Determination of the Proper Operating Range for the CAFCA IIB Fuel Cycle Model

by

Jamie Warburton

Submitted to the
Department of Nuclear Science and Engineering in
Partial Fulfillment of the Requirements for the
Degree of

Bachelor of Science in Nuclear Science and Engineering
at the
Massachusetts Institute of Technology

June 2007

Signature of Author: ______________________
Department of Nuclear Science and Engineering
May 17, 2007

Certified by: ______________________
Mujid Kazimi
Professor of Nuclear Engineering
Thesis Supervisor

Accepted by: ______________________
David G. Cory
Professor of Nuclear Science and Engineering
Chairman, NSE Committee for Undergraduate Students

Determination of the Proper Operating Range for the
CAFCA IIB Fuel Cycle Model

by

Jamie Warburton

Submitted to the Department of Nuclear Science and Engineering on May 18, 2007
In Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Nuclear Science and Engineering

Abstract

The fuel cycle simulation tool, CAFCA II was previously modified to produce the most recent version, CAFCA IIB. The code tracks the mass distribution of transuranics in the fuel cycle in one model and also projects costs for various fuel cycle schemes. The mass distribution model also shows the schedule for deployment of recycling plants. All of these models are dependent on user inputs, some of which specify advanced technology type and capacity, plant lifetime and recycling facility capacity.

The behavior of CAFCA IIB resulting from the most recent modifications are investigated through extensive modeling of various nuclear fuel cycles. By re-modeling nuclear fuel cycle schemes in CAFCA IIB that were modeled in CAFCA II, the two results can be compared and conclusions can be drawn as to an discrepancies between the two. Specifically, the results representing TRU mass balance accumulation in the system, spent fuel separation plant construction and fertile free fuel spent fuel reprocessing plant construction are compared. Thus, these new runs will substantiate the accuracy of past work and expand the number of reactor options that have been evaluated by CAFCA IIB. Additionally, the new data help pinpoint the operating range for CAFCA IIB in which the code is accurate.

Overall, none of the results from the same conditions in CAFCA II and CAFCA IIB matched up perfectly. Therefore, in an effort to further evaluate the effectiveness of CAFCA IIB, the plant lifetime input is tested in order to determine system sensitivities to that factor. This is done by modeling of nuclear fuel cycles while varying that single input, and comparing the results to the base or control case. Results suggest that different combinations of the various parameters are ideal for each different strategy of reactor type.

Thesis Supervisor: Mujid Kazimi
Title: Professor of Nuclear Engineering

Acknowledgements

The author is grateful for comments received during this work from Pavel Hejzlar and Dr. Ed Pilat of MIT.

Table of Contents

List of Figures

List of Tables

Nomenclature

II & IIB	CAFCA II & CAFCA IIB
ABR	Actinide Burner Reactor
CAFCA	Code for Advanced Fuel Cycle Assessment
CONFU	Combined Non-Fertile and UO_2
FFF	Fertile Free Fuel
GFR	Gas-cooled Fast Reactor
GNEP	Global Nuclear Energy Partnership
HM	Heavy Metals (Uranium & Transuranics)
LWR	Light Water Reactor
PL	Plant Lifetime
MA	Minor Actinides
MT	Metric Ton (1,000 kg)
MTHM	Metric Ton of Heavy Metal
SF	Spent Fuel
SFRP	Spent Fuel Recycling Plants
TRU	Transuranics
U	Uranium

Chapter I. Introduction

I.A. The Nuclear Fuel Cycle

The current nuclear fuel cycle in the United States is a once-through cycle, meaning that fuel is used once and then sent to be stored without any reprocessing or recycling. The implications of this type of fuel cycle are that it causes the build up of transuranic elements that maintain high radiotoxicity for thousands of years. This accumulation makes it difficult to guarantee that the resulting dose remains below a specified limit for a long period of time. Also, the decay heat associated with the buildup of actinides creates a need for multiple repositories. These conditions generate the motivation to recycle and burn the TRU which helps manage nuclear waste, and also to conserve uranium resources. The current Global Nuclear Energy Partnership aims to recycle fuel while still safeguarding against proliferation, and reduce the world's dependence on fossil fuels by means of increasing nuclear energy generation.

There are many options for nuclear fuel recycling and reprocessing, however the current problem is how to determine which reprocessing option is optimal given the present nuclear fuel cycle, resources and energy demands. One method to determine which approach to recycling is appropriate is by using a fuel cycle simulation program, such as CAFCA IIB, to evaluate the impact of various options and compare the output results [1]. So far, studies have been done for one set of fuel cycle parameters, however variations need to be considered in order to develop a more comprehensive approach. Along with the many input parameters that CAFCA IIB requires, it is also important to be aware of the current and projected world energy needs, the current and projected operating reactors, and the current and projected burnups to be used for nuclear fuel. With all of these issues in mind, the consequences of nuclear fuel technologies can be assessed using the CAFCA IIB code, thus providing useful insight into the impact of various nuclear system choices on the future of nuclear energy.

I.B. The CAFCA Nuclear Fuel Cycle Model

CAFCA IIB is a program that simulates nuclear fuel cycle systems and tracks nuclear fuel in the various components of a fuel cycle. There is an economic element to the program, which estimates the cost of various fuel cycle strategies and technology choices. In response to the increasing global need for nuclear energy, the simulations in CAFCA IIB are engineered to model the deployment of advanced nuclear technologies, namely advanced reactors and reprocessing options.

CAFCA IIB is written in Matlab, and it simulates the fuel cycle by tracking the mass flow of U and TRU, determining the infrastructure requirements for reactors and recycling facilities, and also tracking the cost of those operations. The front-end of the fuel cycle does not put any constraints on the introduction or development of advanced technologies in CAFCA IIB, so there is no model for the front-end fuel plants. Also, masses undergoing the cooling process are blended together depending on the number of years since discharge and the type of fuel. The code tracks the lifetime of reactors, and therefore also incorporates the decommissioning of reactors into the model generated.

CAFCA IIB is a model for the transition from a once-through to an advanced closed nuclear fuel cycle. The program tracks U and TRU and simulates the deployment of advanced technologies in the context of increasing nuclear energy demand. Advanced technologies include advanced reactors that are capable of burning TRU and recycling plants that are capable of converting SF into fresh fuel. The code provides an output specifying TRU inventory, recycling facility and advanced reactor demand, as well as fuel cycle cost. The outputs in this report have been organized as to present similar cases together other as to facilitate comparison. The power demand model utilized in CAFCA IIB is exponential and assumes an annual growth rate of 2.4%. The first constraint that governs the model is that SF inventory must be reduced as fast as possible, and this factor contributes to the deployment of advanced technologies. Next, advanced technologies must operate at or above a specified minimum capacity factor throughout the lifetime of the technology. So, adding recycling plants is only allowed if those plants can be operated at the minimum capacity for the lifetime of forty years. Advanced reactors can only be built if the model projects that enough fuel will be present for the duration of the sixty-year lifetime of the reactors.

The inputs in CAFCA IIB include the simulation start, middle and end year, with the option of changing some parameters at the middle year. Other inputs include power demands for up to three different geographic regions, year of introduction of recycling technologies, and choice of recycling schemes for both the fast and thermal cases. The industrial capacity to build recycling facilities could be changed at the middle point (year). CAFCA IIB can also take into account the status of reactors currently operational, and incorporate their lifetimes into its calculations. The composition of fuel pins per batch is another input section in the code, along with the composition of batches and the reactor parameters such as number of batches in a core, reactor lifetime, power, cycle length and capacity. The recycling parameters considered include capacity for spent fuel separation, lifetime of recycling plant, loss coefficient of plant and recycling facilities for advanced fuel pins. The priority for spent fuel recycling can also be selected, along with enrichment percentages and losses associated with fabrication.

The cost model in CAFCA IIB calculates the average total production cost of electricity as determined by the capital, operation and maintenance and fuel cycle costs. The model assumes the operation and maintenance costs are fixed, while capital costs depend on the construction time, reactor lifetime and overnight cost of construction. The fuel cycle costs are determined by the cost for each step in the fuel cycle and the cost adjustment necessary to account for carrying charges and time elapsed. The model also predicts recycling prices as a function of a plants' nominal capacity, the result reflecting the effects of economies of scale in recycling plant production.

The final parameters that can be modified in CAFCA IIB are those pertaining to the economic outlook of the time period. These variables include tax rate, electricity fees, uranium mining and both public and private debt. One caveat to this system that must be considered when inputting these parameters is that the time step used is 1.5 years, as opposed to a 1-year time step that may be assumed if not explicitly stated.

All of the input parameters described can be used to either use the fuel cycle simulation module or the economic simulation module as relating to the fuel cycle. Essentially, for the fuel cycle simulation, CAFCA IIB allows the user to input parameters in order to achieve output results that are used to assess the impact of the corresponding choices in the overall fuel cycle strategy.

I.C. Methods

CAFCA IIB will be used to examine the effect of various future technology choices on the accumulation of actinides in the fuel cycle. Only the fuel cycle model will be used for this analysis, not the cost model. Initially, CAFCA IIB will be used with a new iteration scheme to look at the effect of adding recycling in the fuel cycle on the actinide build up. Then, those results will be compared with the results obtained with the old iteration scheme in CAFCA IIB. Runs in the old iteration scheme in CAFCA II have already been completed by A. Aquien [1]. That report dealt entirely in CAFCA II and never in CAFCA IIB (it had not been created yet). In addition to re-running the same cases that were completed in the old scheme, new cases will be generated based on interesting parameters such as recycling plant lifetime seen in Table 1 below.

Table 1: Recycling plant lifetime variations

Recycling Plant Lifetime
30 yr
40 yr
50 yr

The status of reactors currently in operation will not be taken into account in this study, nor will any modifications be made for the composition of fuel pins or composition of batches. The reactor parameters will also be kept constant throughout all runs. The recycling parameters for capacity of spent fuel separation and plant lifetime will be altered to include the variations in Table 1 above and Table 2 below.

Table 2: Recycling facility capacity options

Recycling Facility Capacity (MTHM/yr)		
Small	Separation Capacity	1000
	FFF Reprocessing	50
Medium	Separation Capacity	2000
	FFF Reprocessing	100
Large	Separation Capacity	7000
	FFF Reprocessing	200

The outputs from the three recycling facility capacity options are presented on the same page in the appendices – the small case is first (labeled i), the medium case is next (labeled ii) and the large case is last (labeled iii). Additionally, the recycling technologies have the industrial building of separation capacities seen in Table 3 below.

Table 3: Advanced technologies settings of industrial capacities

Advanced Technologies (MTHM/yr)		
Low	Separation Capacity	125
	FFF Reprocessing	10
High	Separation Capacity	500
	FFF Reprocessing	50

The priority for SF recycling, enrichment percentages and losses associated with fabrication will be left at their default values. The three strategies that CAFCA IIB uses, LWR/CONFU, LWR/ABR and LWR/GFR, have the corresponding core specifications seen in Tables 4, 5 and 6 below. The specifications for this section were taken from the Aquien report [1], however for further reference more detailed CONFU, ABR and GFR resources are provided in Schwageraus et al. [3], Romano et al. [4] and from the CEA Cadarache et al. [5], respectively.

Table 4: LWR core specifications

LWR Core Specifications	
Power	3,000 MWth
Power Density	104.5 kWth/l
Net Electric Output	1,000 MWe
Fuel	UO_2
Enrichment	4.2% U^{235}
Burnup	50 MWd/kg
Number of Batches	3
Refueling Interval	1.5 years

Table 5: ABR core specifications

ABR Core Specifications	
Power	700 MWth
Power Density	76.5 kWth/l
Net Electric Output	315 MWe
Fuel	Metallic Zr-TRU
Number of Batches	2
Refueling Interval	1.2 years

Table 6: GFR core specifications

GFR Core Specifications	
Power	2,400 MWth
Power Density	100 kWth/l
Net Electric Output	1,128 MWe
Fuel	U-TRU carbide
Number of Batches	3
Refueling Interval	2.5 years

All case studies in this report are based on the one-region setting in CAFCA IIB and do not allow for any interaction or exchange of spent fuel with other countries.

Chapter II. CAFCA II Results and Conclusions

Appendices A-D include the results for the TRU balance and SF reprocessing schemes produced from CAFCA II. The CAFCA IIB results are juxtaposed next to the corresponding CAFCA II results for comparison, discussed in Chapter IV. Based on the CAFCA II results it was determined that the capacity for building recycling facilities is more limiting than that for fast reactors with respect to TRU inventory reduction. Additionally, the reduction of TRU inventory in interim storage by 2100 by ABR and CONFU is comparable when the construction rate of advanced technologies is large enough. Finally, TRU recycling in CONFU/LWRs can avoid more TRUs in the system than either fertile-free ABR or GFR. However, if U resource utilization is a goal along with the TRU waste management, then GFRs with a conversion rate of 1.0 are the preferred choice [1].

Chapter III. Overview of Modification from CAFCA II to IIB

CAFCA II and CAFCA IIB are exactly the same except for the modifications to the user interface and changes in the feedback loop that makes sure the capacity factor of the recycling facilities is satisfied before building any additional facilities.

The most apparent modifications to CAFCA II are those pertaining to the user interface. CAFCA IIB has a graphical user interface that is more user-friendly than that of CAFCA II. Warnings regarding limitations of the model and input constraints were added in order to ensure that the user was aware of the acceptable inputs. In this same vein, the inputs for the model can be seen in CAFCA IIB at any point during code operation by selecting the "see current initial conditions" option. This allows the user to check current parameters before, during and after the code-running process so no data is misrepresented due to user error. In an effort to increase the ease of usage of the code, CAFCA II was modified so that more than one screen can be open at a time [2]. A significant improvement in the code is that CAFCA IIB allows the user to save input data, load saved files and save simulation results. This is key for the comparison and analysis of large numbers of simulations.

The inputs to CAFCA IIB are grouped into screens by likeness and the output figures are grouped by region, allowing the user to input similar parameters at the same time and view cohesive results together. The user help file has been modified to be more clear, concise and easy to understand.

The default settings for CAFCA IIB are an LWR/ABR scheme with the ABR introduced in 2040, separation plant capacity of1000 MT/yr, reprocessing plant capacity of 50 MT/yr, and minimum loading factor of 0.60. CAFCA IIB can be used as a stand-alone in the form of CAFCA.EXE on any Windows computer or other machine that has the same operating system as the machine on which the application was compiled. However, the menu for figures does not work in this setting [2].

While no specifics regarding the changes in the fuel cycle model were given, the iteration loop that predicts whether recycling facilities can be built based on TRU accumulation was changed from CAFCA II to CAFCA IIB. The feedback to satisfy the capacity factor of the recycling facilities was also changed. Based on the results comparing the outputs from the two codes discussed in Chapter IV, modifications to this loop have to be made as the results disagree in several cases. It should be noted that the output figure titles changed from "TRU mass balance [MT]," "Spent fuel separation plants" and "FFFsf reprocessing plants" in CAFCA II to "TRU mass balance [MT] – Region 1," "Recycling plants –UO2sf – Region 1" and "Recycling plants – Adv SF- Region 1," respectively, in CAFCA IIB. Chapter V and VI discuss the various parameters of the disagreeing cases and try to pinpoint the appropriate operating range of the code based on this knowledge.

Chapter IV. Comparison of CAFCA II and CAFCA IIB Results

CAFCA II and CAFCA IIB were used to model cases where the plant was either LWR/CONFU, LWR/ABR or LWR/GFR. In each of these cases, the recycling facility capacity was set to small, medium or large (specifications in Table 2), and the advanced technology industrial building capacity was chosen to be either low or high (specifications in Table 3). All possible combinations of these variables were chosen as inputs to CAFCA IIB, and finally all of those permutations were computed for recycling plant lifetimes of 30, 40 or 50 years.

TRU mass balance, spent fuel separation plants and FFF SF reprocessing plants are all output for a single run in CAFCA IIB. Appendices A-D show the results from CAFCA II and CAFCA IIB side-by-side as to evaluate the differences between the two codes when the same inputs are used. The first detail that must be noted is that there are scaling differences between the plots generated from CAFCA II and CAFCA IIB, so while some plots do not look equal, upon investigation of the axes they might be. Overall, none of the results from CAFCA II and CAFCA IIB matched up perfectly. For the LWR/CONFU strategy, the high advanced technology setting was most effective at generating similar results in CAFCA IIB as in CAFCA II. The TRU mass balances are the same and the SFRP plots are almost exactly alike with the exception of the large recycling facility case. The same is true of the LWR/ABR scheme, however the TRU mass balances resulting from this setting do not correspond. In the LWR/GFR scheme, the low and high advanced technologies options were equally successful at replicating CAFCA II results, with none of the TRU mass balance plots matching up nor the large recycling facility capacity SFRP results.

One effect that was not studied was the extrapolation of model behavior as a function of TRU buildup. If the model dependence on TRU accumulation could be discerned from the plots of the TRU mass balance and recycling plant production, then the model could be more effectively studied. Thus, with the model dependence on TRU buildup known, the results of CAFCA II and CAFCA IIB could be compared as far as the dependence on TRU buildup rather than pure plotted results. If the TRU buildup is different in CAFCA II than it is in CAFCA IIB for the same initial conditions, than clearly the SFRP construction is also going to differ between the two codes. But, if the TRU-plant relationship could be determined and compared for each strategy, perhaps the two codes would not seem to perform so differently. It is this TRU-SFRP construction relationship that is most important, as it will govern whatever initial conditions input into either code.

For the low advanced technologies case in the LWR/CONFU strategy, both CAFCA II and CAFCA IIB responded as expected in terms of building SFRP while TRU is present and accumulating (comparison of Figures 1, 2, 7 & 8). For the low advanced technologies case in the LWR/ABR strategy, the TRU mass balances hardly agree and as a result the SFRP results are very different. However, in CAFCA IIB it appears as though TRU is piling up and no plants are being built to deal with it until very late in the time period (Figures 3, 4, 9 & 10). In the LWR/GFR strategy, the TRU mass balances between the two codes do not agree, however the SFRP constructions do agree for the small and medium recycling facility capacities. Additionally, in the large recycling facility capacity case the SFRP plots are very similar, so perhaps some discrepancies could be attributed to changes in scale and axes (Figures 5, 6, 11 & 12).

In the high advanced technologies case in the LWR/CONFU strategy, the TRU mass balances between CAFCA II and CAFCA IIB do not agree, but the SFRP projections do agree for the small and medium recycling facility options (Figures 13, 14, 19 & 20). In the LWR/ABR case, the TRU projections are closer than they were for the LWR/CONFU strategy, however they still don not agree. This result is very interesting because the SFRP figures agree completely in all cases of recycling facility capacities (Figures 15, 16, 21 & 22). For the LWR/GFR strategy, the TRU projections have the same trend, but again do not agree completely. The SFRP figures agree in the small and medium recycling facility capacity models but not in that for the large recycling facility capacity (Figures 17, 18, 23 & 24).

Chapter V. Determination of Sensible Operating Range for CAFCA IIB

V.A. Summary from Comparison of CAFCA II and CAFCA IIB Results

No results from CAFCA II could be replicated exactly in CAFCA IIB with the same initial settings. The differences between the two outputs are mainly due to code changes specifically on the feedback from checking on the expected capacity factor of the recycling facility and advanced reactor assembly. The high advanced technology option performed the best in the CAFCA II and CAFCA IIB comparison. This suggests that the loop affecting the generation of spent fuel recycling facilities was changed in the modification of the codes and therefore while TRU accumulation may stay the same, the model behaves differently in response to it.

V.B. Inspection of CAFCA IIB Results with Recycling PL of 30 Years

Appendices E-H contain the results from the simulations run in CAFCA IIB with a plant lifetime of 30 years, as opposed to the 40 year lifetime used in Appendices A-D. Interestingly enough, the optimal conditions for the 30 year PL that result in plots similar to those in CAFCA II and CAFCA IIB are the same conditions discussed that resulted in the best plots from CAFCA II and CAFCA IIB. This means that the high advanced technologies setting in the LWR/CONFU and LWR/ABR strategies and the low advanced technologies setting in the LWR/GFR strategy are optimal.

The figures for comparison of the TRU for the low CONFU strategy are figure 25 (30 year, CAFCA IIB), figure 2 (40 year, CAFCA IIB) and figure 1 (40 year, CAFCA II). None of these TRU plots are in agreement as far as mass balance trends (the overall mass balance should be different since the recycling plant lifetimes are different). The corresponding SRFP figures are figure 28, figure 8 and figure 7. A trend for the medium plant capacity seems to be present in each of these figures, however the other SRFP figures do not agree in trend or in value.

The figures for comparison of the TRU for the low ABR strategy are figure 26 (30 year, CAFCA IIB), figure 4 (40 year, CAFCA IIB) and figure 3 (40 year, CAFCA II). The trends present in figure 26 agree with those in figure 4 for all plant capacities, however neither agrees with figure 3. The corresponding SFRP figures are figure 29, figure 10 and figure 9. The trends in figure 10 agree with those in figure 29, however neither agrees with those in figure 9.

The figures for comparison of the TRU for the low GFR strategy are figure 27 (30 year, CAFCA IIB), figure 6 (40 year, CAFCA IIB) and figure 5 (40 year, CAFCA II). None of the trends present in any of these figures agree with each other. The corresponding SFRP figures are figure 30, figure 12 and figure 11. All of the trends in these figures agree with each other.

The figures for comparison of the TRU for the high CONFU strategy are figure 31 (30 year, CAFCA IIB), figure 14 (40 year, CAFCA IIB) and figure 13 (40 year, CAFCA II). The trends present in figure 13 agree with those in figure 14 and those in figure 31. The corresponding SRFP figures are figure 34, figure 20 and figure 19. The trends present in figure 19 agree with those present in figure 34 except for those in the small capacity case and the trends in figure 19 agree with those in figure 20 except for in the large capacity case.

The figures for comparison of the TRU for the high ABR strategy are figure 32 (30 year, CAFCA IIB), figure 16 (40 year, CAFCA IIB) and figure 15 (40 year, CAFCA II). The trends present in figure 32 agree with those in figure 15, and seem to agree with but are shifted in figure 15. The corresponding SFRP figures are figure 35, figure 22 and figure 21. All of the trends present in these figures agree with each other.

The figures for comparison of the TRU for the high GFR strategy are figure 33 (30 year, CAFCA IIB), figure 18 (40 year, CAFCA IIB) and figure 17 (40 year, CAFCA II). The trends for all of these figures agree, however in the small capacity case the maximum TRU mass balance is extremely different in figure 33 than it is for the other two figures. The corresponding SFRP figures are figure 36, figure 24 and figure 23. All of the trends in these figures agree except for those in the large capacity case which do not correspond in any of the plots.

V.C. Inspection of CAFCA IIB Results with Recycling PL of 50 Years

Appendices I-L contain the results from the simulation runs in CAFCA IIB with a plant lifetime of 50 years. The optimal conditions for the PL of 40 years are exactly the same as those for the 30 year PL. In these conditions, the TRU and SFRP agree completely with the 30 year PL and almost completely with the 40 year PL. However, even with these conditions, the TRU and SFRP for the LWR/ABR strategy are not accurate. The same is true for the LWR/GFR case where the TRU and SFRP do not correlate to each other well. With this information in mind, the best settings in the 50 year PL case that achieve the most accurate results are in the high advanced technologies setting in the LWR/CONFU and LWR/ABR strategies and the low advanced technologies setting in the LWR/GFR strategy.

The figures for comparison of the TRU for the low CONFU strategy are figure 37 (50 year, CAFCA IIB), figure 2 (40 year, CAFCA IIB) and figure 1 (40 year, CAFCA II). The trends in figure 37 agree with those in figure 2 except for in the medium capacity case and agree with those in figure 1 except for the large capacity case. The corresponding SRFP figures are figure 40, figure 8 and figure 7. The trends present in figure 40 agree with those in figure 7 and figure 8 except for in the large capacity case.

The figures for comparison of the TRU for the low ABR strategy are figure 38 (50 year, CAFCA IIB), figure 4 (40 year, CAFCA IIB) and figure 3 (40 year, CAFCA II). The trends present in figure 38 do not agree with those in figure 3, but do agree with those in figure 4. The corresponding SFRP figures are figure 41, figure 10 and figure 9. The trends in figure 41 only agree with those in figure 9 in the small capacity case, and agree with those in figure 10 except for in the medium capacity case.

The figures for comparison of the TRU for the low GFR strategy are figure 39 (50 year, CAFCA IIB), figure 6 (40 year, CAFCA IIB) and figure 5 (40 year, CAFCA II). The trends present in figure 39 agree with those in figure 5 only in the small capacity case, and agree with the trends in figure 6 in the medium capacity case. Figures 5 and 6 agree in the high capacity case. The corresponding SFRP figures are figure 42, figure 12 and figure 11. The trends present in figure 42 agree with those in figure 11 and figure 12.

The figures for comparison of the TRU for the high CONFU strategy are figure 43 (50 year, CAFCA IIB), figure 14 (40 year, CAFCA IIB) and figure 13 (40 year, CAFCA II). The trends in figure 43 agree with those in figure 13 and figure 14. The corresponding SRFP figures are figure 46, figure 20 and figure 19. All of the trends present in figure 46 agree with those in figure 19 and figure 20.

The figures for comparison of the TRU for the high ABR strategy are figure 44 (50 year, CAFCA IIB), figure 16 (40 year, CAFCA IIB) and figure 15 (40 year, CAFCA II). None of the trends present in any of these figures agree. The corresponding SFRP figures are figure 47, figure 22 and figure 21. The trends present in figure 47 agree with those in figure 21 and figure 22 except for in the medium capacity case.

The figures for comparison of the TRU for the high GFR strategy are figure 45 (50 year, CAFCA IIB), figure 18 (40 year, CAFCA IIB) and figure 17 (40 year, CAFCA II). The large capacity cases in all of these figures agree in trends, however the other two capacity cases do not. The corresponding SFRP figures are figure 48, figure 24 and figure 23. Figure 48 does not agree with figure 24 or figure 23 in the small capacity case, however it does agree with both in the medium and large capacity cases.

Chapter VI. Conclusion

CAFCA II, a fuel cycle simulation tool, was written in Matlab and has since been modified to the latest version CAFCA IIB. By tracking the mass distribution of TRU and U in the nuclear fuel cycle, the code projects the building of recycling facilities based on certain constraints that must always be followed. The main parameters for use in this study are

1. Fuel cycle option: CONFU (introduced in 2015), ABR or GFR fast recycling schemes (either introduced in 2040).
2. Recycling facility capacity: small (1,000 MTHM/yr separation plants and 50 MTHM/yr FFF reprocessing plants), medium (2,000 MTHM/yr separation plants and 100 MTHM/yr FFF reprocessing plants) and large (7,000 MTHM/yr separation plants and 200 MTHM/yr FFF reprocessing plants).
3. Advanced technology building capacity: low case (construction capacity of separation plants is 150 MTHM/yr and construction capacity of FFF reprocessing plants is 15 MTHM/yr, and these numbers double at 2040) and high case (construction capacity of separation plants is 500 MTHM/yr and construction capacity of FFF reprocessing plants is 50 MTHM/yr, and these numbers double at 2040).
4. Recycling plant lifetime: 30, 40 or 50 years.

By investigating all combinations of all of these parameters, the operating range of CAFCA IIB can be determined by seeking out the agreements between TRU mass balance and SFRP building. Additionally, by comparing the various plant lifetimes, the dependence on this particular variable can be determined and agreements across all PL can be assessed.

The low advanced technology setting with 50 year PL is appropriate for determining TRU mass balance in LWR/CONFU. The high advanced technology setting with 30, 40 and 50 year PL works for almost all TRU mass balance and SFRP calculations in LWR/CONFU. The high advanced technology in LWR/ABR is appropriate for the SFRP in the 40 yr PL, but not for the TRU mass balance calculations. Additionally, the SFRP works in the 30 yr PL and is roughly suitable for use in the 50 year PL. The TRU in both of these cases are not in agreement. In the LWR/GFR strategy, both the low and the high advanced technologies are fitting for SFRP in 30 year PL and 50 year PL, however this does not fit for the TRU in either case. The low and high advanced technologies have equal results with the 40 year PL with none of the TRU results corresponding and only approximately 2/3 of the SFRP results corresponding. Thus, the operating range for CAFCA IIB depends on the operating parameters in the simulation. There is no fine line at which the TRU mass balances in CAFCA IIB stop corresponding to the SFRP projections, instead this type of line exists in each setting in the code and under every strategy option.

References

[1]. A. Aquien, M.S. Kazimi and P. Hejzlar, Thesis: *Fuel Cycle Options for Optimized Recycling of Nuclear Fuel,* MIT-NFC-TR-086, Cambridge: MIT Nuclear Fuel Cycle Technology and Policy Program, June 2006.

[2]. Personal communication with Rodney Busquim, May 2007.

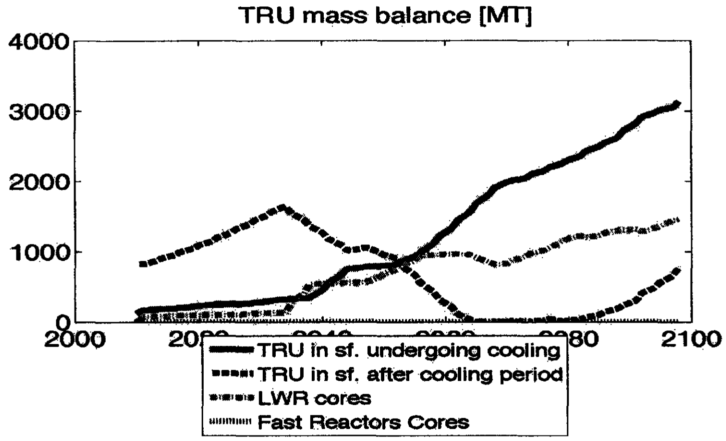
[3] E. Schwageraus, P. Hejzlar, and M.S. Kazimi, *Optimization of the LWR Nuclear Fuel Cycle for Minimum Waste Production*, MIT-NFC-TR-060, CANES, MIT, October 2003

[4] T.Boscher, P. Hejzlar, M.S. Kazimi, N.E. Todreas, and A.Romano, *Alternative Fuel Cycle Strategies For Nuclear Power Generation In the 21st Century*, MIT-NFC-TR-070-Rev. 1, CANES, MIT, June 2005.

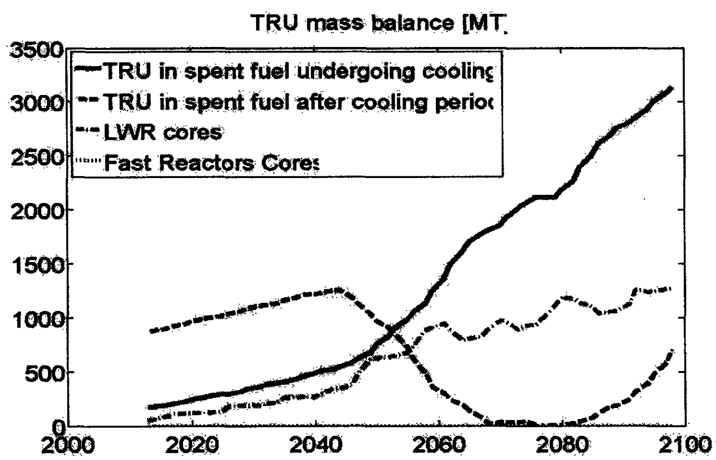
[5] CEA Cadarache, CEA Sacley, Argonne National lab, General Atomics, Brookhaven National Lab, MIT, *Development of Generation IV Advanced gas-Cooled Reactors with Hardened/Fast Neutron Spectrum*, System Design Report GFR023, February 2005.

This page intentionally left blank.

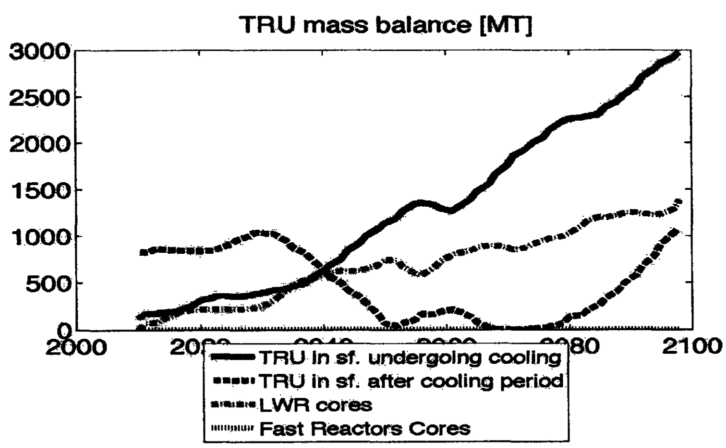
Appendix A: TRU mass balance – Low case with 40 yr. PL (II & IIB)



i)

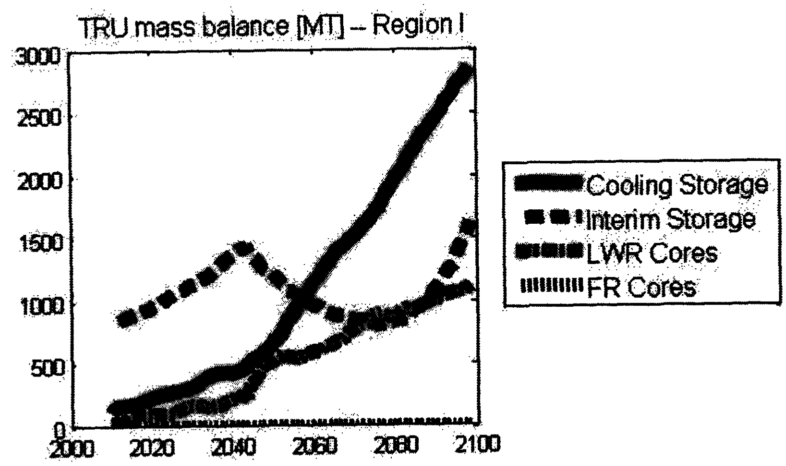


ii)

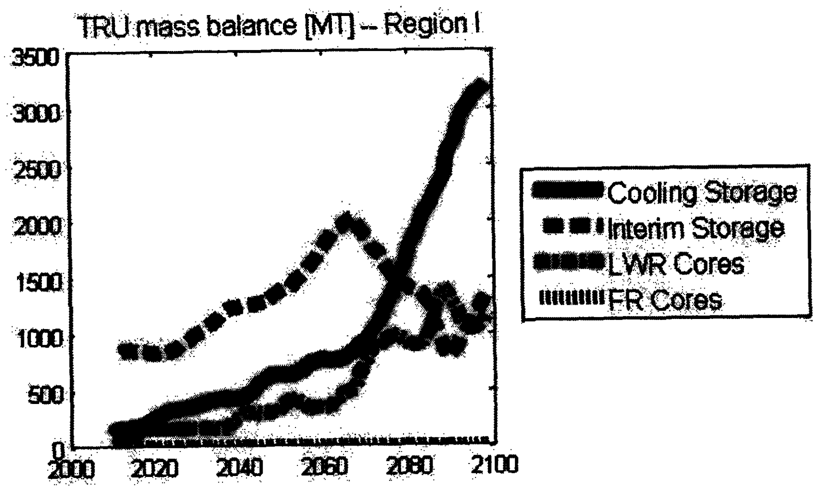


iii)

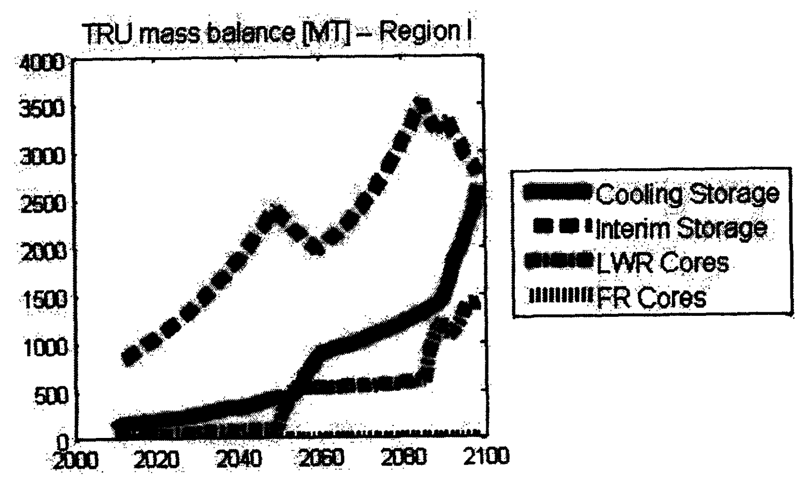
Figure 1: TRU for LWR/CONFU strategy in CAFCA II – Low case, 40 yr. PL



i)

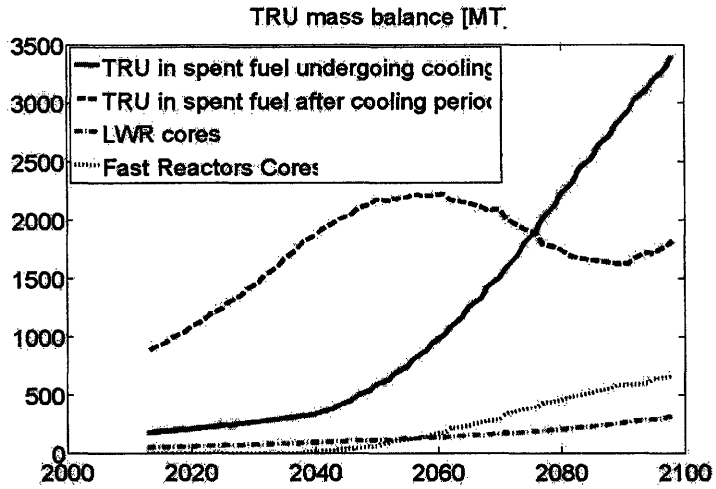


ii)

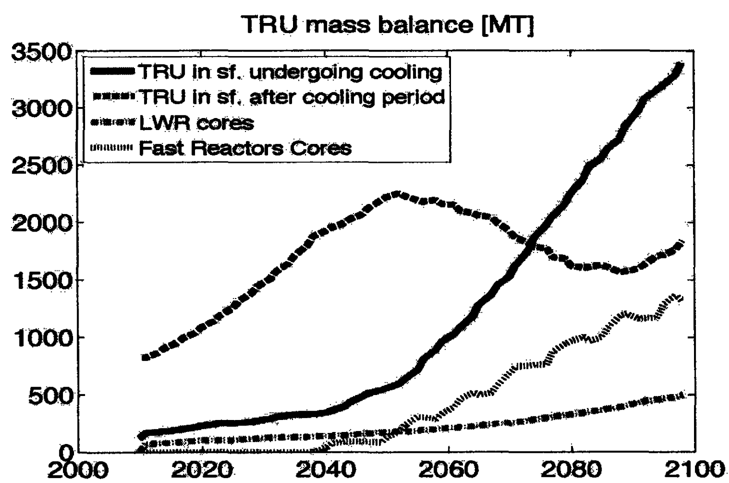


iii)

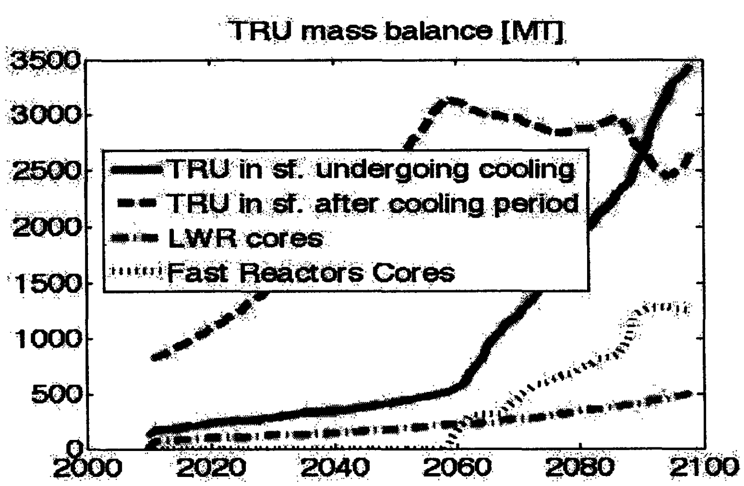
Figure 2: TRU for LWR/CONFU strategy in CAFCA IIB – Low case, 40 yr. PL



i)

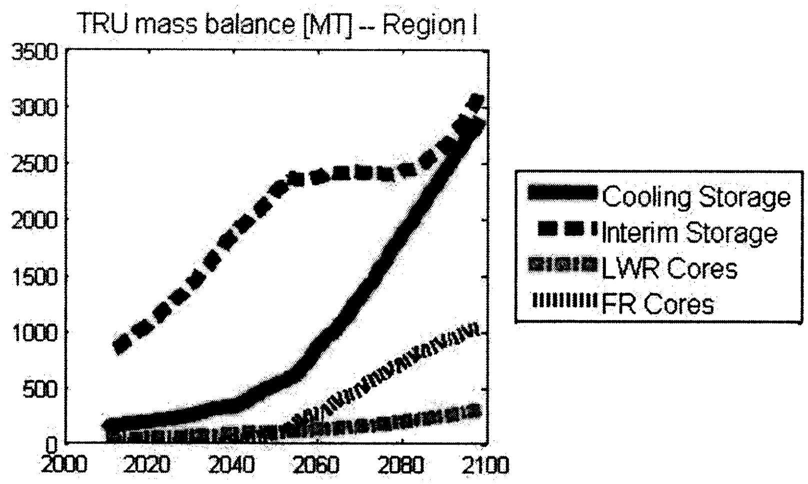


ii)

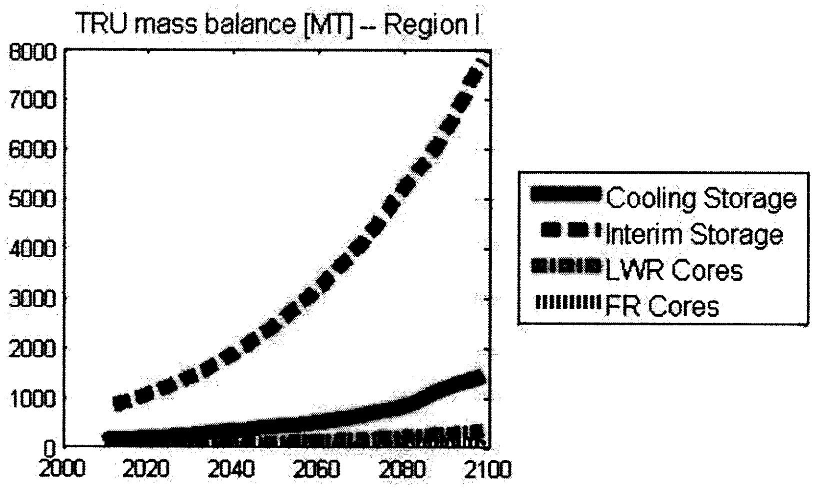


iii)

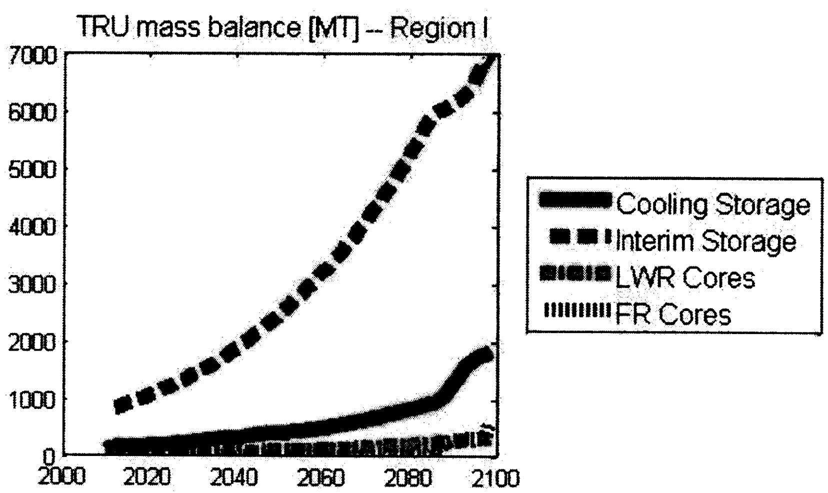
Figure 3: TRU for LWR/ABR strategy in CAFCA II – Low case, 40 yr. PL



i)

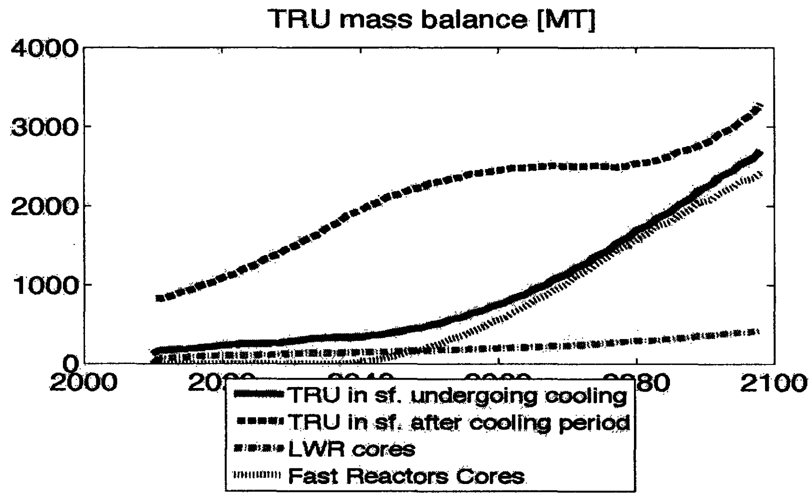


ii)

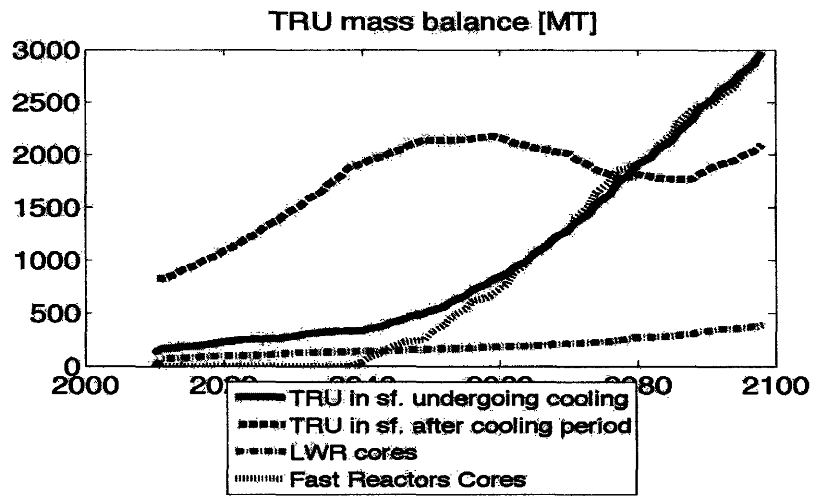


iii)

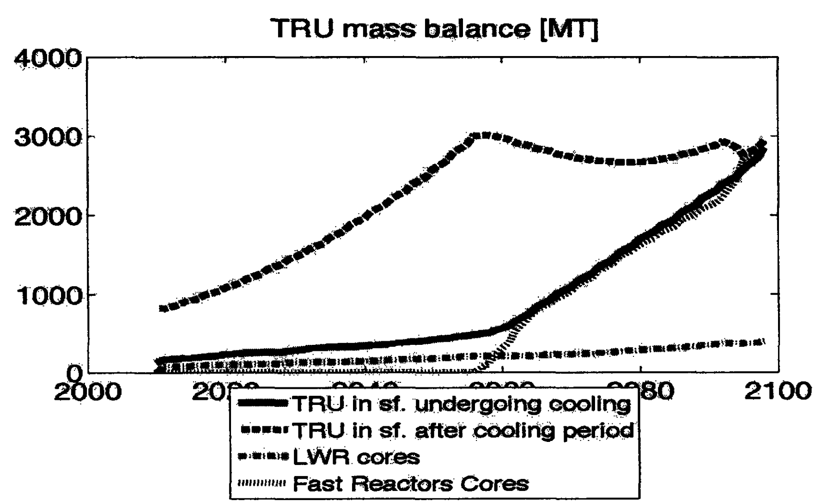
Figure 4: TRU for LWR/ABR strategy in CAFCA IIB – Low case, 40 yr. PL



i)

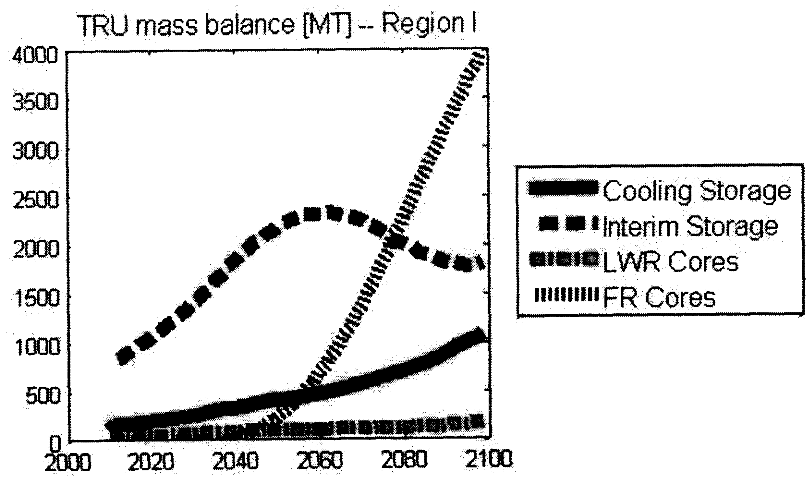


ii)

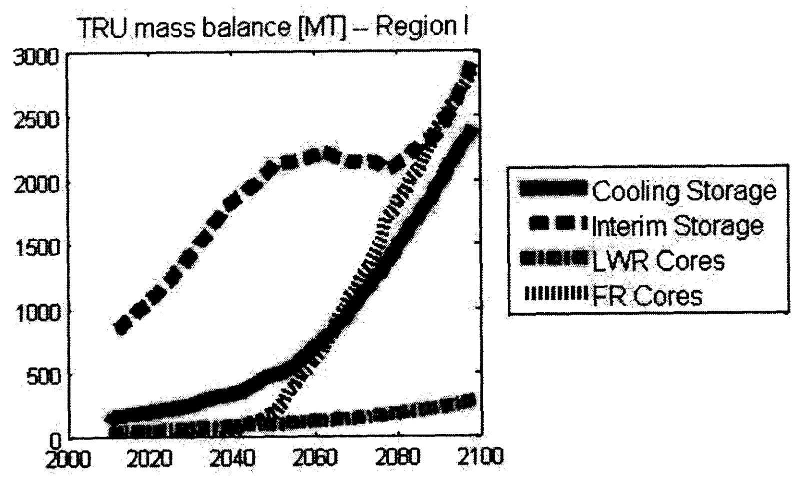


iii)

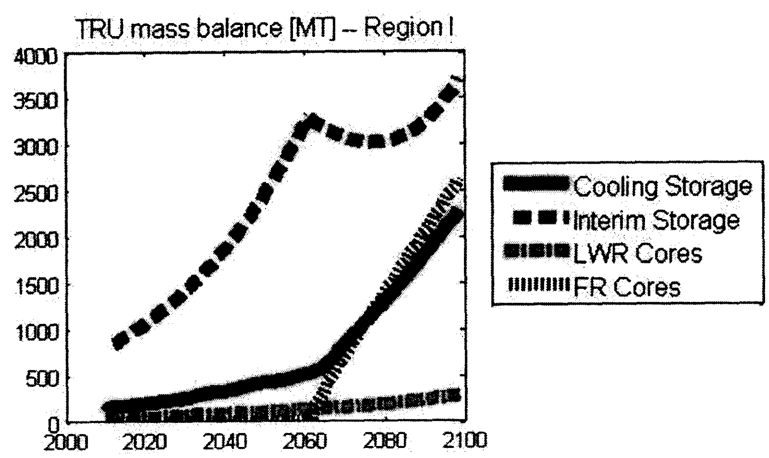
Figure 5: TRU for LWR/GFR strategy in CAFCA II – Low case, 40 yr. PL



i)



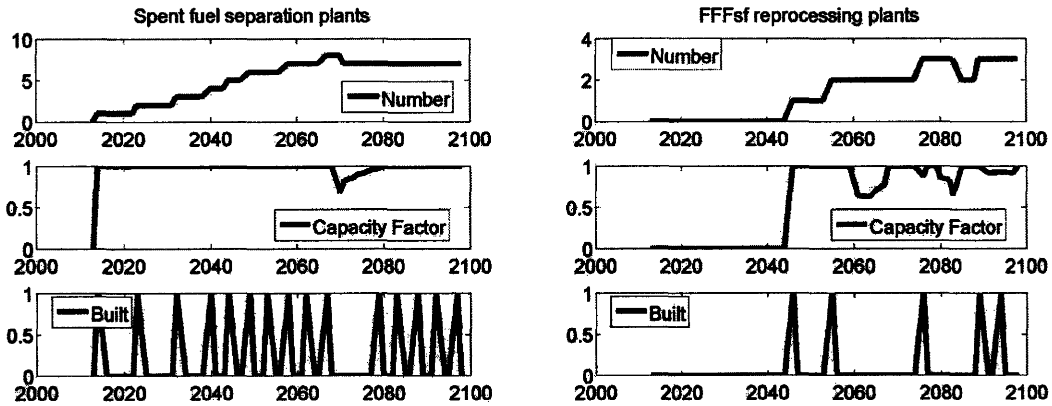
ii)



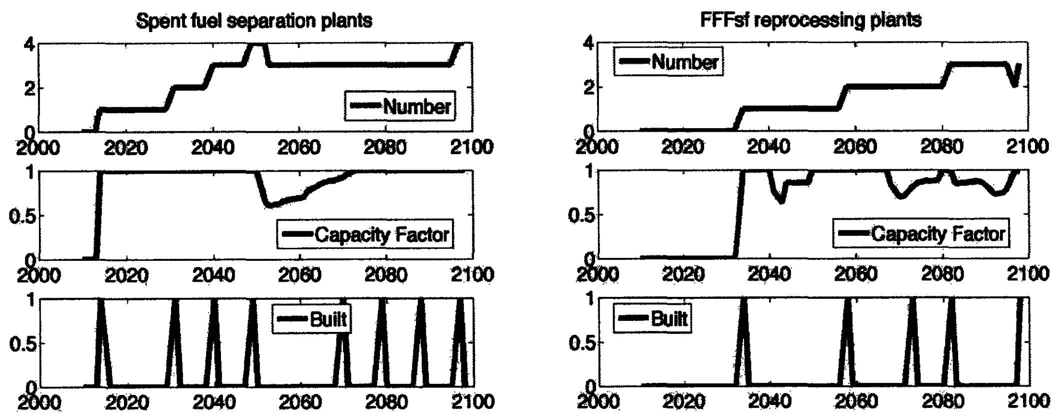
iii)

Figure 6: TRU for LWR/GFR strategy in CAFCA IIB – Low case, 40 yr. PL

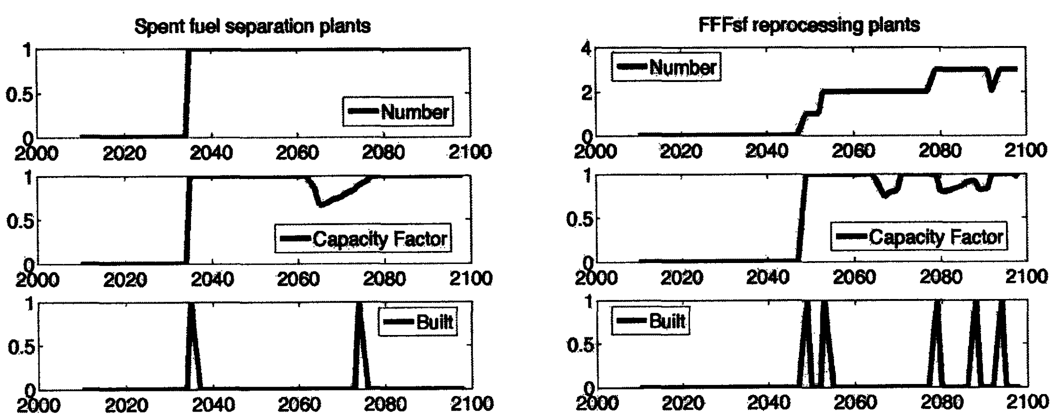
Appendix B: Spent fuel recycling plants – Low case with 40 yr. PL (II & IIB)



i)

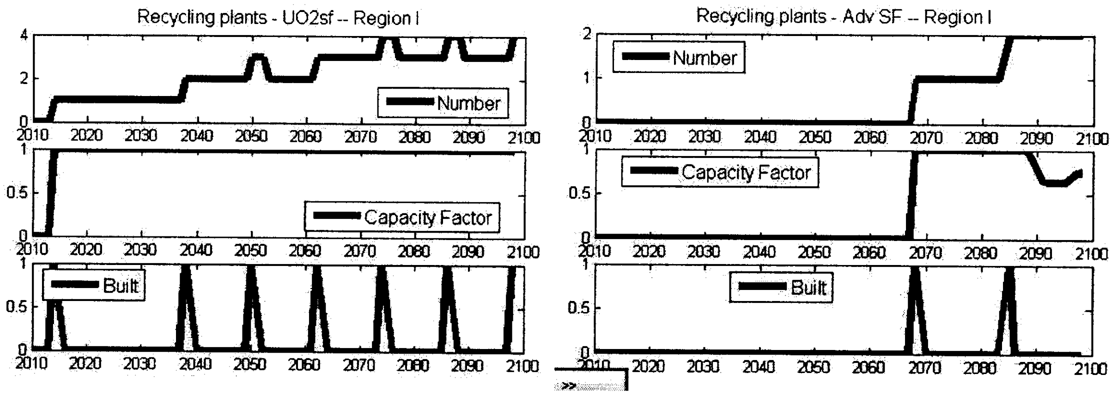


ii)

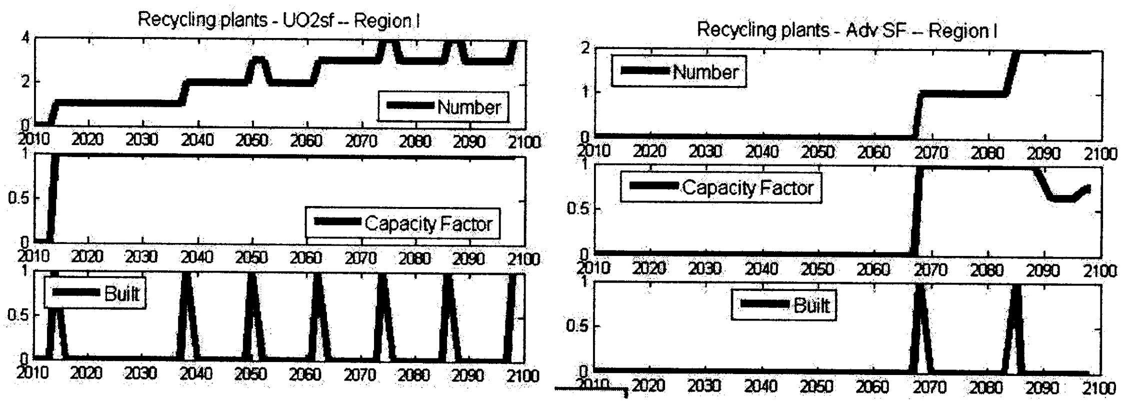


iii)

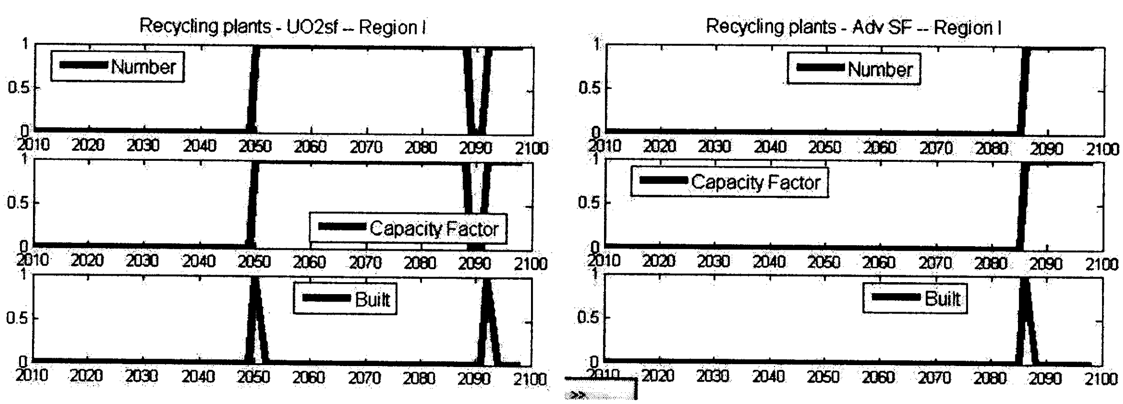
Figure 7: SFRP for LWR/CONFU strategy in CAFCA II – Low case, 40 yr. PL



i)

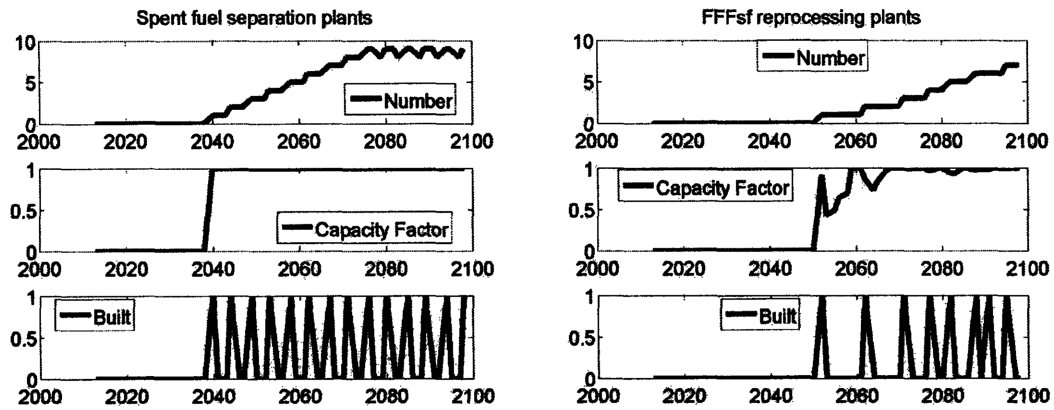


ii)

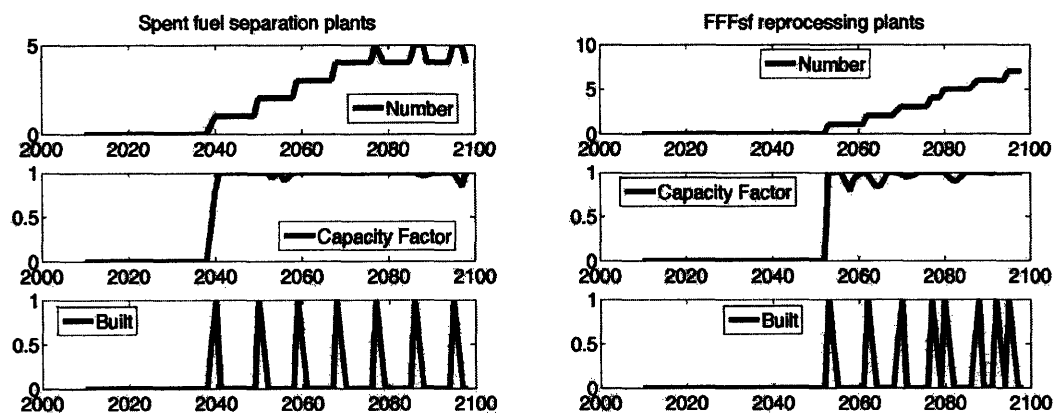


iii)

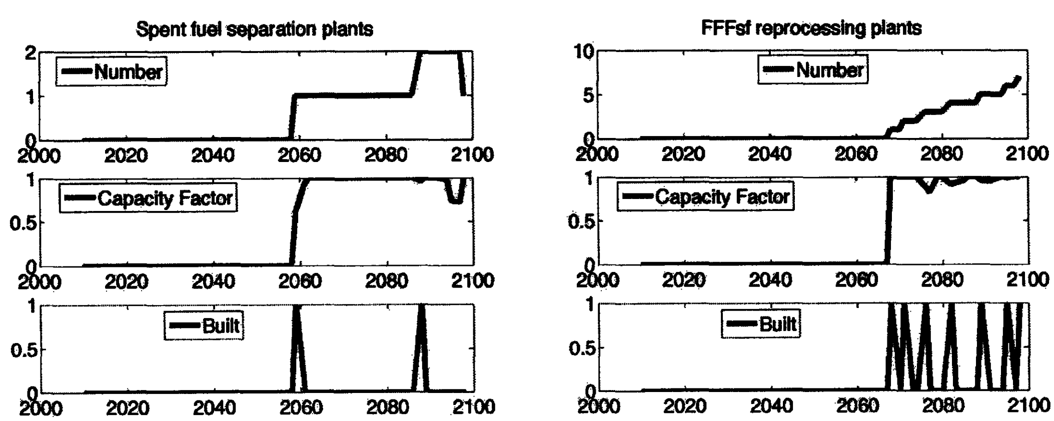
Figure 8: SFRP for LWR/CONFU strategy in CAFCA IIB – Low case, 40 yr. PL



i)



ii)



iii)

Figure 9: SFRP for LWR/ABR strategy in CAFCA II – Low case, 40 yr. PL

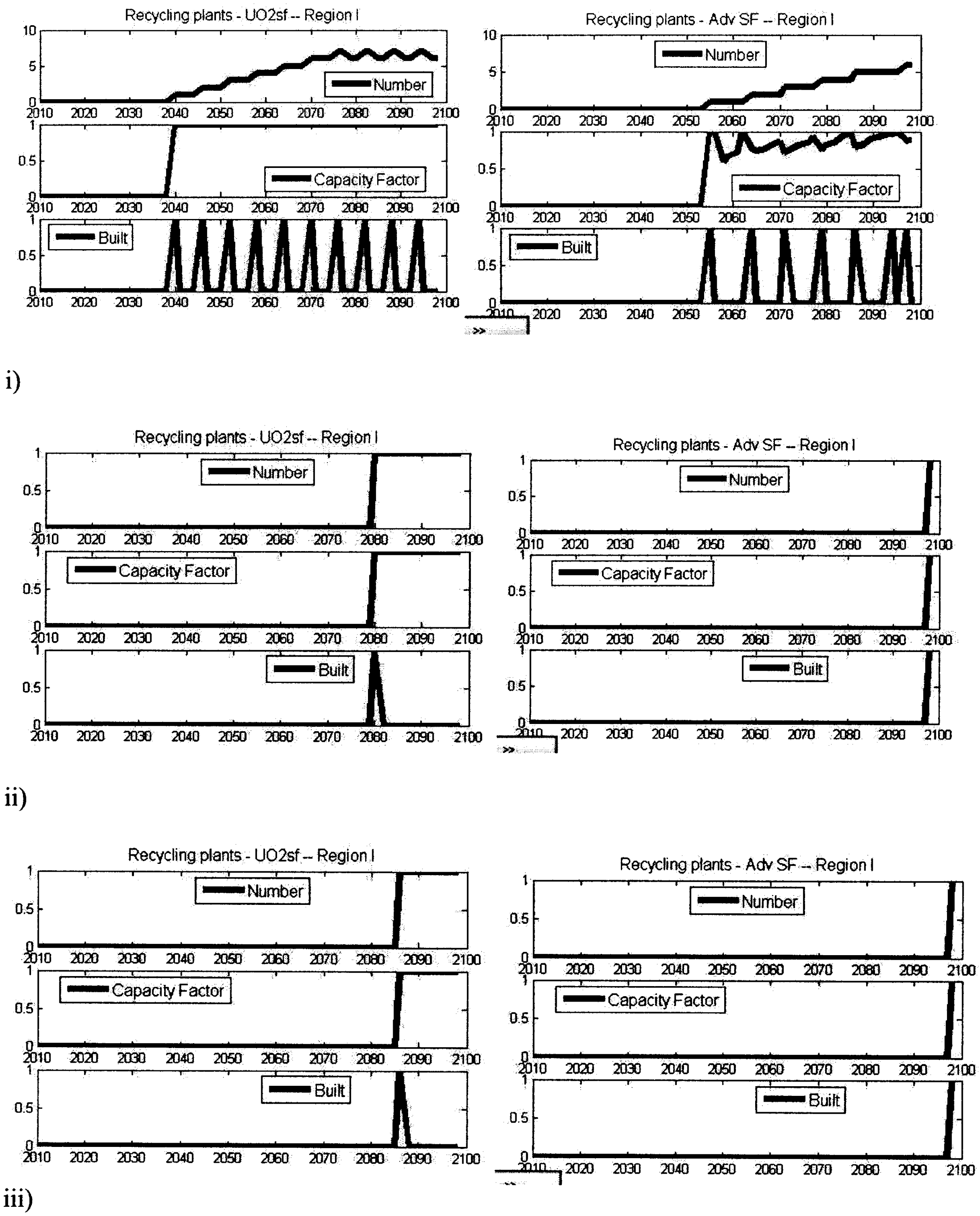
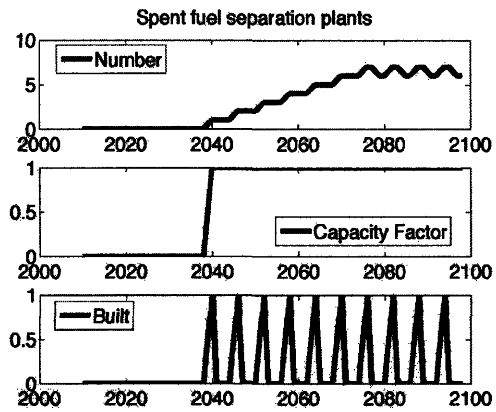
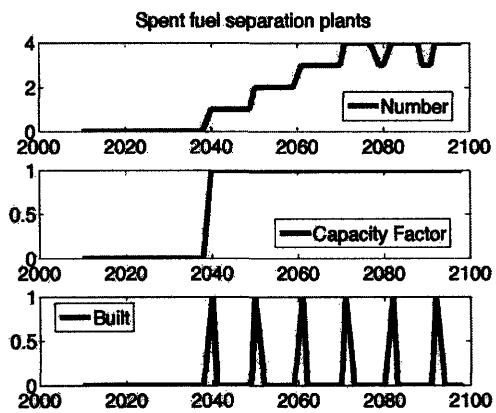


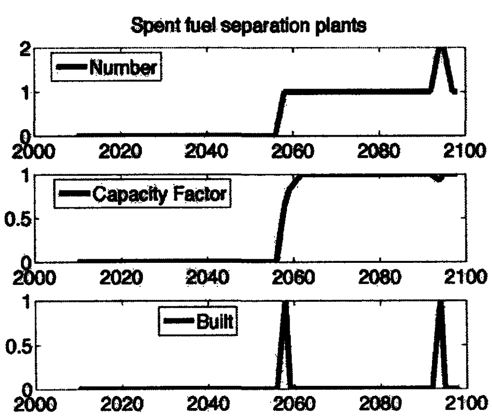
Figure 10: SFRP for LWR/ABR Strategy in CAFCA IIB – Low case, 40 yr. PL



i)

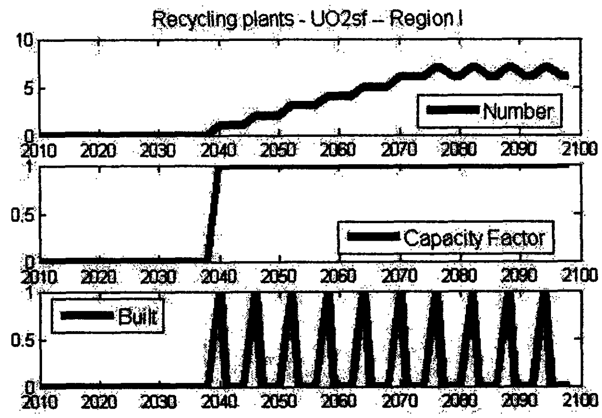


ii)

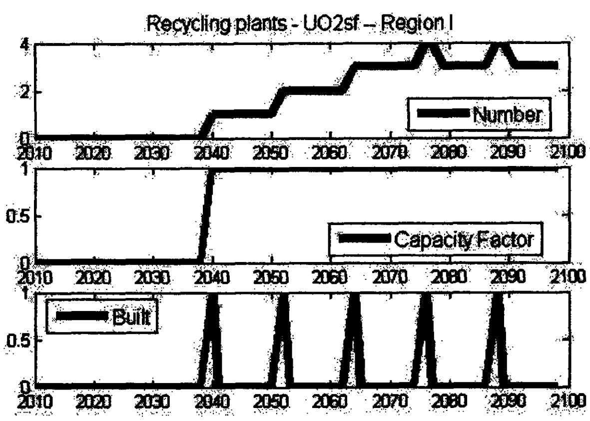


iii)

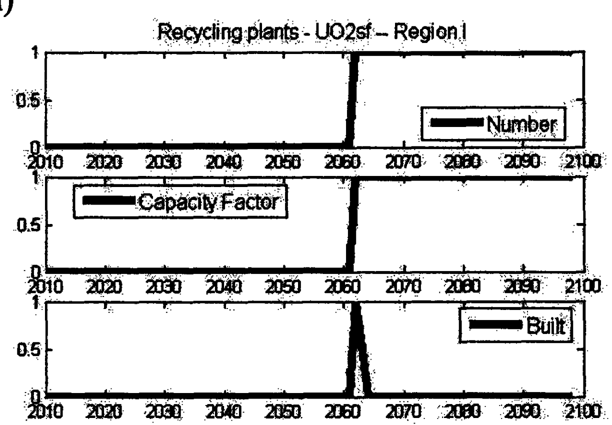
Figure 11: SFRP for LWR/GFR strategy in CAFCA II – Low case, 40 yr. PL



i)



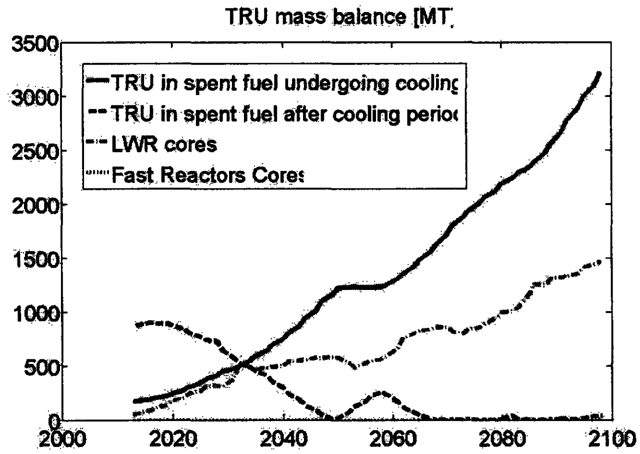
ii)



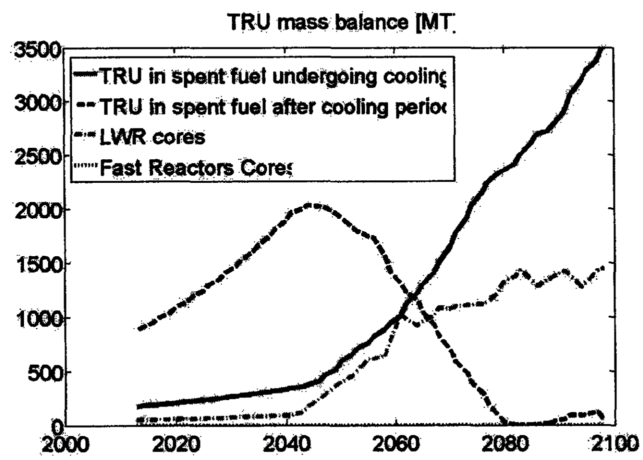
iii)

Figure 12: SFRP for LWR/GFR Strategy in CAFCA IIB – Low case, 40 yr. PL

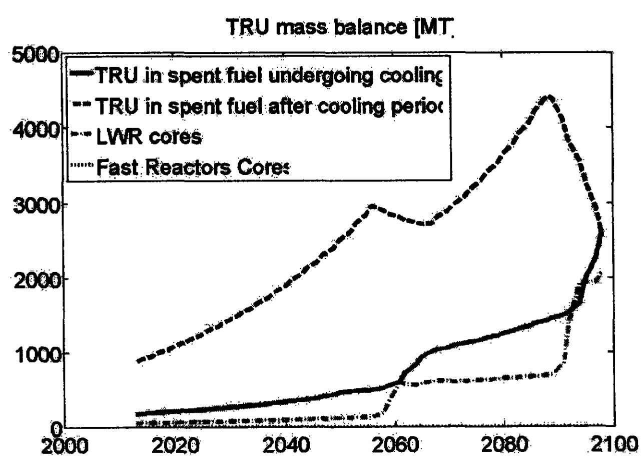
Appendix C: TRU mass balance – High case with 40 year PL (II & IIB)



i)

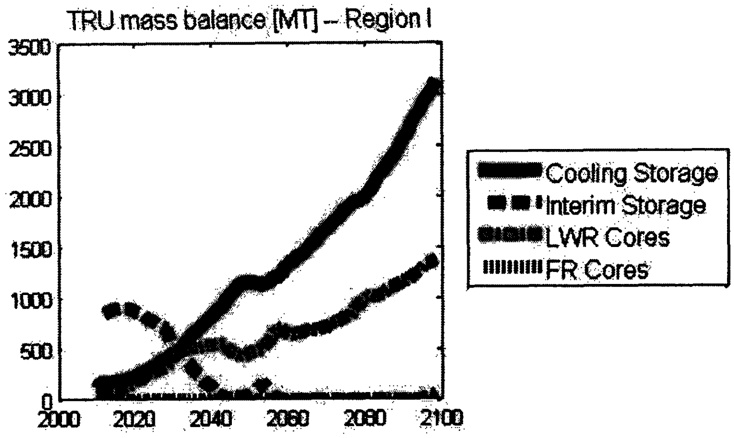


ii)

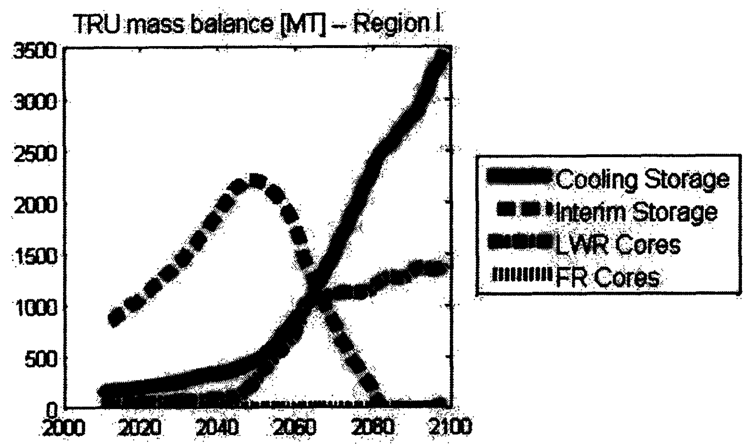


iii)

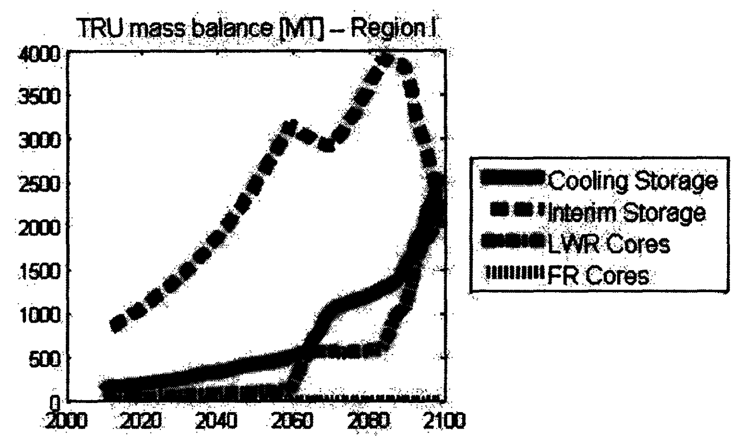
Figure 13: TRU for LWR/CONFU strategy in CAFCA II – High case, 40 yr. PL



i)

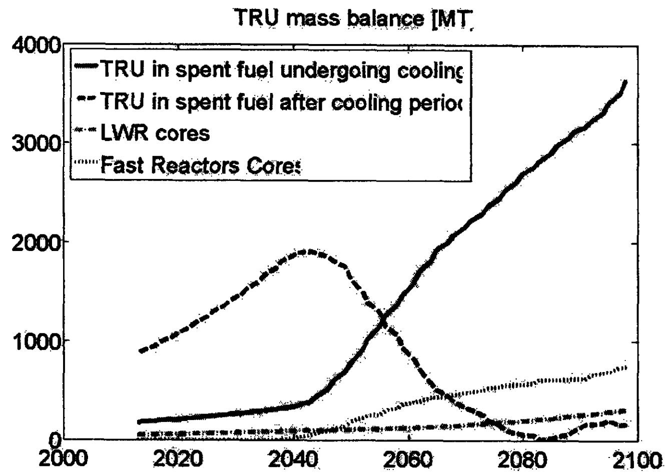


ii)

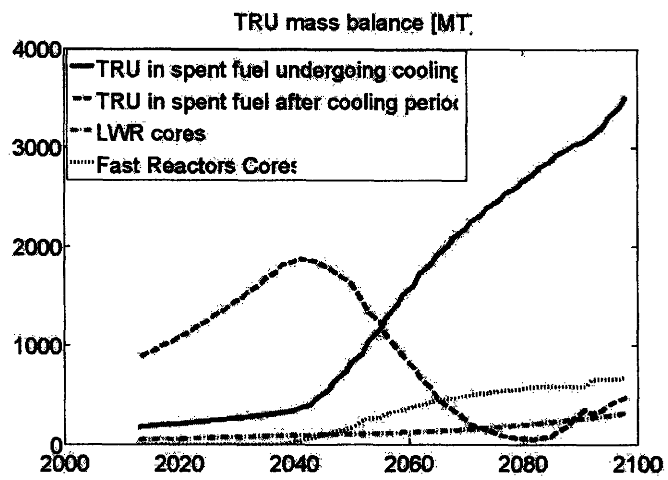


iii)

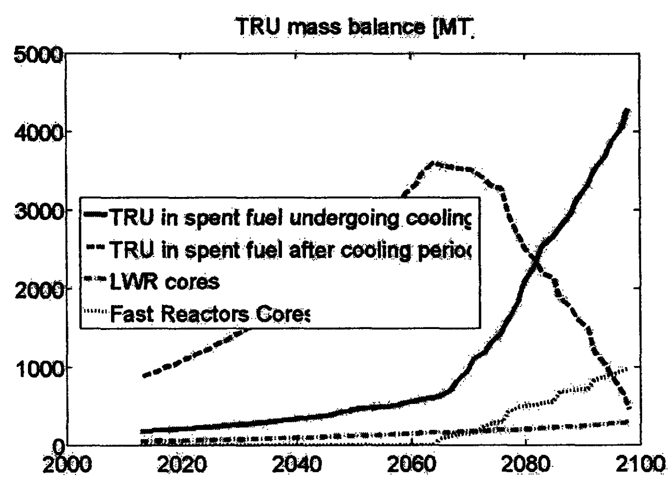
Figure 14: TRU for LWR/CONFU strategy in CAFCA IIB – High case, 40 yr. PL



i)

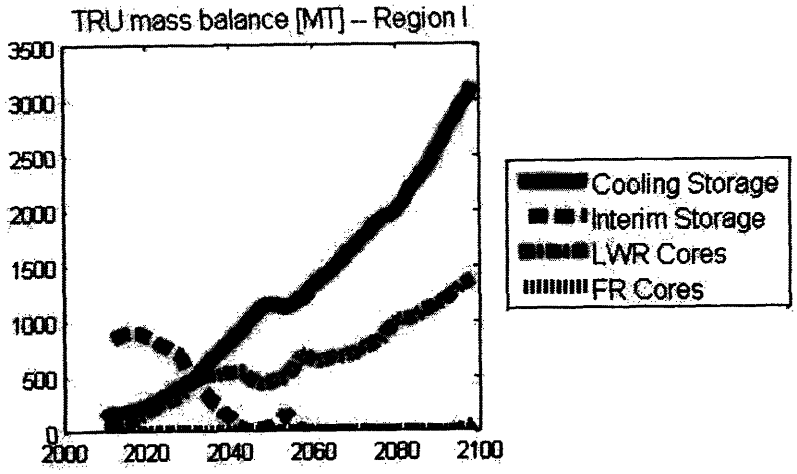


ii)

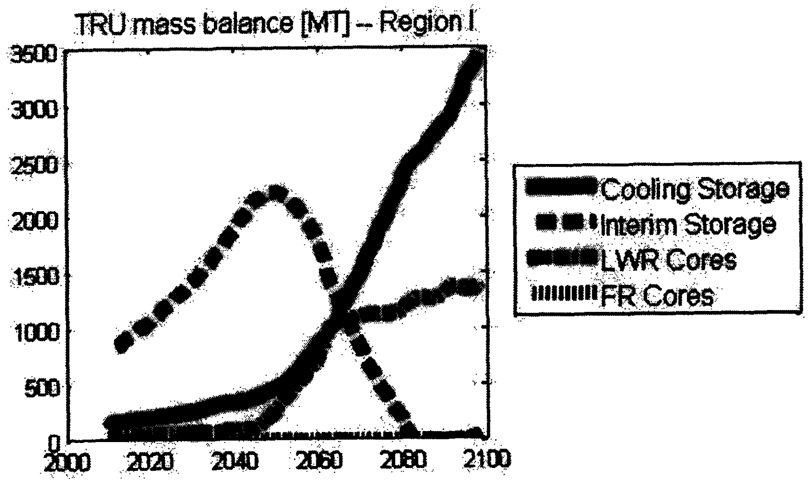


iii)

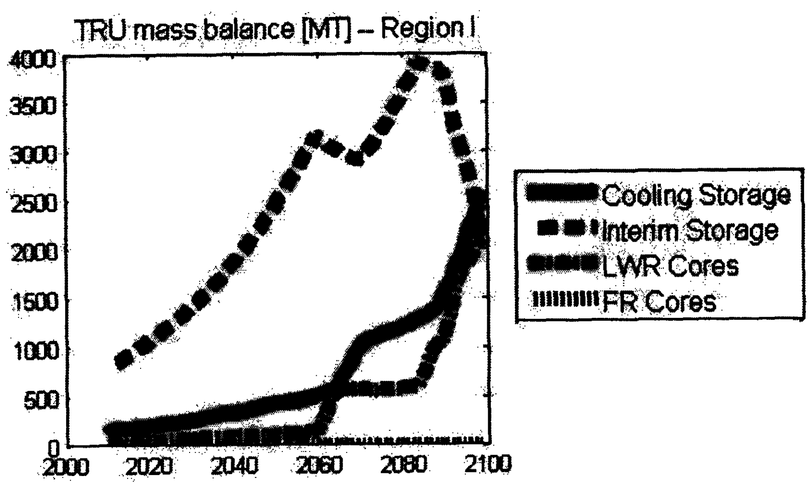
Figure 15: TRU for LWR/ABR strategy in CAFCA II – High case, 40 yr. PL



i)

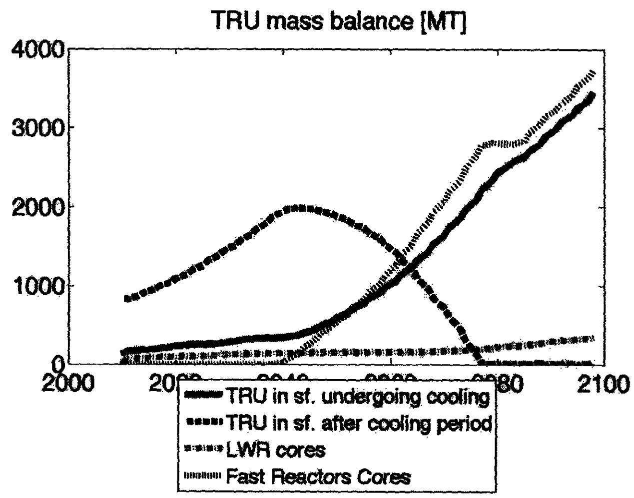


ii)

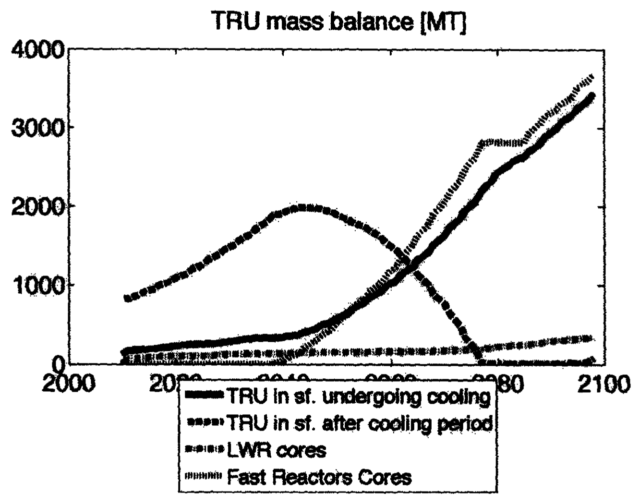


iii)

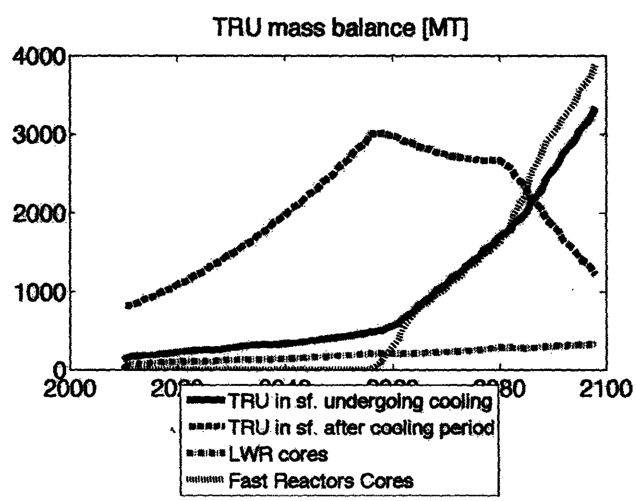
Figure 16: TRU for LWR/ABR strategy in CAFCA IIB – High case, 40 yr. PL



i)

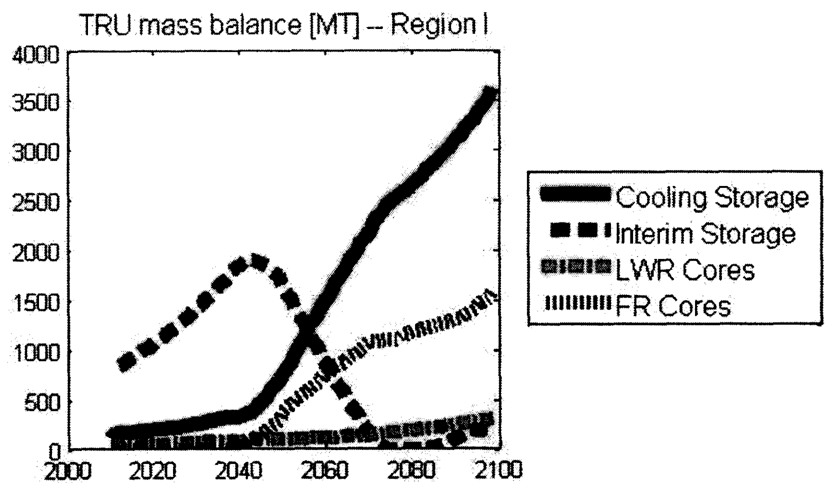


ii)

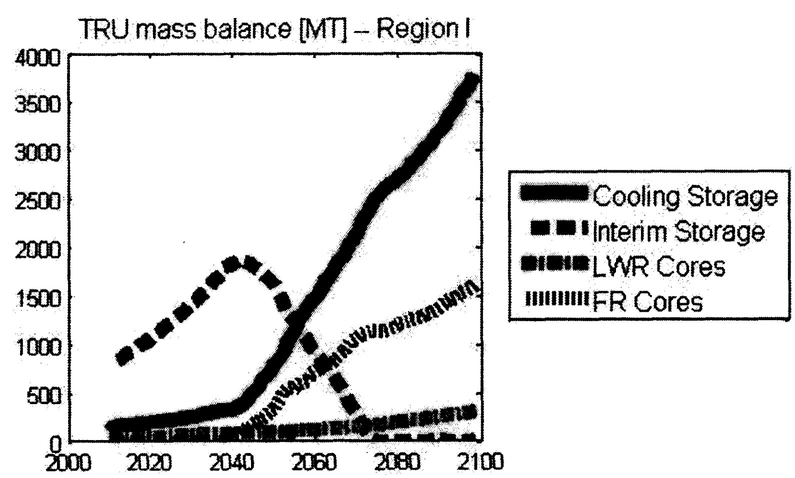


iii)

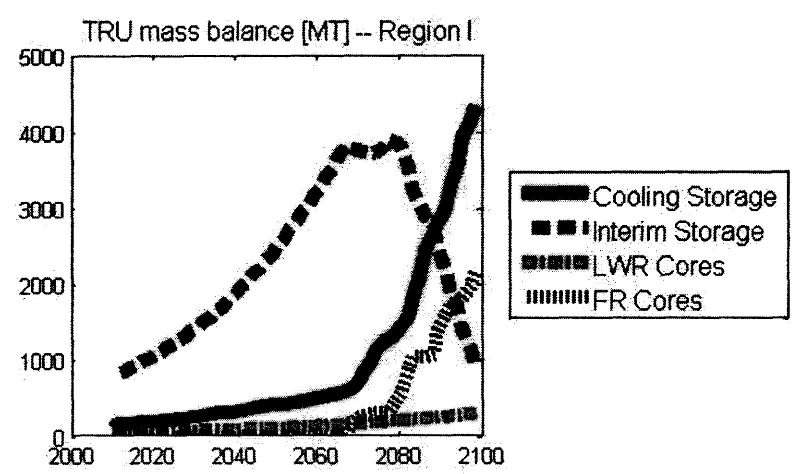
Figure 17: TRU for LWR/GFR strategy in CAFCA II – High case, 40 yr. PL



i)



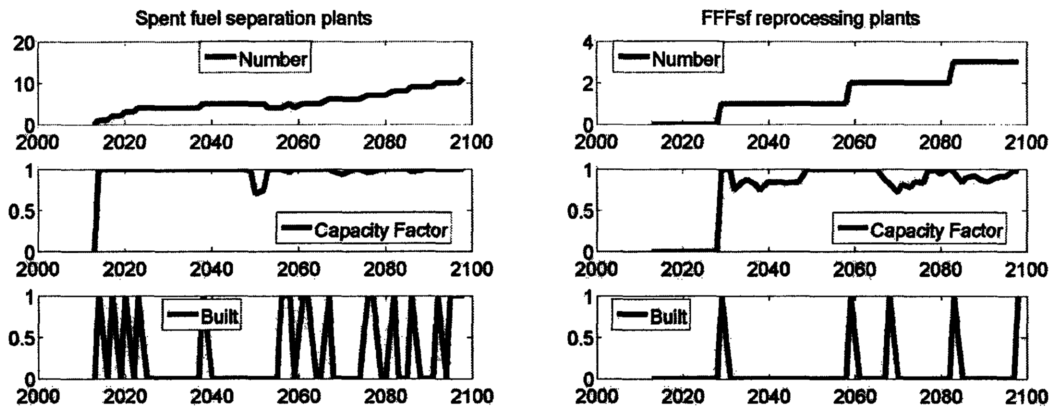
ii)



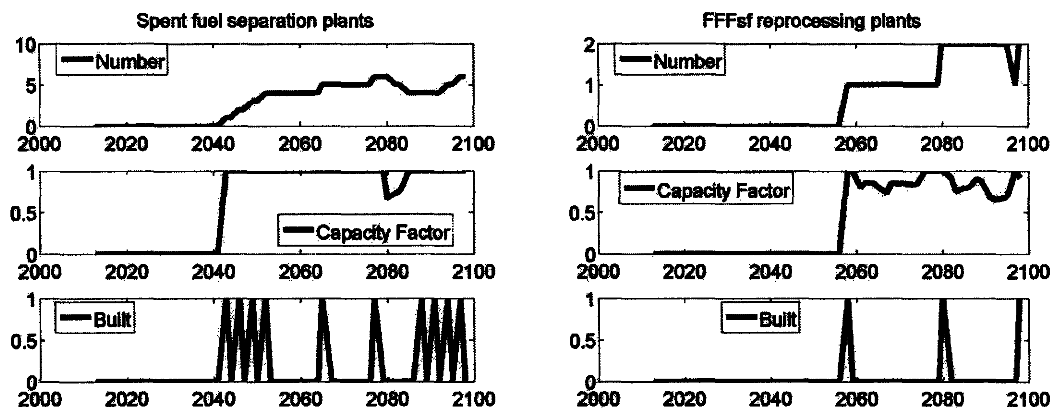
iii)

Figure 18: TRU for LWR/GFR strategy in CAFCA IIB – High case, 40 yr. PL

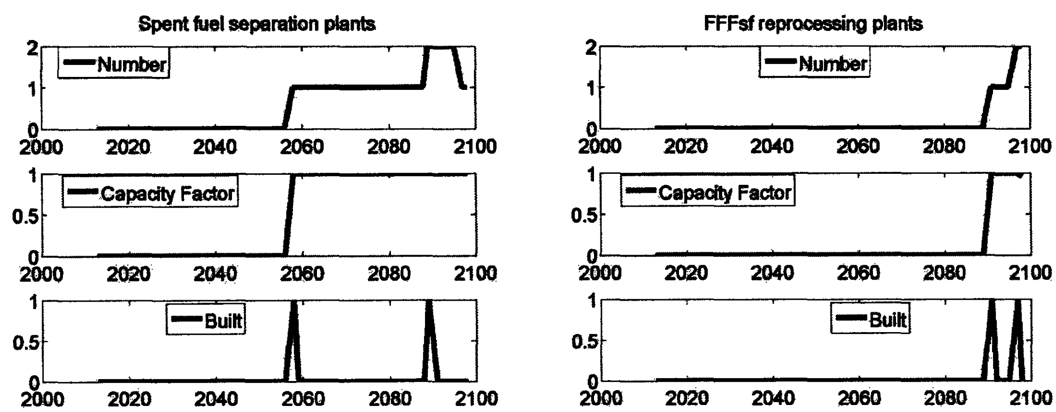
Appendix D: Spent fuel recycling plants – High case with 40 yr. PL (II & IIB)



i)

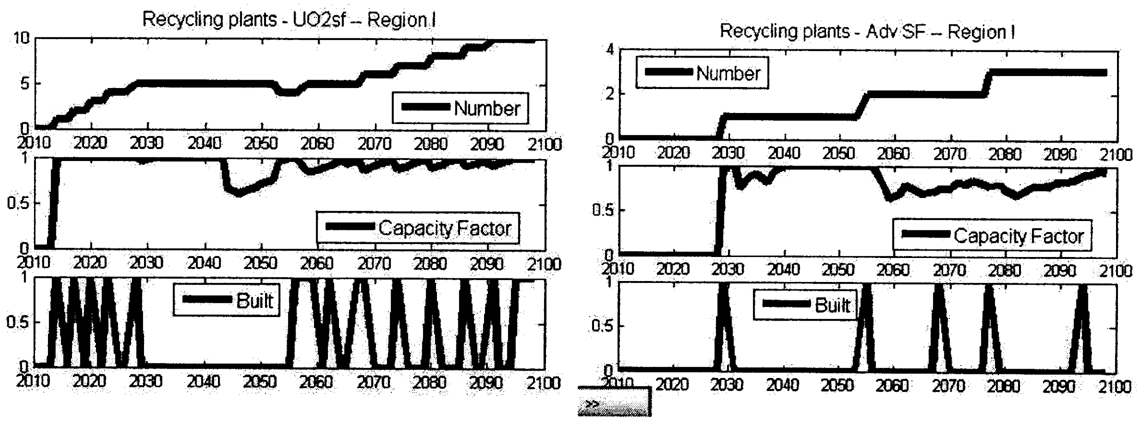


ii)

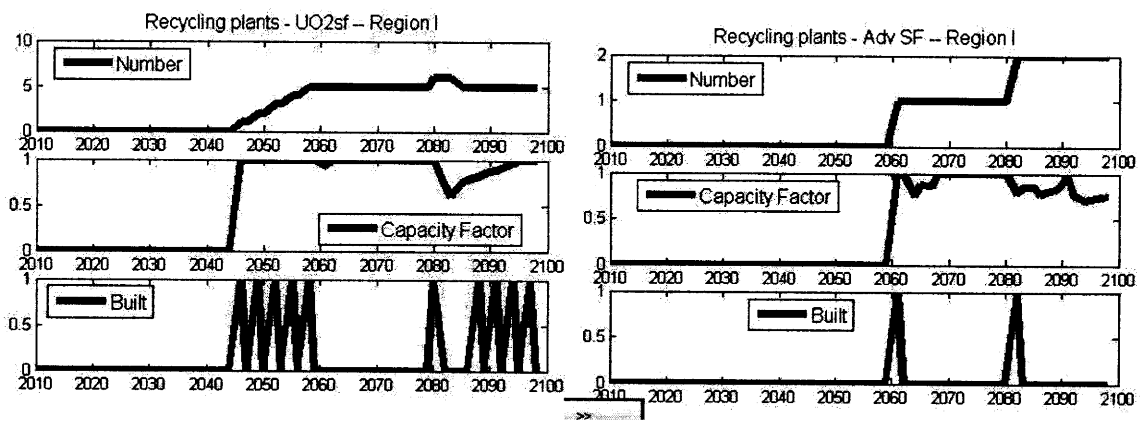


iii)

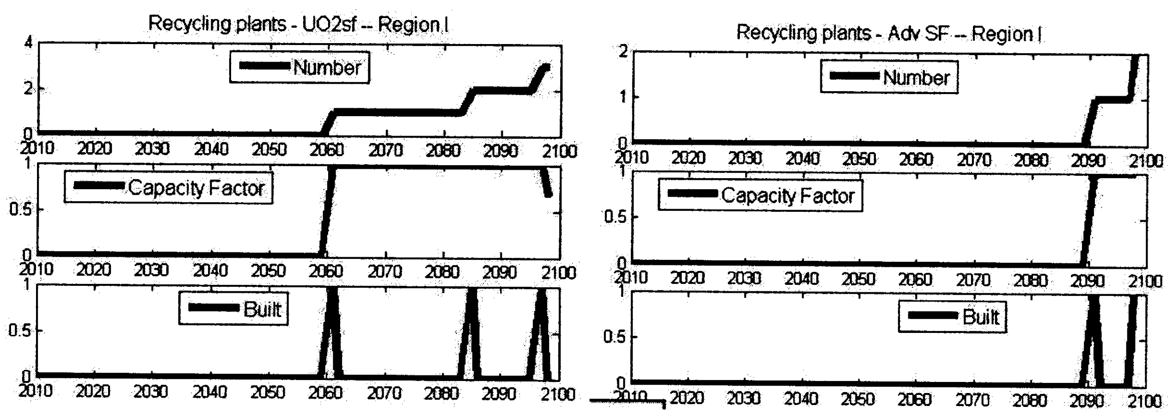
Figure 19: SFRP for LWR/CONFU strategy in CAFCA II – High case, 40 yr. PL



i)

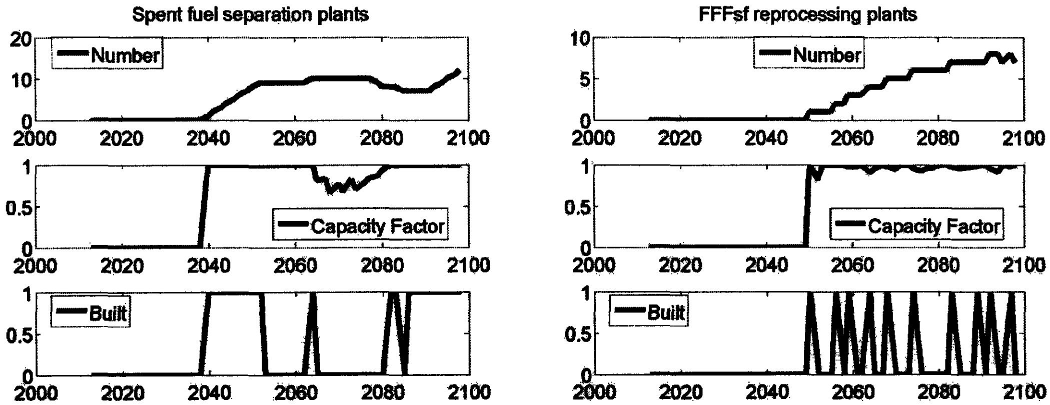


ii)

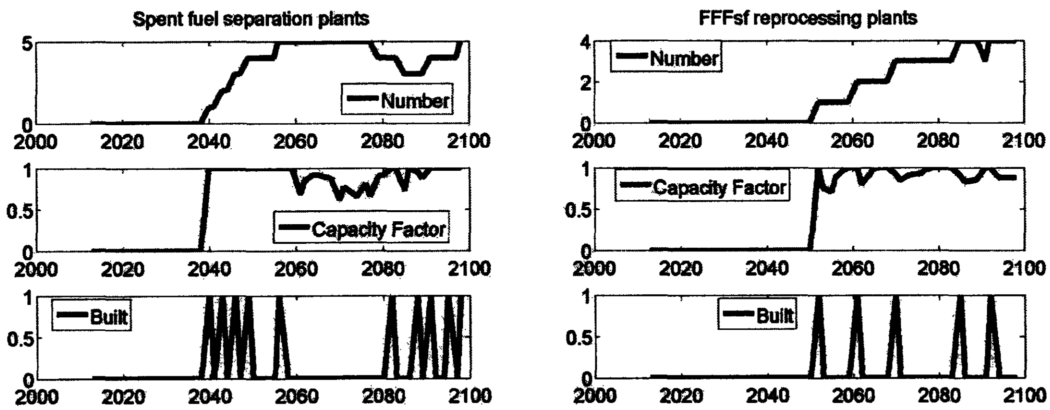


iii)

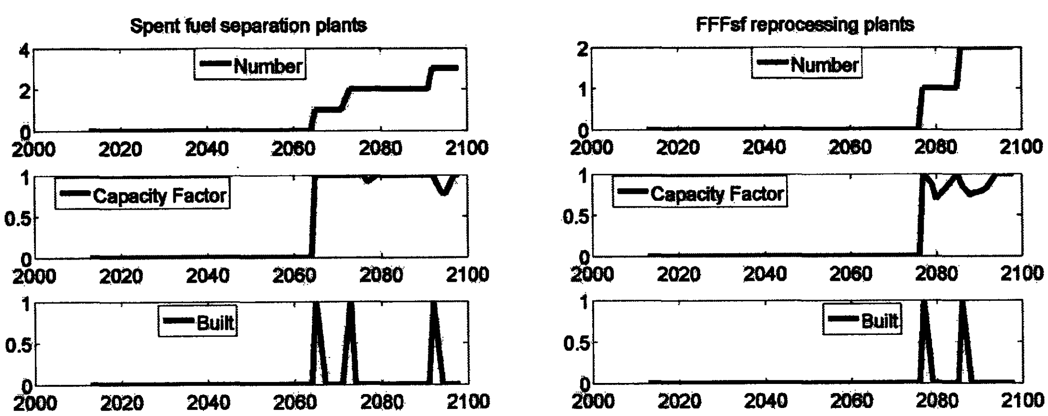
Figure 20: SFRP for LWR/CONFU strategy in CAFCA IIB – High case, 40 yr. PL



i)

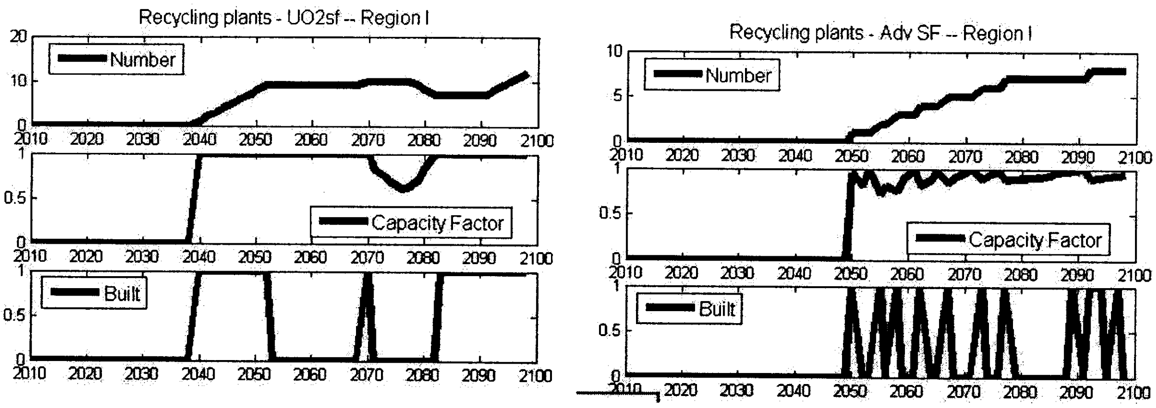


ii)

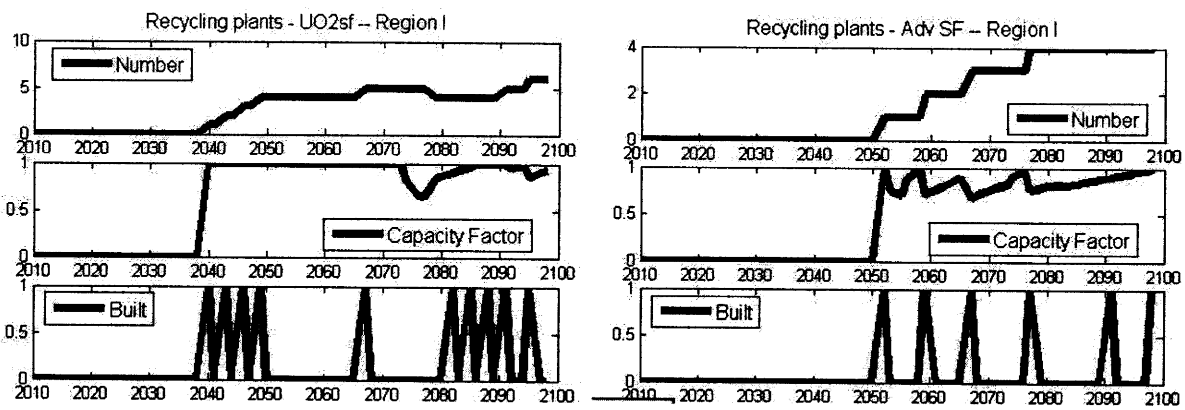


iii)

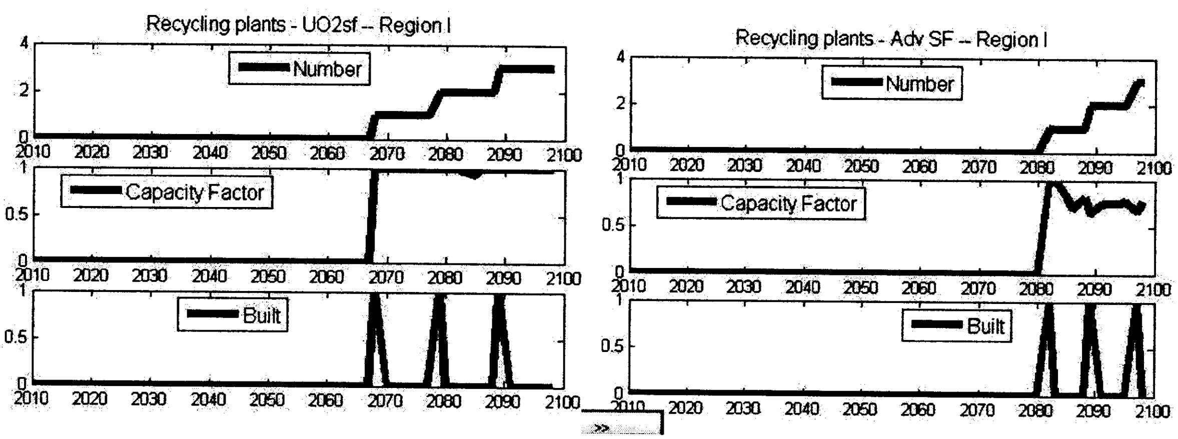
Figure 21: SFRP for LWR/ABR strategy in CAFCA II – High case, 40 yr. PL



i)

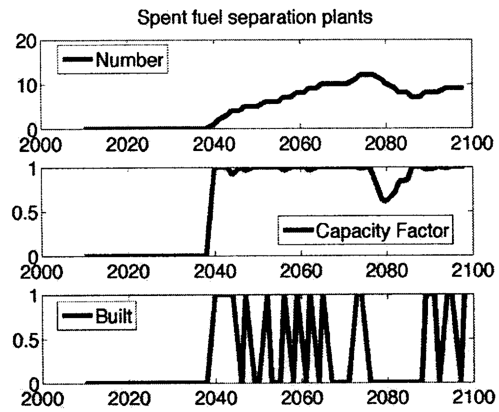


ii)

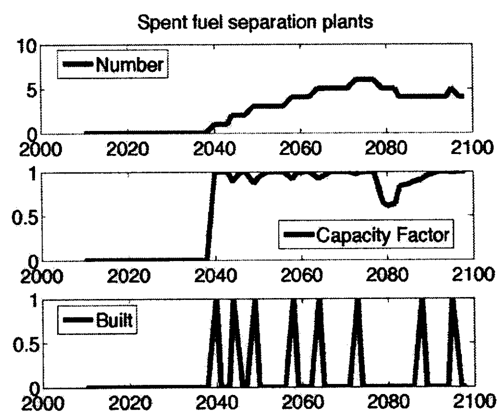


iii)

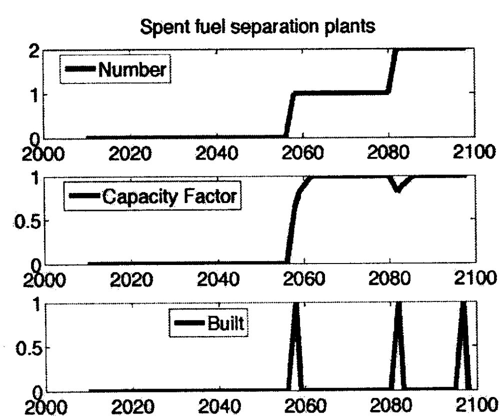
Figure 22: SFRP for LWR/ABR Strategy in CAFCA IIB – High case, 40 yr. PL



i)

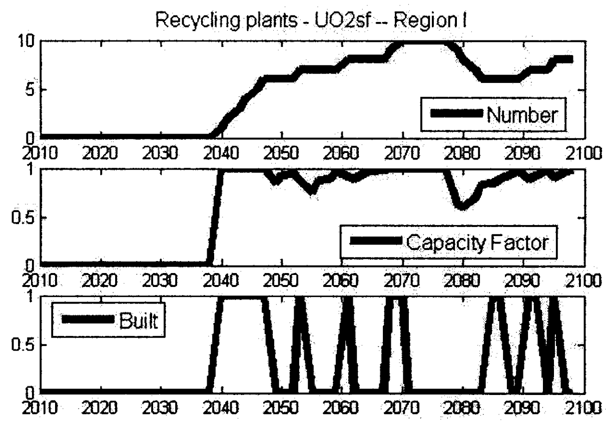


ii)

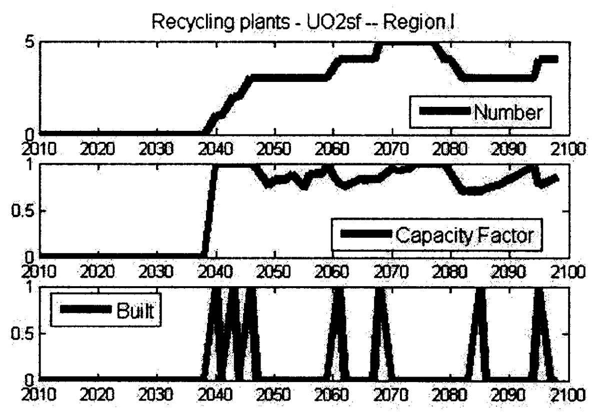


iii)

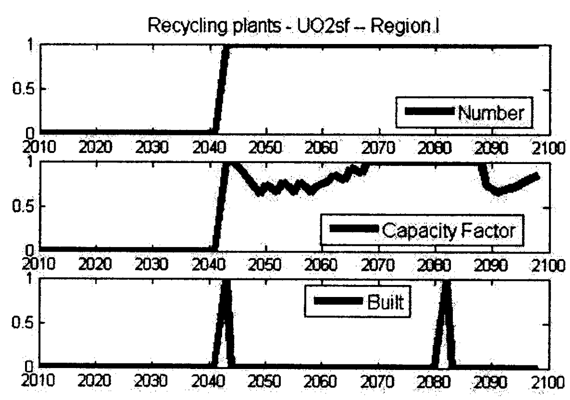
Figure 23: SFRP for LWR/GFR strategy in CAFCA II – High case, 40 yr. PL



i)



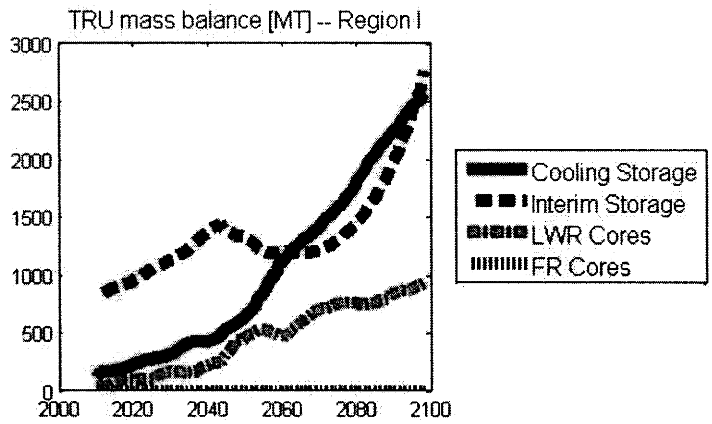
ii)



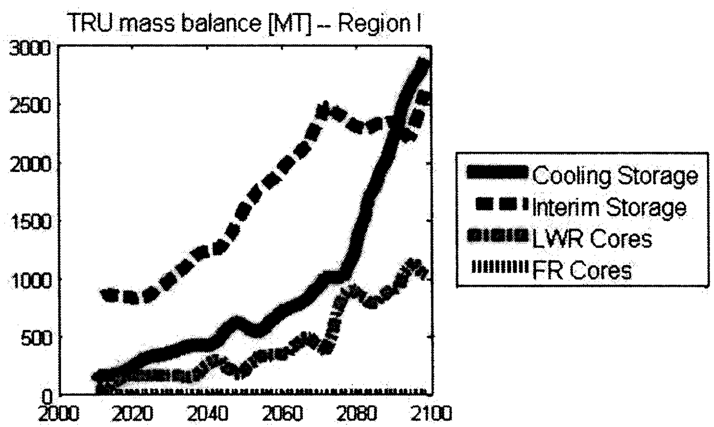
iii)

Figure 24: SFRP for LWR/GFR Strategy in CAFCA IIB – High case, 40 yr. PL

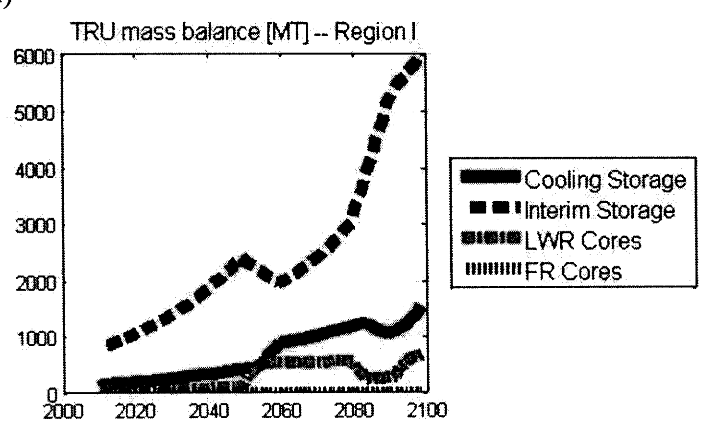
Appendix E: TRU Mass Balance – Low case in CAFCA IIB with 30 year Plant Lifetime



i)

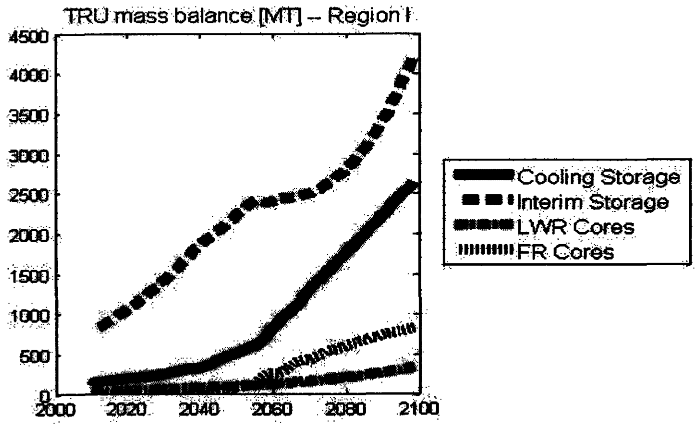


ii)

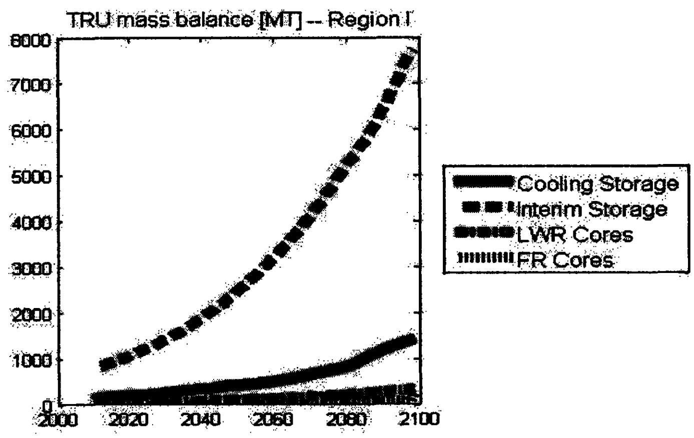


iii)

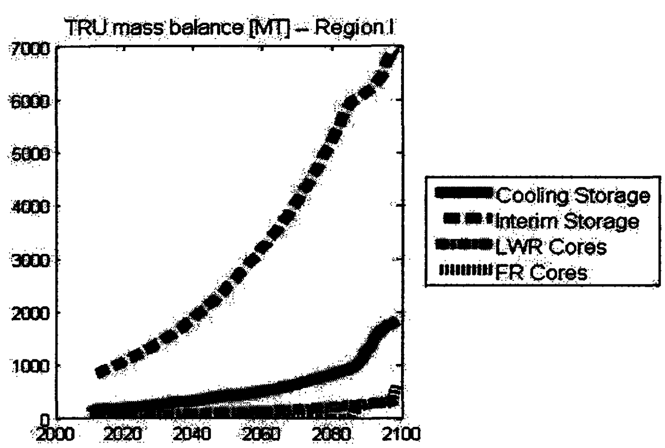
Figure 25: TRU for LWR/CONFU strategy in CAFCA IIB – Low case, 30 yr. PL



i)

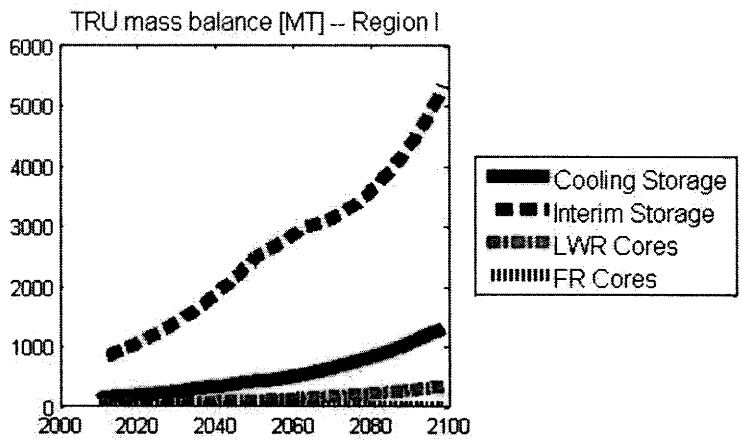


ii)

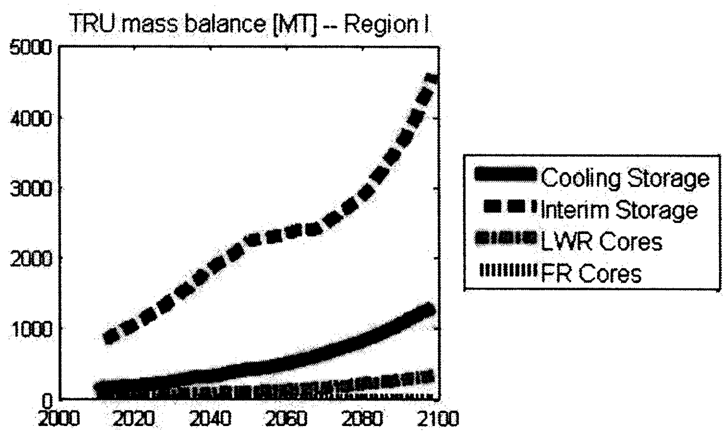


iii)

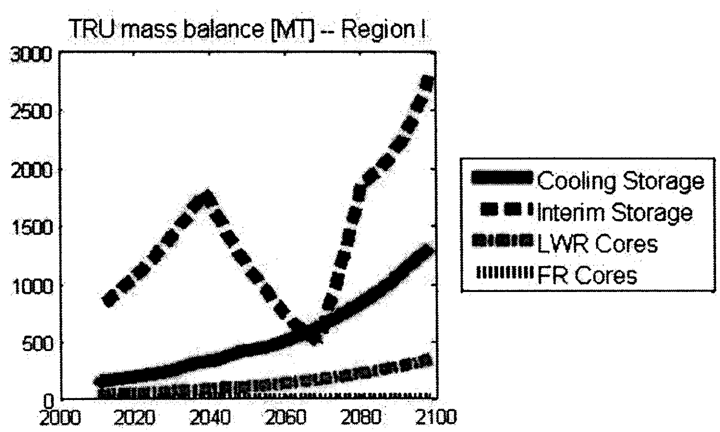
Figure 26: TRU for LWR/ABR strategy in CAFCA IIB – Low case, 30 yr. PL



i)



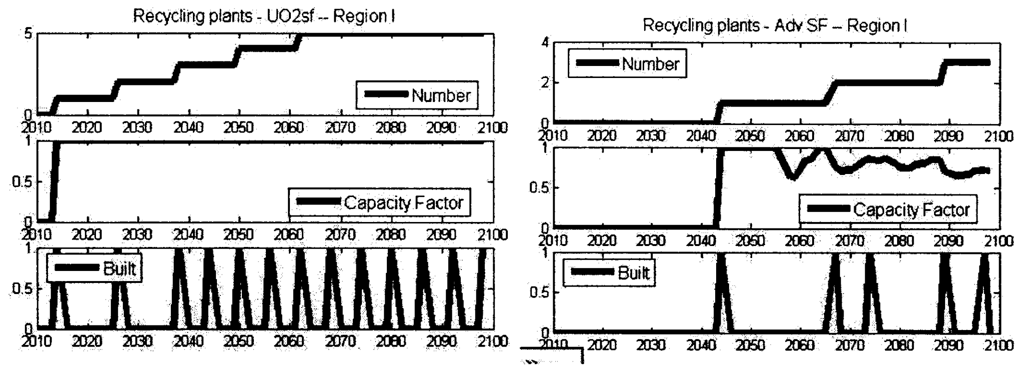
ii)



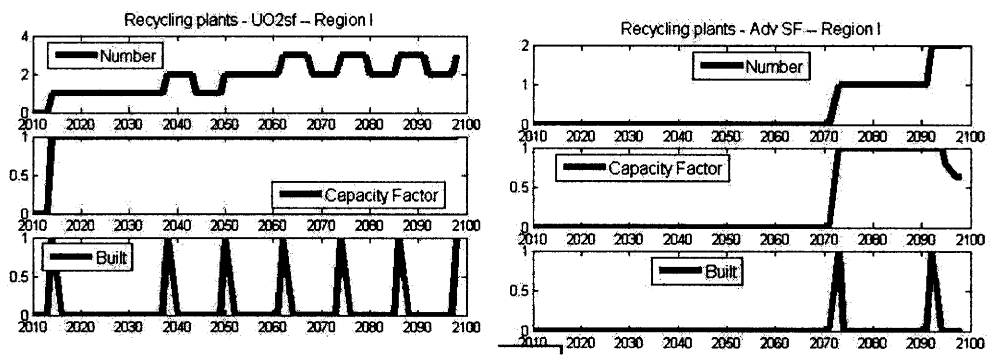
iii)

Figure 27: TRU for LWR/GFR strategy in CAFCA IIB – Low case, 30 yr. PL

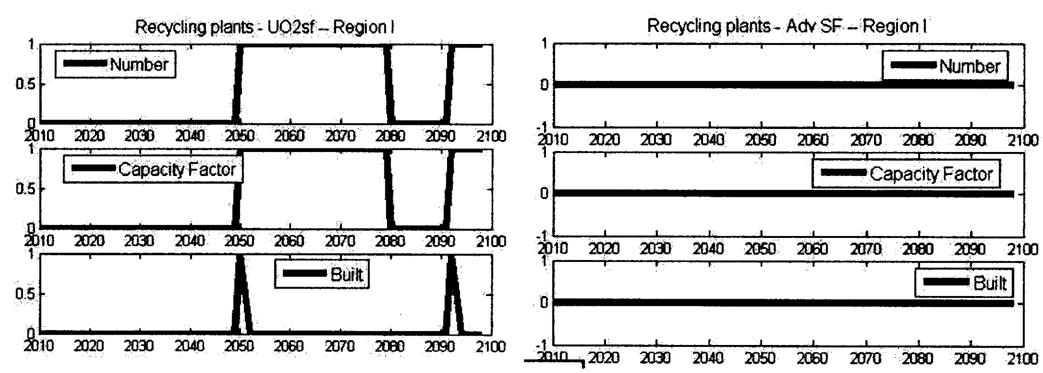
Appendix F: SF Recycling Plants – Low case in CAFCA IIB with 30 year Plant Lifetime



i)

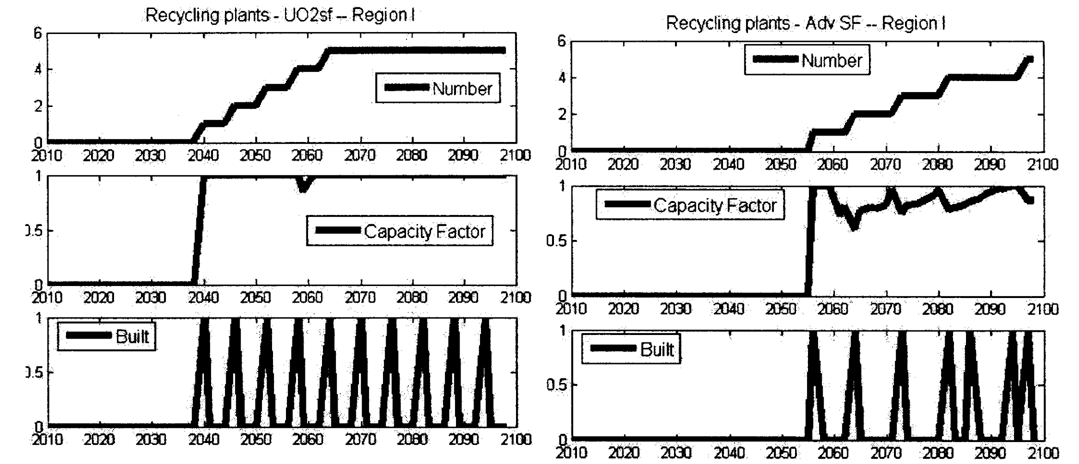


ii)

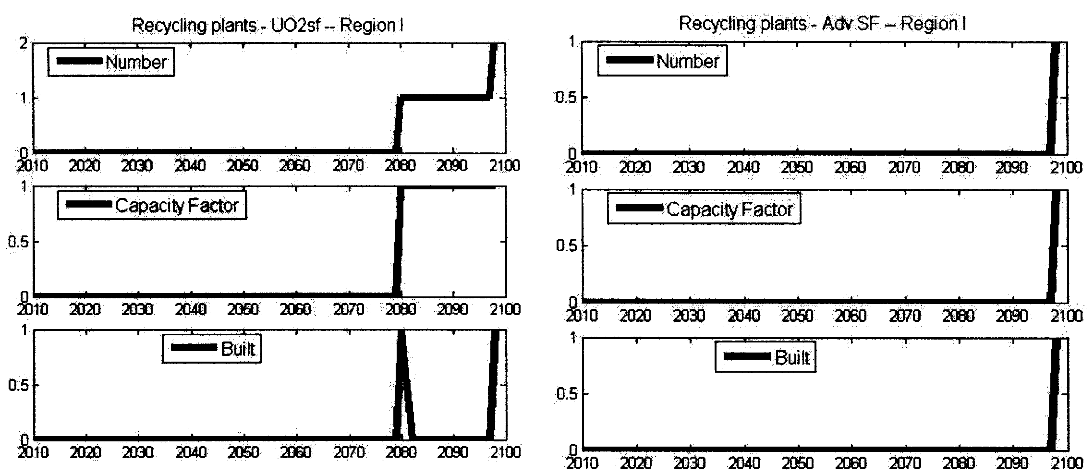


iii)

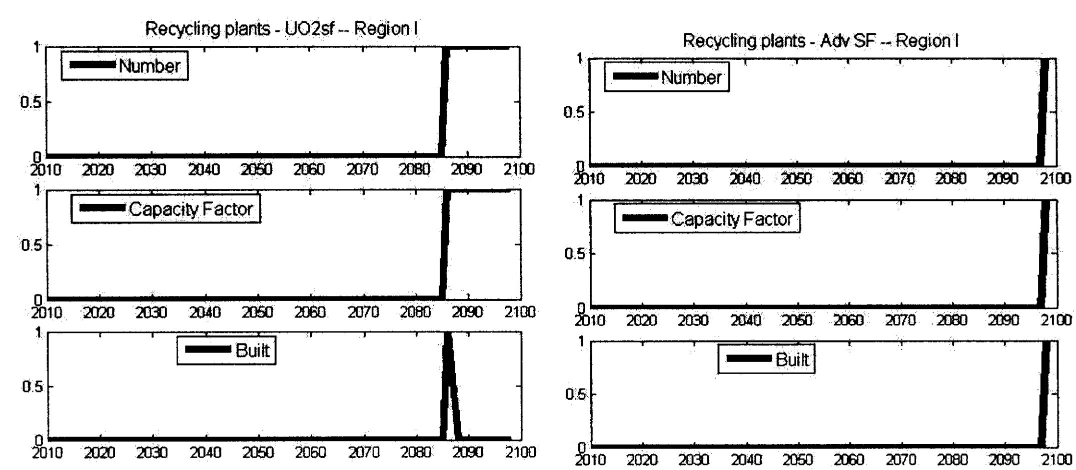
Figure 28: SFRP for LWR/CONFU strategy – Low case, 30 yr. PL



i)

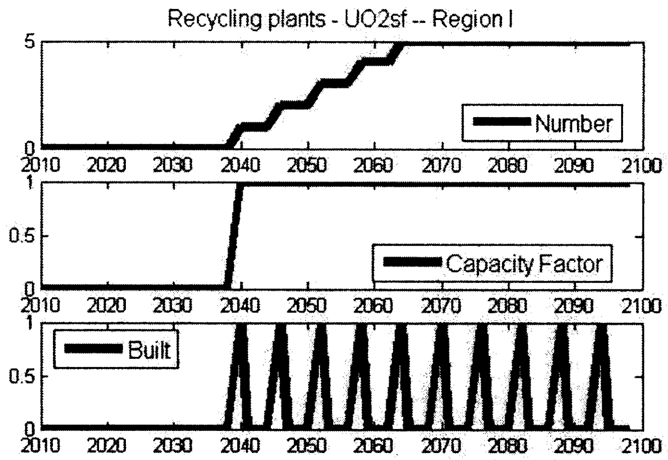


ii)

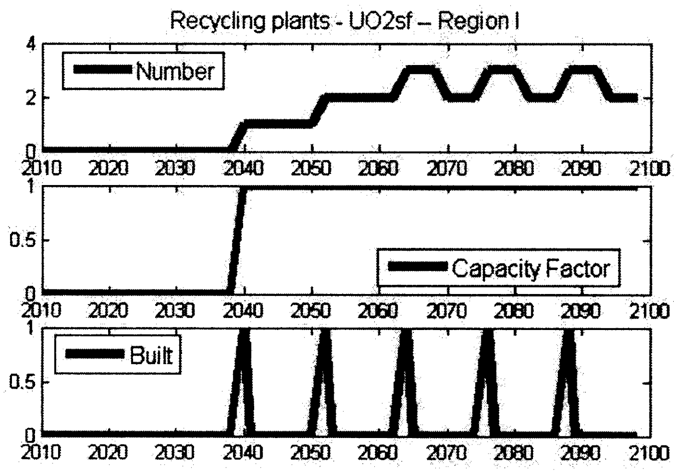


iii)

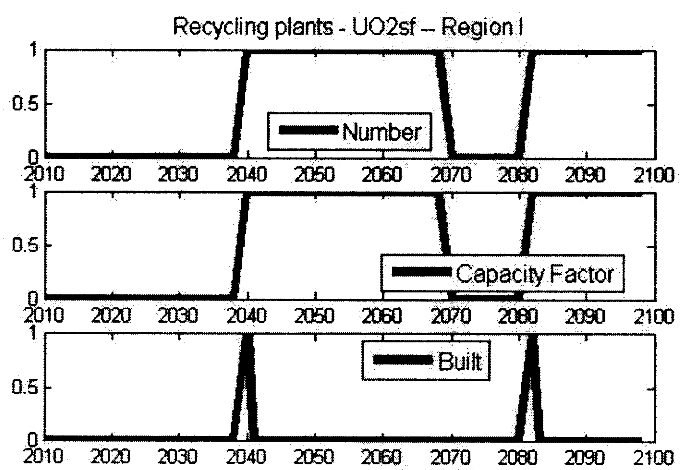
Figure 29: SFRP for LWR/ABR strategy in CAFCA IIB - Low case, 30 yr. PL



i)



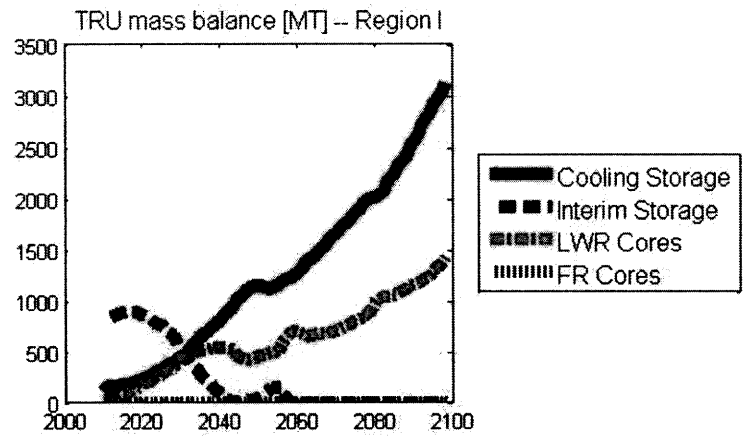
ii)



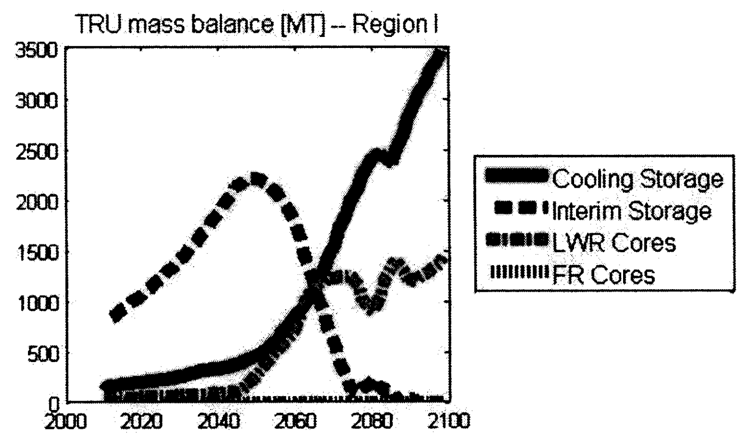
iii)

Figure 30: SFRP for LWR/GFR strategy in CAFCA IIB - Low case, 30 yr. PL

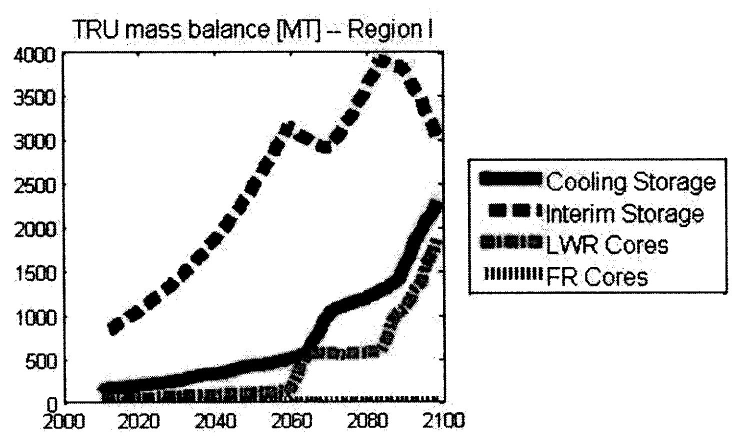
Appendix G: TRU Mass Balance – High case in CAFCA IIB with 30 year Plant Lifetime



i)

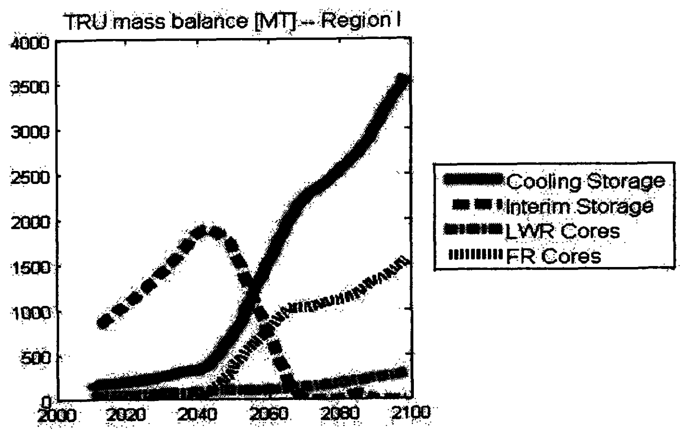


ii)

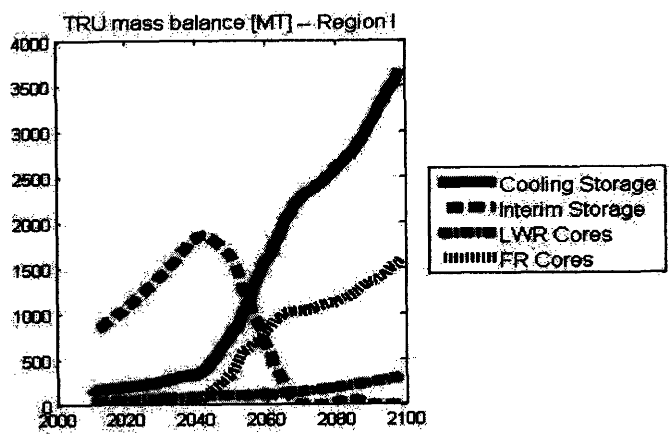


iii)

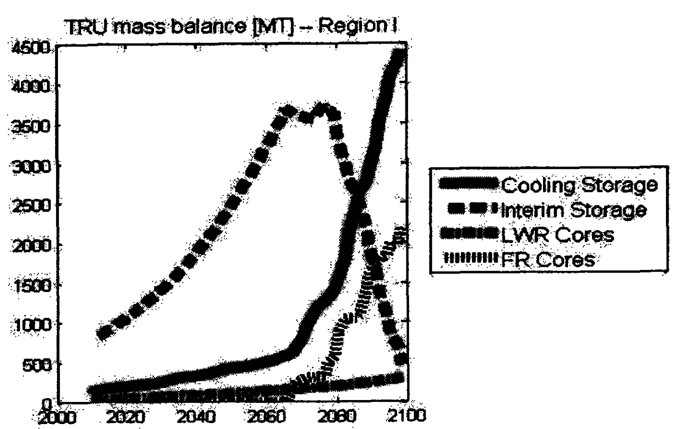
Figure 31: TRU for LWR/CONFU strategy in CAFCA IIB – High case, 30 yr. PL



i)

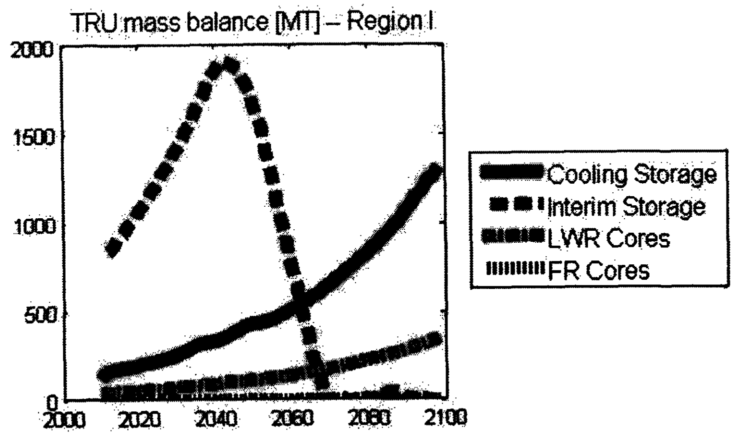


ii)

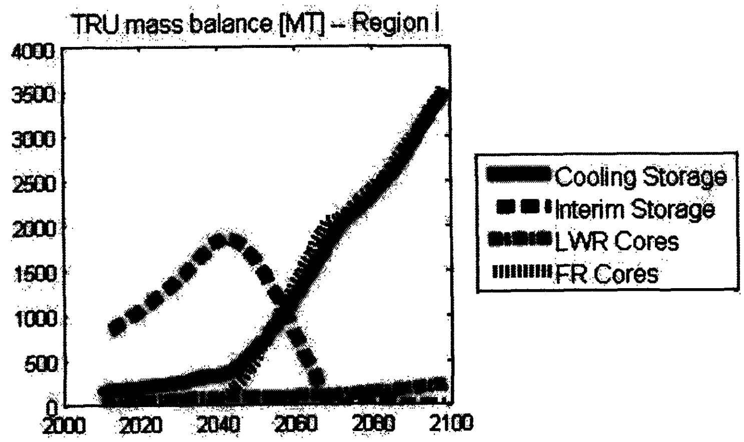


iii)

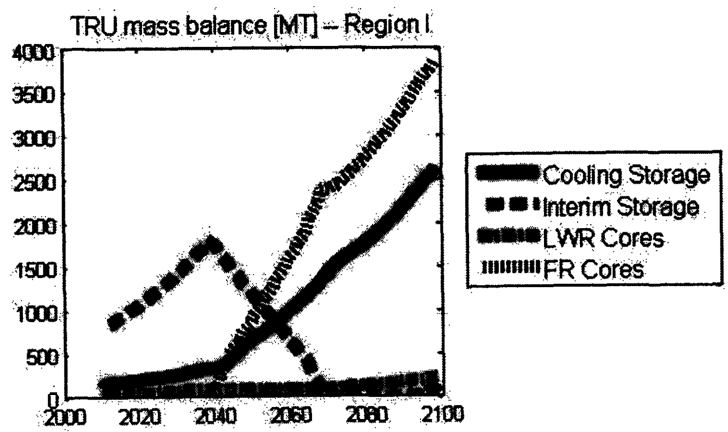
Figure 32: TRU for LWR/ABR strategy – High case, 30 yr. PL



i)



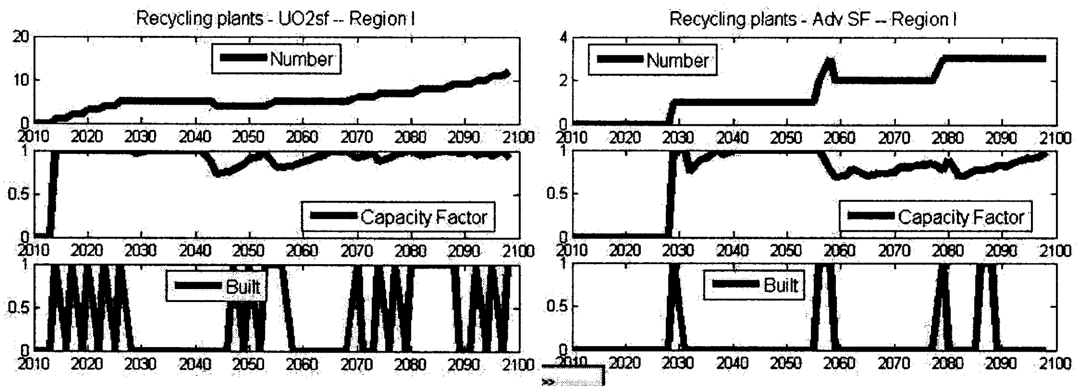
ii)



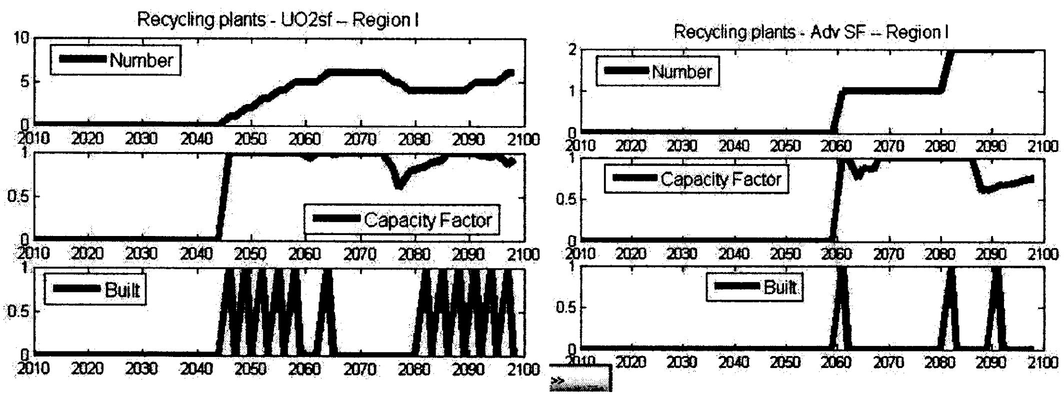
iii)

Figure 33: TRU for LWR/GFR strategy in CAFCA IIB – High case, 30 yr. PL

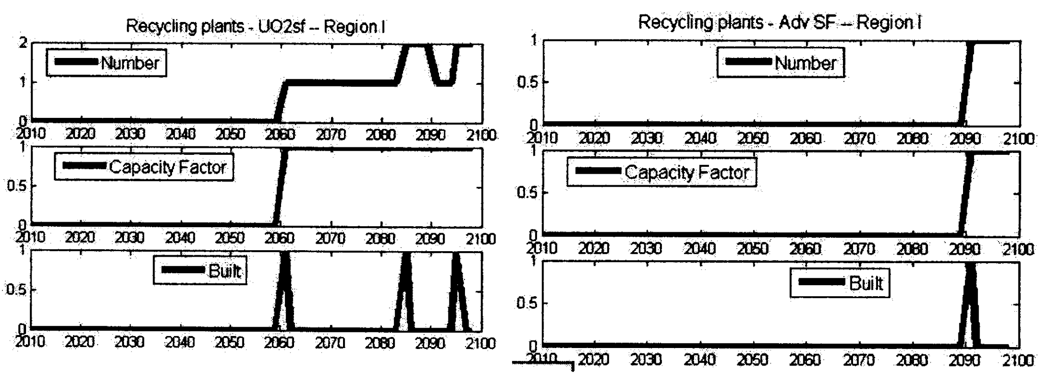
Appendix H: SF Recycling Plants – High case in CAFCA IIB with 30 year Plant Lifetime



i)

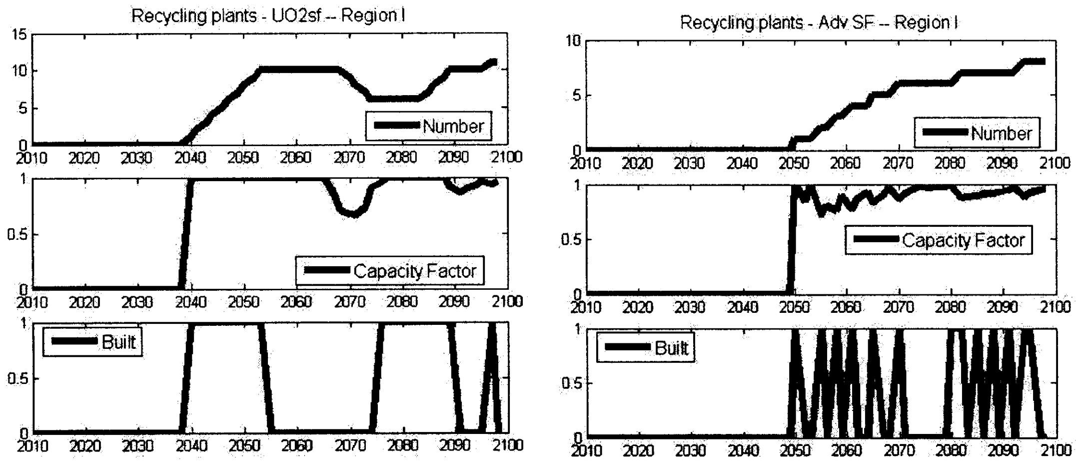


ii)

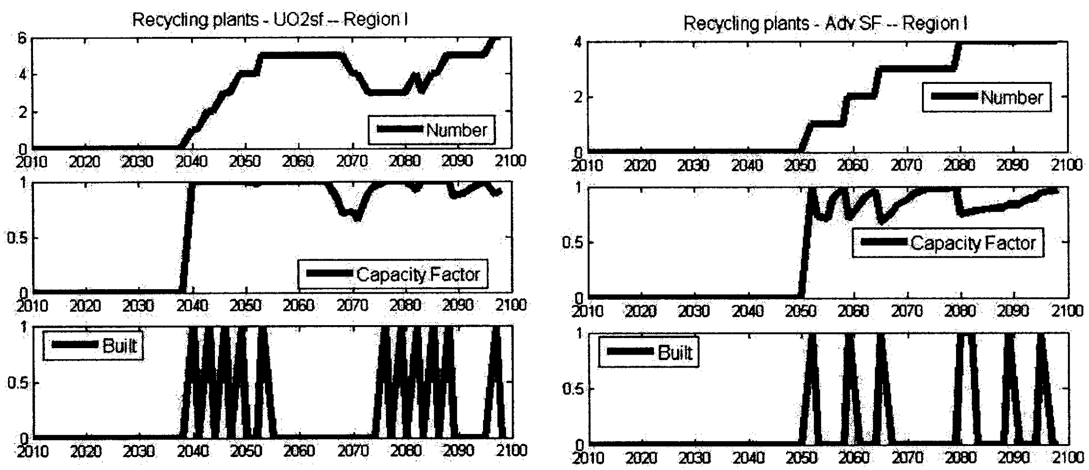


iii)

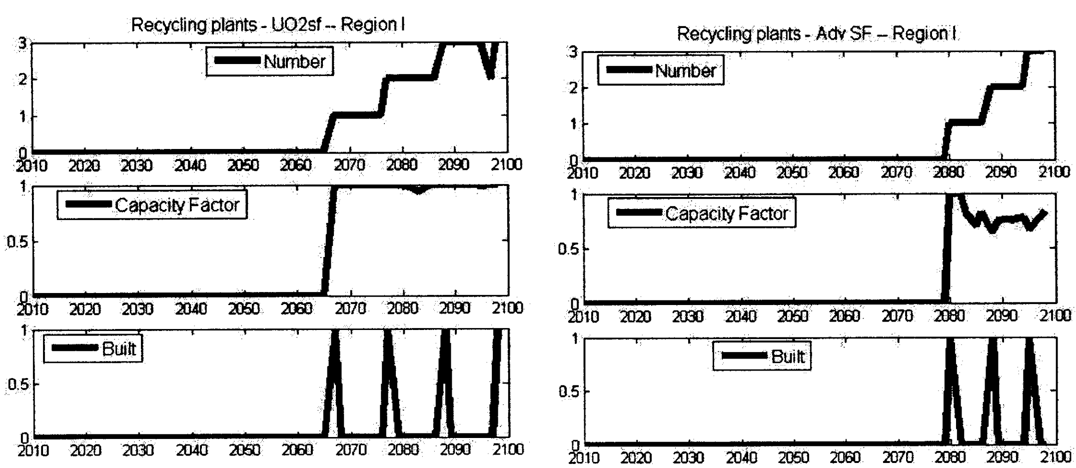
Figure 34: SFRP for LWR/CONFU strategy in CAFCA IIB – High case, 30 yr. PL



i)

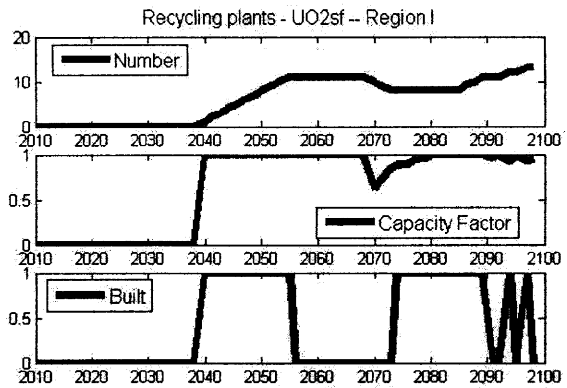


ii)

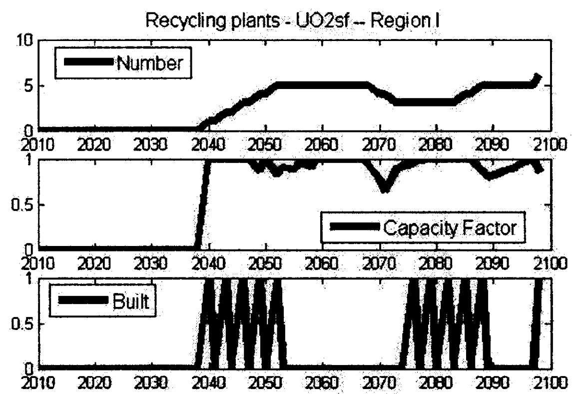


iii)

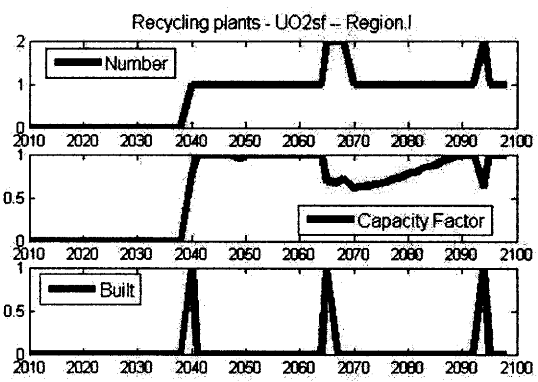
Figure 35: SFRP for LWR/ABR strategy in CAFCA IIB – High case, 30 yr. PL



i)



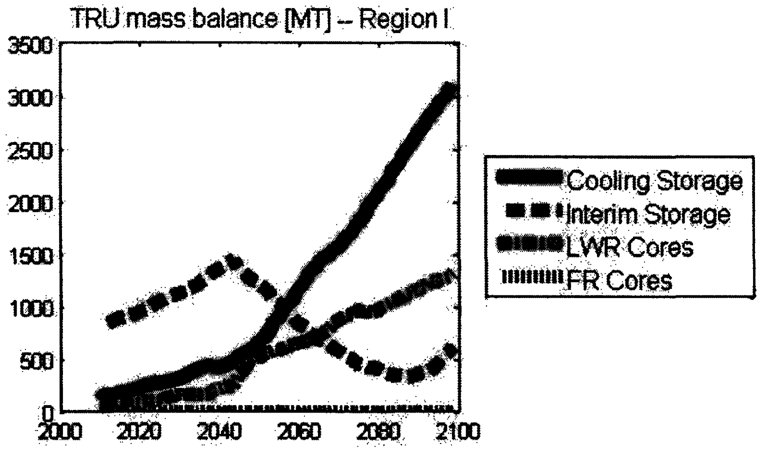
ii)



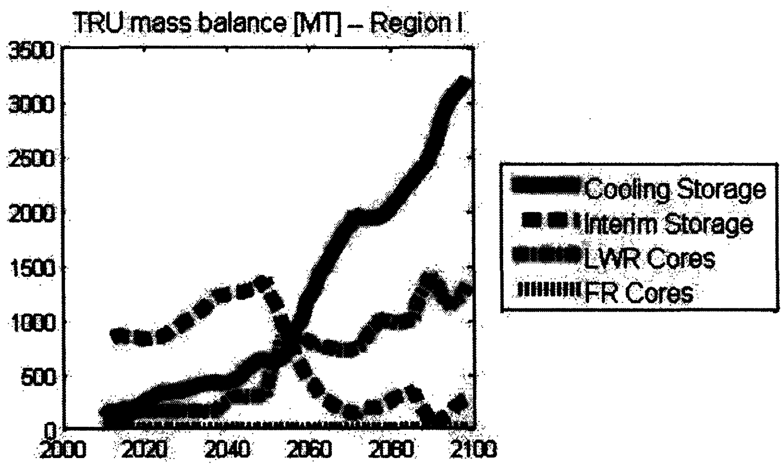
iii)

Figure 36: SFRP for LWR/GFR strategy in CAFCA IIB – High case, 30 yr. PL

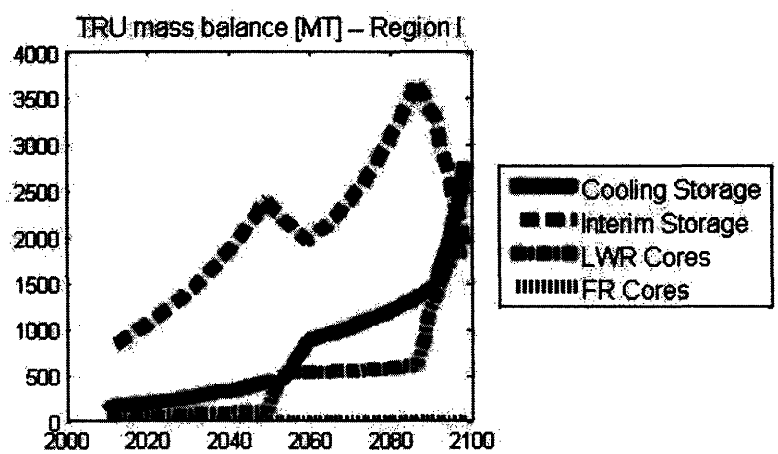
Appendix I: TRU Mass Balance – Low case in CAFCA IIB with 50 year Plant Lifetime



i)

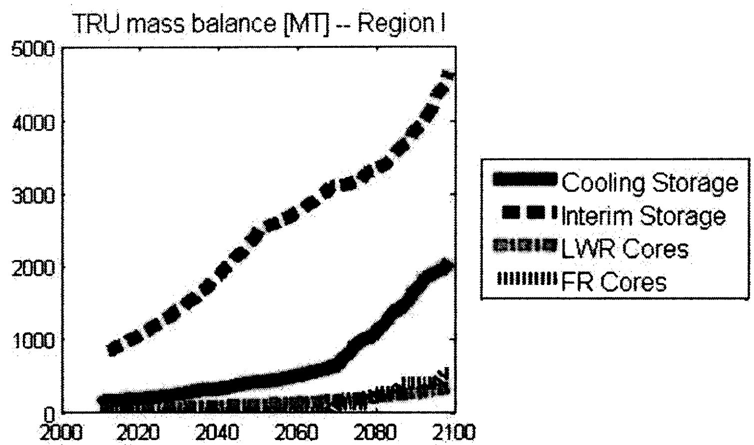


ii)

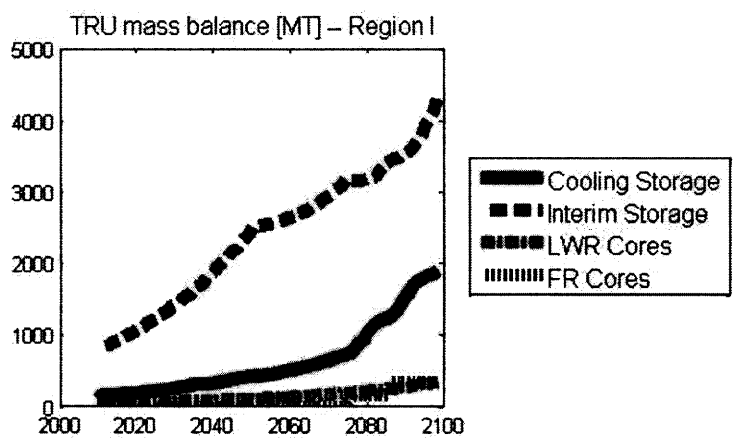


iii)

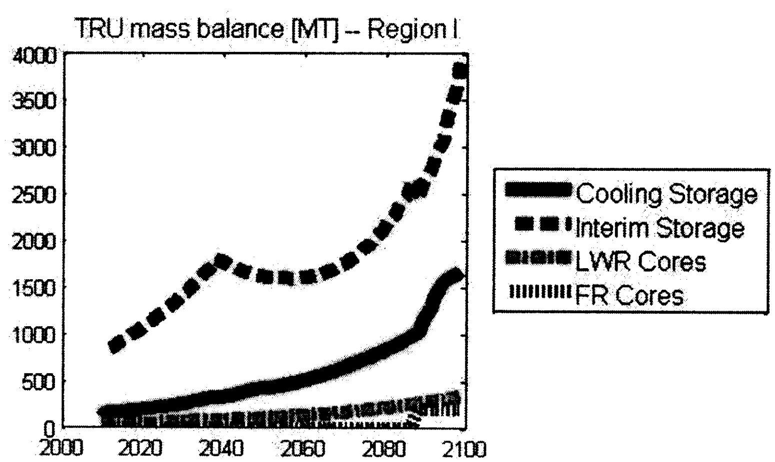
Figure 37: TRU for LWR/CONFU strategy in CAFCA IIB – Low case, 50 yr. PL



i)

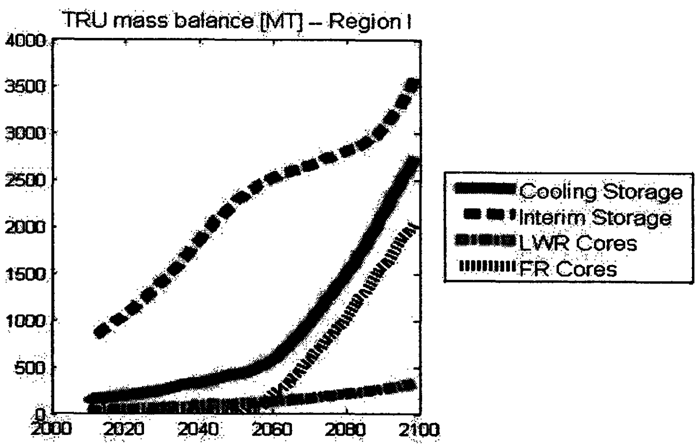


ii)

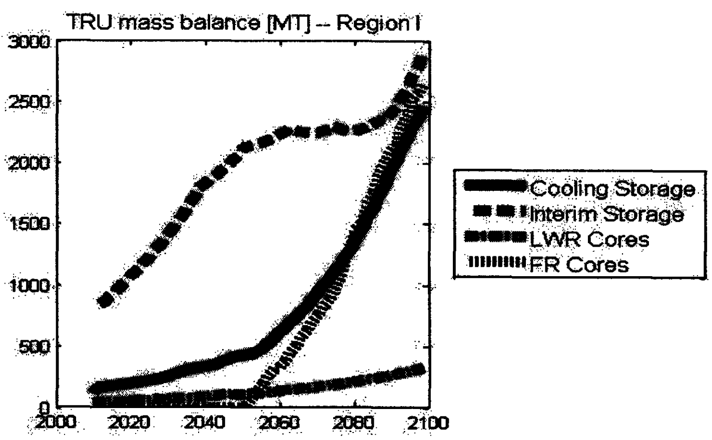


iii)

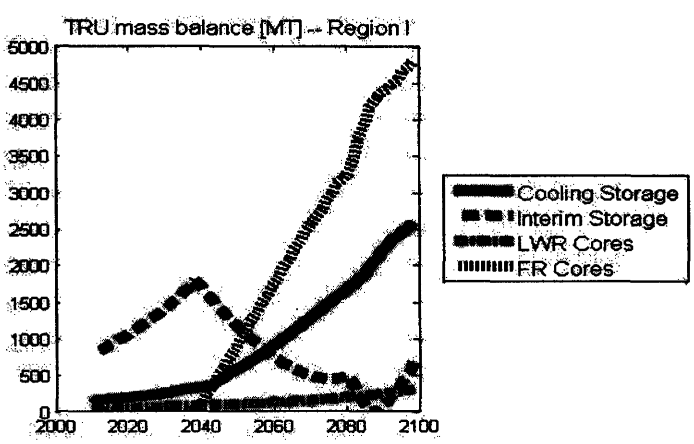
Figure 38: TRU for LWR/ABR strategy in CAFCA IIB – Low case, 50 yr. PL



i)



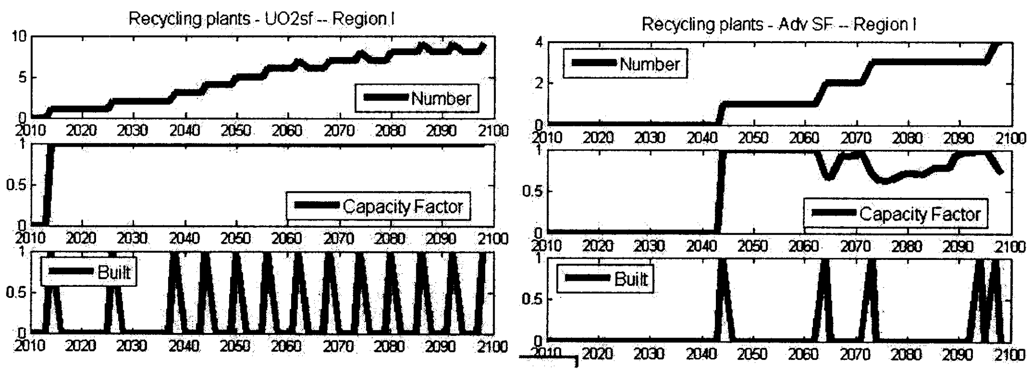
ii)



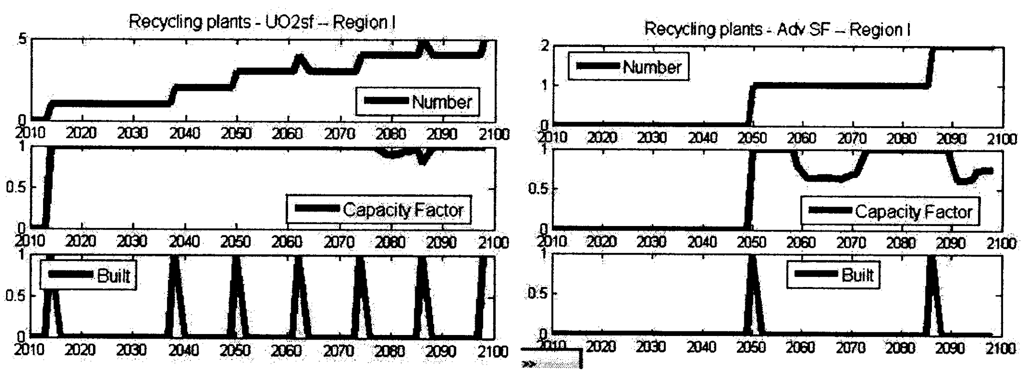
iii)

Figure 39: TRU for LWR/GFR strategy in CAFCA IIB – Low case, 50 yr. PL

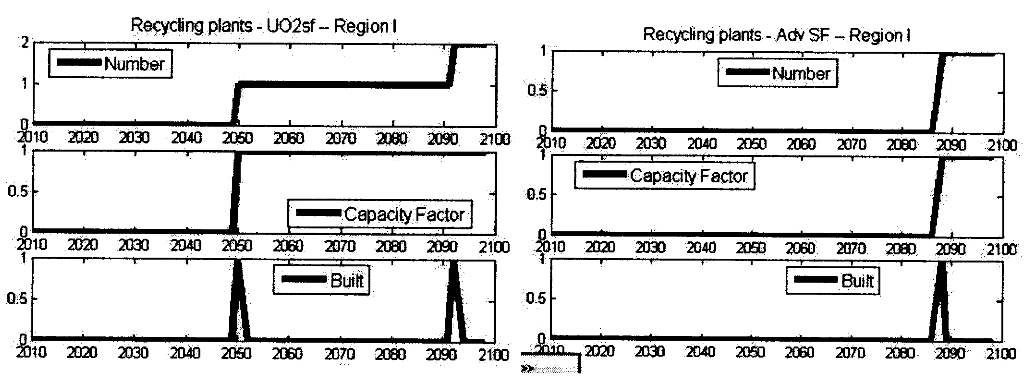
Appendix J: SF Recycling Plants - Low case in CAFCA IIB with 50 year Plant Lifetime



i)



ii)



iii)

Figure 40: SFRP for LWR/CONFU strategy in CAFCA IIB – Low case, 50 yr. PL

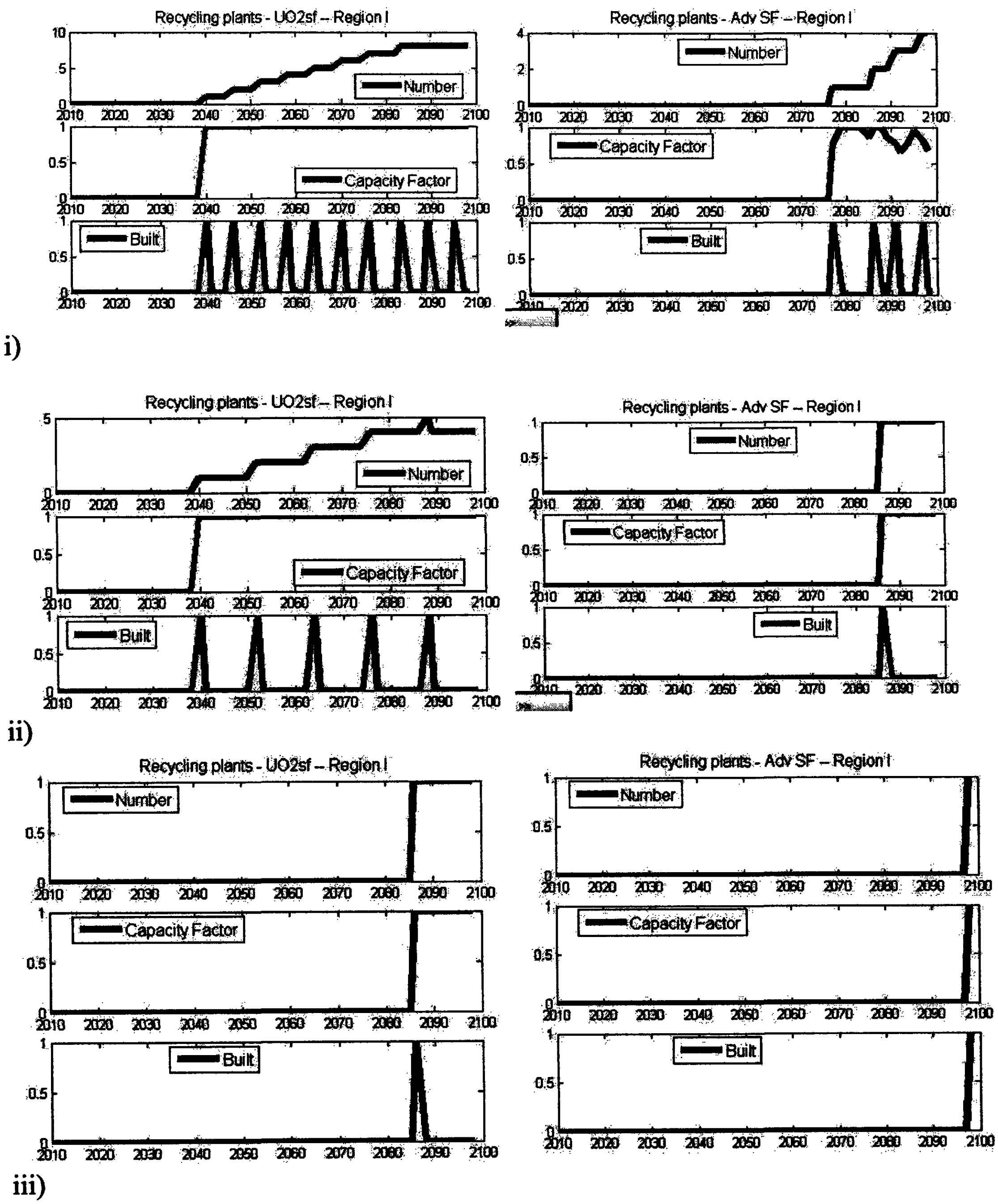
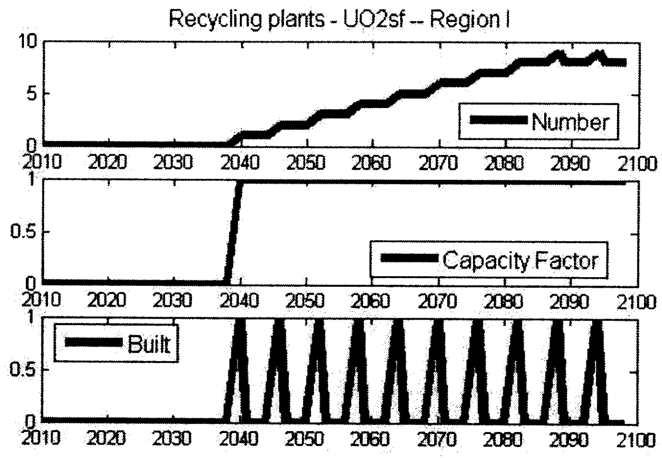
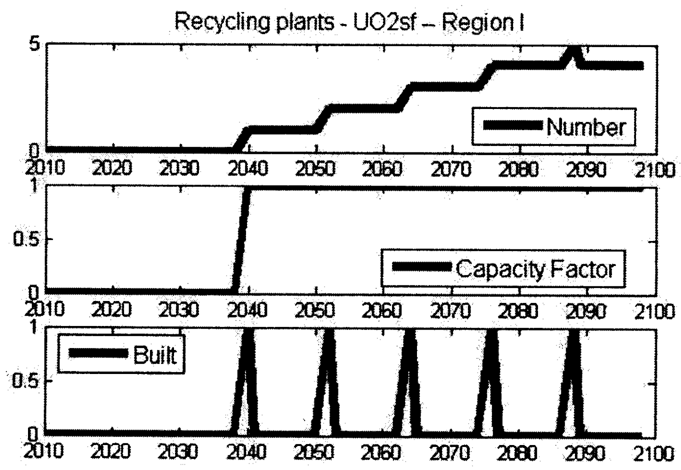


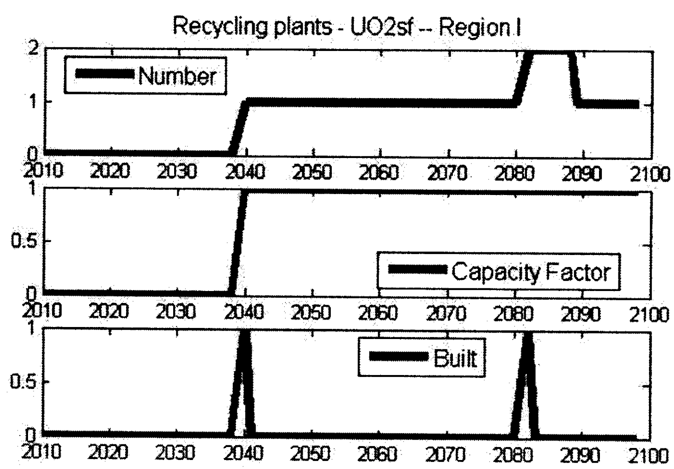
Figure 41: SFRP for LWR/ABR strategy in CAFCA IIB – Low case, 50 yr. PL



i)



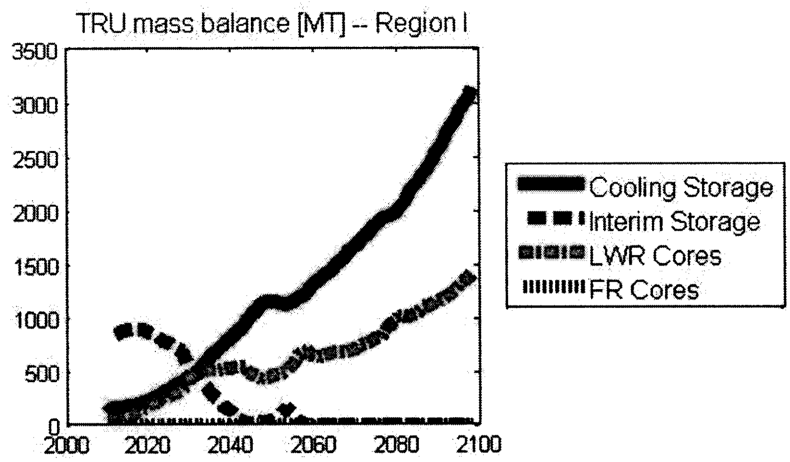
ii)



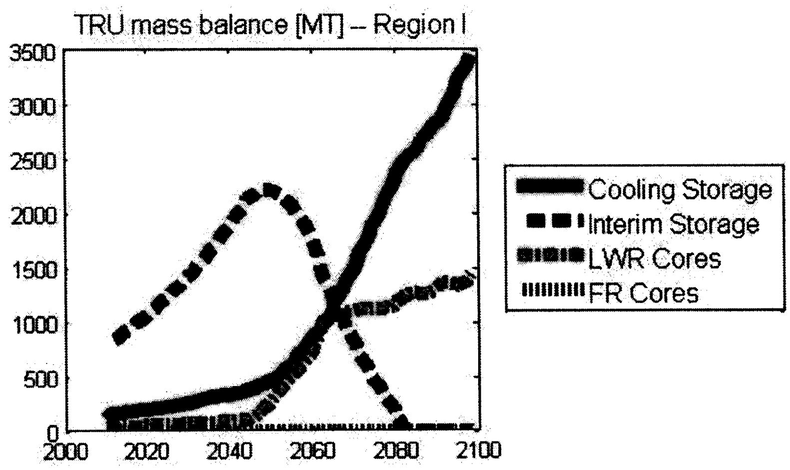
iii)

Figure 42: SFRP for LWR/GFR strategy in CAFCA IIB – Low case, 50 yr. PL

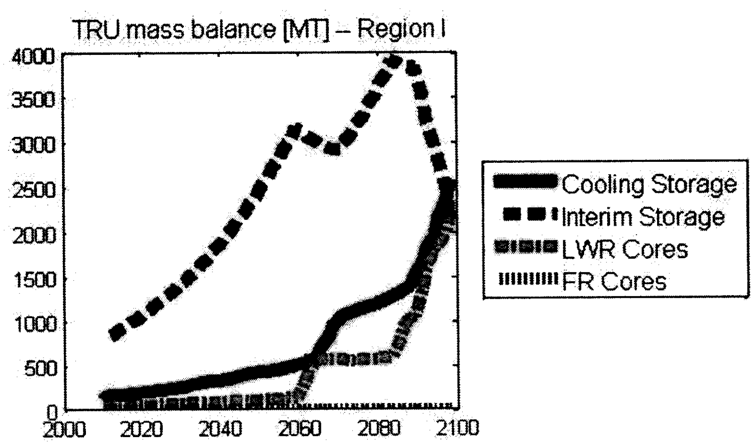
Appendix K: TRU Mass Balance – High case in CAFCA IIB with 50 year Plant Lifetime



i)

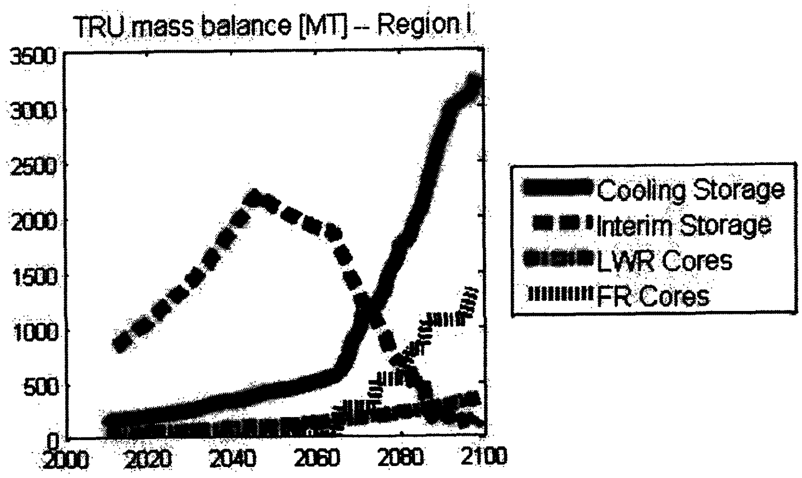


ii)

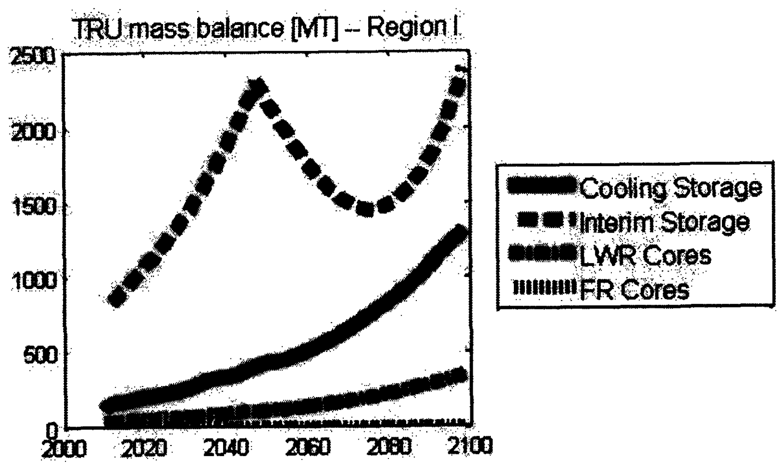


iii)

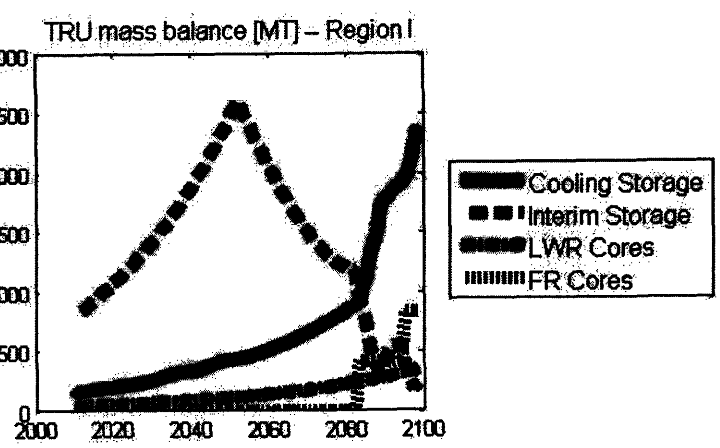
Figure 43: TRU for LWR/CONFU strategy in CAFCA IIB – High case, 50 yr. PL



i)

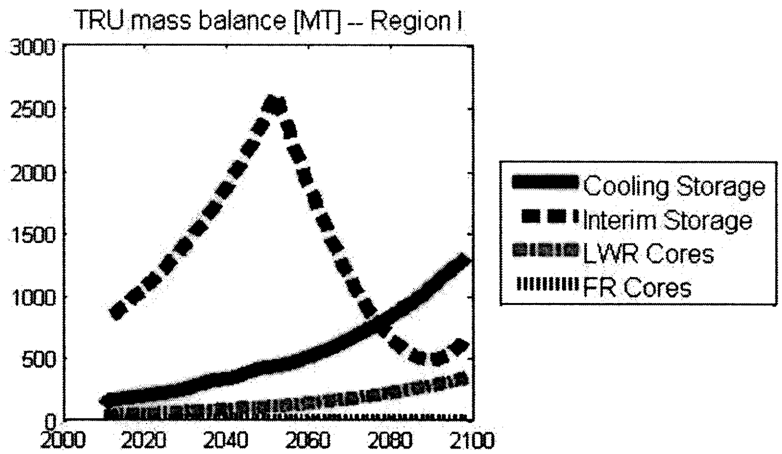


ii)

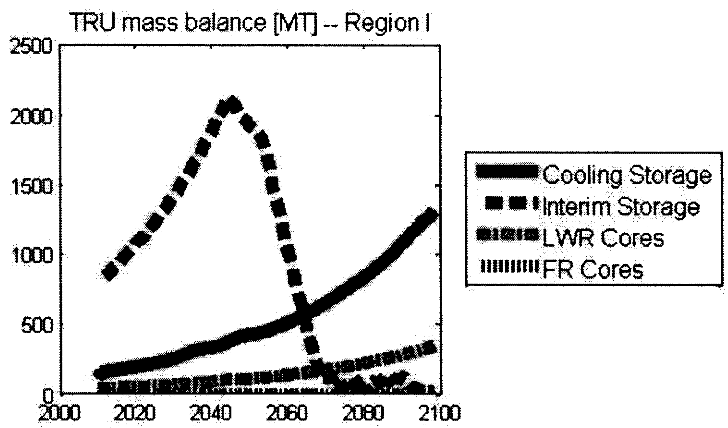


iii)

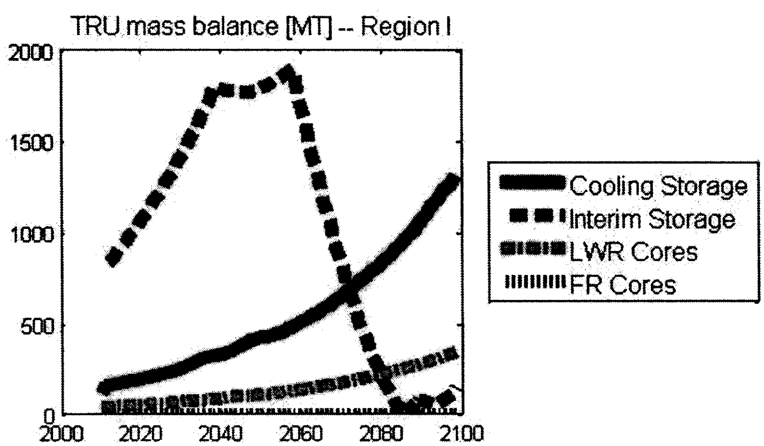
Figure 44: TRU for LWR/ABR strategy in CAFCA IIB – High case, 50 yr. PL



i)



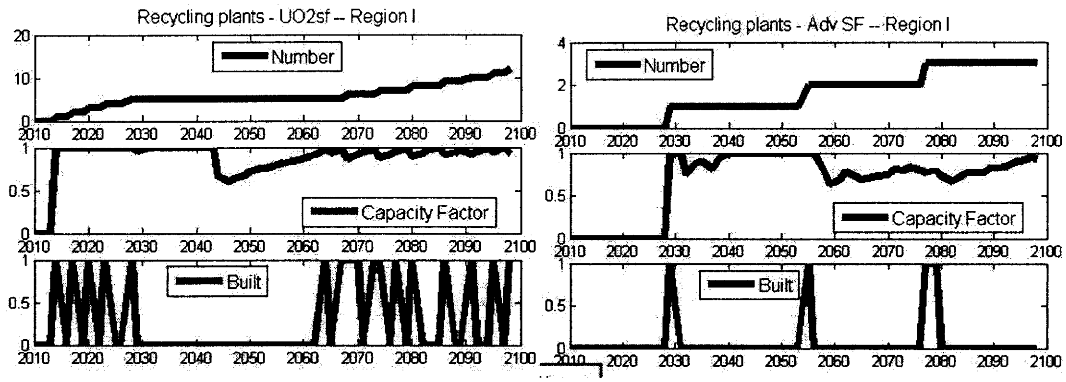
ii)



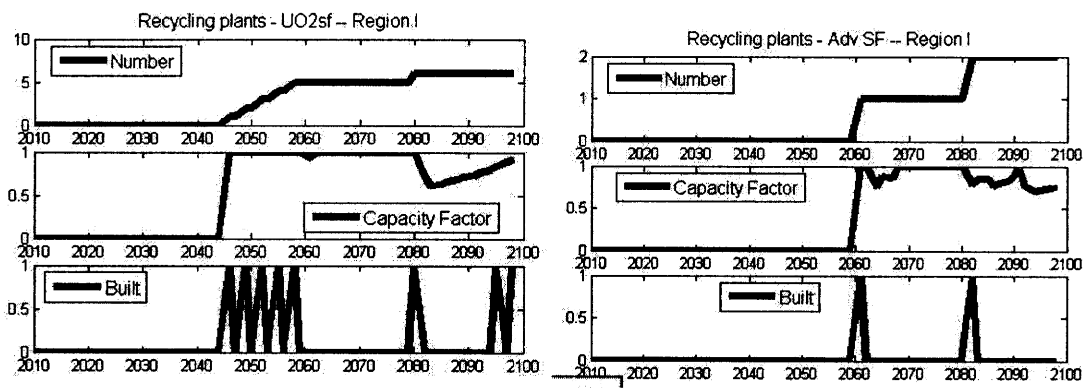
iii)

Figure 45: TRU for LWR/GFR strategy in CAFCA IIB – High case, 50 yr. PL

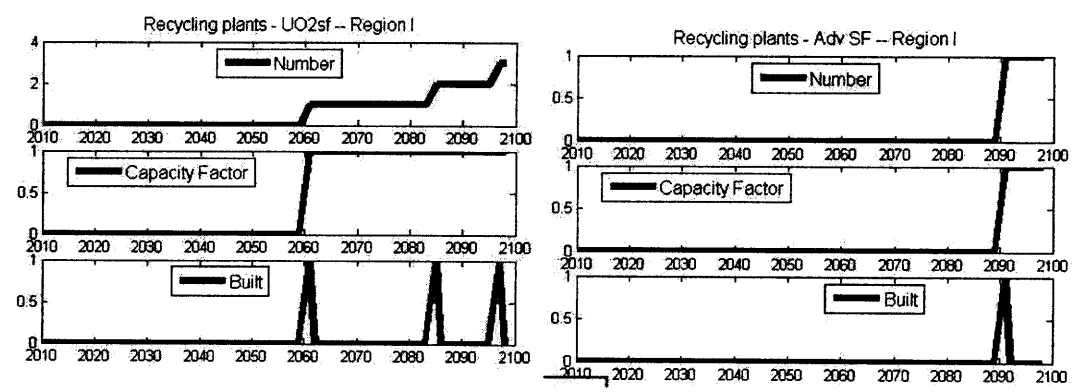
Appendix L: SF Recycling Plants – High case in CAFCA IIB with 50 year Plant Lifetime



i)

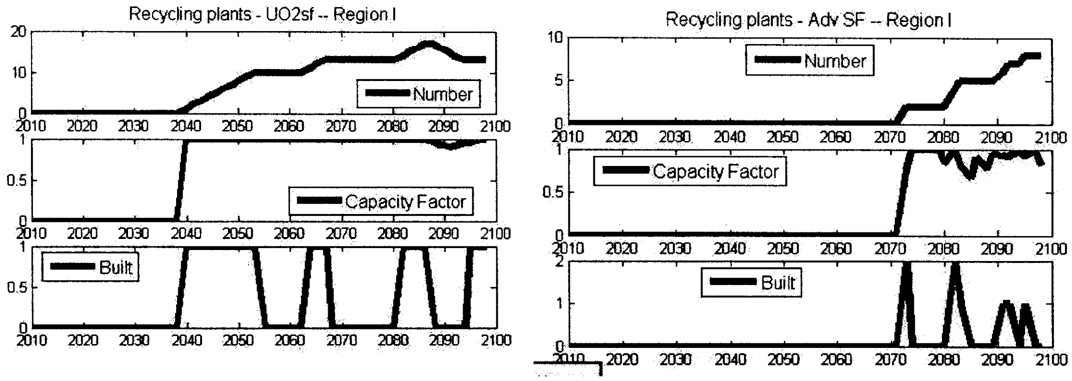


ii)

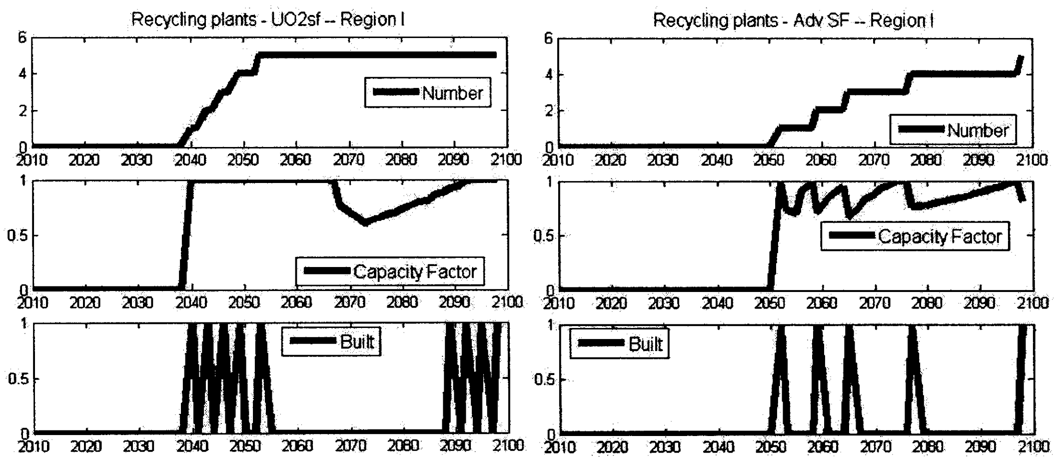


iii)

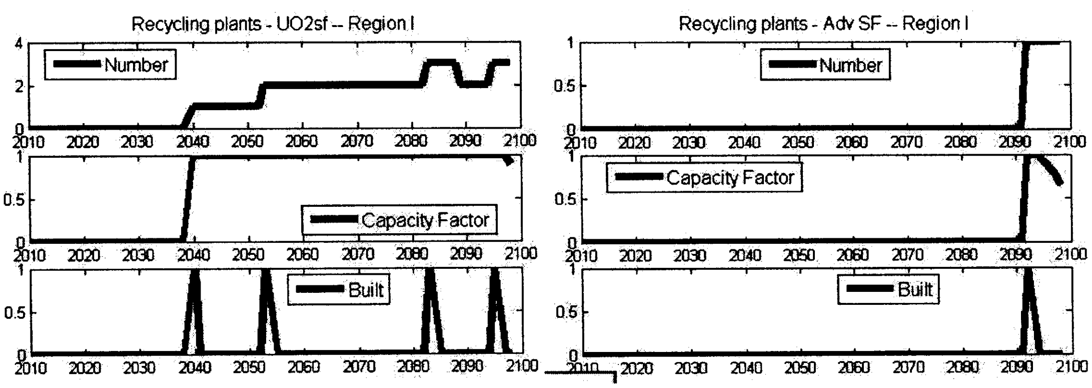
Figure 46: SFRP for LWR/CONFU strategy in CAFCA IIB – High case, 50 yr. PL



i)

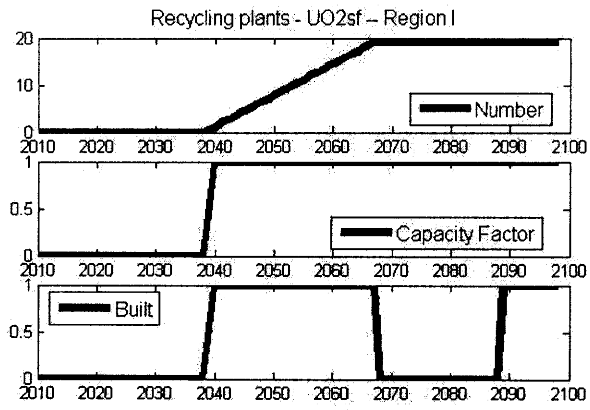


ii)

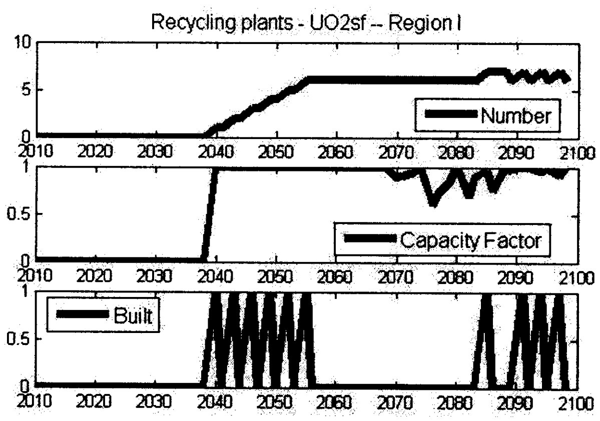


iii)

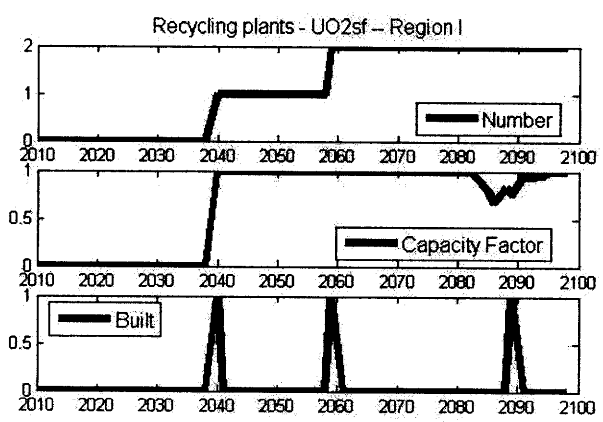
Figure 47: SFRP for LWR/ABR strategy in CAFCA IIB – High case, 50 yr. PL



i)



ii)



iii)

Figure 48: SFRP for LWR/GFR strategy in CAFCA IIB – High case, 50 yr. PL