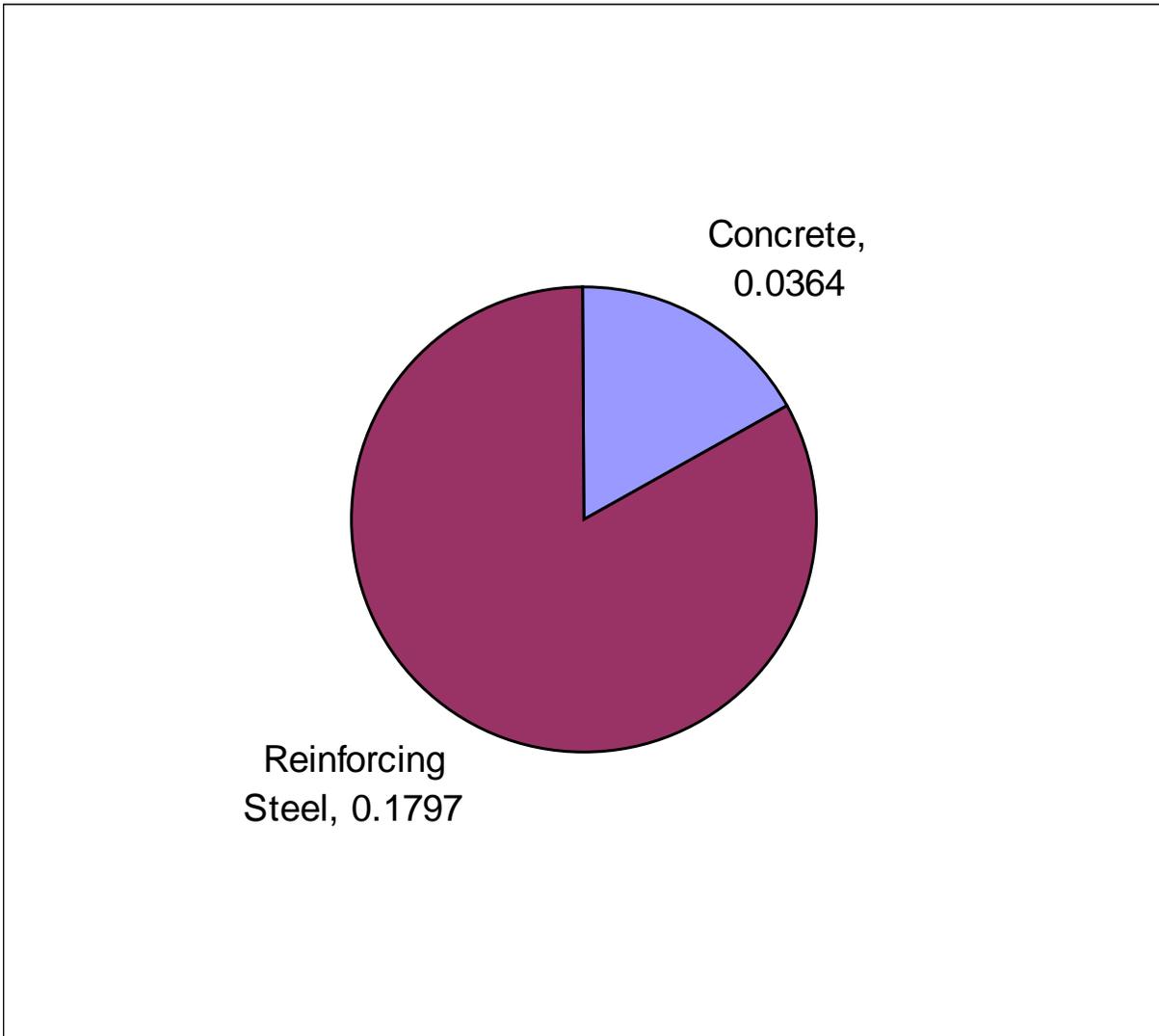
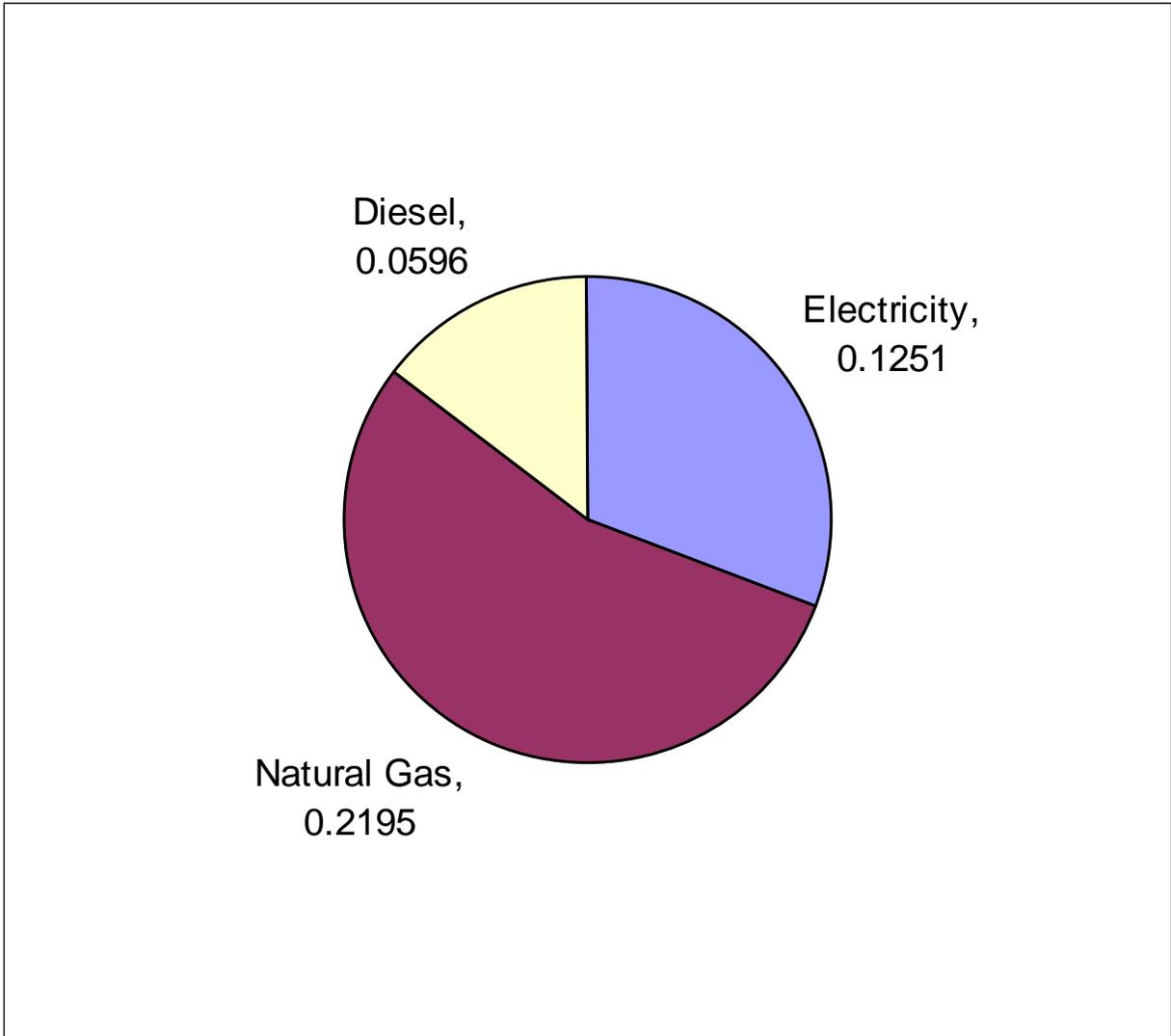


Figure 2. Distribution of Estimated Energy Requirements of the SFR During Decommissioning (GWh/MWe)



References

1. Per F. Peterson, Haihua Zhao, and Robert Petroski. Metal and Concrete Inputs for Several Nuclear Power Plants. UCBTH-05-001, University of California, Berkeley, February 4, 2003.
2. World Nuclear Association. Advanced Nuclear Power Reactors. <http://www.worldnuclear.org/info/inf08.html>, 25 March 2011.
3. Page Athena Institute CEMENT AND STRUCTURAL CONCRETE PRODUCTS: LIFE CYCLE INVENTORY UPDATE #2 - 2005, Ottawa.
4. CEMENT AND STRUCTURAL CONCRETE PRODUCTS: LIFE CYCLE INVENTORY UPDATE, PREPARED BY VENTA, GLASER & ASSOCIATES, OTTAWA, CANADA, OCTOBER 1999.
5. RAW MATERIAL BALANCES, ENERGY PROFILES AND ENVIRONMENTAL UNIT FACTOR ESTIMATES: CEMENT AND STRUCTURAL CONCRETE PRODUCTS, PREPARED BY CANADA CENTRE FOR MINERAL & ENERGY TECHNOLOGY AND RADIAN CANADA INC., OTTAWA, CANADA, OCTOBER 1993.
6. ATHENA INSTITUTE, CRADLE TO GATE LIFE CYCLE ANALYSIS INVENTORY: CANADIAN AND US STEEL PRODUCTION BY TYPE, MARKUS ENGINEERING RESOURCES, MARCH 2002.
7. U.S. DEPARTMENT OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION, DEVELOPMENT AND USE OF PRICE ADJUSTMENT CONTRACT PROVISIONS, DATE: DECEMBER 10, 1980:
[HTTP://WWW.FHWA.DOT.GOV/PROGRAMADMIN/CONTRACTS/TA50803.CFM](http://www.fhwa.dot.gov/programadmin/contracts/TA50803.cfm) – ACCESSED 5/1/11.
8. FINAL ENVIRONMENTAL IMPACT STATEMENT FOR DECOMMISSIONING AND/OR LONG-TERM STEWARDSHIP AT THE WEST VALLEY DEMONSTRATION PROJECT AND WESTERN NEW YORK NUCLEAR SERVICE CENTER – TABLES 4-3, 4-61.