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Background Information for the Presentation to the Swedish National Council for Nuclear Waste's seminar entitled *"The Future of Nuclear Waste – Burden or Benefit?"* in Stockholm, Sweden November 2012

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Executive Summary

Purpose

In May 2012, the US Nuclear Waste Technical Review Board (Board) received an invitation from the Swedish National Council for Nuclear Waste (SNC) to participate in a seminar entitled "The Future of Nuclear Waste—Burden or Benefit?" to be held in Stockholm, Sweden in November 2012. In response to the request by the SNC, the Board performed evaluations of the Swedish nuclear waste program using the Nuclear Waste Assessment System for Technical Evaluation (NUWASTE) (NWTRB, NUWASTE 2011). NUWASTE is a PC-based analytical tool developed by the Board to analyze the various strategies for the storage, disposal, and reprocessing of spent nuclear fuel (SNF) in the U.S. NUWASTE was then applied to the Swedish program and used to determine the reduction in the number of waste packages (both for spent nuclear fuel (SNF) and High level radioactive waste (HLW)) and the mass of fresh uranium required for fuel fabrication should the Swedish government decide to include reprocessing of discharged fuel assemblies in their nuclear strategy. The results from this evaluation were presented at the SNC seminar. This document provides supporting information for the presentation that was made at the seminar by Gene Rowe, technical staff member of the Board.

Evaluation

The evaluations are based on Svensk Kärnbränslehantering AB (SKB) Technical Report TR-10-13, *Spent nuclear fuel for disposal in the KBS-3 repository*, December 2010 (SKB, TR-10-13 2010). This report describes the Swedish nuclear plant characteristics and the projected number of spent fuel assemblies to be discharged from the plants. This information is used as a basis for the evaluations. In addition, the SNC requested further evaluations assuming that all of the presently operating nuclear plants would receive a 10-year life extension. Four datasets were examined, each with eight scenarios, for a total of thirty-two evaluations. The four datasets are defined below.

- Dataset 1
  - Waste stream – existing plants with no life extensions
  - Maximum yearly transportation rate (for disposal and reprocessing) – 300 MT/year
- Dataset 2
  - Waste stream – existing plants with no life extensions
  - Maximum yearly transportation rate (for disposal and reprocessing) – 500 MT/year
- Dataset 3
  - Waste stream – existing plants with 10-year life extensions
  - Maximum yearly transportation rate (for disposal and reprocessing) – 300 MT/year
- Dataset 4
  - Waste stream – existing plants with 10-year life extensions
  - Maximum yearly transportation rate (for disposal and reprocessing) – 500 MT/year

The transportation and disposal assumptions for each dataset are defined in the tables below. The constraints for each scenario are first the yearly reprocessing rate (defined as the maximum metric tons of SNF that can be received at the reprocessing facility, the uranium, plutonium, and fission products and minor actinides separated, and the fission products and minor actinides vitrified in a year) and second the yearly transportation rate (defined as the maximum metric tons of SNF that can be transported to either the repository or reprocessing facility in a year). The yearly disposal rate (defined as the maximum metric tons of SNF that can be received at the repository and disposed in the geologic repository in a year) is equal to the yearly transportation rate minus the yearly reprocessing rate.

Scenarios for Dataset 1 and 3, 300 MT/year Yearly Transportation Rate

Sequence No.	Disposal Start Year	Reprocessing	
		Start Year	Rate (MT/year)
1	2023	2020	200
2		2025	
3		2020	150
4		2025	
5		2020	100
6		2025	
7		2020	50
8		2025	

Scenarios for Dataset 2 and 4, 500 MT/year Yearly Transportation Rate

Sequence No.	Disposal Start Year	Reprocessing	
		Start Year	Rate (MT/year)
1	2023	2020	400
2		2025	
3		2020	300
4		2025	
5		2020	200
6		2025	
7		2020	100
8		2025	

Conclusion

Reprocessing of SNF assemblies and the use of the separated uranium and plutonium for fabrication of new fuel assemblies can reduce the mass of fresh uranium required to fuel the nuclear power plants as well as reduce the total number of SNF and HLW waste packages to be sent for permanent disposal in a geologic repository. The amount of savings depends on the yearly reprocessing rate as well as the date when reprocessing is initiated. This assumes that reprocessing is only used when the separated uranium and plutonium is utilized to replace fresh uranium in the fabrication of fuel for operating reactors. Thus, if new reactors are not built to replace retiring reactors, as assumed in the analysis, delaying the start of reprocessing implies fewer years of remaining reactor lifetime; hence, reduced fuel demands. For the scenarios evaluated, the total number of SNF and HLW waste packages may be reduced by between 3.9% (from 5,504 to 5,287 waste packages) for scenario 1.8 and 42.6% (from 6,447 to 3,703 waste packages) for scenario 4.1, and the percent fresh uranium savings reduced by between 4.7% (from 26,417 MT to 25,183MT) for scenario 1.8 and 40.2% (from 38,624 MT to 23,095 MT) for scenario 4.1, depending on the yearly reprocessing rate and the timing of the start of reprocessing. These results are sensitive to and based upon the past and projected burn-up of fuel. An observation from this evaluation is that the sooner the reprocessing facility begins operation and the larger the yearly reprocessing rate, the greater the potential fresh uranium savings and the greater the potential reduction in the number of waste packages required to dispose of the SNF and HLW.

The relationship between the ratio of assemblies reprocessed to assembly demand and percent fresh uranium savings is approximately linear. If all assemblies discharged in a particular year are reprocessed, and the separated masses of uranium and plutonium are used to fabricate UO_2 and mixed uranium-plutonium oxide (MOX) assemblies, the percent fresh uranium savings is approximately 24% for a SNF burn-up between 45 and 55 GWd/MTU.

Contents

Table of Tables

Table of Figures

1 Introduction

In May 2012, the US Nuclear Waste Technical Review Board (Board) staff met with Dr. Carl-Reinhold Brakenhielm, Vice-Chairman of the Swedish National Council for Nuclear Waste (SNC). During the meeting the Board staff presented evaluations of potential options for dealing with the U.S. spent nuclear fuel (SNF). These evaluations were performed with the Board *Nuclear Waste Assessment System for Technical Evaluation* (NUWASTE) (NWTRB 2011). NUWASTE is a tool developed by the Board that analyzes the various strategies for the storage, disposal, and reprocessing of spent nuclear fuel in the U.S. The system is described in more detail in Section 3.

Dr. Brakenhielm asked if NUWASTE could be used to evaluate nuclear waste options for the Swedish program and if the Board could present the results at an international seminar the SNC was planning for November 2012 in Stockholm, Sweden entitled "The Future of Nuclear Waste—Burden or Benefit?". The Board received a formal invitation in July 2012 to make a presentation at the SNC seminar and the Board agreed to carry out the NUWASTE evaluations of potential impacts of reprocessing the Swedish SNF and present the results.

The Board staff performed evaluations for a total of 32 reprocessing options for the Swedish program. The evaluations calculated the reduction in the number of waste packages and the mass of fresh uranium required for fuel fabrication should the Swedish government decide to include reprocessing of the discharged SNF and the use the separated uranium and plutonium for fabrication into new fuel assemblies in their nuclear strategy. The results of these evaluations were then presented at the seminar. This document provides supporting information for the presentation.

2 Background

2.1 SNF Assembly Isotopic Composition

Fresh uranium consists of two isotopes. The principal component is ^{238}U with a wt% of approximately 99.3%. The remainder is ^{235}U. Only ^{235}U is fissionable with thermal neutrons. Fresh uranium cannot sustain a chain reaction in a light water reactor (LWR) and must be enriched. After the enrichment process, the uranium wt% of the fuel in a new assembly is 95% to 97% ^{238}U and the remainder ^{235}U (i.e. 3% to 5% ^{235}U).

When a ^{235}U atom absorbs a thermal neutron, two outcomes can result. About 84% of the time, a fission event will occur, releasing approximately 200 MeV (Benedict, Pigford, & Levi, 1981) of energy along with several betas, gammas, neutrinos and fission products of lower mass. About 16% of the reactions do not produce fission. Instead, ^{236}U is formed and a gamma radiation is emitted. The formation of ^{236}U is important because ^{236}U can absorb neutrons but does not result in fission in a LWR.

The composition of an irradiated SNF assembly consists of three principal constituents: 1) uranium, 2) plutonium, and 3) fission products and minor actinides. NUWASTE was used to calculate the SNF assembly composition. *Figure 1 - SNF Assembly Composition 50PWR/45BWR GWd/MTU* (gigawatt-days per metric ton of uranium) provides the general isotopic composition of discharged SNF assemblies with burn-up of 50PWR/45BWR GWd/MTU and *Figure 2 - SNF Assembly Composition*

60PWR/55BWR GWd/MTU provide the general isotopic composition of discharged SNF assemblies with burn-up of 60PWR/55BWR GWd/MTU.

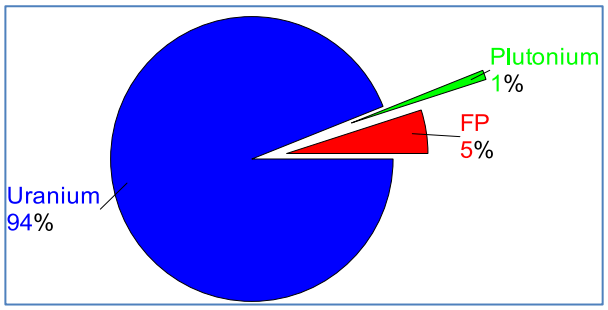


Figure 1 - SNF Assembly Composition 50PWR/45BWR GWd/MTU

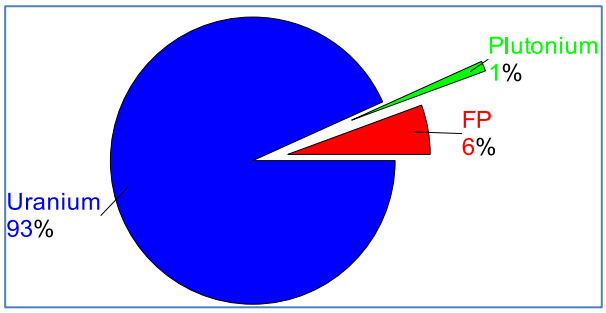


Figure 2 - SNF Assembly Composition 60PWR/55BWR GWd/MTU

2.1.1 Uranium in a SNF Assembly

Uranium is the major element in a SNF assembly, constituting approximately 94% of the total mass. Most of the remaining mass is oxygen that serves to make up the UO_2 ceramic fuel. The uranium consists of approximately 98.5% ^{238}U, 0.8% ^{235}U, with trace amounts of other uranium isotopes. *Figure 3 - Uranium Isotopic Percentages in SNF Assembly 50PWR/45BWR GWd/MTU* provides the uranium isotopic composition of the discharged SNF assemblies with burn-up of 50PWR/45BWR GWd/MTU and *Figure 4 - Uranium Isotopic Percentages in SNF Assembly 60PWR/55BWR GWd/MTU* provides the uranium isotopic composition of the discharged SNF assemblies with burn-up of 60PWR/55BWR GWd/MTU.

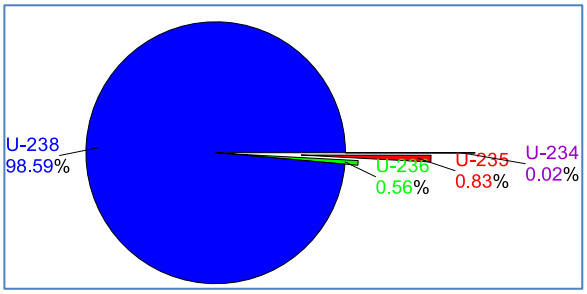


Figure 3 - Uranium Isotopic Percentages in SNF Assembly 50PWR/45BWR GWd/MTU

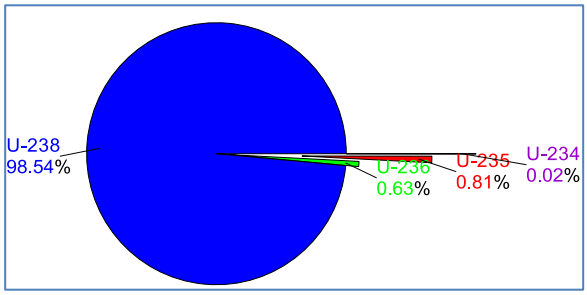


Figure 4 - Uranium Isotopic Percentages in SNF Assembly 60PWR/55BWR GWd/MTU

As discussed above, the buildup of ^{236}U isotope, which is relatively stable, is a neutron absorber but does not result in fission.

2.1.2 Plutonium in a SNF Assembly

Plutonium is first formed mainly by neutron capture in ^{238}U followed by a series of beta decays. There are five major plutonium isotopes of interest: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu. *Figure 5 - Plutonium Isotopic Percentages in SNF Assembly 50PWR/45BWR GWd/MTU* provides the plutonium isotopic composition of the discharged SNF assemblies with burn-up of 50PWR/45BWR GWd/MTU and *Figure 6 - Plutonium Isotopic Percentages in SNF Assembly 60PWR/55BWR GWd/MTU* provides the plutonium isotopic composition of the discharged SNF assemblies with burn-up of 60PWR/55BWR GWd/MTU.

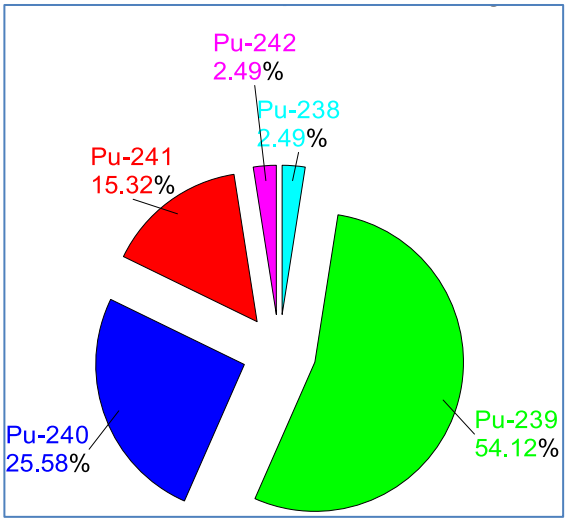


Figure 5 - Plutonium Isotopic Percentages in SNF Assembly 50PWR/45BWR GWd/MTU

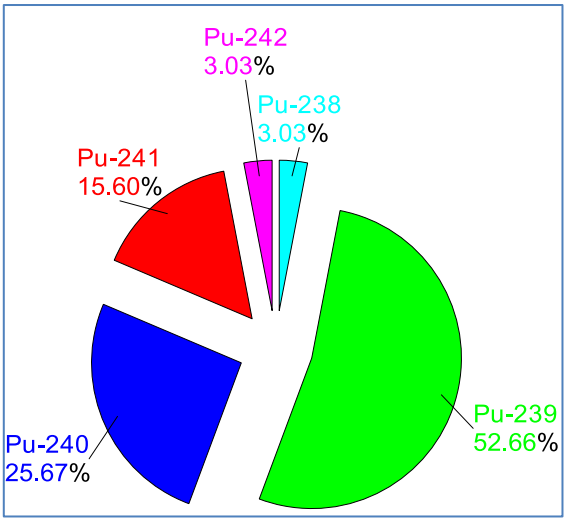


Figure 6 - Plutonium Isotopic Percentages in SNF Assembly 60PWR/55BWR GWd/MTU

^{239}Pu is the most abundant isotope along with ^{240}Pu and ^{241}Pu. Only ^{239}Pu and ^{241}Pu are fissionable and therefore can be effectively used as LWR fuel. From the above calculations, the percent mass in the discharged assembly that is fissionable in a LWR would be the sum of the mass percent of ^{235}U, ^{239}Pu, and ^{241}Pu in the discharged assembly and is calculated as follows:

% Fissionable Mass = %U x Fraction of ^{235}U in U +%Pu x (Fraction of ^{239}Pu in Pu + Fraction of ^{241}Pu in Pu)

For assembly burn-ups of 50PWR/45BWR GWd/MTU:

% Fissionable Mass = 94% x 0.0083 + 1% x (0.5412 + 0.1532) = 1.47%

For assembly burn-ups 60PWR/55BWR GWd/MTU:

% Fissionable Mass = 93% x 0.0081 + 1% x (0.5266 + 0.1560) = 1.44%

Therefore, the percentage of fissionable mass in a SNF assembly is approximately 1.45%.

2.1.3 Fission Products and Minor Actinides in SNF Assembly

When a ^{235}U atom fissions, the atom divides into elements of smaller mass and associated isotopes, or fission products (FPs), and produces approximately 200 MeV (Benedict, Pigford and Levi 1981) of energy. The elements produced from the 235U fission process form a distribution similar to that shown in Figure 7 - Fission Product Yields for 235U (Waterloo n.d.). The two peaks occur at atomic masses of approximately 95 and 140."

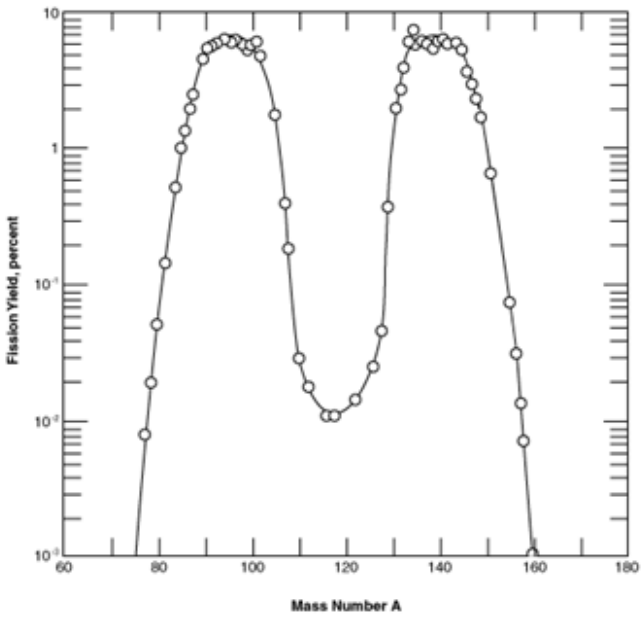


Figure 7 - Fission Product Yields for ^{235}U

Minor actinides are formed through a series of neutron captures and radioactive decays of various heavy elements contained within the fuel assembly. The minor actinides are the 13 elements with atomic numbers from 89 to 103, other than uranium and plutonium. The minor actinides include actinium, thorium, protactinium, neptunium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium. The most important isotopes of the minor actinides in spent nuclear fuel are ^{237}Np, ^{241}Am, ^{243}Am, and ^{242}Cm through ^{248}Cm.

The FP and minor actinides make up approximately 4% to 6% of the total mass, exclusive of oxygen, in a SNF assembly. The percentage of FPs is dependent on the assembly burn-up and increases at a rate of approximately 1% for every 10 GWd/MTU of burn-up. Some of the FP and minor actinides have very long radioactive half-lives and are responsible for the bulk of the radiotoxicity and heat generation in a SNF assembly during the disposal timeframe. FP and minor actinides are not efficiently reused in a LWR since they capture thermal neutrons and are generally not fissionable. Generally if separated from the other isotopes, for an LWR fuel cycle the FPs and minor actinides would be vitrified into glass and transferred to a HLW canister for later disposal in a geologic repository.

2.2 LWR Fuel Cycle

2.2.1 Uranium Mining and Fuel Assembly Fabrication

The LWR fuel cycle begins with uranium ore being mined and milled into U_3O_8 (yellowcake). Tailings, which are the materials left over after separating the uranium, along with the rock material are placed in engineered facilities near the mine (often in mined-out pits). Tailings contain long-lived radioactive materials in low concentrations and toxic materials such as heavy metals. However, the total quantity of radioactive elements is less than in the original ore. It is necessary that these materials be isolated from the environment.

The U_3O_8 is refined in a conversion facility to make UF_6 that has a ^{235}U wt% of approximately 0.7% (the ^{235}U wt% of fresh uranium). UF_6 is a gas at moderate temperatures, and is sent to an enrichment facility that increases the ^{235}U wt% by isotopic separation to between 3.0% and 5.0%. As a result of this process, quantities of uranium, referred to as tails or depleted uranium, are generated. The mass of tails amounts to approximately 90% of the total enrichment facility feed mass and generally has a ^{235}U wt% of between 0.2% and 0.3% specified by economic considerations.

The enriched UF_6 is sent to a fuel fabrication plant and is converted to uranium dioxide (UO_2) that is formed into ceramic fuel pellets by sintering at a high temperature (over 1400°C). The pellets are then encased in metal tubes, usually made of a zirconium alloy (Zircaloy), to form fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies.

The fuel assemblies are sent to a reactor site to be loaded into the nuclear reactor core. Depending on a utility's operating strategy and allowed discharge burn-up, the assemblies can remain in the core for 3 to 5 years. Once removed from the reactor core, the discharged fuel assemblies must be stored underwater at the utility fuel pool for a period of 2 to 5 years to allow the assemblies to cool and the radiation levels to decrease. All reactor sites have spent fuel storage pools. This nuclear fuel cycle is shown in *Figure 8 – Front End of U.S. Open Fuel Cycle*.

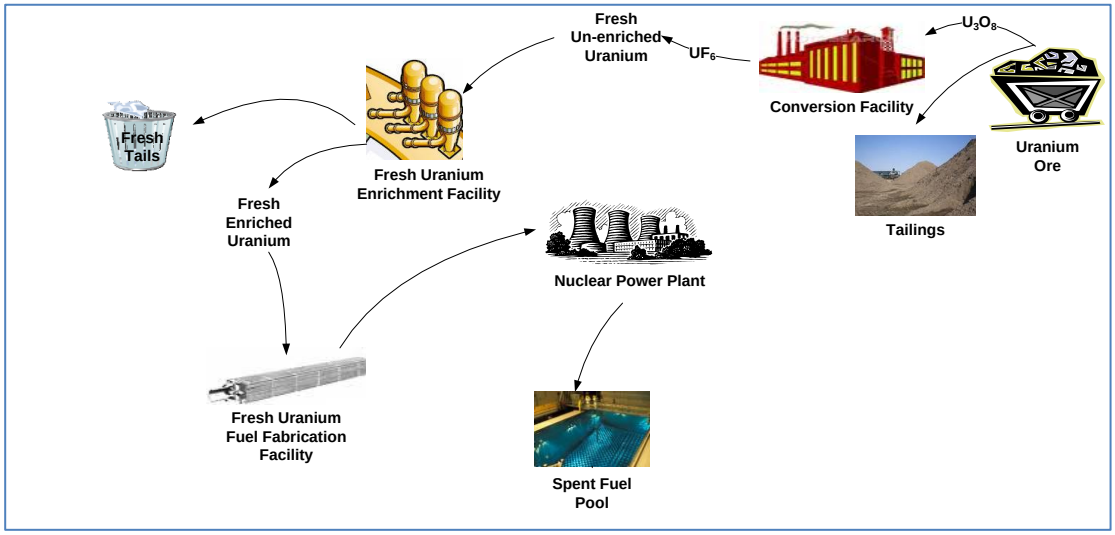


Figure 8 – Front End of U.S. Open Fuel Cycle

2.3 US Spent Fuel Management Options

2.3.1 Long Term Dry- Storage

Dependent on the utility's fuel management philosophy, an average of approximately 20% to 30% of the SNF assemblies are moved to the fuel pool each year. Since fuel storage pools at reactor sites have limited capacity, once the number of assemblies in the fuel pool reached a level that prevents a full core discharge, the assemblies are moved to dry-storage. Moreover, at the end of the operating life of the nuclear facility all of the fuel assemblies must be moved out of the pool and the nuclear facility dismantled and decommissioned. If no permanent storage facilities or repository are available, the SNF assemblies must be placed in dry-storage, either at the reactor site or at an off-site interim storage facility. This process is shown in *Figure 9 – Long Term Dry Storage Process*.

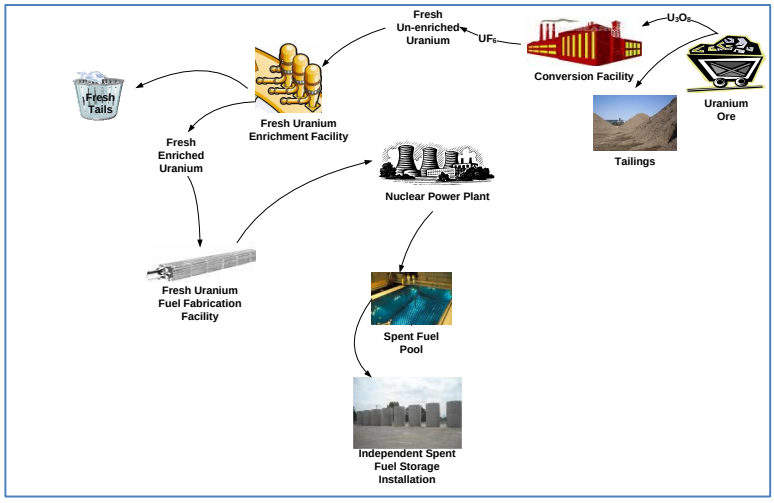


Figure 9 – Long Term Dry Storage Process

2.3.2 Permanent Disposal in a Repository

Should a repository for disposal of the SNF assemblies be delayed, and there is no reprocessing, there are two strategies for handling the SNF assemblies: 1) place SNF assemblies in dry-storage systems as described in Section 2.3.1 and later transport to a geologic repository for permanent disposal, or 2) transport the SNF assemblies to a repository directly from the fuel pool for permanent disposal. If the SNF assemblies are placed in dry-storage, the possibility exists that the assemblies will need to be repackaged into a container that meets the transportation and geologic disposal requirements. The decision as to which path to follow will depend on several factors, such as yearly transportation rate, yearly repository disposal rate, and contractual arrangements between the utility and the DOE. Independent of the path taken, absent reprocessing, all assemblies will eventually require geologic disposal. This is shown in *Figure 10 – Permanent Disposal in Repository Process*.

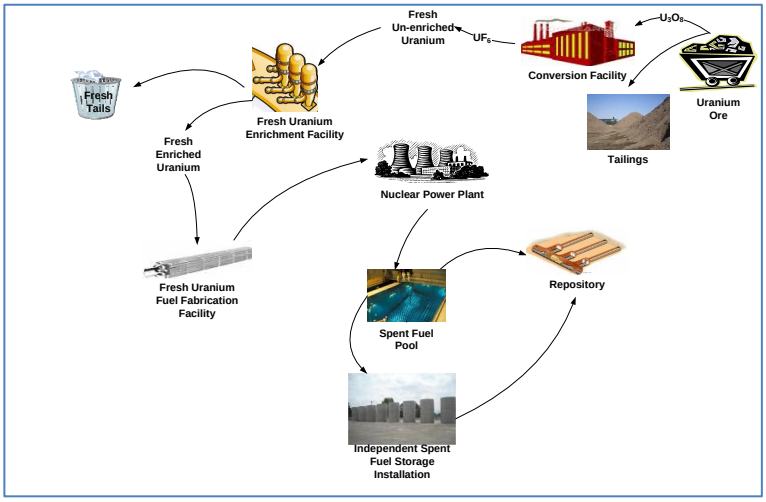


Figure 10 – Permanent Disposal in Repository Process

2.3.3 Repository and Reprocessing Operations

An alternative to disposal of all of the SNF in a repository is to separate the uranium, plutonium and other elements from the SNF assembly, and use the separated plutonium and uranium in the fabrication of new fuel assemblies. This process is commonly referred to as reprocessing. The separated plutonium can be used to produce mixed uranium plutonium oxide (MOX) assemblies. MOX assemblies consist of approximately 6% to 12% plutonium oxide and the remaining uranium oxide (i.e. 88% to 94% uranium oxide). Generally, the uranium oxide comes from the tails produced as a by-product of uranium enriching. A new assembly fabrication facility would be required for the MOX fabrication due to the need for fabrication stages within glove boxes. The separated uranium can be used for fabrication of recycled UO_2 assemblies. The process is similar to that described in Section 2.2.1 for fresh UO_2 assemblies. However, because the recycled uranium contains traces of fission products and other radioactive isotopes it is more contaminated than fresh uranium, and therefore the facilities to process recycled uranium may need to be different from the facilities that process fresh uranium to minimize operator dose and prevent contaminating the fresh fuel fabrication facility. The separated fission products and minor actinides are generally vitrified, transferred into a thin walled canister (referred to as a HLW canister), in preparation for disposal in a repository. *Figure 11 – Reprocessing and Permanent Disposal in Repository Process* shows this process.

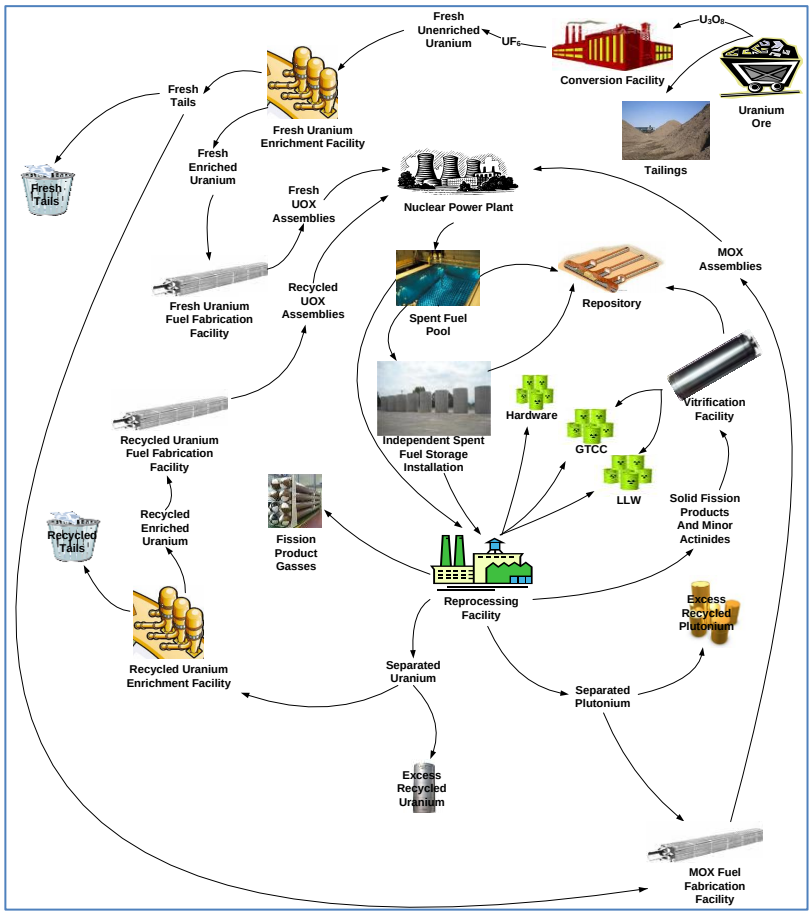


Figure 11 – Reprocessing and Permanent Disposal in Repository Process

The usefulness of the separated uranium and plutonium masses for the fabrication of recycled UO_2 and MOX assemblies depends on the burn-up of the original fuel assemblies. However:

- As the SNF assembly burn-up increases, the weight percent of ^{236}U increases. The presence of ^{236}U in the separated uranium requires that the recycled uranium must be enriched to a higher level than that for fresh uranium in order to compensate for the neutron capture by ^{236}U. In the U.S., there is an administrative limit of 5% (NRC, Fact Sheet on Uranium Enrichment 2012) on the level of ^{235}U enrichment. This limits the burn-up of the original assembly to approximately 55 GWd/MTU in order to achieve the same level of reactivity of the recycled UO_2 assembly as the original UO_2 assembly made using fresh uranium as the enrichment feed stock.

- Due to the nuclear properties of the separated plutonium, and limitations on assembly fabrication processes and materials performance, the percentage of plutonium in a MOX assembly is generally limited to approximately 12.5%. As the discharge burn-up of an assembly increases, the isotopic composition of the plutonium of the SNF changes causing the usefulness of the separated plutonium to decrease due to the decrease in the percentage of fissionable, ^{239}Pu and 241Pu, plutonium isotopes. This behavior, along with the 12.5% loading restriction, limits the burn-up of the original assembly to approximately 55 to 60 GWd/MTU, depending on how long the plutonium has been out of the reactor, in order for the MOX assembly to achieve the same level of reactivity as the original assembly. Because of differences in the nuclear properties of uranium and plutonium, the MOX assemblies will have lower burn-up than the original UO_2 assemblies even though the assemblies have the same reactivity at fabrication.

3 NUWASTE Description

3.1 Objective

NUWASTE is a simulation code developed by the Board to support the evaluation of the US Department of Energy's (DOE) proposed strategies for the storage and disposal of US SNF. A workshop was held in June of 2011 to benchmark NUWASTE against results from AREVA, the Idaho National Laboratory, Massachusetts Institute of Technology, and the UK National Nuclear Laboratory. The results among the five organizations were very consistent and are documented in a report entitled "NWTRB Workshop on Evaluation of Waste Streams Associated with LWR Fuel Cycle Options" (NWTRB 2011, Workshop).

NUWASTE has been designed to allow the analysis of different strategies and to evaluate their impact on:

- number of fresh and recycled UO_2 assemblies fabricated
- number of MOX assemblies fabricated
- repository operation time frame and facility utilization
- reprocessing operation time frame and facility utilization
- number of waste packages generated
- mass of fresh uranium required and percent fresh uranium savings should reprocessing be included in the nuclear fuel cycle
- separative work units (SWUs) required

- mass of fresh and recycled uranium tails
- number and mass of stored SNF assemblies
- number of dry-storage systems
- mass of various secondary waste streams

3.2 Principles

NUWASTE is based on the fundamental principles of physics and chemistry and the mass balance of the number of fuel assemblies and separated masses of 65 isotopes throughout the entire nuclear fuel cycle. NUWASTE only considers today's light water reactor and reprocessing technologies (single recycle) and covers the full life cycle of US nuclear power production, SNF storage, and disposal. NUWASTE is designed to address realistic strategies that DOE may select and implement within the next few decades and includes:

- Extended dry-storage either at the nuclear power plant site or at a centralized interim storage facility.
- Implementation of one or more nuclear waste repositories.
- Reprocessing SNF derived from fresh UO_2 assemblies and subsequently,
  - Re-enrichment of separated uranium for fabrication of recycled UO_2 fuel assemblies.
  - Fabrication of MOX assemblies from the separated plutonium
  - Vitrification of the separated fission product elements and minor actinides.

Since the design, construction and operation of advanced reactor systems will require many decades, the impact of advanced reactor designs was not included in NUWASTE. A simplified flow chart that shows the functions included in NUWASTE is provided in *Figure 12- NUWASTE Assembly/Mass Flow Paths*. The functions include:

12 Facilities

- conversion facility
- fresh uranium enrichment facility
- fresh uranium fabrication facility
- nuclear power plants
- spent fuel pools
- independent spent fuel storage installation
- reprocessing facility
- vitrification facility
- repository
- recycled uranium enrichment facility
- recycled uranium fuel fabrication facility
- MOX fuel fabrication facility

10 Waste Streams

- mass of fresh tails
- mass of recycled tails
- mass of excess separated uranium
- mass of excess separated plutonium
- mass of fission products and minor actinides
- mass of assembly hardware from reprocessing
- mass of GTCC from reprocessing and vitrification
- mass of low level waste (LLW)
- number of HLW canisters
- number of waste packages

In addition, NUWASTE tracks the following parameters, as applicable, at each facility:

- Mass of 65 individual isotopes
- Number of fresh uranium BWR and PWR assemblies
- Number of recycled uranium BWR and PWR assemblies
- Number of MOX assemblies
- Mass and number of assemblies reprocessed
- Mass and number of assemblies disposed of in a geologic repository
- Number of dry-storage systems
- Number of HLW canisters
- Mass of the various secondary waste streams

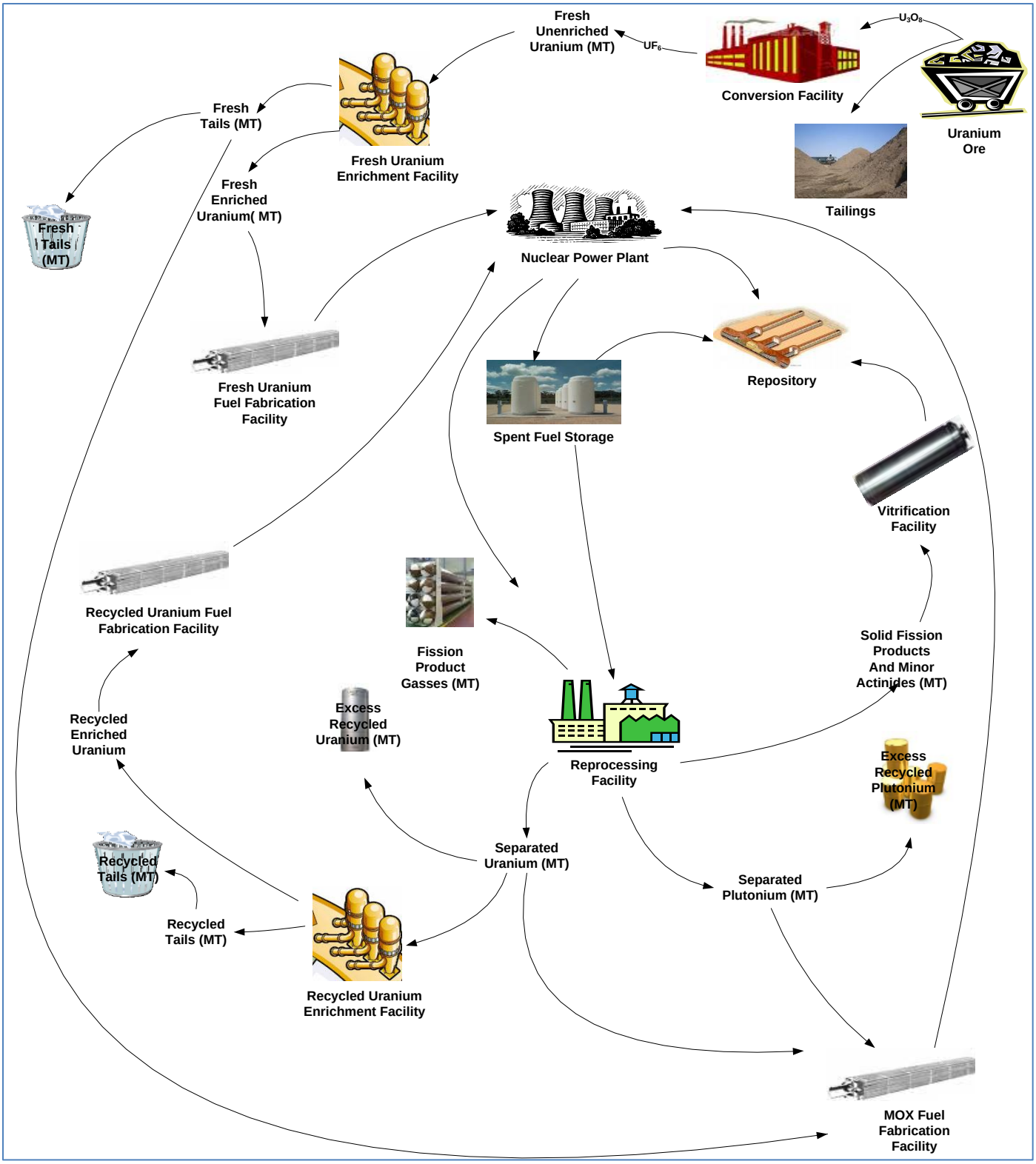


Figure 12- NUWASTE Assembly/Mass Flow Paths

4 Differences between the USA and Swedish Programs

The US assumptions are based on the projected number of discharged assemblies from the US nuclear power plants, a potential repository program with similar receipt and disposal capacities as the Yucca Mountain Program, and various potential reprocessing options. The Swedish assumptions are based on the Svensk Kärnbränslehantering AB (SKB) Technical Report TR-10-13, *Spent nuclear fuel for disposal in the KBS-3 repository*, December, 2010 (SKB, TR-10-13 2010), and various potential reprocessing options. The main differences between the Swedish nuclear waste program and the U.S. Nuclear waste program that affect the analysis completed with NUWASTE are:

- Volume of spent nuclear fuel
    - USA – 611,000 assemblies or 178,000 MTU [assumes 28 new plants that have submitted license application to the NRC (NRC 2012)] and all nuclear power plants receive a 20 year life-time extension beyond 40 years
    - Sweden – 53,950 assemblies or 11,200 MTU (existing plants with no life-time extensions beyond 40 years)
    - Sweden – 62,950 assemblies or 13,100 MTU (existing plants all with 10-year life-time extensions beyond 40 years)
- Storage methodology
    - USA – Dry-storage canisters as necessary based on fuel pool capacity
    - Sweden – Transferred to CLAB (Centralt mellanlager för använt kärnbränsle, Swedish for "Central holding storage for spent nuclear fuel") (SKB, CLAB 2012) after 2 years out-of-reactor
- Disposal thermal limits
    - USA –Maximum 2,300 watts per meter of repository drift length
    - Sweden – Maximum 1,700 watts per waste package
- Waste package capacity
    - USA – 21 PWR or 44 BWR assemblies per waste package
    - Sweden – 4 PWR or 12 BWR assemblies per waste package (fewer than 4 PWR or 12 BWR assemblies may be loaded into a waste package in order to maintain total waste package thermal output to less than 1,700 watts per waste package)

5 NUWASTE applied to the Swedish Nuclear Program

As indicated in Section 4, the Swedish process for handling their SNF is different than in the U.S. Because of this, NUWASTE was modified to better represent the potential Swedish processes. However, several differences are not included in these NUWASTE calculations:

- The waste package capacities were held constant at 4 PWR and 12 BWR assemblies, and a lower number of assemblies per waste package was not considered.
- The criterion for disposal is that the assemblies have to be out-of-reactor for at least 38 years rather than being limited to 1,700 watts per waste package. This is consistent with SKB Technical Report TR-10-13 (SKB, TR-10-13 2010) Section 5.1.
- k_{eff} of repository emplaced waste packages was not verified to be less than 0.95 (NUWASTE does not evaluate criticality).
- No MOX assemblies are included in the initial inventory; all assemblies are either BWR or PWR UO_2.

6 Swedish Waste Stream Input Data to NUWASTE

Table 1 – Swedish Plant Operation Assumption provides the Swedish plant operating assumptions and is based on Table 2-1 of SKB Technical Report TR-10-13 (SKB, TR-10-13 2010).

Table 1 – Swedish Plant Operation Assumption

Existing Plant Data as of December 2010

Site	Unit	Type	MWt	MWe	BOL	EOL	Core Size	Pool Size	Site Pool Status at the End of 2010 Assem	Site Pool Status at the End of 2010 MTU	CLAB Status at the End of 2010 Casks	CLAB Status at the End of 2010 Assem	CLAB Status at the End of 2010 MTU
CLAB-BWR					Sweden						0	23,243	4,067.5
	1	BWR	0	0	2010	2100	0	0	0	0.0	Operating		
CLAB-PWR					Sweden						0	2,426	1,125.7
	1	PWR	0	0	2010	2100	0	0	0	0.0	Operating		
Forsmark					Sweden						0	0	0.0
	1	BWR	3,255	1,087	1980	2030	676	1,392	552	96.0	Operating		
	2	BWR	3,255	1,087	1981	2031	676	1,268	473	83.0	Operating		
	3	BWR	3,775	1,338	1985	2035	700	1,040	166	29.0	Operating		
Oskarshamn					Sweden						0	0	0.0
	1	BWR	1,375	492	1972	2032	448	984	300	52.0	Operating		
	2	BWR	2,300	845	1974	2034	444	1,067	550	95.0	Operating		
	3	BWR	3,900	1,450	1985	2045	700	1,055	200	34.0	Operating		
Ringhals					Sweden						0	0	0.0
	1	BWR	2,540	854	1976	2025	648	1,426	283	49.0	Operating		
	2	PWR	2,652	866	1975	2025	157	432	114	20.0	Operating		
	3	PWR	3,144	1,048	1981	2031	157	381	195	24.0	Operating		
	4	PWR	3,300	1,110	1983	2033	157	364	165	29.0	Operating		

The two BWR Barseback units that have been shut down are not included in Table 1 since all of these assemblies have been transferred to the CLAB facility.

The average assembly burn-up used in NUWASTE is based on the SKB Technical Report TR-10-13, Tables C-3 and C-4, that provide the number of assemblies per canister type and the number of each canister type, and Technical Report TR-10-13 Section 6.2.4 that provides the average burn-up for each

canister type. *Table 2 - Swedish BWR, Number of Canisters, Assemblies, and Burn-up* and *Table 3 – Swedish PWR, Number of Canisters, Assemblies, and Burn-up* below provide a summary of this data.

Table 2 - Swedish BWR, Number of Canisters, Assemblies, and Burn-up

	BWR-I	BWR-II	BWR-III					Total
Assemblies/Canister	12	12	11	10	9	8	7	
# Canisters (Note 1)	2,475	321	10	173	738	732	2	4,451
# Assemblies	29,700	3,852	110	1,730	6,642	5,856	14	47,904
Ave. Burn-up (GWd/MTU) (Note 2)	40.4	47.8	47.8	47.8	47.8	47.8	47.8	43.2
# Assemblies x Ave. Burn-up	1,199,880	184,125	5,258	82,694	317,487	279,916	669	2,069,362

Notes: 1. Technical Report TR-10-13 (SKB, TR-10-13 2010), Table C-3

2. Technical Report TR-10-13, (SKB, TR-10-13 2010) Section 6.2.4

The average burn-up of the BWR assemblies for each canister design, *i*, was calculated as follows:

$$Average\ BWR\ Burnup = \frac{\sum_{i=1}^{i=7} \#\ Assemblies_i\ x\ Ave.Burnup_{\ i}}{\sum_{i=1}^{i=7} \#\ Assemblies_i} = \frac{2{,}069{,}362}{47{,}904} = 43.2\ GWd/MTU$$

Equation 1

Table 3 – Swedish PWR, Number of Canisters, Assemblies, and Burn-up

	PWR-I	PWR-II	PWR-III		Total
Assemblies/Canister	4	4	3	2	
# Canisters (Note 1)	1,057	38	555	2	1,650
# Assemblies	4,228	152	1,665	4	6,049
Ave. Burn-up (GWd/MTU) (Note 2)	44.8	57	57	57	48.4
# Assemblies x Ave. Burn-up	189,414.4	8,664.0	94,905.0	228.0	292,983.4

Notes: 1. Technical Report TR-10-13, *Spent nuclear fuel for disposal in the KBS-3 repository*, December 2010, Table C-4

2. Technical Report TR-10-13, *Spent nuclear fuel for disposal in the KBS-3 repository*, December 2010, Section 6.2.4

The average burn-up of the PWR assemblies was calculated as follows:

$$Average\ PWR\ Burnup = \frac{\sum_{i=1}^{i=7} \#\ Assemblies_i\ x\ Ave.Burnup_{\ i}}{\sum_{i=1}^{i=7} \#\ Assemblies_i} = \frac{292{,}983.4}{6{,}049} = 48.4\ GWd/MTU$$

Equation 2

The number of assemblies discharged from each nuclear power plant per year was calculated as follows:

$$Assemblies\ Discharged\ per\ Year = \frac{MW_t \times Capacity\ Factor \times 365\ days/year}{MWd/MTU \times MTU/Assembly}$$

Equation 3

NUWASTE calculates the number of assemblies that will be in fuel pool storage at the utility sites and in the CLAB (SKB, CLAB 2012) facility each year using the plant parameters defined in *Table 1 – Swedish Plant Operation Assumption*, the average burn-ups calculated in Equations 1 and 2, and for cases with no life extensions and all plants with 10-year life extensions using Equation 3. *Figure 13 - Number of Assemblies, No Life Extension* and Appendix A provides the results with no nuclear plant life extensions. *Figure 14 - Number of Assemblies, 10-Year Life Extension* and Appendix B provides the results with all plants receiving a 10-year life extension. These results yield the total number of assemblies in storage and do not include any disposal or reprocessing. The calculation assumes that assemblies that are 2 years out-of-reactor are sent to the CLAB facility.

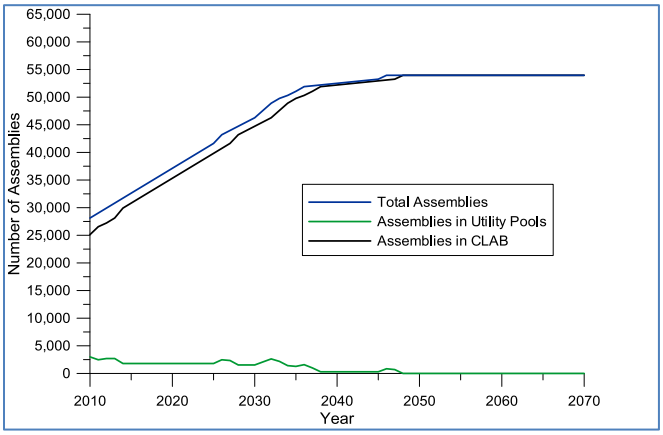


Figure 13 - Number of Assemblies, No Life Extension

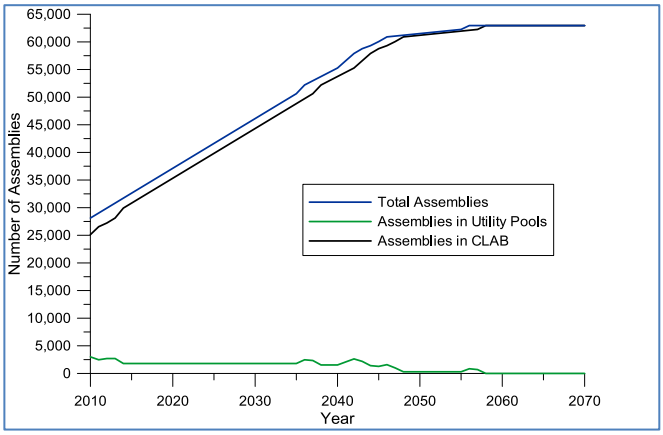


Figure 14 - Number of Assemblies, 10-Year Life Extension

A comparison of the SNF inventory calculated by NUWASTE for the no life extension waste stream and Table 5-2 of Technical Report TR-10-13 is provided in *Table 4 - Comparison of Technical Report TR-10-13 and NUWASTE Assumptions*. The excellent agreement confirms that NUWASTE is consistent with SKB in the prediction of the number of SNF assemblies.

Table 4 - Comparison of Technical Report TR-10-13 and NUWASTE Assumptions

	Number of Assemblies		Average Burn-up (GWd/MTU)	
	TR-10-13 Data	Board Assumptions	TR-10-13 Data	Board Assumptions
BWR	47,904	47,904	No data	43.2
PWR	6,049	6,049	No data	48.4
Total	53,953	53,953	N/A	N/A

7 Swedish Scenarios Evaluated

A total of 32 scenarios were evaluated; four datasets each with eight scenarios. The independent variables used for these scenarios are presented in Section 6.1. As discussed in Section 3.2, a number of output parameters can be evaluated. However, for this analysis, only the impacts on the mass of fresh uranium required and the number of waste packages are evaluated. The results are discussed in Section 8.

7.1 Independent Variables

The independent variables in *Table 5 - Parameters Held Constant for Evaluations of Swedish Scenarios* were held constant for all 32 scenarios analyzed.

Table 5 - Parameters Held Constant for Evaluations of Swedish Scenarios

Parameter	BWR	PWR
Assembly burn-up	43,200 MWd/MTU	48,400 MWd/MTU
Initial uranium mass	0.175 MTU/assembly	0.464 MTU/assembly
Average capacity factor	80%	80%
Assemblies per disposal canister	12	4

The four datasets are defined below.

- Dataset 1
  - Waste stream – existing plants with no life extensions beyond 40 years
  - Maximum yearly transportation rate (for disposal and reprocessing) – 300 MT/year
- Dataset 2
  - Waste stream – existing plants with no life extensions beyond 40 years
  - Maximum yearly transportation rate (for disposal and reprocessing) – 500 MT/year
- Dataset 3
  - Waste stream – existing plants with 10-year life extensions beyond 40 years
  - Maximum yearly transportation rate (for disposal and reprocessing) – 300 MT/year
- Dataset 4
  - Waste stream – existing plants with 10-year life extensions beyond 40 years
  - Maximum yearly transportation rate (for disposal and reprocessing) – 500 MT/year

The reprocessing and disposal assumptions for each dataset are defined in *Table 6 - Scenarios for Dataset 1 and 3, 300 MT/year Yearly Transportation Rate* and *Table 7 - Scenarios for Dataset 2 and 4, 500 MT/year Yearly Transportation Rate*. The constraints for each scenario are first the yearly reprocessing rate (defined as the maximum metric tons of SNF that can be received at the reprocessing facility, the uranium, plutonium, and fission products and minor actinides separated, and the fission products and minor actinides vitrified in a year) and second the yearly transportation rate (defined as the maximum metric tons of SNF that can be transported to either the repository or reprocessing facility in a year). The yearly disposal rate (defined as the maximum metric tons of SNF that can be

received at the repository and disposed in the geologic repository in a year) is equal to the yearly transportation rate minus the yearly reprocessing rate.

Table 6 - Scenarios for Dataset 1 and 3, 300 MT/year Yearly Transportation Rate

Sequence No.	Disposal Start Year	Reprocessing	
		Start Year	Rate (MT/year)
1	2023	2020	200
2		2025	
3		2020	150
4		2025	
5		2020	100
6		2025	
7		2020	50
8		2025	

Table 7 - Scenarios for Dataset 2 and 4, 500 MT/year Yearly Transportation Rate

Sequence No.	Disposal Start Year	Reprocessing	
		Start Year	Rate (MT/year)
1	2023	2020	400
2		2025	
3		2020	300
4		2025	
5		2020	200
6		2025	
7		2020	100
8		2025	

For each of the scenarios in Tables 6 and 7, the separated uranium is re-enriched and used for UO_2 assembly fabrication, and the separated plutonium is combined with the tails from fresh uranium enrichment to fabricate MOX assemblies. The assemblies that are fabricated from recycled uranium or plutonium are not reprocessed a second time.

7.2 Dependent Variables Calculated

7.2.1 Percent Waste Package Savings

Each evaluation assumes that each BWR waste package contains twelve assemblies, each PWR waste package contains four assemblies, and each HLW waste package contains one HLW canister. Each HLW canister contains 0.25 metric tons of fission products and minor actinides as elements. Based on these assumptions, the percent waste package savings is calculated as:

$$\%\ Waste\ Package\ Savings = \frac{DC_B - DC_R}{DC_B} \times 100\%$$

Where:
DC_B = Baseline number of waste packages (no reprocessing)
DC_R = Number of waste packages with reprocessing

7.2.2 Percent Fresh Uranium Savings

The fresh uranium savings is a result of using the separated uranium and plutonium for the fabrication of fuel assemblies rather than using enriched fresh uranium to fabricate the fuel assemblies. The percent fresh uranium savings is calculated as:

$$\%\ Natural\ Uranium\ Savings = \frac{U_B - U_R}{U_B} \times 100\%$$

Where:
U_B = Baseline mass of fresh uranium required (no reprocessing)
U_R = Mass of fresh uranium required with reprocessing

8 Results

8.1 Effect of Yearly Reprocessing Rate and Facility Startup Year

Reprocessing of the SNF assemblies, and the use of the separated uranium and plutonium for fabrication of fuel assemblies, does reduce the mass of fresh uranium required to fuel the nuclear power plants as well as reduce the number of waste packages needed to permanently dispose of the SNF in a geologic repository. The reduction depends on the yearly reprocessing rate as well as when reprocessing is initiated. *Table 8 - Summary of Results* provides the results for the 32 evaluations (four datasets each with 8 scenarios). The data in Table 8 shows that the number of waste packages can be reduced between 3.9% (from 5,504 to 5,287 waste packages) for scenario 1.8 and 42.6% (from 6,447 to 3,703 waste packages) for scenario 4.1, and the percent fresh uranium savings can be between 4.7% (from 26,417 MT to 25,183 MT) for scenario 1.8 and 40.2% (from 38,624 MT to 23,095 MT) for scenario 4.1, depending on yearly reprocessing rate and timing of the reprocessing facility. These results are shown graphically in *Figure 15 – Percent Waste Package Savings for Each Scenario* and *Figure 16 – Percent Fresh Uranium Savings for Each Scenario*. Note reprocessing only occurs when there are reactors operating that can utilize the recycle uranium and plutonium. Given that reactors will be shutting down at their end-of-lifetime, delays in starting or limited yearly reprocessing rate will imply less material recycled at the time of reactor shutdown.

Table 8 - Summary of Results

Scenario	Waste Stream	Disposal Start	Total Processing Capacity (MT/year)	Reprocessing Start	Reprocessing Capacity (MT/year)	Waste Package Savings (%)	Natural Uranium Savings (%)
1.1	No Life Extension	2023	300	2020	200	18.39	21.50
1.2		2023		2025	200	12.25	14.51
1.3		2023		2020	150	14.06	16.59
1.4		2023		2025	150	9.47	11.28
1.5		2023		2020	100	9.77	11.67
1.6		2023		2025	100	6.72	8.01
1.7		2023		2020	50	5.47	6.51
1.8		2023		2025	50	3.94	4.67
2.1		2023	500	2020	400	34.27	37.39
2.2		2023		2025	400	22.97	23.41
2.3		2023		2020	300	25.96	30.67
2.4		2023		2025	300	17.30	20.33
2.5		2023		2020	200	17.75	21.17
2.6		2023		2025	200	12.25	14.51
2.7		2023		2020	100	9.77	11.67
2.8		2023		2025	100	6.72	8.01
3.1	10 Year Life Extension	2023	300	2020	200	25.30	24.29
3.2		2023		2025	200	20.44	19.27
3.3		2023		2020	150	19.37	18.58
3.4		2023		2025	150	15.59	14.85
3.5		2023		2020	100	13.56	12.94
3.6		2023		2025	100	10.94	10.47
3.7		2023		2020	50	7.26	6.97
3.8		2023		2025	50	5.96	5.72
4.1		2023	500	2020	400	42.56	40.21
4.2		2023		2025	400	39.06	35.14
4.3		2023		2020	300	34.47	33.08
4.4		2023		2025	300	29.41	28.31
4.5		2023		2020	200	24.96	24.51
4.6		2023		2025	200	19.96	19.62
4.7		2023		2020	100	13.56	12.94
4.8		2023		2025	100	10.94	10.47

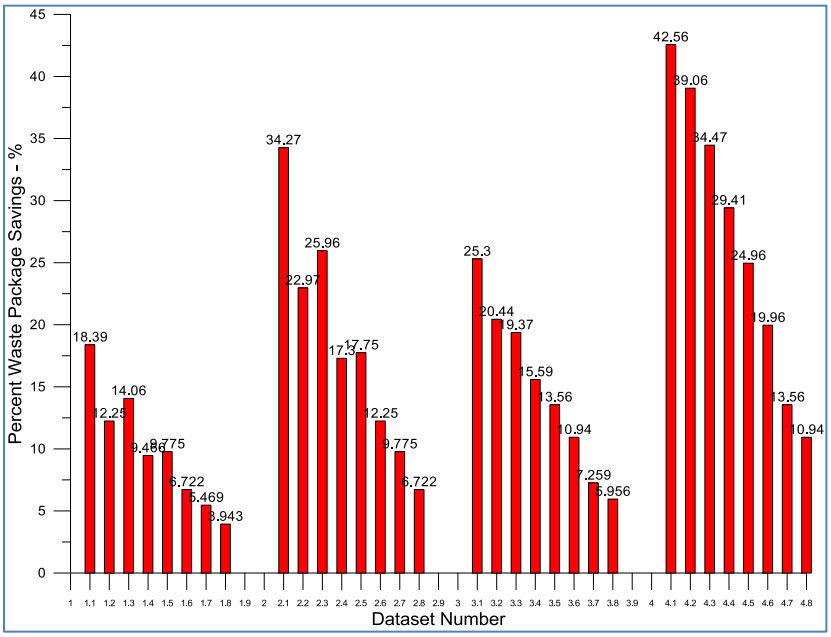


Figure 15 – Percent Waste Package Savings for Each Scenario

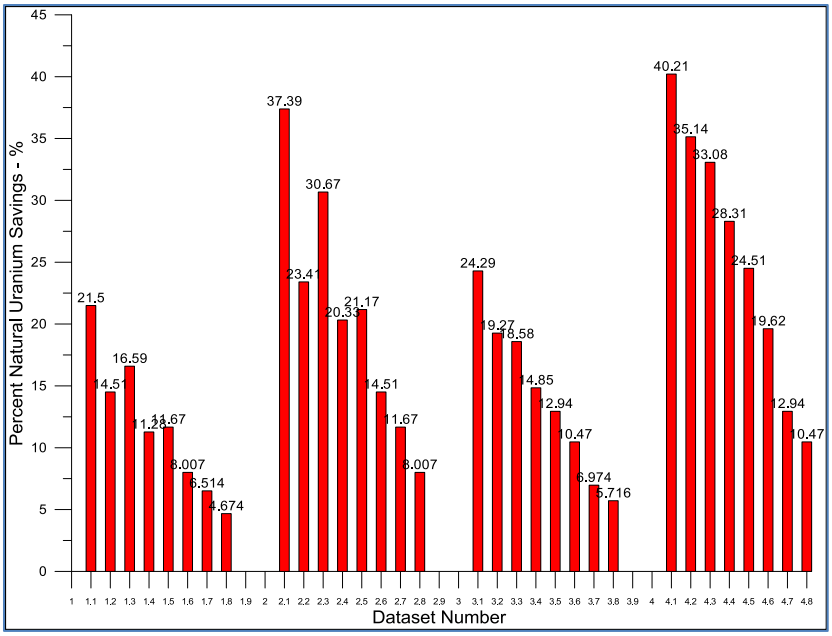


Figure 16 – Percent Fresh Uranium Savings for Each Scenario

From Figures 15 and 16 it can be seen that:

- Comparing the eight bars in each of the four groups in each graph shows the same trend, in that decreasing yearly reprocessing rate or delaying the start of operation of the reprocessing facility will decrease both the percent waste package savings as well as the percent fresh uranium savings. This is due to the fact that fewer SNF assemblies are reprocessed.

- Comparing the first group of eight bars to the second group of eight bars (the 40 year plant operating period scenarios) and the third group of eight bars to the fourth group of eight bars (the 50 year plant operating period scenarios), in each graph show that increasing the yearly transportation rate from 300 MT/year to 500 MT/year allows more assemblies to be transported to the reprocessing facility and thus more assemblies reprocessed and the greater the percent waste package and fresh uranium savings.

- Comparing the first group of eight bars to the third group of eight bars (300 MT/year yearly transportation rate) and the eight bars in the second group of eight bars to the forth group of eight bars (500 MT/year transportation rate), in each graph shows that increasing the plant operating period from 40 years to 50 years increases the number of assemblies available for reprocessing and thus increases both the percent waste package savings as well as the percent fresh uranium savings.

Appendix C contains the material balance diagrams for each scenario. From these material balance diagrams it can be seen that recycling uranium and plutonium would require the provision of services from several additional facilities (reprocessing facility, vitrification facility, MOX assembly fabrication facility, recycled uranium enrichment facility, and recycled uranium assembly fabrication facility) and would also result in the generation of several new waste streams (HLW canisters, hardware from assembly disassembly, GTCC, and LLW). The masses of each of the new waste streams are provided for each scenario in Appendix C.

Appendix D contains the annual processing results for each scenario. The Appendix D has plots of the accumulative MTU discharged, MTU in storage, MTU reprocessed and MTU disposed each year. These graphs provide an indication of the reprocessing and disposal facility utilization. For periods after a facility starts operation, if the yearly processing rate is less than the design rate of the facility, this would indicate that the facility is not utilized to its maximum rate and that delaying the facility startup year may be possible. The possible reasons for low facility utilization are:

Reprocessing Facility
There are two major reasons that the reprocessing facility could have a low utilization;

1) there are no assemblies available that meet the criteria for reprocessing, and
2) there is insufficient future demand for replacement fuel assemblies.

Disposal Facility - There are no assemblies available that meet the criteria for disposal.

8.2 Effect of Ratio of Assemblies Reprocessed to Assembly Demand

The discussion in Section 8.1 evaluates the fresh uranium savings for various reprocessing facility capacities and operating periods. Another approach for evaluating the fresh uranium savings is to evaluate the savings on a single cycle basis, i.e. all assemblies that are discharge are reprocessed and all of the separated uranium and plutonium are used to fabricate fuel assemblies. The following discussion evaluates the fresh uranium savings based on the ratio of assemblies reprocessed to assembly demand, which differs from the self-generated fuel cycle in that not all assemblies discharged are reprocessed.

To assess the impact of assemblies reprocessed versus assembly demand, a single BWR nuclear plant with a core size of 560 assemblies and a discharge of 20% of the assemblies each year was evaluated; see *Figure 17 – Single Cycle BWR SNF Discharge*.

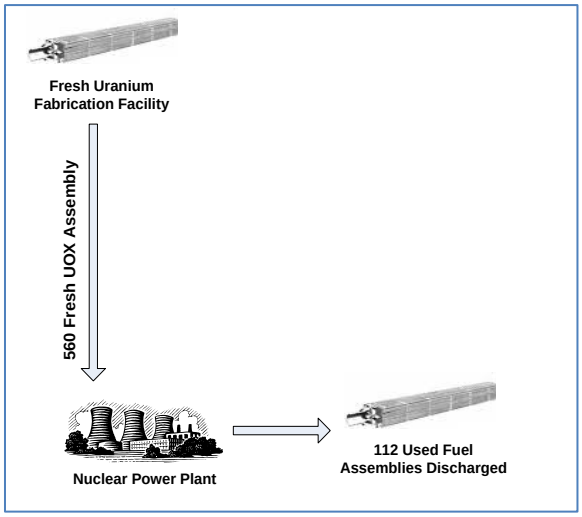


Figure 17 – Single Cycle BWR SNF Discharge

Reprocessing the entire 112 discharge assemblies would result in approximately:

Uranium Yield

112 assemblies x 0.175 MTU/assembly x 94% U = 18.4 MTU

Plutonium Yield

112 assemblies x 0.175 MTU/assembly x 1% Pu = 0.196 MT Pu

HLW Yield

112 assemblies x 0.175 MTU/assembly x 5% FP = 0.98 MT FP

These results are shown in *Figure 18 – Masses from Separation.*

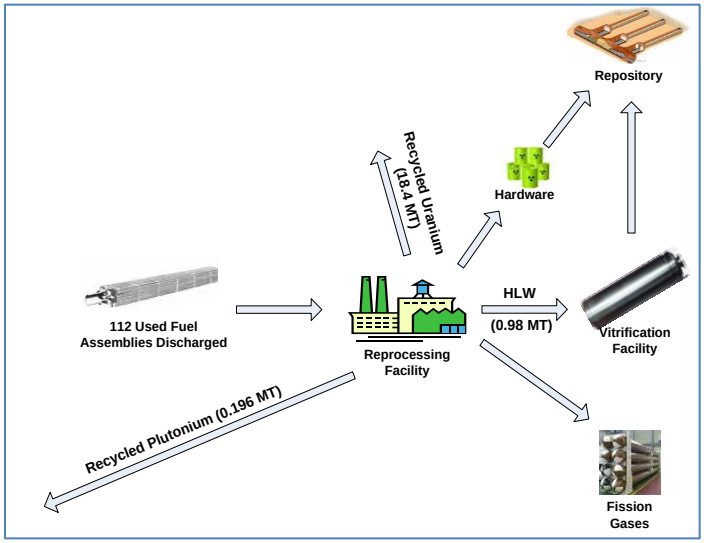


Figure 18 – Masses from Separation

Assuming that all of the separated uranium and plutonium are used to fabricate recycled UO_2 and MOX assemblies, the number of assemblies fabricated can be determined as follows:

Number of Recycled UO_2 Assemblies Fabricated

The mass of feed required and the mass of tails generated as a result of enrichment can be calculated using a simple mass balance approach. Two equations can be written, one for the total masses of uranium, as shown in Equation 4, and one for the ^{235}U masses, as shown in Equation 5.

$$F = E + T$$

Equation 4

$$fF = eE + tT$$

Equation 5

where:

F = Mass of uranium feed (18.4 MT)

E = Mass of enriched uranium

T = Mass of tails

f = Weight % of U^{235} in feed mass (0.8%)

e = Weight % of U^{235} in enriched mass (4.0%)

t = Weight % of U^{235} in tails mass (0.2)

Equations 4 and 5 can be combined to eliminate T, which results in Equation 6:

$$E = F \times \frac{(f - t)}{(e - t)}$$

Equation 6

Using Equation 6, the mass of enriched uranium and the number of recycled uranium assemblies fabricated from recycled uranium are calculated as follows:

Mass of Enriched Uranium

$$E = 18.4 \times \frac{(0.8 - 0.2)}{(4.0 - 0.2)} = 2.9MT$$

Number of Recycled Uranium Assemblies Fabricated

$$\frac{2.9\ (MT\ enriched\ Uranium)}{0.175\ (MT\ per\ Assembly)} \cong 16\ Assemblies$$

Number of MOX Assemblies Fabricated

Assume that MOX assemblies contain 10% plutonium, which is consistent with a discharge burn-up of approximately 45 to 55 GWd/MTU for fresh UO_2 assemblies, depending on the age of the separated plutonium, and each MOX assembly's heavy metal mass is 0.175 MT:

$$\frac{0.196\ MT\ of\ separated\ plutonium}{0.175\ (MT\ per\ Assembly)\ x\ 0.1(fraction\ plutonium\ per\ assembly)} \cong 11\ Assemblies$$

In order to refuel the reactor with the necessary 112 new fuel assemblies, 85 fresh uranium fuel assemblies would be required, see *Figure 19 – Assemblies Needed to Refuel Reactor*.

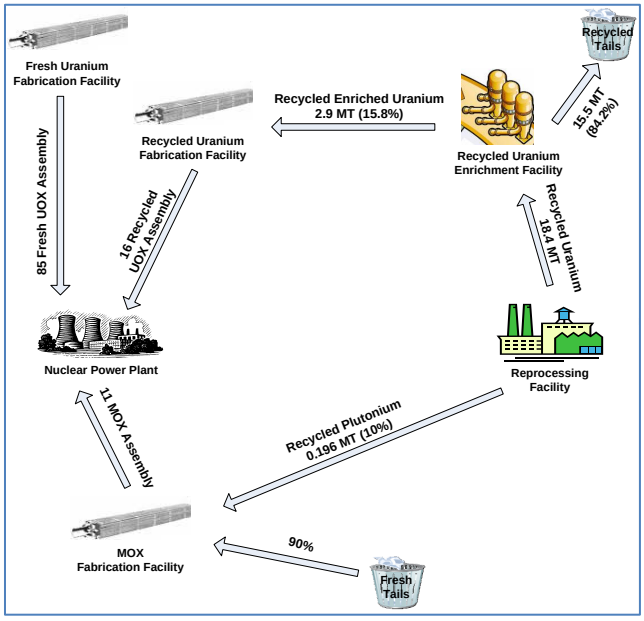


Figure 19 – Assemblies Needed to Refuel Reactor

Thus the scenario depicted in Figure 19 would result in fresh uranium savings of:

- 112 assemblies needed to refuel reactor
  - 16 recycled UO_2 assemblies
  - 11 MOX assemblies
  - 85 fresh UO_2 assemblies
- Reduction in fresh uranium required
  - (16+11)/112 = 24.1%

Therefore, if all discharged assemblies are reprocessed and the separated uranium and plutonium masses are used to fabricate new fuel assemblies, the fresh uranium savings would be approximately 24%.

The scenario discussed above assumes that all discharged assemblies are reprocessed and the number of assemblies required to fuel the nuclear power plants is equal to the number of assemblies discharged, i.e., the ratio of assemblies reprocessed to assembly demand is equal to one. *Table 9 – Percent Fresh Uranium Savings for Various Ratios of Assemblies Reprocessed to Assembly Demand* shows the percent fresh uranium savings for various values for the ratio of assemblies reprocessed to assembly demand. These results are also shown graphically in *Figure 20 – Graph of % Fresh Uranium Savings verses Ratio of Assemblies Reprocessed to Assembly Demand*.

Table 9 – Percent Fresh Uranium Savings for Various Ratios of Assemblies Reprocessed to Assembly Demand

A	B	C	D	E	F	G	H	I	J	K	L	M
Core Size	% Discharded Each Cycle	Number Discharged Assemblies (A x B)	% Discharged Assemblies Recycled	Number Recycled Assemblies (C x D)	MT per Assembly	MT Recycled Uranium (94%) (E x F x 0.94)	MT Enriched Recycled Uranium (15.8%) (G x 0.158)	Number Recycled UO2 Assemblies (H/F)	MT Recycled Plutonium (1%) (E x F x 0.01)	Number Recycled MOX Assemblies (J/(F x 0.1)	Ratio of Assemblies Reprocessed to Assembly Demand (E/C)	% Natural Uranium Savings (I + K)/C
560	20%	112	150%	168	0.175	27.6	4.4	24	0.29	16	1.50	35.7%
560	20%	112	140%	156	0.175	25.7	4.1	23	0.27	15	1.39	33.9%
560	20%	112	130%	145	0.175	23.9	3.8	21	0.25	14	1.29	31.3%
560	20%	112	120%	134	0.175	22.0	3.5	19	0.23	13	1.20	28.6%
560	20%	112	110%	123	0.175	20.2	3.2	18	0.22	12	1.10	26.8%
560	**20%**	**112**	**100%**	**112**	**0.175**	**18.4**	**2.9**	**16**	**0.20**	**11**	**1.00**	**24.1%**
560	20%	112	90%	100	0.175	16.5	2.6	14	0.18	10	0.89	21.4%
560	20%	112	80%	89	0.175	14.6	2.3	13	0.16	8	0.79	18.8%
560	20%	112	70%	78	0.175	12.8	2.0	11	0.14	7	0.70	16.1%
560	20%	112	60%	67	0.175	11.0	1.7	9	0.12	6	0.60	13.4%
560	20%	112	50%	56	0.175	9.2	1.5	8	0.10	5	0.50	11.6%
560	20%	112	40%	44	0.175	7.2	1.1	6	0.08	4	0.39	8.9%
560	20%	112	30%	33	0.175	5.4	0.9	4	0.06	3	0.29	6.3%
560	20%	112	20%	22	0.175	3.6	0.6	3	0.04	2	0.20	4.5%
560	20%	112	10%	11	0.175	1.8	0.3	1	0.02	1	0.10	1.8%

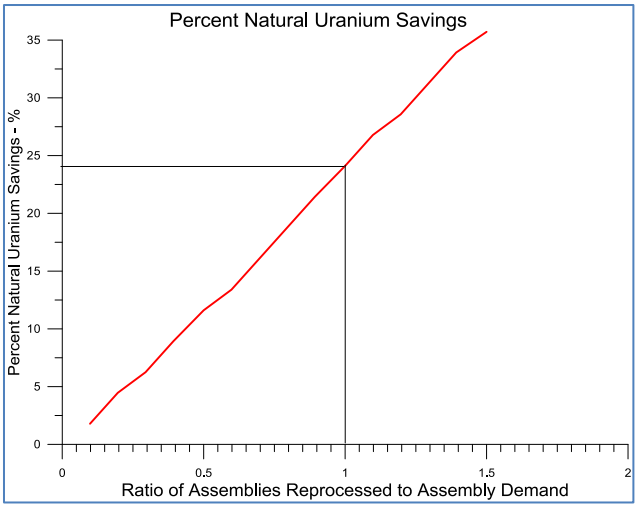


Figure 20 – Graph of % Fresh Uranium Savings verses Ratio of Assemblies Reprocessed to Assembly Demand

Figure 20 – Graph of % Fresh Uranium Savings verses Ratio of Assemblies Reprocessed to Assembly Demand reveals that the relation between the ratio of assemblies reprocessed to assembly demand and percent fresh uranium savings is approximately linear. The "wiggles" in the line are due to the small inventory of assemblies used in the calculation and that only complete assemblies were included in the results.

9 Conclusions

Reprocessing of SNF assemblies and the use of the separated uranium and plutonium for fabrication of new fuel assemblies can reduce the mass of fresh uranium required to fuel the nuclear power plants as well as reduce the total number of SNF and HLW waste packages to be sent for permanent disposal in a geologic repository. The amount of savings depends on the yearly reprocessing rate as well as the date when reprocessing is initiated. This assumes that reprocessing is only used when the separated uranium and plutonium is utilized to replace fresh uranium in the fabrication of fuel for operating reactors. Thus, if new reactors are not built to replace retiring reactors, as assumed in the analysis, delaying the start of reprocessing implies fewer years of remaining reactor lifetime; hence, reduced fuel demands. For the scenarios evaluated, the total number of SNF and HLW waste packages may be reduced by between 3.9% (from 5,504 to 5,287 waste packages) for scenario 1.8 and 42.6% (from 6,447 to 3,703 waste packages) for scenario 4.1, and the percent fresh uranium savings reduced by between 4.7% (from 26,417 MT to 25,183MT) for scenario 1.8 and 40.2% (from 38,624 MT to 23,095 MT) for scenario 4.1, depending on the yearly reprocessing rate and the timing of the start of reprocessing. These results are sensitive to and based upon the past and projected burn-up of fuel. An observation from this evaluation is that the sooner the reprocessing facility begins operation and the larger the yearly reprocessing rate, the greater the potential fresh uranium savings and the greater the potential reduction in the number of waste packages required to dispose of the SNF and HLW.

The relationship between the ratio of assemblies reprocessed to assembly demand and percent fresh uranium savings is approximately linear. If all assemblies discharged in a particular year are reprocessed, and the separated masses of uranium and plutonium are used to fabricate UO_2 and mixed uranium-plutonium oxide (MOX) assemblies, the percent fresh uranium savings is approximately 24% for a SNF burn-up between 45 and 55 GWd/MTU.

10 Acronyms

Board	U.S. Nuclear Waste Technical Review Board
BRC	Blue Ribbon Commission on America's Nuclear Future
BWR	boiling water reactor
CLAB	Centralt mellanlager för använt kärnbränsle, Swedish for "Central holding storage for spent nuclear fuel"
DOE	U.S. Department of Energy
FP	fission products
GTCC	greater than class "C" waste
GWd/MTU	gigawatt days per metric ton uranium
HLW	high-level radioactive waste
LLW	low-level radioactive waste
LWR	light water reactor
MOX	mixed uranium-oxide plutonium-oxide fuel assemblies
MT	metric tons
MTU	metric tons uranium
NRC	Nuclear Regulatory Commission
NUWASTE	Nuclear Waste Assessment System for Technical Evaluation
PWR	pressurized water reactor
SKB	Svensk Kärnbränslehantering AB
SNC	Swedish National Council for Nuclear Waste
SNF	spent nuclear fuel
SWUs	separative work units
UO_2	uranium oxide fuel

11 Glossary of Terms

% fresh uranium savings	The difference between the mass of fresh uranium required with no recycling of uranium and plutonium and the mass of fresh uranium required with recycling implemented divided by the mass of fresh uranium required with no reprocessing times 100.
% waste package savings	The difference between the number of waste packages required with no reprocessing and the number of waste packages required with reprocessing implemented divided by number of waste packages required with no reprocessing times 100.
actinide	The actinide element series encompasses the 15 metallic chemical elements with atomic numbers from 89 to 103, actinium through lawrencium
burn-up	A measure of reactor fuel consumption expressed as the percentage of the fuel atoms that have undergone fission, or the amount of energy produced per unit weight of fuel
CLAB	(Centralt mellanlager för använt kärnbränsle, Swedish for "Central holding storage for spent nuclear fuel"). An independent wet pool facility for the temporary storage of SNF.
dataset	A set of scenarios grouped together to allow evaluation of independent variables for a set of dependent variables.
dependent variables	Parameters that are calculated based on a set of independent variables. An example is the mass of fresh uranium required for assembly fabrication.
dry-storage canisters	Thin walled vessels that contain the SNF assemblies and provide containment for the radioactive material but limited radiation shielding.
facility utilization	A fraction defined as the number of days the facility is actually used divided by the number of days the facility is available
fission products	Fission products are the result of fission by a heavy atomic nucleus. Typically a heavy nucleus such uranium or plutonium undergoes fission by absorbing a neutron and dividing into nuclei of lower mass. The fission process also yields additional neutrons, gammas, betas, and neutrinos. Recoverable energy is released in the form of kinetic energy of the fission fragments and neutrons, and gammas.

geologic repository	A facility for disposing of radioactive waste in excavated geologic media, including surface and subsurface areas of operation and the adjacent part of the fresh setting.
high-level waste European definition	Radioactive waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred meters or more below the surface is the generally recognized option for disposal of HLW.
high-level waste U.S. definition	Highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in concentrations above levels specified in regulations. Any other highly radioactive material that the NRC, consistent with existing law, determines requires permanent isolation by disposal in a geologic repository.
HLW canister	A thin-walled canister that contains the vitrified HLW.
independent variables	Input parameters that define a particular scenario. An example is the yearly reprocessing rate.
keff	The average number of neutrons in a generation compared to the average number of neutrons in the previous generation. For keff = 1, the neutron population remains constant and the system is critical. For keff > 1, the neutron population is increasing and the system is supercritical. For keff < 1, the neutron population is decreasing and the system is subcritical
MT	Metric tons
MTU	Metric tons uranium
secondary waste stream	Waste streams that are generated in the process of disposal or reprocessing of SNF and the operation of other facilities.
sintering	A method used to transform a material from a powder to a ceramic object of a desired shape. In most sintering processes, the powdered material is held in a mold and then heated to a temperature below the melting point.

spent nuclear fuel	Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by chemical reprocessing.
tails	The uranium byproduct resulting from the enrichment of uranium. Tails typically have a ^{235}U wt% of between 0.2% and 0.3%.
vitrification	The processing of fission products and minor actinides that are separated during reprocessing into a glass, usually, achieved by rapidly cooling the mixture through the glass transition.
wt%	In chemistry, the mass fraction wt% is the fraction of one substance with mass m_i to the mass of the total mixture m_{tot} defined as: $$\text{wt\%} = \frac{m_i}{m_{tot}}$$
waste package	The waste form (either SNF or HLW), any filler, shielding, packing, and other absorbent materials used for permanent disposal in a geologic repository.
waste stream	The number and characteristics (type, initial enrichment, and burn-up) of SNF assemblies discharged from the nuclear power plants each year.

12 Bibliography

Benedict, Manson, Thomas H Pigford, and Hans Wolfgang Levi. *Nuclear Chemical Engineering.* Vol. Second Edition. McGraw-Hill, Inc., 1981.

NRC. Combined License Applications for New Reactors. March 29, 2012. http://www.nrc.gov/reactors/new-reactors/col.html.

—. *Fact Sheet on Uranium Enrichment.* March 29, 2012. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/enrichment.html.

NWTRB. *Nuclear Waste Assessment System for Technical Evaluation: Status and Initial Results.* 2011. http://www.nwtrb.gov/reports/nuwaste.pdf.

—. *NWTRB Workshop on Evaluations of Waste Streams Associated with LWR Fuel Cycle Options.* 2011. http://www.nwtrb.gov/meetings/2011/june/workshop.pdf.

SKB. "CLAB." *Swedish Radiation Safety Authority.* December 12, 2012. http://www.stralsakerhetsmyndigheten.se/In-English/About-the-Swedish-Radiation-Safety-Authority1/Our-work-to-enhance-safety-/Facilities-in-Sweden/Clab-/.

—. *Spent nuclear fuel for disposal in the KBS-3 repository, TR-10-13.* 2010. http://www.skb.se/upload/publications/pdf/TR-10-13.pdf.

Waterloo, University of. *Nuclear Fission Yield.* n.d. http://www.science.uwaterloo.ca/~cchieh/cact/nuctek/fissionyield.html.

Appendix A – Swedish waste stream with no life extensions

Table 10 - BWR Assembly Inventory, 40 Year Plant Operating Period

BWR Assembly Inventory by Year

Year	New Assemblies	Total Site Wet Assemblies	Total Site Wet MTU	Total CLAB Assemblies	Total CLAB MTU	Total Assemblies	Total MTU
2010	0	2,524	441.7	23,243	4,067.5	25,767	4,509.2
2011	746	2,042	357.3	24,471	4,282.4	26,513	4,639.8
2012	746	2,238	391.6	25,021	4,378.7	27,259	4,770.3
2013	746	2,238	391.6	25,767	4,509.2	28,005	4,900.9
2014	746	1,492	261.1	27,259	4,770.3	28,751	5,031.4
2015	746	1,492	261.1	28,005	4,900.9	29,497	5,162.0
2016	746	1,492	261.1	28,751	5,031.4	30,243	5,292.5
2017	746	1,492	261.1	29,497	5,162.0	30,989	5,423.1
2018	746	1,492	261.1	30,243	5,292.5	31,735	5,553.6
2019	746	1,492	261.1	30,989	5,423.1	32,481	5,684.2
2020	746	1,492	261.1	31,735	5,553.6	33,227	5,814.7
2021	746	1,492	261.1	32,481	5,684.2	33,973	5,945.3
2022	746	1,492	261.1	33,227	5,814.7	34,719	6,075.8
2023	746	1,492	261.1	33,973	5,945.3	35,465	6,206.4
2024	746	1,492	261.1	34,719	6,075.8	36,211	6,336.9
2025	746	1,492	261.1	35,465	6,206.4	36,957	6,467.5
2026	1,301	2,047	358.2	36,211	6,336.9	38,258	6,695.2
2027	653	1,954	342.0	36,957	6,467.5	38,911	6,809.4
2028	653	1,306	228.6	38,258	6,695.2	39,564	6,923.7
2029	653	1,306	228.6	38,911	6,809.4	40,217	7,038.0
2030	653	1,306	228.6	39,564	6,923.7	40,870	7,152.3
2031	1,210	1,863	326.0	40,217	7,038.0	42,080	7,364.0
2032	1,091	2,301	402.7	40,870	7,152.3	43,171	7,554.9
2033	813	1,904	333.2	42,080	7,364.0	43,984	7,697.2
2034	365	1,178	206.2	43,171	7,554.9	44,349	7,761.1
2035	725	1,090	190.8	43,984	7,697.2	45,074	7,887.9
2036	843	1,568	274.4	44,349	7,761.1	45,917	8,035.5
2037	143	986	172.6	45,074	7,887.9	46,060	8,060.5
2038	143	286	50.1	45,917	8,035.5	46,203	8,085.5
2039	143	286	50.1	46,060	8,060.5	46,346	8,110.5
2040	143	286	50.1	46,203	8,085.5	46,489	8,135.6
2041	143	286	50.1	46,346	8,110.5	46,632	8,160.6
2042	143	286	50.1	46,489	8,135.6	46,775	8,185.6
2043	143	286	50.1	46,632	8,160.6	46,918	8,210.6
2044	143	286	50.1	46,775	8,185.6	47,061	8,235.7
2045	143	286	50.1	46,918	8,210.6	47,204	8,260.7
2046	700	843	147.5	47,061	8,235.7	47,904	8,383.2
2047	0	700	122.5	47,204	8,260.7	47,904	8,383.2
2048	0	0	0.0	47,904	8,383.2	47,904	8,383.2
2049	0	0	0.0	47,904	8,383.2	47,904	8,383.2
2050	0	0	0.0	47,904	8,383.2	47,904	8,383.2

Table 11 - PWR Assembly Inventory, 40 Year Plant Operating Period

PWR Assembly Inventory by Year

Year	New Assemblies	Total Site Wet Assemblies	Total Site Wet MTU	Total CLAB Assemblies	Total CLAB MTU	Total Assemblies	Total MTU
2010	0	474	219.9	2,426	1,125.7	2,900	1,345.6
2011	134	402	186.5	2,632	1,221.2	3,034	1,407.8
2012	134	402	186.5	2,766	1,283.4	3,168	1,470.0
2013	134	402	186.5	2,900	1,345.6	3,302	1,532.1
2014	134	268	124.4	3,168	1,470.0	3,436	1,594.3
2015	134	268	124.4	3,302	1,532.1	3,570	1,656.5
2016	134	268	124.4	3,436	1,594.3	3,704	1,718.7
2017	134	268	124.4	3,570	1,656.5	3,838	1,780.8
2018	134	268	124.4	3,704	1,718.7	3,972	1,843.0
2019	134	268	124.4	3,838	1,780.8	4,106	1,905.2
2020	134	268	124.4	3,972	1,843.0	4,240	1,967.4
2021	134	268	124.4	4,106	1,905.2	4,374	2,029.5
2022	134	268	124.4	4,240	1,967.4	4,508	2,091.7
2023	134	268	124.4	4,374	2,029.5	4,642	2,153.9
2024	134	268	124.4	4,508	2,091.7	4,776	2,216.1
2025	134	268	124.4	4,642	2,153.9	4,910	2,278.2
2026	252	386	179.1	4,776	2,216.1	5,162	2,395.2
2027	95	347	161.0	4,910	2,278.2	5,257	2,439.2
2028	95	190	88.2	5,162	2,395.2	5,352	2,483.3
2029	95	190	88.2	5,257	2,439.2	5,447	2,527.4
2030	95	190	88.2	5,352	2,483.3	5,542	2,571.5
2031	95	190	88.2	5,447	2,527.4	5,637	2,615.6
2032	206	301	139.7	5,542	2,571.5	5,843	2,711.1
2033	49	255	118.3	5,637	2,615.6	5,892	2,733.9
2034	157	206	95.6	5,843	2,711.1	6,049	2,806.7
2035	0	157	72.9	5,892	2,733.9	6,049	2,806.7
2036	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2037	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2038	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2039	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2040	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2041	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2042	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2043	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2044	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2045	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2046	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2047	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2048	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2049	0	0	0.0	6,049	2,806.7	6,049	2,806.7
2050	0	0	0.0	6,049	2,806.7	6,049	2,806.7

Appendix B – Swedish waste stream with 10-year life extension

Table 12 - BWR Assembly Inventory, 50 Year Plant Operating Period

BWR Assembly Inventory by Year

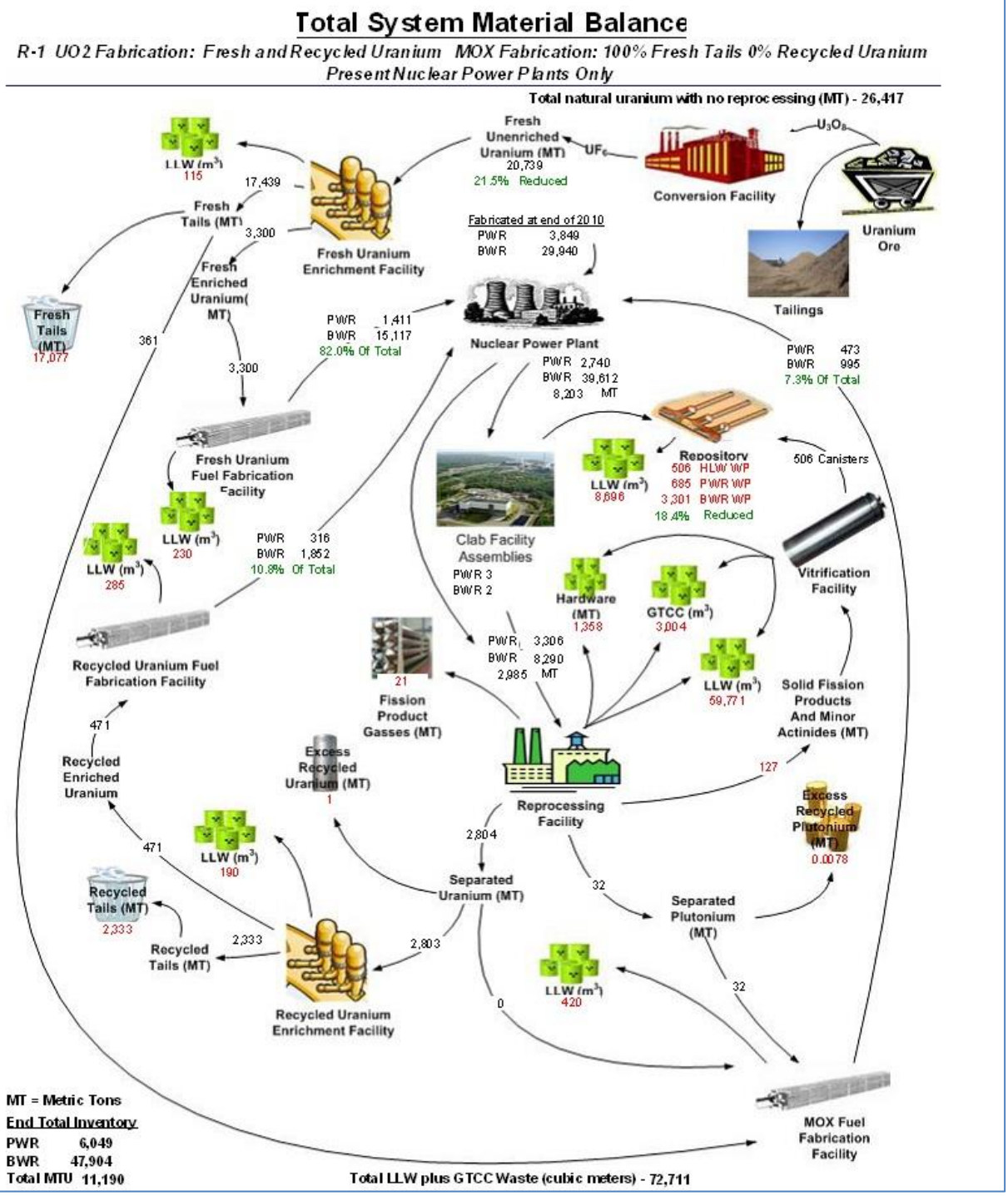
Year	New Assemblies	Total Site Wet Assemblies	Total Site Wet MTU	Total CLAB Assemblies	Total CLAB MTU	Total Assemblies	Total MTU
2010	0	2,524	441.7	22,340	3,909.5	24,864	4,351.2
2011	784	2,128	372.4	23,520	4,116.0	25,648	4,488.4
2012	784	2,352	411.6	24,080	4,214.0	26,432	4,625.6
2013	784	2,352	411.6	24,864	4,351.2	27,216	4,762.8
2014	784	1,568	274.4	26,432	4,625.6	28,000	4,900.0
2015	784	1,568	274.4	27,216	4,762.8	28,784	5,037.2
2016	784	1,568	274.4	28,000	4,900.0	29,568	5,174.4
2017	784	1,568	274.4	28,784	5,037.2	30,352	5,311.6
2018	784	1,568	274.4	29,568	5,174.4	31,136	5,448.8
2019	784	1,568	274.4	30,352	5,311.6	31,920	5,586.0
2020	784	1,568	274.4	31,136	5,448.8	32,704	5,723.2
2021	784	1,568	274.4	31,920	5,586.0	33,488	5,860.4
2022	784	1,568	274.4	32,704	5,723.2	34,272	5,997.6
2023	784	1,568	274.4	33,488	5,860.4	35,056	6,134.8
2024	784	1,568	274.4	34,272	5,997.6	35,840	6,272.0
2025	784	1,568	274.4	35,056	6,134.8	36,624	6,409.2
2026	784	1,568	274.4	35,840	6,272.0	37,408	6,546.4
2027	784	1,568	274.4	36,624	6,409.2	38,192	6,683.6
2028	784	1,568	274.4	37,408	6,546.4	38,976	6,820.8
2029	784	1,568	274.4	38,192	6,683.6	39,760	6,958.0
2030	784	1,568	274.4	38,976	6,820.8	40,544	7,095.2
2031	784	1,568	274.4	39,760	6,958.0	41,328	7,232.4
2032	784	1,568	274.4	40,544	7,095.2	42,112	7,369.6
2033	784	1,568	274.4	41,328	7,232.4	42,896	7,506.8
2034	784	1,568	274.4	42,112	7,369.6	43,680	7,644.0
2035	784	1,568	274.4	42,896	7,506.8	44,464	7,781.2
2036	1,334	2,118	370.7	43,680	7,644.0	45,798	8,014.6
2037	686	2,020	353.5	44,464	7,781.2	46,484	8,134.7
2038	686	1,372	240.1	45,798	8,014.6	47,170	8,254.8
2039	686	1,372	240.1	46,484	8,134.7	47,856	8,374.8
2040	686	1,372	240.1	47,170	8,254.8	48,542	8,494.8
2041	1,237	1,923	336.5	47,856	8,374.8	49,779	8,711.3
2042	1,112	2,349	411.1	48,542	8,494.8	50,891	8,905.9
2043	831	1,943	340.0	49,779	8,711.3	51,722	9,051.3
2044	383	1,214	212.5	50,891	8,905.9	52,105	9,118.4
2045	739	1,122	196.4	51,722	9,051.3	52,844	9,247.7
2046	850	1,589	278.1	52,105	9,118.4	53,694	9,396.5
2047	150	1,000	175.0	52,844	9,247.7	53,844	9,422.7
2048	150	300	52.5	53,694	9,396.5	53,994	9,449.0
2049	150	300	52.5	53,844	9,422.7	54,144	9,475.2
2050	150	300	52.5	53,994	9,449.0	54,294	9,501.5
2051	150	300	52.5	54,144	9,475.2	54,444	9,527.7
2052	150	300	52.5	54,294	9,501.5	54,594	9,554.0
2053	150	300	52.5	54,444	9,527.7	54,744	9,580.2
2054	150	300	52.5	54,594	9,554.0	54,894	9,606.5
2055	150	300	52.5	54,744	9,580.2	55,044	9,632.7
2056	700	850	148.8	54,894	9,606.5	55,744	9,755.2
2057	0	700	122.5	55,044	9,632.7	55,744	9,755.2
2058	0	0	0.0	55,744	9,755.2	55,744	9,755.2
2059	0	0	0.0	55,744	9,755.2	55,744	9,755.2
2060	0	0	0.0	55,744	9,755.2	55,744	9,755.2

Table 13 - PWR Assembly Inventory, 50 Year Plant Operating Period

PWR Assembly Inventory by Year

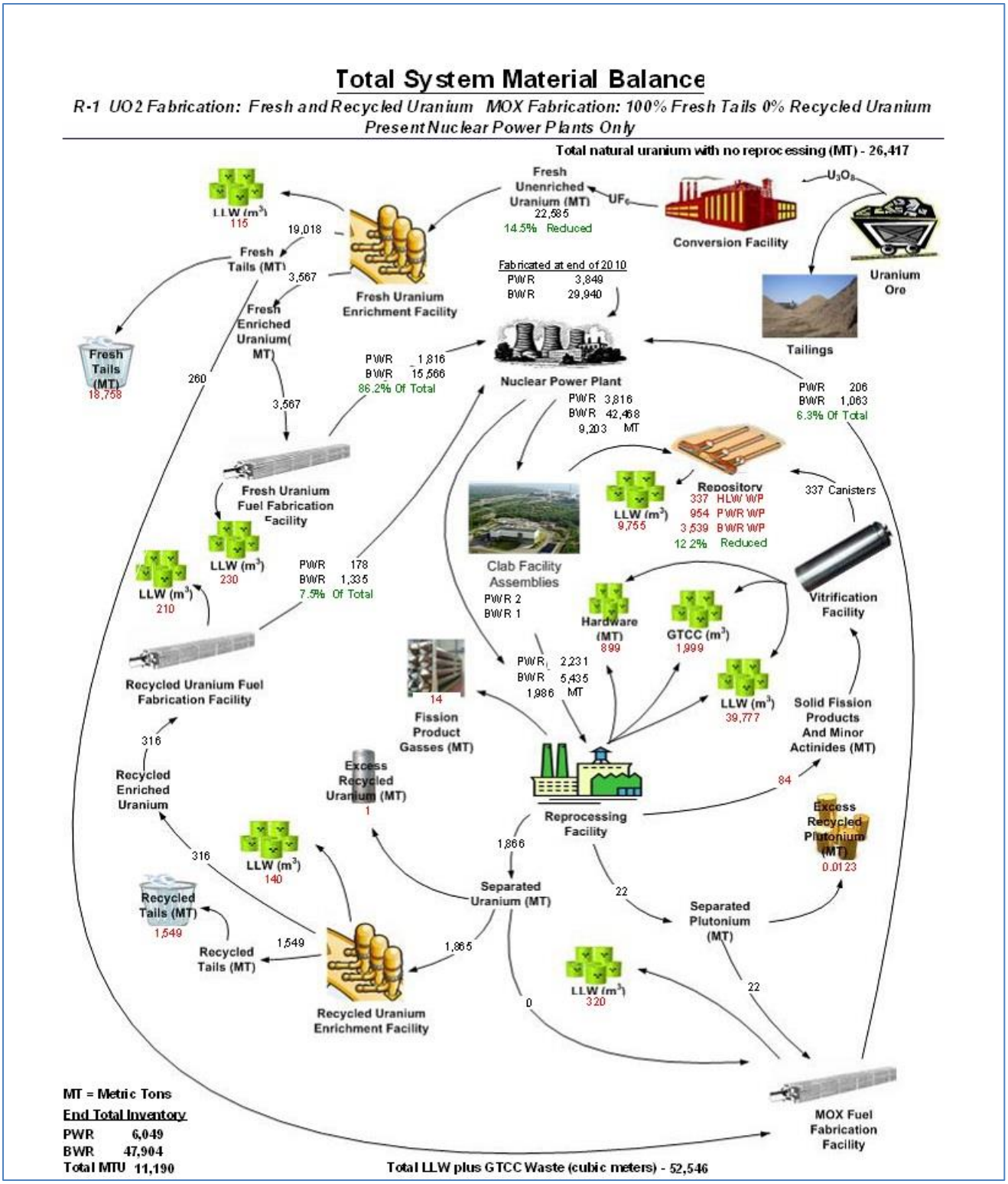
Year	New Assemblies	Total Site Wet Assemblies	Total Site Wet MTU	Total CLAB Assemblies	Total CLAB MTU	Total Assemblies	Total MTU
2010	0	474	219.9	2,788	1,293.6	3,262	1,513.6
2011	116	348	161.5	3,030	1,405.9	3,378	1,567.4
2012	116	348	161.5	3,146	1,459.7	3,494	1,621.2
2013	116	348	161.5	3,262	1,513.6	3,610	1,675.0
2014	116	232	107.7	3,494	1,621.2	3,726	1,728.9
2015	116	232	107.7	3,610	1,675.0	3,842	1,782.7
2016	116	232	107.7	3,726	1,728.9	3,958	1,836.5
2017	116	232	107.7	3,842	1,782.7	4,074	1,890.3
2018	116	232	107.7	3,958	1,836.5	4,190	1,944.2
2019	116	232	107.7	4,074	1,890.3	4,306	1,998.0
2020	116	232	107.7	4,190	1,944.2	4,422	2,051.8
2021	116	232	107.7	4,306	1,998.0	4,538	2,105.6
2022	116	232	107.7	4,422	2,051.8	4,654	2,159.5
2023	116	232	107.7	4,538	2,105.6	4,770	2,213.3
2024	116	232	107.7	4,654	2,159.5	4,886	2,267.1
2025	116	232	107.7	4,770	2,213.3	5,002	2,320.9
2026	116	232	107.7	4,886	2,267.1	5,118	2,374.8
2027	116	232	107.7	5,002	2,320.9	5,234	2,428.6
2028	116	232	107.7	5,118	2,374.8	5,350	2,482.4
2029	116	232	107.7	5,234	2,428.6	5,466	2,536.2
2030	116	232	107.7	5,350	2,482.4	5,582	2,590.1
2031	116	232	107.7	5,466	2,536.2	5,698	2,643.9
2032	116	232	107.7	5,582	2,590.1	5,814	2,697.7
2033	116	232	107.7	5,698	2,643.9	5,930	2,751.5
2034	116	232	107.7	5,814	2,697.7	6,046	2,805.3
2035	116	232	107.7	5,930	2,751.5	6,162	2,859.2
2036	239	355	164.7	6,046	2,805.3	6,401	2,970.1
2037	82	321	149.0	6,162	2,859.2	6,483	3,008.1
2038	82	164	76.1	6,401	2,970.1	6,565	3,046.2
2039	82	164	76.1	6,483	3,008.1	6,647	3,084.2
2040	82	164	76.1	6,565	3,046.2	6,729	3,122.3
2041	82	164	76.1	6,647	3,084.2	6,811	3,160.3
2042	199	281	130.4	6,729	3,122.3	7,010	3,252.6
2043	42	241	111.8	6,811	3,160.3	7,052	3,272.1
2044	157	199	92.3	7,010	3,252.6	7,209	3,345.0
2045	0	157	72.9	7,052	3,272.1	7,209	3,345.0
2046	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2047	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2048	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2049	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2050	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2051	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2052	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2053	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2054	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2055	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2056	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2057	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2058	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2059	0	0	0.0	7,209	3,345.0	7,209	3,345.0
2060	0	0	0.0	7,209	3,345.0	7,209	3,345.0

Appendix C – Material Balance for Each Swedish Scenario



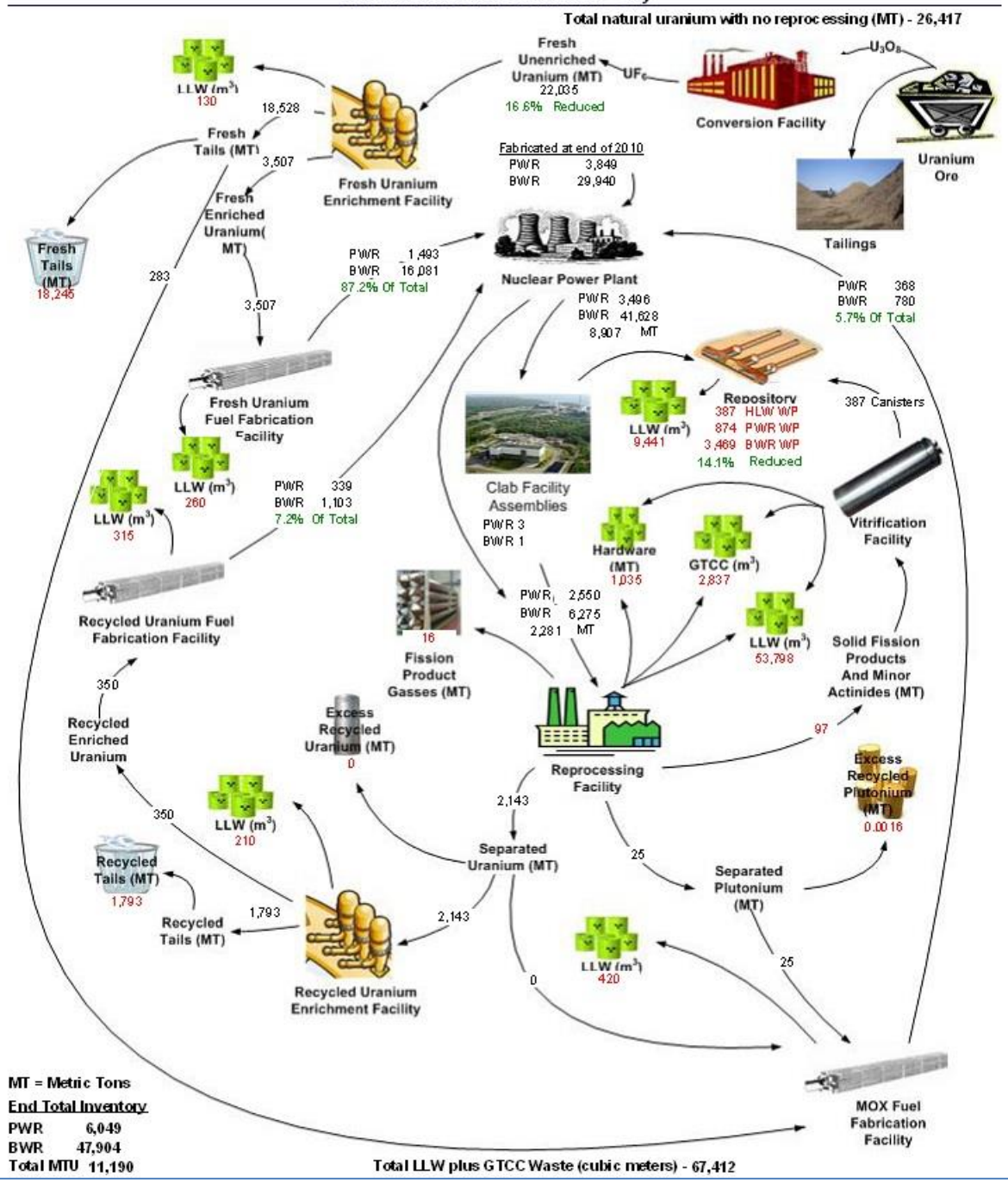
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 21 - Material Balance - Scenario 1.1



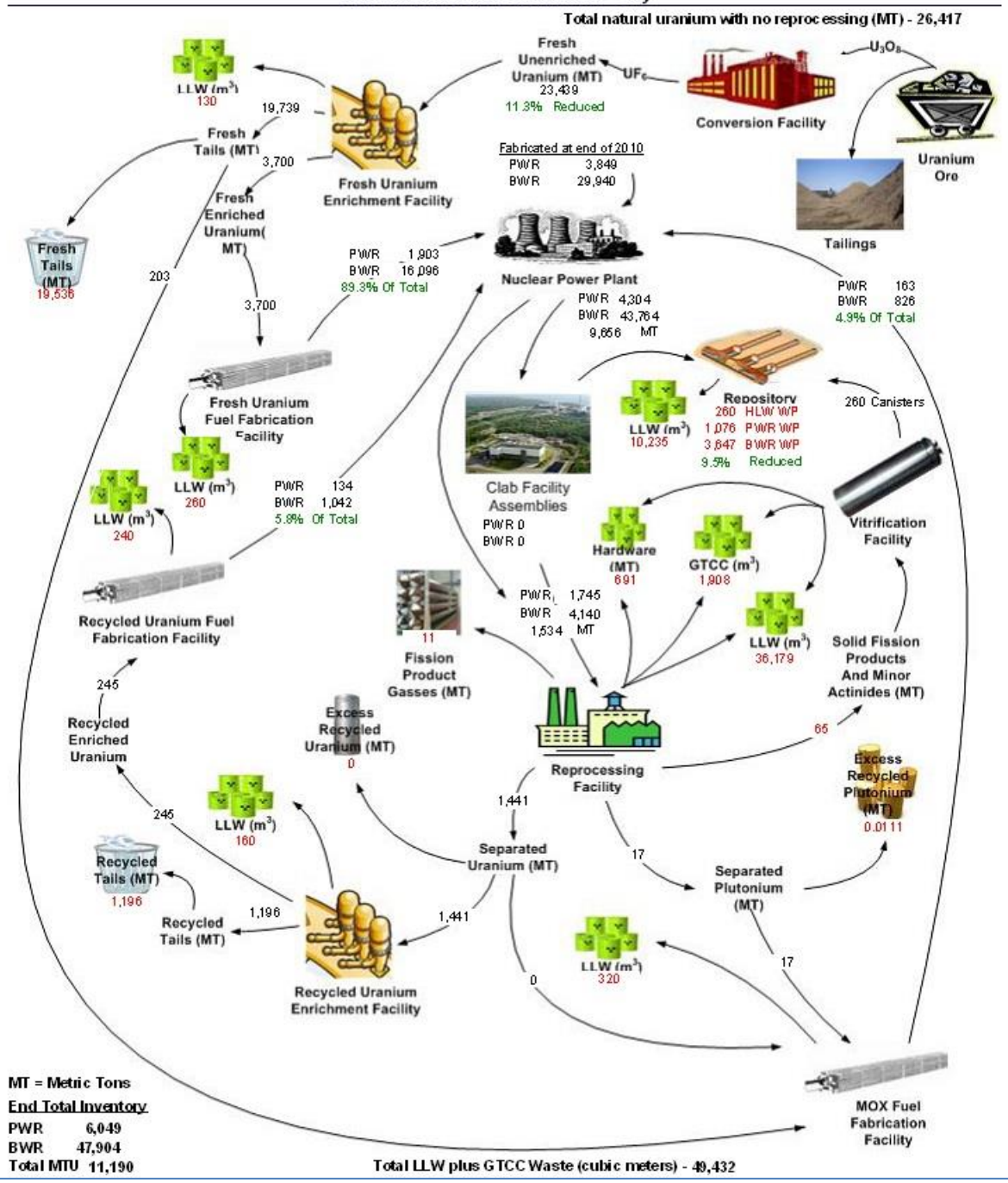
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 22 - Material Balance – Scenario 1.2



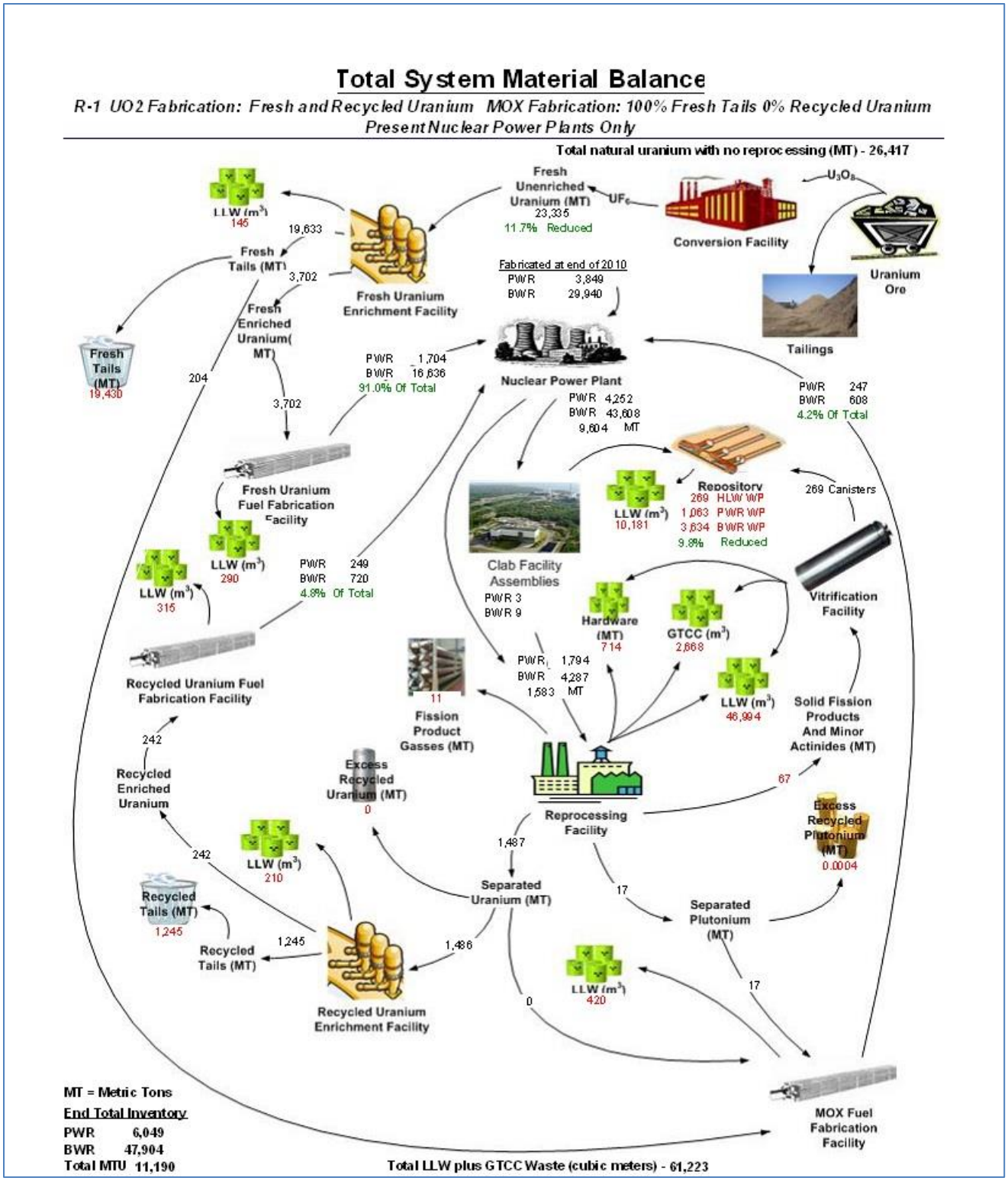
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 23 - Material Balance - Scenario 1.3



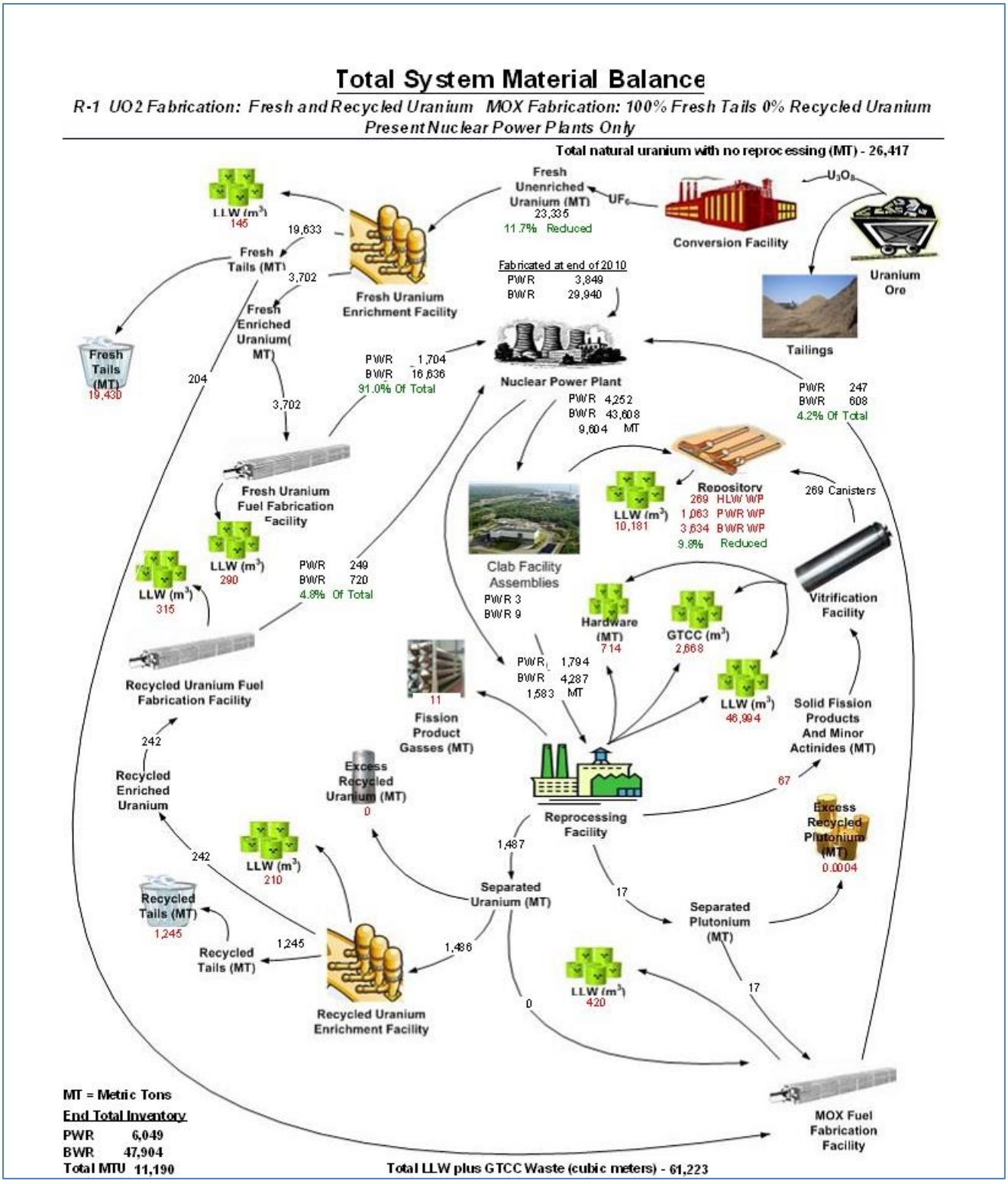
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 24 - Material Balance - Scenario 1.4



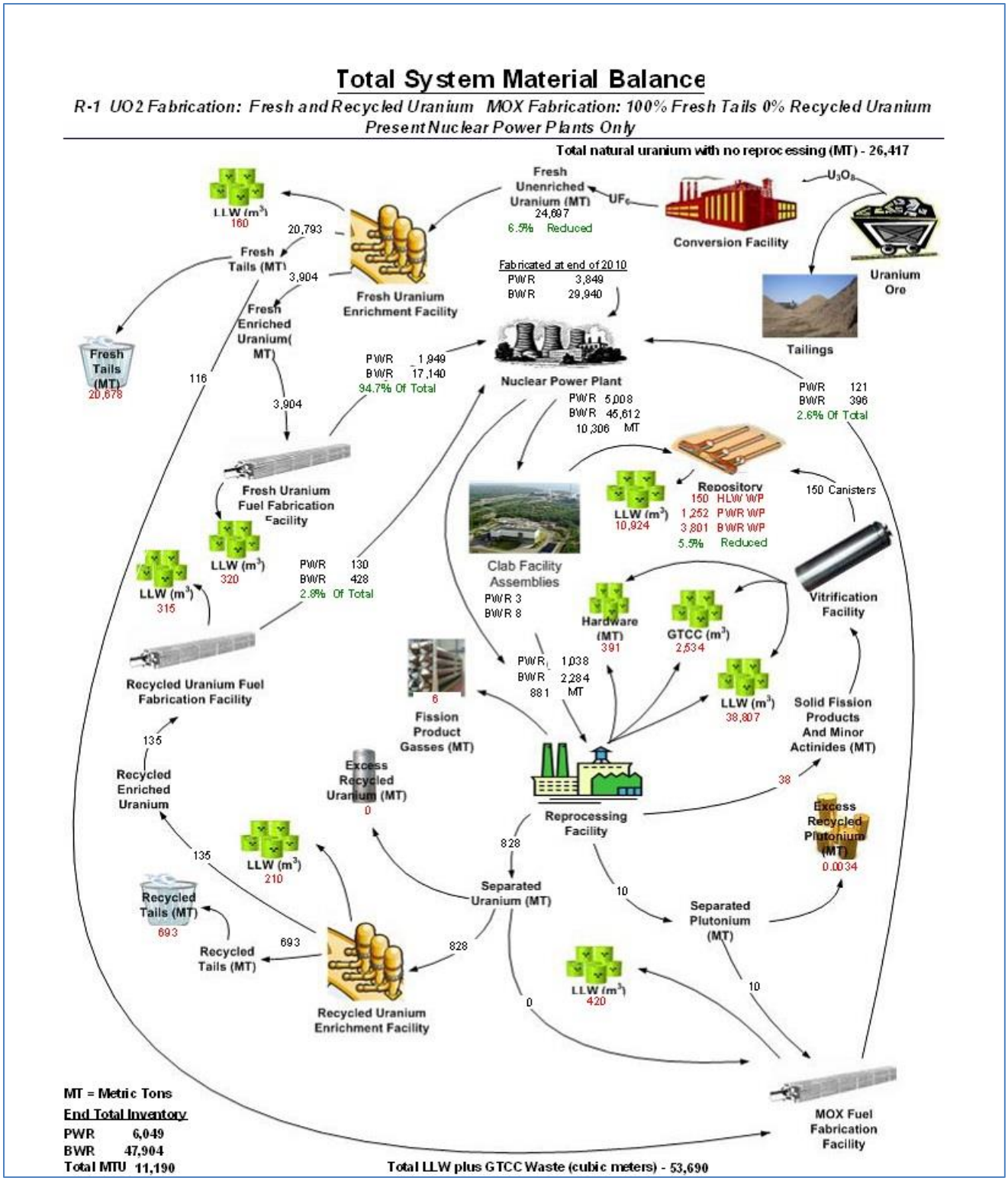
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 25 - Material Balance - Scenario 1.5



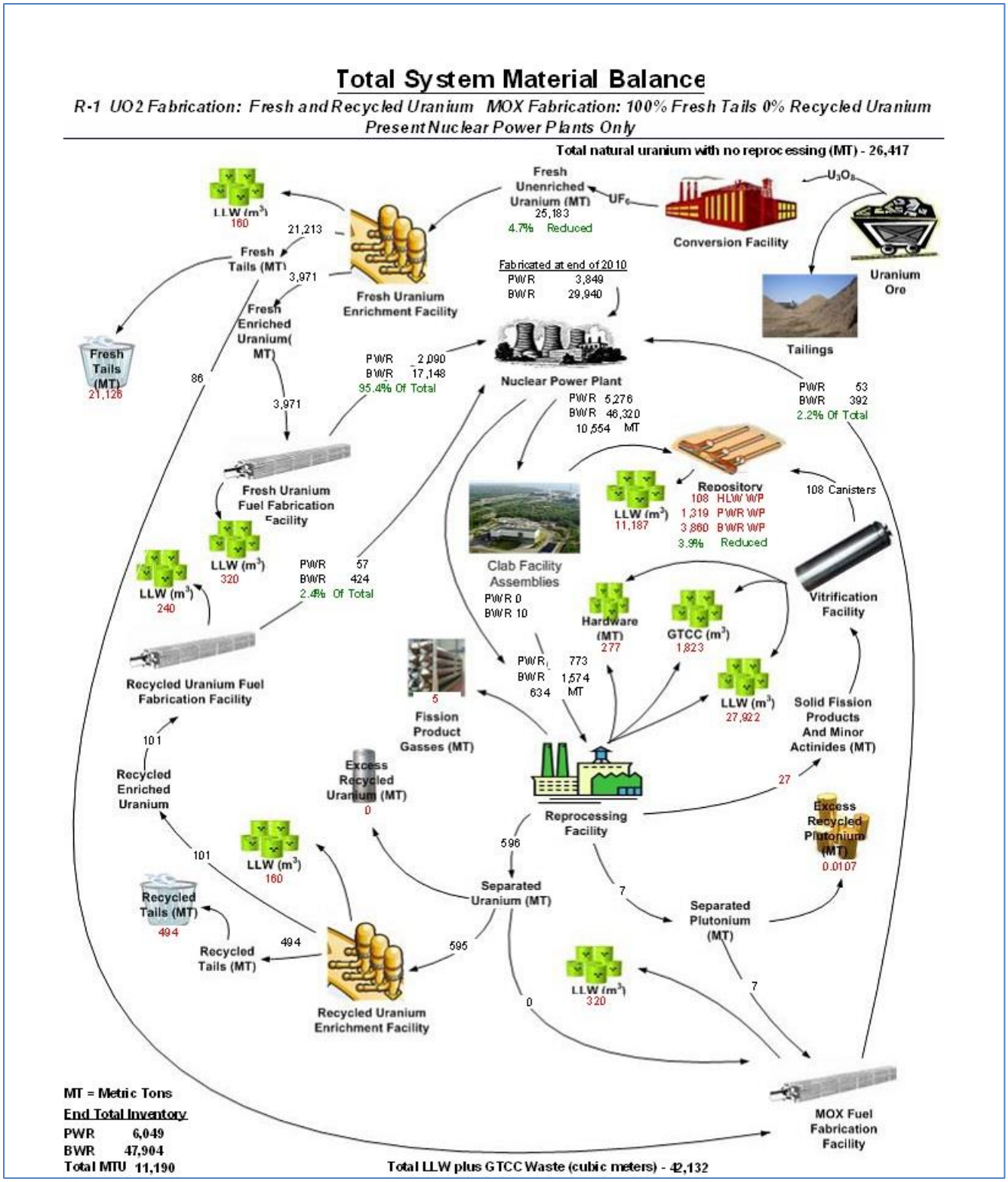
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 26 - Material Balance - Scenario 1.6



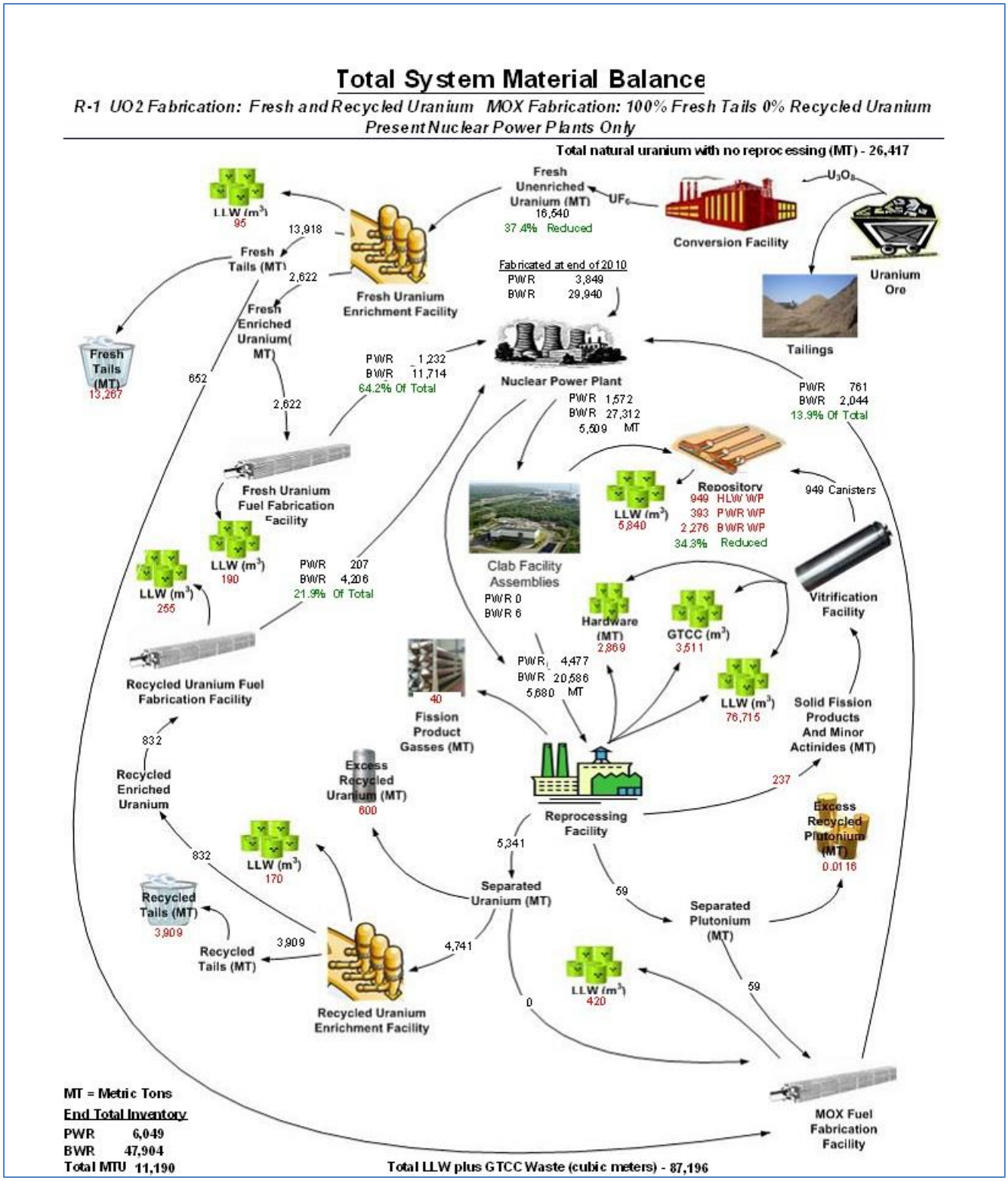
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 27 - Material Balance - Scenario 1.7



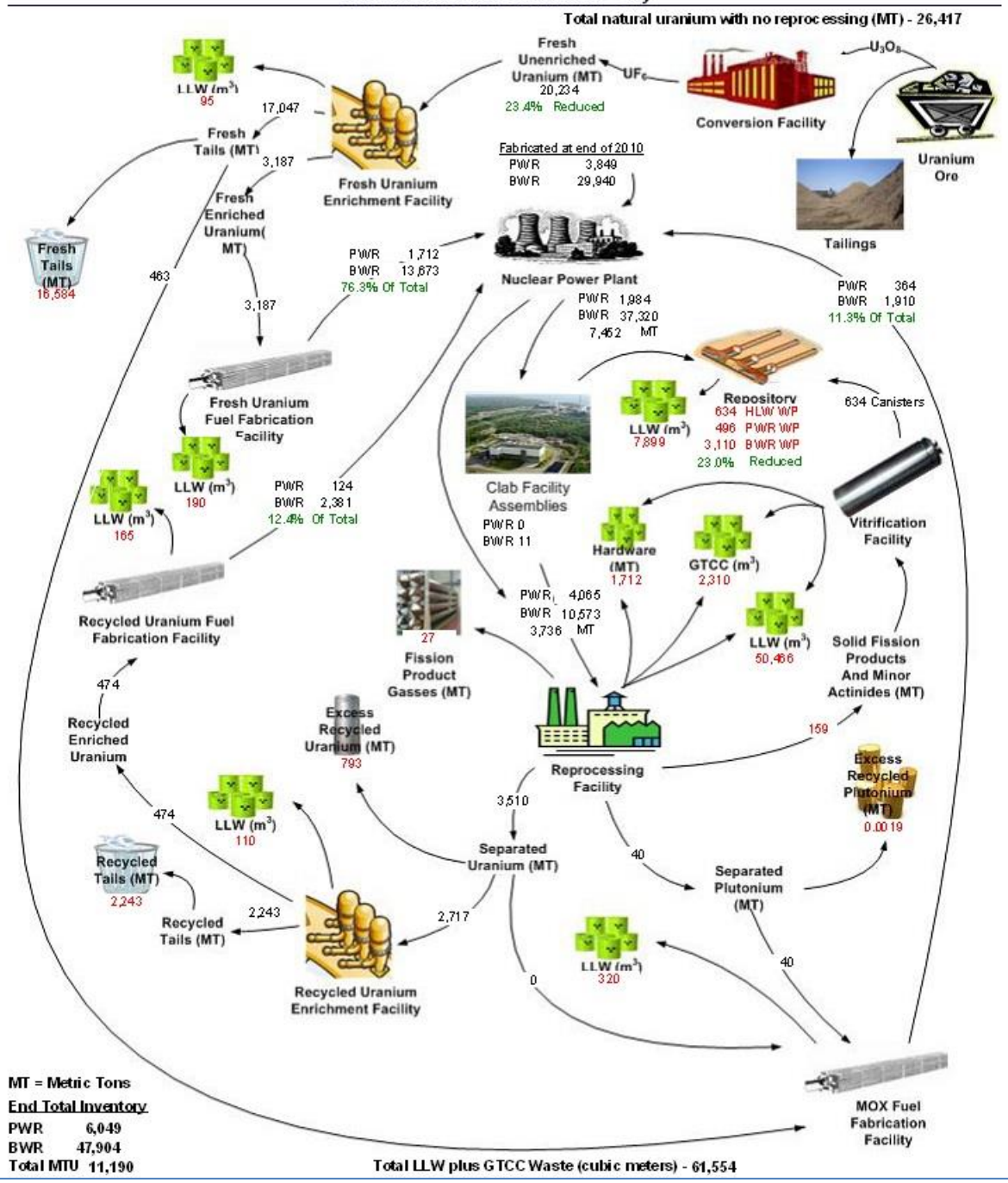
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 28 - Material Balance - Scenario 1.8



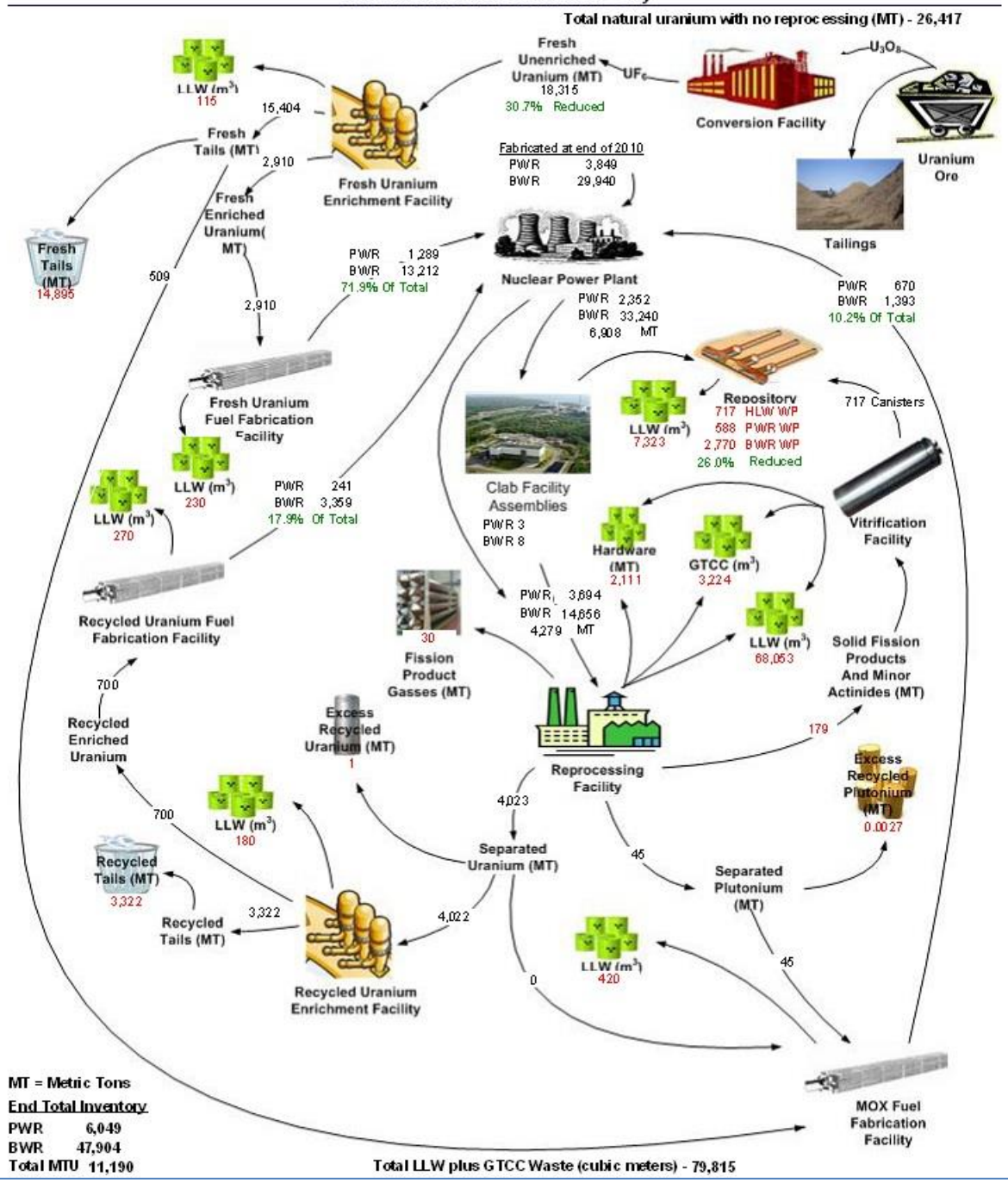
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 29 - Material Balance - Scenario 2.1



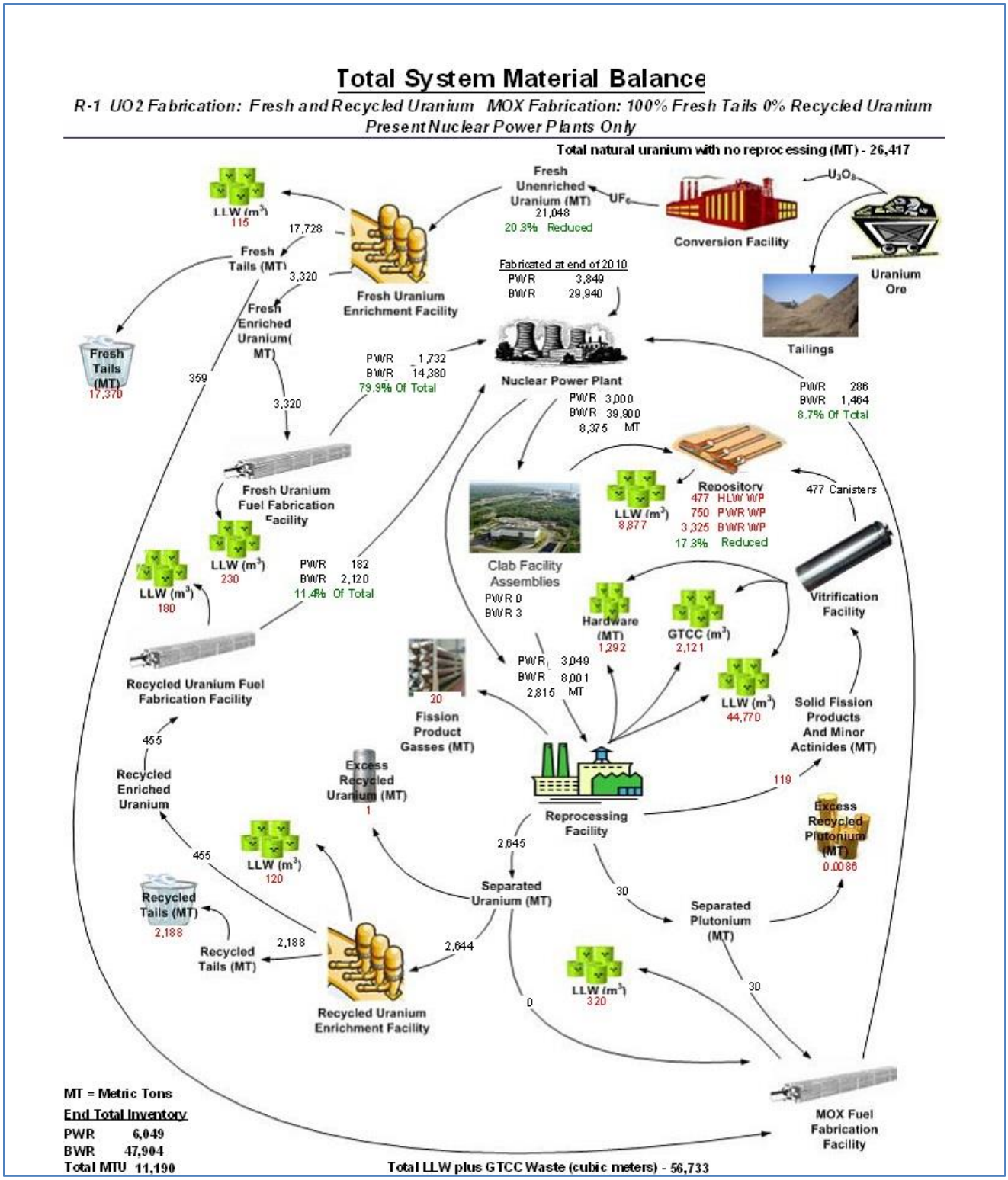
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 30 - Material Balance - Scenario 2.2



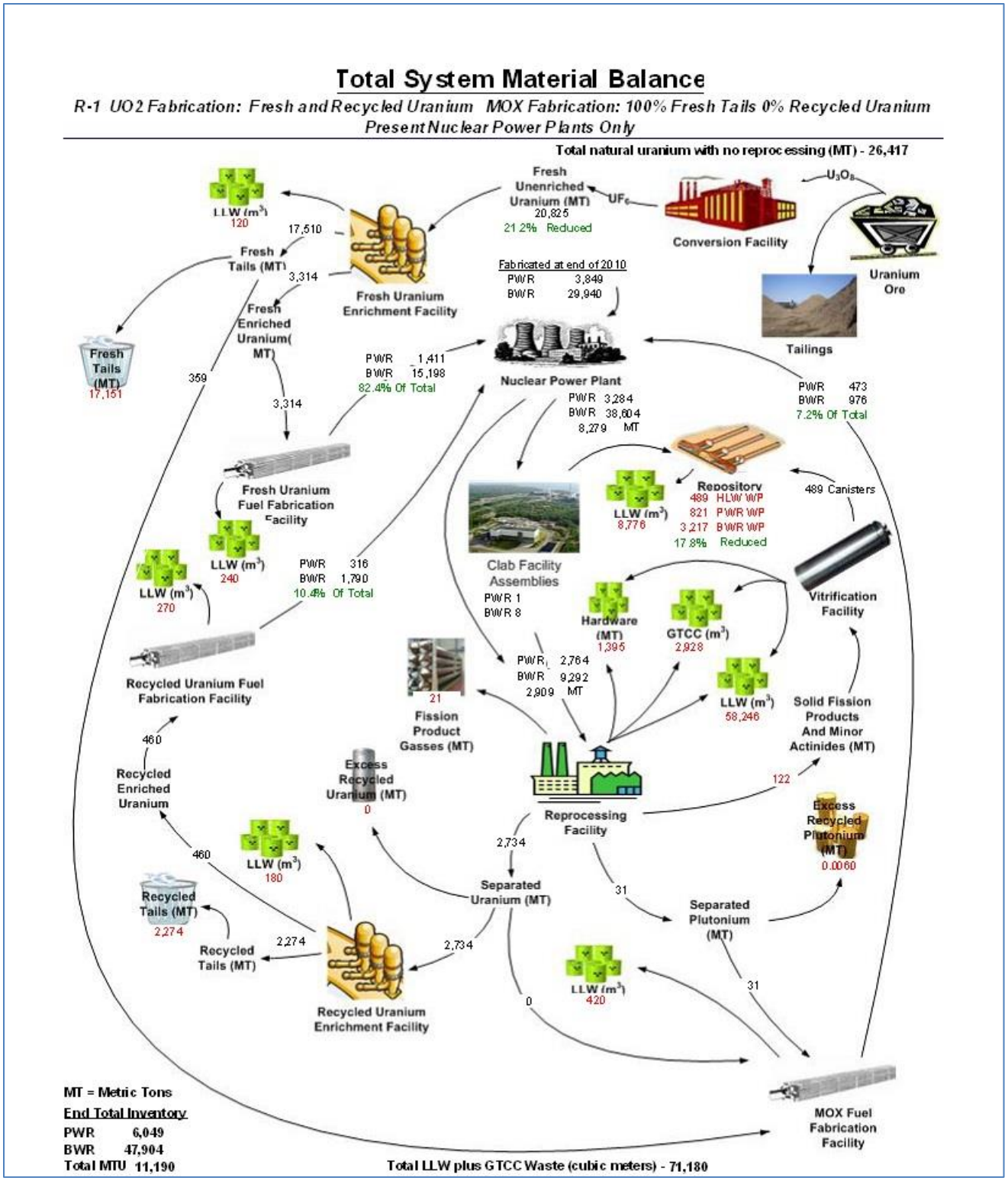
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 31 - Material Balance - Scenario 2.3



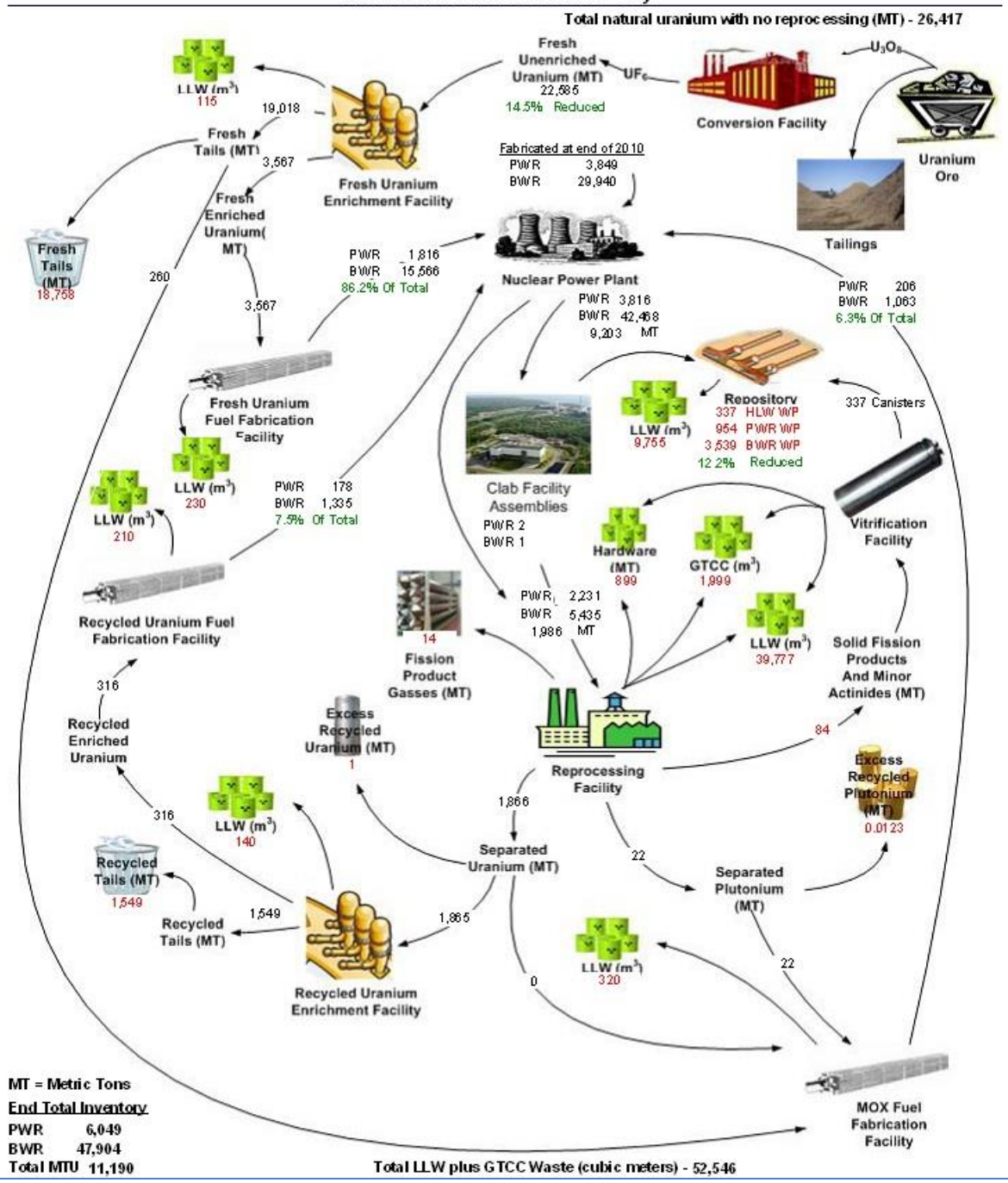
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 32 - Material Balance - Scenario 2.4



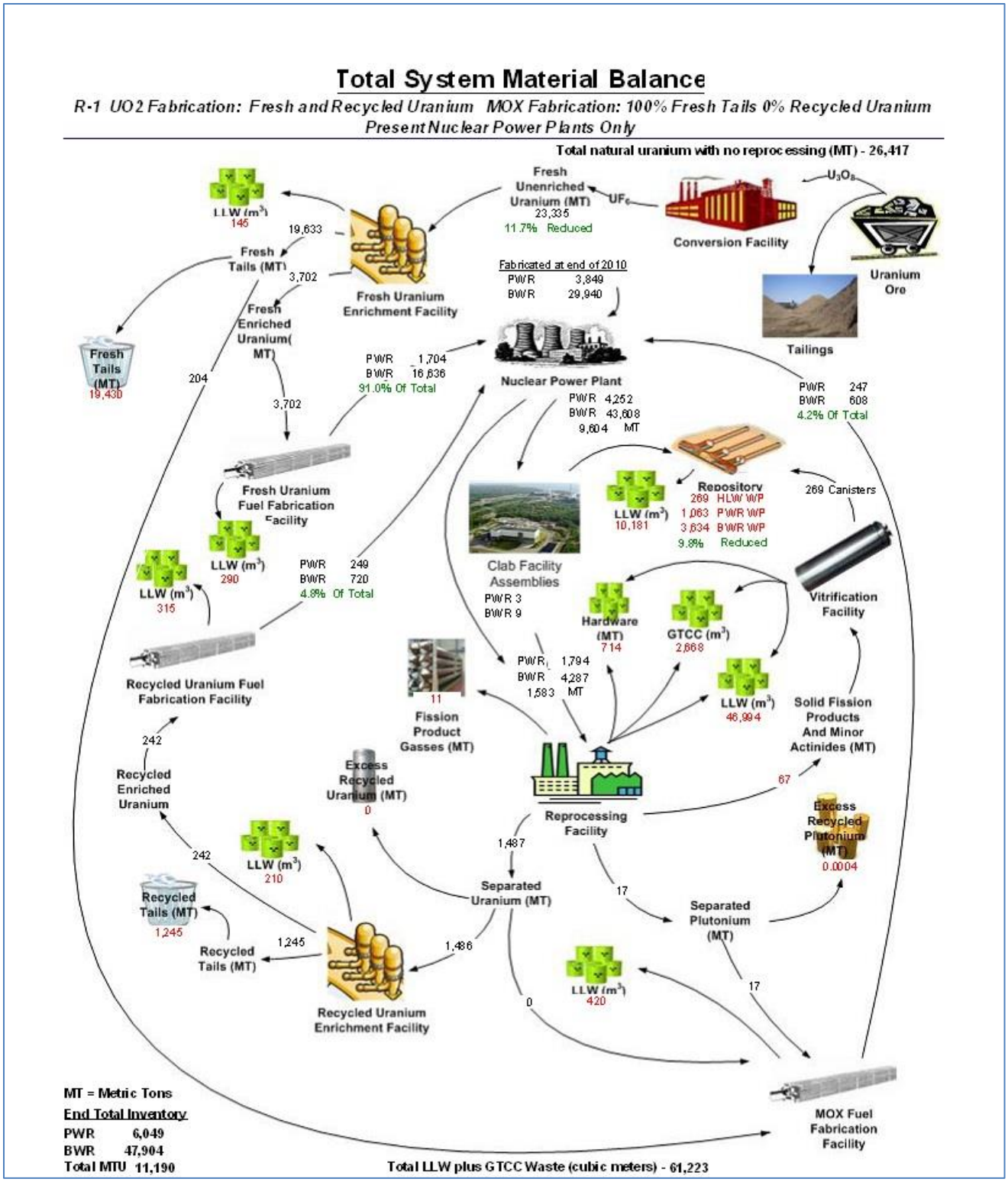
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 33 - Material Balance - Scenario 2.5



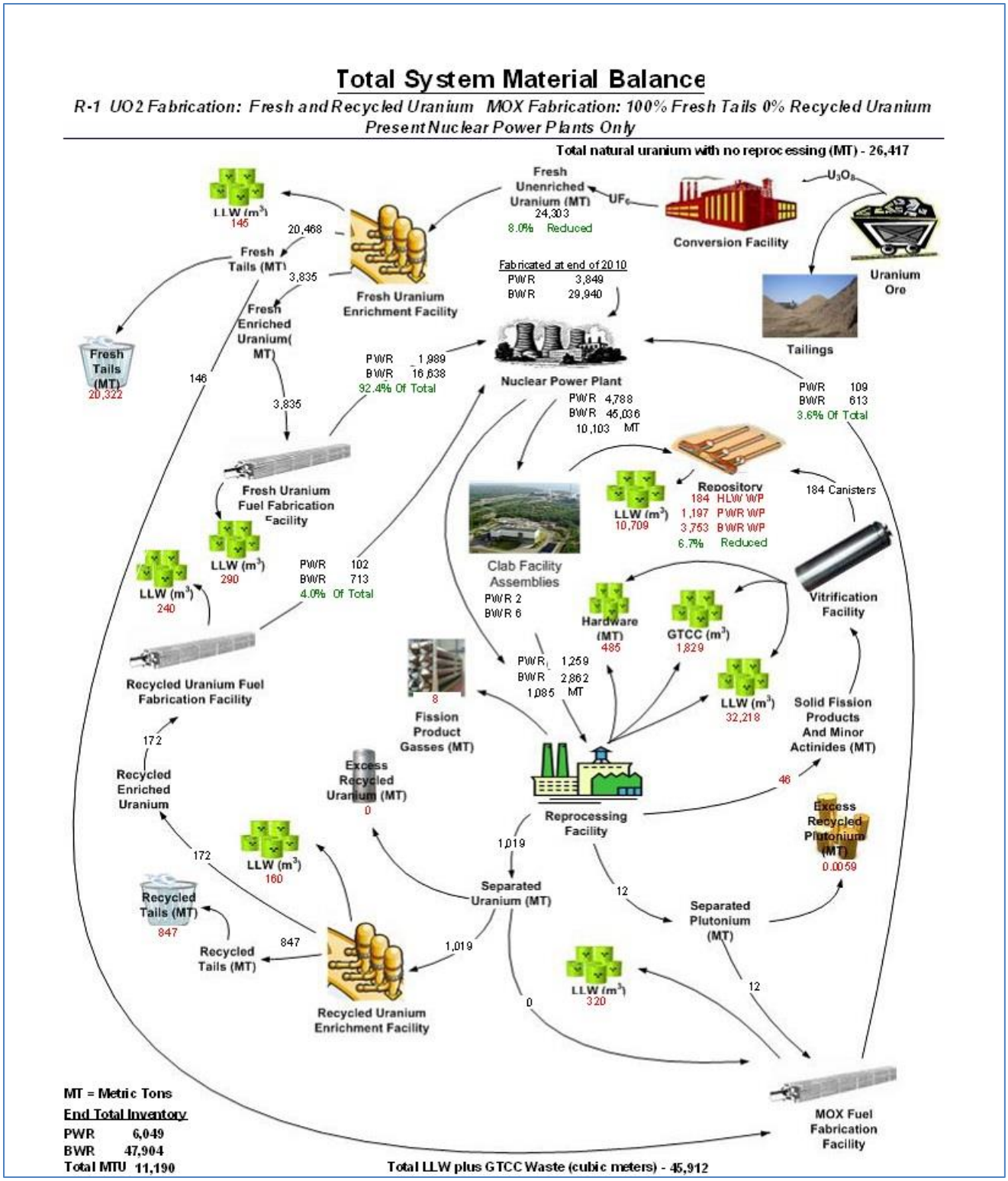
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 34 - Material Balance - Scenario 2.6



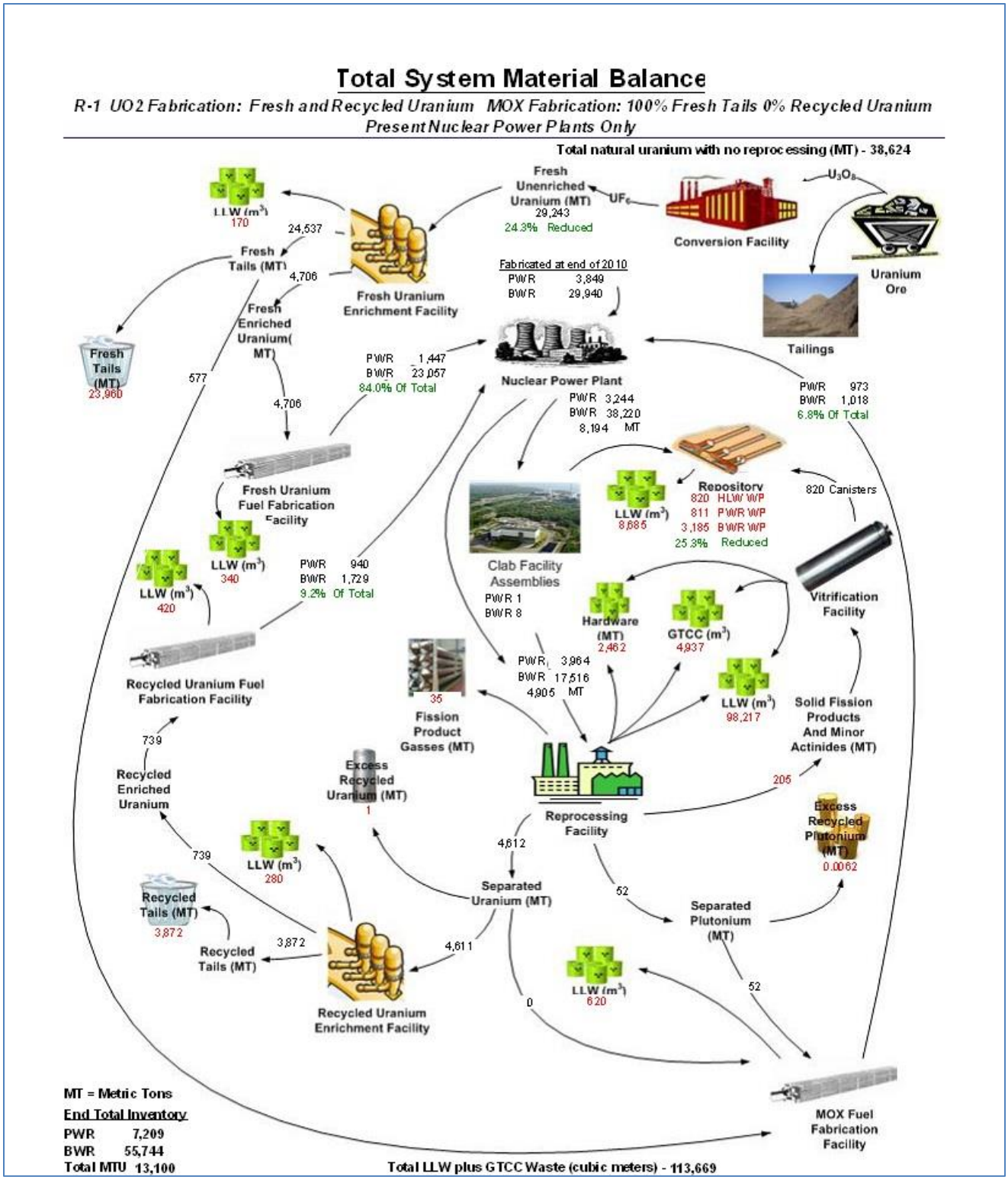
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 35 - Material Balance - Scenario 2.7



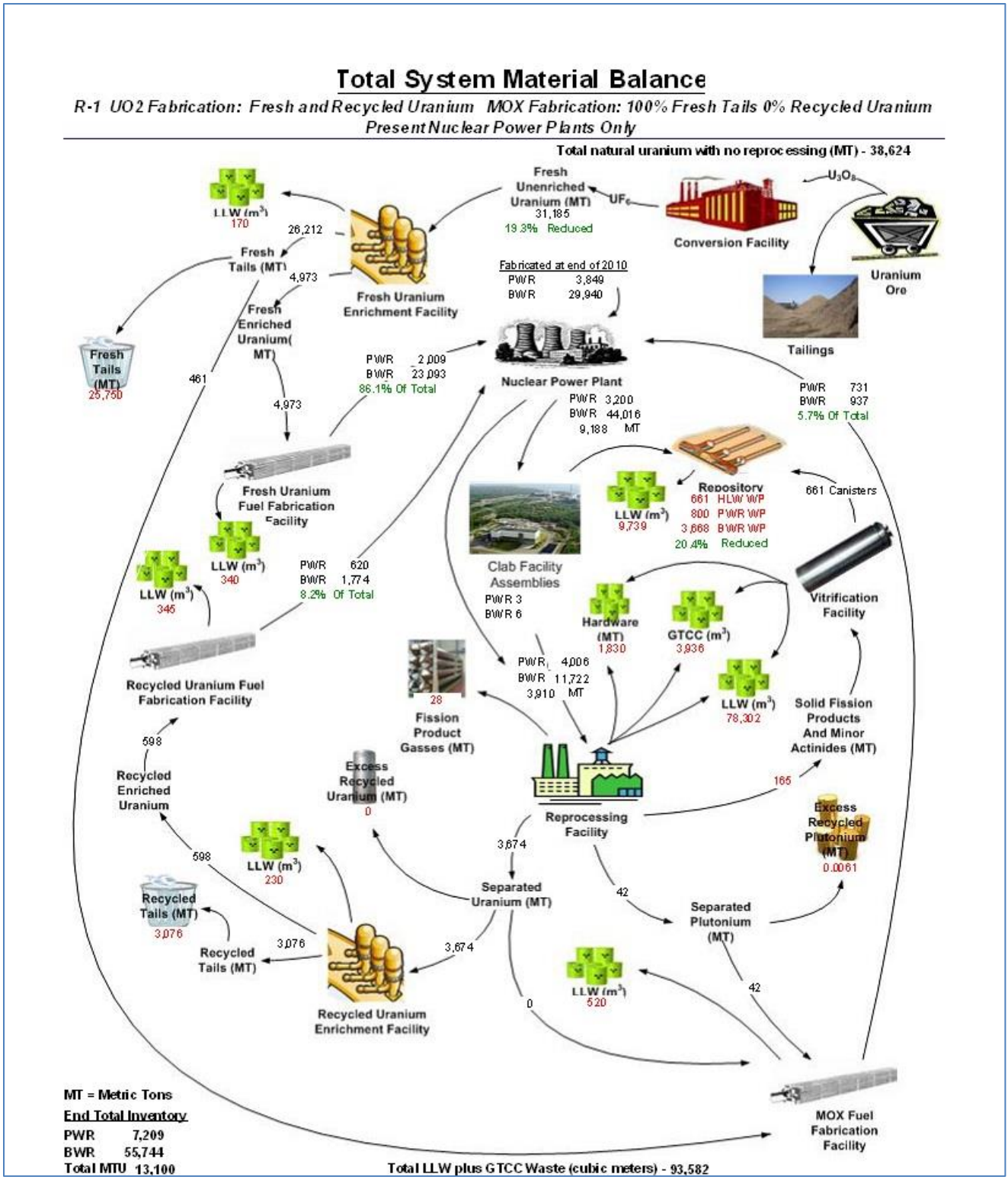
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 36 - Material Balance - Scenario 2.8



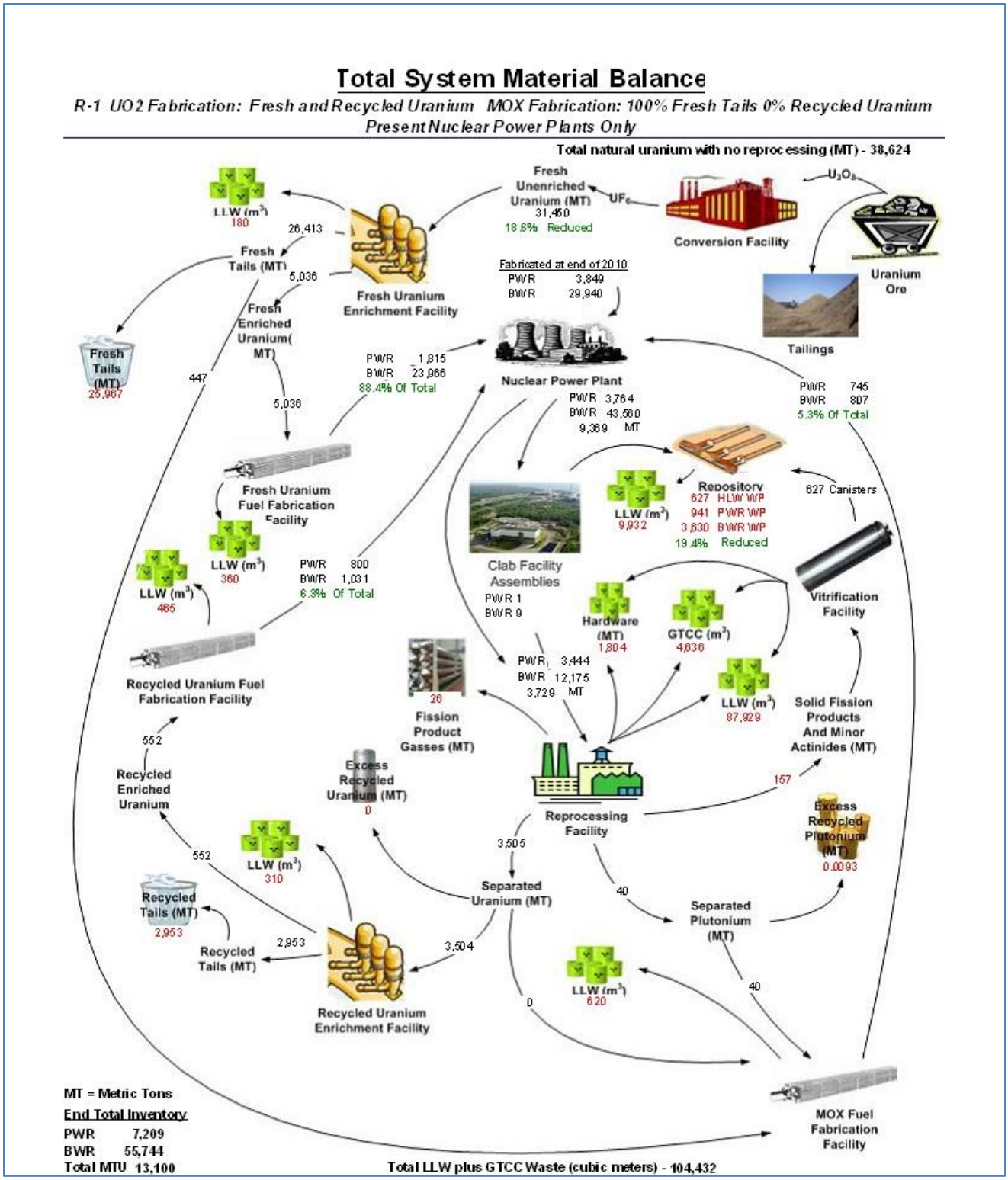
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 37 - Material Balance - Scenario 3.1



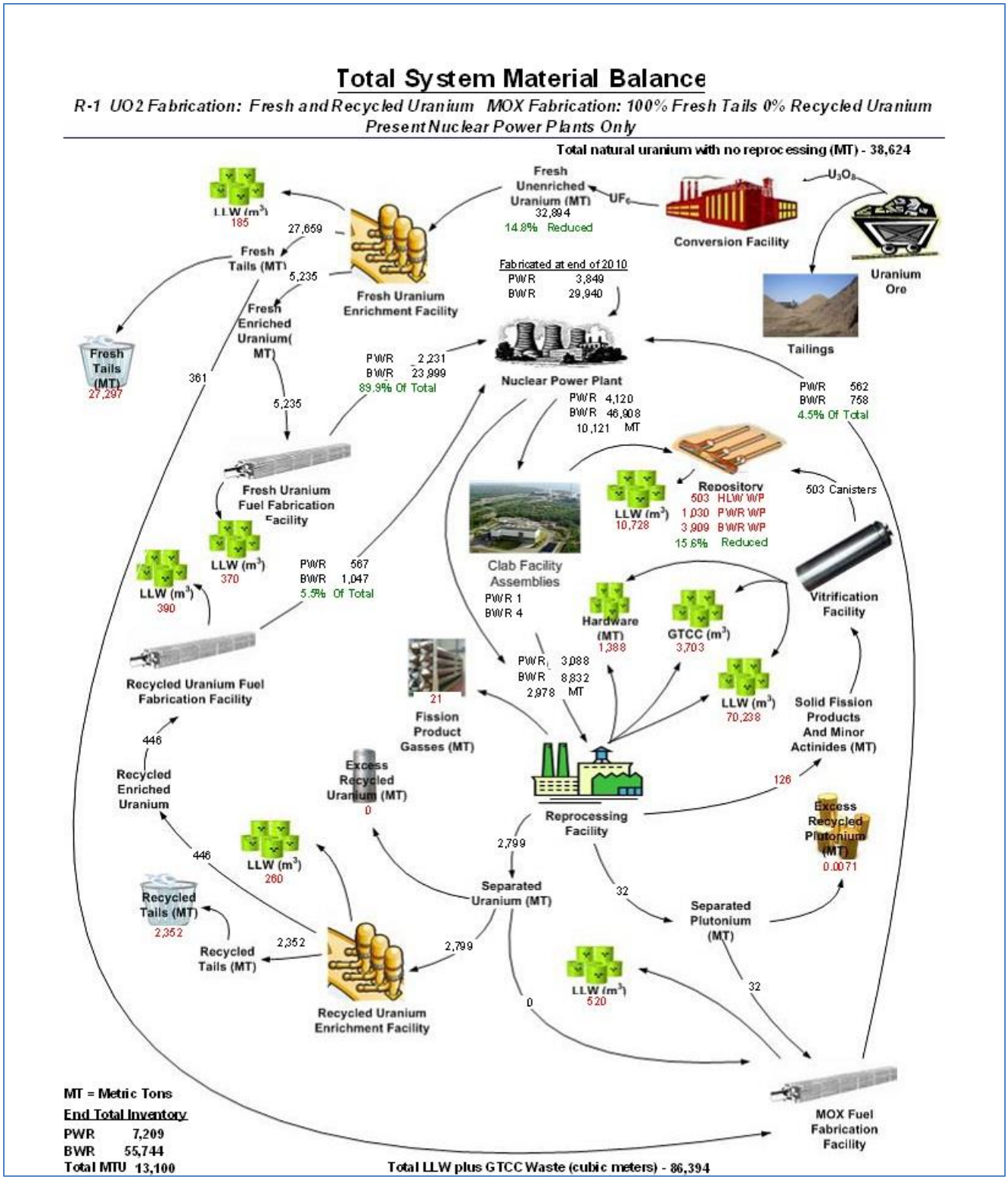
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 38 - Material Balance - Scenario 3.2



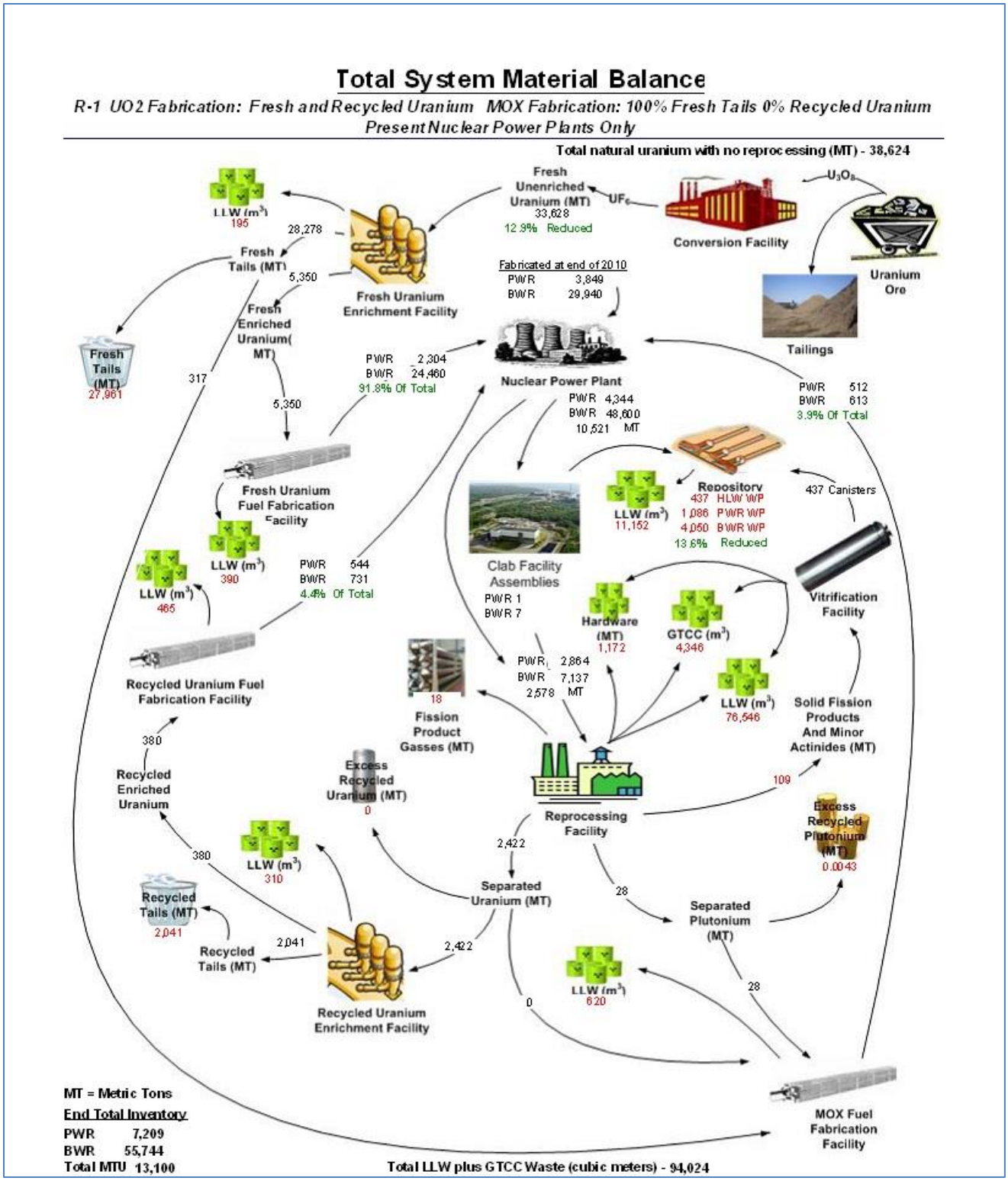
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 39 - Material Balance - Scenario 3.3



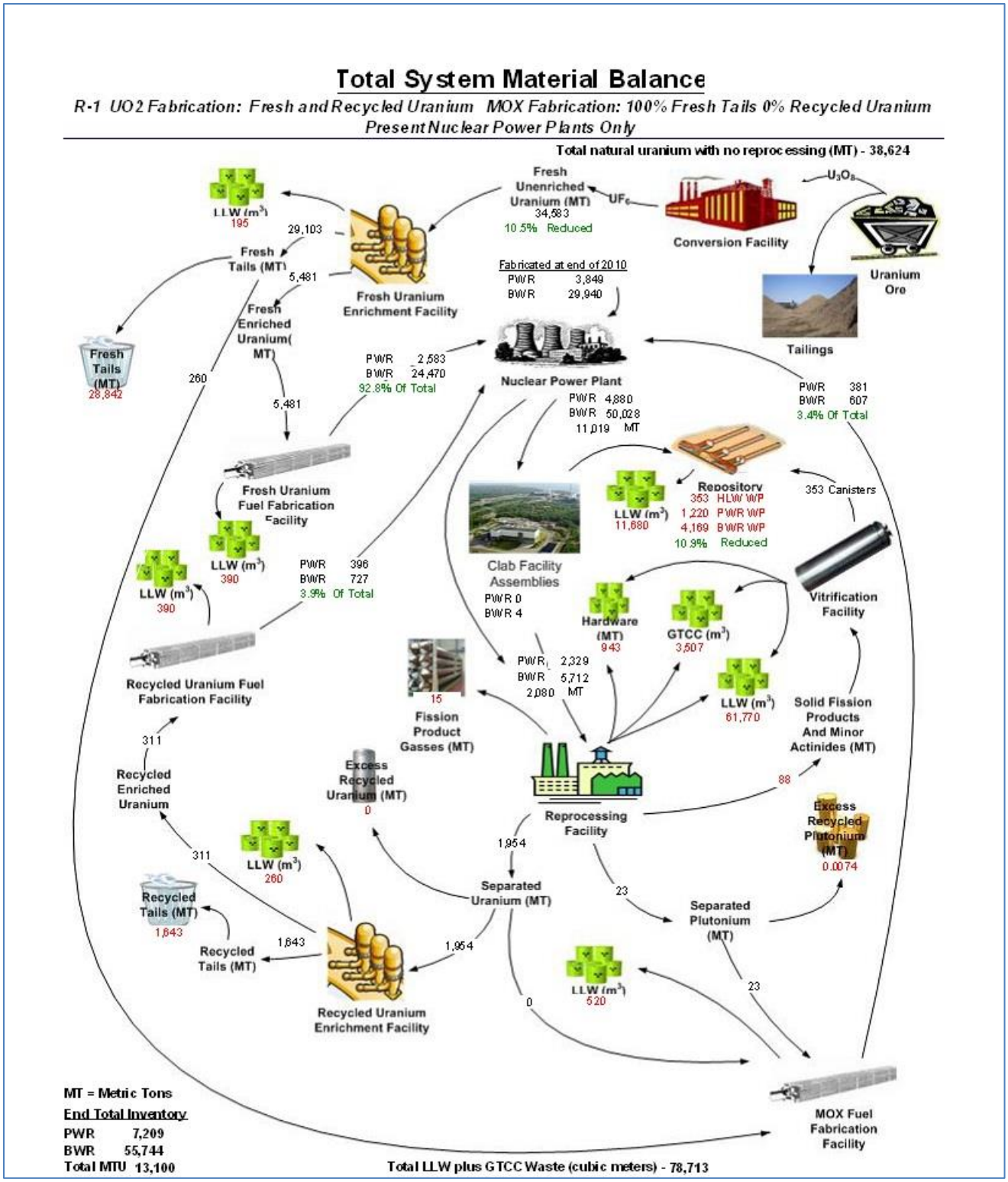
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 40 - Material Balance - Scenario 3.4



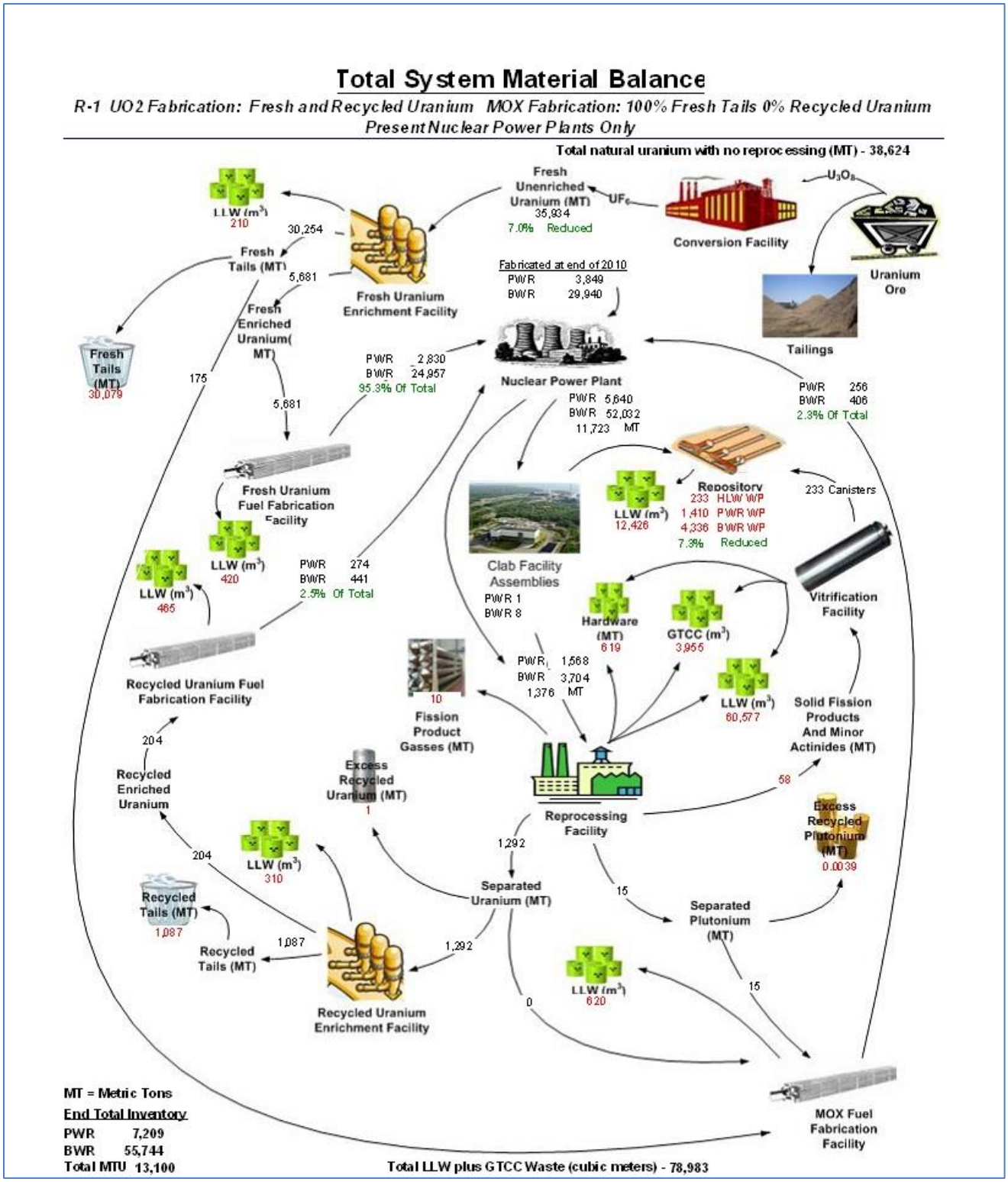
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 41 - Material Balance - Scenario 3.5



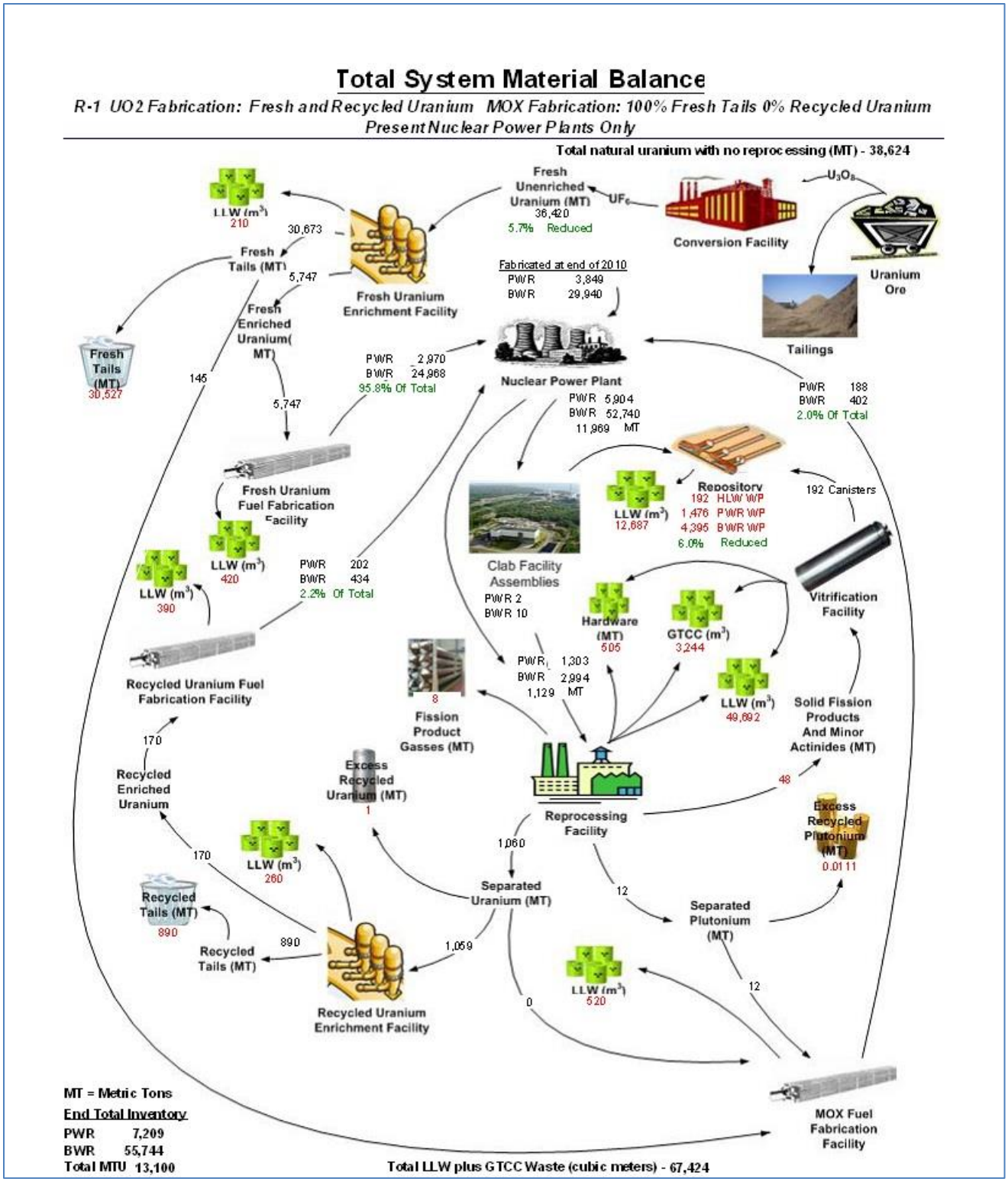
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 42 - Material Balance - Scenario 3.6



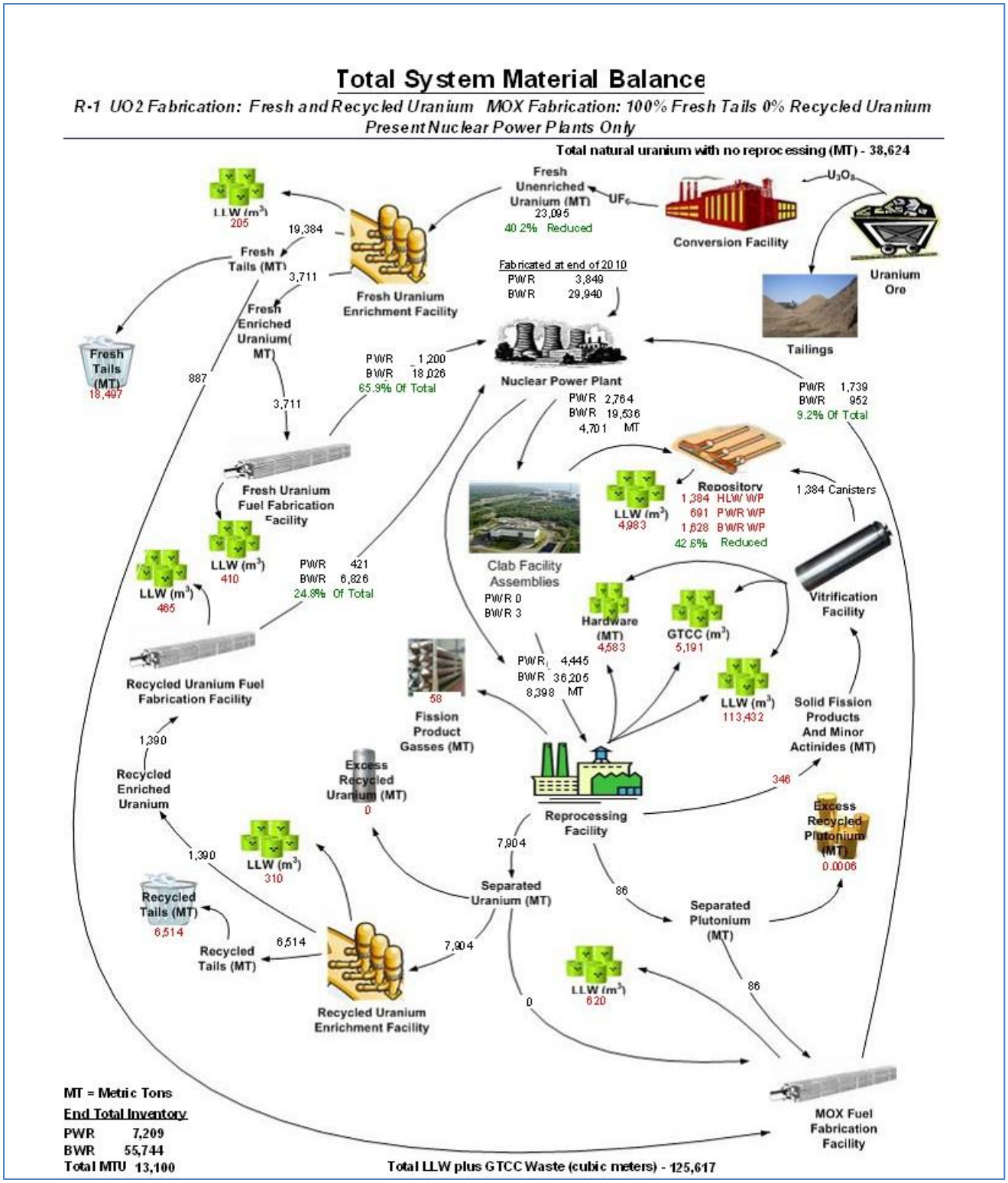
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 43 - Material Balance - Scenario 3.7



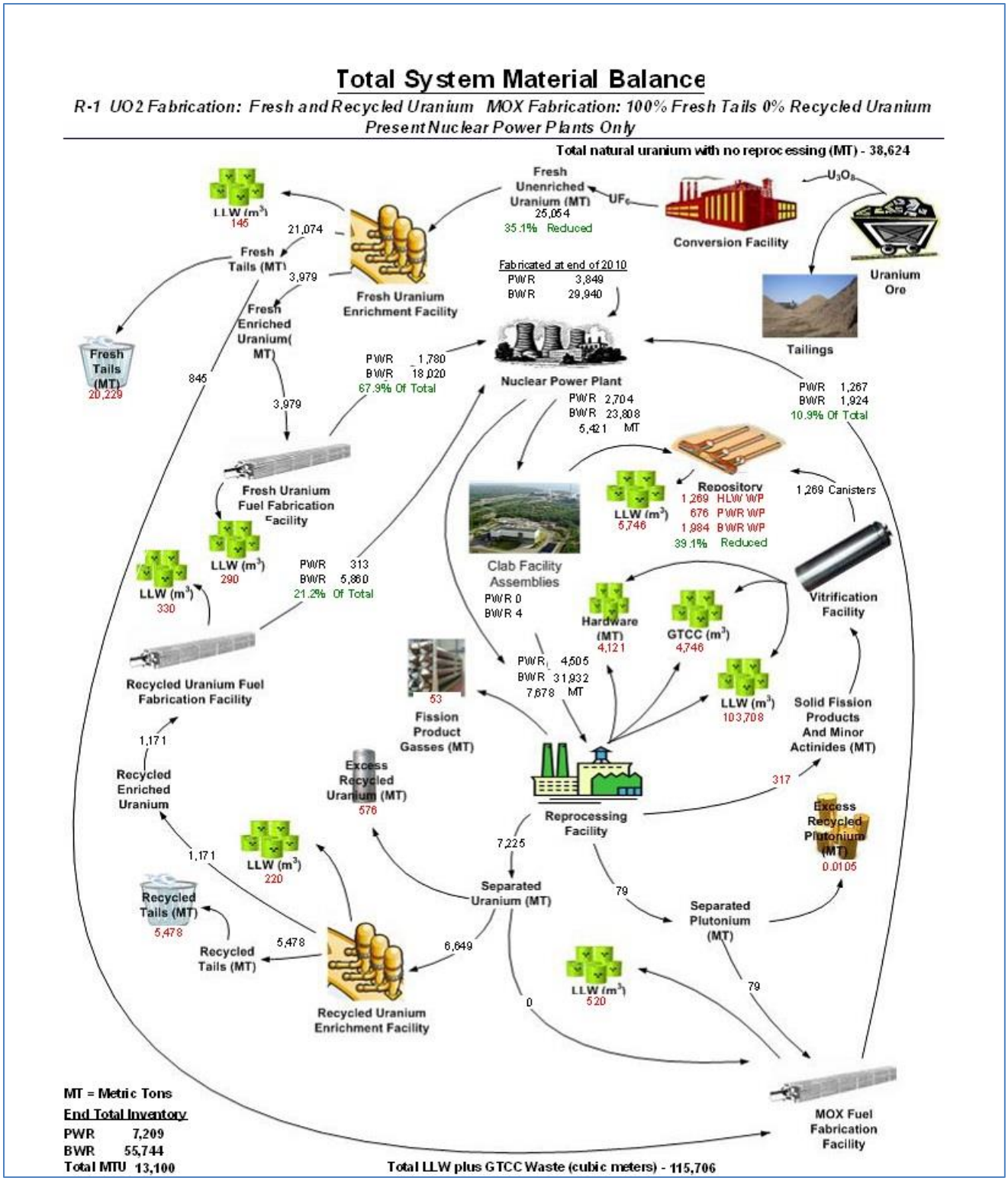
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 500 MT/year
Disposal Starts in 2023

Figure 44 - Material Balance - Scenario 3.8



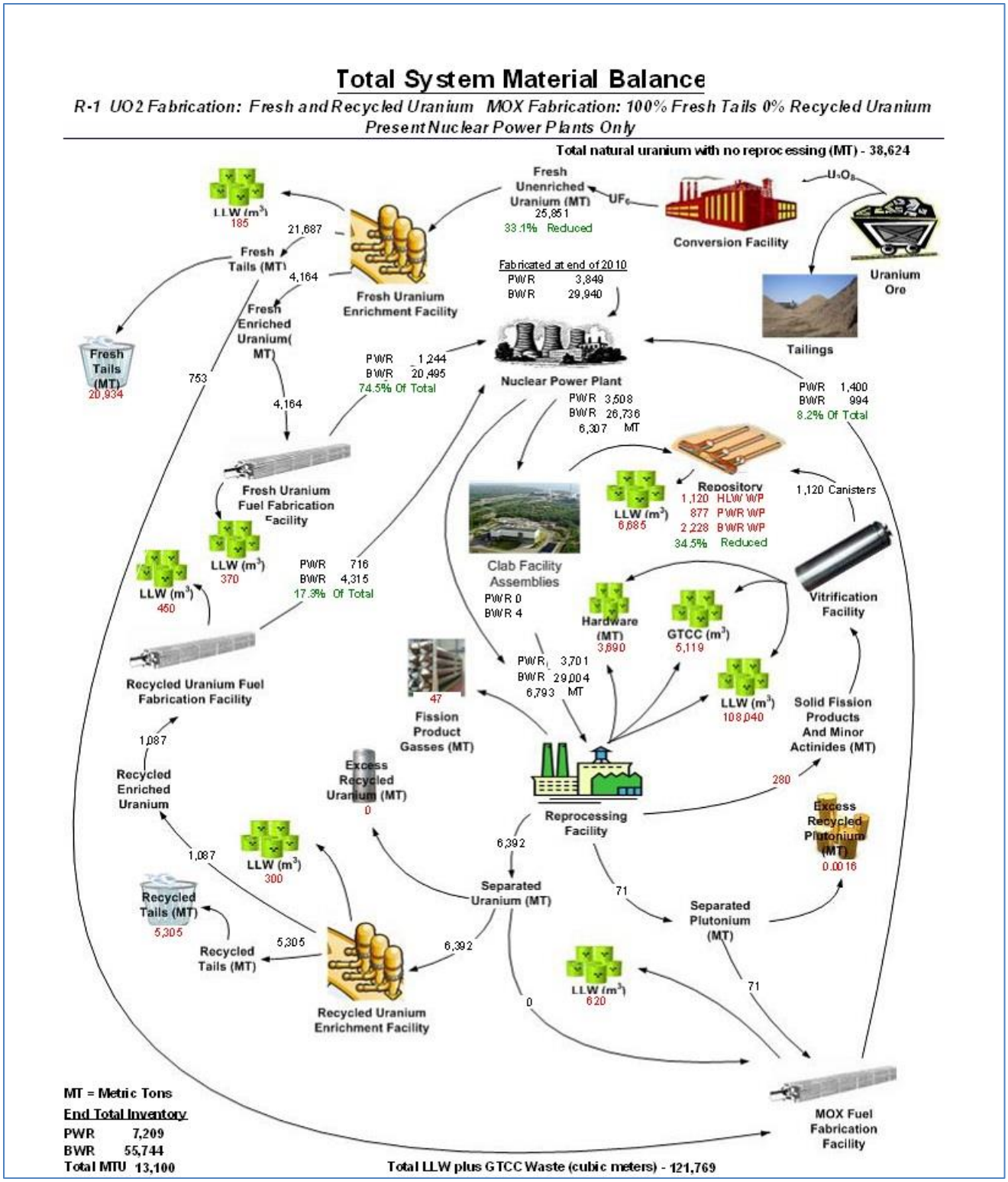
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 45 - Material Balance - Scenario 4.1



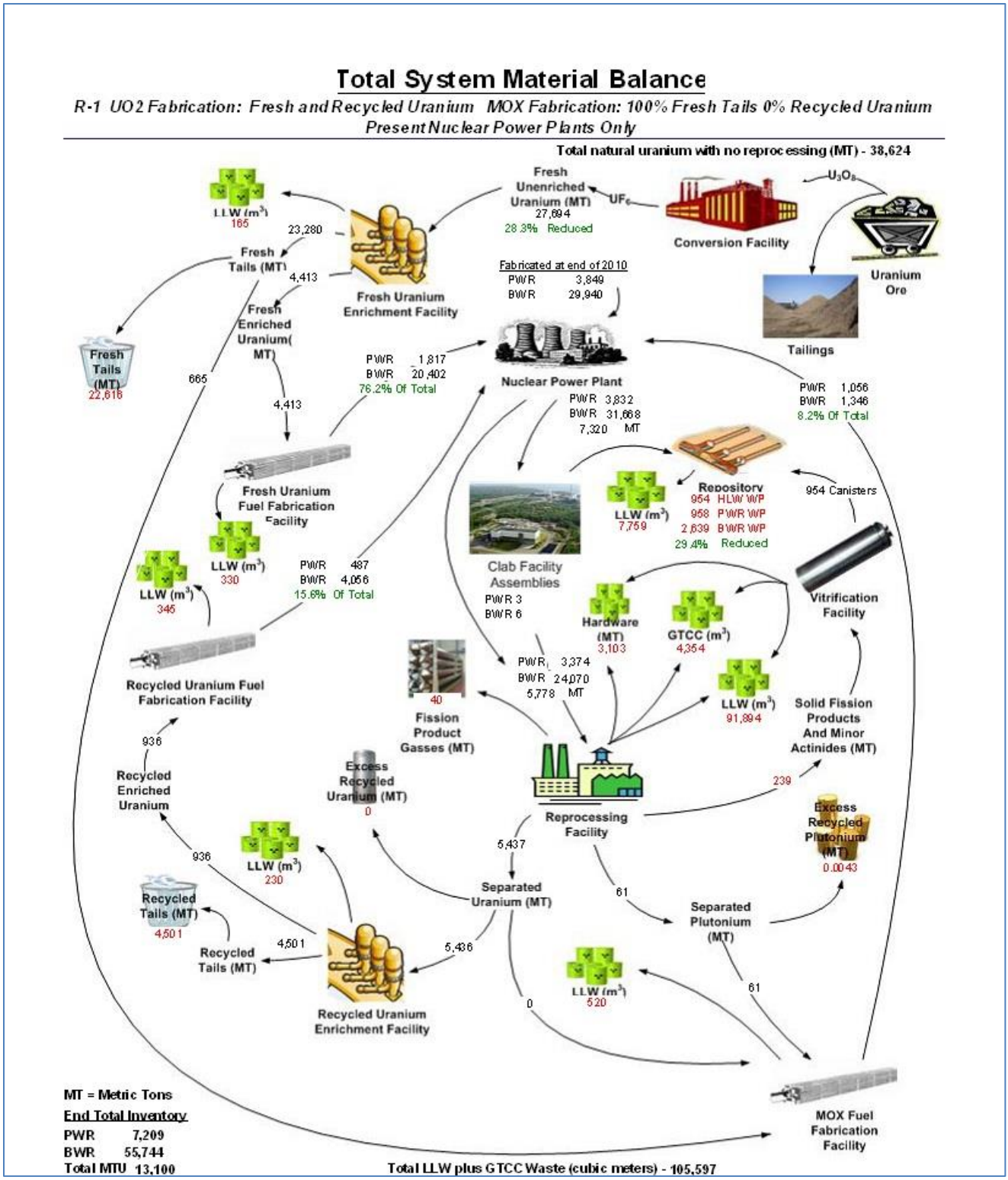
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 46 - Material Balance - Scenario 4.2



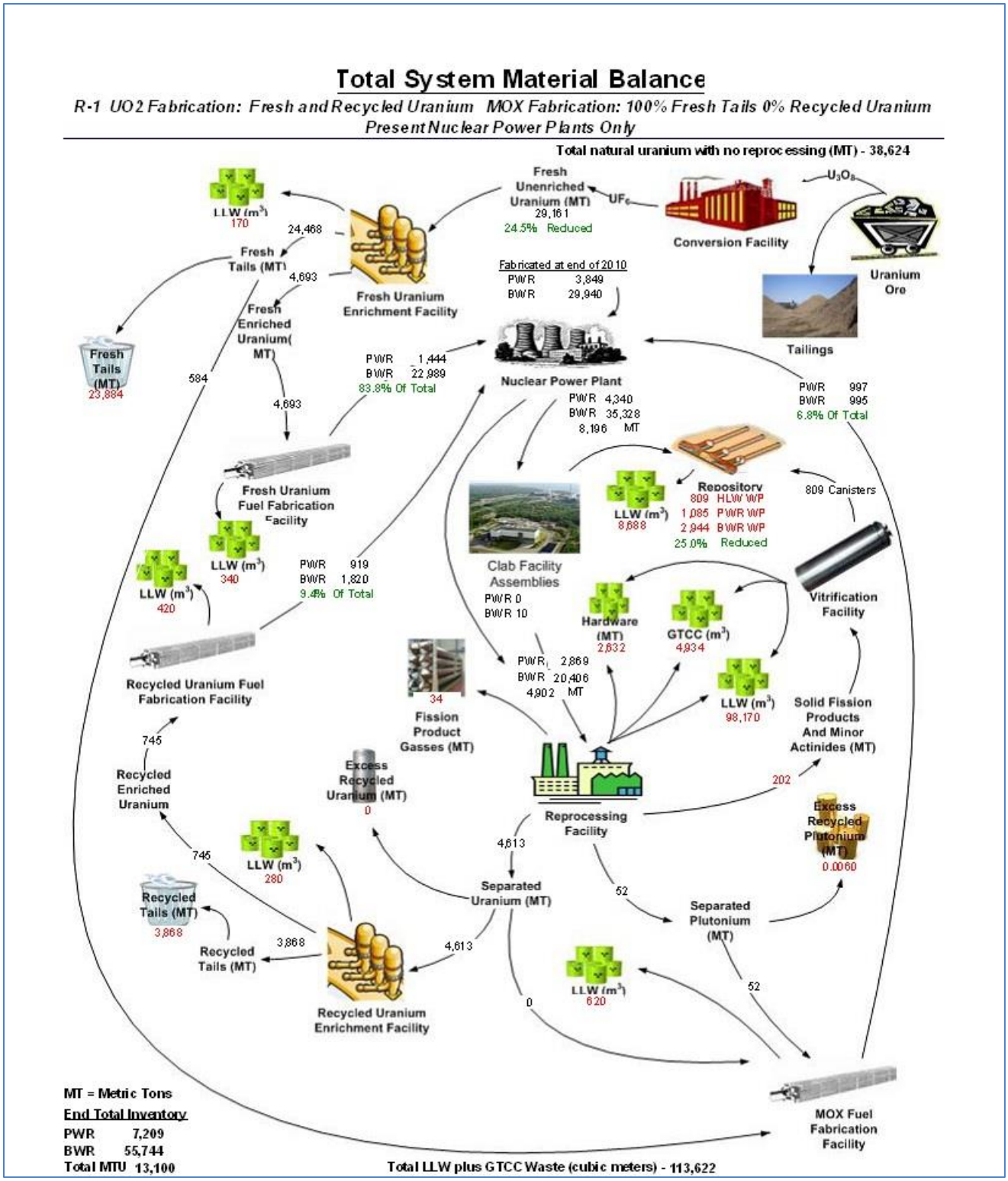
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 47 - Material Balance - Scenario 4.3



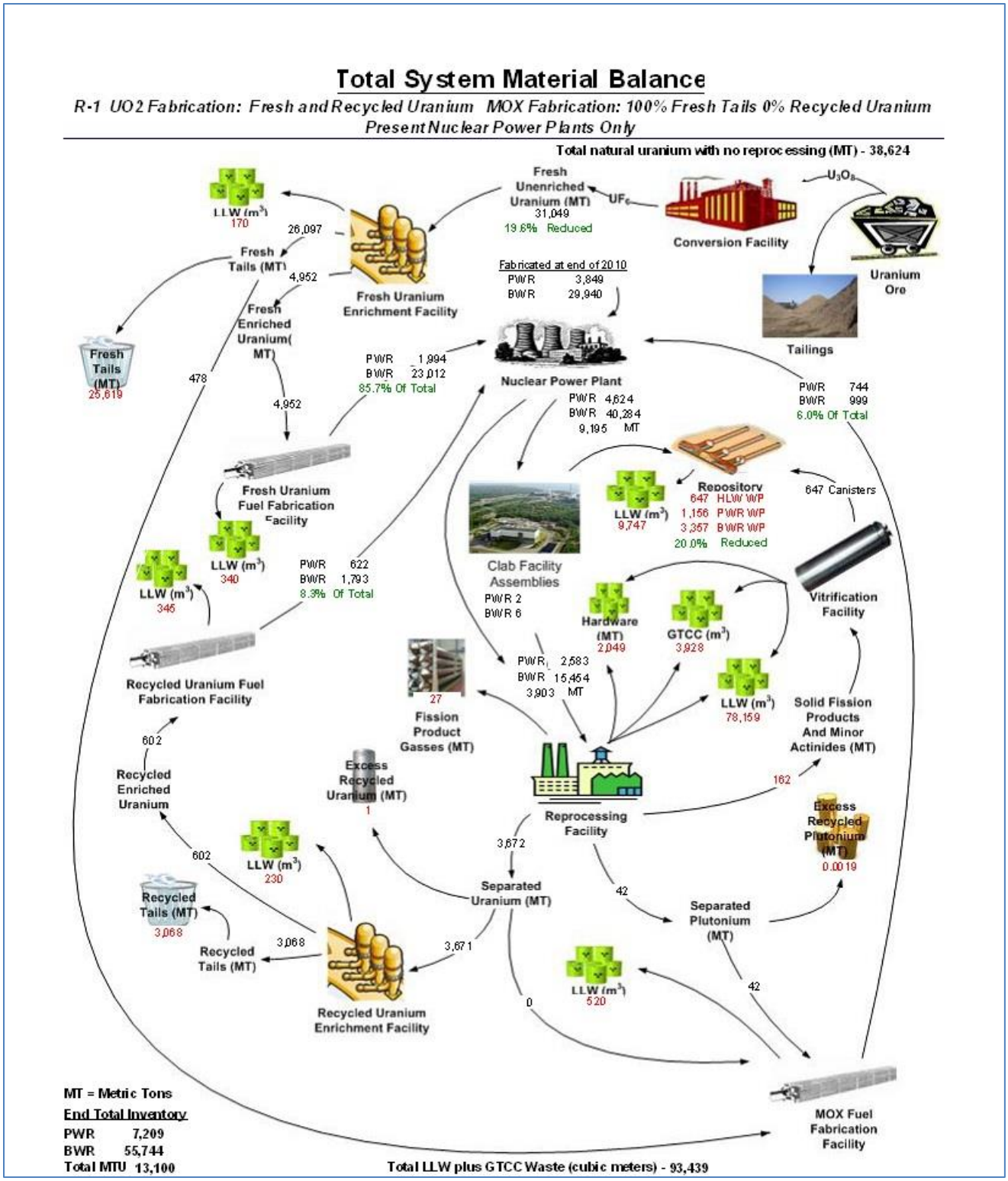
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 48 - Material Balance - Scenario 4.4



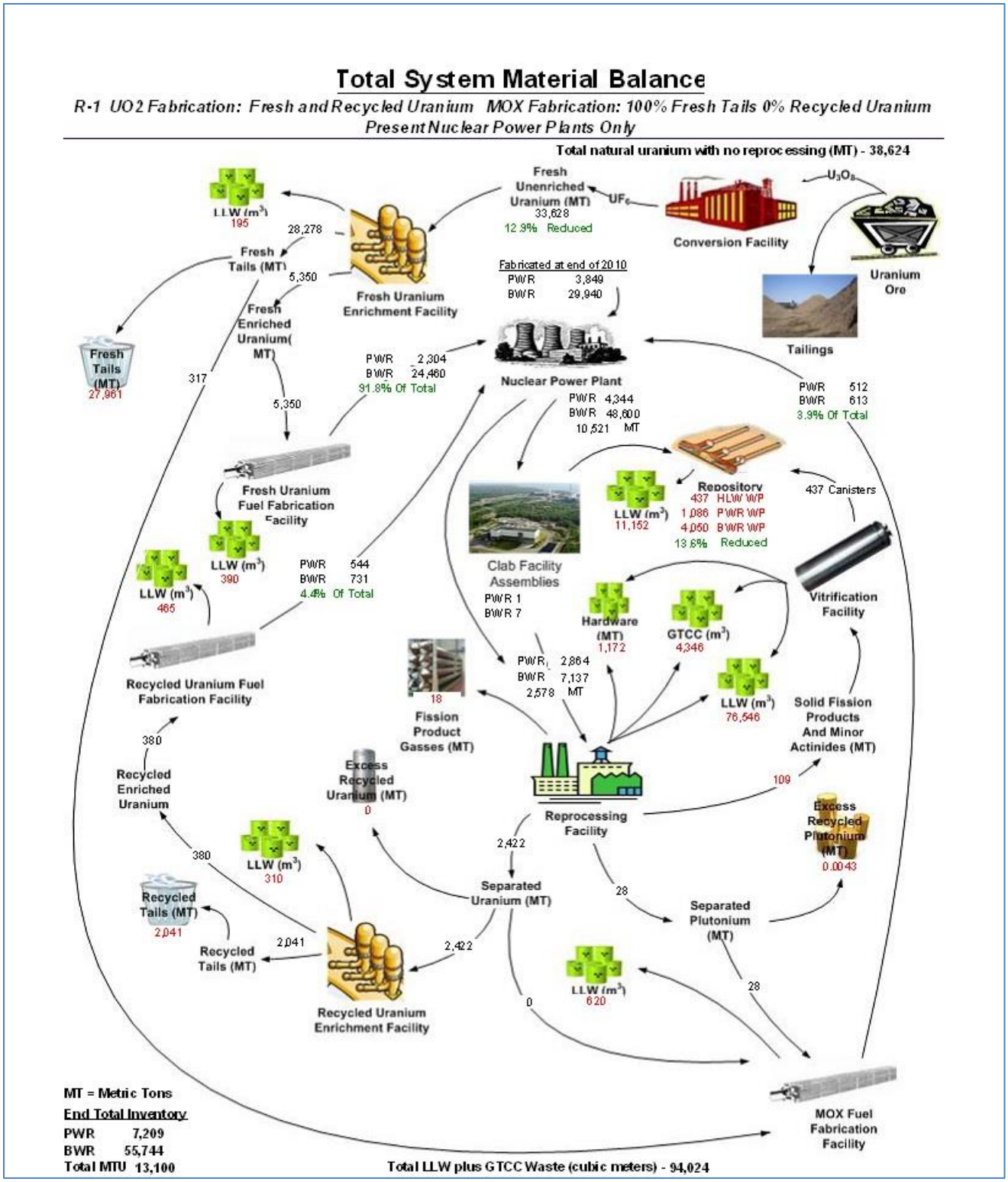
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 49 - Material Balance - Scenario 4.5



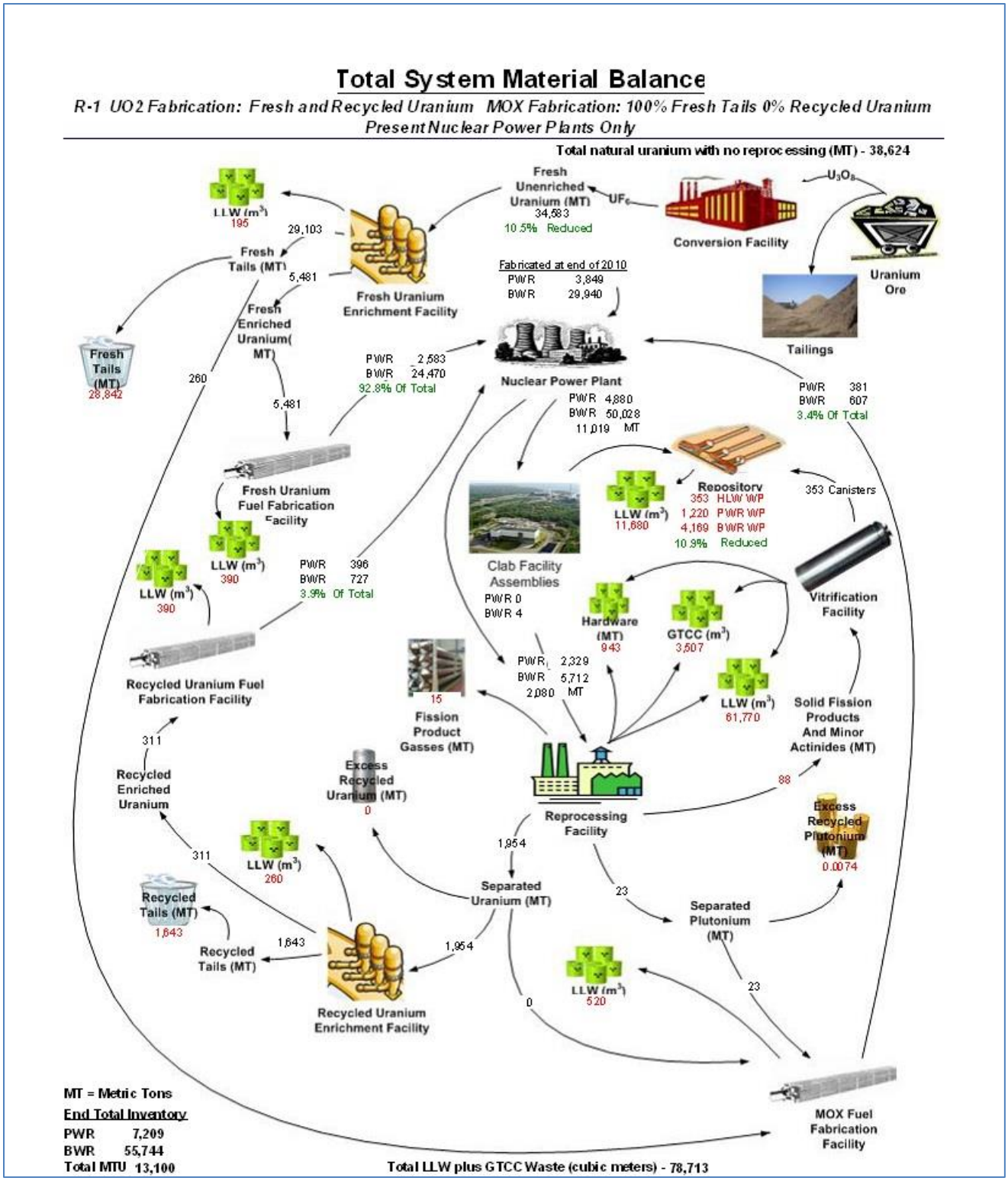
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 50 - Material Balance - Scenario 4.6



Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

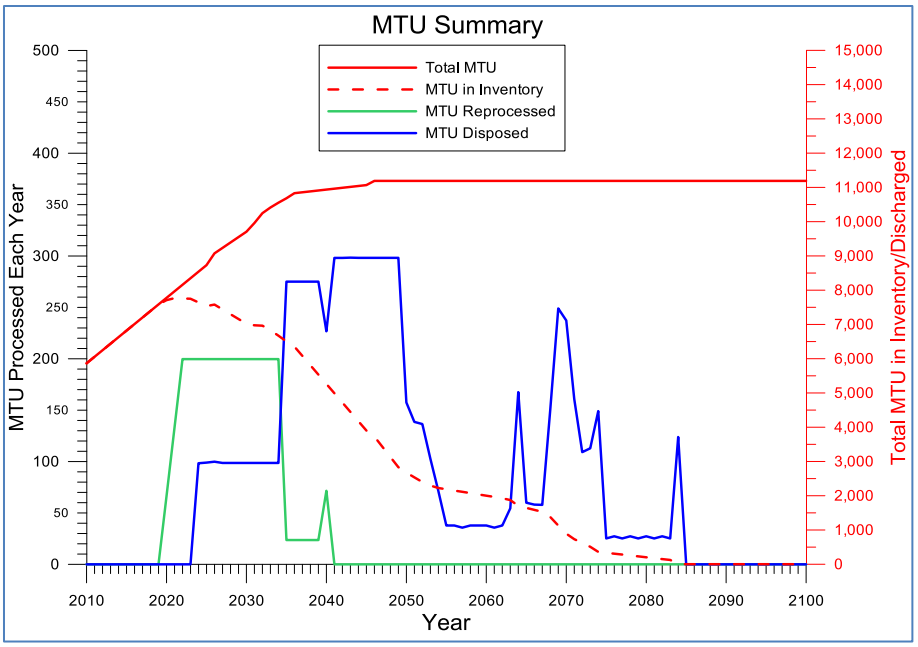
Figure 51 - Material Balance - Scenario 4.7



Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

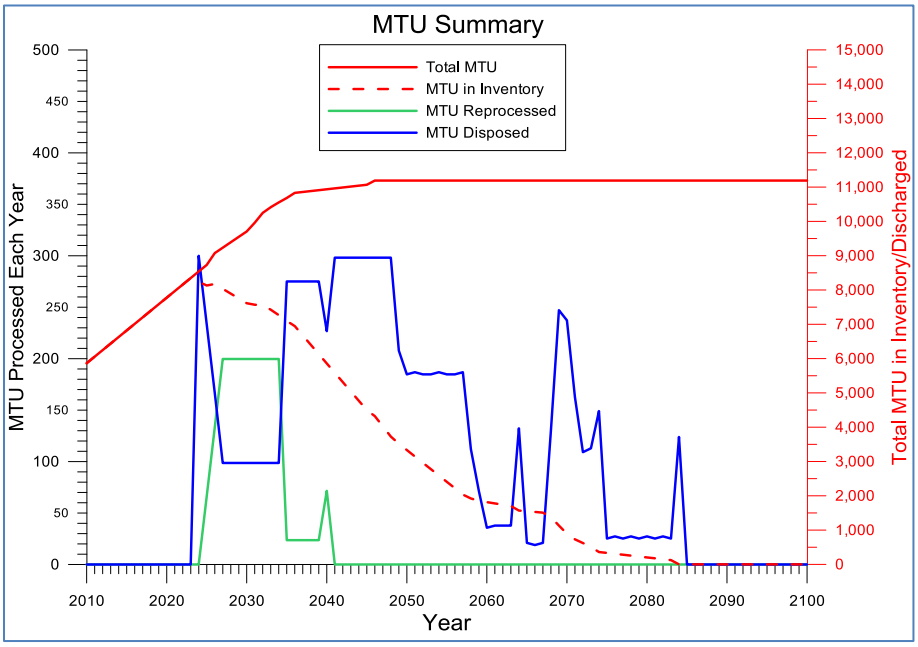
Figure 52 - Material Balance - Scenario 4.8

Appendix D – Annual Processing Results for Each Swedish Scenario



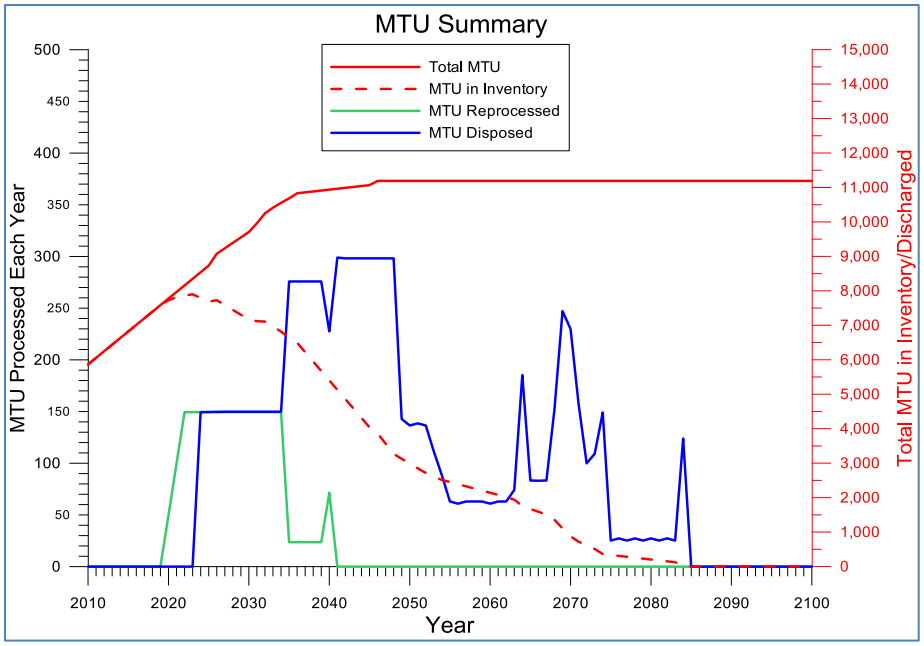
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 53 - Yearly Processing - Scenario 1.1



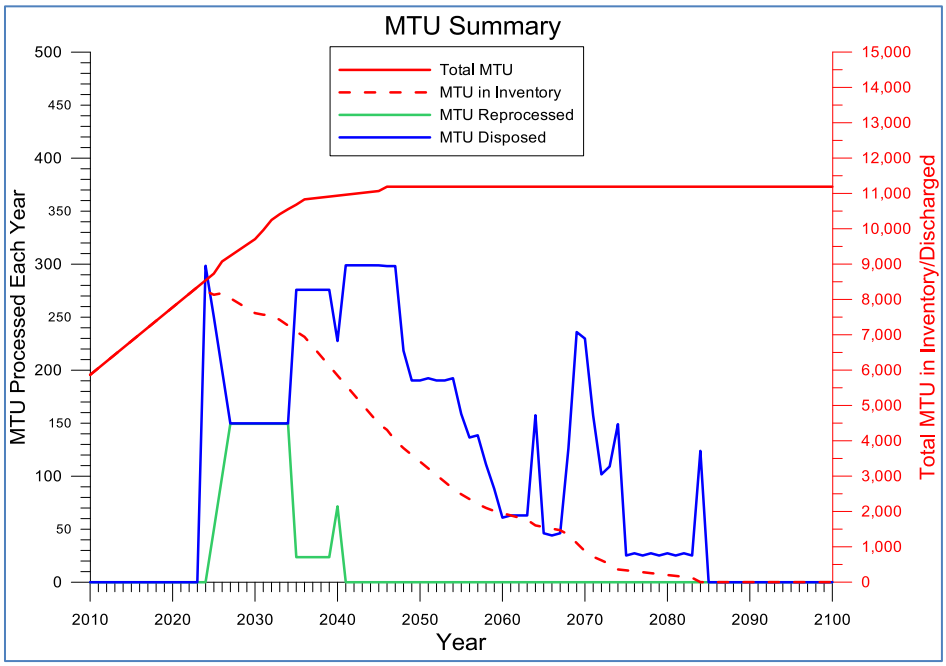
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 54 - Yearly Processing - Scenario 1.2



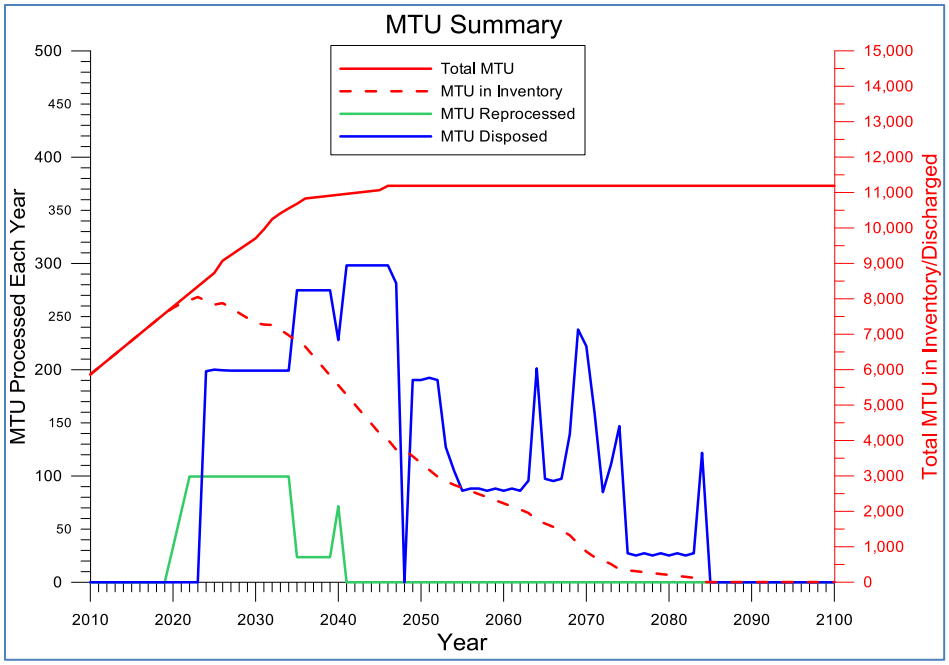
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 55 - Yearly Processing - Scenario 1.3



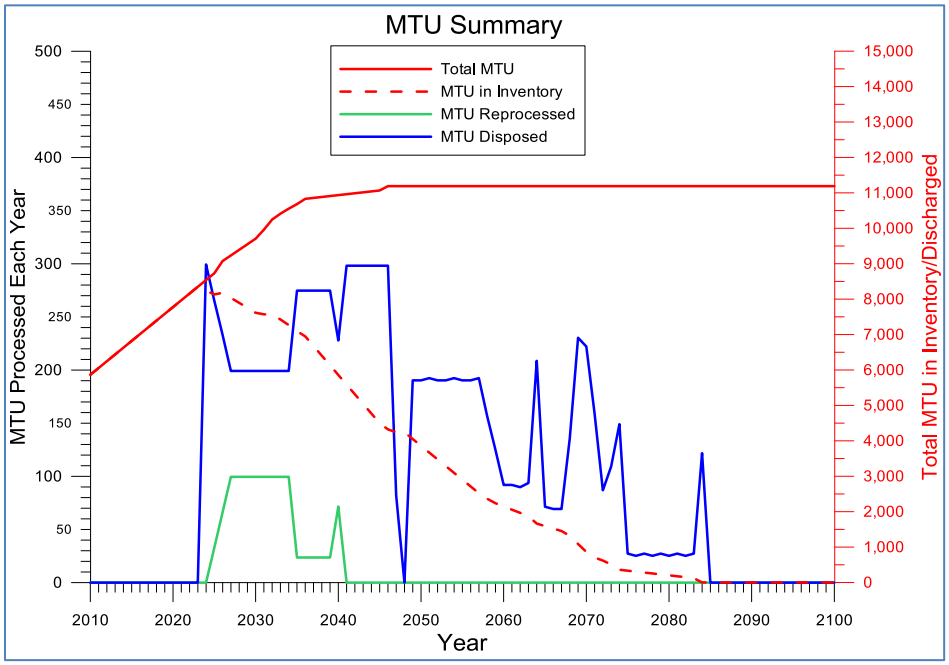
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 56 - Yearly Processing - Scenario 1.4



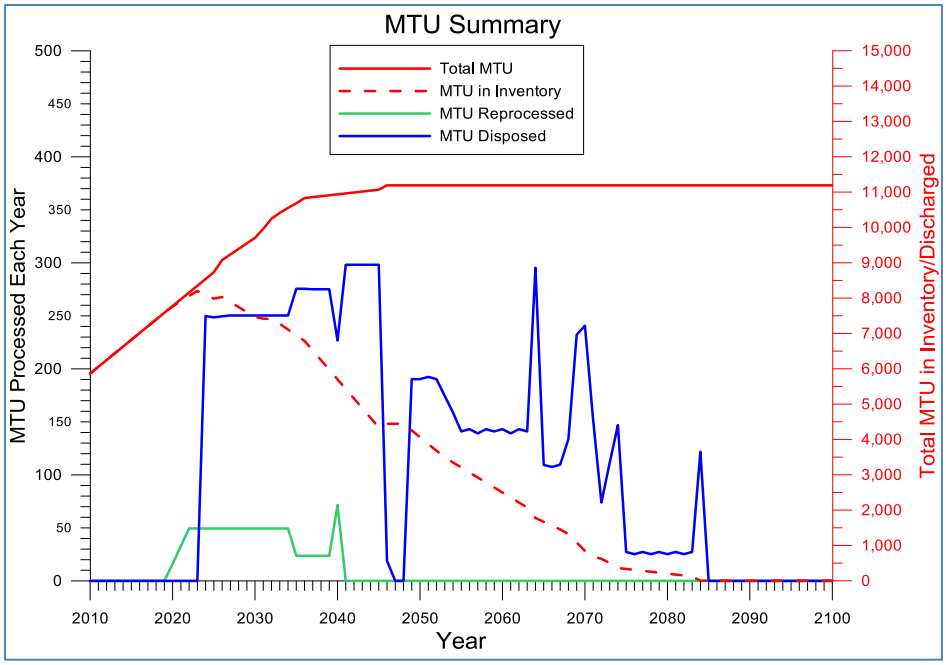
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 57 - Yearly Processing - Scenario 1.5



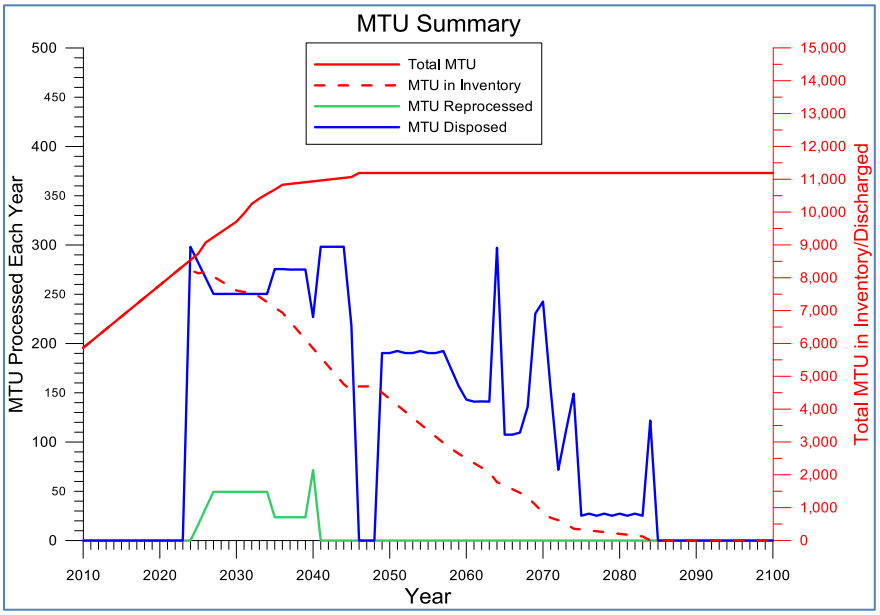
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 58 - Yearly Processing - Scenario 1.6



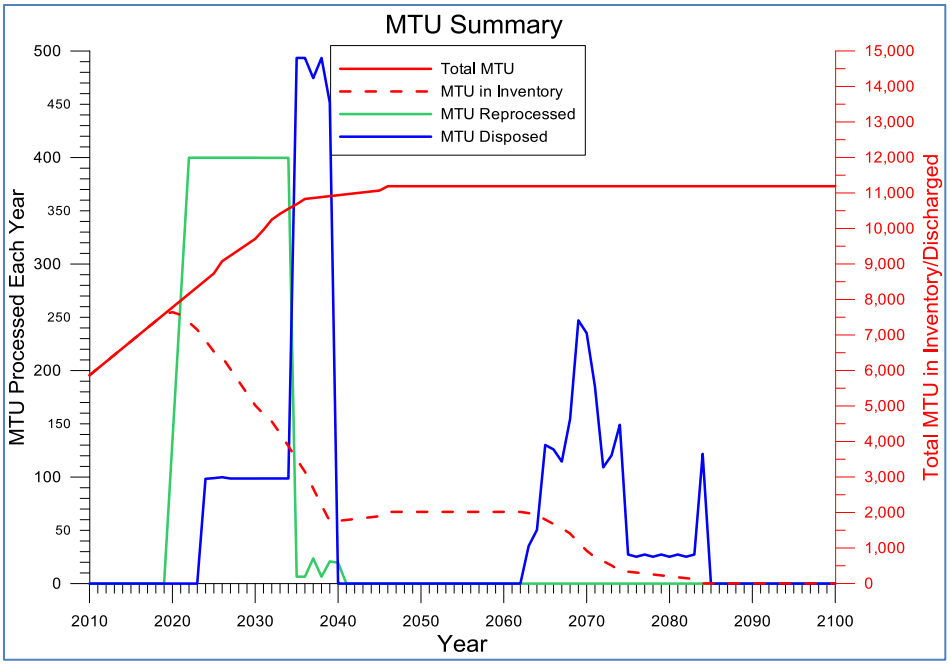
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 59 - Yearly Processing – Scenario 1.7



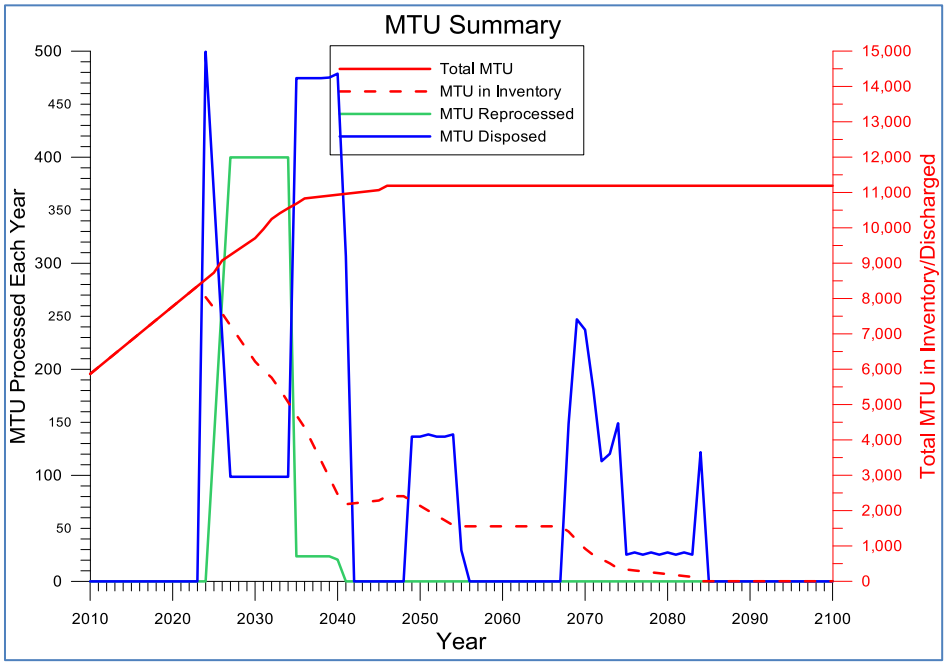
Plant operating period – 40 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 60 - Yearly Processing - Scenario 1.8



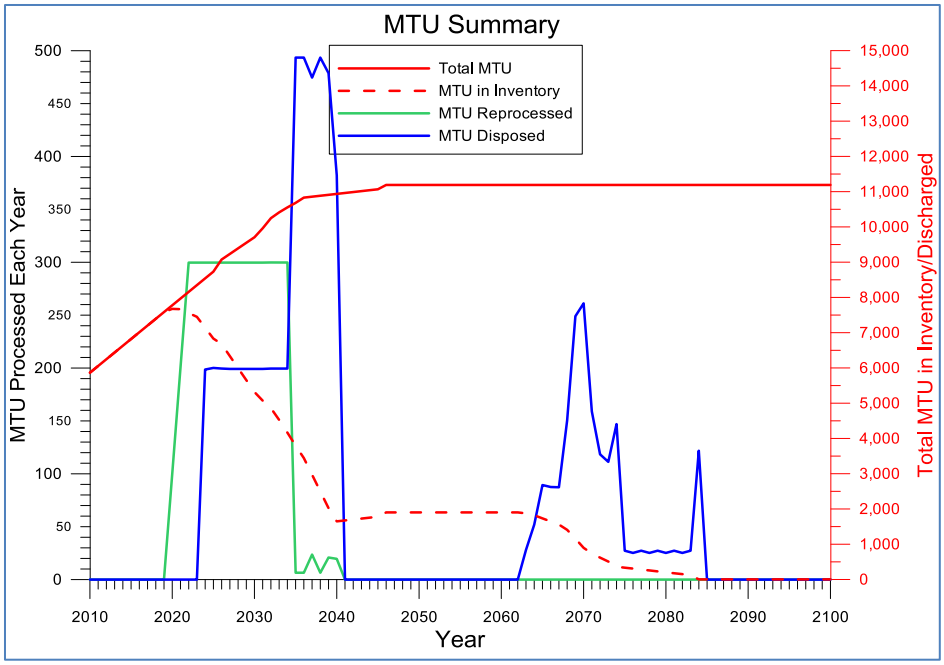
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 61 - Yearly Processing - Scenario 2.1



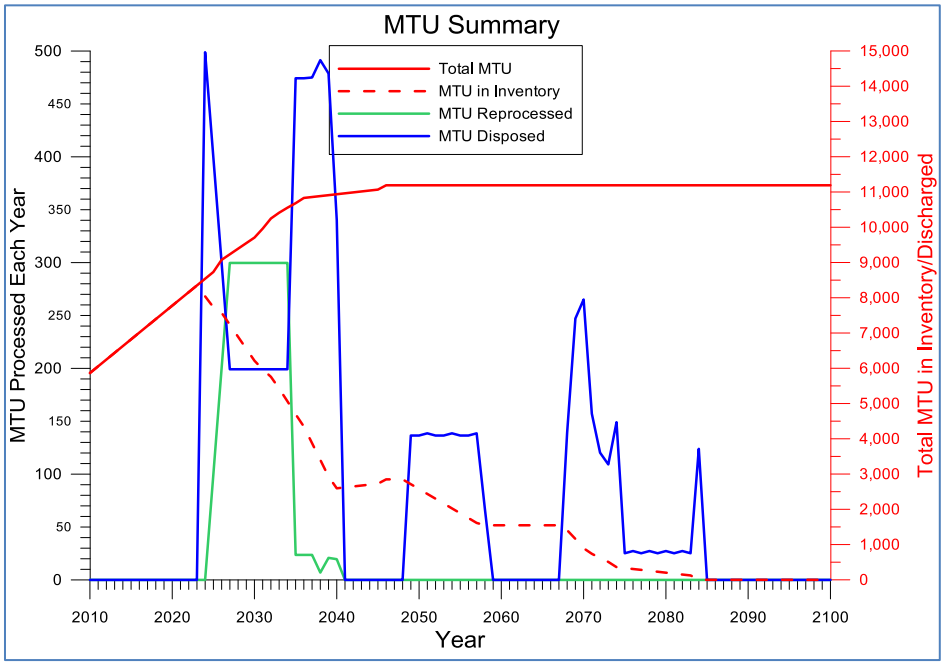
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 62 - Yearly Processing - Scenario 2.2



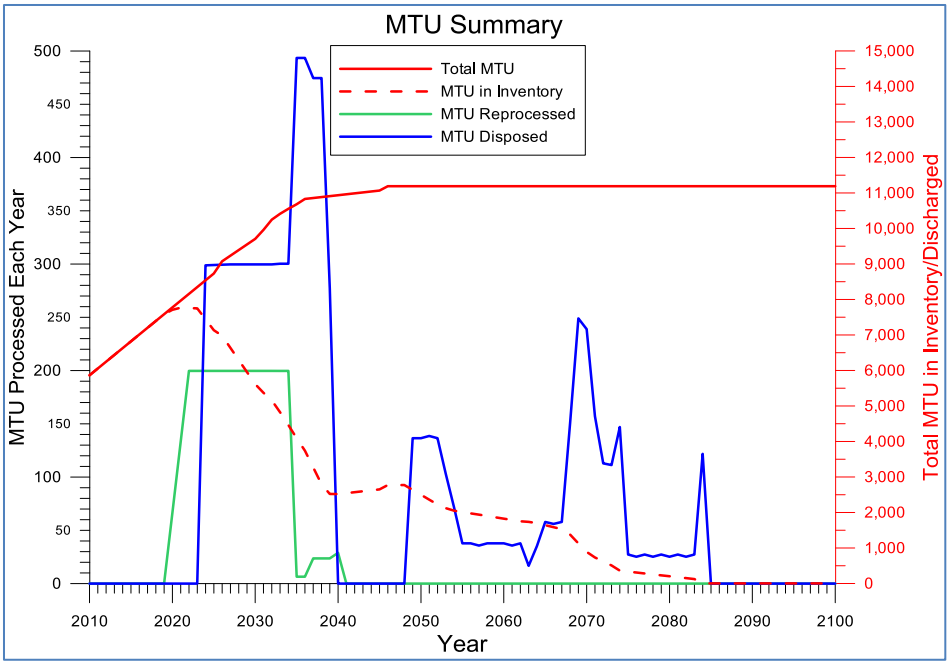
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 63 - Yearly Processing - Scenario 2.3



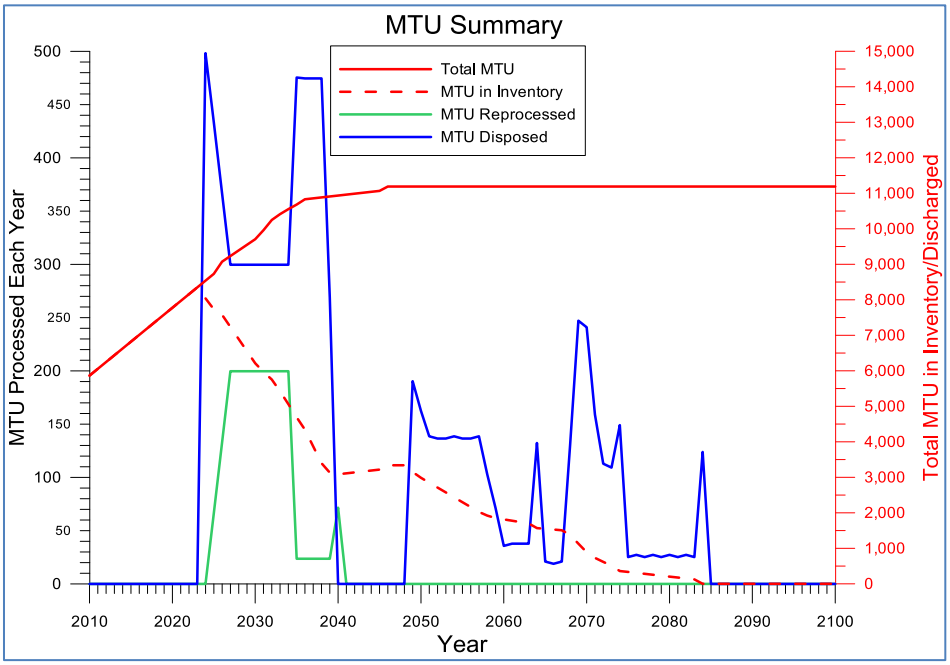
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 64 - Yearly Processing - Scenario 2.4



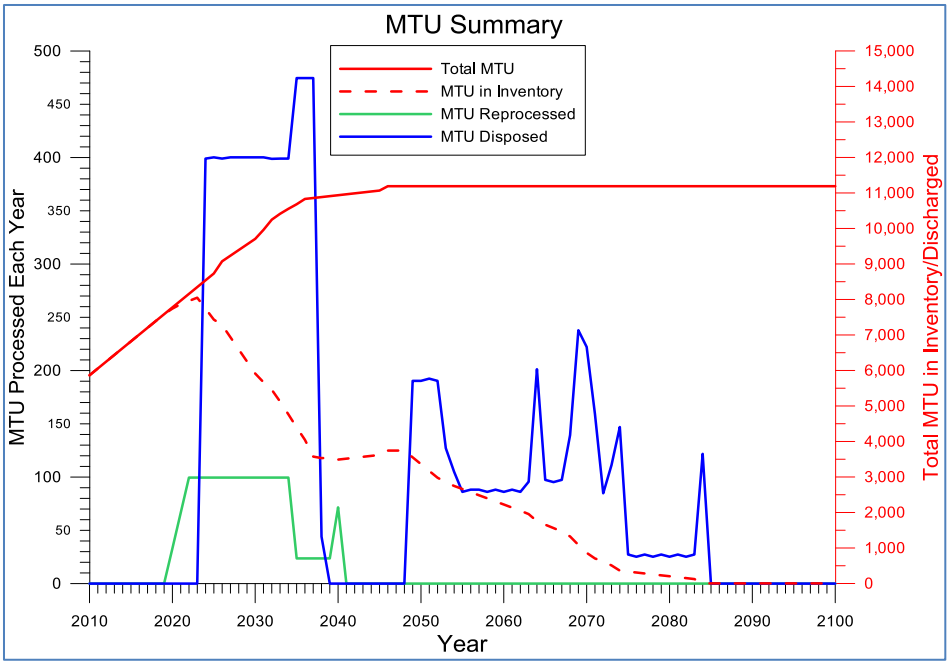
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 65 - Yearly Processing - Scenario 2.5



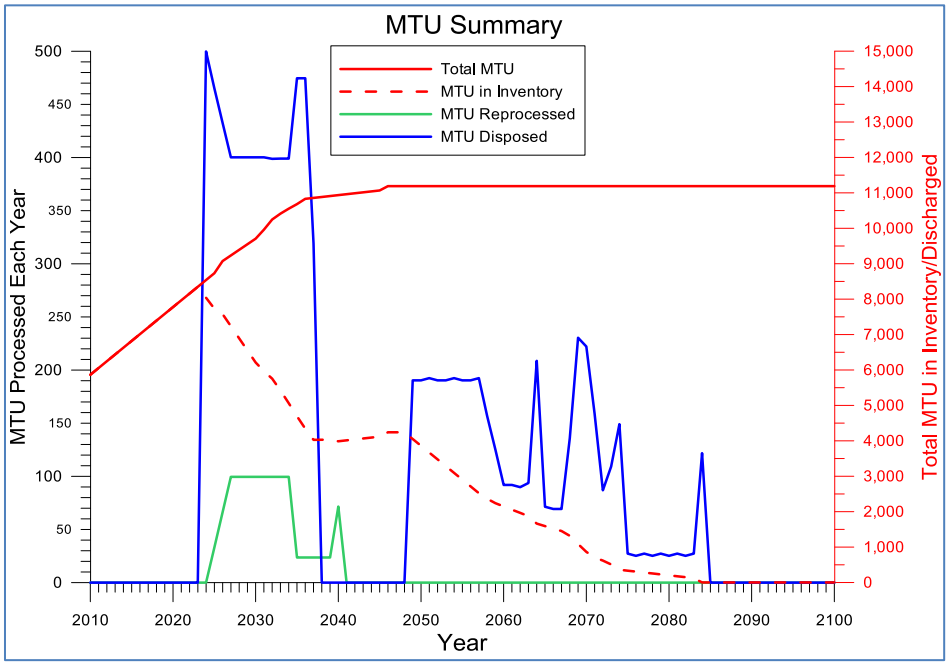
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 66 - Yearly Processing - Scenario 2.6



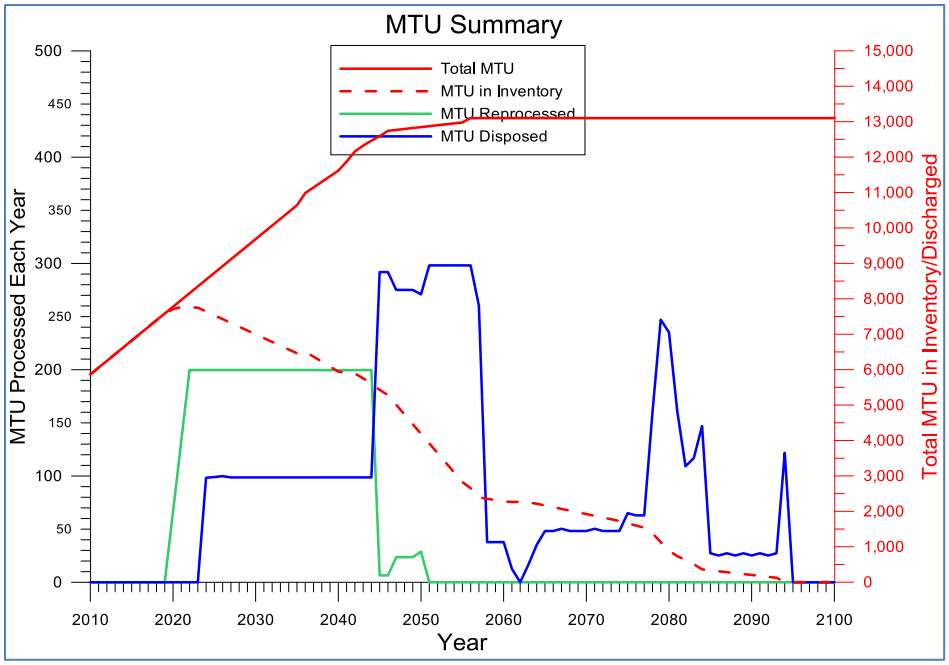
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 67 - Yearly Processing - Scenario 2.7



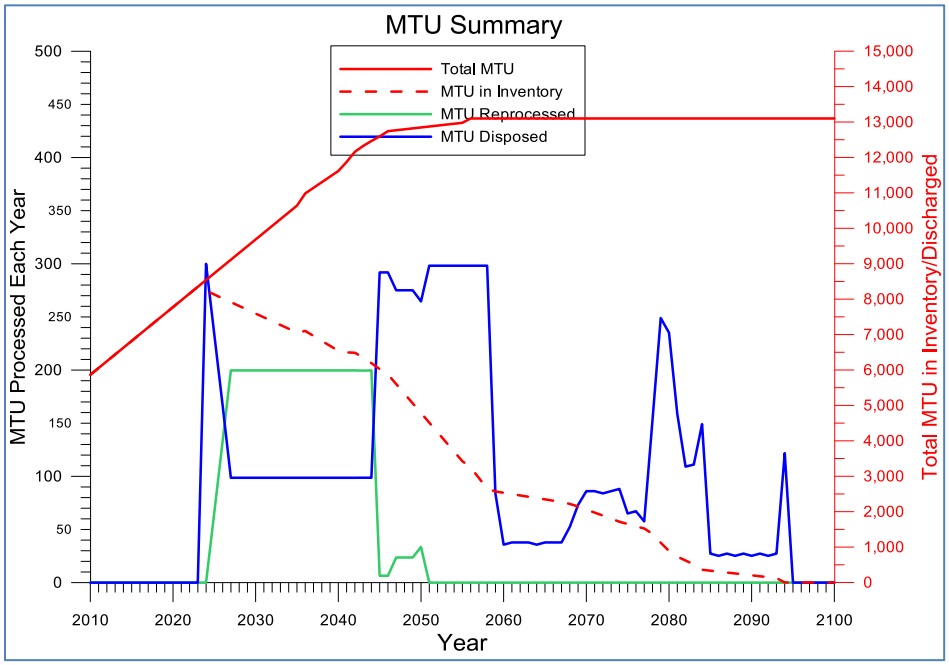
Plant operating period – 40 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 68 - Yearly Processing - Scenario 2.8



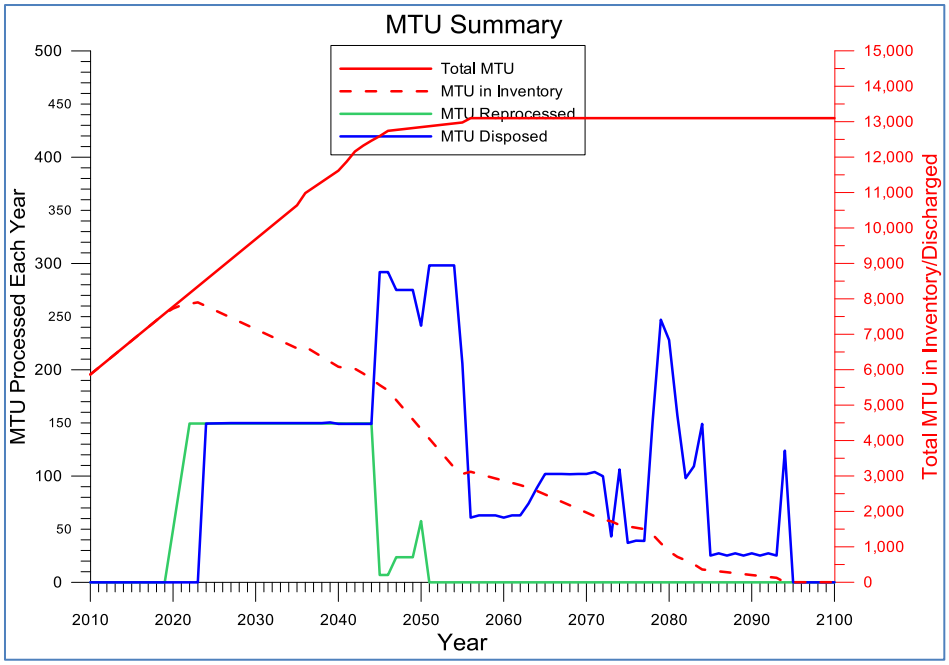
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 69 - Yearly Processing - Scenario 3.1



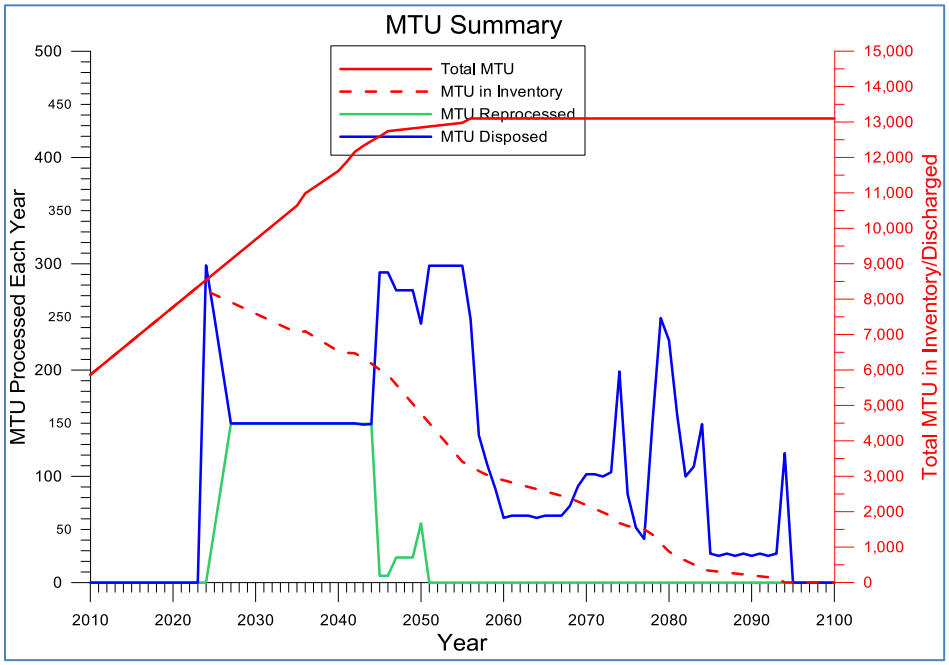
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 70 - Yearly Processing - Scenario 3.2



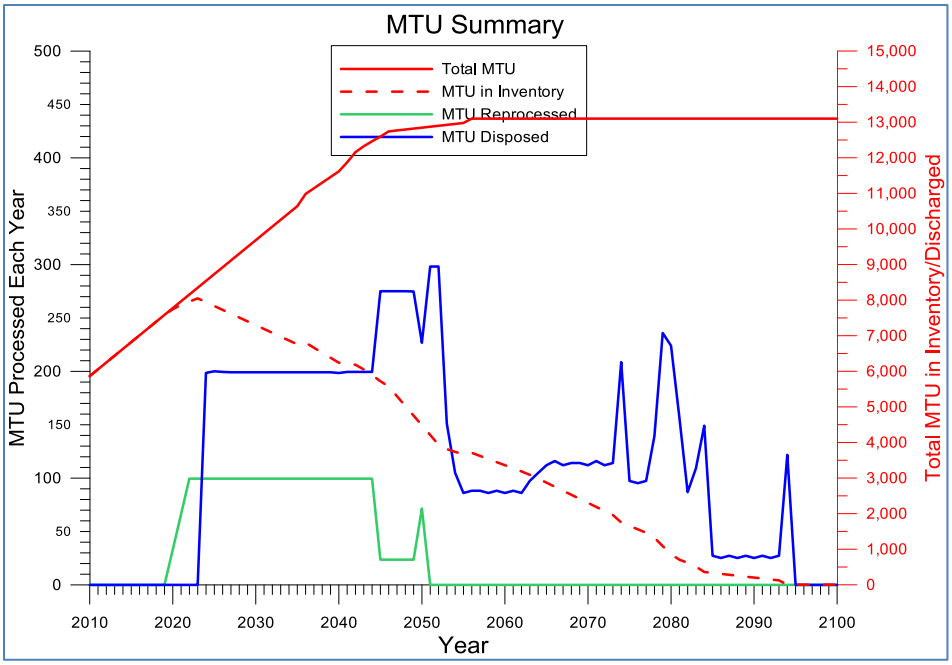
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 71 - Yearly Processing - Scenario 3.3



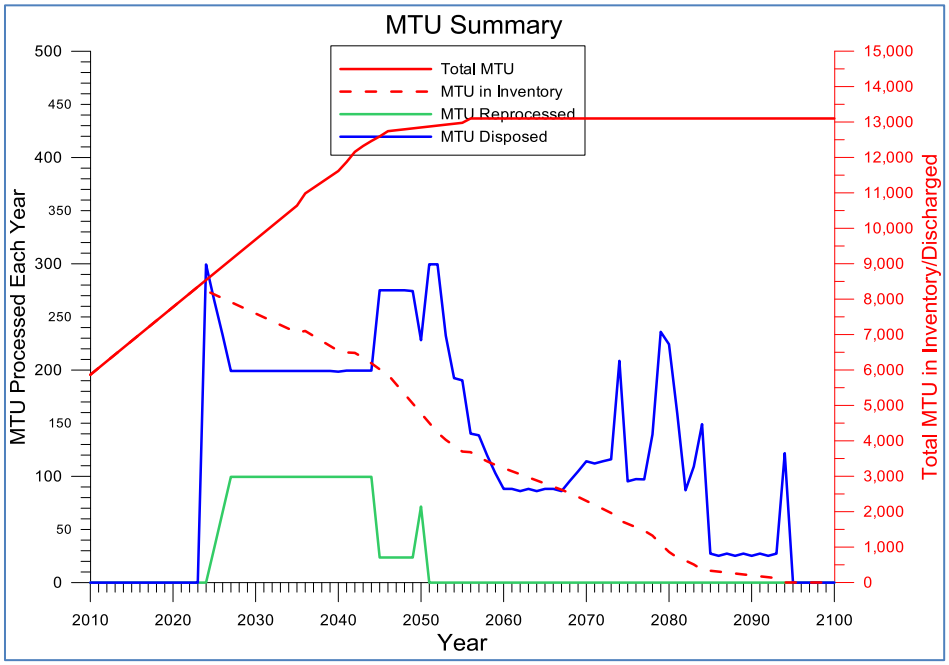
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 150 MT/year
Disposal Starts in 2023

Figure 72 - Yearly Processing - Scenario 3.4



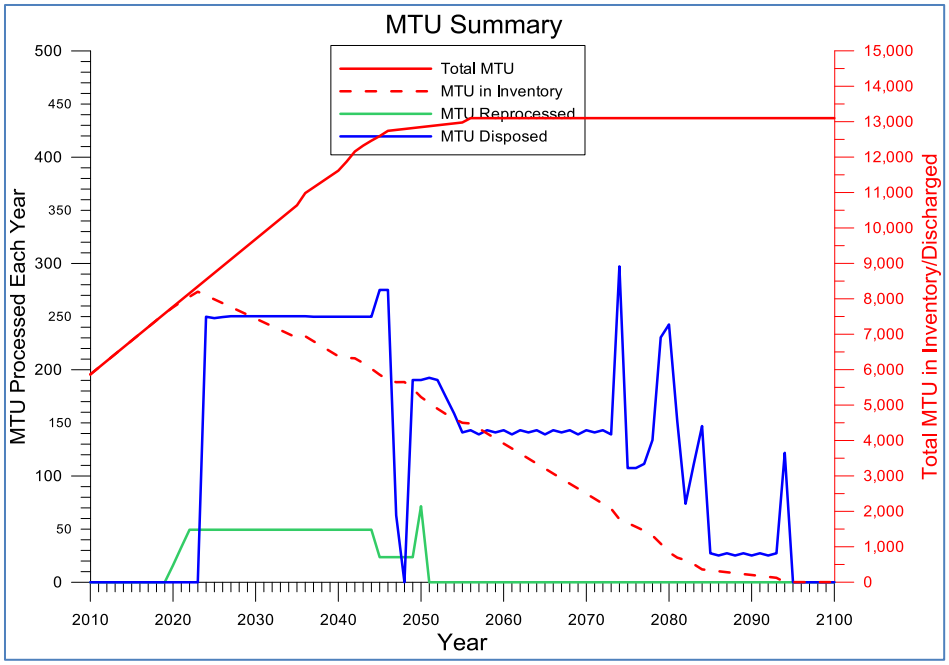
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 73 - Yearly Processing - Scenario 3.5



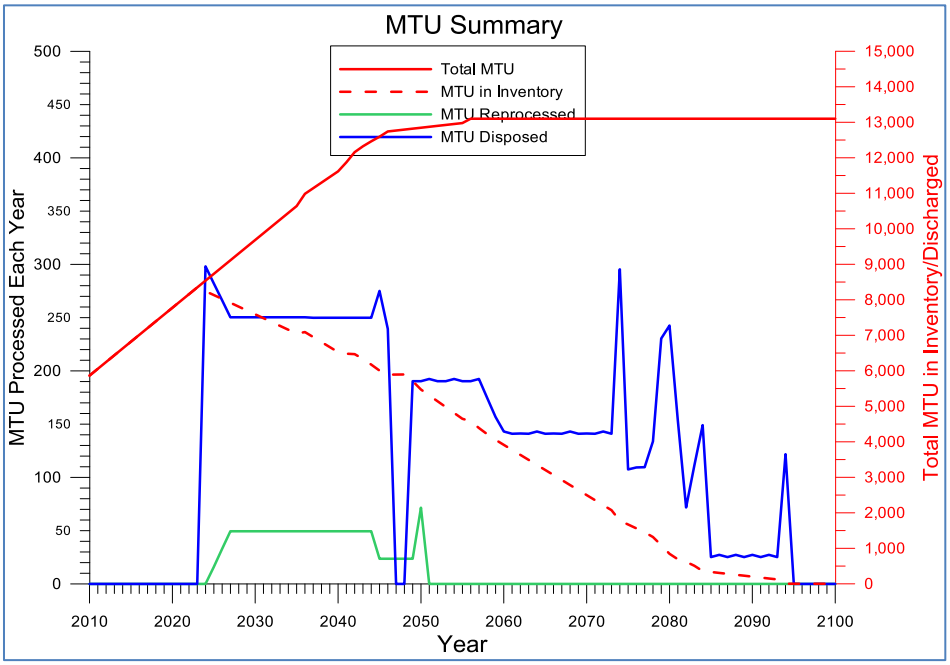
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 74 - Yearly Processing - Scenario 3.6



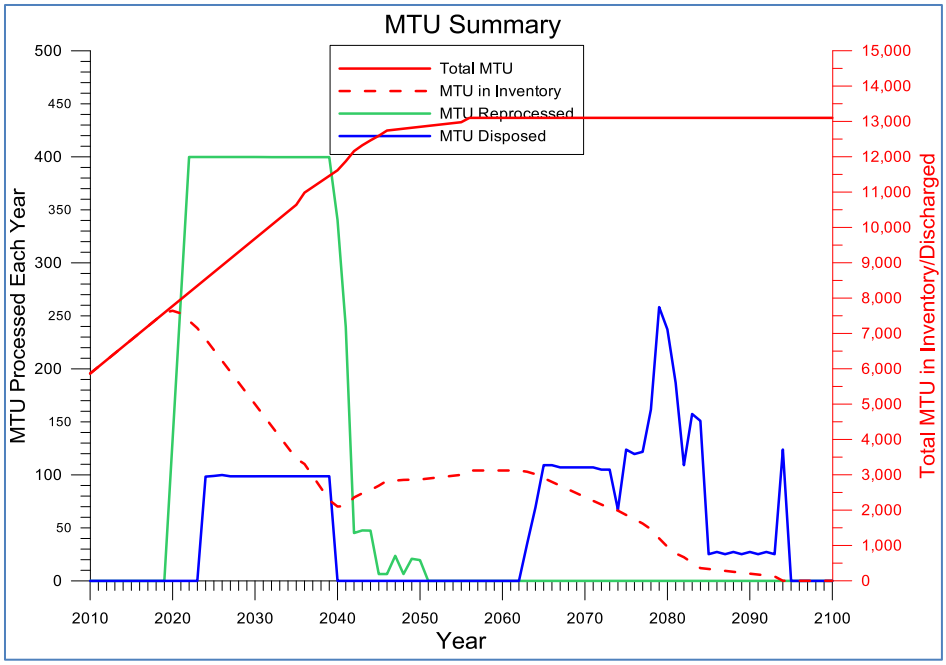
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2020 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 75 - Yearly Processing - Scenario 3.7



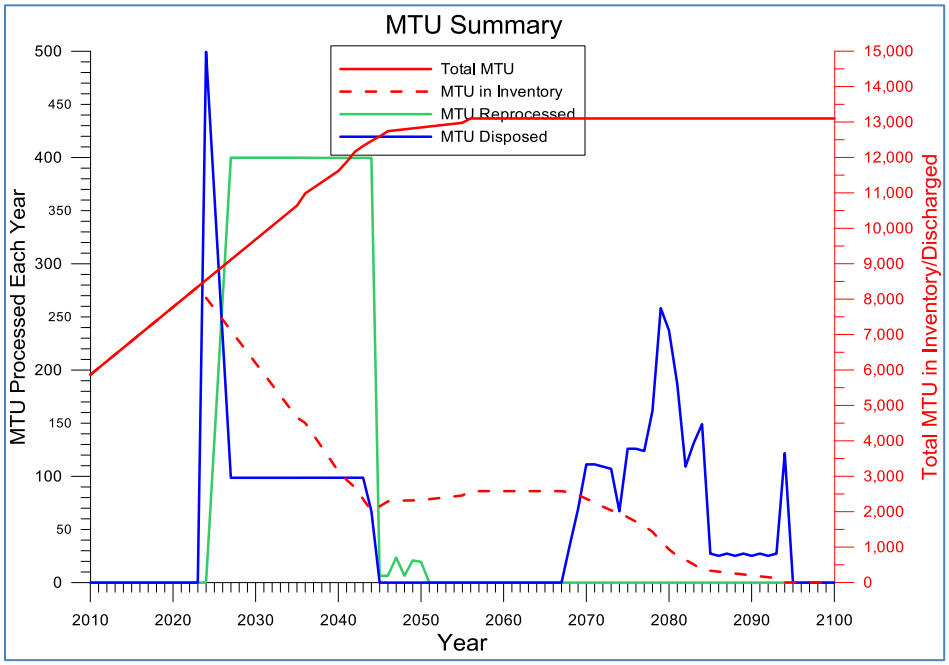
Plant operating period – 50 years
Maximum total transportation rate 300 MT/year
Reprocessing starts in 2025 at maximum rate of 50 MT/year
Disposal Starts in 2023

Figure 76 - Yearly Processing - Scenario 3.8



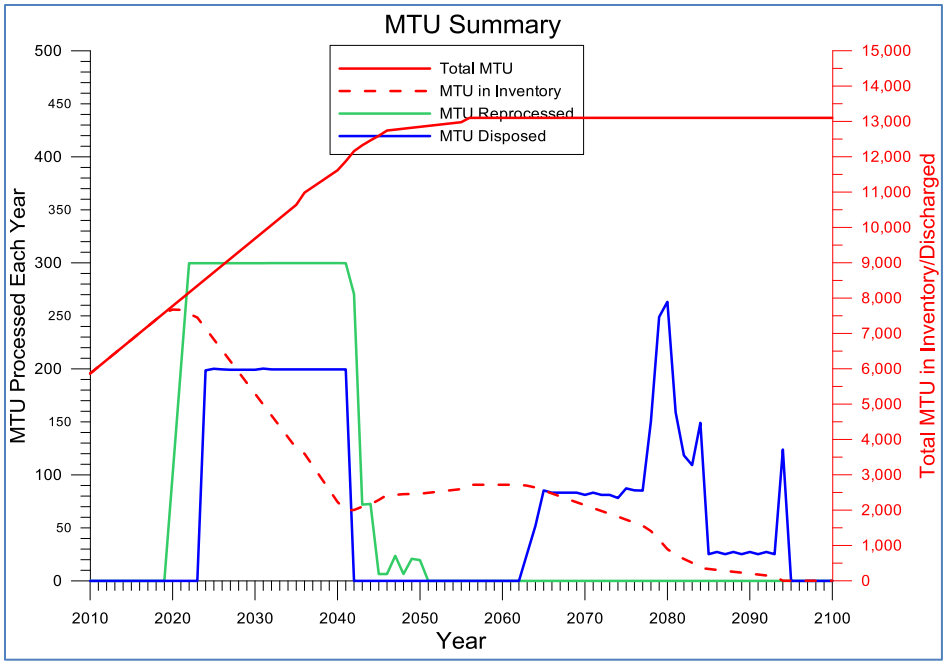
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 77 - Yearly Processing - Scenario 4.1



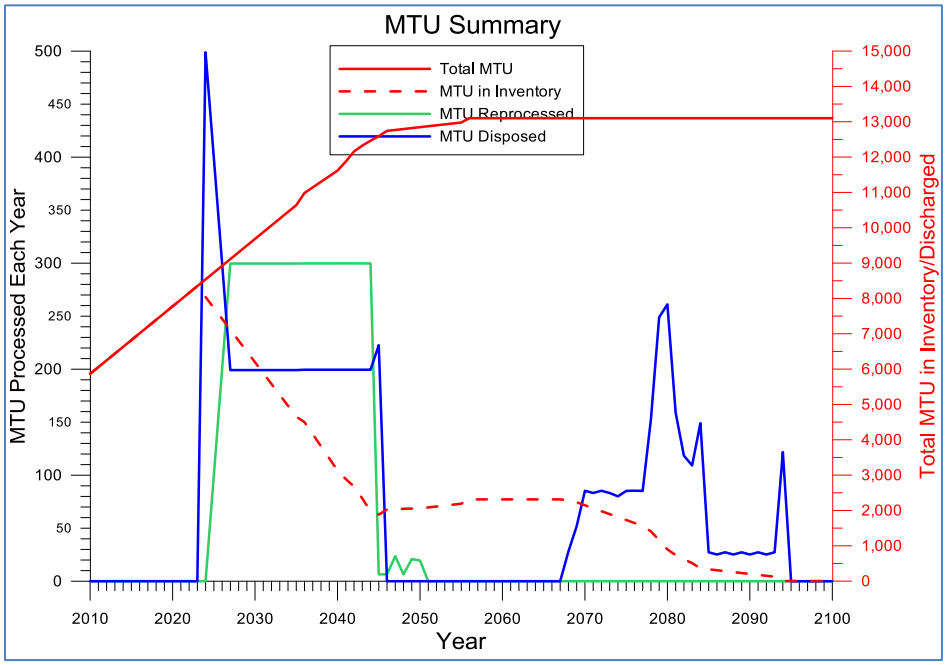
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 400 MT/year
Disposal Starts in 2023

Figure 78 - Yearly Processing - Scenario 4.2



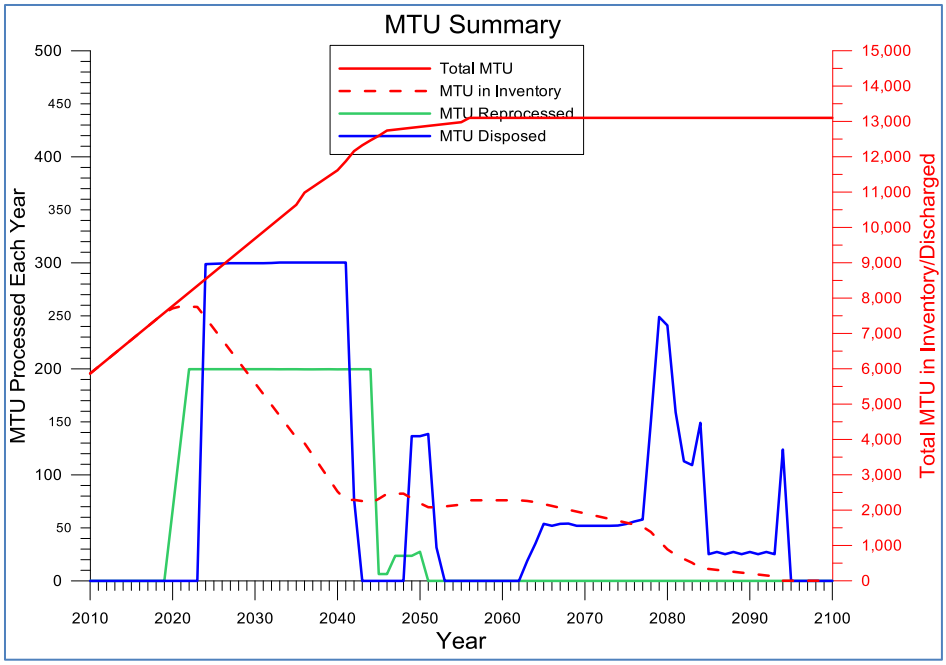
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 79 - Yearly Processing - Scenario 4.3



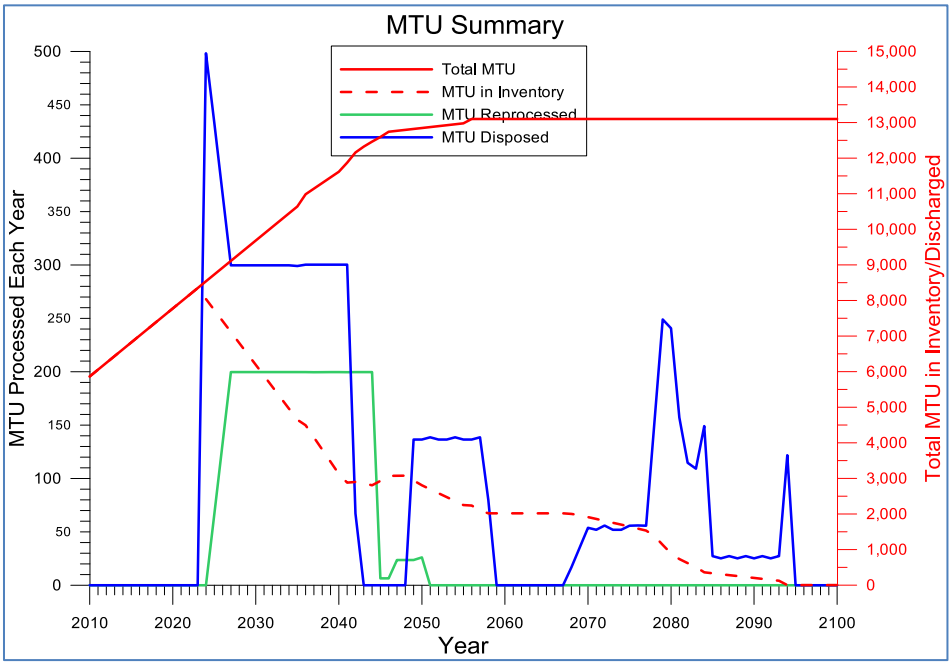
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 300 MT/year
Disposal Starts in 2023

Figure 80 - Yearly Processing - Scenario 4.4



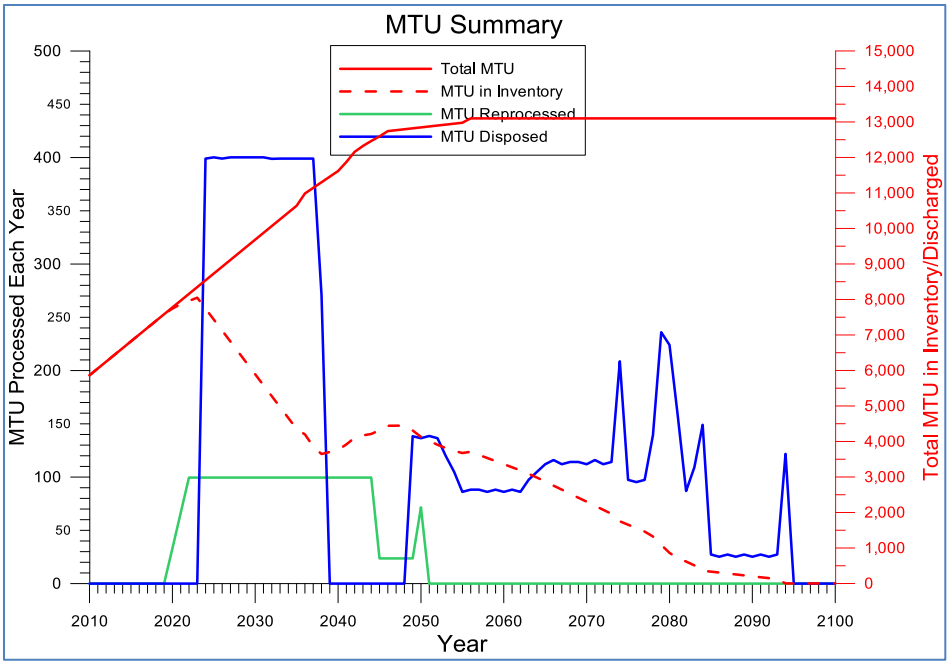
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 81 - Yearly Processing - Scenario 4.5



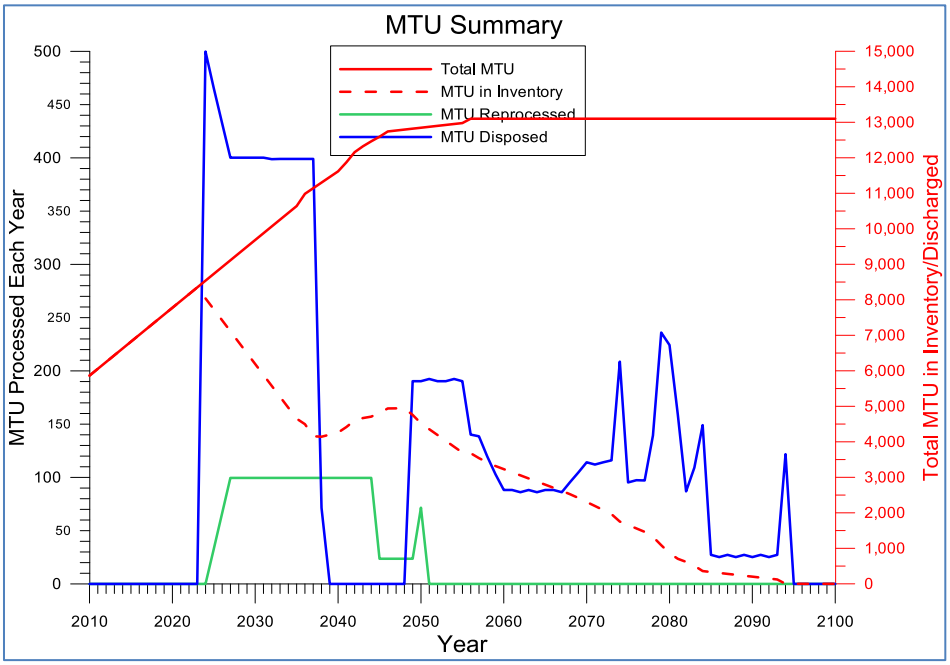
Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 82 - Yearly Processing - Scenario 4.6



Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2020 at maximum rate of 100 MT/year
Disposal Starts in 2023

Figure 83 - Yearly Processing - Scenario 4.7



Plant operating period – 50 years
Maximum total transportation rate 500 MT/year
Reprocessing starts in 2025 at maximum rate of 200 MT/year
Disposal Starts in 2023

Figure 84 - Yearly Processing - Scenario 4.8