IMPACT OF SEPARATION CAPACITY ON TRANSITION TO ADVANCED FUEL CYCLES.

A Thesis
Presented to
The Academic Faculty

by

Abiodun Idowu Adeniyi

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Nuclear and Radiological Engineering in the
School of Mechanical Engineering

Georgia Institute of Technology
May 2013

IMPACT OF SEPARATION CAPACITY ON TRANSITION TO ADVANCED FUEL CYCLES.

Approved by:

Dr. Bojan Petrovic, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Nolan Hertel
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Weston Stacey
School of Mechanical Engineering
Georgia Institute of Technology

Date Approved: March 15th, 2013

This work is dedicated to the memory of my late parents: Chief Oludayo Depomu, Mrs. Aduke Oludayo, Dr. Ademola Odubela, and Mrs. Nuratu Odubela, for their support, and encouragement, which sent me on the path of this achievement.

ACKNOWLEDGEMENTS

This thesis work would not have been possible without the immense guidance of Professor Bojan Petrovic, my advisor. He was not only supervising my research work, he provided many valuable advices. He exposed me to academia and nuclear industry, and helped established industrial contacts and internships. His expertise in nuclear fuel cycle helped defined the scope of my work.

I would like to thank my committee members, Professor Weston Stacey and Professor Nolan Hertel: both are outstanding professors. My first visit to a national laboratory was made possible through Professor Hertel. Professor Stacey’s patience and advice did help put my career back on track twice!

I would also like to thank my wife; Foluso, and my children; Semilore, Inioluwa and Ifeoluwa for their love, understanding and unflinching support throughout this period. I never had enough time for anyone of them during the period of this work. I love you all and promise to make up for the lost time.

I also want to thank my friends; Cal Abel, Tim Flaspoehler, David Koch, Bop Andrew, Adam Lord, Mickum Spenser, Dr. Kevin Connolly, Saam Yasseri, Prof. Femi Omitaomu, Pastor Joe Takon. Some contributed tutorial hours, moral and material support, while other contributed prayers and spiritual guidance.

A special thanks to Mrs. Glenda Johnson of the School of Mechanical engineering, she was an outstanding administrator. Dr. Comas Haynes, FACES coordinator for both financial and moral support. Dr. Steve Piet and Dr. Jake Jacobson both of INL for their help and advice on VISION.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1TFC	One tier advanced fuel cycle
2TFC	Two tier advanced fuel cycle
AFCI	Advanced Fuel Cycle Initiative
Aq	Aqueous separation
BR	Breeding ratio
BU	Burnup, sometimes incorrectly used as burned uranium
BWR	Boiling water reactor, a type of Light Water Reactor (LWR)
COEX	Co-Extraction producing RU and UPu as products and everything else as a waste
CR	Transuranic Conversion Ratio (TRU produced/TRU destroyed)
CY	Calendar Year
DU	Depleted uranium, the low U235 tailings from uranium enrichment
E-chem	Electrochemical separation, also known as pyro-processing
EU	Enriched uranium, the high U235 produce from uranium enrichment
FP	Fission Product
FPY	Full Power Year
FuRe	Full recycling
GNEP	Global Nuclear Energy Partnership
GWe	Gigawatt-electric
GWth	Gigawatt-thermal
HEU	Highly enriched uranium
HLW	High level waste

IMF	Inert Matrix Fuel (thermal reactor fuel without uranium)
INL	Idaho National Laboratory
kT	Kilotonnes, one thousand metric tonnes
LCOE	Levelized cost of electricity
LFCC	Levelized fuel cycle cost
LLW	Low level waste
LSF	Legacy Spent Fuel, pre-2000 inventory of discharged LWR fuel
LUE	Low enriched uranium
LWR	Light Water Reactor
LWR-MF	Light Water Reactor Mixed Fuel, can use multiple fuels
LWR-MOX	MOX fuel in Light Water Reactors
MF	Mixed Fuel in a thermal reactor, e.g., MOX or IMF
MOX	Mixed Oxide fuel, (UOX and one or more e.g. MOX-Pu or MOX-TRU)
MRS	Managed (monitored) Retrievable Storage
PWR	Pressurized water reactor
RU	Recovered uranium from a separation process
SF	Spent Fuel, also called used fuel
SFR	Sodium cooled Fast Reactor
SWU	Separative Work Unit
TRU	Transuranics (Plutonium and higher on periodic table)
UOX	Uranium Oxide
UREX	Uranium Extraction
UREX+1	UREX; U and all-TRU as product streams, FP waste streams

UREX+2	UREX; U and NpPu as products, FP waste streams. AmCm as waste
UREX+3	UREX; U, NpPu, and AmCm as products, FP as waste
UREX+4	UREX; U, NpPu, Am, and Cm as products, FP as waste
VISION	Verifiable Fuel Cycle Simulation

SUMMARY

One of the proposed solutions to the issue of waste volume is to transition from once through nuclear fuel cycle to advanced fuel cycles with used fuel recycling option. In any advanced fuel cycles with recycling options, the type and amount of separation technology deployed play a crucial role in the overall performance of the fuel cycle.

In this work, a scenario study involving two advanced fuel cycles in addition to the once through fuel cycle were evaluated using VISION nuclear fuel cycle simulation code. The advanced fuel cycles were setup to transition completely to full recycling without any light water reactor by assuming all LWR currently in operation will have 20 years of operating life extension and no new LWR will be constructed thereafter. Several different separation capacities (1kT/yr, 2kT/yr and 4 kT/yr) were deployed and the overall impact of these capacities was analyzed in terms of resources utilization, used fuel and waste material generated and the amount of storage space required. Economic parameter (LCOE, LFCC, etc) analysis was also performed using VISION.ECON.

Results presented in this work suggest that the need for LWR-UNF storage can be minimized if sufficient separation capacity is deployed early in the fuel cycle. It can also be concluded that a FuRe system without LEU will not be feasible, thus SFRs must be designed for optional use of LEU fuel. Otherwise LWRs must continue to be part of the mix to keep the near term cost of generating electricity competitive.

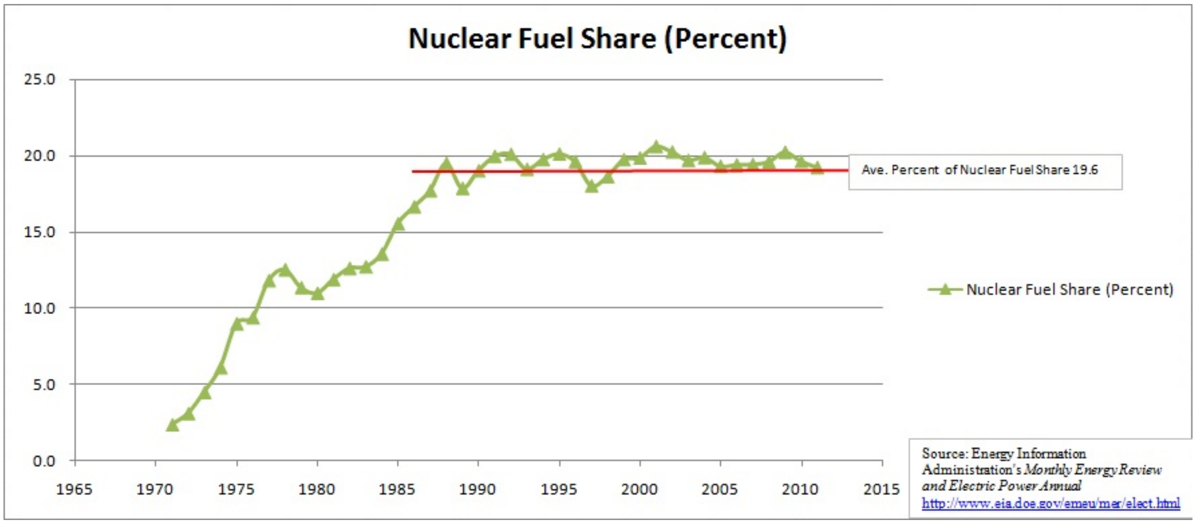
It was observed that the higher amount of separation capacity deployed in the advanced fuel cycles led to higher LFCC and LCOE, but also translates into less environmental impact on both front and back end of the fuel cycle.

CHAPTER 1

INTRODUCTION

1.1 Impact of Nuclear Energy

Nuclear Energy is an important source of energy in the United States (US), contributing on average about 20% of total energy production over the last two decades [1]. It is estimated that this proportion will hold over the next few decades, Fig. 1.1, in order to hold the status quo, while comprehensive national energy policy (described as an "all of the above approach" energy policy) is being developed.



Source: Energy Information Administration's *Monthly Energy Review and Electric Power Annual* http://www.eia.doe.gov/emeu/mer/elect.html

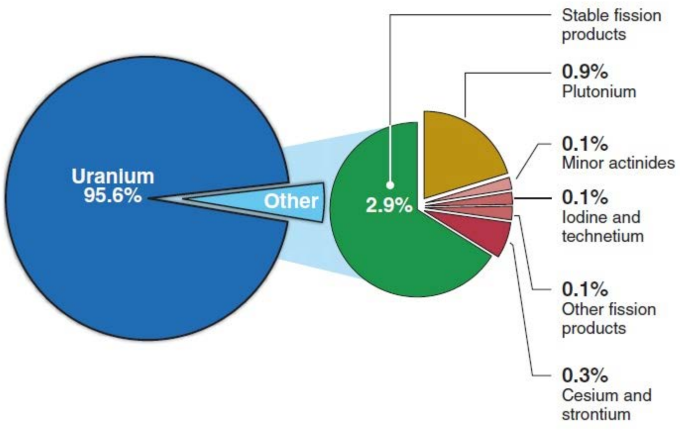
Figure 1.1: US nuclear generating statistics 1971 – 2011 [1]

Nuclear energy is one of the few environmental friendly sources of energy; emitting close to zero greenhouse gases, generating highly compact waste streams (current waste imbroglios are political not technical), and has a limited environmental footprint on land. Nuclear energy industry (and its coattails effect) generates significant non-outsourceable economic benefits during the entire life-cycle of the nuclear power plant. Nuclear energy therefore for all its merits will continue to be part of the energy mix of the US.

1.2 US Nuclear Energy Resource Use

The used nuclear fuel (UNF) is estimated at 42,616 metric tons in 2000 [2] and growing at an annual rate of ~2,000 metric tons; will continue to be stored in above-surface storage sites across the country, until a suitable final destination is built. The UNF was not supposed to be recycled according to the current US nuclear power policy, thereby creating a waste disposal nightmare in terms of disposal space requirement. If Yucca Mountain Repository had been completed, the design capacity for civilian nuclear waste would have been filled up by 2011 (assuming there is no limit on deposit rate), and a new repository required.

Less than1% of the energy content of uranium in nuclear fuel is actually extracted based on once through fuel cycle (OTC), with about 95% of recoverable energy locked up in UNF to be buried someday. Fig. 1.2 depicts a representative composition of UNF from a Light Water Reactor (LWR) after a once through cycle. The OTC does not use resources well, when compared to other alternative nuclear fuel cycles.



Source: GAO analysis of DOE data.

Figure 1.2: Composition of used nuclear fuel (UNF) [3]

It is therefore desirable to deploy nuclear fuel cycles that improve resources utilization, as is being done in France. There are on-going efforts to explore the possibility of deploying advanced nuclear fuel cycles: using advanced reactor technology, in the US that should increase the utilization of uranium resources. Most of these efforts suggest that a full recycling policy will be the most adequate, but full-scale commercial deployment of this technology may not occur until much later. This uncertainty in deployment timeframe led the department of energy (DOE) to define modified open cycles (MOC) in *DOE 2010 Nuclear Energy Research Development Roadmap* [4], these MOCs should achieve the following in terms of nuclear material utilization:

- *Improve uranium resource availability*
- *Improve uranium utilization*
- *Minimize waste generation, and*
- *Provide adequate capability and capacity to manage all waste produced.*

1.3 Nuclear Energy Resource Use Simulation

Analysis of nuclear fuel cycles are generally performed using either equilibrium (steady-state) model or dynamic model. In equilibrium model, constant mass flows are usually assumed and the analysis relies heavily on batch assumptions. For example the existence of perfectly operating reactors and other fuel cycle facilities, is assumed for all the facilities, regardless of technological readiness level, political and economic constraints. The time needed for nuclear fuel cycle (NFC) in equilibrium model to get to equilibrium state tends to be very long and as such is sometimes neglected. The equilibrium model however enables clear and direct comparison to be made between systems in different NFCs; it also offers the advantage of low level of uncertainties.

The dynamic model is time-dependent, and it is possible to simulate decades of realistic NFCs, while incorporating all necessary fuel cycle parameters. Dynamic models are most suitable to the study of NFCs where transitioning from one type of fuel cycle (e.g. once through cycle) to another, involving complex interdependence of many factors (e.g. 2 tier continuous recycling). Dynamic models help provide better ways to evaluate what-if scenarios, but have high level of uncertainty compared to equilibrium models.

Nuclear fuel cycle components interact in a very complex and dynamic ways and as a result are very difficult to analyze accurately using equilibrium models. To analyze this complexity, a tool capable of predicting future outcomes based on changes in different input requirements is needed. This tool is scenario study using dynamic models. Scenario study had been used successfully in financial and geopolitical studies to analyze policy impacts on financial instruments, environment, war outcome and effects and so on. Scenario studies present multiple outcomes from which the best outcome can be pursued as opposed to equilibrium analysis. In NFC application, scenario study facilitates transition analysis, thus giving valuable insight into long time performance of NFC components and especially how they interact during transition.

Different NFC scenario codes have been developed with the goal of studying different aspects of the NFC. The section below provides an overview of some of the existing codes. Most of the NFC Scenario codes are designed for commercial application and are therefore not publicly available for review.

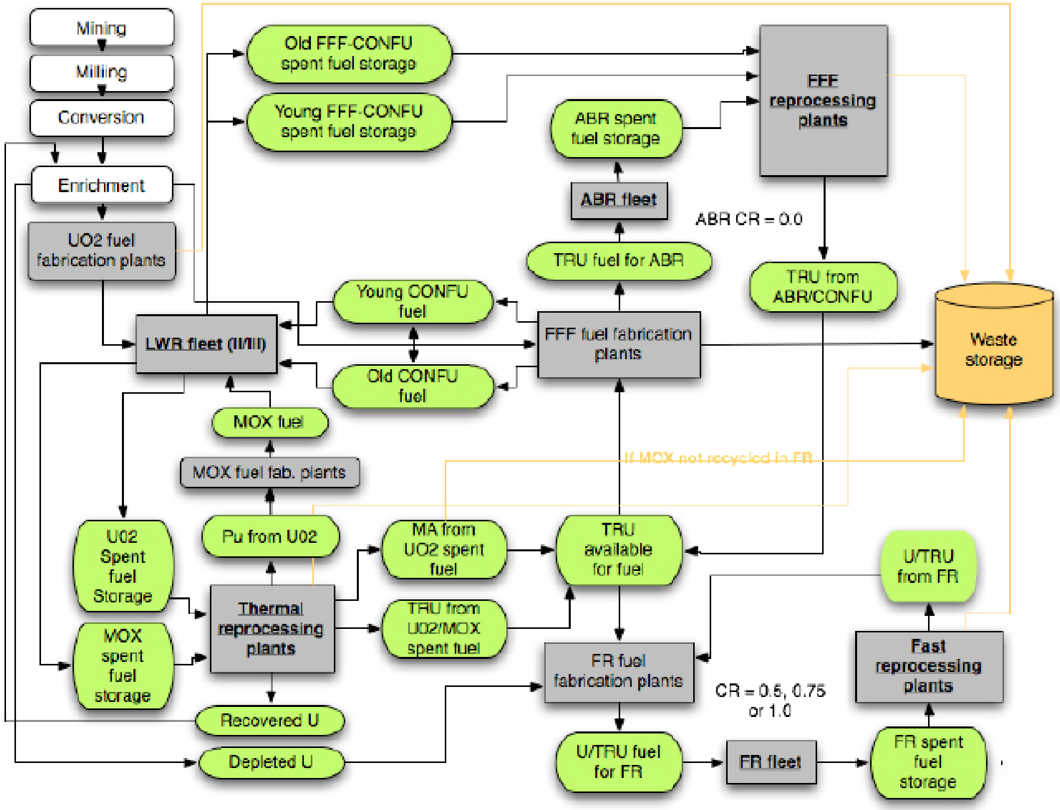
1.4 Review of NFC Scenario Codes

According to Juchau et al, [5], nuclear fuel cycle scenario codes can be categorized into annualized fuel tracking codes (equilibrium model); that track fuel material based on annual average mass flows, or discrete fuel tracking codes (dynamic model); which has the capability of tracking material movement in discrete fuel batches or assemblies.

The codes that track material discretely are more suitable for modeling individual as well as grouped nuclear facilities. When coupled with depletion codes, they can be used to model all the stages of NFC effectively. A key application will be for nuclear material proliferation resistance simulation, which requires that materials at various stages of fuel cycle be tracked discretely and in real time, using a well established transport model.

There exist different NFC codes built for different application in NFC studies. A review of some of the codes is presented below.

CAFCA (**C**ode for **A**dvanced **F**uel **C**ycles **A**ssessment) developed by MIT [6], as a nuclear fuel scenario codes designed for closing the nuclear fuel cycle. The current version of the code CAFCA-SD models NFC as a continuous flow among fleets of homogenous facilities, the CAFCA architecture is shown in Fig. 1.3. It has the capability for transuranic (TRU) recycling using actinide burning in the thermal spectrum using CONFU (COmbined Non-Fertile and UO_2) in LWR and Fast Spectrum fertile-free actinide burning in Actinide Burner Reactors (ABR). It also has isotopic composition tracking capability for radioisotope decay analysis in nuclear fuel cycle. It allows for simultaneous deployment of several nuclear technologies in the scenario and can simulate worldwide nuclear resources as well as regional nuclear resources, but lacks the ability to track material discretely from individual facilities. CAFCA also performs a limited economic analysis.



CAFCA high-level structure diagram: Inventories (rounded rectangles), mass flows (arrows) and facilities (grey rectangles), Front-end steps (white rectangles).

Figure 1.3: CAFCA architecture [6]

DANESS (**D**ynamic **A**nalysis of **N**uclear **E**nergy **S**ystem **S**trategies) is a commercial product, developed at ANL. DANESS is designed as a multi-layer code Fig. 1.4; it has four different layers, namely: Physics, Nuclear Energy Systems, Assessment and the Policy layers. The physics layer in DANESS does not perform fuel depletion analysis; it was designed as a layer where most of the material analysis takes place. The fuel recipe (which describes the connection between initial and final fuel isotopic concentrations) has to be provided exogenously to the code. DANESS can simulate 10 different reactors with 10 different fuel recipes per scenario. DANESS can simulate worldwide nuclear resources as well as regional resources and can also be used for non electricity applications such as heat generation modeling and sea water desalination. DANESS [7] can be used for: *Analysis of development paths for nuclear energy, Integrated process model, Parameter scoping for new designs, Economic analysis of nuclear energy systems, and Government policy formulation.*

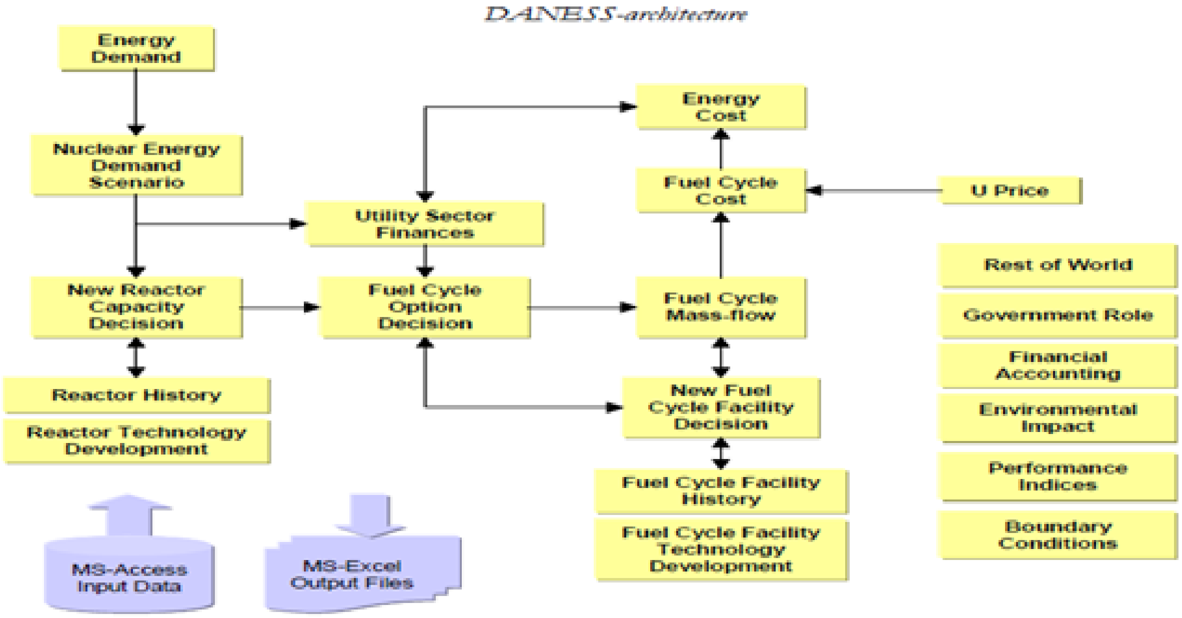


Figure 1.4: DANESS architecture [7]

VISION (**V**er**i**fiable Fuel Cycle **Si**mulati**on, INL**) According to [8] is a robust code with a lot of flexibility for the user. VISION is a system dynamic nuclear fuel cycle analysis code developed for the Advanced Fuel Cycle Initiative (AFCI) studies through collaboration between national laboratories and universities.

This is the leading tool for NFC endorsed by the Department of Energy (DOE) to provide insight into mass flow, material distribution and economic assessments of advanced fuel cycles. It allows modeling of a number of recycling strategies as well as spent fuel components separation technologies. The user has control over what should be separated. VISION has the capability to model a single reactor as well as all global nuclear reactor resources, however in a multi reactor scenario studies, the code cannot track material discretely.

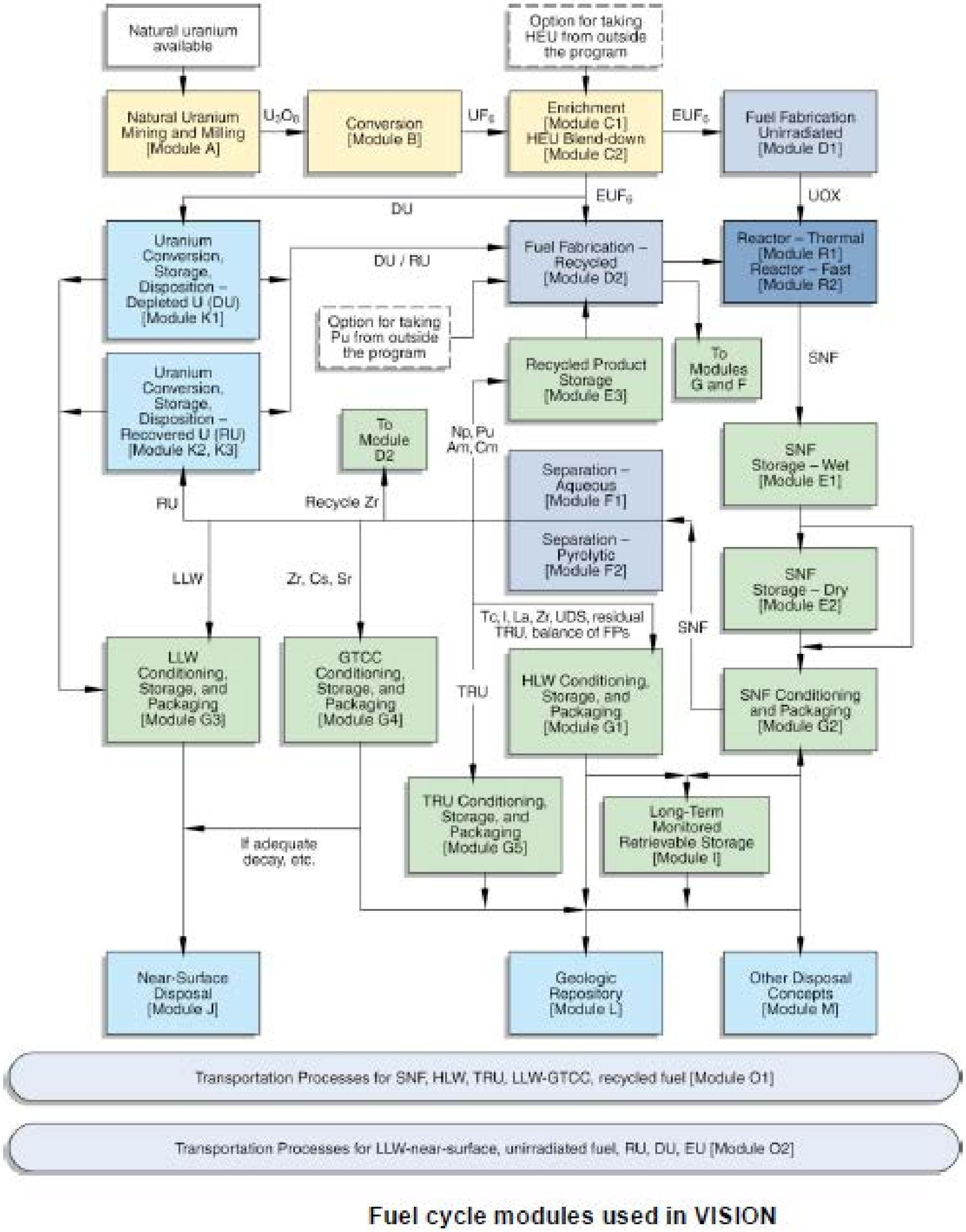
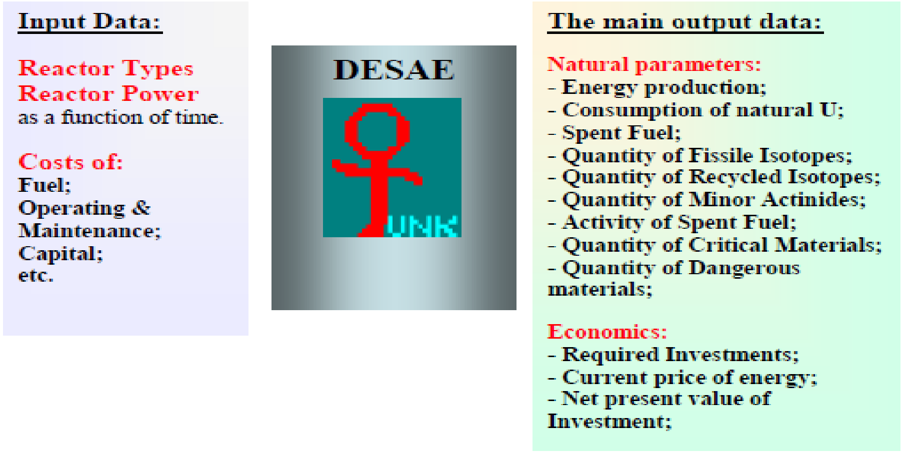


Figure 1.5: VISION architecture [8]

VISION uses a post –processing module, VISION-ECON to perform detailed capital and operating cost analysis and provide levelized unit cost for all fuel cycle components (apart from those in the front-end with exception of fabrication). The current cost analysis in VISION however does not include demand and supply analysis. The material and information flow is shown in Fig.1.5.

DESAE (**D**ynamics of **E**nergy **S**ystems of **A**tomic **E**nergy) is being developed at Russian research center Kurchastov Institute. It has multiple options for analyzing different nuclear energy development scenarios, [9]. These options includes: regional & global analysis of nuclear energy systems, different nuclear energy application (electricity, heat, hydrogen generation, desalination, etc). DESAE performs detailed economic analysis, has modules representing all the activities in the fuel cycle, analysis of non-fuel materials (such as construction materials, reactor materials, etc.), the code also has capability to simulate both U- and Th- based fuels, and can also be used to transmute minor actinides [10], perform waste modeling, and has both open and closed cycle capability. In a scenario study, DESAE 2.2 can only support seven different reactors in parallel, and can only track 17 isotopes. The input and output data structure of DESAE is shown in Fig.1.6 and the code's architecture is shown in Fig.1.7



Input Data:

Reactor Types
Reactor Power
as a function of time.

Costs of:
Fuel;
Operating & Maintenance;
Capital;
etc.

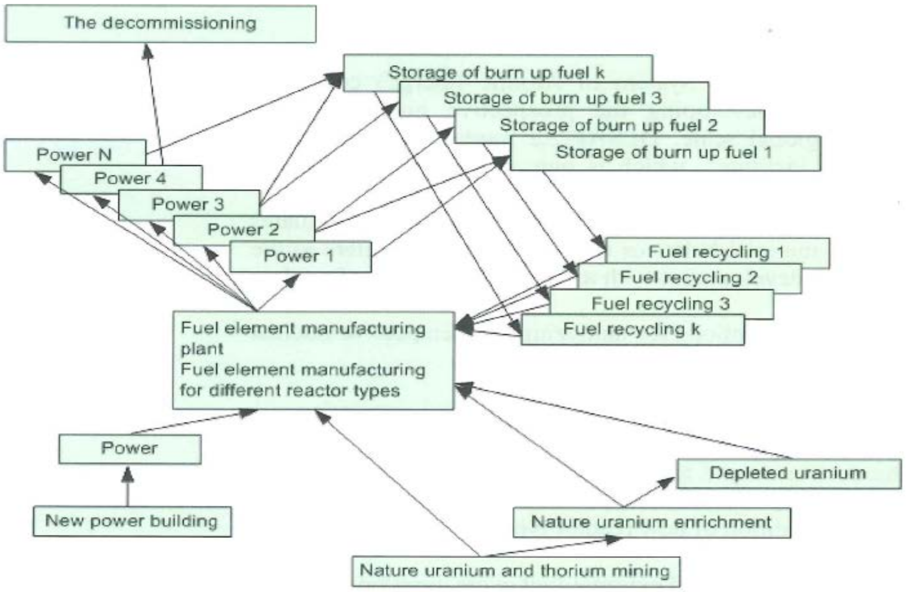
The main output data:

Natural parameters:
- **Energy production;**
- **Consumption of natural U;**
- **Spent Fuel;**
- **Quantity of Fissile Isotopes;**
- **Quantity of Recycled Isotopes;**
- **Quantity of Minor Actinides;**
- **Activity of Spent Fuel;**
- **Quantity of Critical Materials;**
- **Quantity of Dangerous materials;**

Economics:
- **Required Investments;**
- **Current price of energy;**
- **Net present value of Investment;**

Main input and output data of DESAE code.

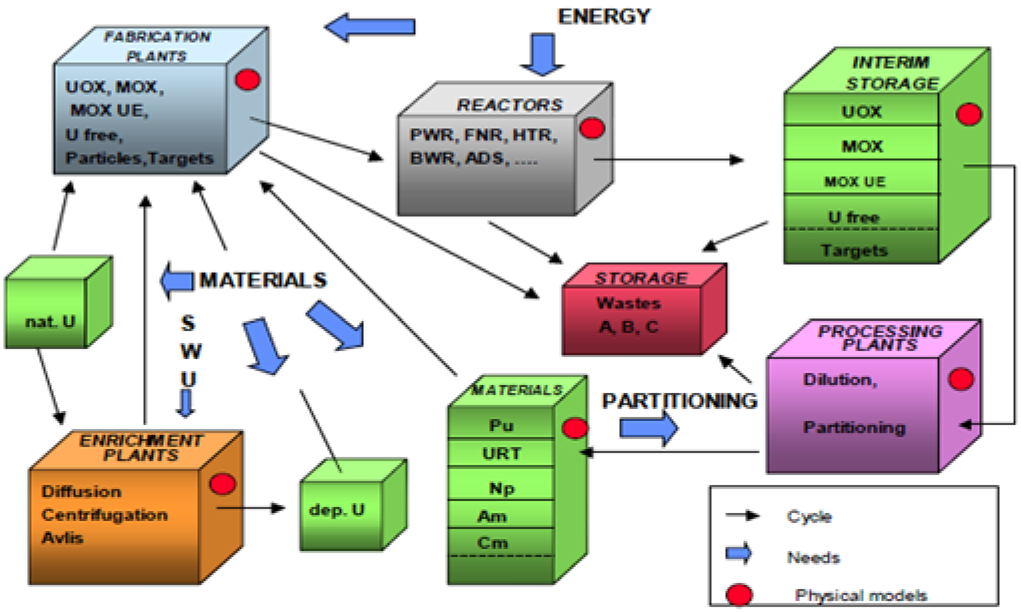
Figure 1.6: Input and output data structure of DESAE code. [9]



The structure of DESAE 2.2 mathematical model

Figure 1.7: DESAE 2.2 architecture [9]

COSI (**CO**mmelini-**SI**cart) is being developed by the CEA: French Atomic Energy Commission. It has capability for short, medium and long term nuclear fuel cycle scenario studies [11], and can model all nuclear related facilities in the entire fuel cycle. COSI can track up to 200+ isotopes depending on the version of the depletion code used. It uses different depletion codes for thermal reactors (CESAR 4/5) and fast spectrum reactors (ERANOS). COSI is flexible, allows constraints specification at different facilities in the fuel cycle. The code also has different reprocessing possibilities, minor actinides partitioning, various dilution methods and reprocesses fuel based on FIFO/LIFO method. The economic analysis of COSI is well developed, and supports detailed material balance analysis. COSI has waste management as well as proliferation resistance analysis capabilities [12]. COSI architecture is shown in Fig.1.8



COSI modelling scheme

Figure 1.8: COSI architecture [11]

VISTA/NFCSS (Nuclear Fuel Cycle Simulation System). Is being developed by a consortium of contractors and experts for the International Atomic Energy Agency. It is the only nuclear fuel scenario code that is accessible through the internet [11]. NFCSS is simple to use because of its well developed user's GUI and can be used to estimate long-term fuel cycle requirements. The user can simulate single or multiple reactors (park form), model local, regional and global nuclear energy systems. The user can define new fuel recipes (with the entire initial isotopic component) and new reactors (with all the reactor characteristics). The code has an in-built depletion code called CAIN, but in the current version it can only tracks 14 isotopes, cannot perform multi tier scenario analysis and has no direct economic analysis. The thorium based fuel capability is still being developed. It has a very limited waste management capability and cannot be used for non-proliferation analysis.

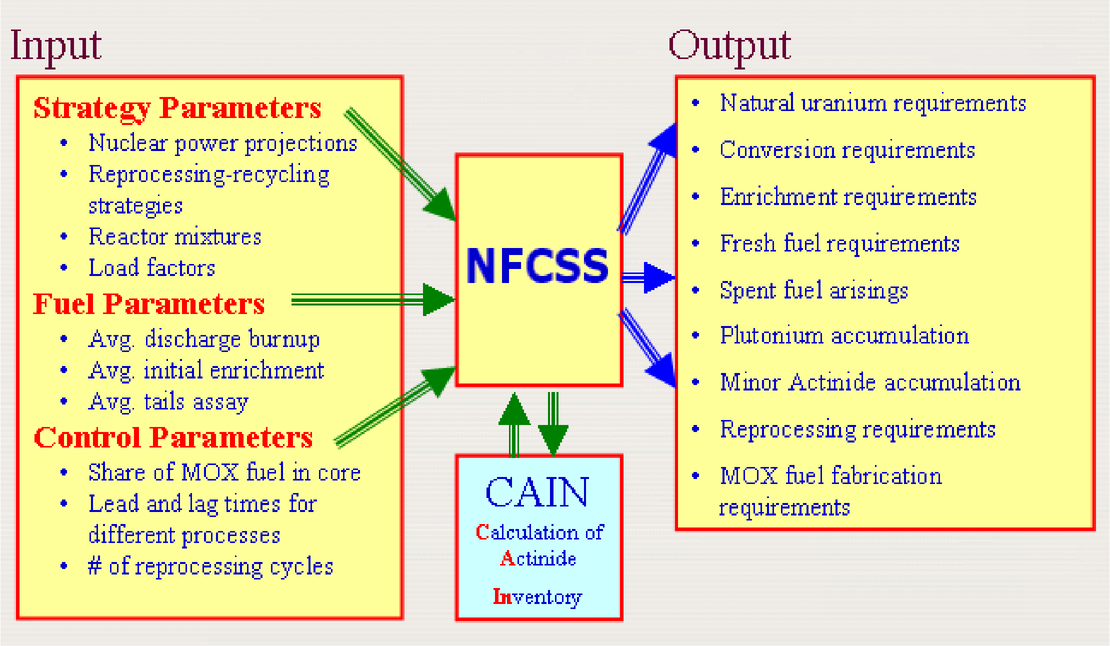


Figure 1.9: Input and output data structure of VISTA/NFCSS [13]

NUWASTE (**NU**clear **W**aste **A**ssessment **S**ystem for **T**echnical **E**valuation). Developed by the U.S. Nuclear Waste Technical Review Board [14]; to support its technical evaluation DOE Used Nuclear Fuel and High Level Waste (HLW) management activities. NUWASTE models individual reactor facilities and the discrete movement of fuel to and from the reactors.

The code main focus is on repository impact of a limited recycle scenario. The operation and material flow process is shown in Fig. 1.10.

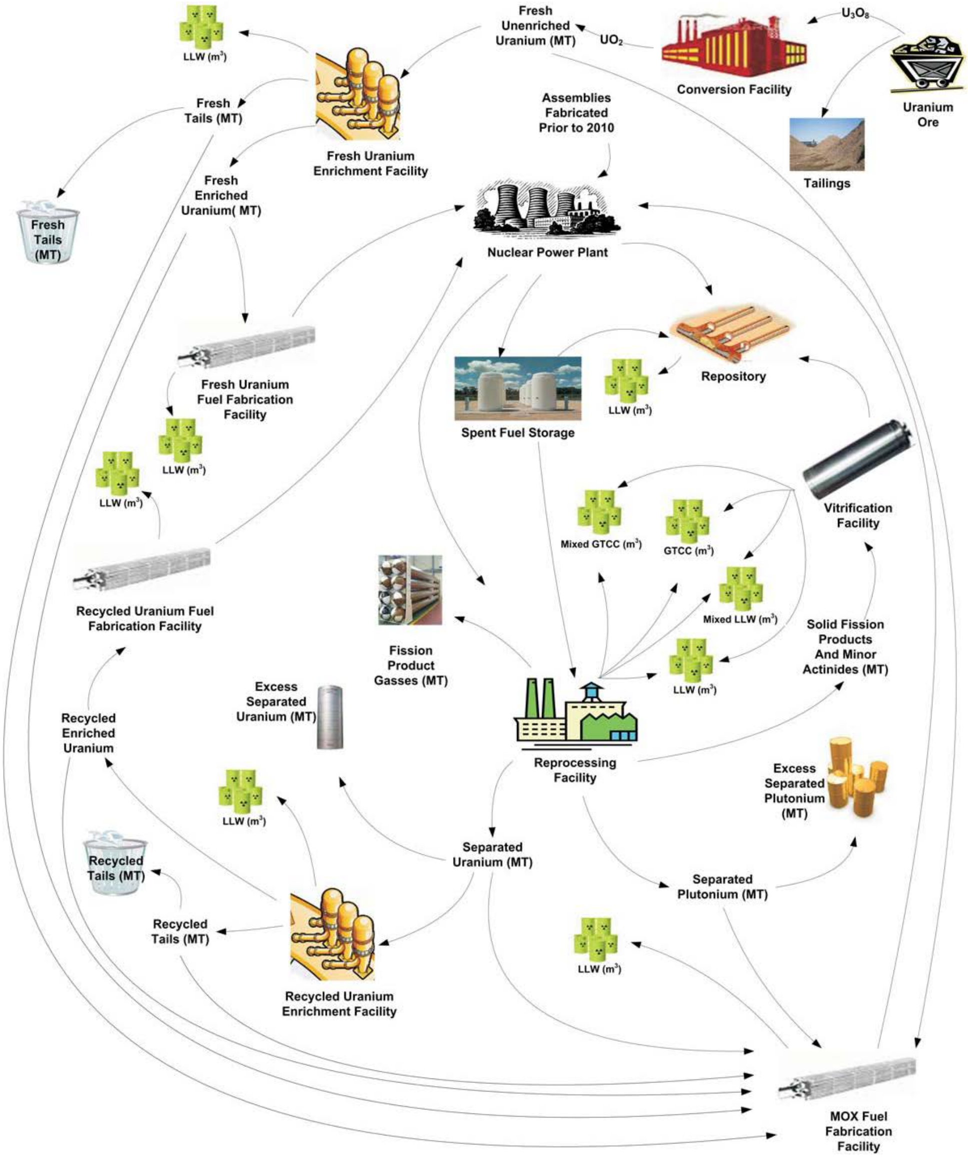


Figure 1.10: Process operation and material flows currently included in NUWASTE [14]

1.5 Dynamic Analysis of NFC Using VISION

To investigate the requirements listed in section 1.2, nuclear energy scenario studies were defined and analyzed using VISION. Results obtained from some of previous scenario studies [15, 16] indicate that, deployed separation capacity have significant impact on every aspect of the NFC. The present work extends these nuclear energy scenario studies with emphasis on the amount of separation capacity and their impact on NFC metrics such as *resources utilization, waste storage requirement, environmental impact of waste, and NFC cost*.

1.5.1 Background on VISION Model

VISION is a "best-estimate" R&D application software developed to analyze detailed dynamic evolution of different nuclear fuel cycles. The VISION model was built using commercial support software Excel® and Powersim Studio [16], and operates on system dynamic principles developed by Prof. J. Forrester [17]. Detailed description and mechanics of operation of VISION can be found in [18, 19, 20]. The basic structure of VISION model is shown in Fig. 1.11, while a more functional structure is depicted in Fig.1.12. Each of the modules is color coded to facilitate easy analysis and tracking.

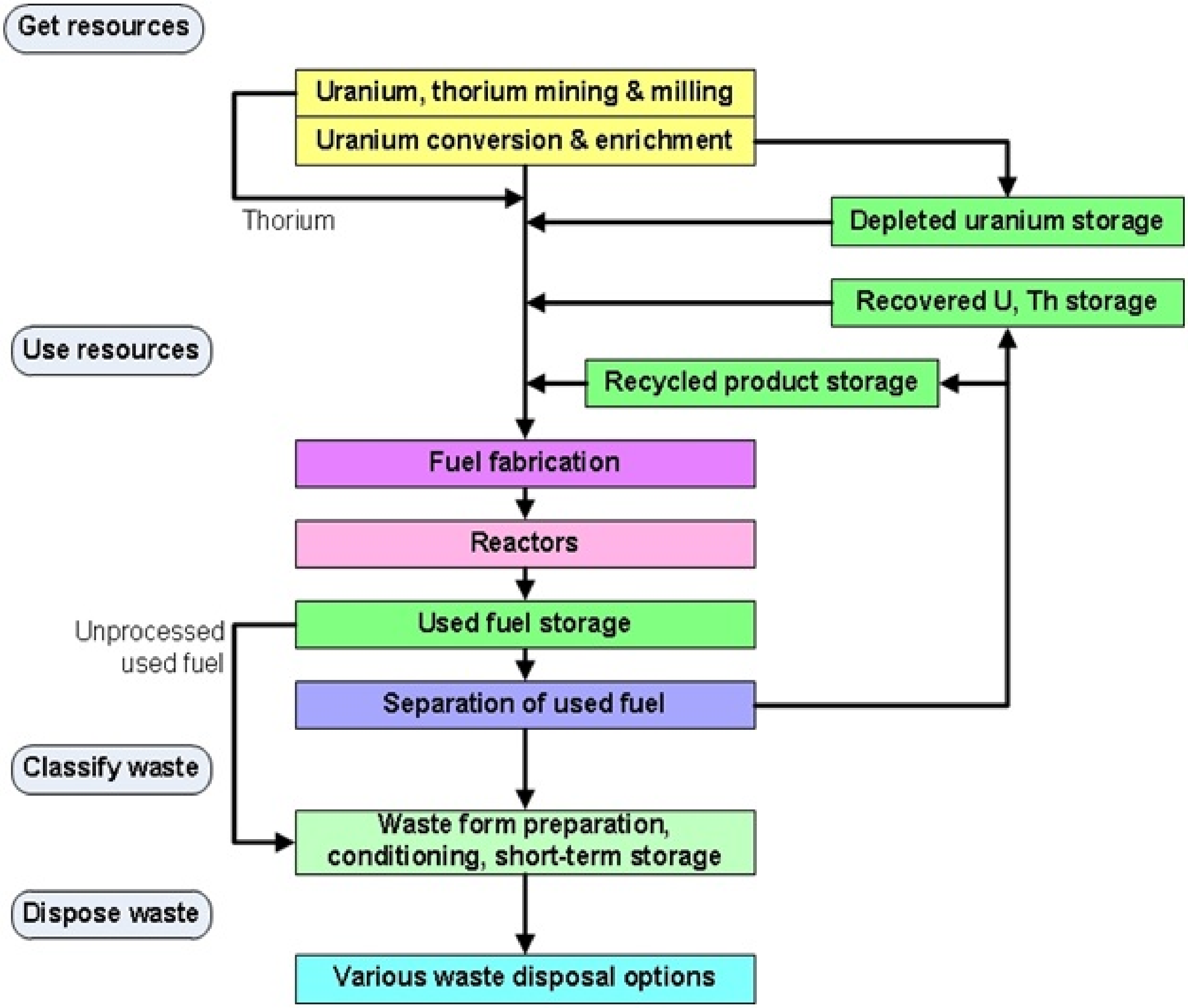


Figure 1.11: Basic structure of VISION model [19]

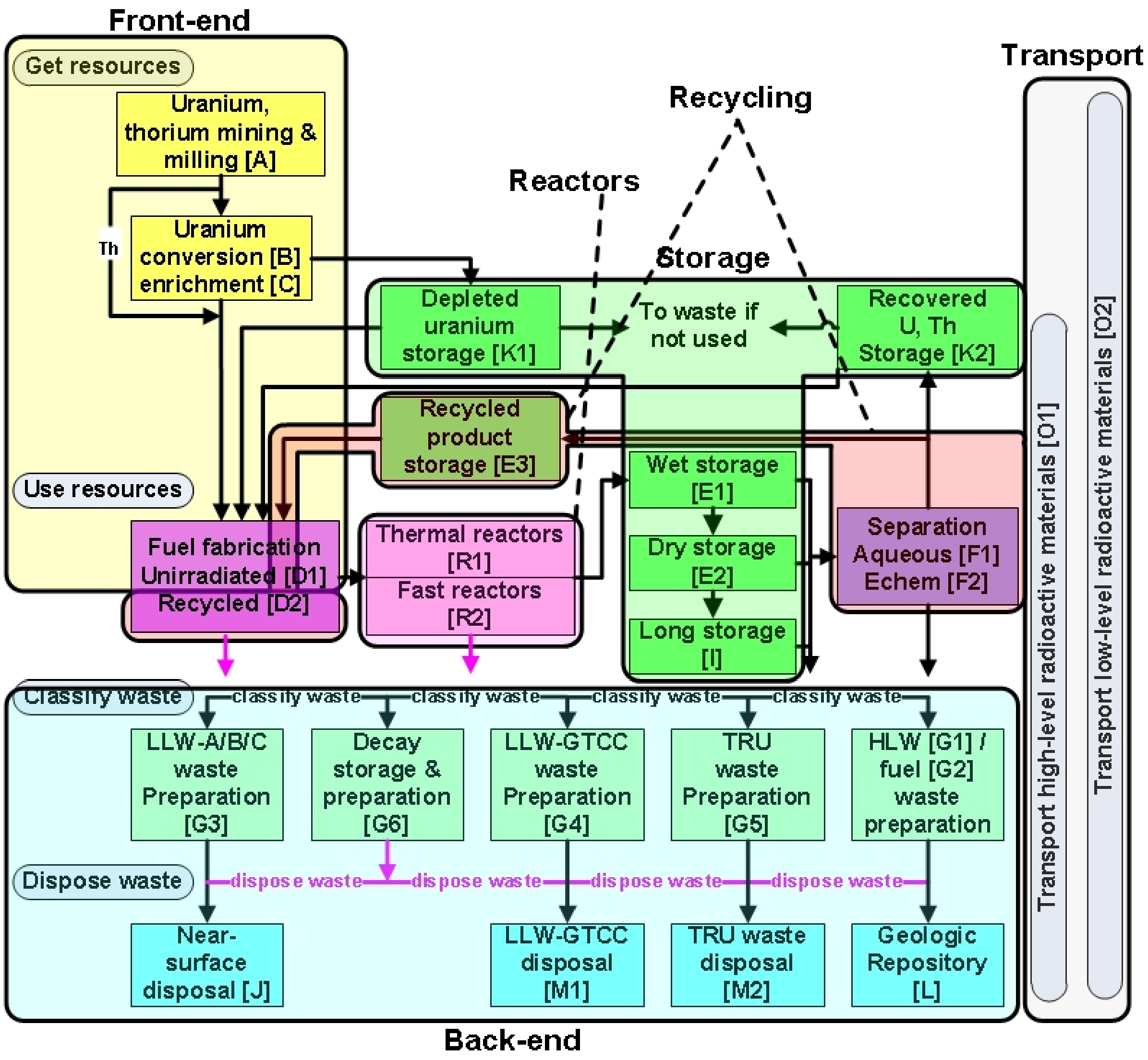


Figure 1.12: VISION functional modular structure. [19]

1.5.2 Background on VISION.ECON

VISION.ECON was designed also as part of the AFCI project but is not currently coupled with any of the advanced releases of the VISION model. The economic submodel retrieves data from the main VISION model (the flow process is shown in Fig. 1.13) at every time interval specified in the main model and uses this data with cost input based on “AFC 2007

Cost Basis" report [21] to calculate modular costs, which is the cost for implementing each module (Fig. 1.12) in the NFC.

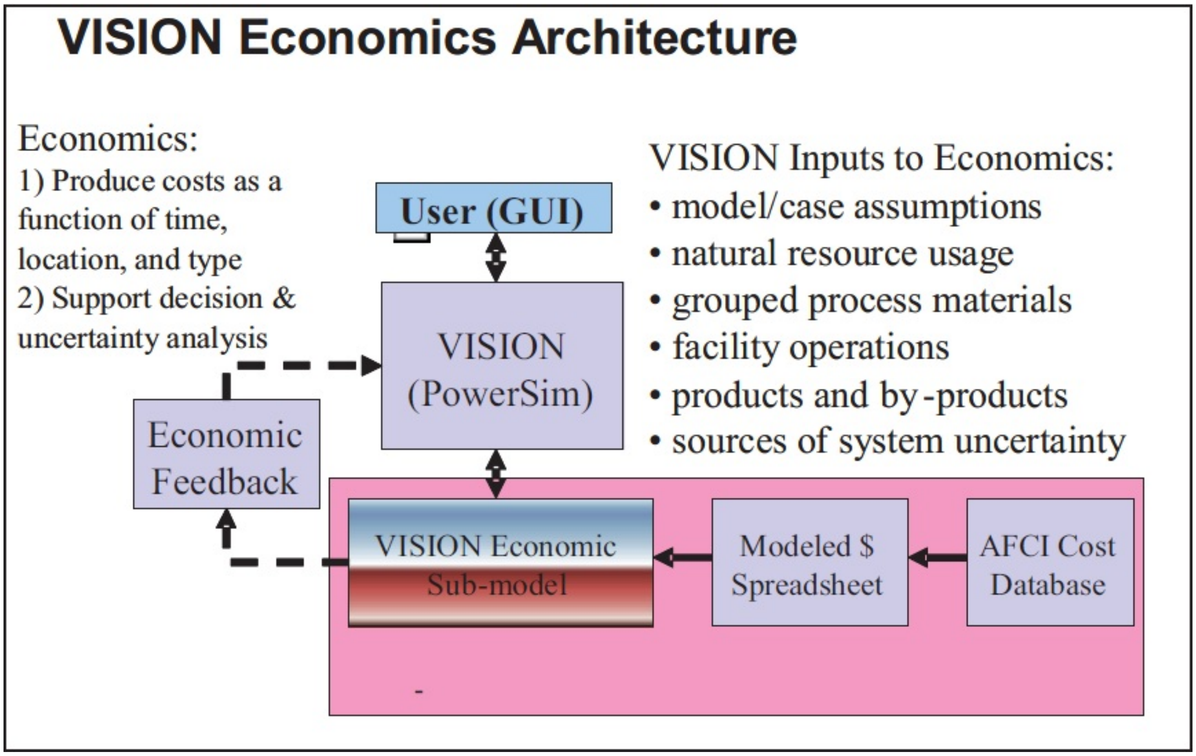
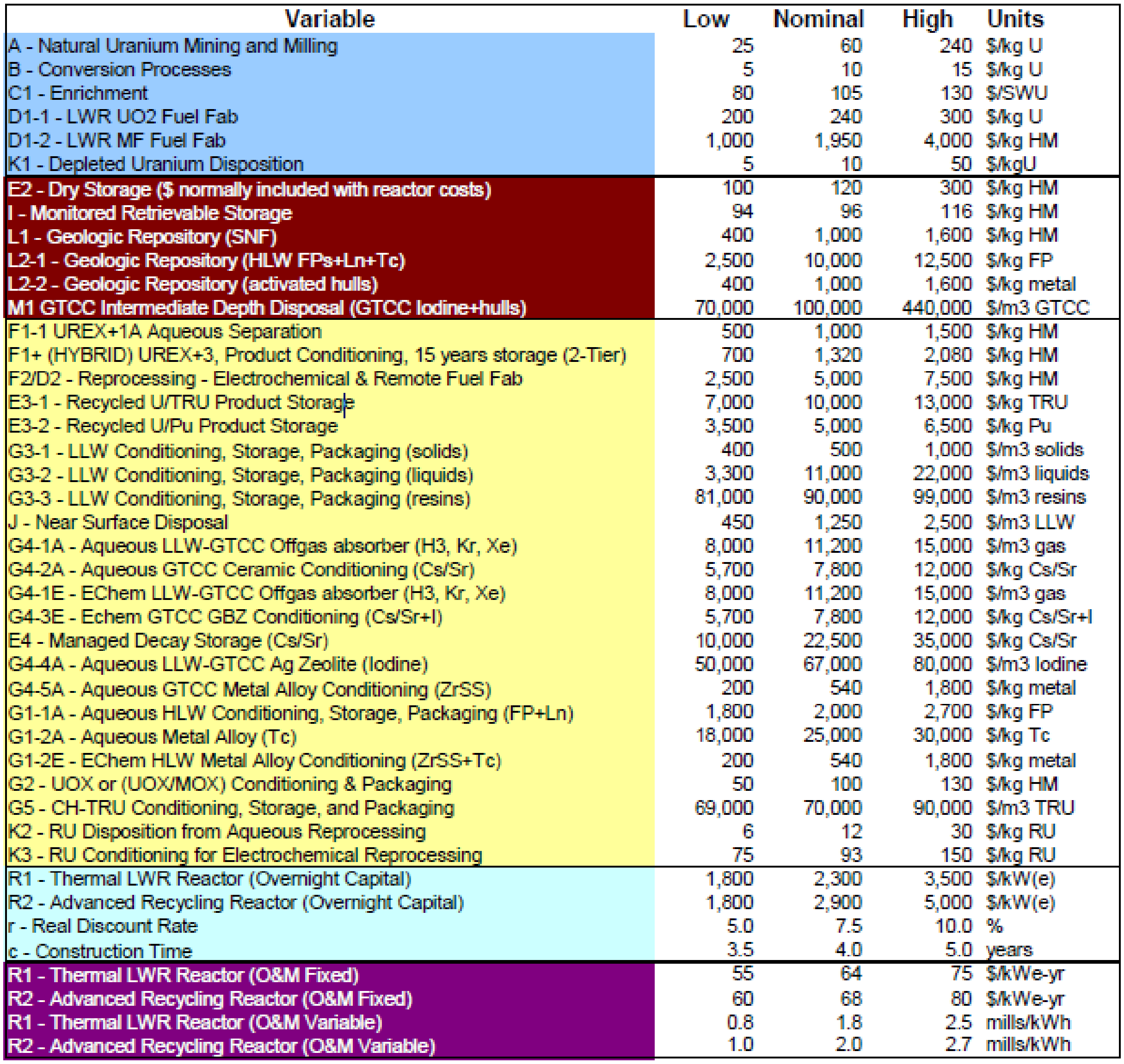


Figure 1.13: VISION economics architecture [22]

The cost analysis is performed in two stages: first, annual costs are calculated, by multiplying the mass flow rate at that time step with cost per unit for that module; this allows for cost tracking through the entire system.

The second cost analysis is performed using cost distributions. The cost input data file contains three columns: a low, nominal and high cost values as shown in Fig. 1.15 (with 2007 US dollar value), which sets bounds for either triangular or uniform cost distributions. A Monte Carlo sampling (within Powersim) is used to randomly select values from a triangular or uniform distribution based on the low, nominal and high values. The cost estimate from each of the

Monte Carlo runs is multiplied by the total final flow (sum of the mass flows from each year) for each module to create a cost distribution; each of the module costs are also summed to create a distribution for the total cost.



Variable	Low	Nominal	High	Units
A - Natural Uranium Mining and Milling	25	60	240	$/kg U
B - Conversion Processes	5	10	15	$/kg U
C1 - Enrichment	80	105	130	$/SWU
D1-1 - LWR UO2 Fuel Fab	200	240	300	$/kg U
D1-2 - LWR MF Fuel Fab	1,000	1,950	4,000	$/kg HM
K1 - Depleted Uranium Disposition	5	10	50	$/kgU
E2 - Dry Storage ($ normally included with reactor costs)	100	120	300	$/kg HM
I - Monitored Retrievable Storage	94	96	116	$/kg HM
L1 - Geologic Repository (SNF)	400	1,000	1,600	$/kg HM
L2-1 - Geologic Repository (HLW FPs+Ln+Tc)	2,500	10,000	12,500	$/kg FP
L2-2 - Geologic Repository (activated hulls)	400	1,000	1,600	$/kg metal
M1 GTCC Intermediate Depth Disposal (GTCC Iodine+hulls)	70,000	100,000	440,000	$/m3 GTCC
F1-1 UREX+1A Aqueous Separation	500	1,000	1,500	$/kg HM
F1+ (HYBRID) UREX+3, Product Conditioning, 15 years storage (2-Tier)	700	1,320	2,080	$/kg HM
F2/D2 - Reprocessing - Electrochemical & Remote Fuel Fab	2,500	5,000	7,500	$/kg HM
E3-1 - Recycled U/TRU Product Storage	7,000	10,000	13,000	$/kg TRU
E3-2 - Recycled U/Pu Product Storage	3,500	5,000	6,500	$/kg Pu
G3-1 - LLW Conditioning, Storage, Packaging (solids)	400	500	1,000	$/m3 solids
G3-2 - LLW Conditioning, Storage, Packaging (liquids)	3,300	11,000	22,000	$/m3 liquids
G3-3 - LLW Conditioning, Storage, Packaging (resins)	81,000	90,000	99,000	$/m3 resins
J - Near Surface Disposal	450	1,250	2,500	$/m3 LLW
G4-1A - Aqueous LLW-GTCC Offgas absorber (H3, Kr, Xe)	8,000	11,200	15,000	$/m3 gas
G4-2A - Aqueous GTCC Ceramic Conditioning (Cs/Sr)	5,700	7,800	12,000	$/kg Cs/Sr
G4-1E - EChem LLW-GTCC Offgas absorber (H3, Kr, Xe)	8,000	11,200	15,000	$/m3 gas
G4-3E - Echem GTCC GBZ Conditioning (Cs/Sr+I)	5,700	7,800	12,000	$/kg Cs/Sr+I
E4 - Managed Decay Storage (Cs/Sr)	10,000	22,500	35,000	$/kg Cs/Sr
G4-4A - Aqueous LLW-GTCC Ag Zeolite (Iodine)	50,000	67,000	80,000	$/m3 Iodine
G4-5A - Aqueous GTCC Metal Alloy Conditioning (ZrSS)	200	540	1,800	$/kg metal
G1-1A - Aqueous HLW Conditioning, Storage, Packaging (FP+Ln)	1,800	2,000	2,700	$/kg FP
G1-2A - Aqueous Metal Alloy (Tc)	18,000	25,000	30,000	$/kg Tc
G1-2E - EChem HLW Metal Alloy Conditioning (ZrSS+Tc)	200	540	1,800	$/kg metal
G2 - UOX or (UOX/MOX) Conditioning & Packaging	50	100	130	$/kg HM
G5 - CH-TRU Conditioning, Storage, and Packaging	69,000	70,000	90,000	$/m3 TRU
K2 - RU Disposition from Aqueous Reprocessing	6	12	30	$/kg RU
K3 - RU Conditioning for Electrochemical Reprocessing	75	93	150	$/kg RU
R1 - Thermal LWR Reactor (Overnight Capital)	1,800	2,300	3,500	$/kW(e)
R2 - Advanced Recycling Reactor (Overnight Capital)	1,800	2,900	5,000	$/kW(e)
r - Real Discount Rate	5.0	7.5	10.0	%
c - Construction Time	3.5	4.0	5.0	years
R1 - Thermal LWR Reactor (O&M Fixed)	55	64	75	$/kWe-yr
R2 - Advanced Recycling Reactor (O&M Fixed)	60	68	80	$/kWe-yr
R1 - Thermal LWR Reactor (O&M Variable)	0.8	1.8	2.5	mills/kWh
R2 - Advanced Recycling Reactor (O&M Variable)	1.0	2.0	2.7	mills/kWh

Figure 1.15: Sample excel input file for cost distribution in 2007 US $. [22]

1.6 Previous VISION Studies

VISION was originally developed as part of the AFCI program and was the tool used for NFC analysis. Continuous development and use has kept the code in a state of the art. VISION is currently the only advanced NFC analysis code supported by the DOE, its platform and structure is currently in consideration for the DOE Virtual Nuclear Hub project. VISION had been used as a tool for Thesis works [20, 23, 24, 25]. Tyler Schweitzer in [20] used an earlier version of VISION to investigate areas of uncertainties in advanced fuel cycles, when facilities are being ordered to support change in energy demand. His work led to improved algorithm for facilities interaction in other releases of the code. Taylor in [23] developed Material, Economics, and Proliferation Assessment Tool (MEPAT) based on the structure and algorithms used VISION. She provided insight into how internationalization of fuels supply system works by measuring metrics such as material movement, cost as well as proliferation concerns. Oliver in [24] used VISION as a validation tool for Global Evaluation of Nuclear Infrastructure Utilization Scenarios (GENIUS) software design. GENIUSv2 is multi-region discrete nuclear fuel cycle simulation software, designed to model individual components of the NFC as opposed to VISION which models the components as a fleet. Also Shannon in [25] used VISION to model different approaches for recycling and transmuting used nuclear fuel. He compared effects of using static and dynamic fuel recipes when loading used fuel for recycling scenarios. He found in his analysis that using dynamic fuel recipe reduces the level of uncertainty in separated inventories.

The VISION code is also one of the standards used for NFC benchmark analysis for new NFC codes [16, 26, 27] development. Guerin et al [16] used the code (in addition to other codes) to benchmark CAFCA. The nuclear energy agency (NEA) also used VISION in their benchmark study on nuclear fuel cycle transition scenarios analysis codes [26].

VISION had also been used in NFC scenario studies. Shropshire et.al. [27] used VISION to perform Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems. The analysis in his study provided a technology oriented baseline system cost comparison between the open fuel cycle and closed fuel cycle systems, with better understanding of their overall cost trends, cost sensitivities, and trade-offs. Adeniyi et.al [28] used the code to investigate the impact of limiting reprocessing capacity on nuclear materials utilization in advanced fuel cycles. VISION was also used by Dixon et.al. [29] to perform dynamic analysis of transitioning from once through cycle to other advanced fuel cycles. Their analysis confirmed that waste management benefits can be realized if recycling is initiated, and that fast reactor deployment can be significantly hindered in multi-tiered fuel cycle systems.

1.7 Thesis Organization

The work presented in this thesis will describe the impact of separation capacity deployed in advanced fuel cycles and analyze two advanced fuel cycle scenarios using the VISION model and VISION.ECON submodel and compare the results to a once through fuel cycle result.

Analysis of some advanced nuclear fuel cycles had provided insights into how fuel cycle components interact and inter-depend on one another. For example the dependency on separation facility (size, rate of construction and time of deployment), on fast reactor performance, waste storage requirements and so on is well documented. Jacobson et.al [30] concluded that in a fuel cycle where all available TRU is used for fast reactors and fuel fabrication is not limiting, the reprocessing capacity is the single largest factor impacting fast reactor availability.

In advanced fuel cycles where used fuel cycle recycling is permitted, shortage of separation capacity will always create a bottle-neck, while excessive separation capacity will add unnecessary additional cost to the fuel cycle cost. In these advanced fuel cycles, when there is insufficient TRU, to support fast reactor deployment, LWR are built to make-up for the shortage and cater to the energy need at that point.

This research work is an attempt to study the impact of separation capacity in a fuel cycle where the current US fleet of nuclear reactors is replaced over time by fast reactors, with complete elimination of LWR at some point. This fuel cycle scenario will be discussed fully in chapter 3.

VISION methodology, presented in chapter 2, will describe the routing and separation strategy used in VISION and how reactors and their support facilities are built in accordance with the proper demand functions. Following this are descriptions of the different fuel cycles simulations. In addition to scenario description, results from these fuel cycles scenarios will be presented in Chapter 3 with brief discussions. Resource utilization will be presented in Chapter 4, while environmental impact of these cycles will be presented in Chapter 5. The economic impact analysis will be presented in Chapter 6, while conclusion and recommendations for future works will be presented in Chapter 7, which also concludes the thesis.

CHAPTER 2

VISION METHODOLOGY

2.1 Methodology Overview

This methodology chapter present how some of the complexities in VISION are controlled and how one of them is used to investigate the characteristics of advanced fuel cycles. There are two major control modes that control the operation in VISION, a reactor-centric and a separation-centric mode [19]. The reactor-centric mode translates various user inputs such as energy growth and determines how many reactors operate each year, see Fig. 2.1.

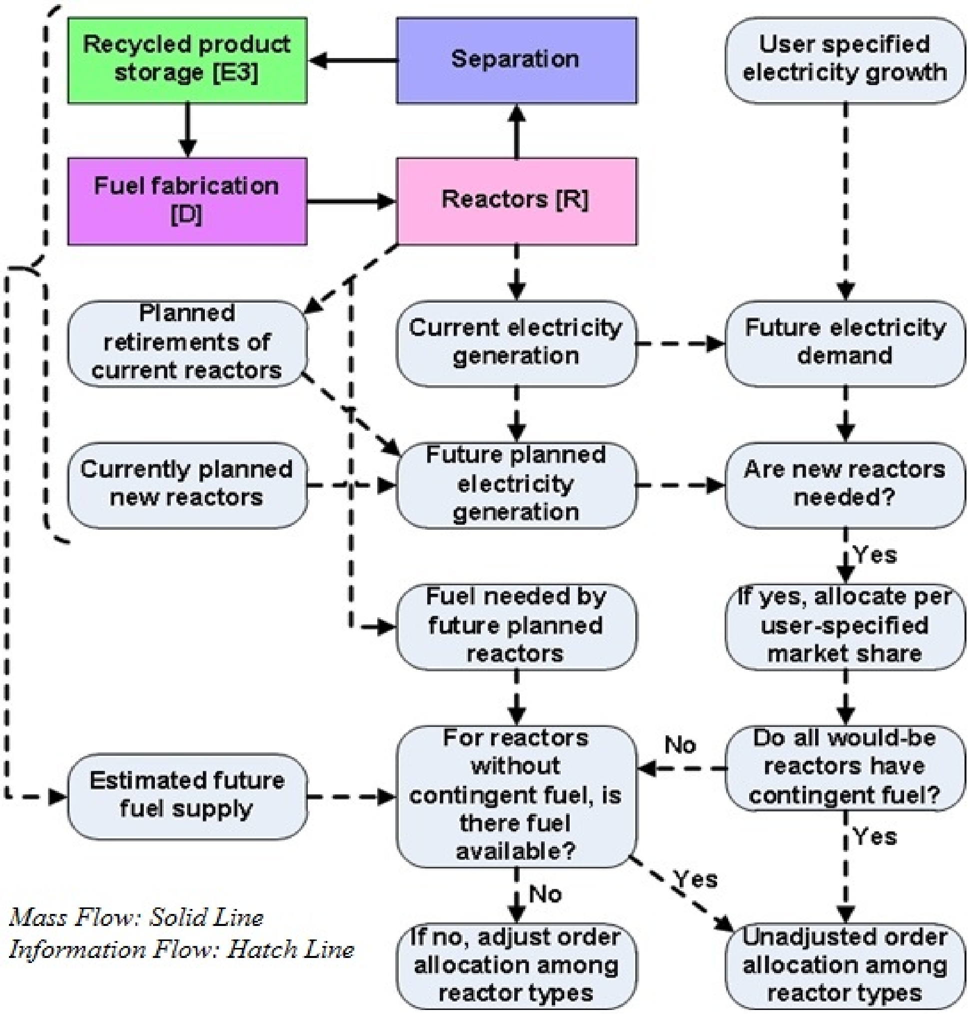
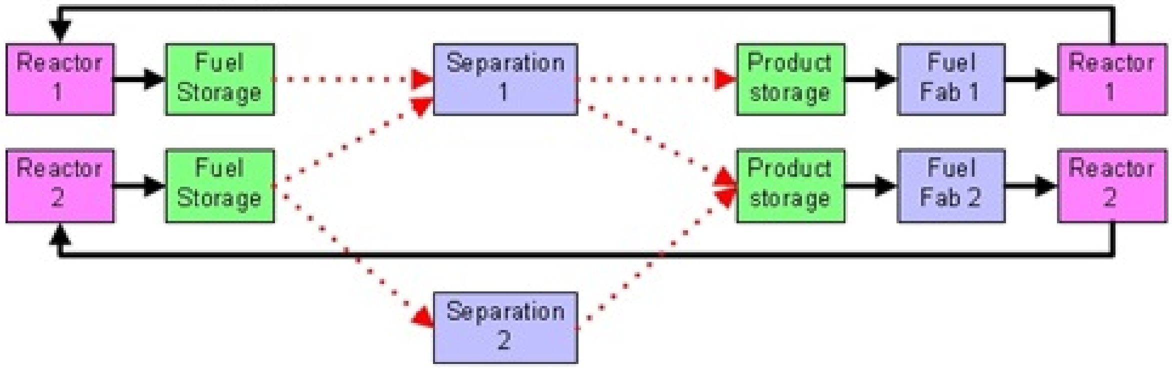


Figure 2.1: Mass and information flows for reactor ordering [19]

The separation-centric mode uses the amount of available separation capacity to determine waste stream performance of the fuel cycle, the only exception being in a once-through fuel cycle. The separation algorithm in VISION uses matrices system to route and separate used fuel into different streams, as illustrated in Fig. 2.2

VISION routing approach



Pull from storage buffer to fill Separation capacity. Separation 1 pulls first, then Separation 2, etc. Fuel stays in storage until pulled.

Priority order - reactor 1, then reactor 2, etc.

Push from Separation into one product storage for each Fuel Fab. Products pushed whether Fuel Fab ready to use or not.

Percent allocation – X % to Fuel Fab 1, Y % to Fuel Fab 2, etc.

Figure 2.2: VISION routing approach [19]

The mathematical model for decision making logic in VISION operates in a circular form [20], see mass flow section of Fig.2.1. It is based entirely on demand – supply model, where supply in one module is used to meet demand in another module, also see Fig.1.3. The initiating driver of demand is usually the electricity growth expected over a certain period of time. To meet this demand, VISION deploys different algorithms, to construct all necessary facilities, especially the fuel function algorithm, which determines availability of enough fuel for the reactor’s entire operating life. If there is insufficient fuel; the reactor is simply not built. In a situation where the reactor has to be built, all necessary facilities for mining, conversion, fuel fabrication, etc, have to be built.

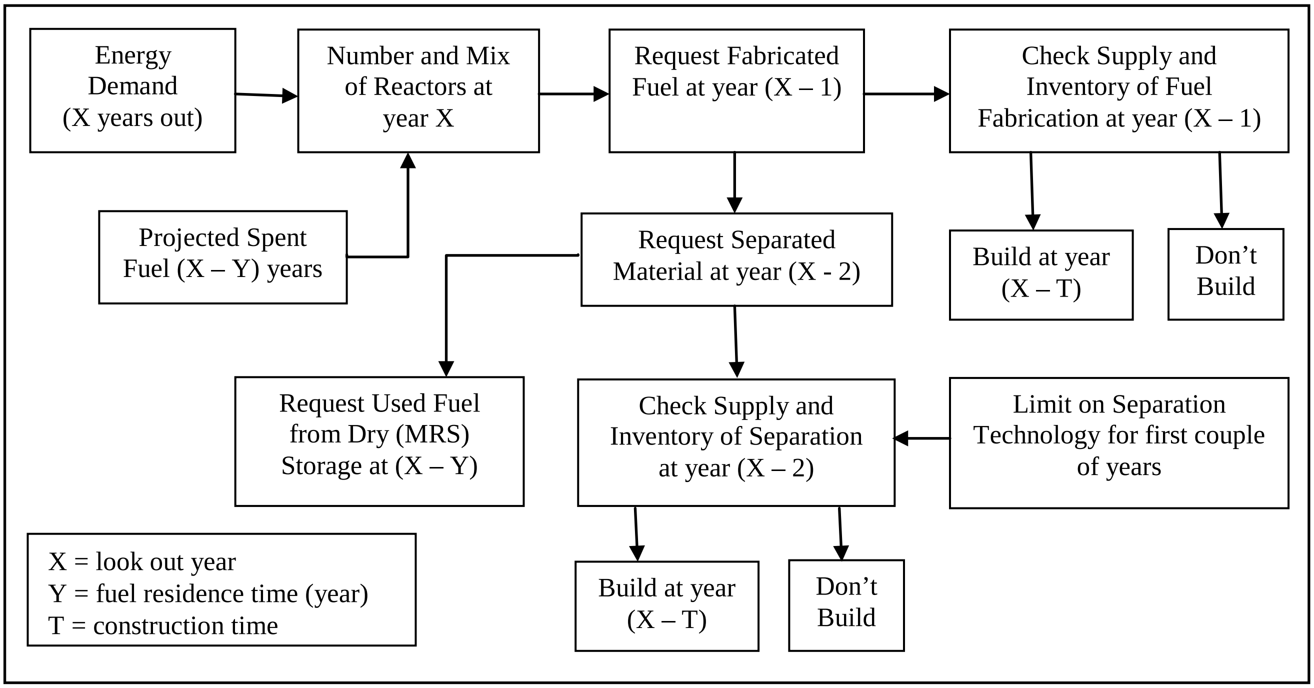


Figure 2.3: Example of fuel function algorithm flow in a closed NFC [20]

A modified example from [20] of fuel function algorithm is shown in Fig.2.3, for a closed fuel cycle. Energy demand in the close cycle above is projected to increase in X years in this example; this increase requires building additional reactor capacity, which in turn requires more fuel fabrication facility to be built. To avoid fuel mismatch for advanced reactors at their startup, an estimate of available UNF is performed when the advanced reactors are ordered. To build adequate supply of fuel for the advanced reactors expected in X years, there must be enough supply of UNF, if not, more Light Water Reactors, (LWR) must be built (in our scenario, we built the fast reactor, but run it on low enriched uranium). Having sufficient UNF inventory without adequate separation capacity will create a bottle neck, to avoid this, new separation capacity has to be built. This interdependence of fuel cycle facilities creates the circular form mentioned above.

2.2 VISION Separation-Centric Control Mode

As discussed in section 2.1, the separation-centric control mode has great impact on the performance of any advanced fuel cycle. Insufficient amount of separation capacity can make deployment of advanced fuel cycles impossible and will make them likely more expensive, when such fuel cycles are setup with backup/contingent fuels. VISION relies on a system of complex equations, (see detail analysis of relevant equations in [20]) and very complex separation and routing matrices systems Fig. 2.2, to determine what amount of separation capacity to build

2.2.1 Recycling and Separation Strategy in VISION

To accumulate inventory in the storage buffers as shown in Fig. 2.2, VISION uses a combination of equations and isotopic percentages specified in separation matrix: describing the separation method used, an example is presented in Table 2-1.

The decision to build a separation facility (x) is made based on logical conditions given by 2.1a and 2.1b [20].

$$S^{x}_{t+\Delta t^{x}} + \left(I^{x}_{t+\Delta t^{x}}\right)_{Usable} \geq D^{x}_{t+\Delta t^{x}} \qquad (2.1a)$$

$$S^{x}_{t+\Delta t^{x}} + \left(I^{x}_{t+\Delta t^{x}}\right)_{Usable} < D^{x}_{t+\Delta t^{x}} \qquad (2.1b)$$

Where:

$D^{x}_{t+\Delta t^{x}}$ - is the demand function

$S^{x}_{t+\Delta t^{x}}$ - is the supply function

$\left(I^{x}_{t+\Delta t^{x}}\right)_{Usable}$ - is the amount of usable separation capacity available at time t

If condition 2.1a is true, there is no need to build additional separation capacity (x) at time t, however if condition 2.1b is true, the model will start building a new separation capacity (x) at time t. Further details are given in [20].

To build the inventory of separated materials, VISION multiplies the total separation capacity available with isotopic percentages defined in separation matrix.

Table 2-1: Illustrative Separation Matrix Showing UREX+1 streams [18]

OUTPUT STREAM												
		Pu Np Am Cm Recycle Stream	RU Stream	I Stream	Gas Stream	Tc Stream	Cs Sr Stream	LnFP Stream	Discard Stream	UDS Stream	Zr SS Stream
INPUT STREAM	Ra to Pa							100	Not used,	Not used, 25% of the Tc goes with this stream, but is included with the Tc waste for ultimate disposal anyway	Not used, such mass accounted for via co-flows
	U		99.9					0.1			
	Np	99.9						0.1			
	Pu	99.9						0.1			
	Am	99.9						0.1			
	Cm-Cf	99.9						0.1			
	H3				99.9			0.1			
	C14							100			
	Kr				99.9			0.1			
	Sr, Cs						99.9	0.1			
	Tc					99.9		0.1			
	I			99.9				0.1			
	FP other							100			
	RU = recovered uranium, FP = fission product, Ln = lanthanides, UDS = undissolved solids. Sum of numbers in each row must equal to 100. The separation efficiency matrix does not address cladding isotopes, e.g., steel										

This inventory of separated materials must be sufficient to fabricate fuels for the entire life time operation of any would-be deployed reactor; otherwise the reactor will not be built. Fig.2.4 illustrates how this requirement is met in VISION. The amount of available fuel is determined using the flow function in Fig. 2.4 and Equation 2.2. The limiting material, which must be sufficient in the separated material inventory, is dependent on the type of fuel to be fabricated, for example it is Pu for fast reactor fuels.

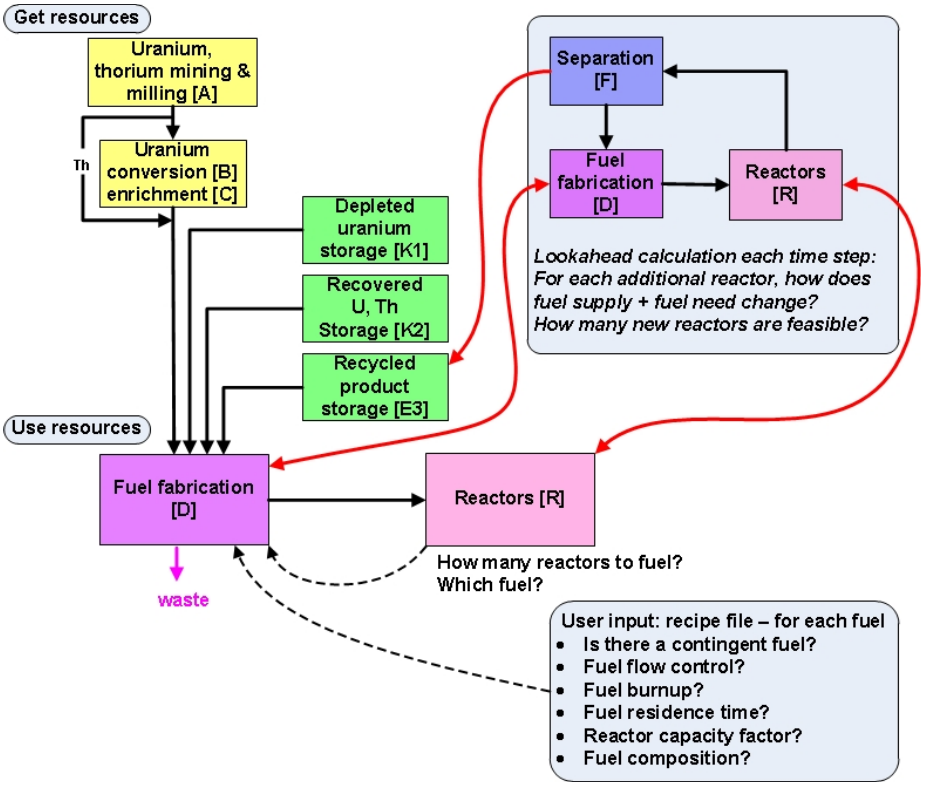


Fig. 2.4: Mass (solid lines) and information (dashed lines) flows relevant to fuel fabrication, with look-ahead (reactor lifetime) [19]

$$fuel\left(\frac{kt}{yr}\right)\ available\ per\ reactor\ =\frac{available\ \ rate\ \ (kt/yr)-limiting\ \ material\ \ (kt/yr)}{fraction\ \ of\ rate\ limiting\ \ material\ \ to\ fuel\ (\frac{kt/yr}{kt/yr})}\tag{2.2}$$

The available fuel is calculated as follows.

- What is the fuel flow control specified for this fuel, e.g., Pu?
- What is the relationship of the rate-limiting material, e.g., Pu to the fuel mass? For example, if Pu is the flow control, what is the value of mass-Pu/mass-fuel, which is determined by the input recipe of the fuel in question?
- How much (in kilotonnes) of the rate-limiting material (e.g. Pu) is in the feedstock that has been put together for that reactor type.

Thus in advanced fuel cycle with recycling, advanced reactor fuel availability is dependent on the amount of the fuel-limiting isotope available in the separated material. The higher the stock of this material, the more likely will advanced reactor be deployed.

CHAPTER 3

NUCLEAR FUEL CYCLE SCENARIO RESULTS

3.1 Nuclear Fuel Cycle Setups

Three energy scenarios were setup using the information and parameters shown in Table 3.1. All current thermal reactors in the US were modeled as LWRs without distinction between BWR and PWR, and every LWR reactor built after 2010 is assumed to be capable of operating with a full core of mixed oxide (MOX) fuel. The fast reactors deployed in the study were modeled as sodium cooled fast reactors (SFR) with a break even breeding ratio.

Three nuclear fuel cycles were used in the different scenarios setups considered in this study:

- Once-Through Cycle (OTC also known as open cycle; current US option) Fig.3.1 (section A), which assumes a single pass through a reactor; the existing fuel (used fuel) is designated for geologic disposal.

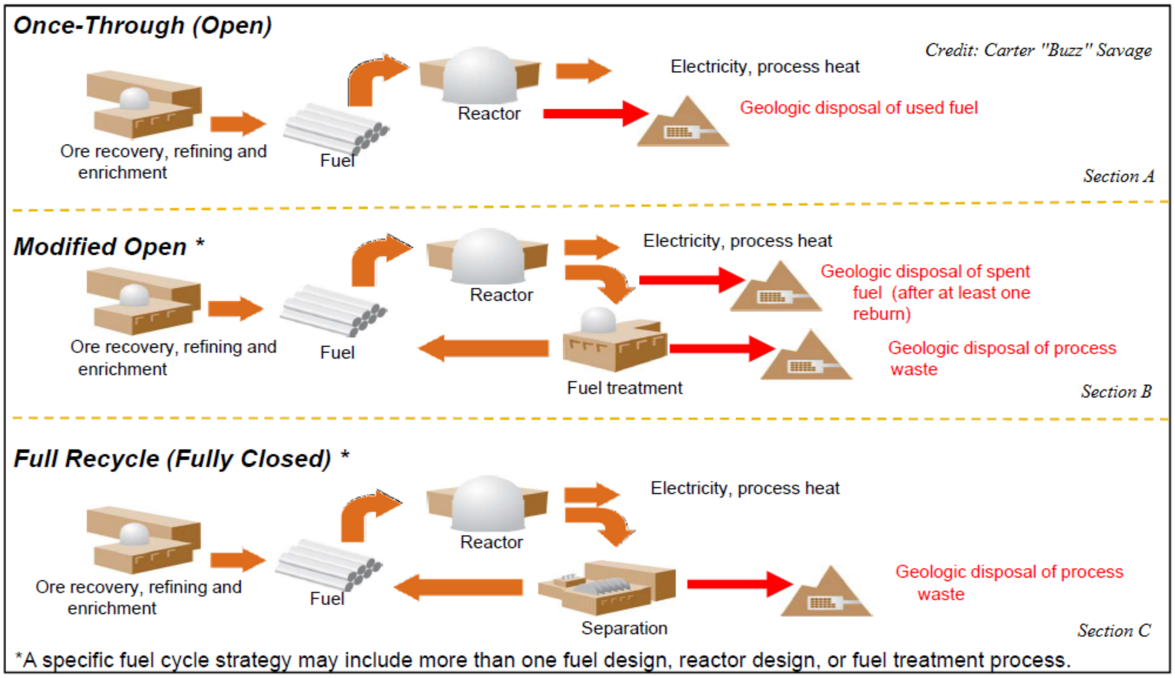


Figure 3.1: Nuclear fuel cycles [31]

- The Modified Open Cycle (MOC, proposed by DOE) Fig.3.1 (section B), is a cycle with limited or no used fuel separation and recycling (usually one recycle pass), or cycles with higher burnup, all designed to extract more energy from the fuel. In MOC, spent fuel (as opposed to used fuel) and high-level waste are disposed in a geologic repository.

- The Full Recycling (FuRe) Cycle, Fig.3.1 (section C); nuclear fuel is recycled with separation and allowed to pass through the reactor multiple times. Only materials designated as waste is disposed according to the waste classification.

Table 3.1: Nuclear Energy Scenario Parameters

	Parameters	Unit	Values
General			
	Introduction of first full-recycling reactor (i.e., fast reactor)	Year	2050
	Electricity demand growth rate	% per year	1.0
	U.S. nuclear electricity capacity in 2010	GWe-yr	100
	U.S. used nuclear fuel (UNF) inventory in 2010	ton HM	61482
	U.S. TRU inventory in 2010	ton	600
LWR – LWRMOX			
	Fuel form		UO_2, UO_2-MOX
	Electrical Power	MWe	1000
	Thermal Efficiency	%	34
	Average discharge burnup	GWd/t	50
	Average LEU enrichment	%	4.3
	Reactor capacity factor	%	90
	Life time	Years	60
	Cooling time in interim wet storage	Years	5
SFR – Full-recycling reactor			
	Fuel form		U-TRU-Zr alloy
	Electrical Power	MWe	380
	Thermal Efficiency	%	38
	Average discharge burnup	GWd/t	70 – 100
	Breeding ratio		1.0-1.2 (1.0 used in this study)
	Reactor capacity factor	%	90
	Life time	Years	60
	Cooling time in interim storage	Years	1
Reprocessing			
	Reprocessing start (depends on reactor)		Varied
	TRU recovery factor in reprocessing	%	99.9
	Reprocessing capacity	ton HM / year	Varied
	Total reprocessing time (including fabrication, transportation)	Years	2

In terms of nuclear materials utilization, the OTC is the least efficient; close to 95% of usable nuclear material remains in the UNF designated for storage and disposal. FuRe is the best cycle in terms of material utilization; almost all of the extractable energy can be extracted from the fuel, in the MOC cycle, more energy can be extracted from the fuel compared to OTC, but the cost may not be justified.

3.1.1 Once Through (Open) Cycle Scenario

For the OTC scenario, it was assumed that the LWR capacity increased to meet the 1% growth in nuclear energy demand. As shown in Fig. 3.2, there is no separation or reprocessing of UNF. Instead, the discharged fuel (DF) is sent to interim storage (wet, then dry) and later to a permanent disposal repository.

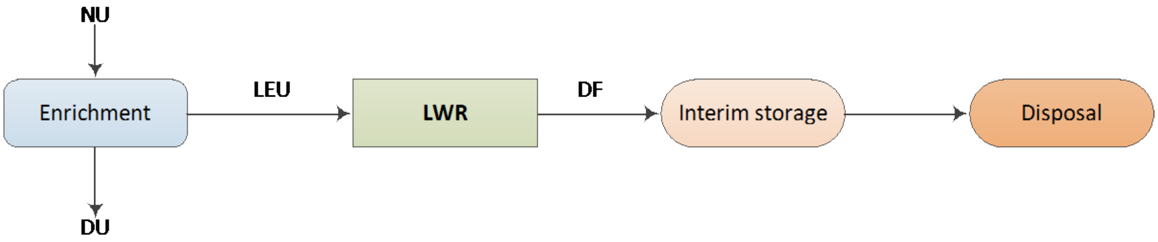


Figure 3.2: Once through (open) cycle scenario

3.1.2 1-Tier Fuel Cycle (1TFC) Scenario

The 1TFC scenario (Fig.3.3) was setup using a combination of OTC (Fig.3.1 section A) and FuRe (Fig.3.1 section C). OTC was deployed until 2050 when the setup transitioned to FuRe. It was assumed that the LWR capacity increases until 2050 to fulfill the growing energy demand, still at 1%, after which only fast reactors are built. Consequently, all LWRs are out of service by 2110. Reprocessing of UNF inventory (legacy used fuel) and discharged fuel (DF) starts in 2048 using UREX+1 separation technology, while an electrochemical process was used for the separation of discharged SFR fuel. The recovered TRU from the UNF inventory was used for the startup in SFR cores. The SFR breeding ratio (BR) is assumed to be break-even (BR = 1.0). This implies that there is no TRU limit to building new SFRs until the UNF inventory is completely exhausted. Except for the startup cycle, additional external TRU feed is not required due to the break-even breeding ratio. If TRU is not available for the new SFRs (due to exhausting of legacy UNF inventory), low-enriched uranium (LEU) and depleted uranium (DU) was used as the contingent (or back-up) fuel for the SFRs. Otherwise, no SFRs will be built (this is VISION requirement) if there is insufficient TRU-based fuel. All high level waste (HLW) in addition to low level fission products (LLFP) as well as some losses (0.1% loss assumed in UREX+1) are sent to geologic repository.

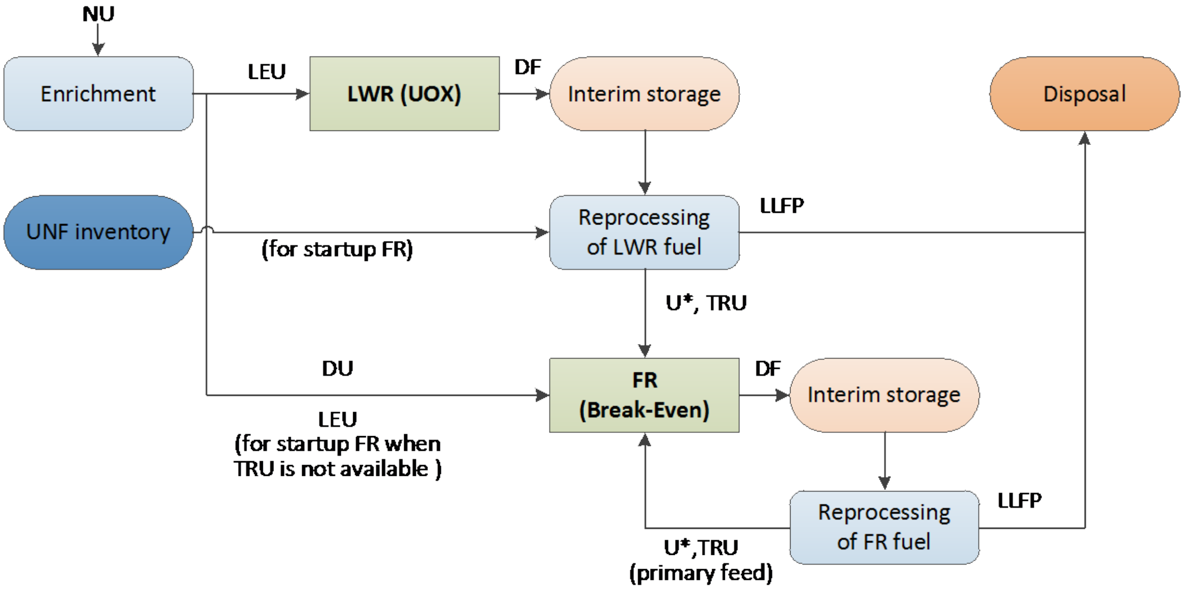


Figure 3.3: 1-Tier fuel cycle scenario

3.1.3 2-Tier Fuel Cycle (2TFC) Scenario

The 2TFC scenario (Fig. 3.4) was setup using a combination of OTC, MOC (Fig.3.1 section B) and FuRe. OTC was deployed until 2020, when separation capability was added, and the setup transitioned to the MOC setup. At 2050, the MOC setup also transitioned to FuRe setup.

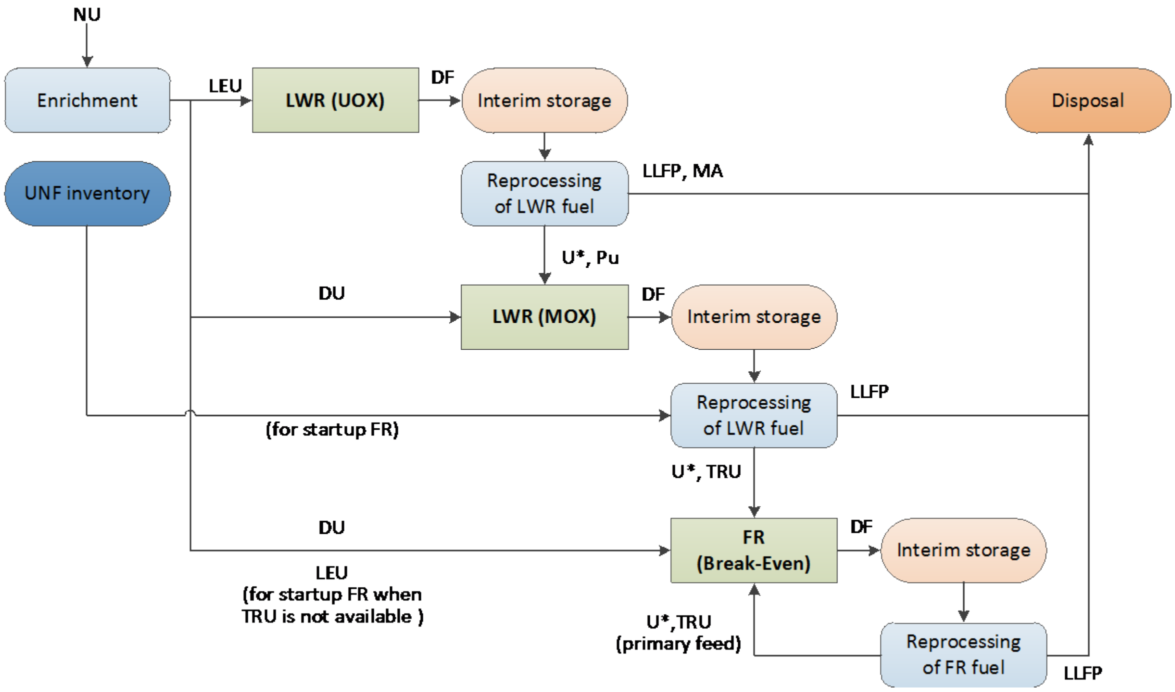


Figure 3.4: 2-Tiers fuel cycle scenario

Reprocessing of UNF inventory (legacy used fuel) and DF starts in 2020 by recycling U + Pu from discharged LWR-UOX fuel as well as from the legacy used fuel using UREX+3. Reprocessing of DF from LWR-MOX starts after the mandatory cooling time in temporary storage. After 2050, no new LWRs are constructed, only SFRs. Thus, all LWRs are completely replaced by full-recycling reactors after 2110. The recovered TRU/U from discharged LWR-MOX fuel is used as a makeup TRU feed for SFRs, if there is insufficient TRU/U from discharged LWR-UOX fuel. If there is insufficient TRU from any source, LEU is used to support

FR deployment. All high level waste (HLW) in addition to low level fission products (LLFP) as well as some losses (0.1% loss assumed in UREX+1) are sent to geologic repository.

3.2 General Scenario Parameters

All three NFC scenarios were setup to run for 150 years starting in year 2000 with all US nuclear energy historical data up to year 2010 obtained from DOE EIA, Nuclear Energy Institute (NEI), VISION User Guide 2011, and VISION Technical Manual 2012. Total US electric energy capacity predicted by VISION was 460.58 GWe in 2000 with nuclear contributing 88.53 GWe. A total of 103 reactors was assumed at the start in 2000, with all being PWR. All new PWR built from year 2000 were assumed to be Mixed-Oxide fuel capable. All fast reactors introduced starting from year 2050 were sodium cooled. A total of 42,000 ton of UNF was assumed to be available in year 2000; no distinction was made about burn-up of these legacy fuels. Every other necessary parameter was as defined in Table 3.1.

In all the three scenarios, all fuel cycle parameters were kept unchanged except in OTC, which has no recycling and no separation requirement. The only varying parameter is the separation capacity of the LWR-UOX UNF, separation capacities for used MOX and used SFR fuel were assumed unlimiting. In the 1TFC and 2TFC, different simulations were run using separation capacity of 1kT/yr, 2 kT/yr, and 4 kT/yr, for the LWR-UOX UNF. The results of these different simulations are presented in the following sections.

3.3 Once-Through Fuel Cycle Setup Results

This scenario was setup as described in section 3.1.1. The material flow in the cycle is shown in Figs. 3.3.1 – 7.

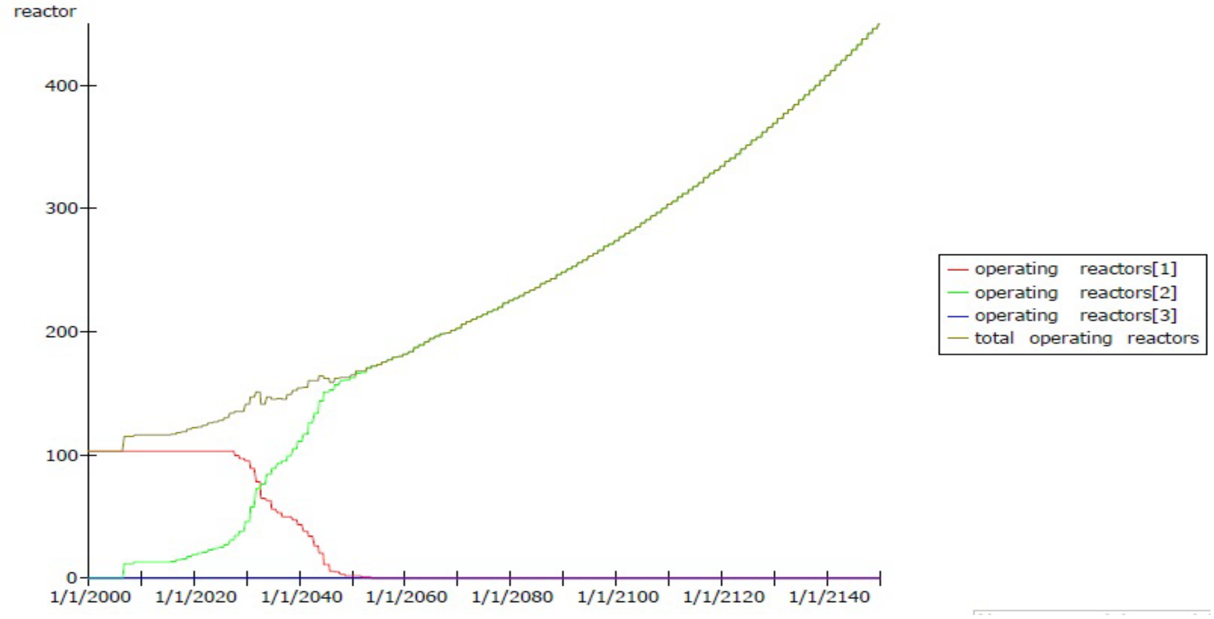


Figure 3.3.1: Total number of reactors deployed per year by reactor type in OTC.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

The LWR deployed in the OTC scenario were defined in Table 3.1. These reactors (operating reactors[2]) are capable of using mixed fuel (MOX fuel) with the exception of reactors existing before year 2000 (operating reactors[1]). However no MOX fuel was loaded, since there is no reprocessing and recycling in the OTC setup. The number of LWR deployed is in direct proportion to the nuclear energy demand shown in Fig. 3.3.2.

The electricity generated by VISION matched the amount of nuclear power contribution based on the 1% electricity growth rate assumed. In year 2000 total electricity energy capacity generated in the US was about 460.58 GWe with nuclear power contributing 19.54% or 88.53 GWe. The percentage contributed by nuclear power was about 19.76% for the scenario life time. Thus in year 2150, total electricity capacity generated in US (at 1% growth) is 2060.33 GWe-yr with nuclear power contributing 407.26 GWe-yr. The total number of LWRs needed to maintain approximately 20% nuclear power contribution is 847 reactors: 103 retired legacy reactors, 294 retired fresh reactors, and 450 reactors still in operation in year 2150. Fig.3.3.1 shows total number of operating reactors per year.

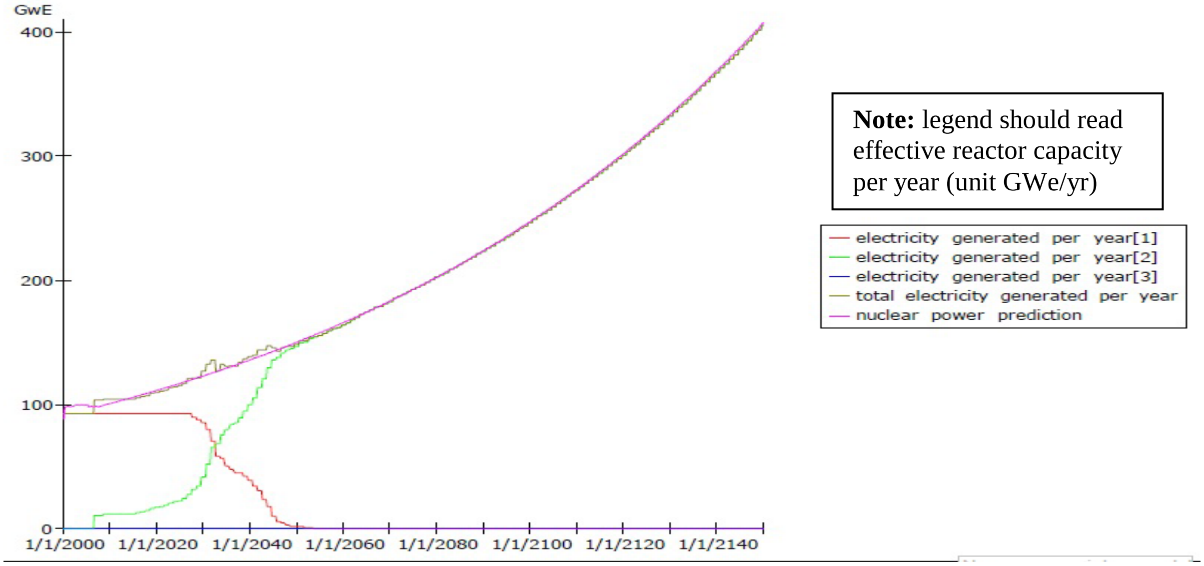

Note: legend should read effective reactor capacity per year (unit GWe/yr)

Figure 3.3.2: Effective reactor capacity per year (GWe/yr) by reactor in OTC.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

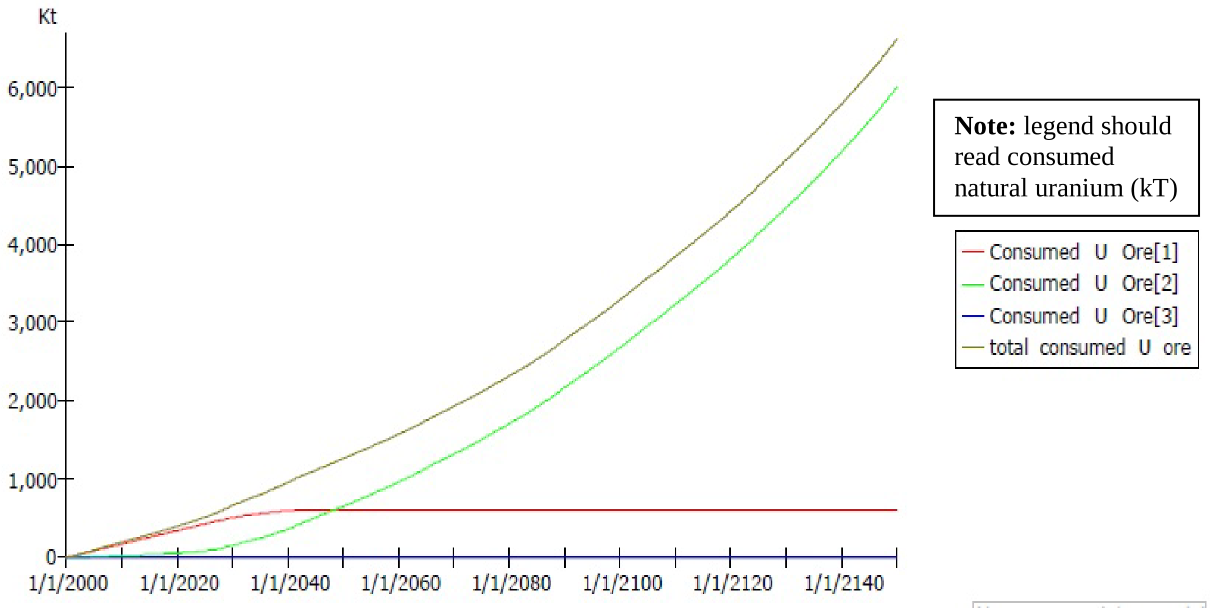

Note: legend should read consumed natural uranium (kT)

Figure 3.3.3: Cumulative consumed natural uranium by reactor in OTC.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

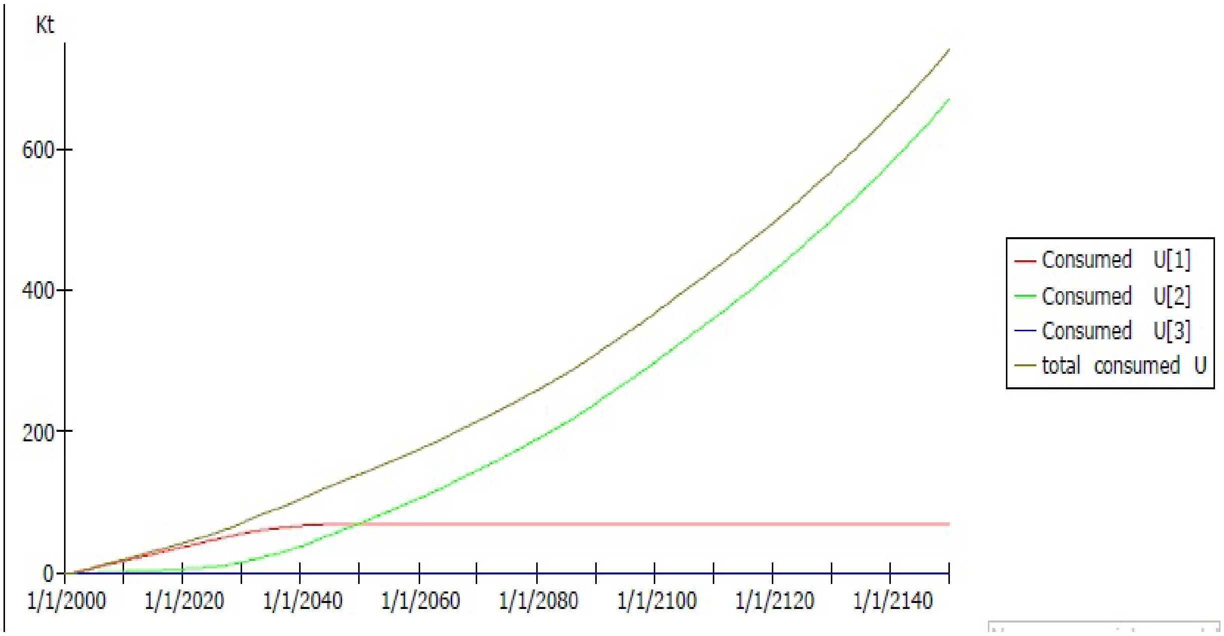


Figure 3.3.4: Cumulative consumed 4.3% enriched uranium by reactor in OTC.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

Total cumulative natural uranium consumed was about 6600 kT (Fig.3.3.3). This translates to 770.92 kT of 4.3% enriched uranium (Fig.3.3.4), for making UOX fuel, with 0.25% tail assay, 0.711% U-235 concentration in natural uranium, 0.1% process loss. The total amount of SWU required for fabricating the UOX fuel, is shown in Fig.3.3.5. The amount of SWU correlates with the total amount of natural uranium consumed.

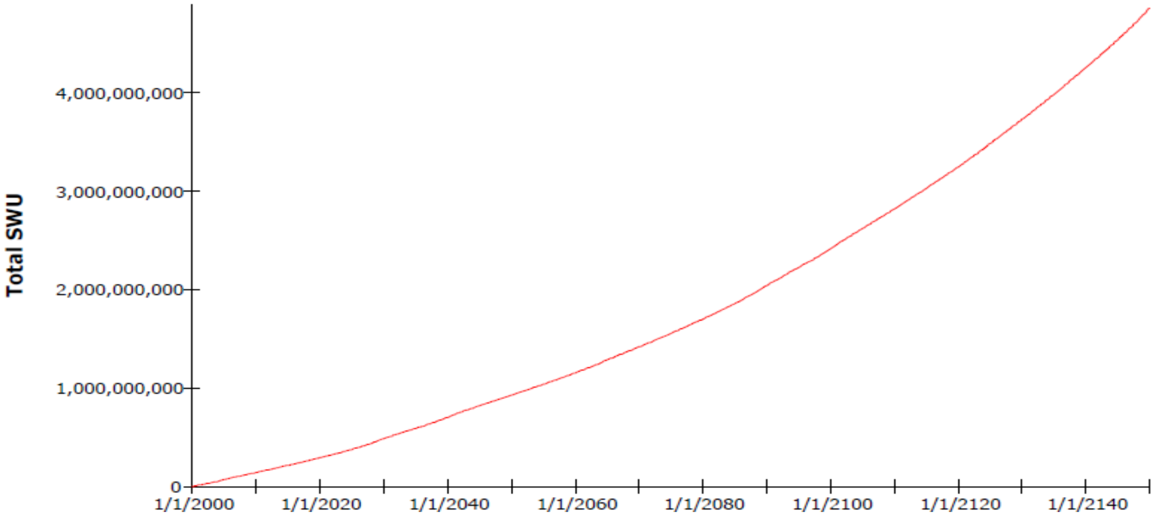


Figure 3.3.5: Cumulative separative work unit in OTC.

The annual cost breakdown of the OTC scenario is shown in Fig. 3.3.6, with reactor costs dominating the cost profile.

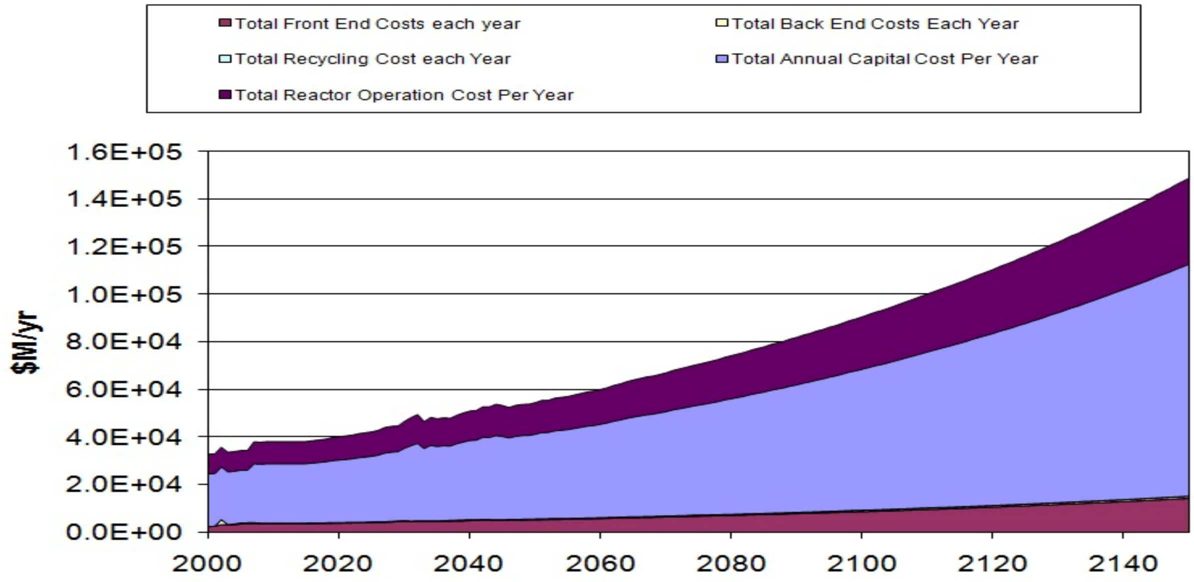


Figure 3.3.6: Annual cost breakdown of fuel cycle in OTC.

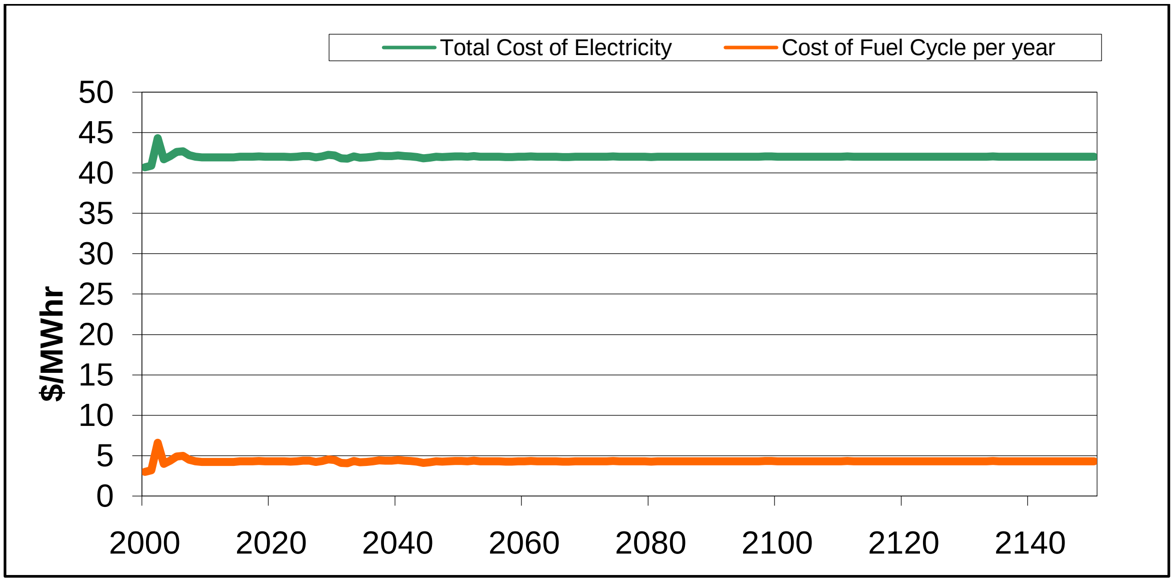


Figure 3.3.7: Annual unit cost breakdown ($/MWhr) in OTC.

Detailed analysis of cost is presented in chapter 6. The NFC economic analysis was based on the nominal rate (Fig.1.14) modified by adding a 3% escalation rate to compensate for inflation on the 2007 US$ values quoted. The levelized fuel cycle cost (LFCC) was about 10% of the levelized cost of electricity (LCOE). The approximate cost of electricity in the OTC is 43 $/MWhr (4.3 cents/kWhr), Fig.3.3.7. This is about the same rate of LCOE (4.4 – 5.2 cents/kWhr) as quoted by the Georgia Public Service Commission [32] for year 2012 winter rate.

3.4 1-Tier (1TFC) Fuel Cycle Scenario.

The 1TFC fuel cycle scenario was setup as described in section 3.1.2. Three different separation capacities: 1kT/yr, 2kT/yr, and 4kT/yr were used. Data for the 1kT/yr scenario are presented here, while data for 2kT/yr and 4kT/yr are available in Appendix A.

3.4.1 1-Tier with 1 kT/yr Separation Capacity Fuel Cycle Scenario.

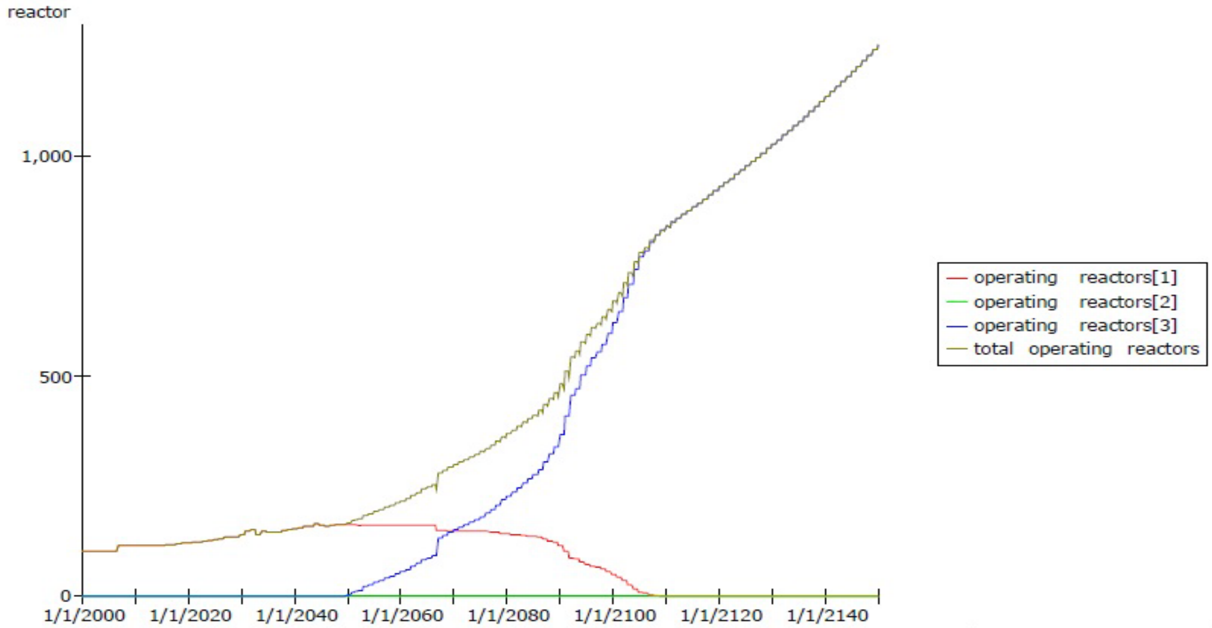


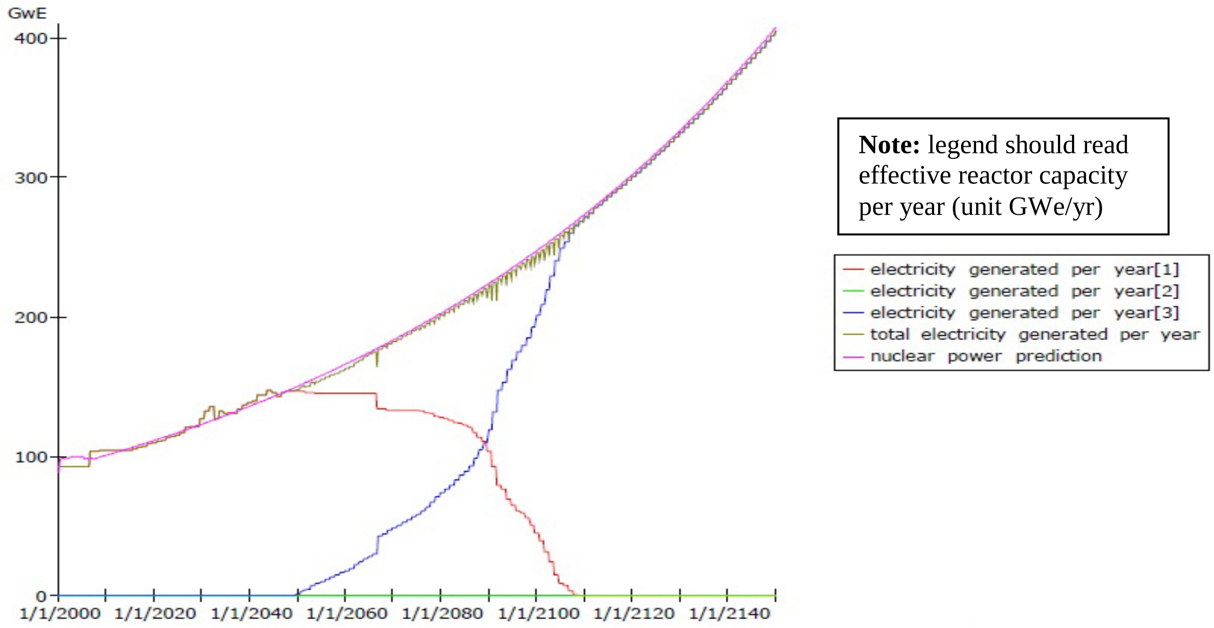
Figure 3.4.1: Total number of reactors deployed per year by reactor type in 1TFC – 1kT/yr capacity. [1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

The LWRs and the SFRs deployed in the 1TFC scenario were defined in Table 3.1. The 1TFC actually operated in the OTC mode for 50 years before transitioning to a mixed cycle

(OTC + FuRe) in year 2050. However no LWRs were deployed after 2049, thereby allowing all LWRs to be retired in 2110. All LWRs (operating reactors[1]) deployed after 2000 were capable of using MOX, but no MOX fuel was used in this scenario.

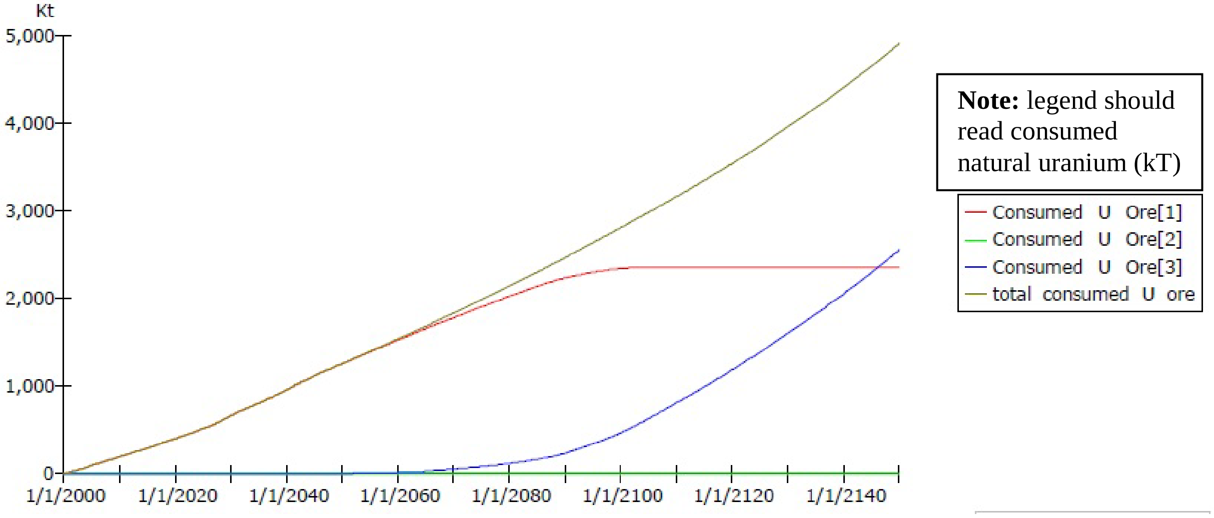
The electricity generated by VISION in this scenario still matched the amount of Nuclear power contribution in the OTC scenario.

The total number of reactors deployed in this scenario is directly proportional to the nuclear energy demand shown in Fig.3.4.2. A total of 264 LWRs (103 retired legacy LWRs and 161 retired new LWRs) in addition to 1622 SFRs (368 retired and 1254 still operating as of 2150) were deployed to meet the same energy demand in 1TFC compared to OTC. Fig.3.4. 1 shows total number of operating reactors per year.



Note: legend should read effective reactor capacity per year (unit GWe/yr)

Figure 3.4.2: Effective reactor capacity per year by reactor in 1TFC-1kT/yr capacity.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR



Note: legend should read consumed natural uranium (kT)

Figure 3.4.3: Cumulative consumed natural uranium by reactor in 1TFC-1kT/yr capacity. [1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

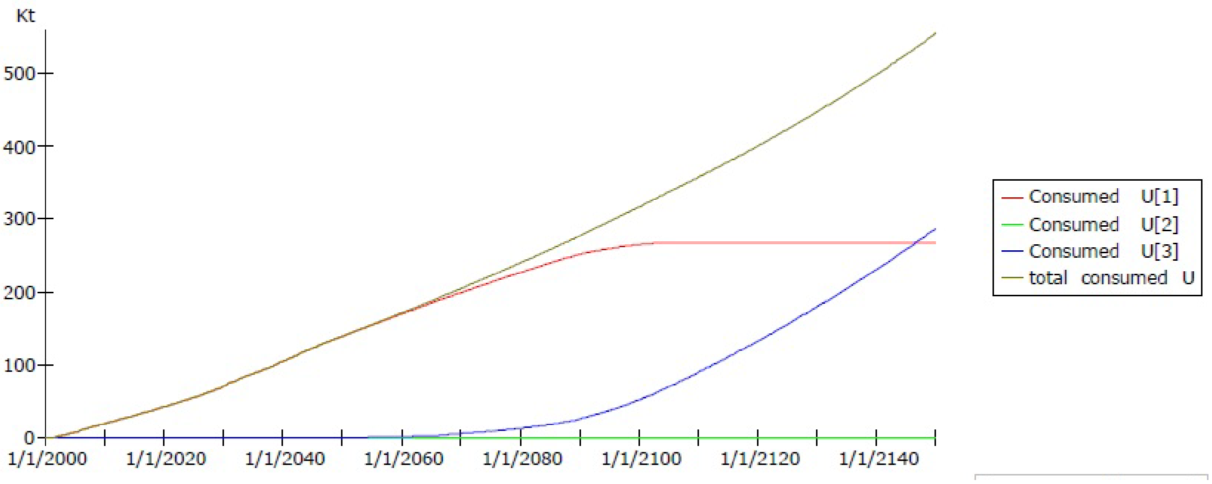


Figure 3.4.1.4: Cumulative consumed 4.3% enriched uranium by reactor in 1TFC-1 kT/yr capacity. [1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

Total cumulative natural uranium consumed was about 4908 kT (6600 kT in OTC) Fig.3.4.3 about 25% saving compared to OTC. This translates to 555.11 kT (770.92 kT in OTC) of 4.3% enriched uranium (Fig.3.4.4), about 28% saving compared to OTC, for making 4.3% enriched UOX fuel, with 0.25% tail assay, 0.711% U-235 concentration in natural uranium, and 0.1% process loss. The total amount of SWU required for fabricating the UOX fuel, is shown in

Fig.3.4.5. The amount of SWU also correlates with the total amount of natural uranium consumed.

The amount of enriched uranium consumed in 1TFC was further increased by the fact that new SFRs were setup to use LEU as a backup fuel for startup when SFR fuel is insufficient. The separation capacity deployed in this scenario was inadequate, and not enough materials to make SFR fuel are separated.

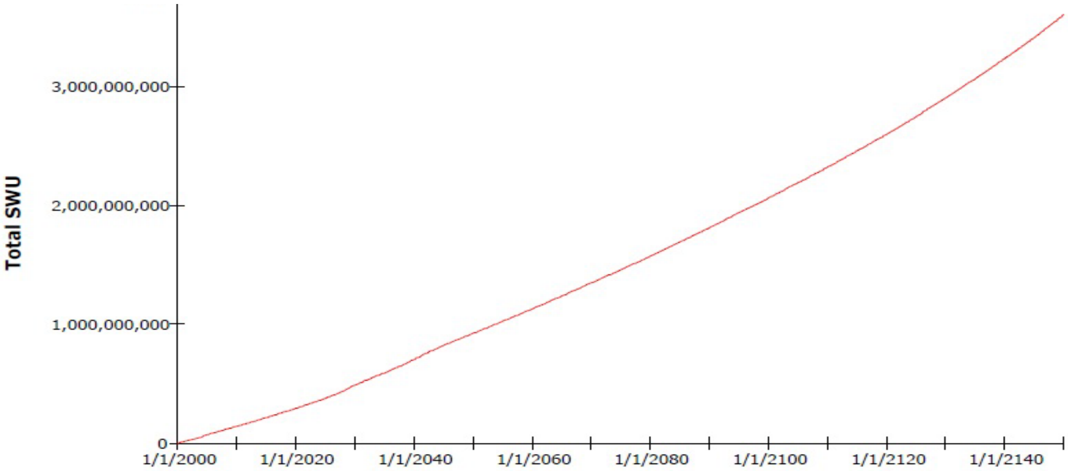


Figure 3.4.5: Cumulative separative work unit in 1TFC – 1kT/yr capacity.

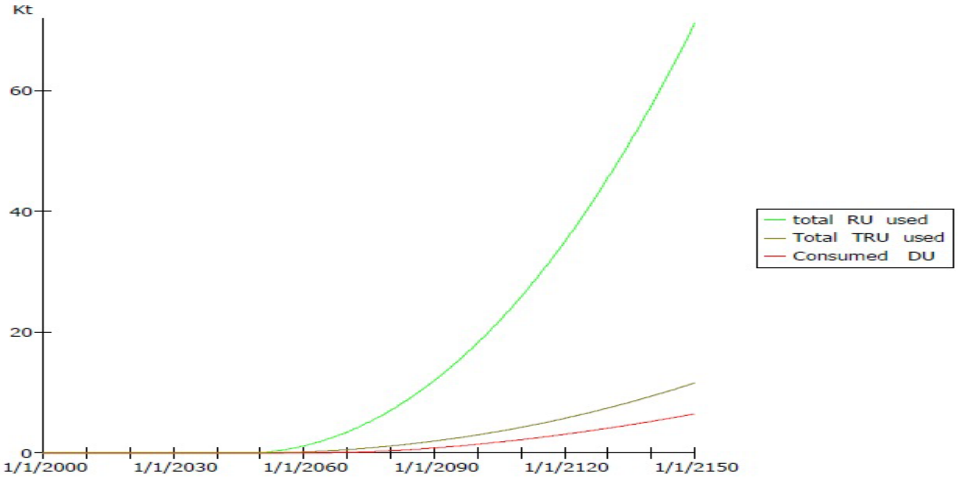


Figure 3.4.6: RU, TRU and DU used for fuel fabrication in 1TFC – 1 kT/yr capacity.

In the 1TFC about 70 kT of recovered uranium (RU), 12 kT of transuranic (TRU) and 8 kT of depleted uranium (DU) were recycled because of the deployment of SFRs fuel, Fig. 3.4.6.

The annual cost breakdown of the 1TFC – 1kT/yr capacity scenario is shown in Fig. 3.4.7, with reactor costs dominating the cost profile.

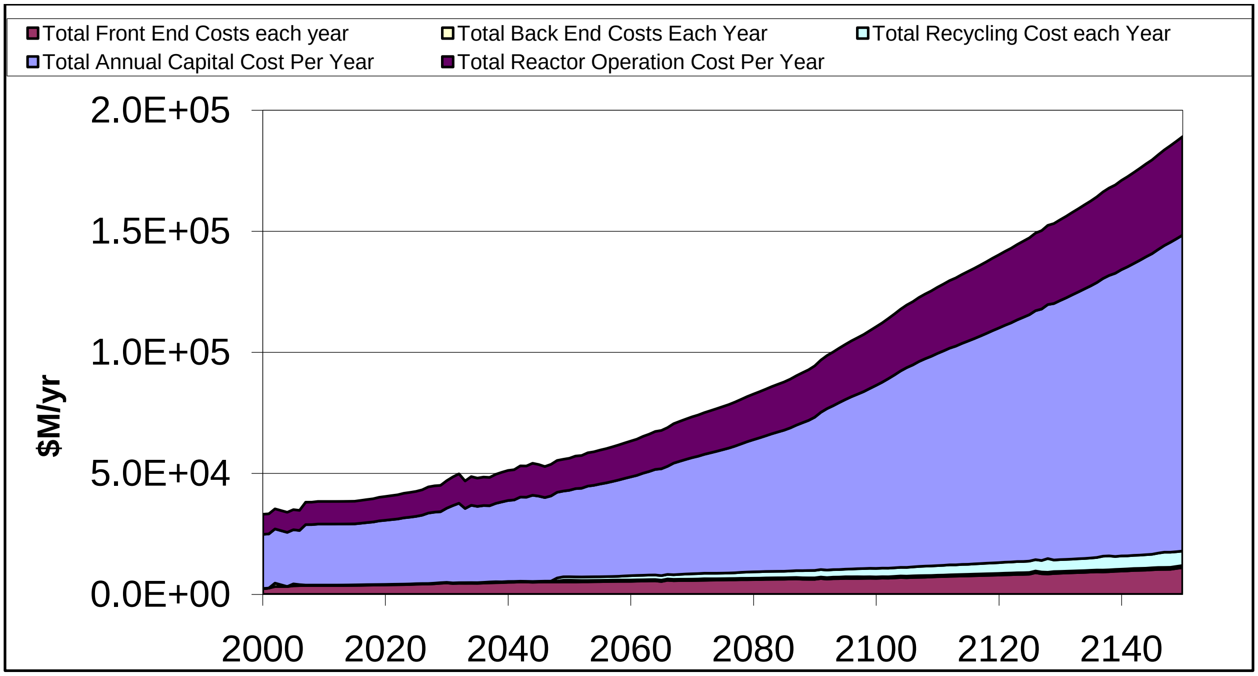


Figure 3.4.7: Annual cost breakdown of fuel cycle in 1TFC – 1kT/yr capacity.

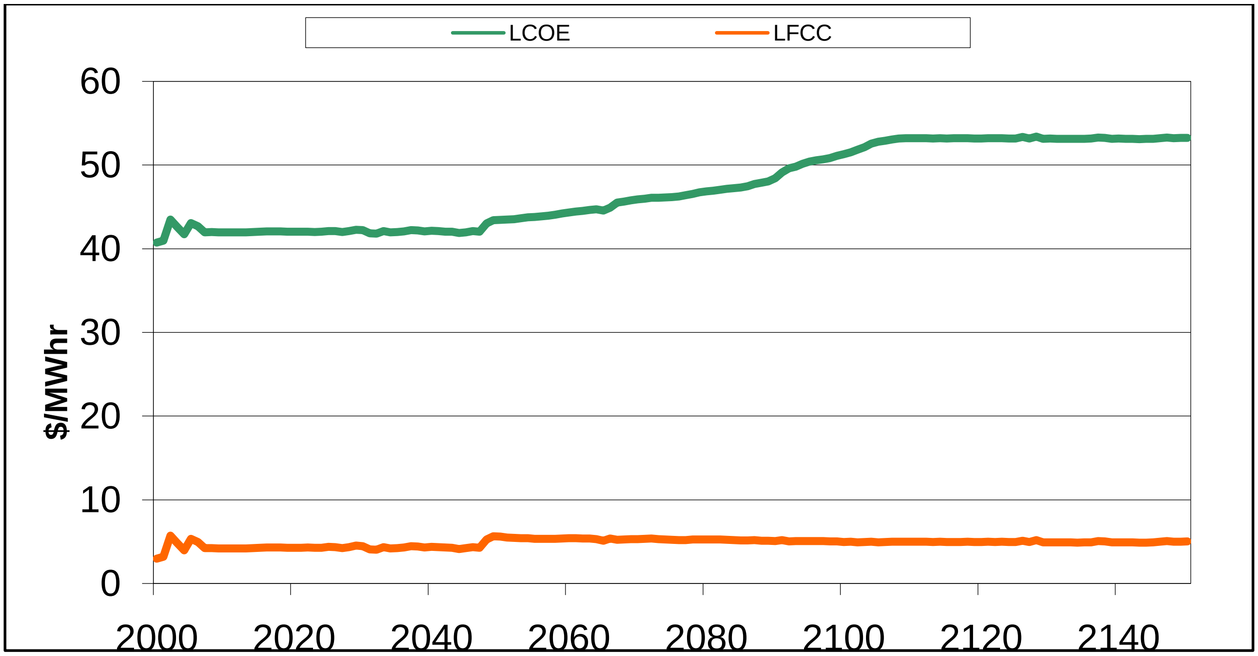


Figure 3.4.8: Annual unit cost breakdown ($/MWhr) in 1TFC – 1kT/yr capacity.

In the 1TFC, the levelized fuel cycle cost (LFCC) was about 10% of the levelized cost of electricity (LCOE) before deployment of SFR in 2050. The LFCC and LCOE however varied during the transition to FuRe, after which the cost stabilized at about 5 $/MWhr for the LFCC and about 54 $/MWhr for the LCOE, Fig.3.4.8.

3.5 2-Tier (2TFC) Fuel Cycle Scenario Initial Results

The 2TFC fuel cycle scenario was setup as described in section 3.1.3. Three different separation capacities: 1kT/yr, 2kT/yr, and 4kT/yr were used. Data for the 1kT/yr scenario are presented here, while data for 2kT/yr and 4kT/yr are available in Appendix A.

3.5.1 2-Tier with 1 kT/yr Separation Capacity Fuel Cycle Scenario

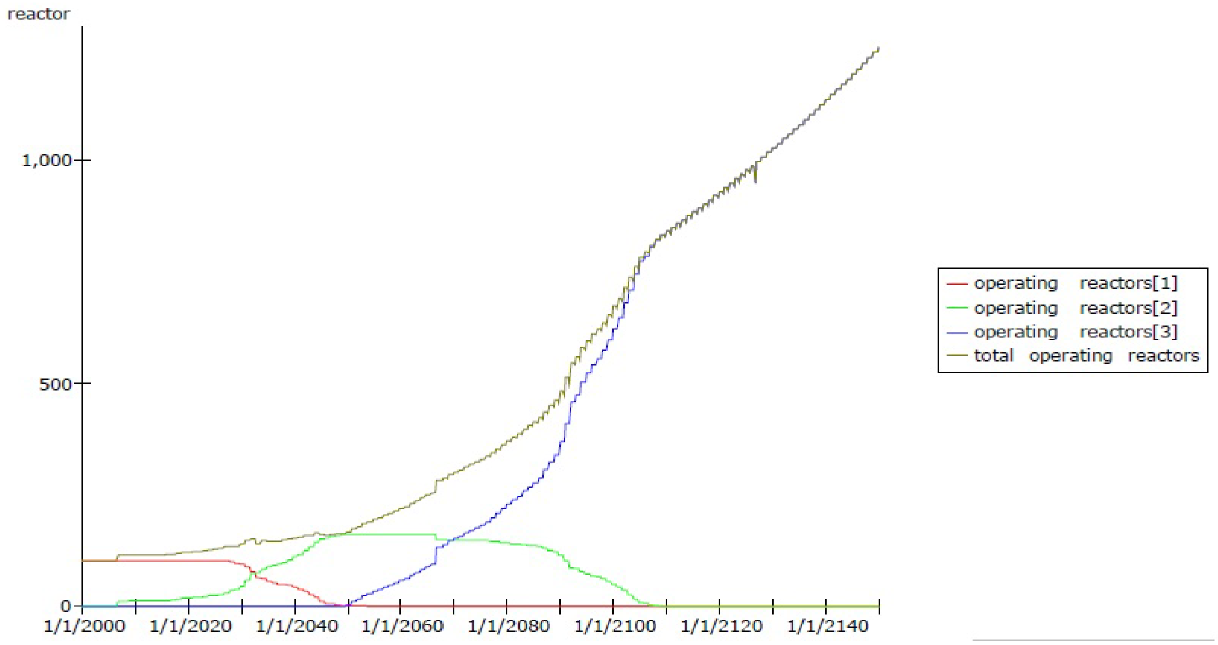
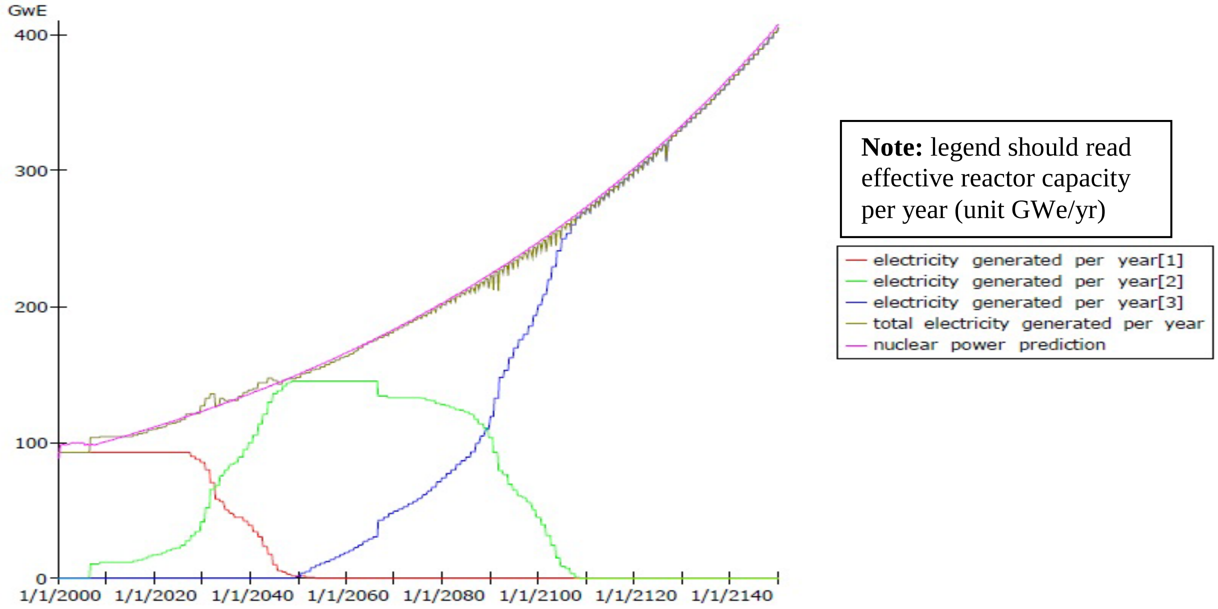


Figure 3.5.1: Total number of reactor deployed per year by reactor in 2TFC – 1kT/yr capacity
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

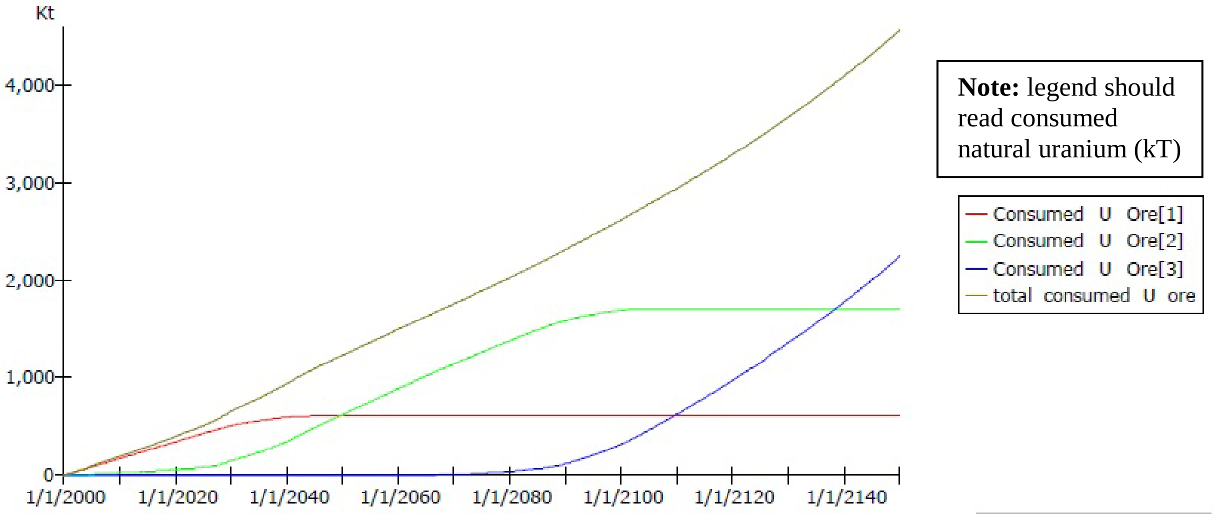
The parameters for the LWRs and SFRs deployed in the 2TFC scenario were defined in Table 3.1. The 2TFC operated primarily in the OTC mode for 20 years, then operated in essentially MOC mode for another 30 years before transitioning to mix of MOC + FuRe cycle, which was the mode for another 50 - 60 years and then finally to FuRe with 100% SFRs. However no LWRs were deployed after 2049, thereby allowing all LWRs to be retired in 2110. All LWRs (operating reactors[1]) deployed after 2000 were capable of using MOX, but it was observed that very little MOX fuel was used due to insufficient separation capacity.

The electricity generated by VISION in this scenario still matched the amount of Nuclear power contribution in the OTC scenario. The total number of reactors deployed is in this scenario is directly proportional to the nuclear energy demand shown in Fig.3.5.2. A total of 264 LWRs (103 retired legacy and 161 retired new) in addition to 1623 SFRs (369 retired and 1254 still operating as of 2150) were deployed to meet the same energy demand in 2TFC compared to OTC. Fig.3.5.1 shows the total number of operating reactors per year. It is important to point out that only 1 extra SFR (retired) was required as a result of the deployment of MOC. The implication for this setup (2TFC) is that the reactor cost will not be a major factor in the economic analysis and in making decision between 1TFC and 2TFC.



Note: legend should read effective reactor capacity per year (unit GWe/yr)

Figure 3.5.1.2: Effective reactor capacity per year by reactor in 2TFC-1kT/yr capacity.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR



Note: legend should read consumed natural uranium (kT)

Figure 3.5.1.3: Cumulative consumed natural uranium by reactor in 2TFC-1kT/yr capacity.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

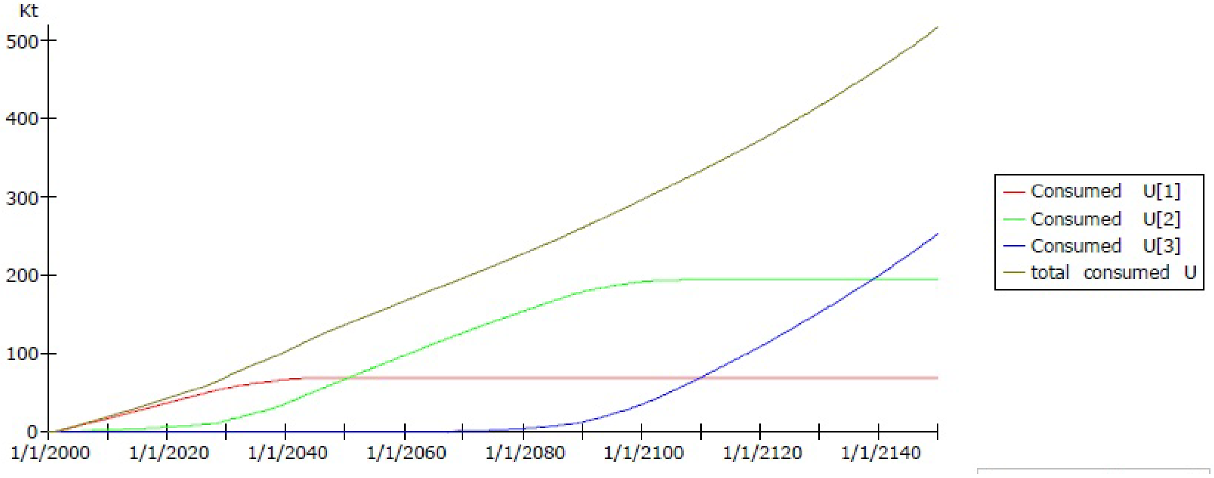


Figure 3.5.1.4: Cumulative consumed uranium by reactor in 2TFC-1 kT/yr capacity.
[1] = LWR-UOX [2] = LWR-UOX-MOX capable [3] = SFR

Total cumulative natural uranium consumed was about 4550 kT (4908 kT in 1TFC and 6600kT in OTC) of natural uranium (Fig.3.5.3) about 30% saving compared to OTC. This translates to 514.48 kT (555.11 kT in 1TFC and 770.92 kT in OTC) of uranium (Fig.3.5.4), about 33% saving compared to OTC, for making 4.3% % enriched UOX fuel, with 0.25% tail assay, 0.711% U-235 concentration in natural uranium, and 0.1% process loss. The total amount of SWU required for fabricating the UOX fuel, is shown in Fig.3.5.5. The amount of SWU also correlates with the total amount of enriched uranium consumed.

The amount of enriched uranium consumed in 2TFC was further increased by the fact that new SFRs were setup to use LEU as a backup fuel for startup when SFR fuel is insufficient. The separation capacity deployed in this scenario was inadequate, and not enough materials to make SFR fuel are separated.

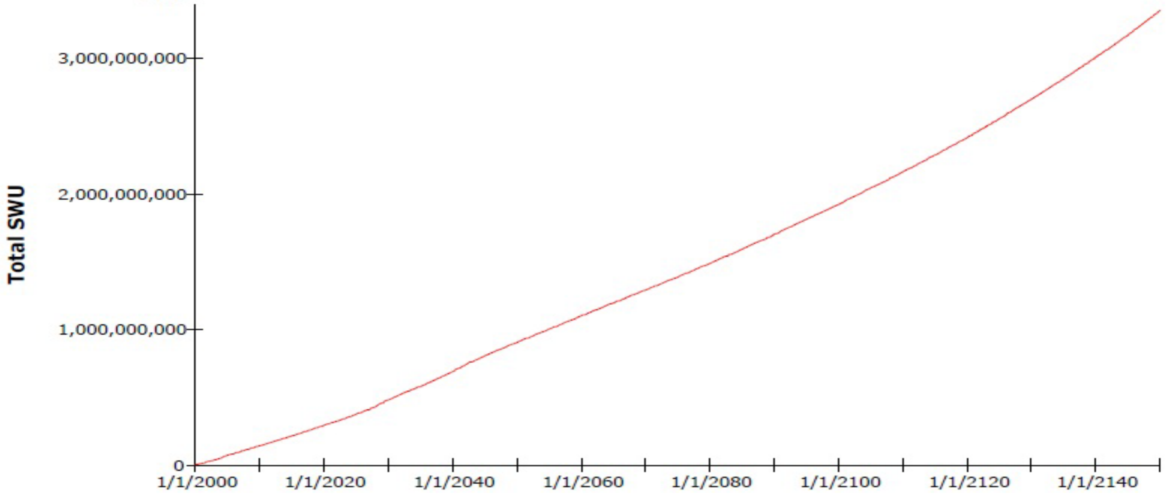


Figure 3.5.1.5: Cumulative separative work unit in 2TFC – 1kT/yr capacity.

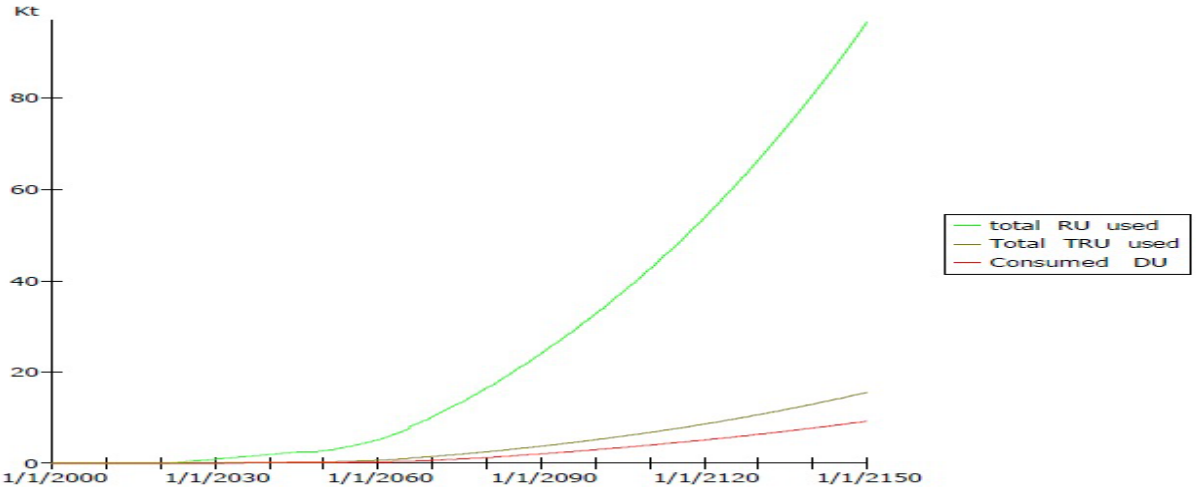


Figure 3.5.1.6: RU, TRU and DU used for fuel fabrication in 2TFC – 1 kT/yr capacity.

In the 2TFC about 95 kT, a 21% increase compared to 1TFC (about 70 kT in 1TFC) of recovered uranium (RU), about 16 kT, 33% increase compared to 1TFC (about 12 kT in 1TFC) of transuranic (TRU) and about 12 kT, a 50% increase compared to 1TFC (about 8 kT in 1TFC) of depleted uranium (DU) were recycled because of the deployment of LWR-MOX and SFRs Fig.3.5.6.

The annual cost breakdown of the 2TFC – 1kT/yr capacity scenario is shown in Fig. 3.5.1.7, with reactor costs also dominating the cost profile.

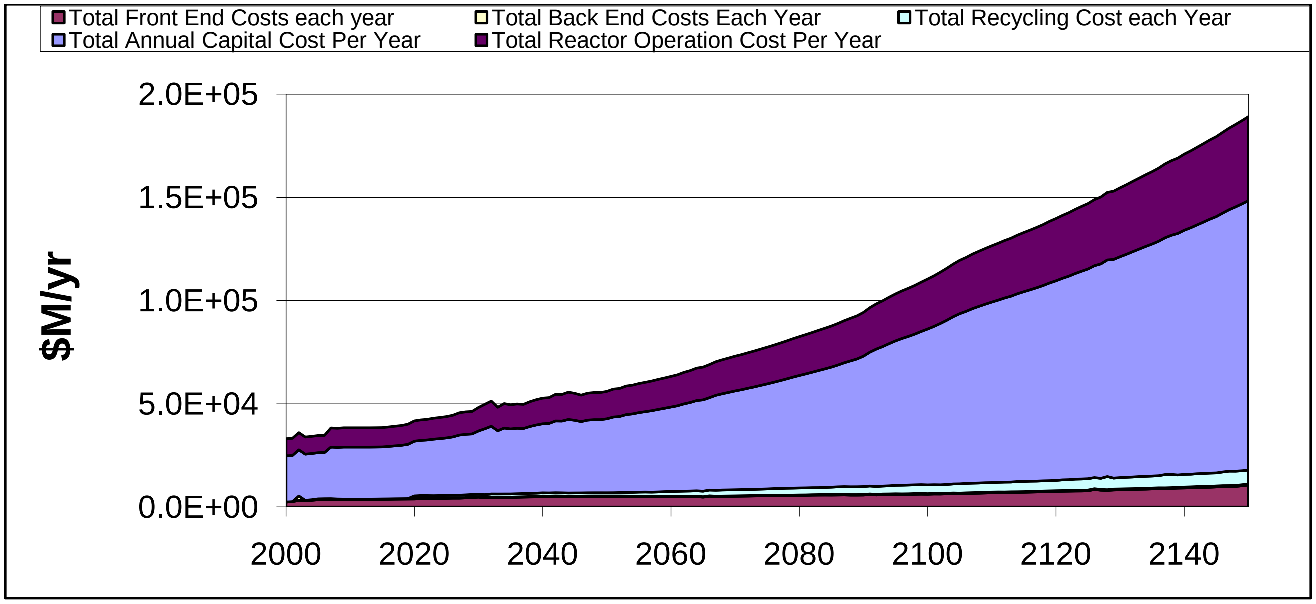


Figure 3.5.7: annual cost breakdown of fuel cycle in 2TFC – 1kT/yr capacity.

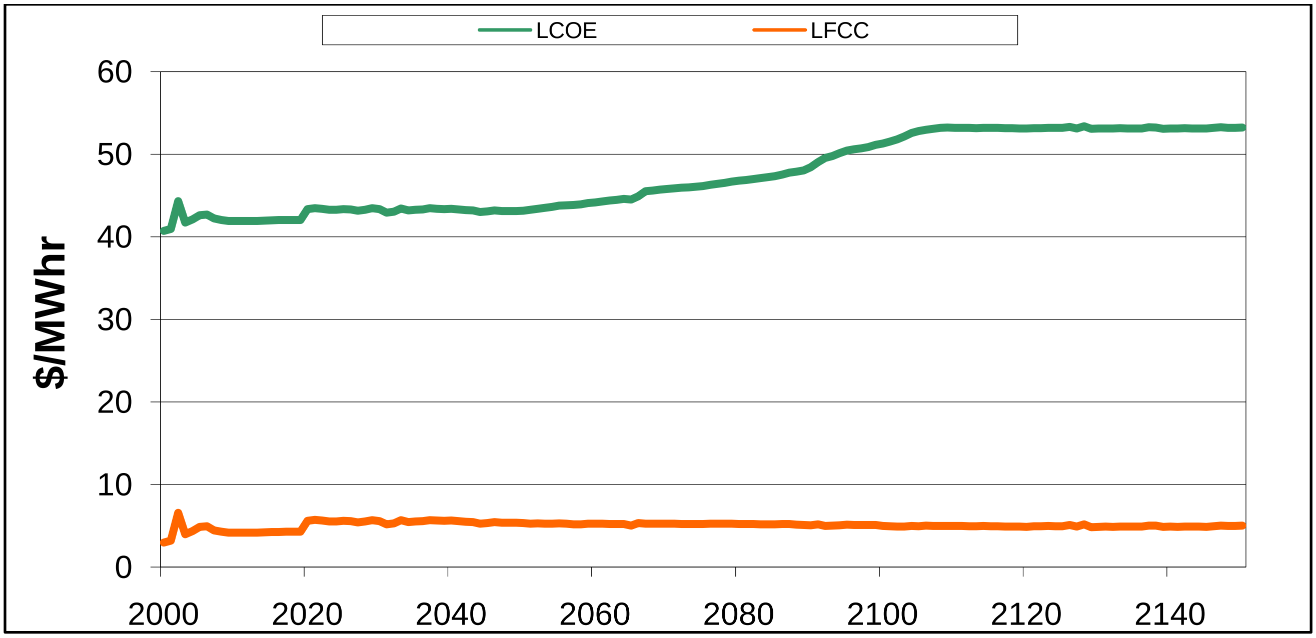


Figure 3.5.8: Annual unit cost breakdown in 2TFC – 1kT/yr capacity.

In the 2TFC, percent of LFCC was about 10% of LCOE during OTC and MOC stages just before 2050 when SFRs are deployed. However the LFCC and LOCE are both higher compared to the same period in1TFC. The LFCC and LCOE however varied during the transition to FuRe, after which the cost stabilized at about 5 $/MWhr for the LFCC and about 54 $/MWhr for the LCOE, Fig.3.5.8, the same Fig. as in 1TFC. This indicates that LFCC and LCOE alone will not be sufficient for deciding between 1FTC and 2TFC.

CHAPTER 4

NUCLEAR MATERIAL AND FACILITY UTILIZATION

4.1 Nuclear Reactors Deployed

The fleet of nuclear reactors deployed in all the scenarios is as represented in Fig.4.1.1 and 4.1.2. Two types of LWRs are used in the setup, one capable of using UOX fuel only (reactor1 or R1), and the other capable of using both UOX and MOX fuels (reactor2 or R2). Both R1 and R2 are the same in terms of operating parameter (Table 3.1), and have comparable reactor and operational costs (Fig.1.14). The SFR (reactor3 or R3) uses metallic fuel (U-TRU-Zr alloy). Specifications for all reactors are contained in Table 3.1.

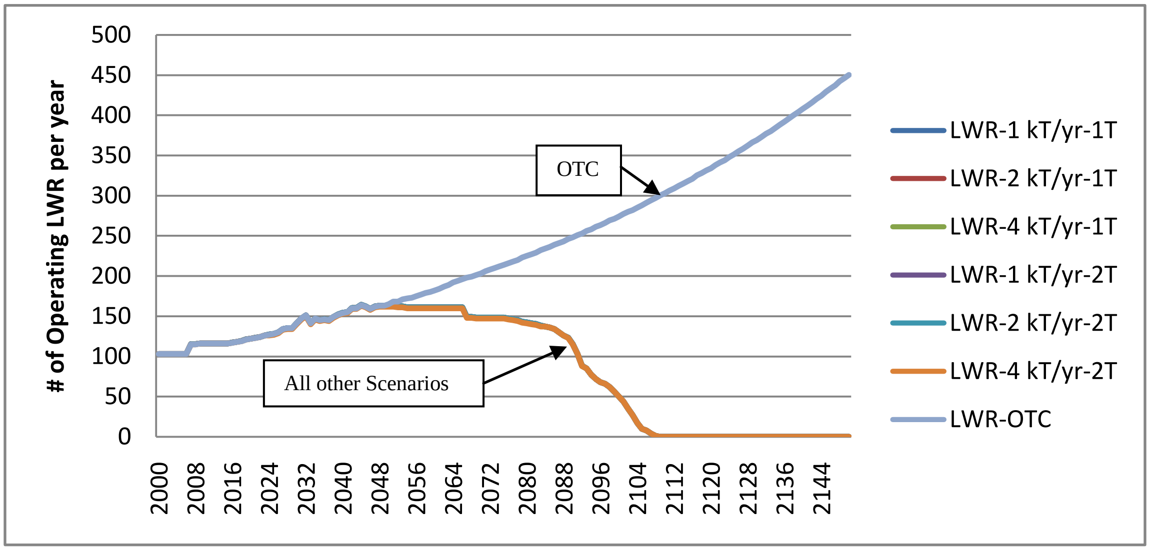


Figure 4.1.1 Number of LWR (R1 & R2) deployed per year.

LWR deployment followed the same pattern for both 1TFC and 2TFC for all the three separation capacities. This is another supporting fact that reactor capital cost and reactor operating cost will not be sufficient to discriminate between the two advanced fuel cycles. The deployment pattern in OTC however follows the energy demand profile in Fig.4.1.3. The total number of LWR deployed during the 150 year of simulation to support 1% energy growth and maintain 19.62% share of nuclear electricity generation is shown in Table 4.1.

Table 4.1: Total LWRs Deployed by Year 2150

Total LWR Deployed by Year 2150							
	1kT/yr-1T	**2kT/yr-1T**	**4kT/yr-1T**	**1kT/yr-2T**	**2kT/yr-2T**	**4kT/yr-2T**	**OTC**
Retired	264	264	264	264	264	263	397
Operating	0	0	0	0	0	0	450
Total	264	264	264	264	264	263	847

Total number of LWR deployed is about the same (264 reactors) in both 1TFC and 2TFC. The number is more than tripled in OTC because of the once through setup.

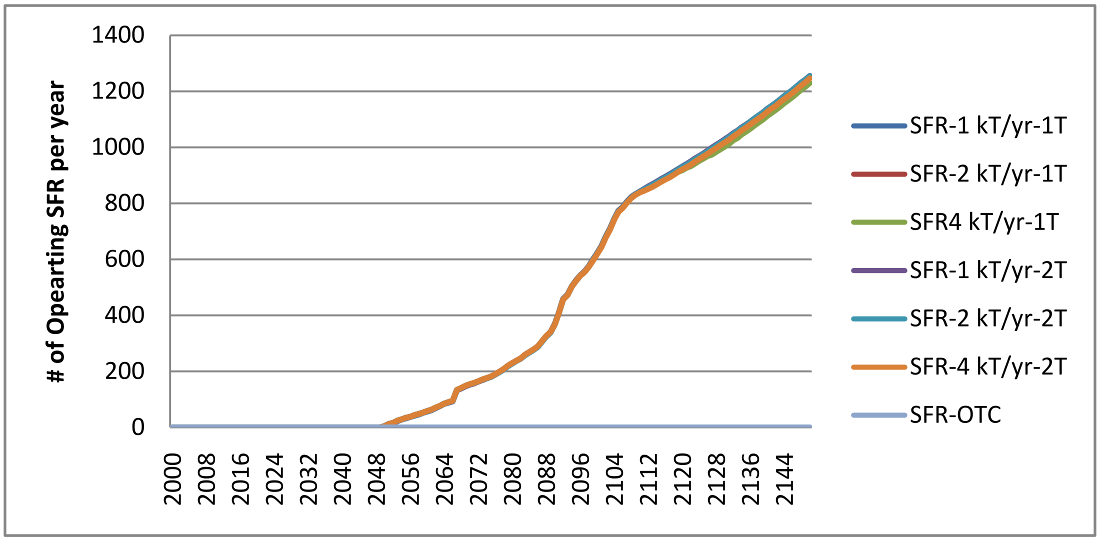


Figure 4.1.2 Number of operating SFRs (R3) per year.

Fig.4.1.2 shows that SFR deployment rate is the same in both 1TFC and 2TFC for all the three separation capacities. This also supports the conclusion that reactor capital cost and reactor operating cost will not be sufficient to discriminate between the two advanced fuel cycles. There is no SFR deployed in OTC since no used fuel separation is allowed in that cycle. The total number of SFR deployed during the 150 year of simulation to support 1% energy growth and maintain 19.62% share of nuclear electricity generation is shown in Table 4.2.

Table 4.2: Total SFRs Deployed by Year 2150

Total SFR Deployed by Year 2150							
	1kT/yr-1T	**2kT/yr-1T**	**4kT/yr-1T**	**1kT/yr-2T**	**2kT/yr-2T**	**4kT/yr-2T**	**OTC**
Retired	368	368	369	369	367	369	0
Operating	1254	1254	1229	1254	1254	1246	0
Total	1622	1622	1598	1623	1621	1615	0

Total number of SFR deployed is about the same (about 1622 reactors) for separation capacities below 4 kT/yr, in both 1TFC and 2TFC. The number of SFR required for the same nuclear energy generation is however lower when the separation capacity is 4 kT/yr. This suggests that the number of SFR required may further be reduced by deploying more separation capacity.

Total nuclear energy generated, Fig.4.1.3, is the same for all the scenarios except in 4kT/yr-1T which fell below predicted demand around 2120. It can be concluded that any of the scenarios will be suitable for meeting energy demand.

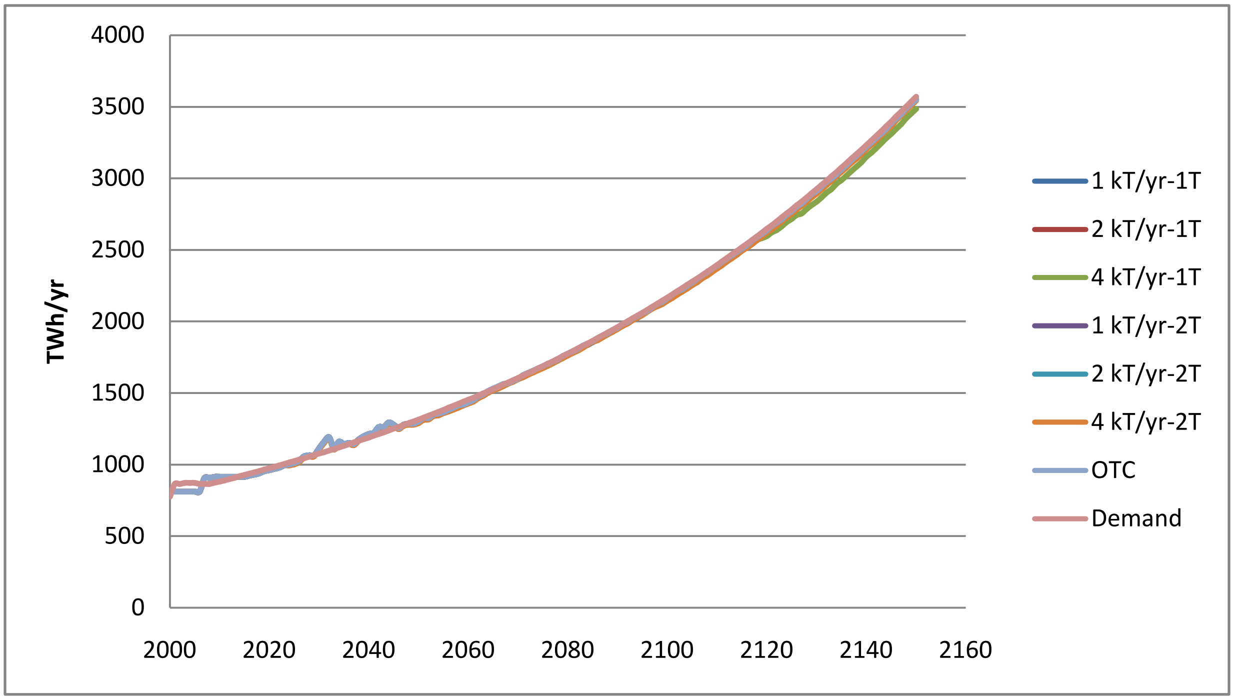


Figure 4.1.3 Nuclear energy generated vs demand in all scenarios in TWh/Yr

4.2 Separation Capacity Deployed and Percentage Used

Three different separation technologies were deployed in all the advanced fuel cycles setup. A separation loss of 0.1% was assumed for the UREX+ (UREX+1 & UREX+3) technology and 3% loss was assumed for the Electrochemical technology.

In 1TFC, used fuel from LWR-UOx was separated using UREX+1 technology, all recovered uranium and TRU were designated for SFR fuel fabrication, other materials and losses were designated for disposal. While used fuel from SFR were separated using electrochemical separation technology, HLW, spent fuel and separation losses was designated for geological disposal, all other materials were used for fuel fabrication to be recycled in the SFRs.

In 2TFC, used fuel from LWR-UOX was initially (between 2000 - 2110) separated using UREX+3 technology, all recovered uranium and neptunium + plutonium (NpPu) separated were designated for MOX fuel fabrication and americium + curium (AmCm) separated were designated for SFR fuel fabrication. After year 2110, UREX+1 was used to separate any UOX used fuel (mostly from SFR startup core). UREX+1 was used to separate all used MOX fuel. While used fuel from SFR was separated using electrochemical separation technology, only HLW and separation losses was designated for geological disposal, all other materials were used for fuel fabrication to be recycled in the SFRs.

In both 1TFC and 2TFC scenarios separation capacities for LWR-MOX and SFR UNF were setup as 2 kT/yr and 10 kT/yr respectively. This assumption was necessary in other to focus on UOx separation, and based on previous scenario study [28] that had identified LWR-UOX separation as a bottleneck. Separation capacity of used UOX fuel was deployed as shown in Table 4.3.

Tabel 4.3: Separation capacity deployed for UOX separation and deployment time.

	1TFC	**2TFC**
Capacity Deployed	**Year Deployed**	**Year Deployed**
1 kT/yr	2048	2020
2 kT/yr	2048	2020
4 kT/yr	2048	2020

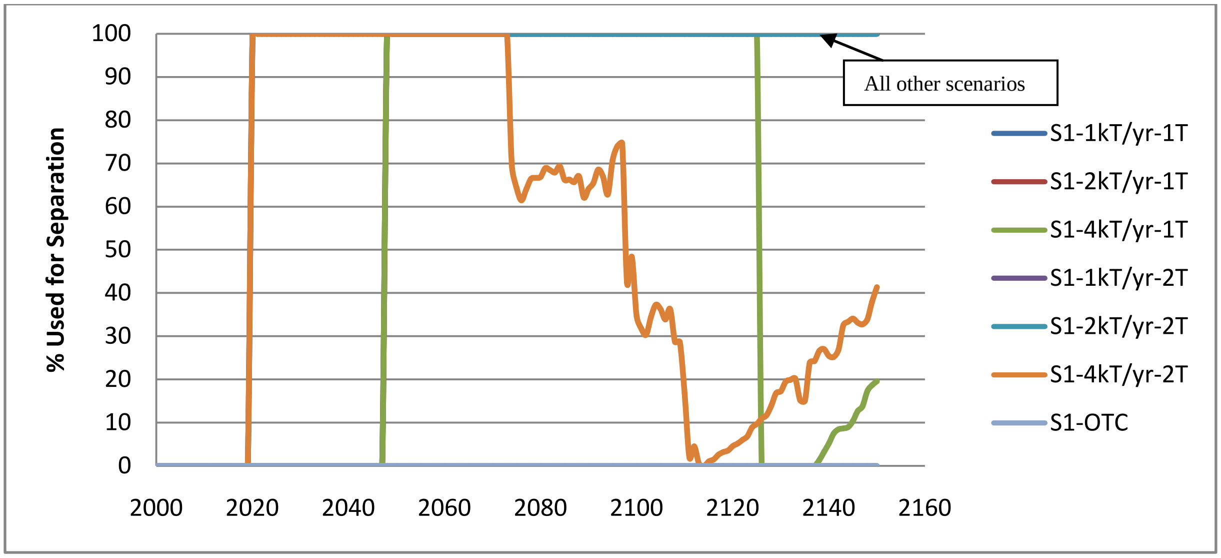


Figure 4.2.2 Percentage of deployed separation capacity used for UOX fuel separation.

Fig.4.2.2 indicates the degree of bottleneck created as a result of in-adequate separation capacity deployed. In all scenarios, any separation facility operating at 100% capacity indicates that there are more UNF inventories (especially the legacy UNF inventory) to be separated.

In all 2TFC scenarios, capacities 1 kT/yr and 2 kT/yr were never adequate for the entire simulation period. However at 4 kT/yr capacity, it took over 50 years of inadequate separation capacity, before the level of UNF inventory was significantly reduced.

The same pattern of bottleneck operation was observed in 1TFC, for 1 kT/yr and 2 kT/yr separation capacities for the 150 years of simulation. The deployment of 4 kT/yr separation capacity in 2048 (just before SFR deployment), did not offer any improvement compared to the same amount of capacity deployed in 2TFC. It took over 80 years before separation capacity adequacy was achieved.

Separation facilities operating experience (France & UK) suggests that it is practically impossible to operate a commercial separation facility at 100% installed capacity.

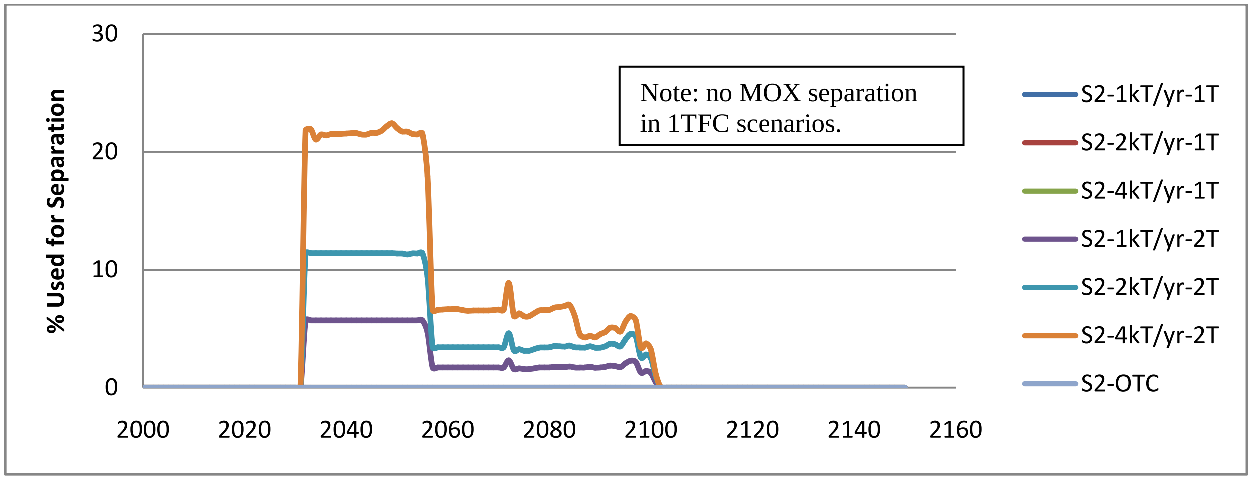


Figure 4.2.3 Percentage of deployed separation capacity used for MOX fuel separation.

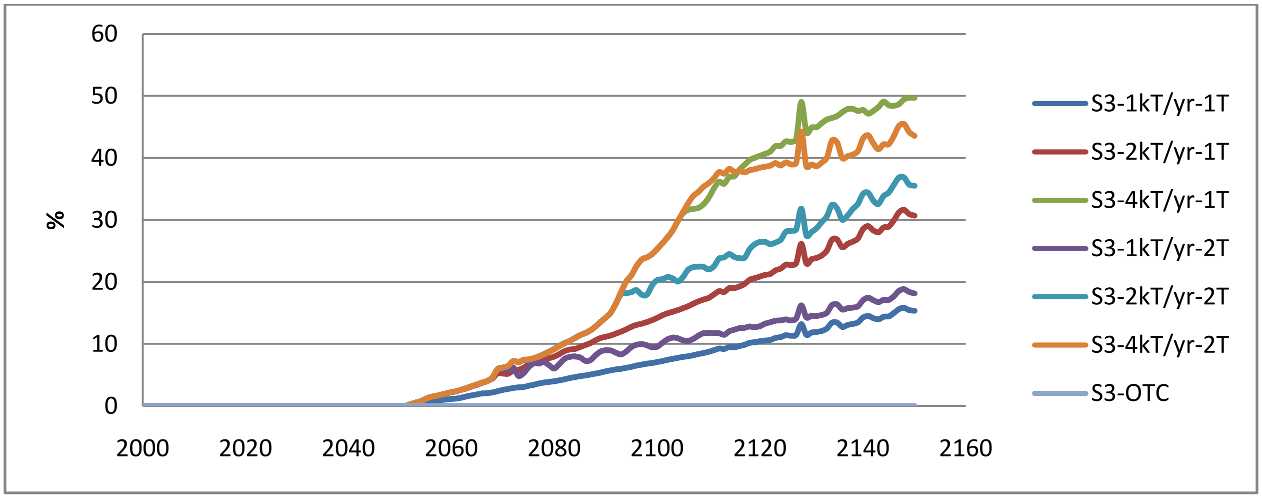


Figure 4.2.4 Percentage of deployed separation capacity used for SFR fuel separation.

In Fig.4.2.3 and 4.2.4, the percentage of deployed MOX and SFR fuel separation capacities used in all scenarios is well below 100%. This implies that the assumed capacities in the simulations were adequate (or perhaps oversized) and did not limit the output. In some cases (e.g all 2TFC and all 1TFC below 4 kT/yr), the assumed capacities can be reduced by about 50% without impacting the resource utilization. This will however impact cost analysis, since the cost of building and operating the facilities will be cut in half.

4.3 Uranium Resource Utilization

4.3.1 Natural Uranium Consumed

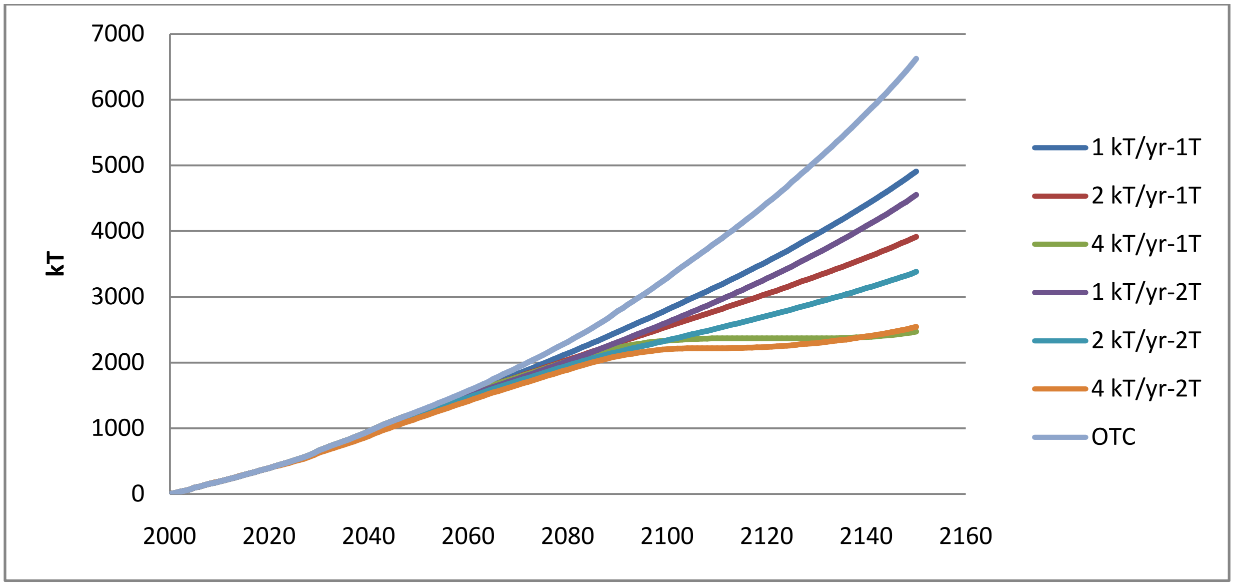


Figure 4.3.1 Natural uranium consumed in OTC, 1TFC and 2TFC as function of separation capacities.

In the OTC, about 6600 kT of natural uranium was mined to sustain the LWRs for 150 year operation. A significant amount of natural uranium was saved by deploying advanced fuel cycles with recycling options. The amount of saving is related proportional to the amount of separation capacity deployed in these advanced cycles, Fig.4.3.1.

In 1TFC, with a 1 kT/yr separation capacity deployed in year 2048, a saving of 25.86% was achieved, while a saving of 40.86% was achieved by doubling the separation capacity for the same period. By quadrupling the separation capacity (4 kT/yr), the saving in the amount of natural uranium required to sustain the LWRs is 62.68%.

In 2TFC, with a 1 kT/yr separation capacity deployed in year 2020, a saving of 31.28% was achieved, about 5% more than was achieved in 1TFC as a result of deploying separation capacity early. A saving of 48.94% (about 8% more than obtained in 1TFC) was achieved by doubling the separation capacity for the same period. By quadrupling the separation capacity (4 kT/yr), the saving in the amount of natural uranium required was 61.58% (which is about 1% less 1TFC saving). The explanation for this can be found in Fig.4.3.1 and 4.3.2, note that the saving in natural uranium mined in 2TFC at 4 kT/yr was more than 1TFC for the same separation capacity until year 2130. The rise in natural uranium (and fresh uranium) which started around year 2120 in 2TFC and 2030 in 1TFC was due to the fact that the SFRs were setup to use LEU for startup in case of shortage of SFR fuel. This modification in VISION is necessary to achieve 100% transition to SFR.

4.3.2 Enriched Uranium (4.3% enr.) Fuel Consumed

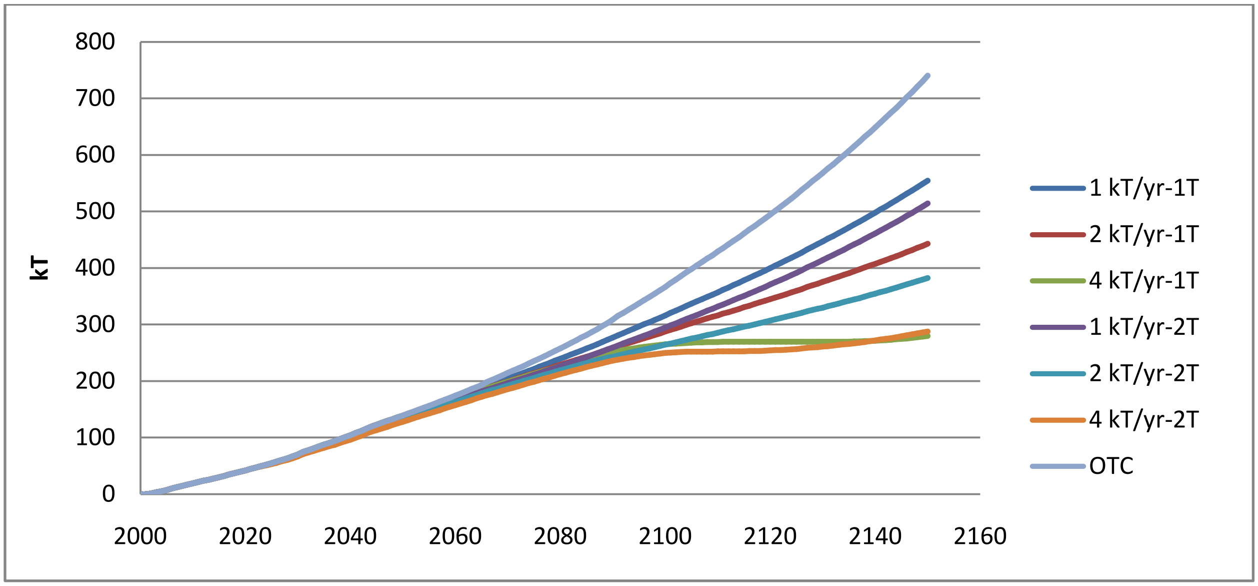


Figure 4.3.2 Enriched uranium consumed in OTC, 1TFC and 2TFC at different separation capacity.

It can be concluded that the saving pattern for the amount of uranium consumed follows a similar pattern as in Fig.4.3.1, and the same conclusion can be drawn.

4.3.3 Transuranics Used for Fuel Fabrication

In Fig.4.3.3 it is observed that the amount of TRU consumed (for re-fabricating fuel) is directly proportional to the amount of separation capacity deployed. It can also be concluded that early deployment of separation facility as in 2TFC has a positive impact on the amount of TRU consumed in the fuel cycle.

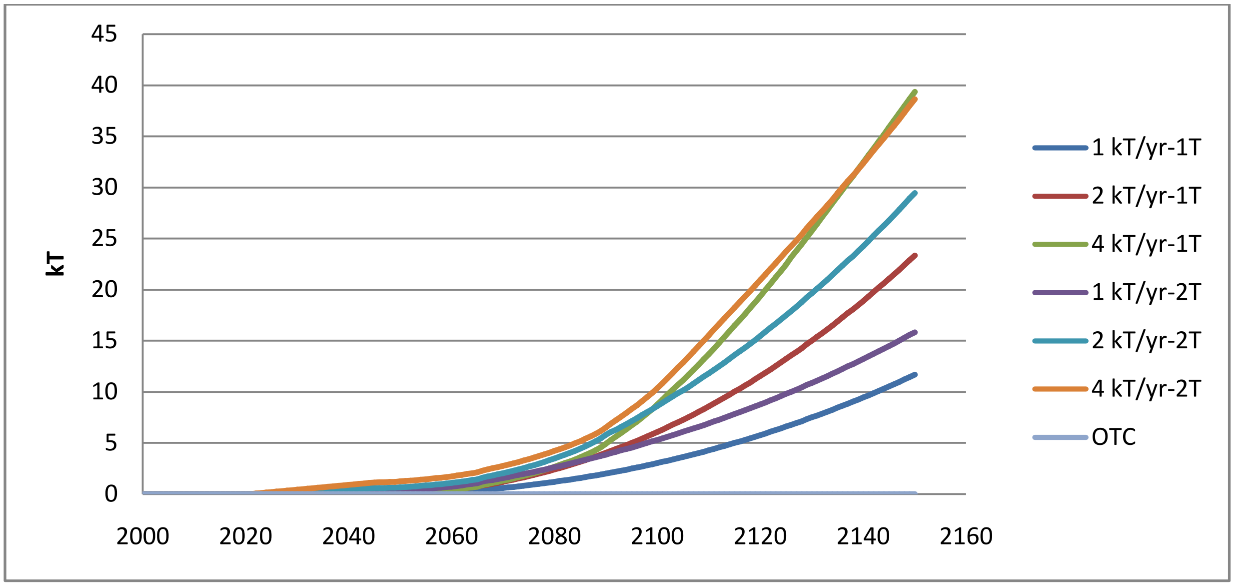


Figure 4.3.3 TRU used for fuel fabrication at different separation capacity.

In 1TFC, doubling the amount of separation capacity resulted in almost 100% increase in the amount of TRU consumed. At 4 kT/yr separation capacity, the percentage increase is 237%. In 2TFC, doubling the separation capacity resulted in 86% increase in the amount of TRU consumed. Deploying 4 kT/yr separation capacity in the 2TFC resulted in 144% increase in consumption of TRU.

Direct comparison of TRU consumption in both advanced cycles however indicated that 2TFC was better for burning TRU. At 1 kT/yr capacity, 36% more TRU was consumed in 2TFC. At 2 kT/yr separation capacity, 26% more TRU was consumed in 2TFC. However when 4 kT/yr separation capacity was deployed in both 1TFC and 2TFC, about the same amount of total TRU was consumed. Thus suggesting that at a higher separation capacity, more TRU will be consumed irrespective of the advance fuel cycle deployed.

4.3.4 Recovered (Separated) Uranium Used for Fuel Fabrication

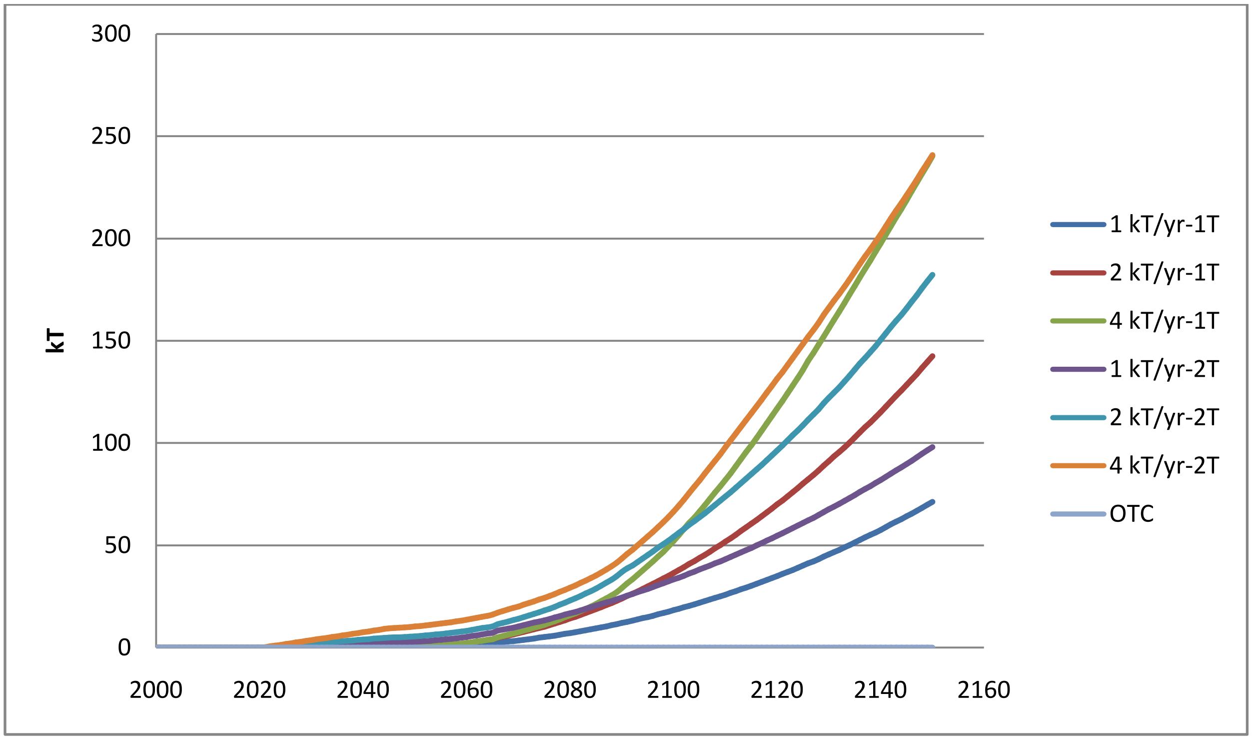


Figure 4.3.4 Total amount of recovered uranium (RU) used for fuel fabrication at different separation capacity.

Uranium utilization was impacted by the introduction of advanced fuel cycles, as was shown in Fig.4.3.1 and 4.3.2 and now Fig.4.3.4 which shows the amount of recovered uranium obtained from the separation process that was used for both MOX and SFR fuel fabrication, this amount will result in some savings in SWU. The saving in SWU is shown in Fig.4.3.5 to be a function of the separation capacity deployed.

4.3.5 Separative Work Unit per Year

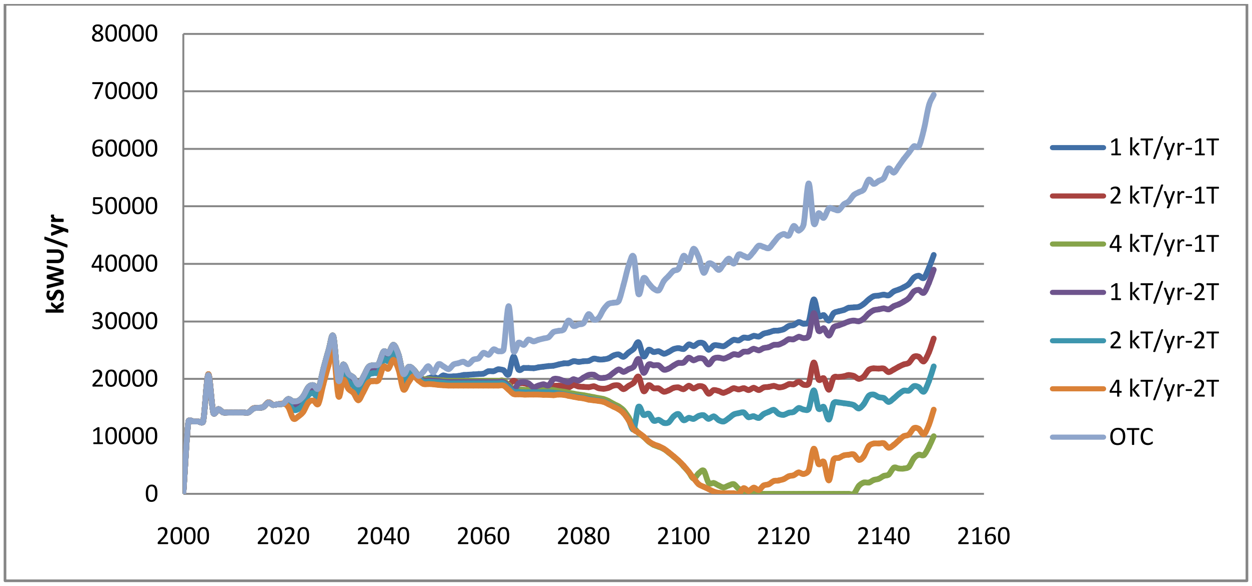


Figure 4.3.5 Annual SWU requirement at different separation capacity.

The annual SWU requirement as expected was highest in OTC and lowest in the scenarios with highest separation capacity. The higher the separation capacity the lower the annual SWU requirement, Fig. 4.3.5, which is a confirmation that less natural uranium is being consumed in the fuel cycle. The SWU requirement was also expected to be zero after year 2110, since no LWR is expected to be in operation after that date, however, this was not the case in scenarios having less than 4 kT/yr separation capacity. The reason for this observation was that newly deployed SFRs continuously use LEU fuel in their start-up core whenever fast reactor fuel is insufficient for the initial core load.

The only exception to this observation was when 4 kT/yr separation capacity was deployed in 1TFC and the SWU requirement fell to zero around year 2110, but picked up again in year 2135. Similarly, in 2TFC SWU requirement was observed to zero around year 2108 but picked up again in around year 2115. The results confirm and quantitatively illustrate that it will be impossible to transition to 100% SFR fuel cycles without deploying adequate separation capacity.

CHAPTER 5

ENVIRONMENTAL IMPACT OF DIFFERENT NUCLEAR FUEL CYCLES SCENARIOS

All energy sources have impact on the environment during their life cycle, but nuclear power life cycle generates very little green-house gases. However the issue of waste generated as a result of nuclear power operation is a major drawback to the general acceptability of nuclear power as a source of energy.

Some of the waste metrics parameters will be examined in this chapter. A comparison will be drawn among the seven scenarios considered in this work; some of these parameters are storage requirement, for spent fuel, used fuel, high level waste, etc., in wet, dry, monitored retrievable storage and permanent repository.

5.1 UNF Storage Requirements

The requirements for UNF and other wastes streams coming from nuclear power plant operation will be examined using the wet storage, dry storage, monitored retrievable storage, and repository.

By design of the scenarios in this study, repository facilities were not assumed, instead the UNF were stored in MRS, where they can be retrieved for reprocessing or moved to a permanent repository whenever such repository becomes available. This is also in line with the current policy push for above the surface storage of UNF in well-designed casks for at least 100 years.

All UNF from LWRs in our scenarios has to be cooled for a minimum of 10 years after removal from reactors, before it is sent to reprocessing (if reprocessing is needed). A total of 4 years is spent in wet storage, 1 year in dry storage and the casks are then moved to MRS for a minimum of 5 years before the UNF can be reprocessed. For SFR UNF only 2 years of cooling is required before the UNF is sent for separation and recycling.

5.1.1 Wet Storage Requirement

Wet storage facilities are currently an integral part of all existing nuclear power plants in the US. In all the scenarios studied, we considered about 21 kT of legacy UNF existing in wet storage prior to year 2000; that was immediately moved into dry storage facilities and then into MRS, where it was available to be retrieved for separation and reprocessing.

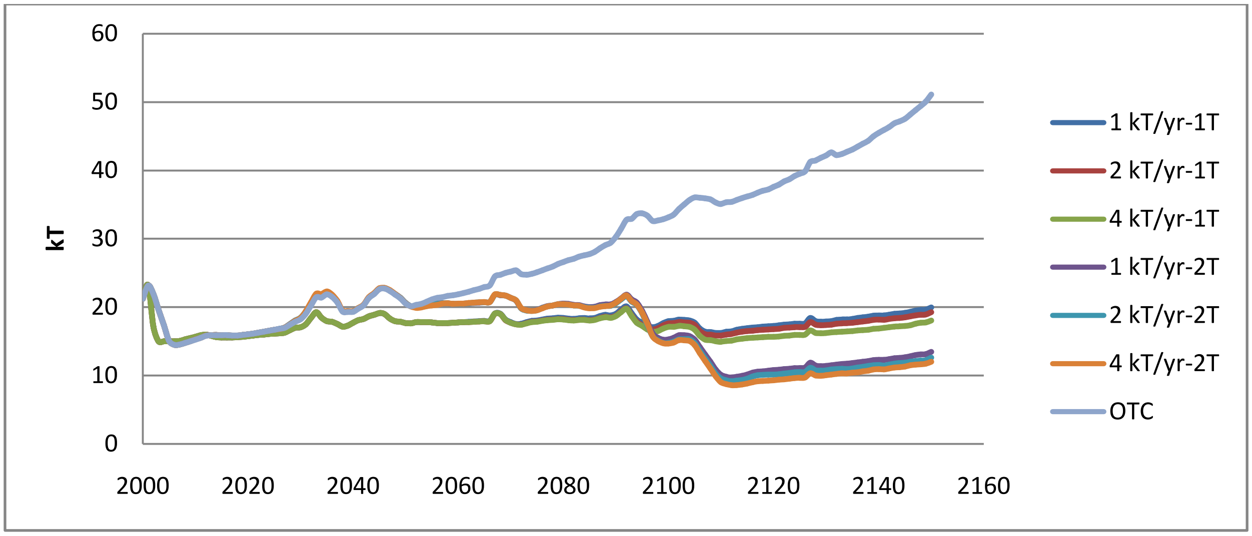


Figure 5.1.1 UNF in Wet Storage at different separation capacity.

The wet storage requirements as shown in Fig. 5.1.1 was highest in OTC. In 2TFC and 1TFC, the wet storage requirement was initially higher for 2TFC; this is because of the separation routing system in VISION. Note that all LWR-UOx UNF in 2TFC has to undergo a total of 8 years in wet storage cooling before getting to a SFR, as opposed to 4 years wet storage cooling time in 1TFC.

The wet storage requirement in 1TFC is the steadiest; a storage size of about 20 kT appears to be all that is needed to handle all the UNF in wet storage. OTC requires a steady increase in the storage capacity, thus additional capacity has to be constructed with addition of new reactors. In the OTC portion of both 1TFC and 2TFC, the wet storage requirement was about the same as in OTC. After 2020 when reprocessing started in 2TFC, the initial requirement for UNF in wet storage was higher than in 1TFC due to additional cooling time required at MOC stage of 2TFC. However after all LWRs were retired from operation in 2110, the wet storage requirement in 2TFC fell sharply below the 1TFC level.

It is important to note that the separation capacity appears to have less impact on the wet storage requirement shown in Fig. 5.1.1, as opposed to the time of deployment of separation facility.

5.1.2 Dry Storage

Dry storage (dry cask farms) facilities are being built as an integral part of existing nuclear power plants in the US. In all the scenarios studied, we also considered about 21 kT of legacy UNF existing in dry storage prior to year 2000; all this was immediately moved into MRS, and were later retrieved for separation and reprocessing.

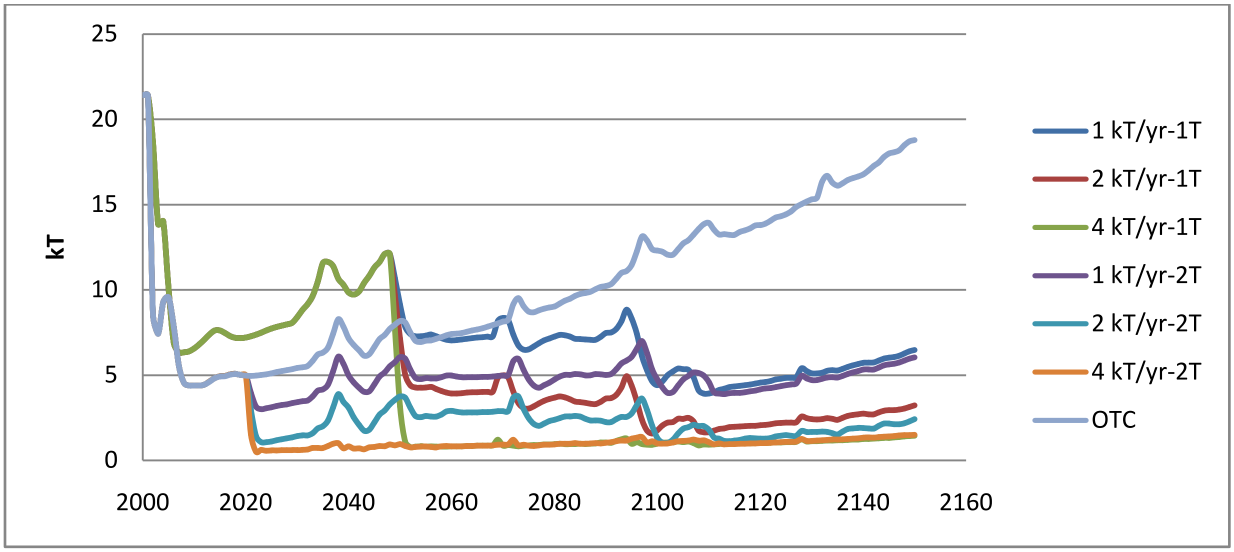


Figure 5.1.2 UNF in Dry Storage at different separation capacity.

The dry storage requirement was also highest in OTC since UNF from this cycle had been designated as no-recycling. In 2TFC and 1TFC both the separation capacity and separation facility deployment time has impact on the dry storage requirement shown in Fig. 5.1.2. At 4 kT/yr separation capacity, the least storage requirement was observed for both 1TFC and 2TFC compared to other separation capacities. In all scenarios having separation capacity more than 1 kt/yr, the dry storage requirement was significantly lower; about 85% at 4 kT/yr and about 80% at 2 kT/yr less compared to OTC. The saving in dry storage requirement at 1 kT/yr separation capacity is over 60% compared to OTC.

The dry storage requirement at 4 kT/yr is the steadiest; a storage size of about 3 kT/yr appears to be all that is needed to handle all the UNF in dry storage. OTC requires a steady increase in dry storage capacity, thus increasing additional capacity has to be constructed with addition of new reactors.

5.1.3 Monitored Retrievable Storage

The designation of UNF to be stored in MRS was done to allow for the possibility of material retrieval in advanced fuel cycle that requires material separation and recycling. The UNF from OTC was designated for this storage to allow direct comparison. The amount of storage requirement in MRS will be the capacity of permanent repository space needed (in addition to HLW storage requirement), if that facility is constructed with retrieval capability.

The information in Fig. 5.1.3 suggests that at 4 kT/yr separation capacity that no additional storage space will be necessary at some point for UNF (in both 2TFC and 1TFC) after the dry storage. The no MRS requirement was noticeable early (around 2070) due to early deployment of separation and recycling. While the same observation for 1TFC was late, around 2125, this was due to late deployment of separation facility and recycling resulting in backlog of UNF in both dry storage and MRS.

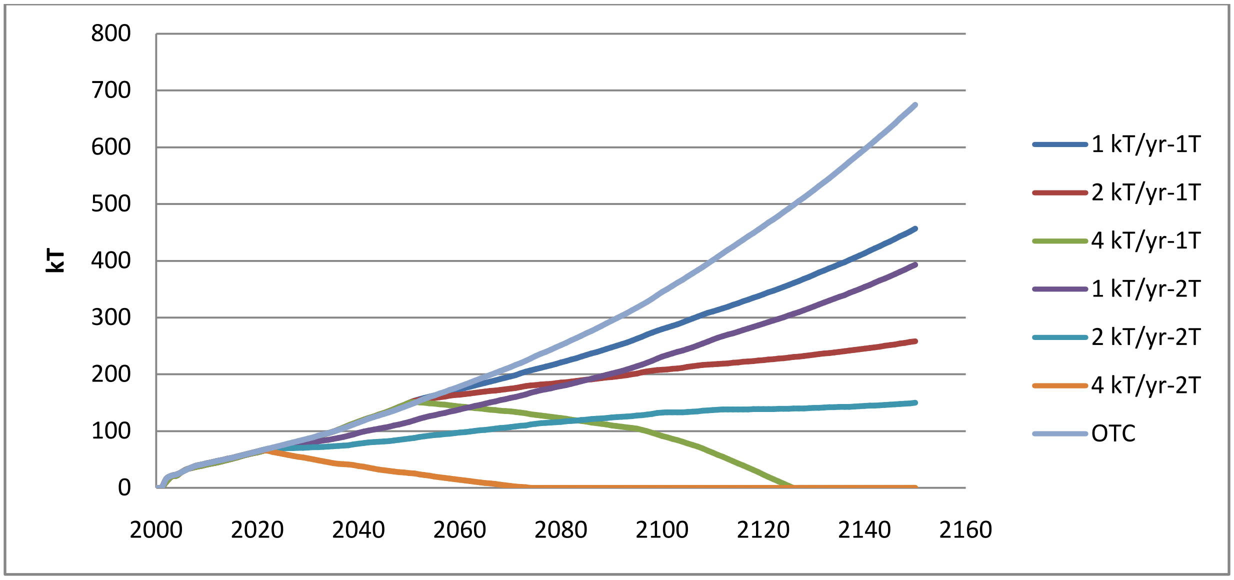


Figure 5.1.3: UNF in Monitored Retrievable storage at different separation capacity.

According to Fig. 5.1.3, about seven Yucca mountain-sized repositories will be required to store UNF. In 2TFC and 1TFC the requirement varies depending on the separation capacity. At 4kT/yr, two Yucca-sized repositories will be needed for the initial storage in 2TFC, while three such repositories are needed for the same purpose in 1TFC. At 2kT/yr, three and five Yucca-sized repository will be needed to store the UNF, in both 2TFC and 1TFC respectively. At 1kT/yr about seven such repositories will be needed to handle the UNF in both 2TFC and 1TFC.

5.1.4 Spent Fuel in Repository

In all the scenarios, no UNF was designated for permanent repository. This was done to facilitate simulation of centralized monitored retrievable storage system. The UNF from OTC was designated for this storage system as well to facilitate direct comparison of the three cycles.

5.1.5 High Level Waste for Permanent Disposal in Repository

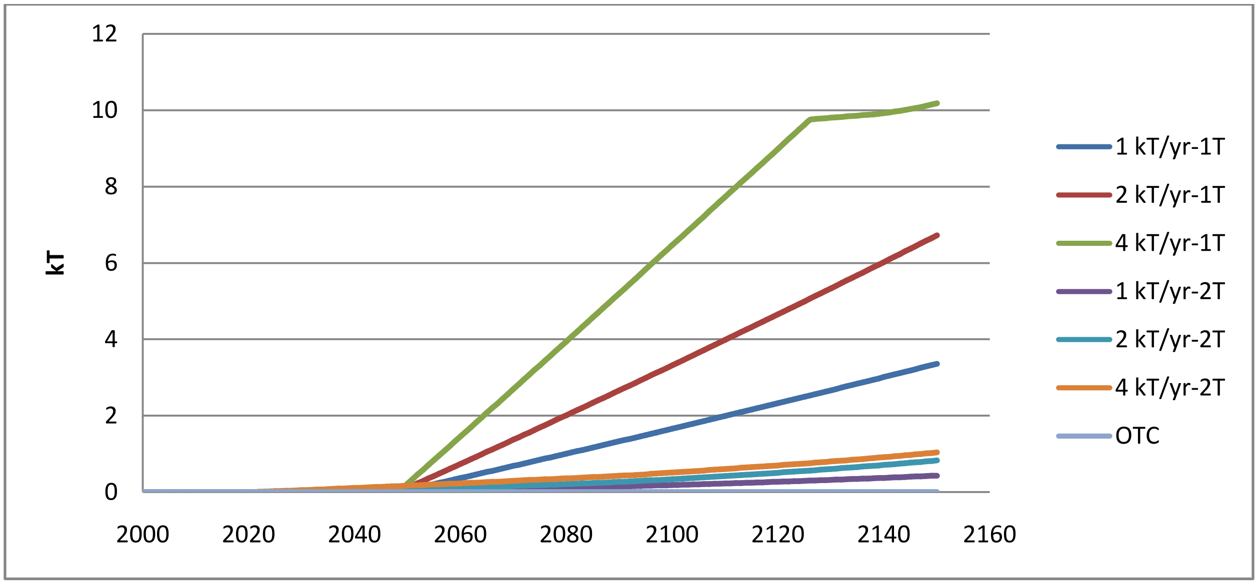


Figure 5.1.4 High level waste (HLW) in permanent repository

Fig. 5.1.4 shows the amount of high level wastes, from both 2TFC and 1TFC. There is no HLW from OTC since there is no separation of UNF. For other cycles, as expected, the lower the separation capacity, the lower the amount of separated HLW in both 2TFC and 1TFC. However it was also observed that the amount of separated HLW in 2TFC was significantly lower compared to 1TFC, for all separation capacities. It is important to point out that separation capacity for multi-pass fuel UNF (i.e. recycled fuel) as used in MOX and SFR fuel had no separation capacity limitation imposed. It therefore appears that the deployment of MOX capable LWR in 2TFC and the early separation facility deployment actually reduced the amount of HLW that will be disposed.

The amount of storage required for storing UNF at wet, dry, MRS locations was tracked at three different points in the scenarios. The result is shown in Table 5.1. The storage space requirement for permanently storing HLW material was also tracked. In OTC the storage requirement increased continuously. In the other advanced cycles the storage space requirement trend varies at different point for different separation capacities deployed.

Table 5.1: Storage capacity (kT) required at 50 years, 100 years and 150 years.

			Separation Capacity Deployed						
			1 kT/yr-1T	**2 kT/yr-1T**	**4 kT/yr-1T**	**1 kT/yr-2T**	**2 kT/yr-2T**	**4 kT/yr-2T**	**OTC**
Storage Requirement (kT)	**WET**	**50 yr**	17.686	17.688	17.688	20.598	20.609	20.566	20.534
		100 yr	17.926	17.598	17.104	15.298	14.759	14.669	33.157
		150 yr	19.956	19.241	18.038	13.456	12.593	11.995	51.115
	DRY	**50 yr**	9.142	7.142	3.142	6.052	3.747	0.952	8.162
		100 yr	4.409	1.760	0.974	4.745	1.313	0.997	12.301
		150 yr	6.459	3.218	1.438	6.040	2.413	1.502	18.776
	MRS	**50 yr**	149.829	149.829	149.829	116.303	86.673	25.947	145.887
		100 yr	279.686	207.667	91.427	230.869	132.496	0.000	344.729
		150 yr	456.210	258.259	0.000	392.832	149.645	0.000	674.622
	HLW	**50 yr**	0.055	0.110	0.219	0.045	0.091	0.170	0.000
		100 yr	1.660	3.319	6.461	0.187	0.339	0.514	0.000
		150 yr	3.361	6.723	10.183	0.434	0.828	1.040	0.000

CHAPTER 6

NUCLEAR FUEL CYCLE COST ANALYSIS

The information provided in this section is for comparing the three fuel cycles analyzed in this project.

There are a lot of areas in the analysis where input data are not well defined; as a result most of the initial costs are based on projections, assumptions and estimations and include large uncertainties. Where those data are available, as in the UREX+ separation technology, they are usually proprietary in nature, thus educated guess work is necessary to develop cost inputs. The cost of operating centralized monitored retrievable facility is not available as such facility does not yet exist, and had to be assumed.

All the above examples constitute areas of uncertainties in this cost analysis section of this study. Reference [22] has a detailed analysis of the various cost inputs and how they were obtained and developed for use in VISION-ECON. However, these uncertainties may not affect our analysis since all the three fuel cycles simulation are based on the same parameters, components, and time frame. Thus we should be able to compare these cycles using VISION-ECON without introducing significant error.

In section 1.3.2, an introduction into how VISION.ECON works was provided and Fig.1.15 contains the cost input data obtained from [22]. A 3% escalation to account for inflation and convert the 2007$ to 2012$ was added to the rates in Table 1.6. The actual cost input table for our simulation is provided in the Appendix B.

Some of the key definitions of terms in VISION-ECON as defined in [22], are hereby presented to shed more light on our analysis. Reference [22] also has detailed information about these definitions.

6.1 Definition of Economic Terms in VISION-ECON

* The total non-fuel related annualized and levelized reactor cost calculated in VISION.ECON is a sum of annual capital recovery (including interest) and the operations and maintenance (O&M) costs and is calculated using combination of Equations 6.1 to 6.10.

* The capital recovery portion of the overall reactor annualized cost is calculated using a fixed charge rate (which in this case is a capital recovery factor) to account for interest charges from amortization of the estimated total capital investment cost (TCIC). The total capital investment cost includes two major parts:

*The overnight capital cost (OCC) and the interest during construction (IDC).

$$\text{Total Overnight Capital Cost (OCC)} = \text{Base costs} + \text{Owners costs} + \text{Contingency} \quad \ldots\ 6.1$$

* Interest During Construction (IDC) is estimated using the S-Curve as shown in Fig.6.1 [22]

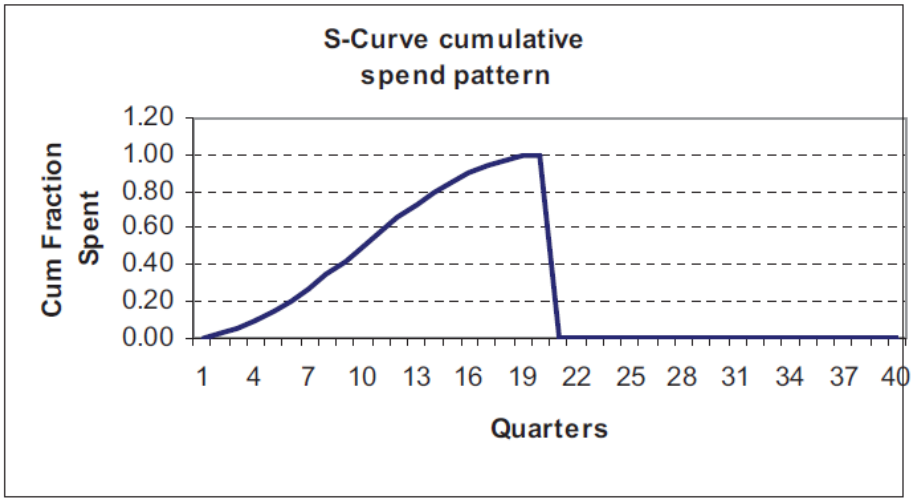


Figure 6.1 S-Curve for estimating IDC

$$IDC = \left(\frac{Qpt \times ((1+Iqt)^n - 1)}{Iqt} \times \left(1 + \frac{Iqt}{2}\right) - OCC\right) \times S \quad \ldots\ldots\ldots 6.2$$

Where:

Qpt is quarterly payment

Iqt is the quarterly interest

$$Iqt = \frac{\left(\left(1+\left(\frac{Iyr}{4}\right)\right)^{4} - 1\right)}{4} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.3$$

Iyr is yearly interest

n is number of quarters

S is shape factor from Fig. 6.1.

* The total capital investment costs (or TCIC):

TCIC (in \$M) = OCC + IDC (both in \$M) ……………………………6.4

* Amortization by a capital recovery factor, Capital Recovery Factor (CRF):

$$\text{CRF} = (r * (1+r)^{yr}) / ((1+r)^{yr} - 1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.5$$

Where:

r = Annual Cost of Capital (5%)

yr = Capital Recovery Period (years)

* The annual capital recovery cost (ANNCAP), usually expressed in \$M/yr, is:

ANNCAP = CRF x TCIC ……………………………………..…………..6.6

* Dividing this annual amount by the annual energy production (AEP) (in KWh/yr) gives the capital component of the LUEC (expressed in mills/KWhr or \$/MW hr).

LUEC = ANNCAP / AEP ……………………………….…………6.7

* Reactor non-fuel O&M are separated into fixed and variable cost components (by reactor).

- Fixed O&M costs are based on reactor net electrical capacity (size, $/kW(e)-yr)
- Variable O&M costs depending on annual electricity generation, (units of mills/kW(e)-hr).

The fixed and variable costs are normalized by their dependent factors and summed into the Reactor O&M Cost per year.

Total Reactor O&M Var. Cost = {(Variable O&M Cost) x (Electricity Produced)}$_{reactor}$ ……6.8

Total Reactor O&M Fixed Cost = {(Fixed O&M Cost) x (Reactor Power)}$_{reactor}$ ………..…6.9

* Total Reactor O&M Cost / year = (Total Var. O&M Cost + Total Fixed O&M Cost) …....6.10

Operating cost as defined in VISION does not include the cost of fuel, but does include the cost of wet storage, operation, and maintenance. The cost of fuel is treated separately and added to overall cost.

6.2 NFC Front End Cost Analysis

For the purpose of fuel cycle economic analysis, we defined the front end costs to include the cost of:

1. Uranium ore mining and milling,
2. Uranium conversion
3. Enrichment
4. Fuel fabrication
5. Depleted Uranium storage/disposition

Every other cost such as transportation, securing, storage, etc. had being embedded into the cost at different stages above.

The total of these costs per annum as a function of separation capacity is shown in Fig. 6.2

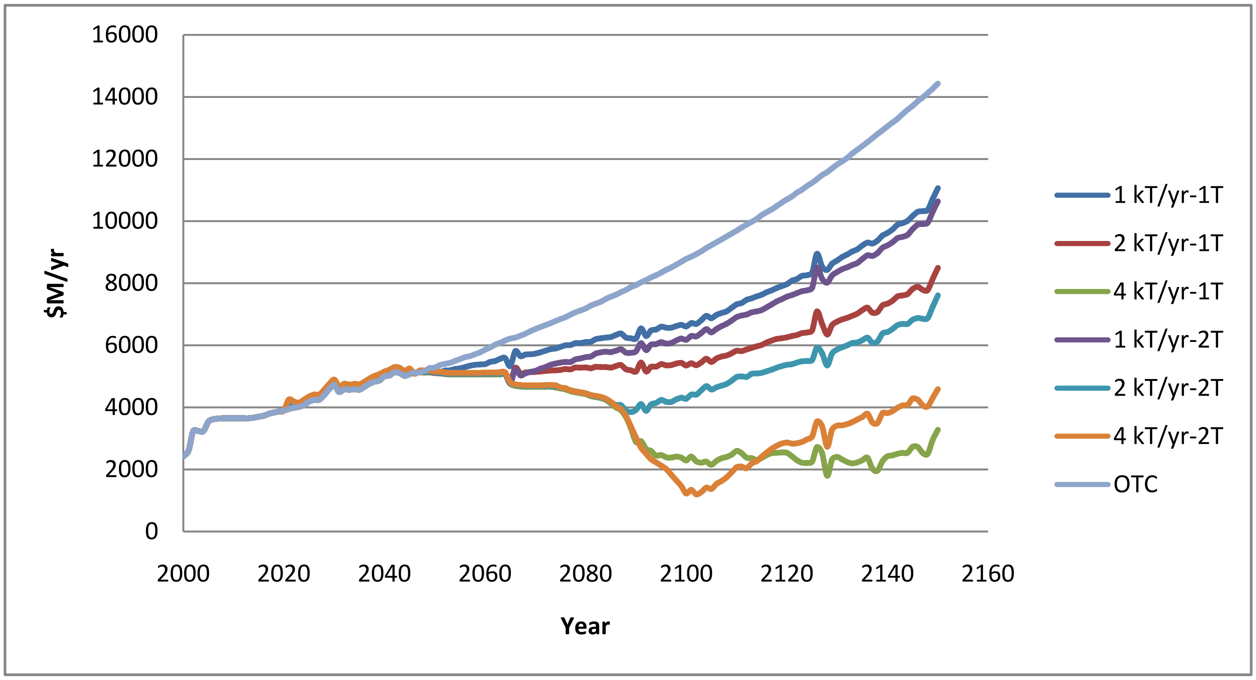


Figure 6.2 NFC front end cost per annum at different separation capacity.

The total front end cost ($M/yr) was significantly higher in OTC. The cost profiles for all the scenarios seem to follow the Natural uranium consumption requirement, section 4.3. The lower the amount of LEU consumed in a scenario, the lower the front end cost for that cycle.

The cost saving was also a function of the separation capacity deployed; as profoundly indicated by both 4 kT/yr profiles. The reversal in the cost trend for these 4 kT/yr profiles was due to LEU being loaded into the SFR cores. Only SFR is allowed to be constructed in our setup to simulate a 100% transition to full recycling with only SFR.

The cost saving after year 2090 is on the average 74% for 4 kT/yr – 2T, and 76% for 4 kT/yr-1T. The saving was lower at lower separation capacity (about 25% at 1 kT/yr separation capacity), an indication that higher saving can be achieved on the front end if higher separation capacity is deployed.

6.3 NFC Back End Cost Analysis

We also classify the following costs as back end cost for the purpose of this project.

1. Cost of Monitored Retrievable Storage
2. Cost of UNF in repository
3. Cost of HLW in repository
4. Cost of intermediate depth (near surface) disposal of very LLW

It should be noted that the cost of wet and dry storage was not included in the above list. This was because these costs were built into the cost of reactor, since these two facilities are usually co-located with the reactor and are usually part of the initial requirement for reactor plant construction approval; more detailed explanation on the justification is provided in [22].

This assumption built into VISION-ECON may introduce bias against SFR in advanced fuel cycle setup, for example in Fig. 5.1.2, the amount of dry storage required did not vary as the number of reactors, yet their cost must have been built into reactor cost.

The total back end cost per annum as a function of separation capacity per annum is shown in Fig. 6.3.

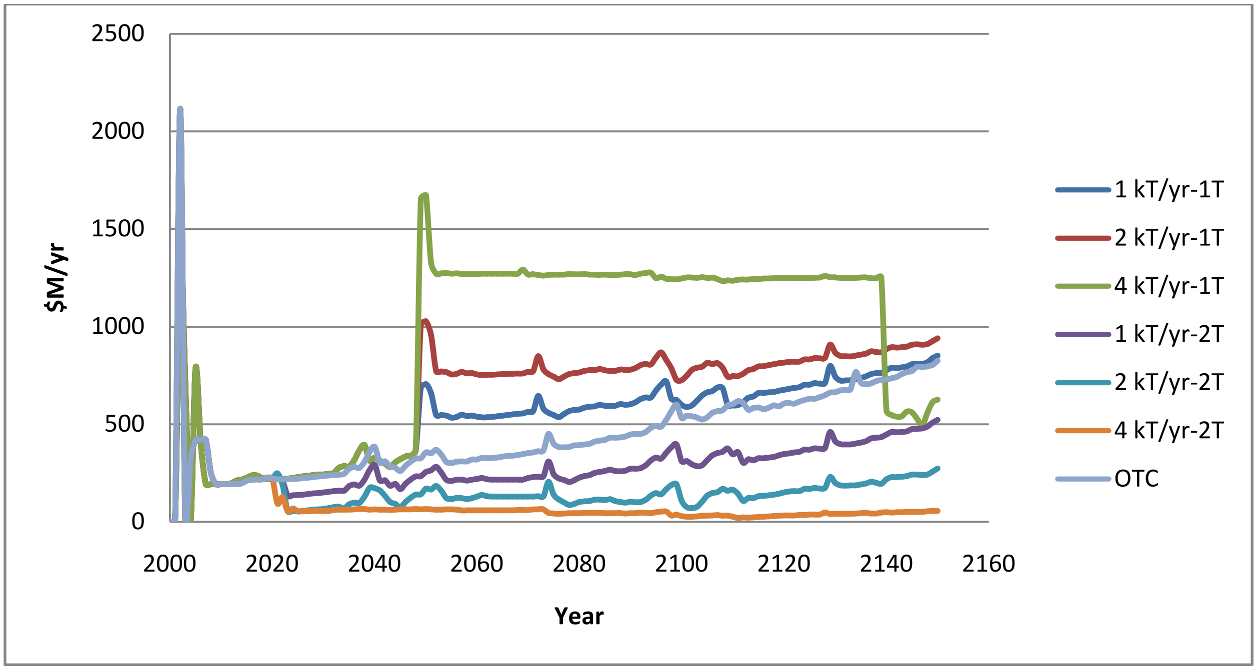


Figure 6.3 NFC back end cost at different separation capacity.

The information presented in Fig. 6.3 is revealing, the cost profiles show sensitivity to time of deployment of separation facility. The HLW (high level waste, fission products, lanthanide and technetium) storage requirement is the cost driver in this section and as shown in Fig. 5.1.5, HLW storage requirement is higher (late separation deployment date and high HLW separated using UREX+1) in all the 1TFC compared to other cycles. This requirement was translated into the high back end cost for the 1TFC as shown. In 2TFC where separation started in 2020, the amount of HLW and MRS storage required was lower for all the separation capacity deployed compared to other cycles (no HLW in OTC). The back end cost therefore is much lower in 2TFC. It is important to note the very low cost of the 4 kt/yr-2T, which was due to almost "no" MRS required as discussed in chapter 5.

6.4 NFC UNF Recycling Cost Analysis

The recycling cost was treated separate from the back end cost described above in order to allow for separation capacity analysis since that was goal of this research. The separation also allows for direct comparison of the two advanced fuel cycles. The OTC of course has no cost in this category.

The following costs were classified as recycling related:

1. UNF separation cost as a function of fuel type and separation type
2. Recycled product storage cost
3. LLW + TRU + UOX-MOX conditioning cost
4. Cost of near surface disposal
5. Cost of managed decay storage
6. Cost of total co-flow storage
7. Cost of reprocessed Uranium storage
8. Cost of greater than class C (GTCC) waste storage

The total recycling cost per annum for different scenarios and separation capacities is shown in Fig. 6.4

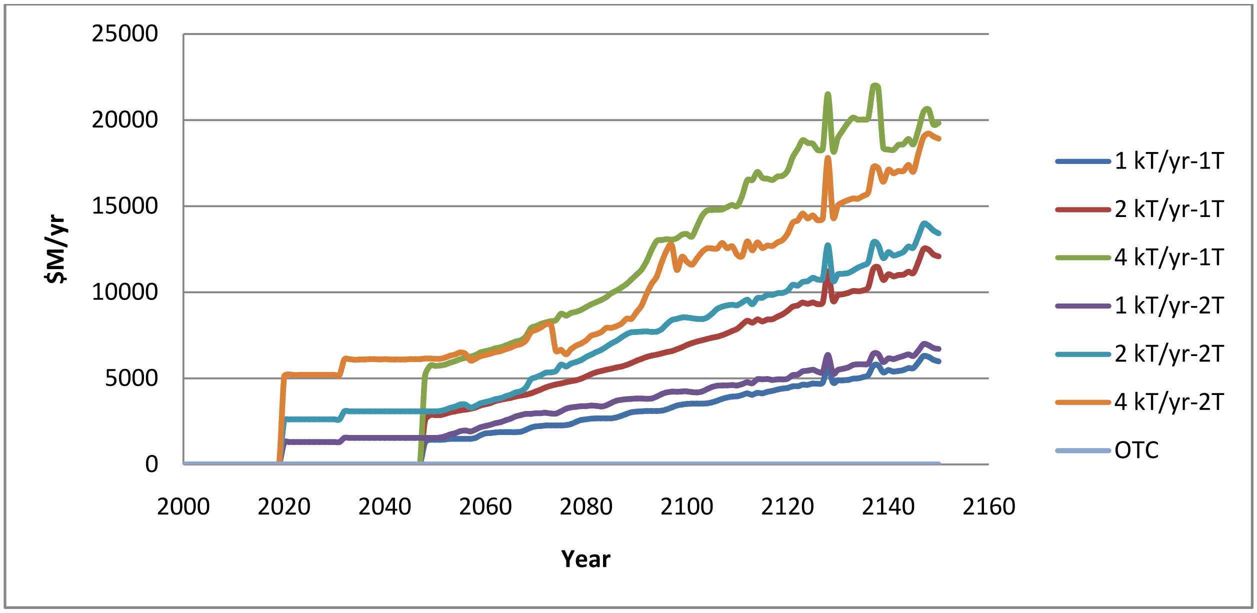


Figure 6.4 NFC UNF recycling cost per annum at different separation capacity.

As expected the recycling cost exhibited a direct relationship to the amount of separation capacity deployed. The cost ratio for the three separation capacities is 1:2:4. The separation technology (UREX+1, UREX+3 and Electrochemical) appear to have no direct impact on the scenarios (if the separation start date is factored into the analysis), since each of the scenarios has a combination of these technologies in their setup.

It was observed that the recycling cost is the highest annual cost driver in the advanced fuel cycles considered.

6.5 NFC Reactor Cost Analysis

The total cost of all reactors was defined to include the following:

1. Total annual capital cost
2. Total annual reactor operation cost

The input for reactor capital cost analysis is shown Fig. B1 in Appendix B. Note that the low cost estimates in the respective triangular probability distributions are the same for LWR and SFR. However, the SFR nominal and high cost was assumed about 20% and 40% higher, respectively, than the corresponding LWR cost. These cost estimates are based on [21]. It is likely that the nominal SFR cost could be reduced if many SFRs are deployed.

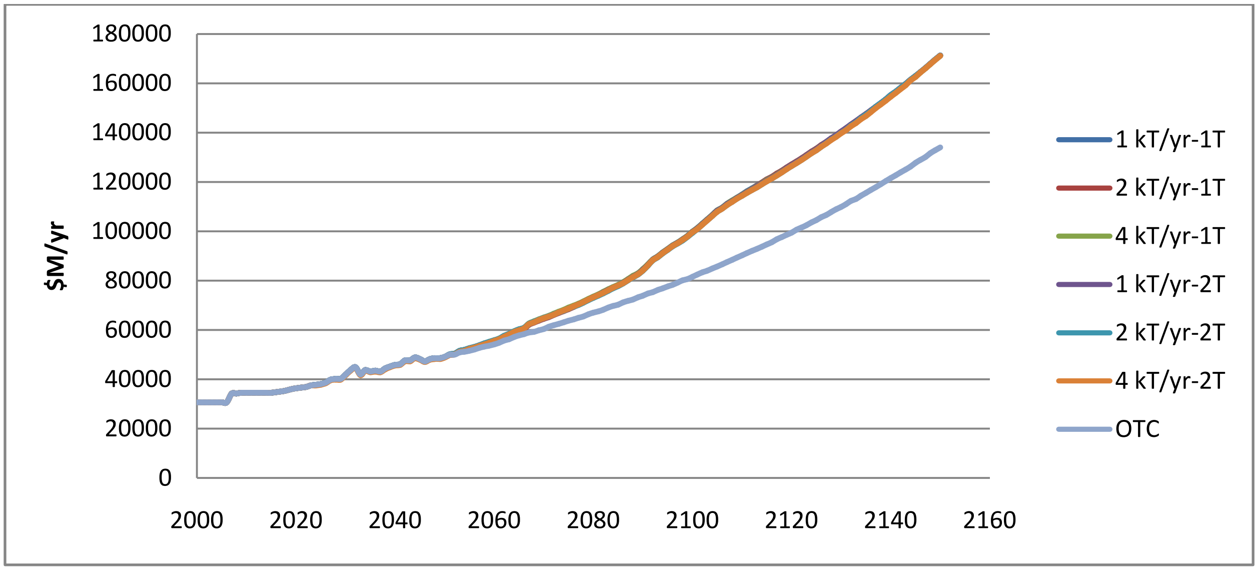


Figure 6.5 Reactor cost per annum at different separation capacity.

The cost comparison made in this project can be seen in Fig. 6.5. Note that the reactor cost is the same for years before deployment of separation facility around 2020 in 2TFC. This was because all the fuel cycles have about the same components prior to UNF separation start date. Note also that for all the scenarios except for OTC after around 2050, all Reactor costs are about the same, see section 4.1 for more on reactor deployment, which contributed to this cost output.

It is therefore insufficient to use reactor cost to discriminate between the advanced fuel cycle scenarios of 1TFC and 2TFC. Based on this cost result, it may be safe to conclude that the annual cost of reactors will be the same irrespective of the separation capacity and the reactor type deployed. Since all non-OTC scenarios end up with very similar number of reactors, Tables 4.1 and 4.2.

6.6 Levelized Fuel Cycle Cost

The levelized fuel cycle cost is defined as:

$$(\mathrm{LFCC})_{\mathrm{yearly}} = (\text{Total Fuel Cycle Cost / Total Electricity Produced})_{\mathrm{yearly}} \ldots\ldots\ldots 6.11$$

Where:

$$(\mathrm{FCC})_{\mathrm{yearly}} = (\text{Front End Cost + Back End Cost + Recycling Cost})_{\mathrm{yearly}} \ldots\ldots\ldots 6.12$$

Total electricity produced is measured in kWHr/yr and the FCC is measured in \$M/yr, the unit of LFCC is in \$/MWhr (1 mill/KWhr = 1 \$/MWhr = 0.1 cent/KWhr). The LFCC of all the NFC scenarios is shown in Fig. 6.6.1.

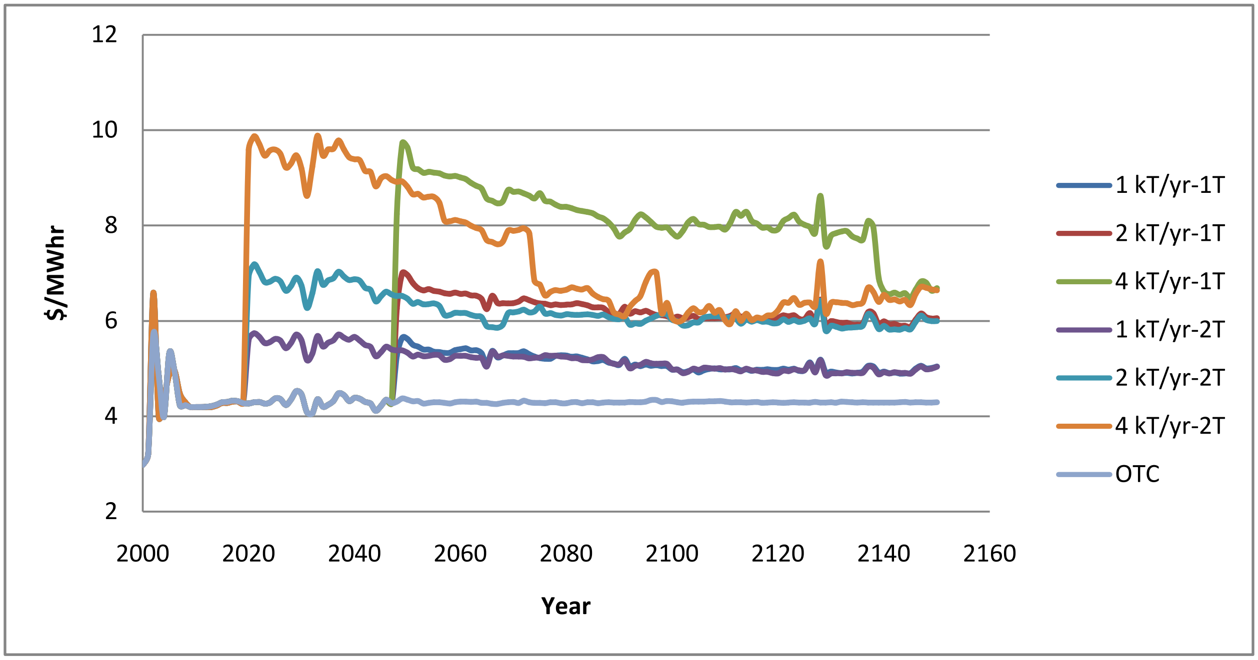


Figure 6.6.1 Levelized Fuel Cycle Cost in \$/MWhr at different separation capacity.

The initial jump in LFCC can be attributed mostly to the cost of handling the legacy used fuel that is being moved from dry storage to MRS. The LFCC thereafter stabilized to around 4.4 $/MWhr for all the scenarios until separation facilities and recycling operation began as in 2TFC in 2020 and 2050 in 1TFC. The LFCC of about 4.4 $/MWhr was observed for the entire simulation period in OTC. This trend was expected since the fuel cycle operation in OTC is steady and resources utilization is directly proportional to the amount of electricity produced.

The LFCC in both 2TFC and 1TFC reflect the fluctuation of the different operations within them. The characteristics are initial spike in cost and a trend towards steady cost as the fuel cycle operation becomes stable. The case of 1kT/yr separation capacity for both advanced cycles indicates there is no difference in LFCC for both. The LFCC converged to about 5.0 $/MWhr for both cycles.

Similar trend was displayed in cases involving 2kT/yr and 4kT/yr separation capacity. In these cases the LFCC appear to converge between 6.0 $/MWhr for 2 kT/yr and to about 6.5 $/MWhr for 4 kT/yr. The only exception being 1TFC with 4kT/yr, which has sustained high LFCC for most of its cycle, compared to other scenarios. The high LFCC in this setup was the result of the SFRs in this scenario operating for most part of their cycle on 100% SFRs fuel and the high back end cost as discussed in section 6.3. Note that the LFCC in this scenario actually converges towards the 6.5 $/MWhr toward the end (around 2140 - 2150). The reason for the convergence was reduction in the back end storage cost (especially in cost due to MRS requirement, sections 5.1.2 and 5.1.3). This same convergence was noticed in the 2TFC with 4kT/yr separation around 2070.

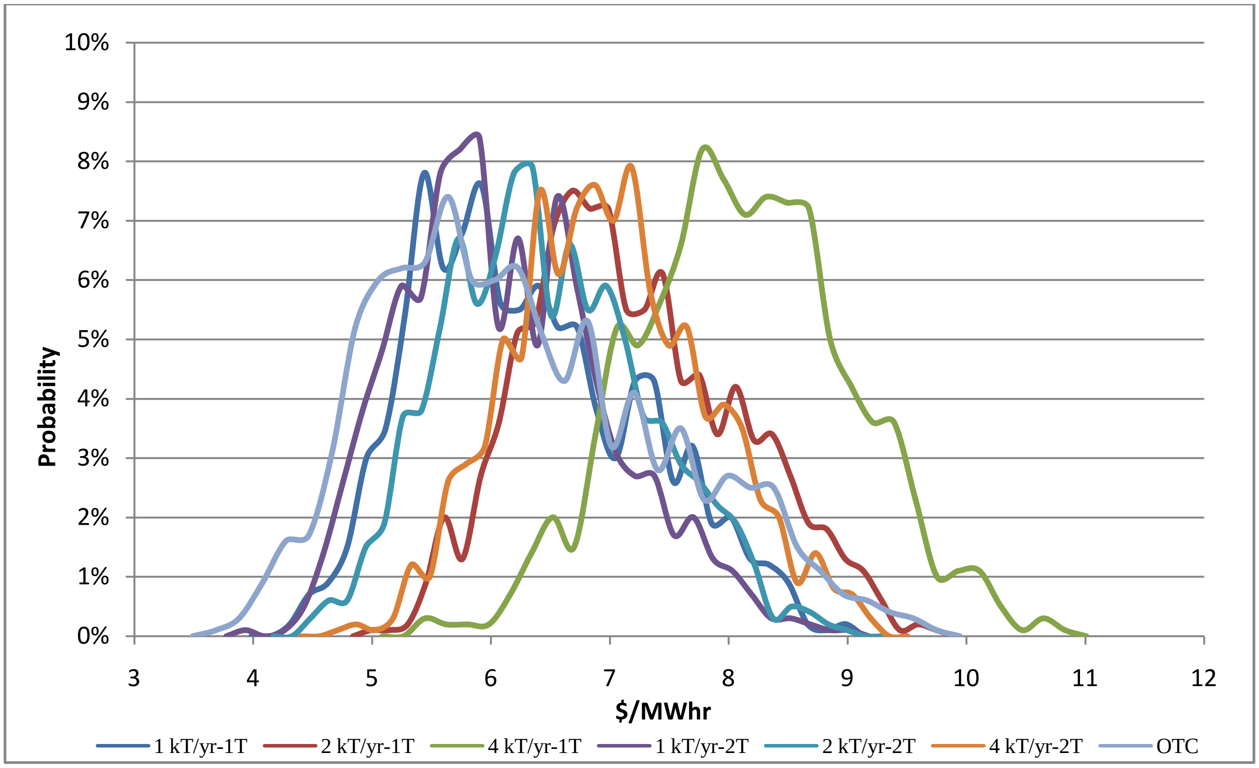


Figure 6.6.2 Distribution of LFCC in $/MWhr at different separation capacity.

The distribution of the LFCC obtained using Monte Carlo - with triangular distribution cost probability is shown in Fig. 6.6.2. The LFCC distributions for almost all lower separation capacity cases were almost the same as for OTC distributions, and the most probable LFCC appears the be in the range 5.5 – 6.5 $/MWhr. At higher separation capacity, the range was closer to 6.8 – 7.2 $/MWhr. The cost distribution for 4 kT/yr – 1T was outside these two ranges because of the reasons previously discussed (section 6.3)

6.7 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity is defined as:

$(\text{LCOE})_{\text{yearly}} = (\text{Total Cost Of Electricity / Total Electricity Produced})_{\text{yearly}}$ ………6.13

Where:

$(\text{COE})_{\text{yearly}} = (\text{Fuel Cycle Cost + Reactor Cost})_{\text{yearly}}$ ………………………………6.14

Total electricity produced is measured in kW(e)hr and both the FCC and reactor cost are measured in $M/yr. The unit of LCOE is in $/MWhr (1 mill/kWhr = 1 $/MWhr = 0.1 cent/kWhr). The LCOE of all scenarios is shown in Fig. 6.7.1.

The initial jump in LCOE can be attributed mostly to the cost of handling the legacy used fuel that is being moved from dry storage to MRS. The LCOE thereafter stabilized to around 42 $/MWhr for all the scenarios until separation facilities and recycling operation began in 2TFC in 2020 and 2050 in 1TFC. The LCOE of about 42 $/MWhr was observed for the entire simulation period in OTC. This trend was expected since the fuel cycle operation total reactor cost in OTC is steady and resources utilization is directly proportional to the amount of electricity produced.

The LCOE (like LFCC) in both 2TFC and 1TFC reflects the fluctuation of the different components within them. The characteristics are an initial spike in cost, a trend towards steady cost (as the fuel cycle operation becomes stable), then a gradual rise after no new LWR is built and then a steady cost after all LWR are withdrawn from service.

The case of 1kT/yr separation capacity for both advanced cycles indicates there is no difference in LCOE profile for both. Similar trend was displayed in cases involving 2kT/yr. The case of 4kT/yr separation capacity however is different for both 1TFC and 2TFC.

The recycling operation deployed in the advanced fuel cycles resulted in the LCOE costing about 12 - 14 $/MWhr (more than OTC) at the end of the simulation depending on the separation capacity deployed. This is about 20 – 23% increase in cost which corresponds partly to the cost of separation and fabrication of advanced fuels, and partly to the variation assumed in the SFR reactor capital cost. This implies that if one or both of those cost components could be reduced, the LCOE will also be reduced.

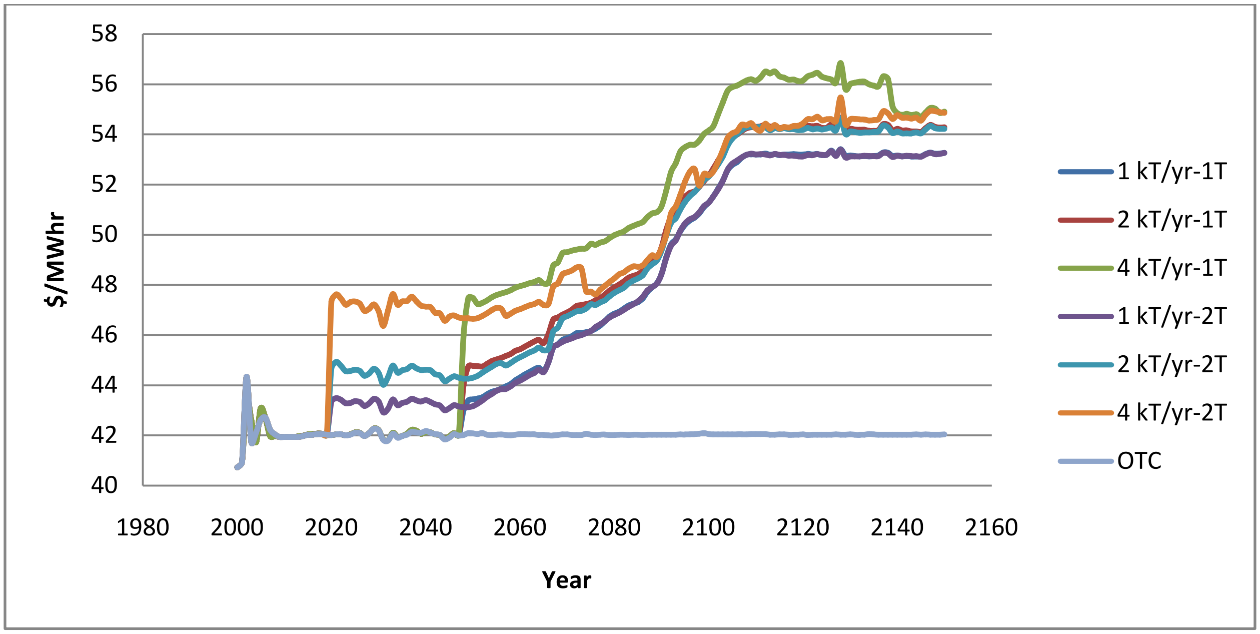


Figure 6.7.1 Levelized Cost of Electricity in $/MWhr at different separation capacity.

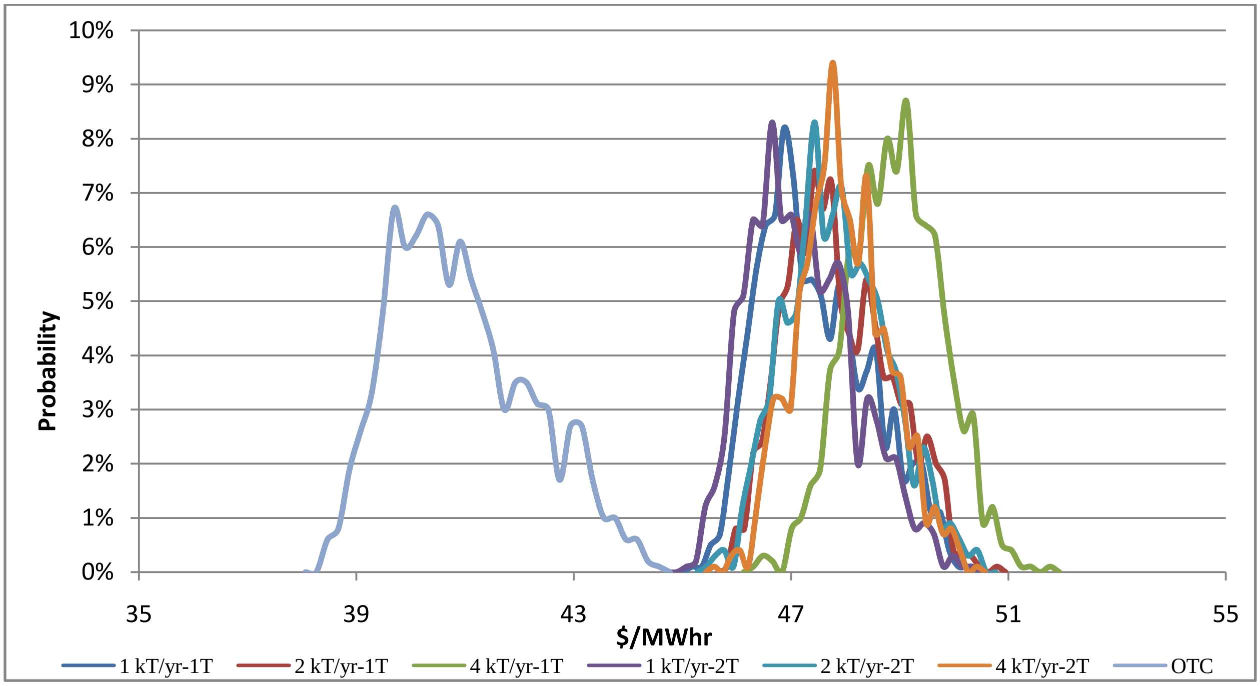


Figure 6.7.2 Distribution of LCOE in $/MWhr at different separation capacity.

The probabilistic distribution of the LCOE obtained using Monte Carlo simulations - with triangular cost distribution probability is shown in Fig. 6.7.2. The LCOE distributions for almost all lower separation capacity cases were almost the same, and all were higher compared to LCOE for OTC distributions. The most probable LCOE for OTC appears to be ~ 40 \$/MWhr. The most probable LCOE for 1kT/yr separation capacity in both 1TFC and 2TFC is ~ 46 \$/MWhr. In both 2TFC and 1TFC with 2kT/yr separation capacity as well as 2TFC with 4kT/yr separation capacity, the most probable LCOE is ~ 47 \$/MWhr. The most probable LCOE for 1TFC with 4kT/yr separation capacity is ~ 49 \$/MWhr, a value higher than any other due to the reasons previously discussed (sections 6.3 and 6.6).

CHAPTER 7

CONCLUSION AND FUTURE WORKS

7.1 Conclusion

A comparative study was performed of two advanced fuel cycle scenarios; 1TFC and 2TFC, both designed by combining OTC, MOC and FuRe nuclear fuel cycles. Results from these advanced cycles were also compared to those obtained from an all OTC simulation.

While there have been studies regarding transitioning from the current once-through nuclear fuel cycle policy, attention towards transitioning to a fuel cycle without any LWR is still very limited in the US. This study examined fuel cycle scenarios with a complete transition to FuRe using only SFR, with focus on how the separation capacity deployed for LWR-UOX UNF separation might affect such transition.

Results presented in this work suggest that the need for LWR-UNF storage can be minimized if sufficient separation capacity is deployed early in the fuel cycle. It can also be concluded that a FuRe system without LEU will not be feasible, thus SFRs must be designed for optional use of LEU fuel. Otherwise LWRs must continue to be part of the mix to keep the near term cost of generating electricity competitive.

While the higher amount of separation capacity deployed in the advanced fuel cycles led to higher LFCC and LCOE, it also translates into less environmental impact on both front and back end of the fuel cycle. Therefore if proper credits; like the “MOX Credit” suggested in GEN4-ECONS nuclear fuel cycle economic analysis for using reprocessed materials [33], is assigned, these may compensate for the apparent higher cost.

The amount of separation capacity deployed has a significant impact on the ability of both 1TFC and 2TFC, to achieve the objectives stated in the DOE 2010 *Nuclear Energy Research Development Roadmap* for advanced fuel cycles.

It can be concluded that both 1TFC and 2TFC are better than OTC with respect to resources utilization and environmental impact, but the OTC is still preferable in terms of cost. The choice between 1TFC and 2TFC will largely depend on the overall fuel cycle goal, since parameters obtained for both are very similar.

7.2 Future Work

The nuclear fuel cycle is a multi component complex dynamic system. Only one aspect (separation capacity of LWR-UOX UNF) of these complexities was modeled in this work. Varying the percentage of nuclear generated electricity as opposed to the 19.6% (assumed “maintain status quo”) used in the current work - this is equivalent to increasing the nuclear growth rate, and will provide useful insight into what might be needed to handle a full blown nuclear renaissance.

Data already obtained can be analyzed to perform detailed waste management studies to extract information on radiotoxicity, heat rate, waste isotopic composition, low level waste disposal requirements, etc. Nuclear material tacking and proliferation analysis information can also be extracted from current data generated.

The MOC in the current scenarios can also be modified to include other MOC setups as defined under the initial screening evaluation process (ISEP) activities [34] some potential candidates include a LWR-ThOX + LWR-U233 and FFH-Th + LWR-U233, both using thorium based fuels.

Impacts of the SFR breeding ratio on the use of resources also deserve attention. Further optimization of the separation capacity and its deployment schedule may provide additional insight and improved transition scenarios.

APPENDIX A

2kT/yr and 4kT/yr SCENARIOS VISION OUTPUT

The results presented in this appendix are the other outputs from VISION. Part of these results; for OTC and 1kT/yr separation capacity was discussed in chapter 3.

A.1 1-Tier with 2 kT/yr Separation Capacity Fuel Cycle Scenario.

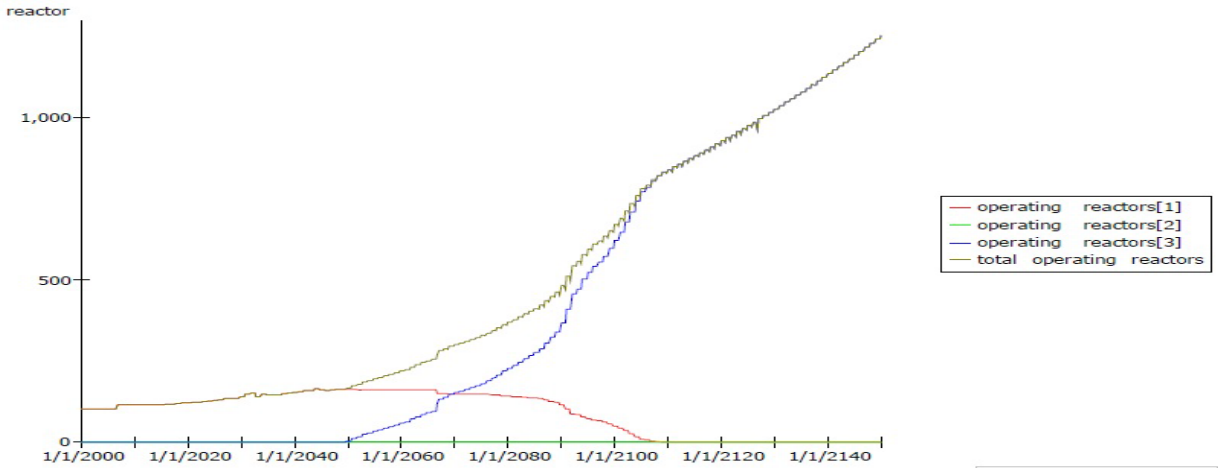


Figure A.1.1: Total number of reactor deployed per year by reactor in 1TFC – 2kT/yr capacity

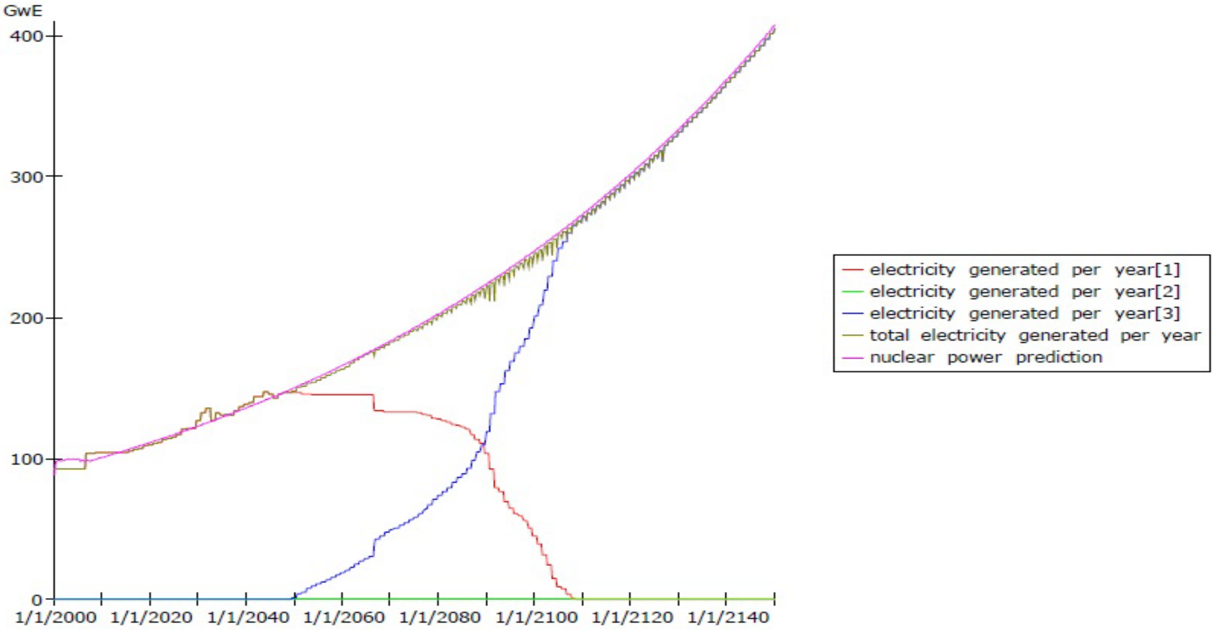


Figure A.1.2: Effective reactor capacity per year by reactor in 1TFC - 2kT/yr capacity.

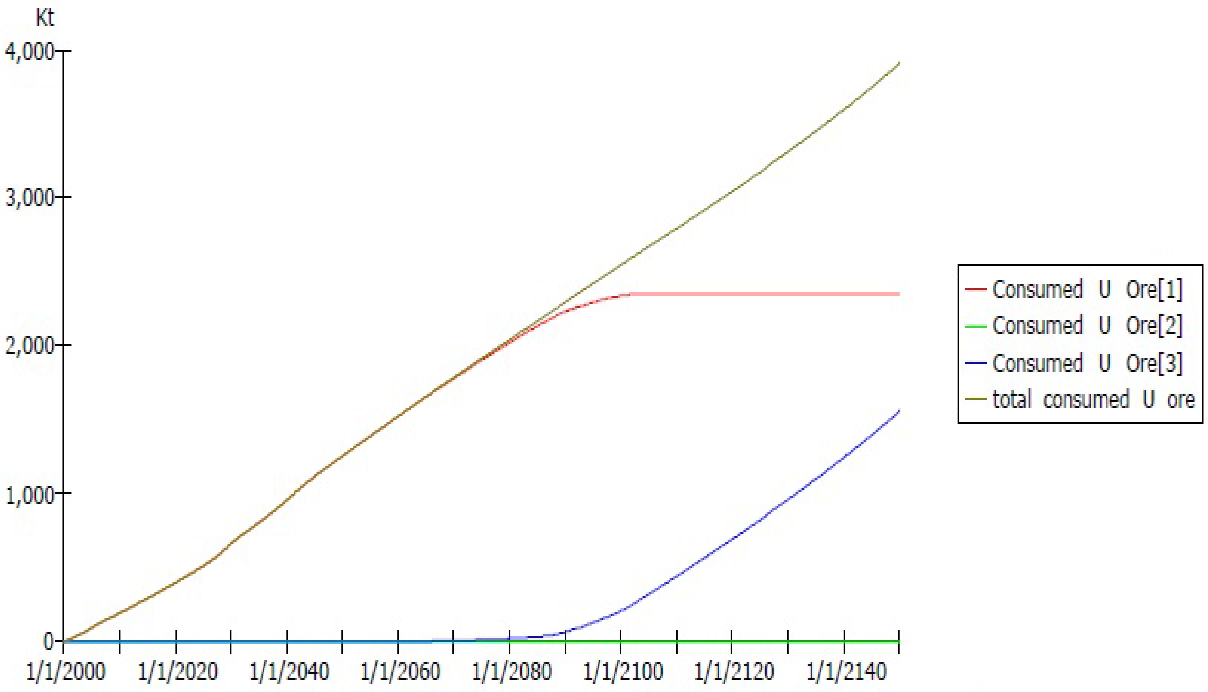


Figure A.1.3: Cumulative consumed natural uranium by reactor in 1TFC - 2kT/yr capacity.

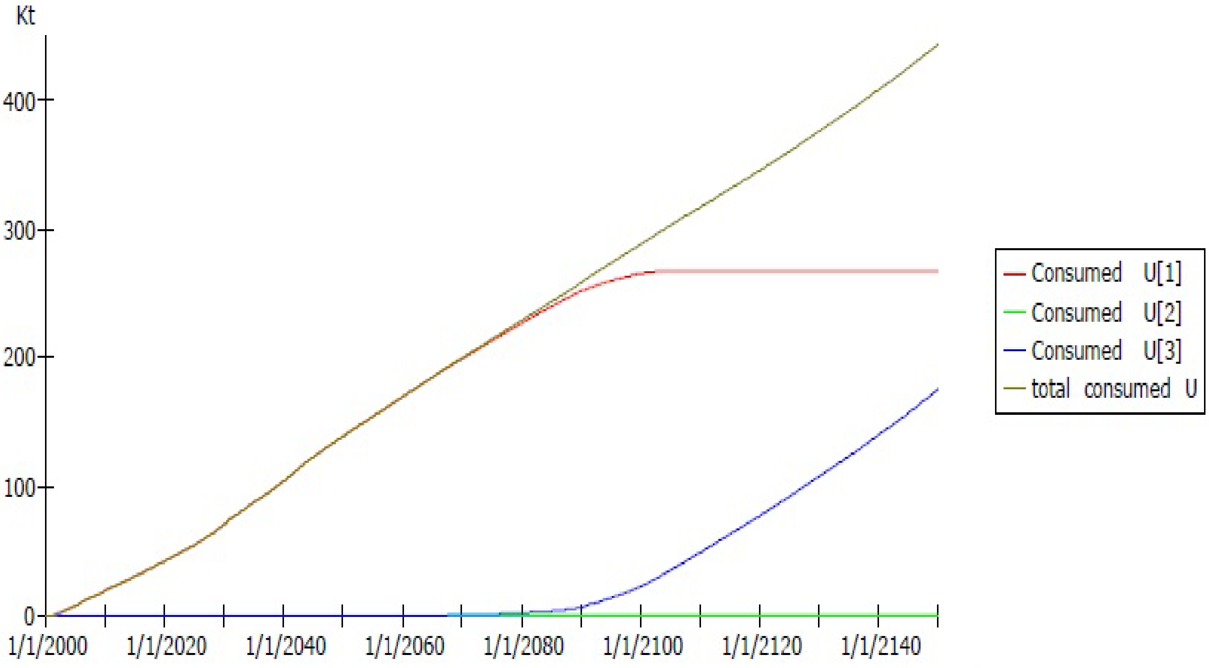


Figure A.1.4: Cumulative consumed enriched uranium by reactor in 1TFC-2 kT/yr capacity.

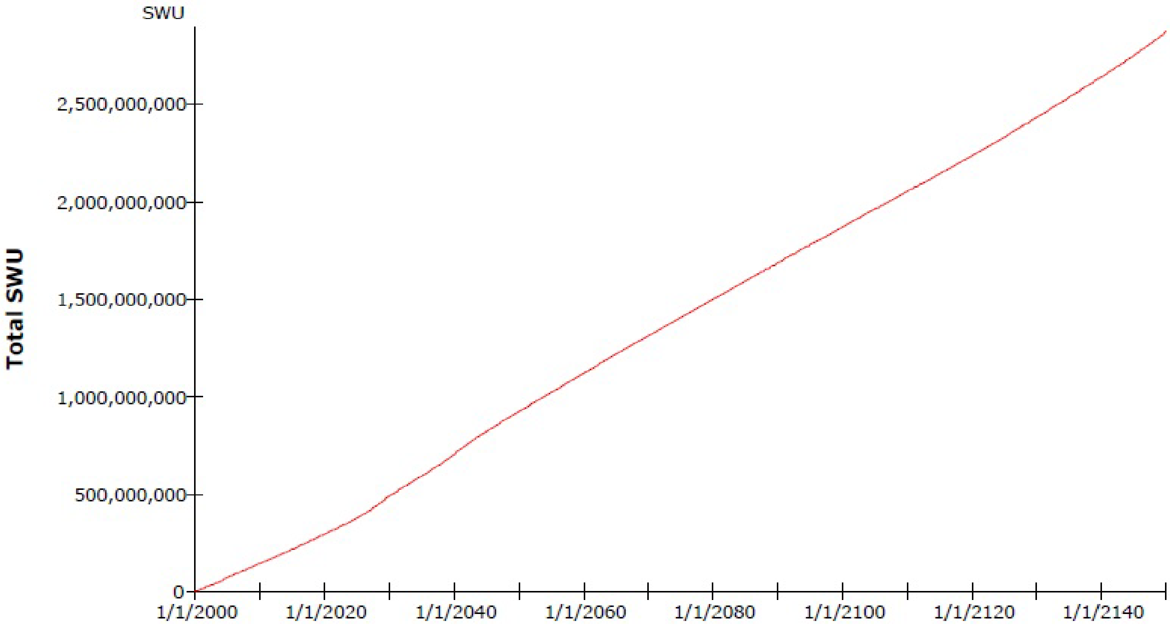


Figure A.1.5: Cumulative separative work unit in 1TFC – 2kT/yr capacity.

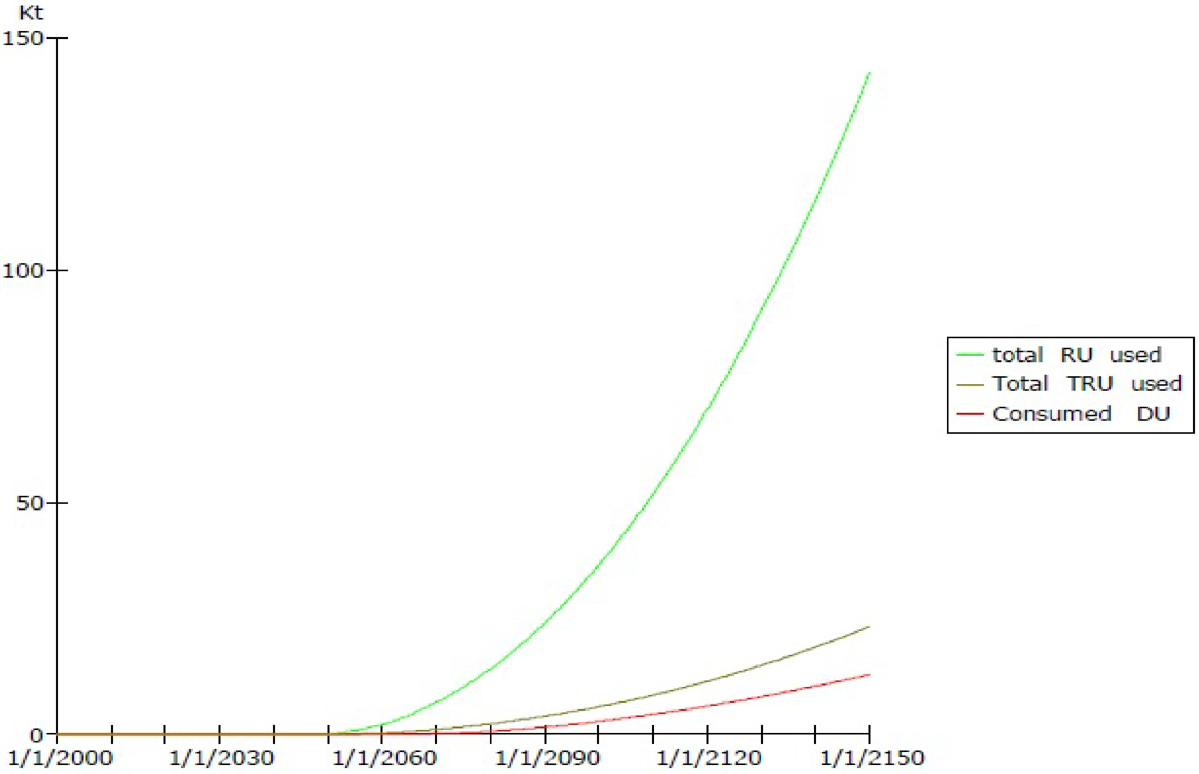


Figure A.1.6: RU, TRU and DU used for fuel fabrication in 1TFC – 2kT/yr capacity.

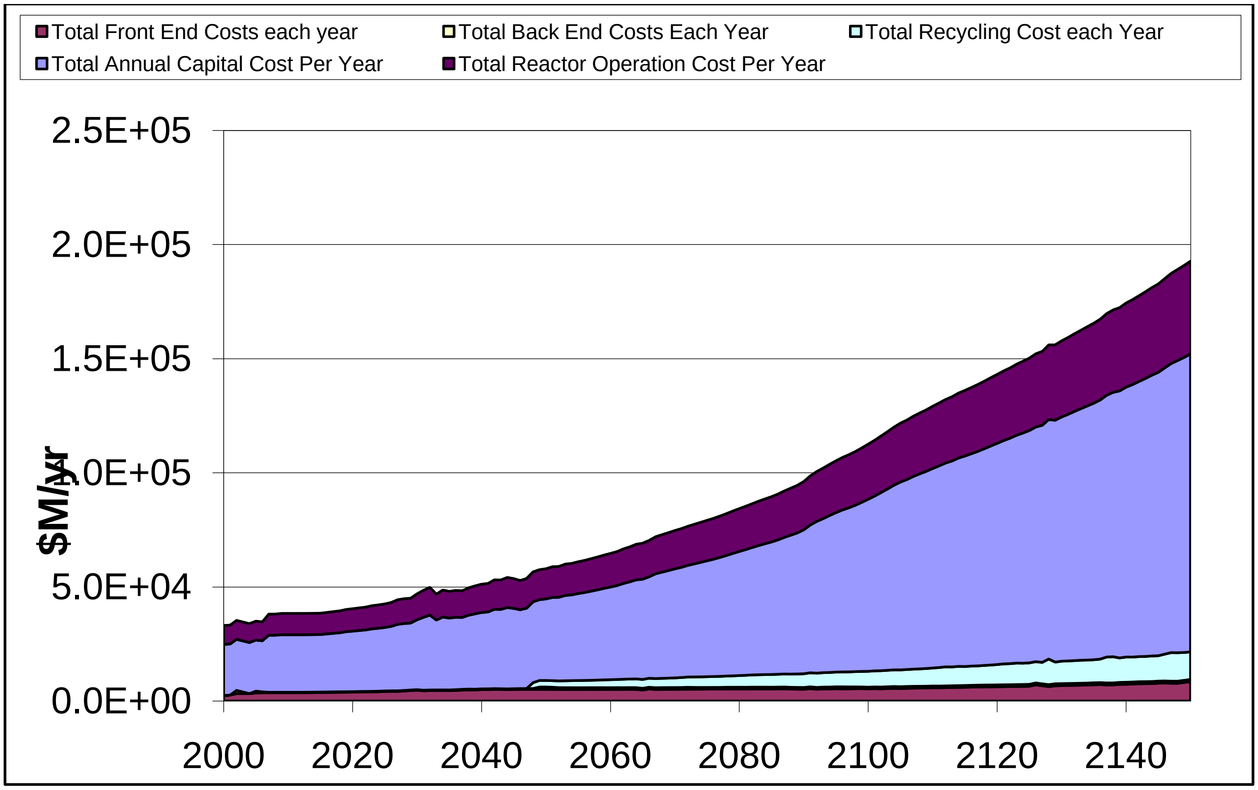


Figure A.1.7: annual cost breakdown of fuel cycle in 1TFC – 2kT/yr capacity.

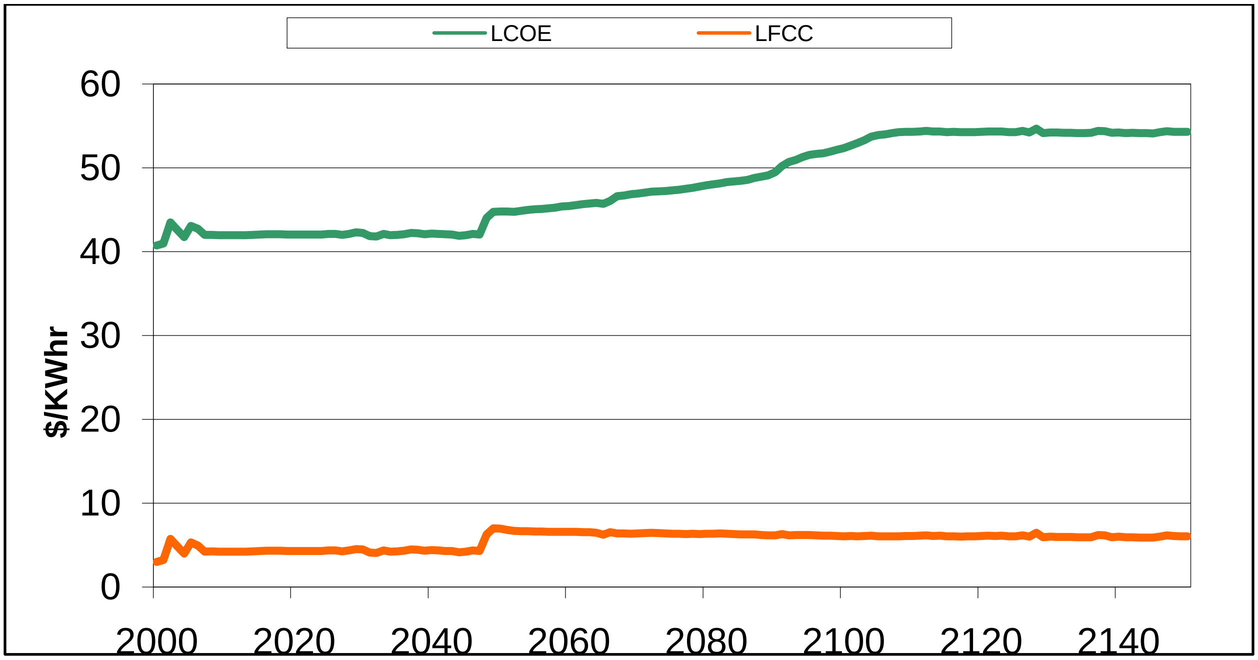


Figure A.1.8: Annual unit cost breakdown in 1TFC– 2kt/yr capacity.

A.2 1-Tier with 4 kT/yr Separation Capacity Fuel Cycle Scenario.

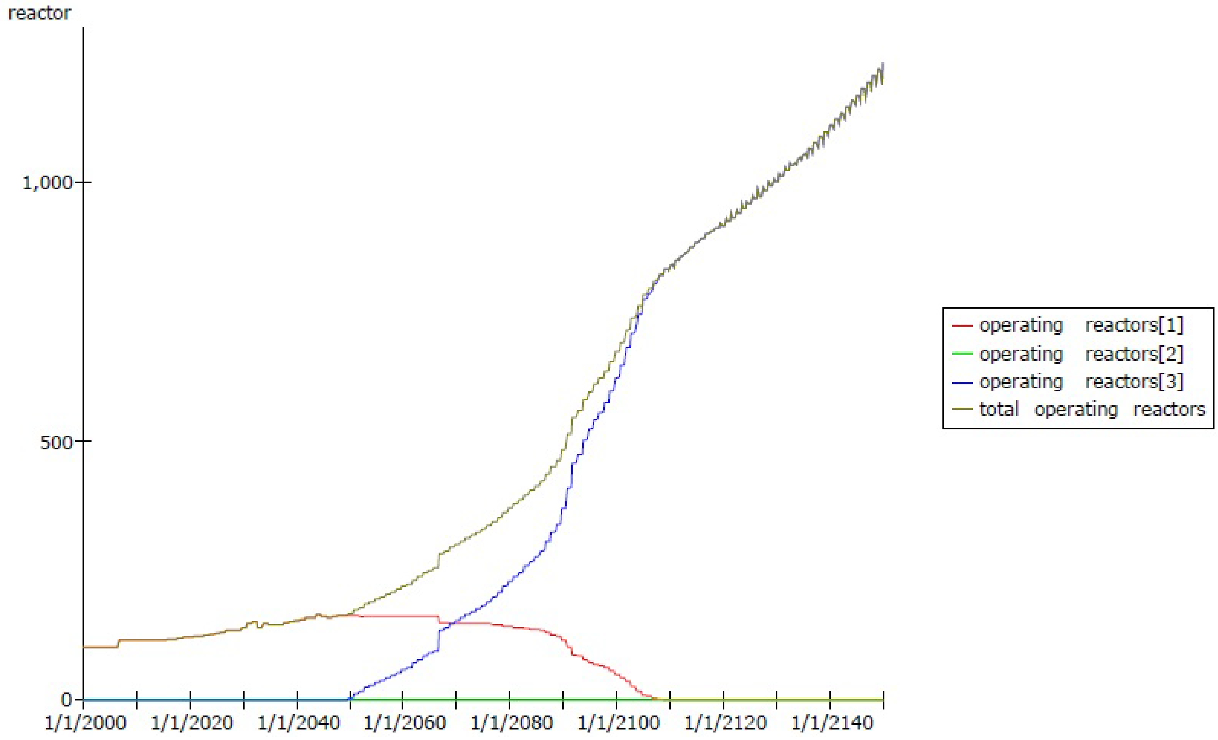


Figure A.2.1: Total number of reactor deployed per year by reactor in 1TFC – 4kT/yr capacity

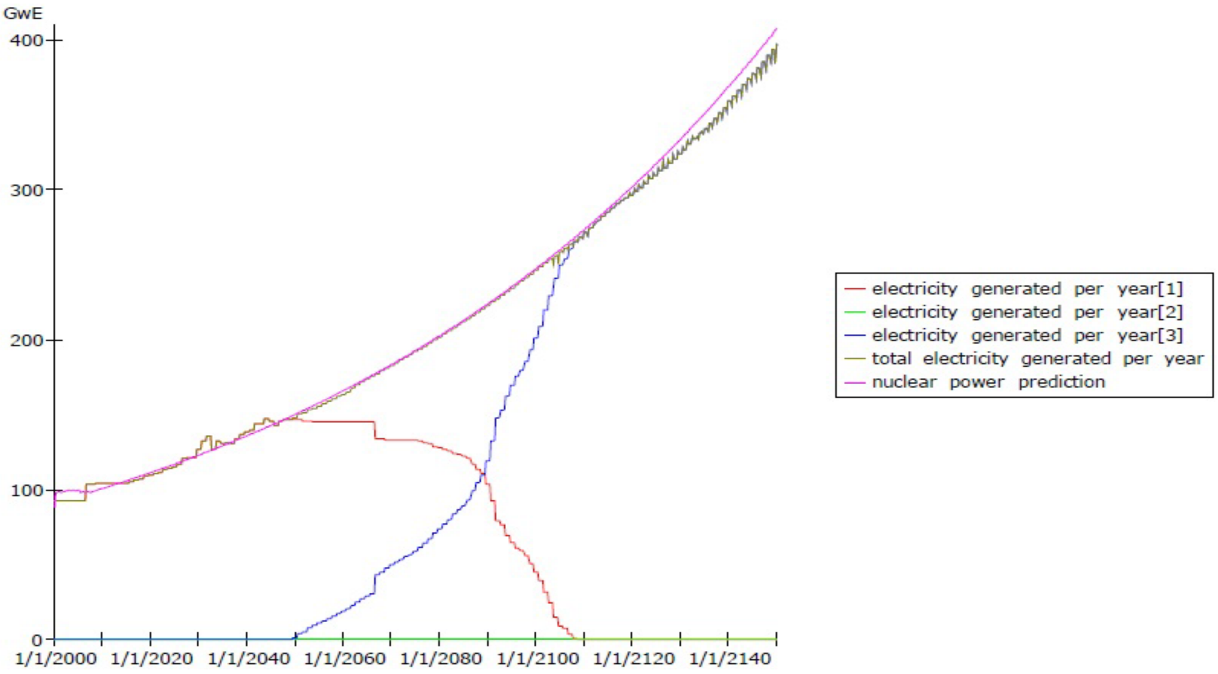


Figure A.2.2: Effective reactor capacity per year by reactor in 1TFC- 4kT/yr capacity.

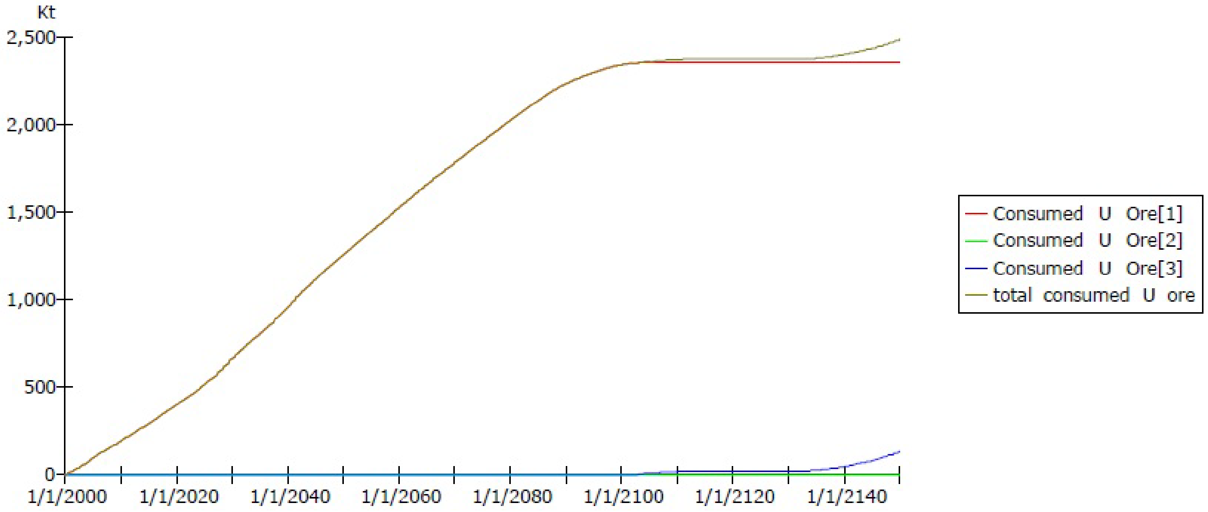


Figure A.2.3: Cumulative consumed natural uranium by reactor in 1TFC - 4kT/yr capacity.

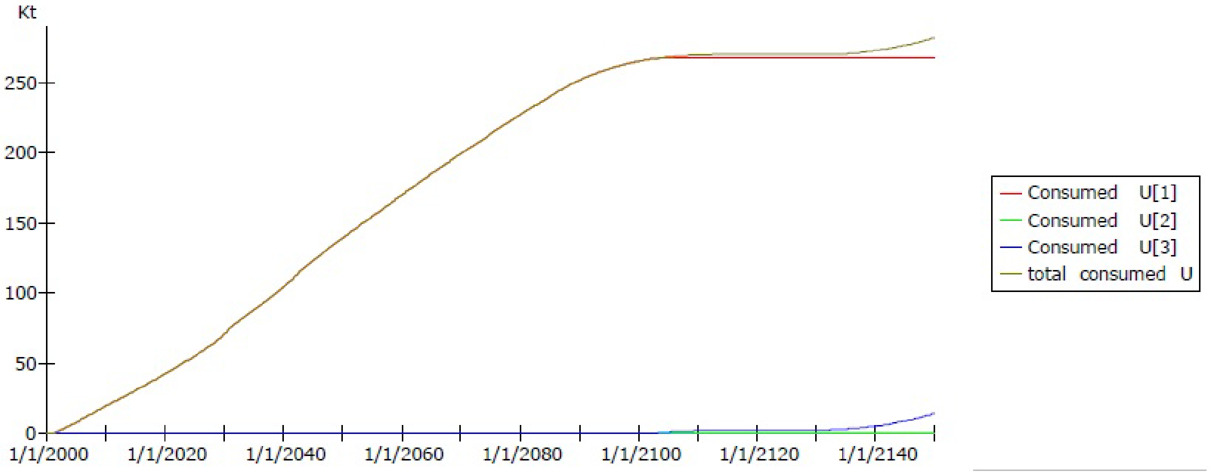


Figure A.2.4: Cumulative consumed enriched uranium by reactor in 1TFC - 4 kT/yr capacity.

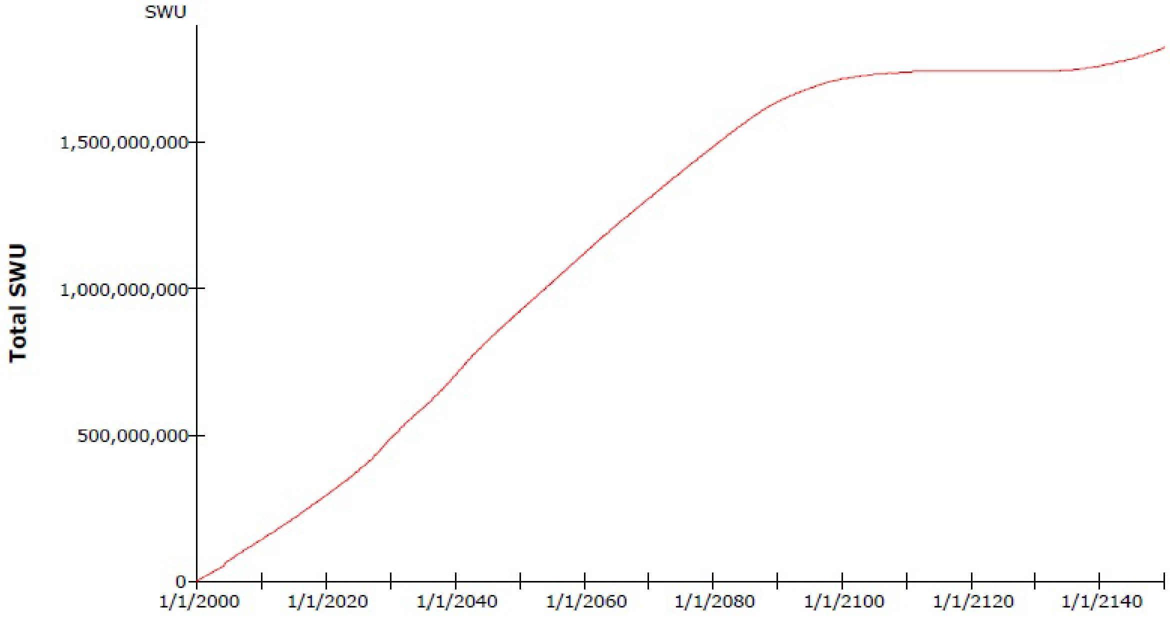


Figure A.2.5: Cumulative separative work unit in 1TFC – 4kT/yr capacity.

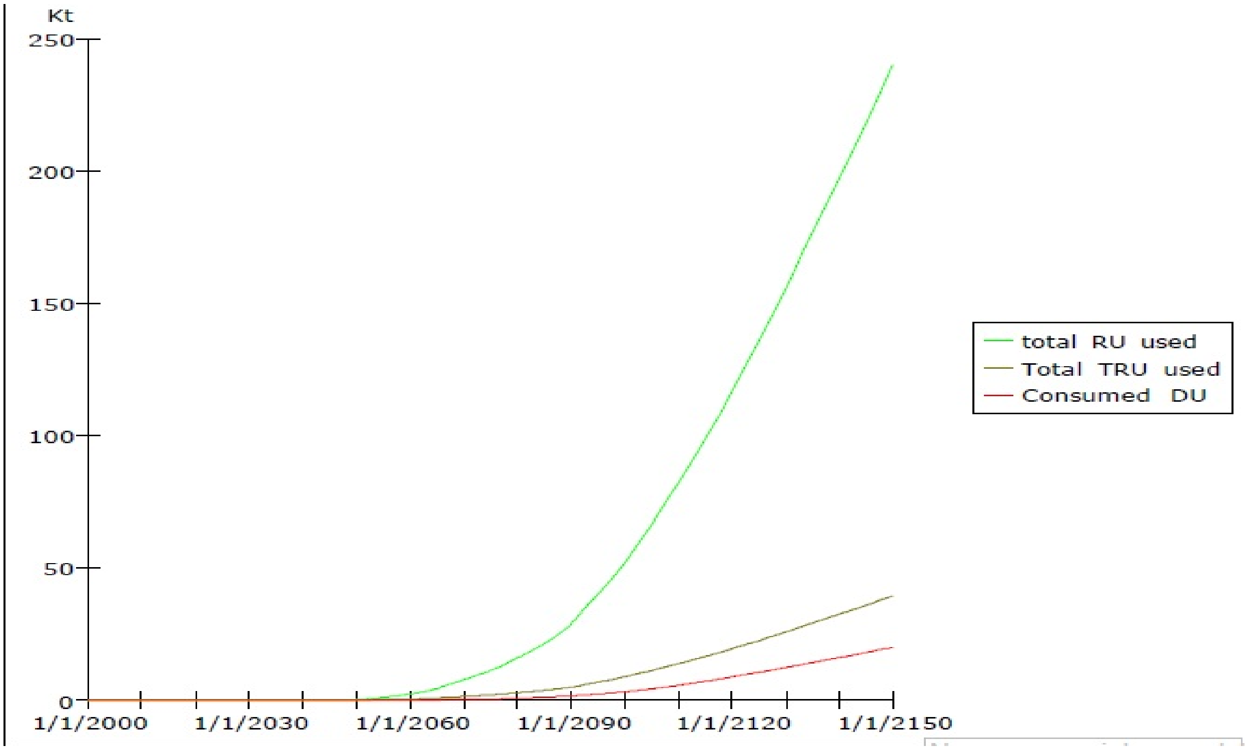


Figure A.2.6: RU, TRU and DU used for fuel fabrication in 1TFC – 4kT/yr capacity.

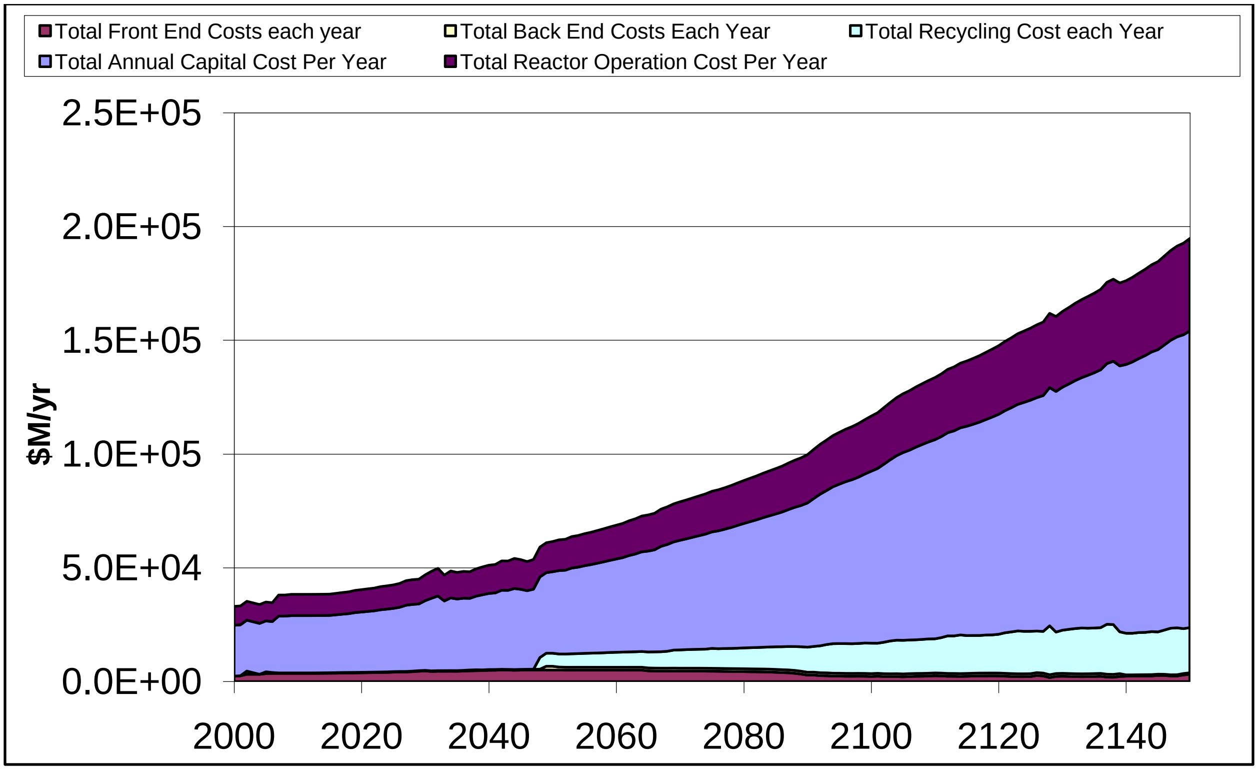


Figure A.2.7: Annual cost breakdown of fuel cycle in 1TFC – 4kT/yr capacity.

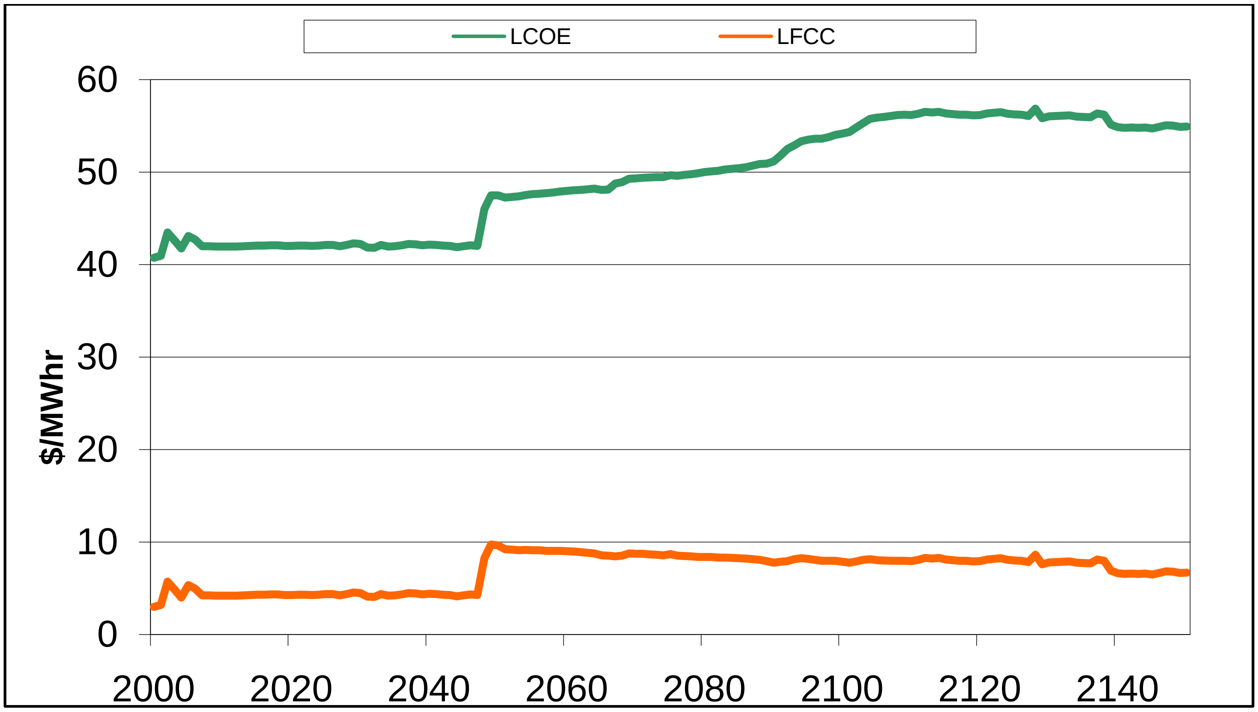


Figure A.2.8: Annual unit cost breakdown in 1TFC – 4kt/yr capacity.

A.3 2-Tier with 2 kT/yr Separation Capacity Fuel Cycle Scenario.

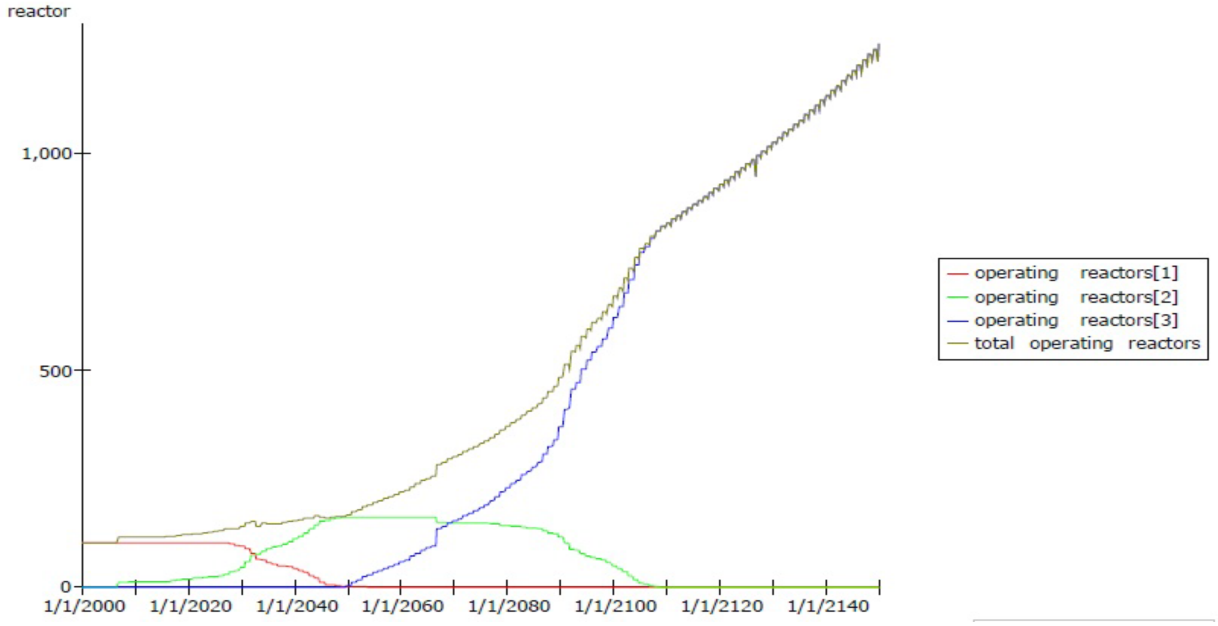


Figure A.3.1: Total number of reactor deployed per year by reactor in 2Tier – 2kT/yr capacity

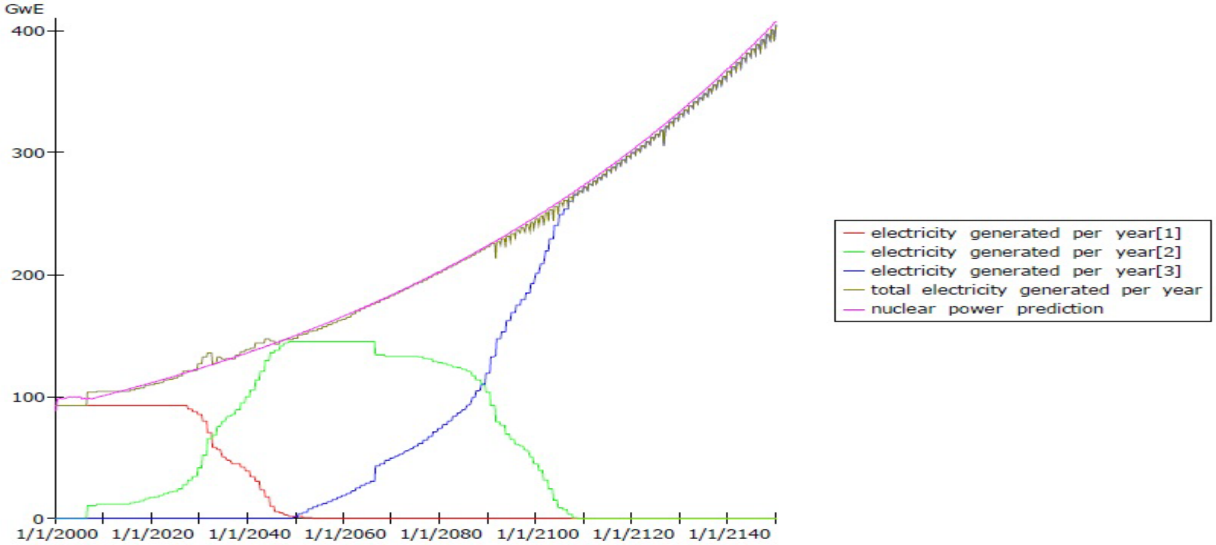


Figure A.3.2: Effective reactor capacity per year by reactor in 2TFC - 2kT/yr capacity.

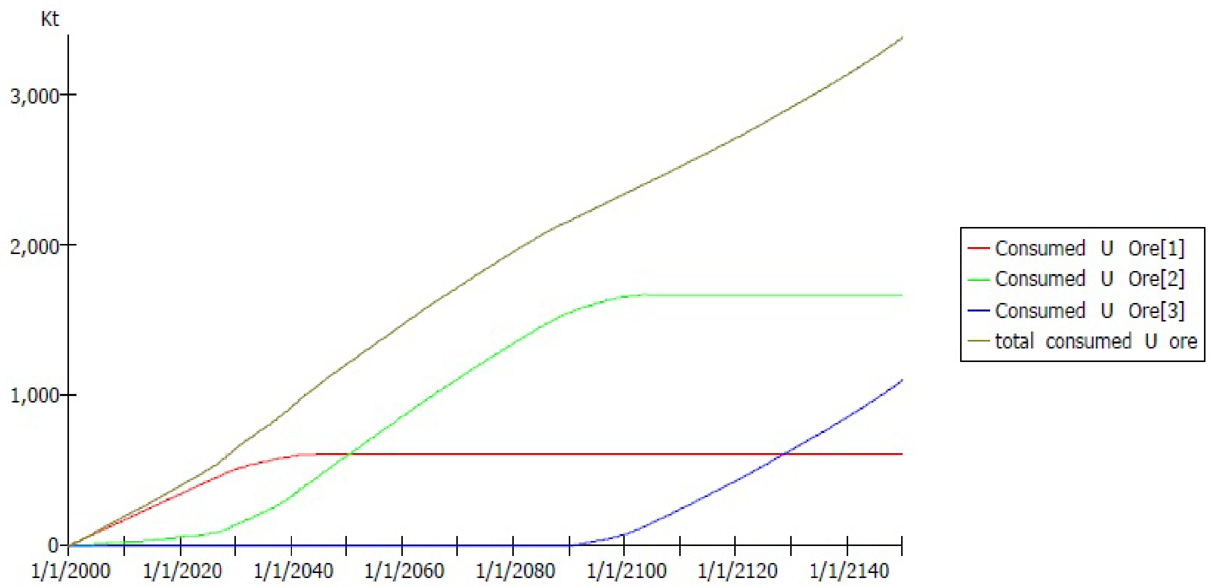


Figure A.3.3: Cumulative consumed natural uranium by reactor in 2TFC-2kT/yr capacity.

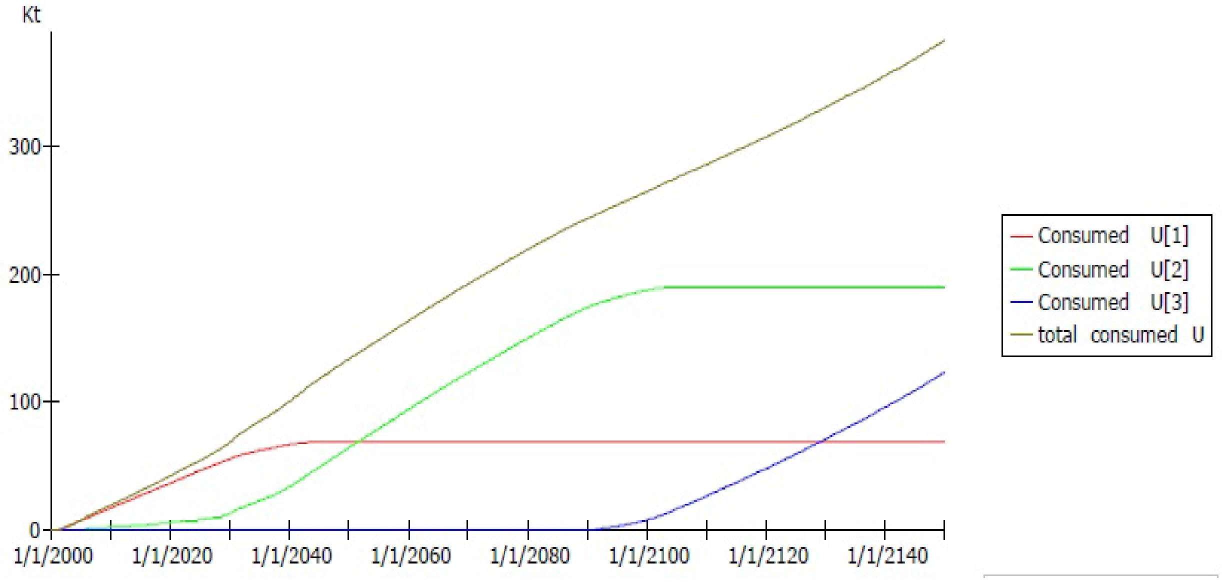


Figure A.3.4: Cumulative consumed enriched uranium by reactor in 2TFC-2 kT/yr capacity.

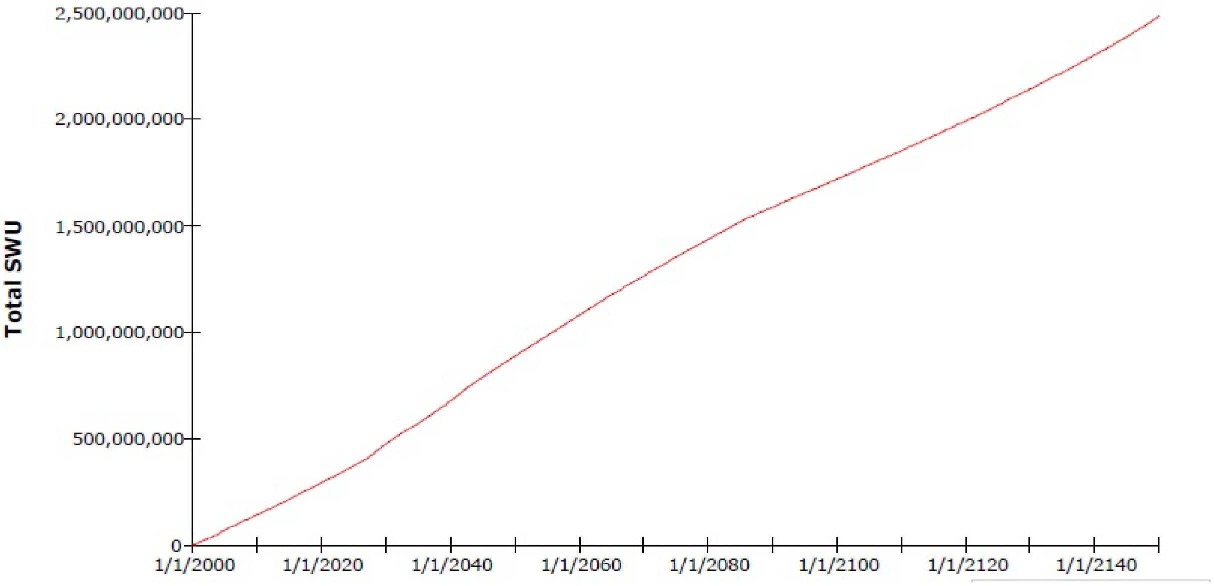


Figure A.3.5: Cumulative separative work unit in 2TFC – 2kT/yr capacity.

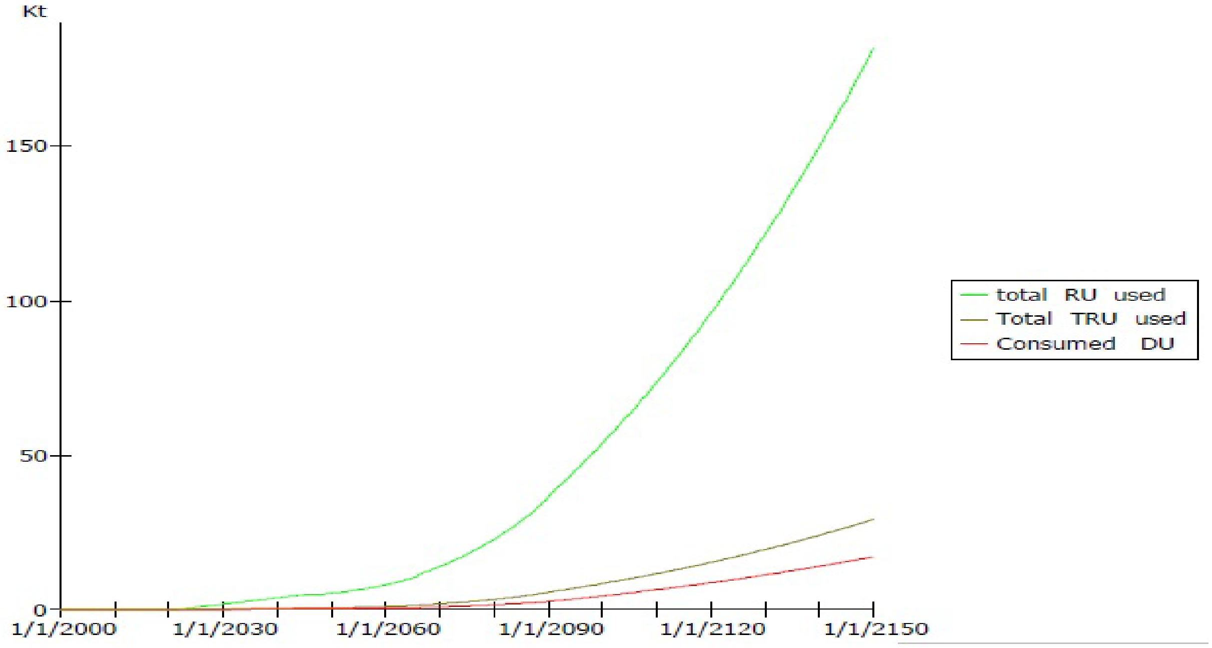


Figure A.3.6: RU, TRU and DU used for fuel fabrication in 2TFC – 2kT/yr capacity.

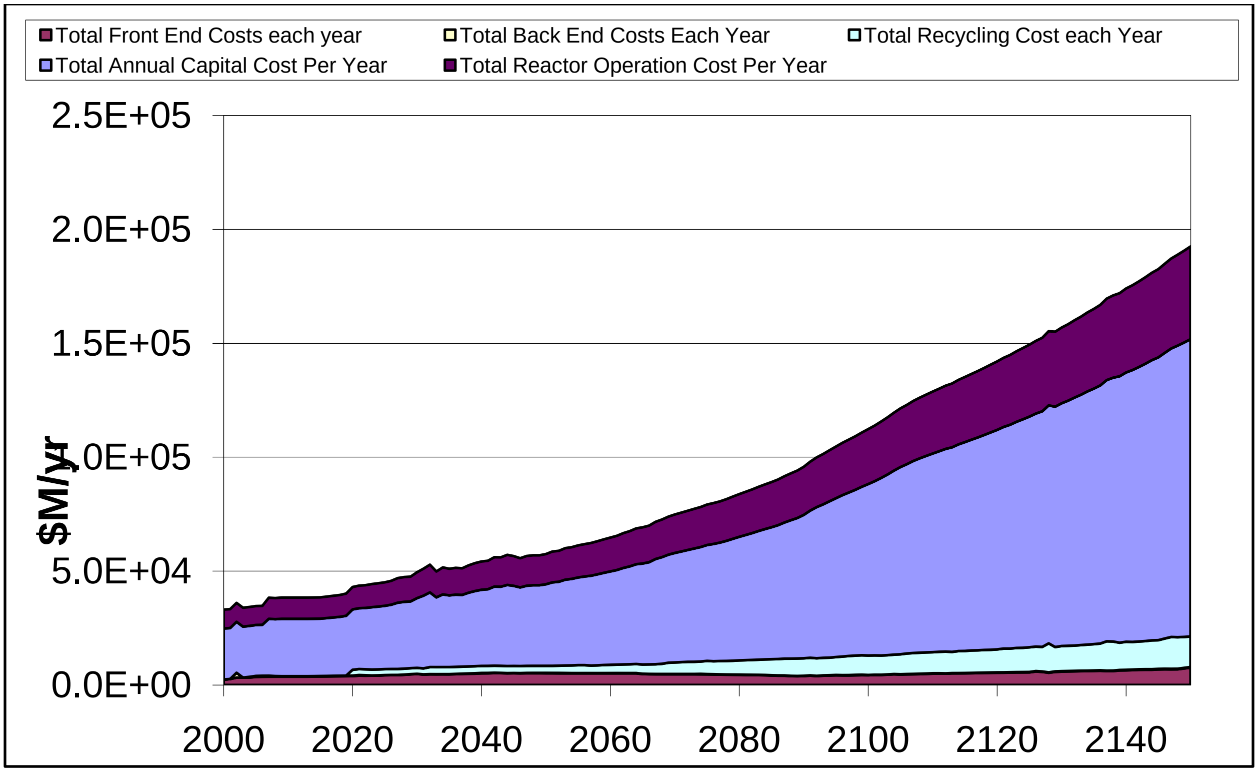


Figure A.3.7: annual cost breakdown of fuel cycle in 2TFC – 2kT/yr capacity.

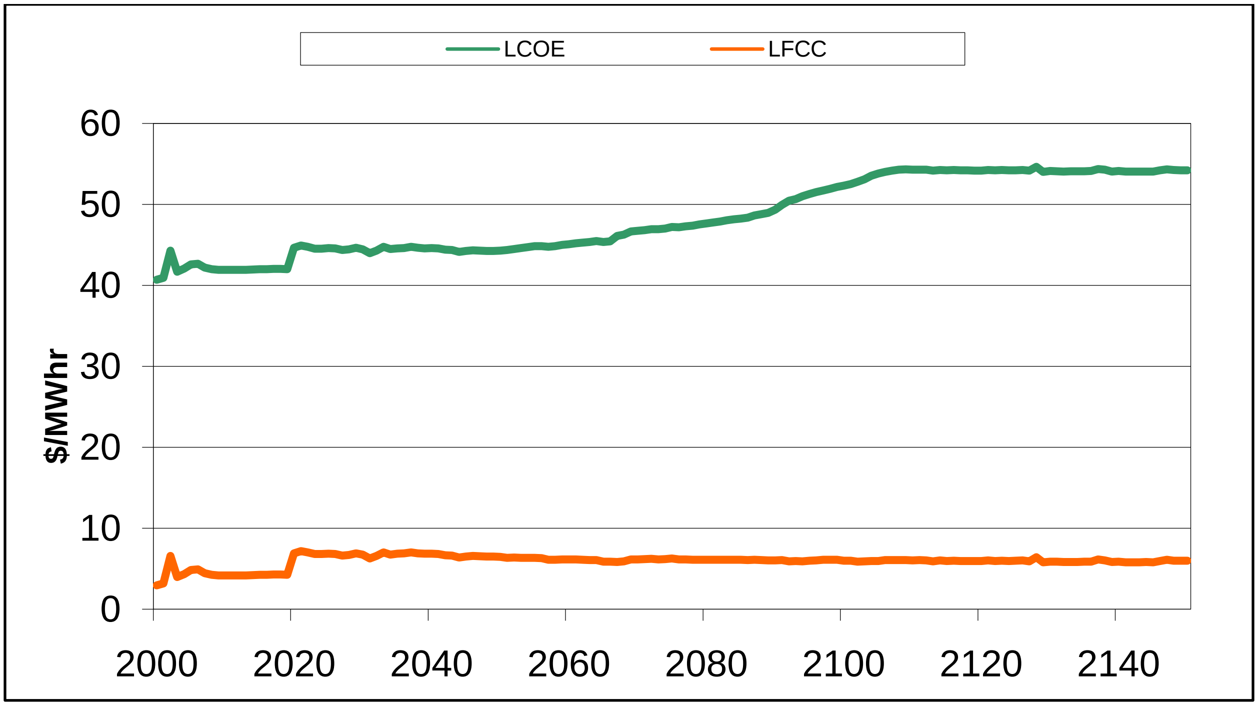


Figure A.3.8: Annual unit cost breakdown in 2TFC – 2kT/yr capacity.

A.4 2-Tier with 4 kT/yr Separation Capacity Fuel Cycle Scenario.

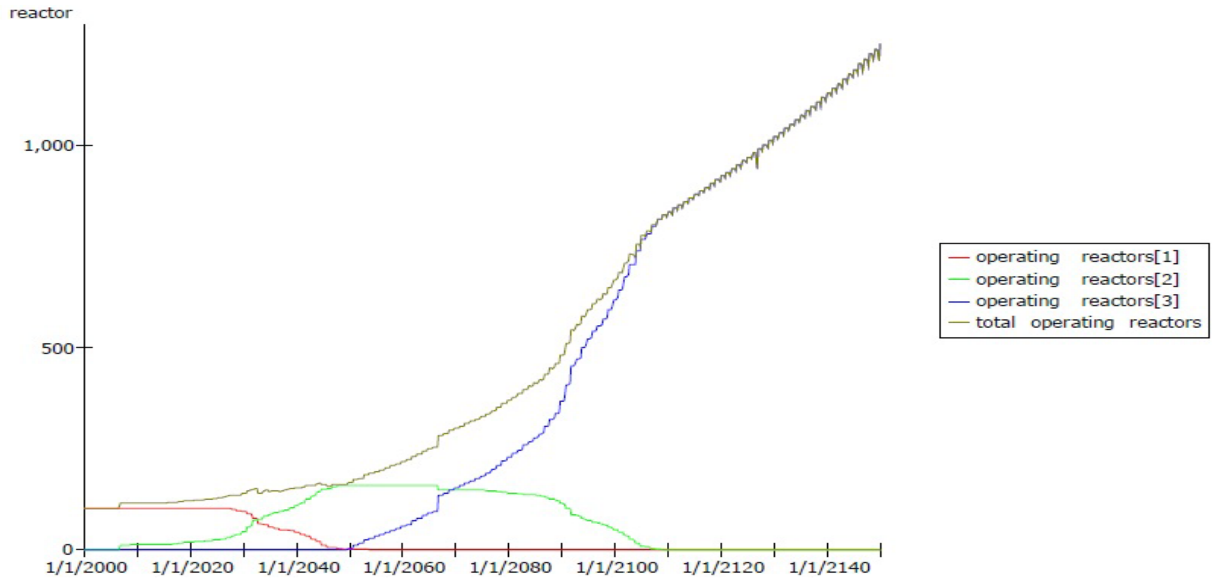


Figure A.4.1: Total number of reactor deployed per year by reactor in 2TFC – 4kT/yr capacity

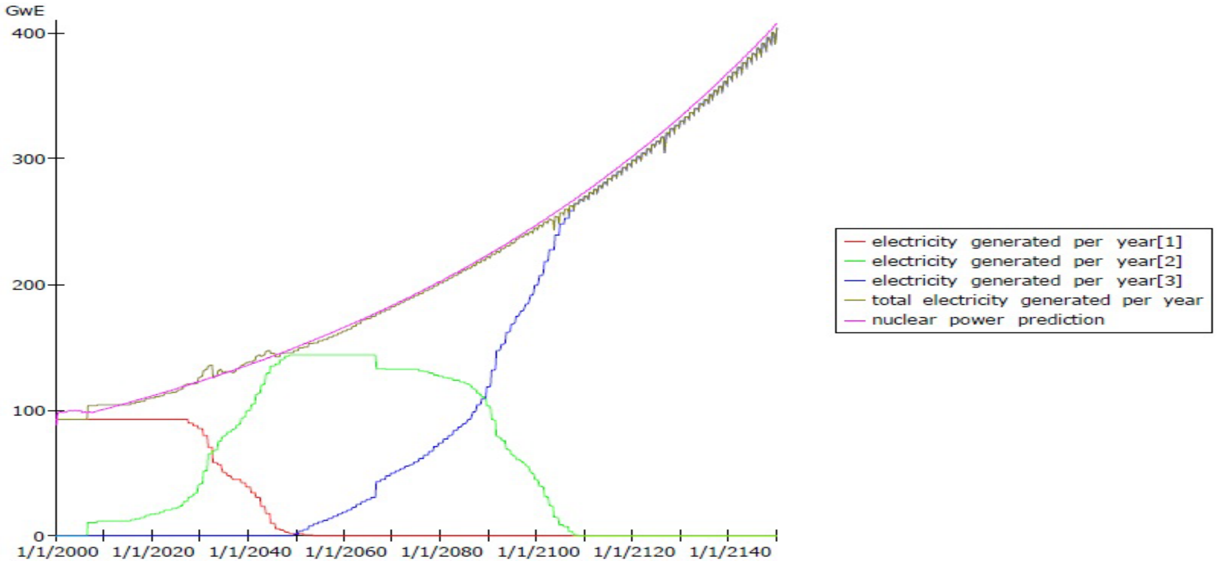


Figure A.4.2: Effective reactor capacity per year by reactor in 2TFC-4kT/yr capacity.

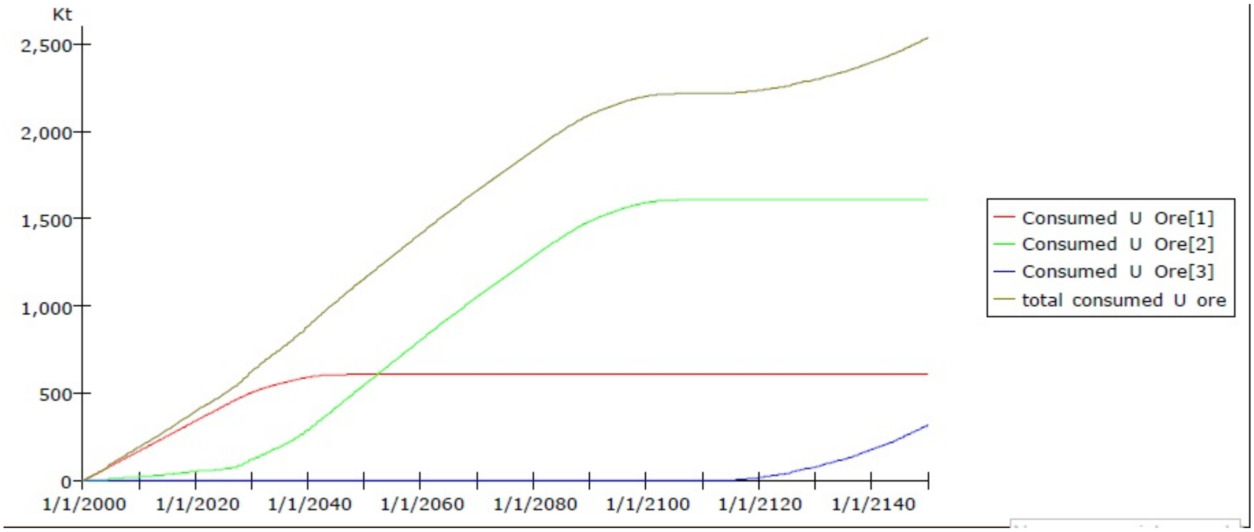


Figure A.4.3: Cumulative consumed natural uranium by reactor in 2TFC-4kT/yr capacity.

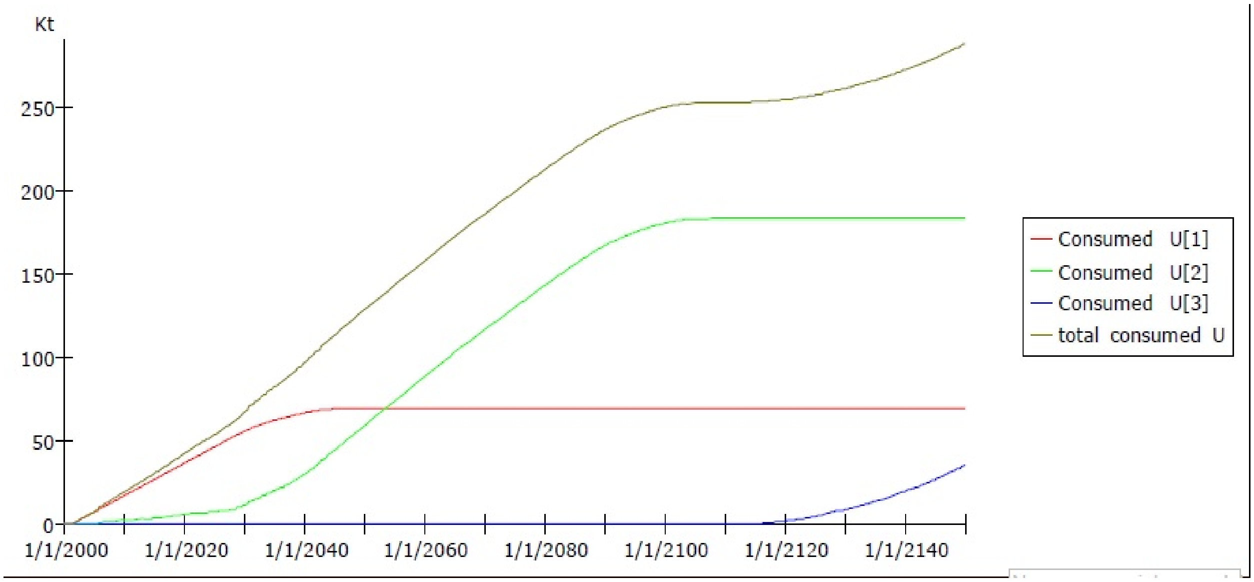


Figure A.4.4: Cumulative consumed enriched uranium by reactor in 2TFC-4 kT/yr capacity.

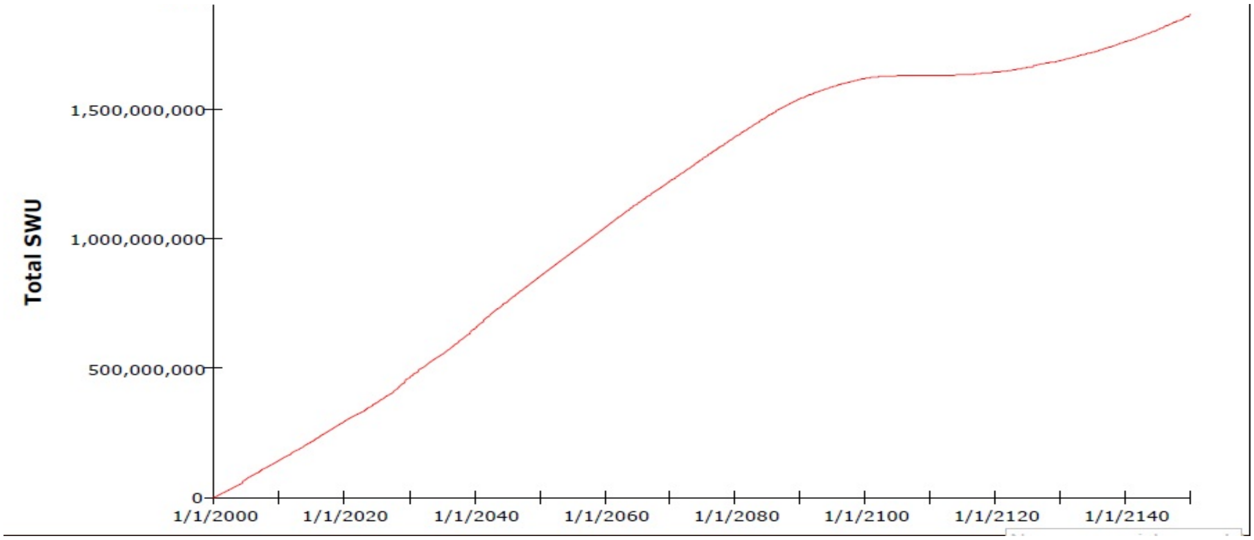


Figure A.4.5: Cumulative separative work unit in 2TFC – 4kT/yr capacity.

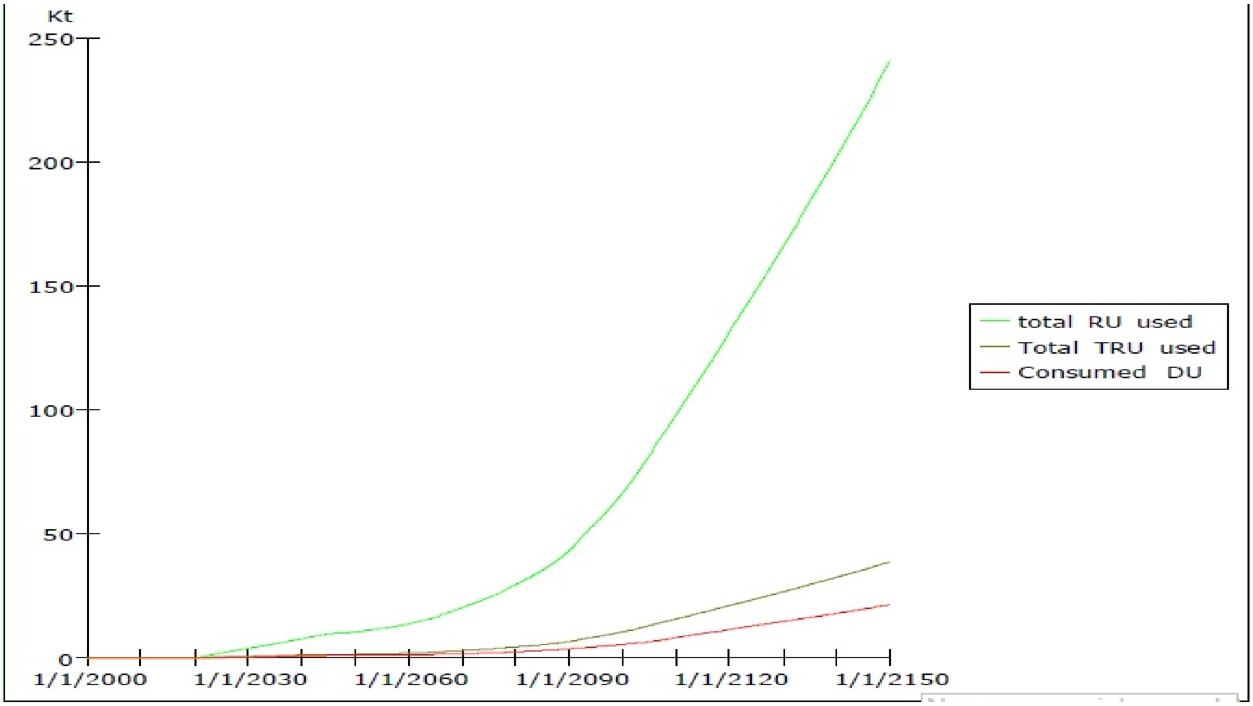


Figure A.4.6: RU, TRU and DU used for fuel fabrication in 2TFC– 4kT/yr capacity.

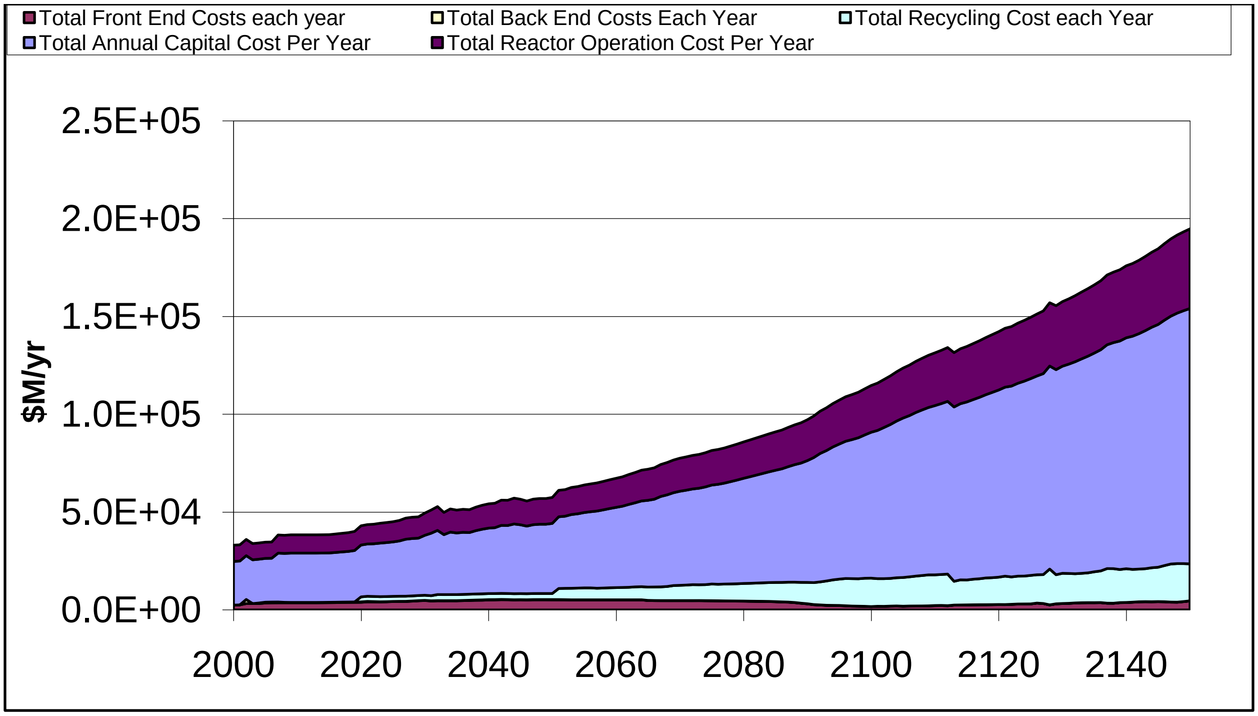


Figure A.4.7: annual cost breakdown of fuel cycle in 2TFC – 4kT/yr capacity.

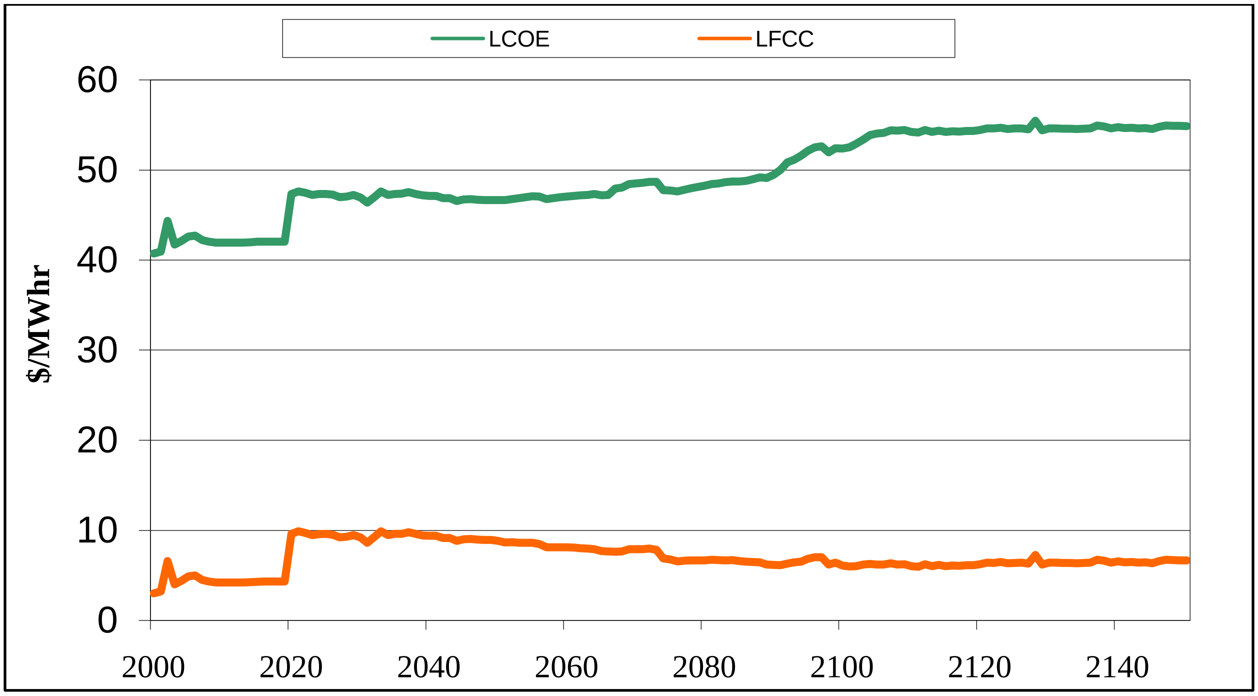
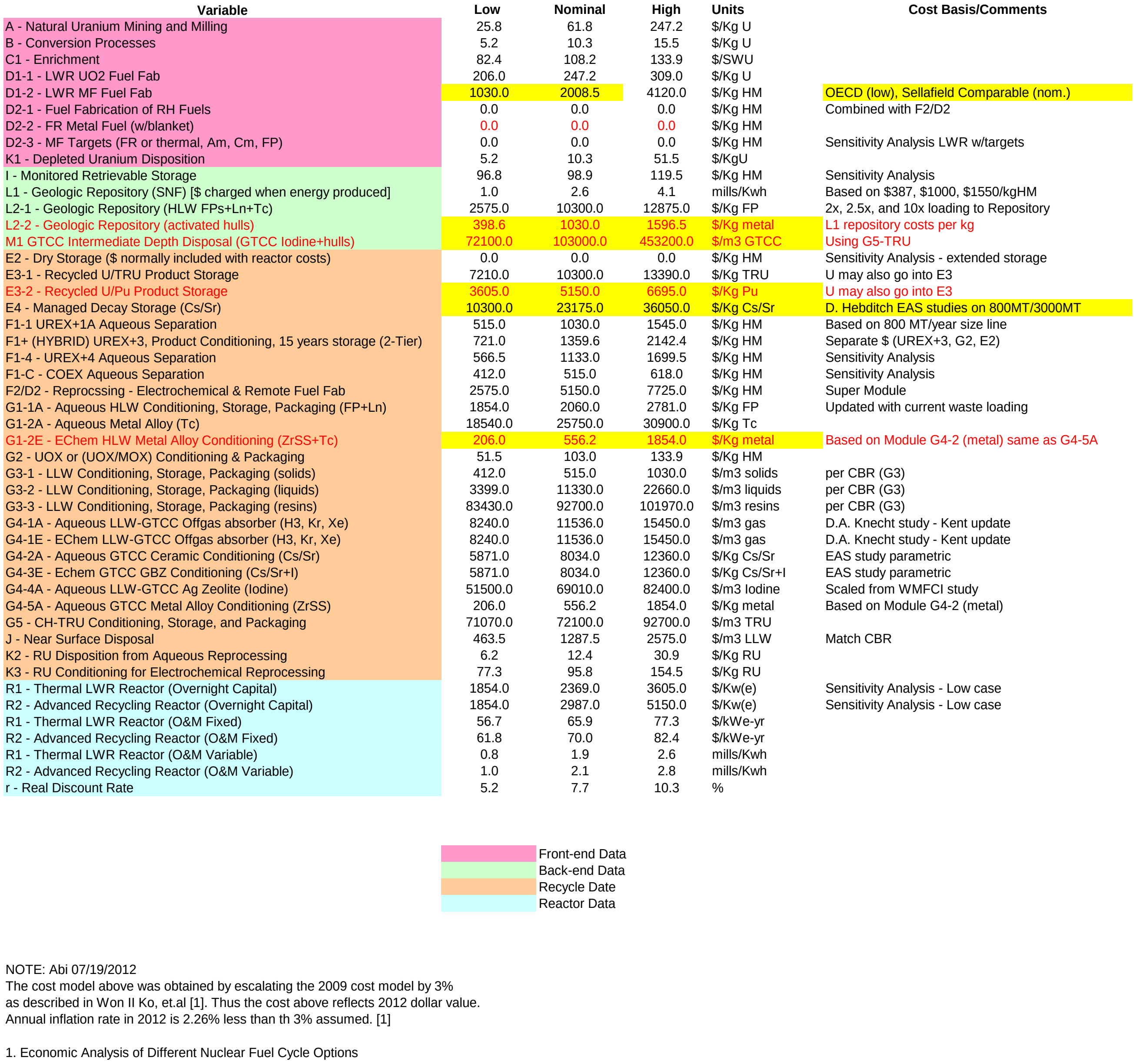


Figure A.4.8: Annual unit cost breakdown in 2TFC – 4kt/yr capacity.

APPENDIX B

COST INPUT FILE USED IN VISION-ECONS

All the cost input used in all scenarios is defined as shown in Fig. B.1, the cost for each module is defined separately. This allows economic impact of each component to be tracked.



Variable	Low	Nominal	High	Units	Cost Basis/Comments
A - Natural Uranium Mining and Milling	25.8	61.8	247.2	$/Kg U	
B - Conversion Processes	5.2	10.3	15.5	$/Kg U	
C1 - Enrichment	82.4	108.2	133.9	$/SWU	
D1-1 - LWR UO2 Fuel Fab	206.0	247.2	309.0	$/Kg U	
D1-2 - LWR MF Fuel Fab	1030.0	2008.5	4120.0	$/Kg HM	OECD (low), Sellafield Comparable (nom.)
D2-1 - Fuel Fabrication of RH Fuels	0.0	0.0	0.0	$/Kg HM	Combined with F2/D2
D2-2 - FR Metal Fuel (w/blanket)	0.0	0.0	0.0	$/Kg HM	
D2-3 - MF Targets (FR or thermal, Am, Cm, FP)	0.0	0.0	0.0	$/Kg HM	Sensitivity Analysis LWR w/targets
K1 - Depleted Uranium Disposition	5.2	10.3	51.5	$/KgU	
I - Monitored Retrievable Storage	96.8	98.9	119.5	$/Kg HM	Sensitivity Analysis
L1 - Geologic Repository (SNF) [$ charged when energy produced]	1.0	2.6	4.1	mills/Kwh	Based on $387, $1000, $1550/kgHM
L2-1 - Geologic Repository (HLW FPs+Ln+Tc)	2575.0	10300.0	12875.0	$/Kg FP	2x, 2.5x, and 10x loading to Repository
L2-2 - Geologic Repository (activated hulls)	398.6	1030.0	1596.5	$/Kg metal	L1 repository costs per kg
M1 GTCC Intermediate Depth Disposal (GTCC Iodine+hulls)	72100.0	103000.0	453200.0	$/m3 GTCC	Using G5-TRU
E2 - Dry Storage ($ normally included with reactor costs)	0.0	0.0	0.0	$/Kg HM	Sensitivity Analysis - extended storage
E3-1 - Recycled U/TRU Product Storage	7210.0	10300.0	13390.0	$/Kg TRU	U may also go into E3
E3-2 - Recycled U/Pu Product Storage	3605.0	5150.0	6695.0	$/Kg Pu	U may also go into E3
E4 - Managed Decay Storage (Cs/Sr)	10300.0	23175.0	36050.0	$/Kg Cs/Sr	D. Hebditch EAS studies on 800MT/3000MT
F1-1 UREX+1A Aqueous Separation	515.0	1030.0	1545.0	$/Kg HM	Based on 800 MT/year size line
F1+ (HYBRID) UREX+3, Product Conditioning, 15 years storage (2-Tier)	721.0	1359.6	2142.4	$/Kg HM	Separate $ (UREX+3, G2, E2)
F1-4 - UREX+4 Aqueous Separation	566.5	1133.0	1699.5	$/Kg HM	Sensitivity Analysis
F1-C - COEX Aqueous Separation	412.0	515.0	618.0	$/Kg HM	Sensitivity Analysis
F2/D2 - Reprocssing - Electrochemical & Remote Fuel Fab	2575.0	5150.0	7725.0	$/Kg HM	Super Module
G1-1A - Aqueous HLW Conditioning, Storage, Packaging (FP+Ln)	1854.0	2060.0	2781.0	$/Kg FP	Updated with current waste loading
G1-2A - Aqueous Metal Alloy (Tc)	18540.0	25750.0	30900.0	$/Kg Tc	
G1-2E - EChem HLW Metal Alloy Conditioning (ZrSS+Tc)	206.0	556.2	1854.0	$/Kg metal	Based on Module G4-2 (metal) same as G4-5A
G2 - UOX or (UOX/MOX) Conditioning & Packaging	51.5	103.0	133.9	$/Kg HM	
G3-1 - LLW Conditioning, Storage, Packaging (solids)	412.0	515.0	1030.0	$/m3 solids	per CBR (G3)
G3-2 - LLW Conditioning, Storage, Packaging (liquids)	3399.0	11330.0	22660.0	$/m3 liquids	per CBR (G3)
G3-3 - LLW Conditioning, Storage, Packaging (resins)	83430.0	92700.0	101970.0	$/m3 resins	per CBR (G3)
G4-1A - Aqueous LLW-GTCC Offgas absorber (H3, Kr, Xe)	8240.0	11536.0	15450.0	$/m3 gas	D.A. Knecht study - Kent update
G4-1E - EChem LLW-GTCC Offgas absorber (H3, Kr, Xe)	8240.0	11536.0	15450.0	$/m3 gas	D.A. Knecht study - Kent update
G4-2A - Aqueous GTCC Ceramic Conditioning (Cs/Sr)	5871.0	8034.0	12360.0	$/Kg Cs/Sr	EAS study parametric
G4-3E - Echem GTCC GBZ Conditioning (Cs/Sr+I)	5871.0	8034.0	12360.0	$/Kg Cs/Sr+I	EAS study parametric
G4-4A - Aqueous LLW-GTCC Ag Zeolite (Iodine)	51500.0	69010.0	82400.0	$/m3 Iodine	Scaled from WMFCI study
G4-5A - Aqueous GTCC Metal Alloy Conditioning (ZrSS)	206.0	556.2	1854.0	$/Kg metal	Based on Module G4-2 (metal)
G5 - CH-TRU Conditioning, Storage, and Packaging	71070.0	72100.0	92700.0	$/m3 TRU	
J - Near Surface Disposal	463.5	1287.5	2575.0	$/m3 LLW	Match CBR
K2 - RU Disposition from Aqueous Reprocessing	6.2	12.4	30.9	$/Kg RU	
K3 - RU Conditioning for Electrochemical Reprocessing	77.3	95.8	154.5	$/Kg RU	
R1 - Thermal LWR Reactor (Overnight Capital)	1854.0	2369.0	3605.0	$/Kw(e)	Sensitivity Analysis - Low case
R2 - Advanced Recycling Reactor (Overnight Capital)	1854.0	2987.0	5150.0	$/Kw(e)	Sensitivity Analysis - Low case
R1 - Thermal LWR Reactor (O&M Fixed)	56.7	65.9	77.3	$/kWe-yr	
R2 - Advanced Recycling Reactor (O&M Fixed)	61.8	70.0	82.4	$/kWe-yr	
R1 - Thermal LWR Reactor (O&M Variable)	0.8	1.9	2.6	mills/Kwh	
R2 - Advanced Recycling Reactor (O&M Variable)	1.0	2.1	2.8	mills/Kwh	
r - Real Discount Rate	5.2	7.7	10.3	%	

▨ Front-end Data
▨ Back-end Data
▨ Recycle Date
▨ Reactor Data

NOTE: Abi 07/19/2012
The cost model above was obtained by escalating the 2009 cost model by 3%
as described in Won Il Ko, et.al [1]. Thus the cost above reflects 2012 dollar value.
Annual inflation rate in 2012 is 2.26% less than th 3% assumed. [1]

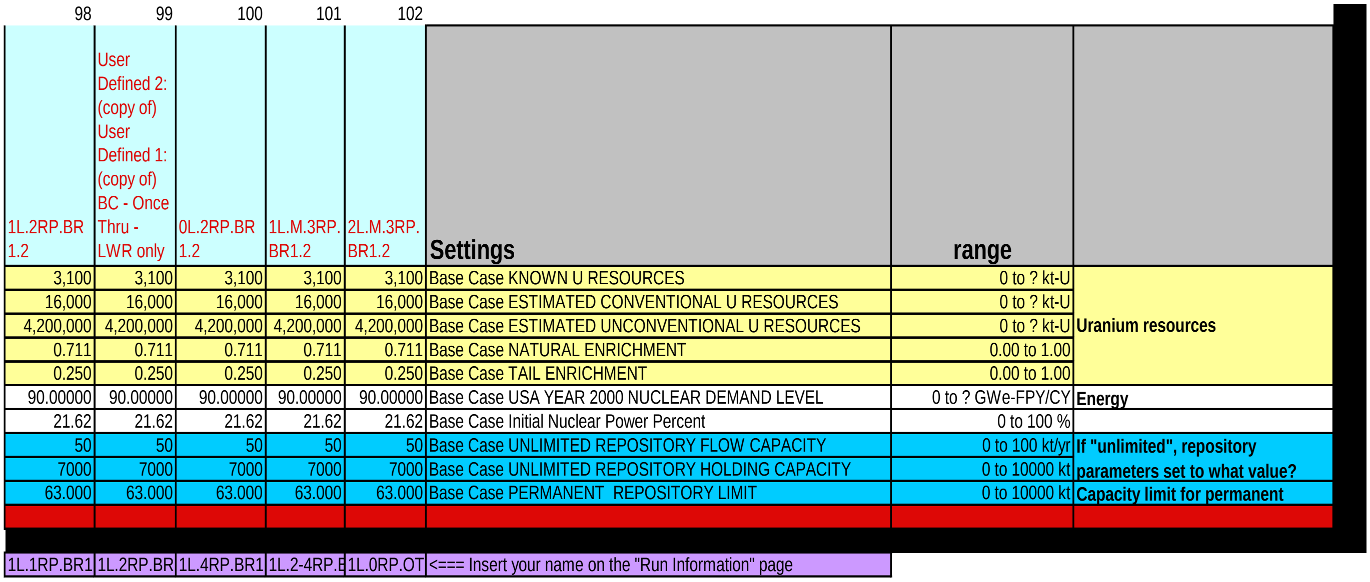
1. Economic Analysis of Different Nuclear Fuel Cycle Options

Figure B.1: Cost distribution in 2012 US $ for VISION-ECONS analysis.

APPENDIX C

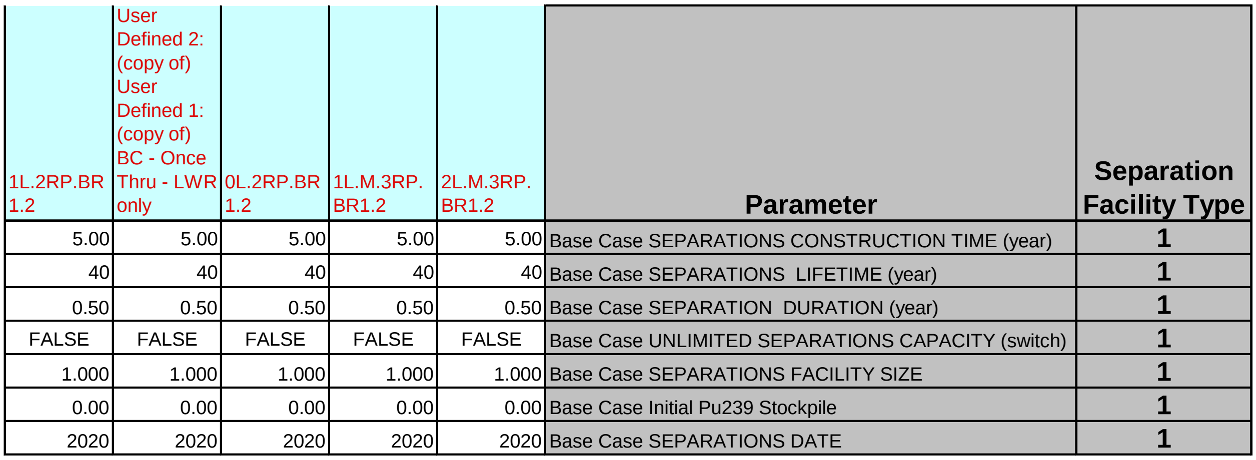
VISION PARAMETER FILES

C.1:Some input files used in scenario study.



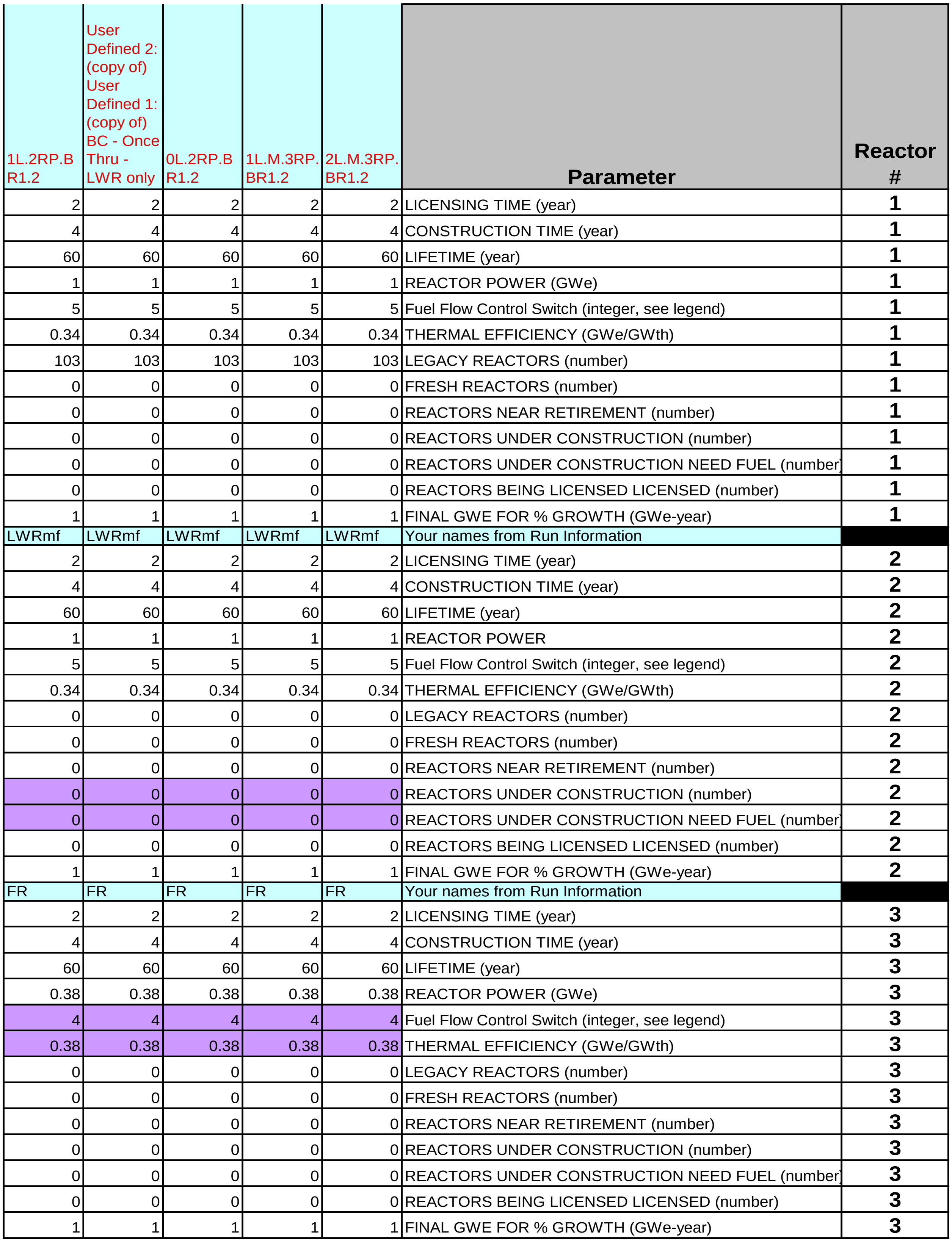
98	99	100	101	102			
1L.2RP.BR 1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR 1.2	1L.M.3RP. BR1.2	2L.M.3RP. BR1.2	**Settings**	**range**	
3,100	3,100	3,100	3,100	3,100	Base Case KNOWN U RESOURCES	0 to ? kt-U	**Uranium resources**
16,000	16,000	16,000	16,000	16,000	Base Case ESTIMATED CONVENTIONAL U RESOURCES	0 to ? kt-U	
4,200,000	4,200,000	4,200,000	4,200,000	4,200,000	Base Case ESTIMATED UNCONVENTIONAL U RESOURCES	0 to ? kt-U	
0.711	0.711	0.711	0.711	0.711	Base Case NATURAL ENRICHMENT	0.00 to 1.00	
0.250	0.250	0.250	0.250	0.250	Base Case TAIL ENRICHMENT	0.00 to 1.00	
90.00000	90.00000	90.00000	90.00000	90.00000	Base Case USA YEAR 2000 NUCLEAR DEMAND LEVEL	0 to ? GWe-FPY/CY	**Energy**
21.62	21.62	21.62	21.62	21.62	Base Case Initial Nuclear Power Percent	0 to 100 %	
50	50	50	50	50	Base Case UNLIMITED REPOSITORY FLOW CAPACITY	0 to 100 kt/yr	**If "unlimited", repository**
7000	7000	7000	7000	7000	Base Case UNLIMITED REPOSITORY HOLDING CAPACITY	0 to 10000 kt	**parameters set to what value?**
63.000	63.000	63.000	63.000	63.000	Base Case PERMANENT REPOSITORY LIMIT	0 to 10000 kt	**Capacity limit for permanent**
1L.1RP.BR1	1L.2RP.BR	1L.4RP.BR1	1L.2-4RP.E	1L.0RP.OT	<=== Insert your name on the "Run Information" page		

Figure C.1: Some base case (BC) input parameters



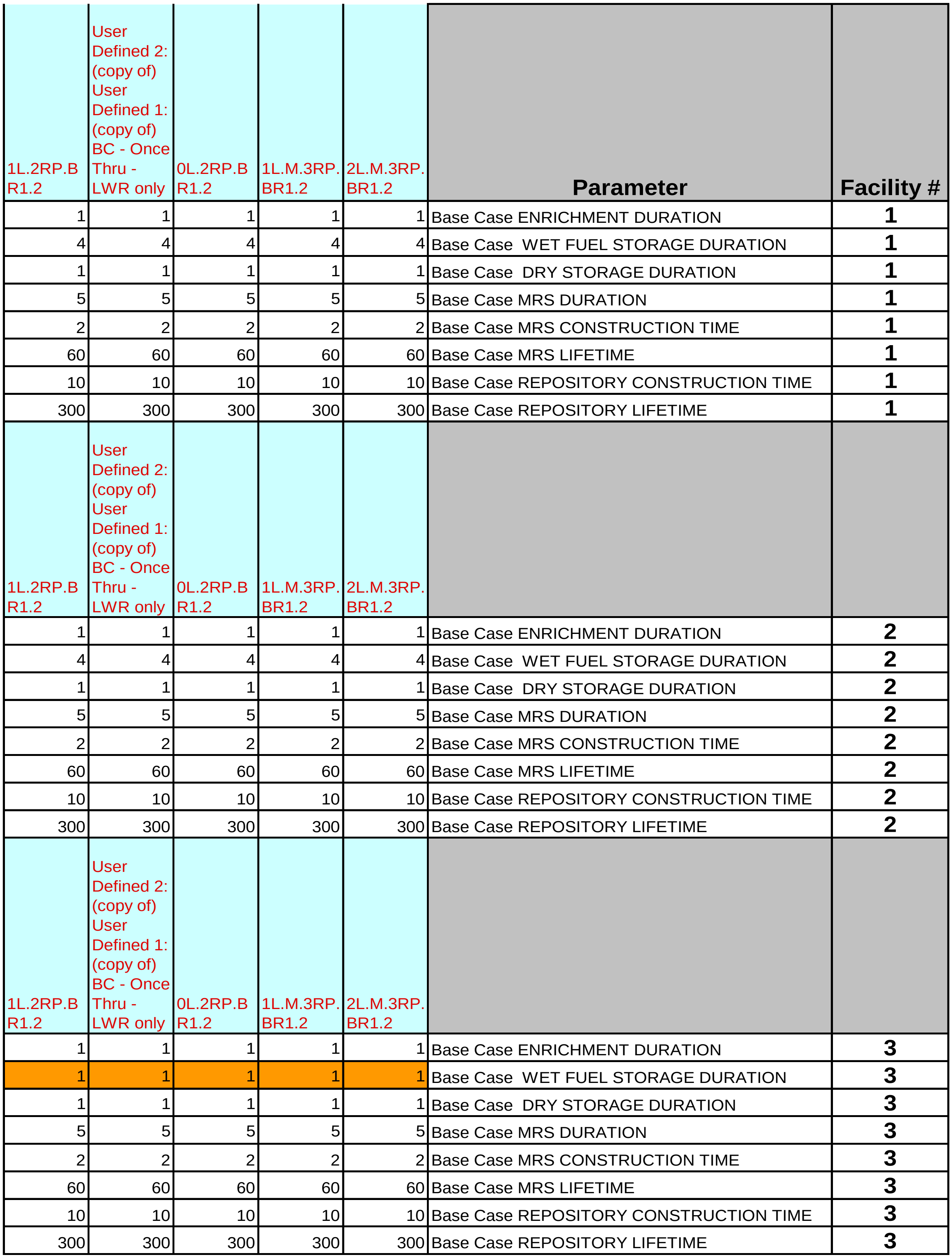
1L.2RP.BR 1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR 1.2	1L.M.3RP. BR1.2	2L.M.3RP. BR1.2	**Parameter**	**Separation Facility Type**
5.00	5.00	5.00	5.00	5.00	Base Case SEPARATIONS CONSTRUCTION TIME (year)	**1**
40	40	40	40	40	Base Case SEPARATIONS LIFETIME (year)	**1**
0.50	0.50	0.50	0.50	0.50	Base Case SEPARATION DURATION (year)	**1**
FALSE	FALSE	FALSE	FALSE	FALSE	Base Case UNLIMITED SEPARATIONS CAPACITY (switch)	**1**
1.000	1.000	1.000	1.000	1.000	Base Case SEPARATIONS FACILITY SIZE	**1**
0.00	0.00	0.00	0.00	0.00	Base Case Initial Pu239 Stockpile	**1**
2020	2020	2020	2020	2020	Base Case SEPARATIONS DATE	**1**

Figure C2: VISION separation facility design and operating parameters



1L.2RP.BR1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR1.2	1L.M.3RP.BR1.2	2L.M.3RP.BR1.2	**Parameter**	**Reactor #**
2	2	2	2	2	LICENSING TIME (year)	**1**
4	4	4	4	4	CONSTRUCTION TIME (year)	**1**
60	60	60	60	60	LIFETIME (year)	**1**
1	1	1	1	1	REACTOR POWER (GWe)	**1**
5	5	5	5	5	Fuel Flow Control Switch (integer, see legend)	**1**
0.34	0.34	0.34	0.34	0.34	THERMAL EFFICIENCY (GWe/GWth)	**1**
103	103	103	103	103	LEGACY REACTORS (number)	**1**
0	0	0	0	0	FRESH REACTORS (number)	**1**
0	0	0	0	0	REACTORS NEAR RETIREMENT (number)	**1**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION (number)	**1**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION NEED FUEL (number)	**1**
0	0	0	0	0	REACTORS BEING LICENSED LICENSED (number)	**1**
1	1	1	1	1	FINAL GWE FOR % GROWTH (GWe-year)	**1**
LWRmf	LWRmf	LWRmf	LWRmf	LWRmf	Your names from Run Information	
2	2	2	2	2	LICENSING TIME (year)	**2**
4	4	4	4	4	CONSTRUCTION TIME (year)	**2**
60	60	60	60	60	LIFETIME (year)	**2**
1	1	1	1	1	REACTOR POWER	**2**
5	5	5	5	5	Fuel Flow Control Switch (integer, see legend)	**2**
0.34	0.34	0.34	0.34	0.34	THERMAL EFFICIENCY (GWe/GWth)	**2**
0	0	0	0	0	LEGACY REACTORS (number)	**2**
0	0	0	0	0	FRESH REACTORS (number)	**2**
0	0	0	0	0	REACTORS NEAR RETIREMENT (number)	**2**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION (number)	**2**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION NEED FUEL (number)	**2**
0	0	0	0	0	REACTORS BEING LICENSED LICENSED (number)	**2**
1	1	1	1	1	FINAL GWE FOR % GROWTH (GWe-year)	**2**
FR	FR	FR	FR	FR	Your names from Run Information	
2	2	2	2	2	LICENSING TIME (year)	**3**
4	4	4	4	4	CONSTRUCTION TIME (year)	**3**
60	60	60	60	60	LIFETIME (year)	**3**
0.38	0.38	0.38	0.38	0.38	REACTOR POWER (GWe)	**3**
4	4	4	4	4	Fuel Flow Control Switch (integer, see legend)	**3**
0.38	0.38	0.38	0.38	0.38	THERMAL EFFICIENCY (GWe/GWth)	**3**
0	0	0	0	0	LEGACY REACTORS (number)	**3**
0	0	0	0	0	FRESH REACTORS (number)	**3**
0	0	0	0	0	REACTORS NEAR RETIREMENT (number)	**3**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION (number)	**3**
0	0	0	0	0	REACTORS UNDER CONSTRUCTION NEED FUEL (number)	**3**
0	0	0	0	0	REACTORS BEING LICENSED LICENSED (number)	**3**
1	1	1	1	1	FINAL GWE FOR % GROWTH (GWe-year)	**3**

Figure C.3: Scenario reactor parameter



1L.2RP.BR1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR1.2	1L.M.3RP.BR1.2	2L.M.3RP.BR1.2	Parameter	Facility #
1	1	1	1	1	Base Case ENRICHMENT DURATION	**1**
4	4	4	4	4	Base Case WET FUEL STORAGE DURATION	**1**
1	1	1	1	1	Base Case DRY STORAGE DURATION	**1**
5	5	5	5	5	Base Case MRS DURATION	**1**
2	2	2	2	2	Base Case MRS CONSTRUCTION TIME	**1**
60	60	60	60	60	Base Case MRS LIFETIME	**1**
10	10	10	10	10	Base Case REPOSITORY CONSTRUCTION TIME	**1**
300	300	300	300	300	Base Case REPOSITORY LIFETIME	**1**
1L.2RP.BR1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR1.2	1L.M.3RP.BR1.2	2L.M.3RP.BR1.2		
1	1	1	1	1	Base Case ENRICHMENT DURATION	**2**
4	4	4	4	4	Base Case WET FUEL STORAGE DURATION	**2**
1	1	1	1	1	Base Case DRY STORAGE DURATION	**2**
5	5	5	5	5	Base Case MRS DURATION	**2**
2	2	2	2	2	Base Case MRS CONSTRUCTION TIME	**2**
60	60	60	60	60	Base Case MRS LIFETIME	**2**
10	10	10	10	10	Base Case REPOSITORY CONSTRUCTION TIME	**2**
300	300	300	300	300	Base Case REPOSITORY LIFETIME	**2**
1L.2RP.BR1.2	User Defined 2: (copy of) User Defined 1: (copy of) BC - Once Thru - LWR only	0L.2RP.BR1.2	1L.M.3RP.BR1.2	2L.M.3RP.BR1.2		
1	1	1	1	1	Base Case ENRICHMENT DURATION	**3**
1	1	1	1	1	Base Case WET FUEL STORAGE DURATION	**3**
1	1	1	1	1	Base Case DRY STORAGE DURATION	**3**
5	5	5	5	5	Base Case MRS DURATION	**3**
2	2	2	2	2	Base Case MRS CONSTRUCTION TIME	**3**
60	60	60	60	60	Base Case MRS LIFETIME	**3**
10	10	10	10	10	Base Case REPOSITORY CONSTRUCTION TIME	**3**
300	300	300	300	300	Base Case REPOSITORY LIFETIME	**3**

Figure C.4: Other facilities parameter use in scenario study.

REFERENCES

[1] EIA "Monthly Energy Review and Electric Power Annual" http://www.eia.doe.gov/emeu/mer/elect.html Accessed 04/2012

[2] DOE EIA "Nuclear Spent Fuel Data" http://www.eia.gov/cneaf/nuclear/spent_fuel/ussnftab3.html

[3] GAO "Nuclear Fuel Cycle Options" GAO 12-70; Report to Congress. http://www.gao.gov/assets/590/585783.pdf Accessed Jan. 2012.

[4] DOE "*Nuclear Energy Research Development Roadmap"* Report to Congress. http://www.ne.doe.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf Accessed June 2010.

[5] Juchau, A.C. et.al, "Modeling the Nuclear Fuel Cycle." Fuel Cycle and Management, NUCLEAR TECHNOLOGY Vol. 171 August 2010.

[6] Guerin, et al., *A Benchmark Study of Computer Codes for System Analysis of the Nuclear Fuel Cycle.* Nuclear Fuel Cycle and Technology Program. Massachusetts Institute of Technology. – MIT-NFC-TR-105 – April 2009

[7] Argonne National Laboratory. "DANESS v4.5 Users Manual."

[8] Jacobson, J.J., et.al, "VISION: Verifiable Fuel Cycle Simulation Model." Advances in Nuclear Fuel Management IV (ANFM 2009), April 2009.

[9] Andrianova, E. A., et .al. "Dynamic of Energy System of Atomic Energy (DESAE 2.2) Code User Manual."

[10] Tsibulskiy, V. et.al. "DESAE Integrated Computer Model for Performing Global Analysis in INPRO Assessment Studies," International Conference on Nuclear Engineering "ICONE 14" 17-20 July 2006, Miami, Florida, USA

[11] Salvatores, M. et. al. "Nuclear Fuel Cycle Synergies and Regional Scenarios for Europe." Nuclear Energy Agency, Organisation for Economic Co-operation Development. OECD 2009 NEA No. 6857

[12] Salvatores, M. et.al. “Results of the Regional Scenario Studies.” Sixth Framework Programme; Research and Training on Nuclear Energy Coordination Action. Contract No. FI6W-Contract Number 036418.

[13] International Atomic energy Agency. “Nuclear Fuel Cycle Simulation System (VISTA) User Manual.” IAEA-TECDOC – 1535. http://www-nfcis.iaea.org/NFCSS/documents/NFCSS-User%20Manual%20Rev%202.pdf

[14] NUWASTE Status and Initial Report. http://www.nwtrb.gov/reports/nuwaste.pdf

[15] Kazimi M. S., et al., *The Future of the Nuclear Fuel Cycle.* Massachusetts Institute of Technology. 2011

[16] Powersim Studio, http://www.powersim.com/

[17] Guerin, Laurent. *Impact of Alternative Nuclear Fuel Cycle Options on Infrastructure and Fuel Requirements, Actinide and Waste Inventories, and Economics.* Massachusetts Institute of Technology. 2007.

[18] User Guide for VISION 3.4. Verifiable Fuel Cycle Simulation Model Idaho national Laboratory. INL/EXT-09-16645 Rev 3, June 2011.

[19] Software Requirements, Design, Verification, and Validation for the Verifiable Fuel Cycle Simulation (VISION) Model. INL/EXT-12-24534. Rev 0, June 2012.

[20] Schweitzer T, *Improved Building Methodology and Analysis of Delay Scenarios of Advanced Nuclear Fuel Cycles with the* ***V****eri****fi****able Fuel Cycle* ***Si****mulati****on*** *Model (VISION).* Master Thesis. 2008.

[21] Shropshire, E. D. et.al, “Advanced Fuel Cycle Cost Basis. INL/EXT-07-12107.

[22] Shropshire, E. D. et.al, “Advanced Fuel Cycle Economics Tools, Algorithms, and Methodologies. INL/EXT-09-15483.

[23] Taylor, J. P. *An Analysis of International Nuclear Fuel Supply Options.* Ph.D Thesis 2010.

[24] Oliver, K. M. *GENIUSV2: Software Design and Mathematical Formulations for Multi-Region Discrete Nuclear Fuel Cycle Simulation and Analysis.* Master Thesis 2009.

[25] Shannon, K. Y. *Nuclear Fuel Cycle Modeling Approaches for Recycling and Transmutation of Spent Nuclear Fuel.* Master Thesis 2008.

[26] Benchmark Study on Nuclear Fuel Cycle Transition Scenarios Analysis Codes. http://www.oecd-nea.org/science/docs/2012/nsc-wpfc-doc2012-16.pdf Accessed 09/12

[27] Shropshire, E. D. et.al, "Advanced Fuel Cycle Economics Analysis of Light-Water Reactor and Fast Burner reactor Systems". INL/EXT-09-15254.

[28] Adeniyi, A, et. al, "Impact of Limited Reprocessing Capacity on Nuclear Material Utilization in Advanced Fuel Cycles" Proceedings of the 9th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids Zadar, Croatia, 3-6 June 2012.

[29] Dixon, B. et.al, "Dynamic Analysis of Fuel Cycle Transitioning". INL/CON-09-16301.

[30] Jacobson, J.J. et al. "Assessment of deployment scenarios of new fuel cycle technologies".

[31]Savage, C. "Fuel Cycle Research and Development: Moving to a Long-Term, Science-Based, Goal-Oriented Program". http://www.nrc.gov/public-involve/conference-symposia/ric/past/2010/slides/w8schwabppv.pdf Last Accessed March 2013.

[32] Georgia Public Service Commission for the 2012 winter rate. Accessed September 2012.

http://www.psc.state.ga.us/calc/electric/gpcalc.asp.

[33] G4-ECONS Version 2.0 User Manual. Generation IV International Forum Cost Estimating Methodology. March 2008.

[34] DOE "A Screening Method for Guiding R & D Decisions: Pilot Application to Nuclear Fuel Cycle Options" http://energy.gov/sites/prod/files/4.3_DOE_NE_Screening%20Brochure_web.pdf. Accessed 05/2012.