ECONOMIC ANALYSIS METHODOLOGY OF OPEN AND CLOSED NUCLEAR FUEL CYCLES

AÇIK VE KAPALI NÜKLEER YAKIT ÇEVRİMLERİNİN EKONOMİK ANALİZİ

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ABSTRACT

This study is concerned with the economical analysis of alternative fuel cycles. Cost calculations for the five fuel cycles selected (Once- Through, Standard Reprocessing with Natural Uranium as fertile makeup, Standard Reprocessing with Recovered Uranium as fertile makeup, Complete Coprocessing with Enriched Uranium as fissile makeup, and Complete Coprocessing with Plutonium as fissile makeup) are performed using NFCCOST code which is written using FORTRAN computer language.

The main objective is to determine which fuel cycle is the best choice for certain economical conditions. Unit fabricated fuel costs are calculated and compared for fuel cycles selected. Break-even natural uranium, reprocessing and MOX fuel fabrication costs are determined for different cost conditions. Lifetime levelised fuel cycle costs are calculated and shares and effects of unit process costs in and on the fuel cycle cost are investigated.

Keywords: Fuel cycle cost, economic analysis, open and closed nuclear fuel cycles

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ÖZ

Bu çalışma alternatif yakıt çevrimlerinin ekonomik analizleriyle ilgilidir. Seçilen beş yakıt çevrimi için (Açık çevrim, standart yeniden işleme ile elde olunan Pu'un doğal U ile karıştırıldığı kapalı çevrim, standart yeniden işleme ile elde olunan Pu'un geri kazanılan U ile karıştırıldığı kapalı çevrim, beraberce yeniden işleme ile elde olunan (U+Pu)'un zenginleştirilmiş U ile karıştırıldığı kapalı çevrim, beraberce yeniden işleme ile elde olunan (U+Pu)'un Pu ile karıştırıldığı kapalı çevrim) FORTRAN bilgisayar dilinde yazılan NFCCOST kodu kullanılarak maliyet analizleri yapılmıştır.

Bu çalışmanın temel amacı belirli ekonomik koşullarda hangi yakıt çevriminin en iyi seçim olacağını belirlemektir. Seçilen yakıt çevrimleri için reaktöre girmeye hazır yakıtın birim maliyetleri hesaplanmış ve karşılaştırılmıştır. Değişik fiyat koşulları için kapalı çevrim maliyetini açık çevrim maliyetine eşit kılan doğal uranyum, yeniden işleme ve MOX fabrikasyon maliyetleri hesaplanmıştır. Reaktör ömrü üzerinden ayarlanmış yakıt çevrim maliyetleri hesaplanmış ve birim işlem maliyetlerinin toplam yakıt çevrimi maliyeti içindeki payı ve etkisi incelenmiştir.

Anahtar Sözcükler: Yakıt çevrim maliyeti, ekonomik analiz, açık ve kapalı nükleer yakıt çevrimleri

Danışman: Doç. Dr. H. Okan Zabunoğlu, Hacettepe Universitesi, Nükleer Enerji Mühendisliği Bölümü, Nükleer Enerji Mühendisliği Anabilim Dalı

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1. INTRODUCTION

1.1. The Nuclear Fuel Cycle

The nuclear fuel cycle is the path followed by the fuel in its various states, from mining the ore to the disposal of the final wastes. The cycle consists of “front-end” steps that take place after spent fuel (SF) is discharged from reactor.

The cycle is named “open” if SF is planned to be directly disposed of.

The cycle is “closed” if SF is reprocessed for recovering valuable materials in it; in a closed cycle, what goes into final disposal is “High-level waste” consisting of fission products and relatively small amounts of some actinides.

Figure 1.1 shows a general flow diagram of the nuclear fuel cycle.

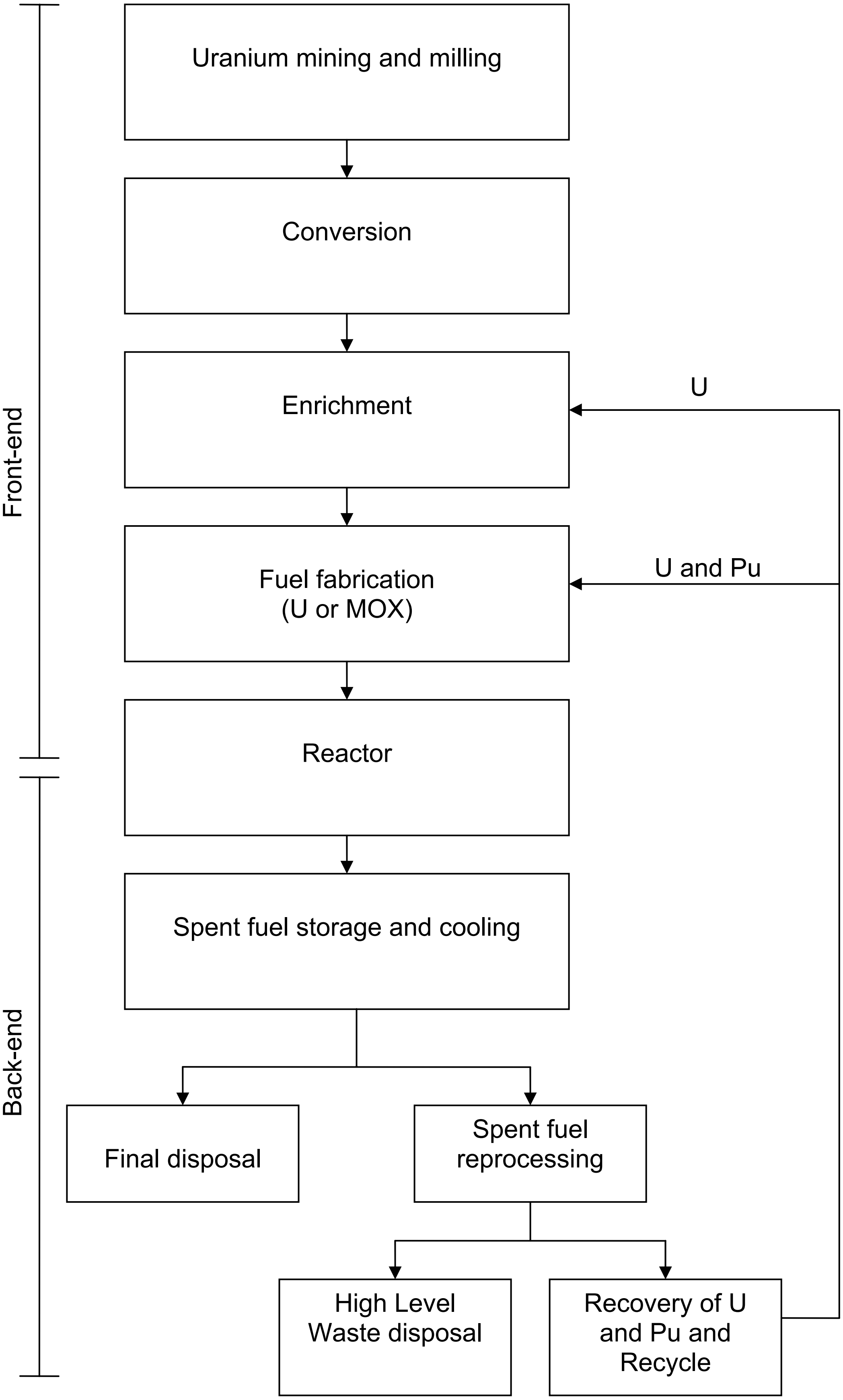

Figure 1.1. Generalized nuclear fuel cycle

1.1.1. Front End of the Nuclear Fuel Cycle

1.1.1.1. Uranium Mining, Milling and Conversion

Uranium is usually mined by either surface (open-cut) or underground mining techniques, depending on the depth at which the ore body is found.

Mined uranium ores are processed by grinding the ore materials to a uniform particle size and then treating the ore to extract the uranium by chemical leaching. The milling process yields dry powder-form material consisting of natural uranium, 'yellowcake', which is sold on the uranium market as U_3O_8.

Because uranium needs to be in the form of a gas before it can be enriched, the U_3O_8 is converted into the gaseous uranium hexafluoride (UF_6) at a conversion plant.

1.1.1.2. Enrichment

Since natural uranium contains only about 0.71 percent of the U-235 isotope and most reactors around the world use fuel containing more than 3 percent U-235, an enrichment step is necessary. Gaseous diffusion and gas centrifuge are the commonly used uranium enrichment methods.

1.1.1.3. Fabrication

Enriched UF_6 is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2) powder and pressed into small pellets. These pellets are inserted into thin tubes, usually of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel elements or assemblies for use in the core of the nuclear reactor.

1.1.2. Back End of the Nuclear Fuel Cycle

1.1.2.1. Interim Storage

During its stay in the rector core, substantial changes take place in the fuel. Parallel to the decrease of the quantity of fissile material (U-235) radioactive nuclei are produced. On one hand, fission products are produced due to fission events, on the other hand, the nuclei present in fuel (U-235, U-238) capture neutrons and transuranic isotopes evolve via series of decays. The activity of the SF is so high that it must be cooled; otherwise it may melt due to the heat released during radioactive decays. The most common method of storing SF is to use water pools which provide both cooling and shielding.

1.1.2.2. Reprocessing of Spent Fuel

SF discharged from light water reactors contains appreciable quantities of fissile (U-235, Pu-239), fertile (U-238) and other radioactive materials. These fissile and fertile materials can be chemically separated and recovered from the SF. Reprocessing is a series of physical and chemical operations that separate uranium and plutonium from fission products and other actinides. Solvent extraction is the method of reprocessing.

1.1.2.3. High Level Wastes from Reprocessing

Besides the recovered uranium and plutonium reprocessing plants produce solid, liquid and gaseous wastes. Despite small quantities involved, high level wastes from reprocessing require very great care in handling, storage and disposal because they contain fission products and transuranic elements which emit alpha, beta and gamma radiation at high levels, as well as a lot of heat arises mainly from the fission products, which mostly have short half-lives.

1.1.2.4. Final Disposal

When reprocessing option is not adopted, SF itself is considered as high level waste because of its high level of radioactivity. After removal from the reactor, the SF will normally be stored in pools at reactor site and then may be transferred to an interim store.

Fuel assemblies may, after a period of cooling, be encapsulated directly or be disassembled using remote handling techniques.

Following encapsulation, the entire amount of SF is treated as HLW and is planned to be disposed of in deep geological repositories.

1.1.2.5. Recycling

Recycling is the reintroduction of the uranium and plutonium recovered from SF into a reactor for additional energy production.

Reprocessed uranium will differ significantly from natural uranium. The U-236 isotope is a strong neutron absorber and reduces the reactivity of the reprocessed uranium. The presence of U-236 makes the reprocessed uranium more difficult to handle and also necessitates the reenrichment of such uranium to a U-235 fraction higher than that required with natural uranium feed.

Plutonium is formed in uranium fuel during the operation of reactor. Plutonium has substantial potential as source of energy, and in fact is a significant contributor to the energy produced in a uranium fueled reactor. Plutonium can be used in MOX fuel in thermal reactors, such as pressurized water reactor (PWR) or boiling water reactor (BWR), or in fast reactors. The term MOX refers to reactor fuel made from a mixture of plutonium and uranium oxide. When a fraction of a light water reactor (LWR) core; normally fueled with UO_2, is replaced by MOX fuel, many characteristics of the core change because of the different physical, chemical and neutronic properties of the MOX fuel relative to UO_2. Physically and chemically, MOX fuel behaves in much the same way as pure UO_2. But closer attention must be paid to the neutronic differences between UO_2 and MOX fuels. There are two reasons for the neutronic differences. The first is that the MOX fuel contains many plutonium isotopes (Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242). Pu-239 and Pu-241 are fissile while the others act as neutron poisons in LWRs; and as irradiation increases, the relative fraction of fissile plutonium decreases. The second reason is the parameters like cross-sections, neutrons emitted per fission, neutron lifetime, delayed neutrons, etc., are significantly different for plutonium compared to uranium.

The problems with recycled plutonium come from the increased activity of all the isotopes involved and, more importantly from change of the relative isotopic composition of such plutonium with time.

1.2. Fuel Cycle Options

1.2.1. Once-Through Cycle

If SF is not reprocessed, it is considered as high level waste, and the cycle is called "once-through (OT)". Figure 1.2. shows the material flow for the once-through LWR cycle.

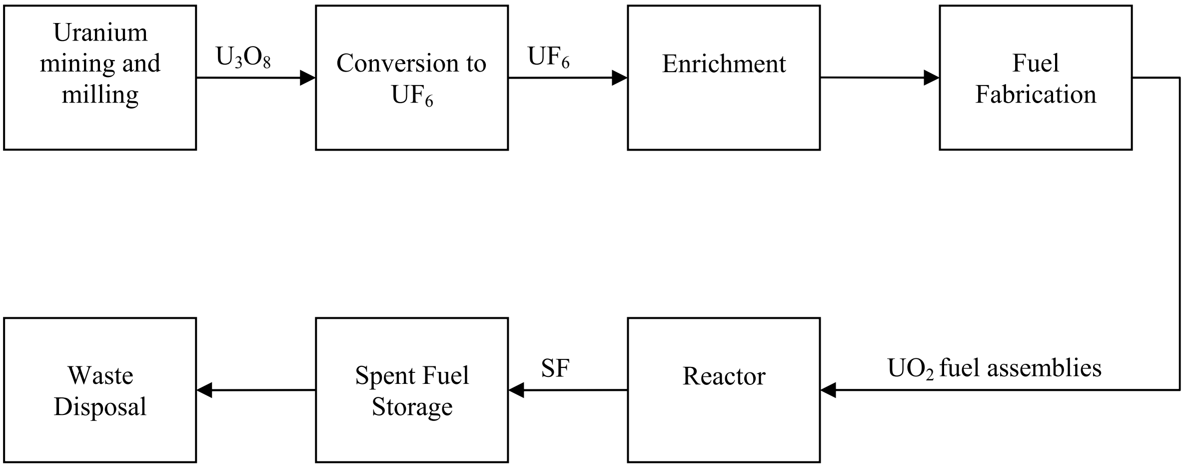

Figure 1.2. Once-through cycle

1.2.2. Closed Cycle

When fuel is reprocessed to recover and recycle the uranium and plutonium isotopes, the cycle is called "closed".

1.2.2.1. Closed Cycle with Standard Reprocessing

In the closed cycle with standard reprocessing, uranium and plutonium in SF are first separated from waste products, and then separated from each other. The recovered uranium can be returned to the conversion plant for conversion to UF_6 and subsequent reenrichment. The recovered plutonium is blended with a fertile material in order to produce MOX with an appropriate fissile content. Natural uranium (NU), recovered uranium (RU) and depleted uranium (DU) can be used as fertile makeup materials. Closed cycles applying standard reprocessing (SR) are then denoted as:

SRNU: Natural uranium is used as fertile makeup material, SRRU: Recovered uranium is used as fertile makeup material,

SRDU: Depleted uranium is used as fertile makeup material.

Figure 1.3. shows the material flow for closed cycle with standard reprocessing.

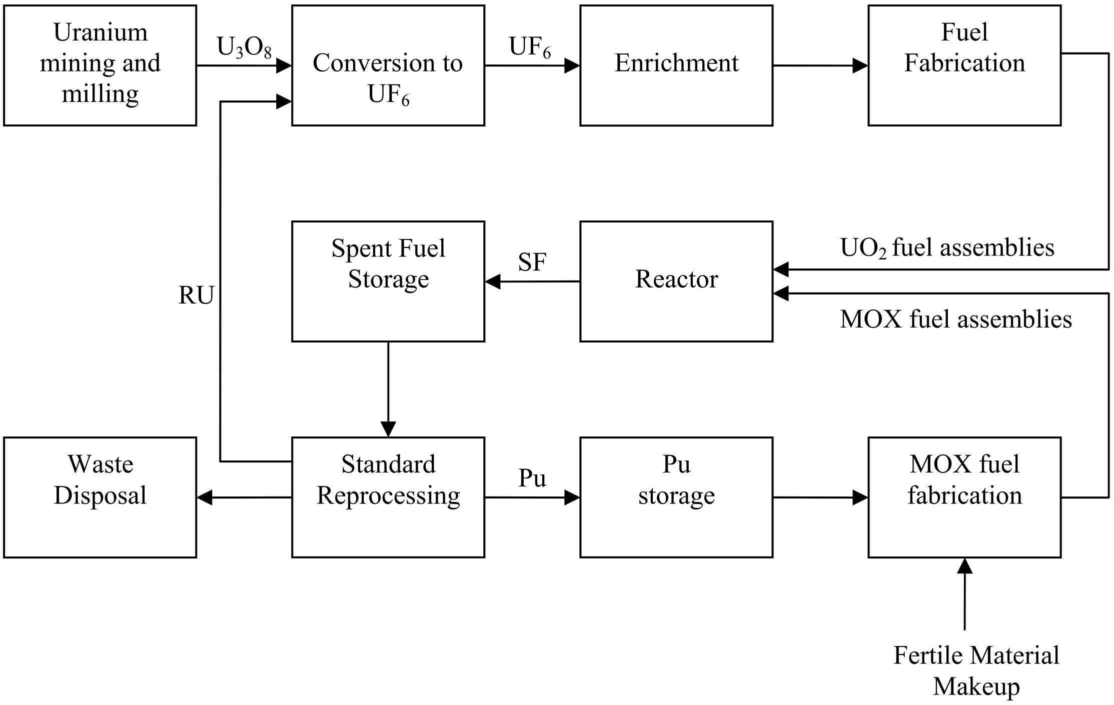

Figure 1.3. Closed cycle with standard reprocessing

1.2.2.2. Closed Cycle with Complete Coprocessing

In the closed cycle with complete coprocessing, uranium and plutonium in SF are separated from waste products together. The product of complete coprocessing is a mixed uranium and plutonium solution. This product is blended with a fissile makeup material for producing MOX with a proper fissile content. Enriched uranium (EU) and plutonium from a standard reprocessing plant can be used as fissile makeup materials. Closed cycles applying complete coprocessing (CC) are then denoted as:

CCEU: Enriched uranium is used as fissile makeup material,

CCPu: Plutonium from standard reprocessing is used as fissile makeup material.

Figure 1.4. shows the material flow for closed cycle with complete coprocessing.

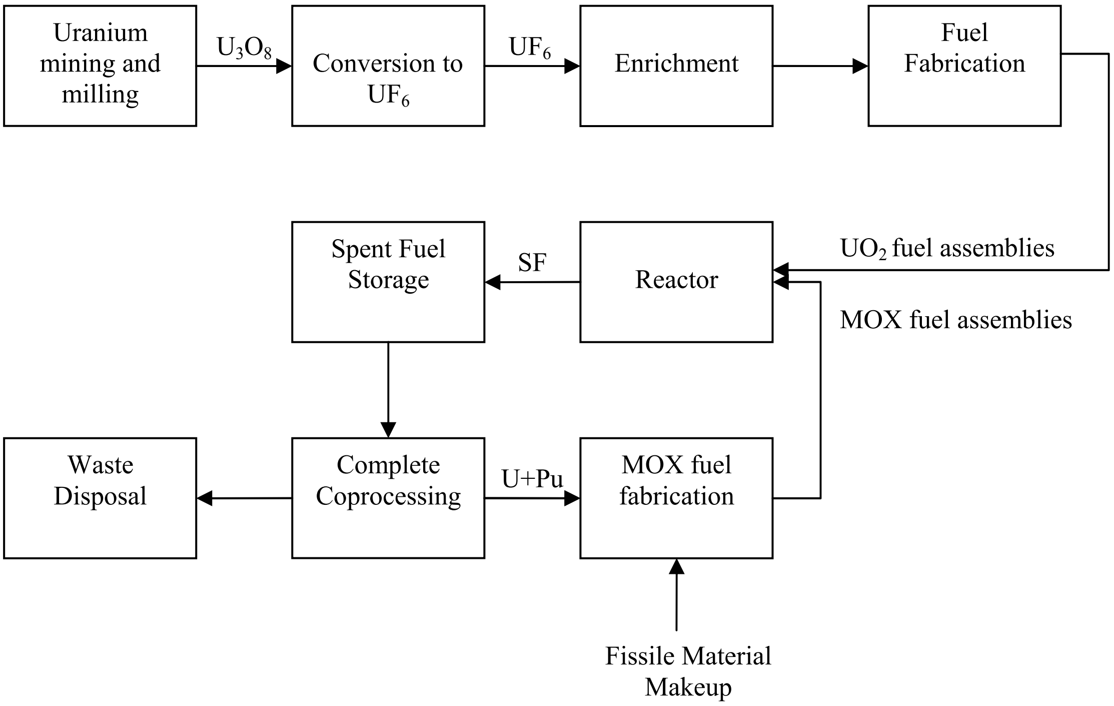

Figure 1.4. Closed cycle with complete coprocessing

1.2.2.3. Closed Cycle with Reprocessing Spent MOX

In this cycle, after SF is reprocessed to recover U and Pu in it, the recovered uranium is recycled and the recovered plutonium is used to produce MOX fuel, then MOX fuel is irradiated in the reactor. After irradiation, spent MOX (SMOX) is reprocessed to recover plutonium. This plutonium is used to produce new MOX fuel and this MOX fuel is also sent to reactor. After irradiation, spent MOX fuel (SMOX1) can be reprocessed or disposed, depending on its fissile content and neutronic properties. Figure 1.5. shows the material flow for closed cycle with MOX reprocessing.

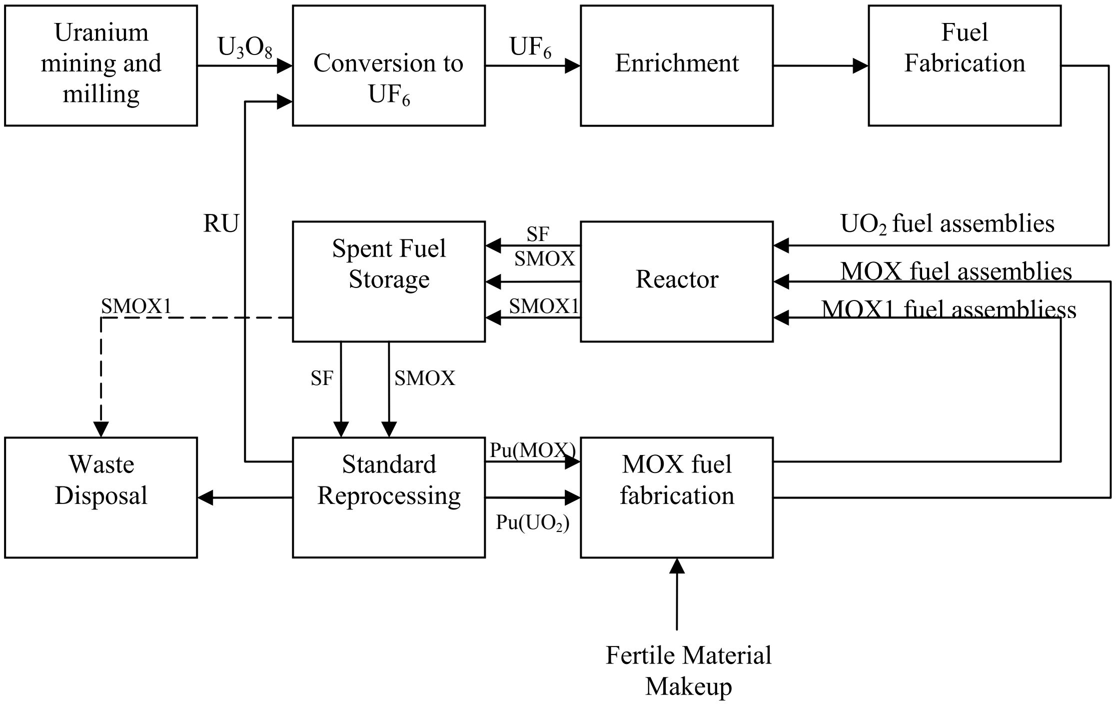

Figure 1.5. Closed cycle with reprocessing spent MOX

2. BURNUP-ENRICHMENT CALCULATIONS

2.1. Reference Reactor

The reference reactor chosen for this study is a typical pressurized water reactor of 1000 MWe. Main characteristics of reference reactor are given in Table 2.1.

Table 2.1. Main characteristics of reference reactor

Reactor Type	PWR
Fuel Type	UO_2
Fuel Enrichment (wt %)	3.3
Power (MWe)	1000
Thermal Efficiency (%)	32.5
Capacity Factor (%)	80
Fuel Exposure Time (day)	1100
Burnup (MWd/tU)	33000

2.2. Non-linear Reactivity Model

Linear and non-linear reactivity models are used to determine the discharge burnup of light water reactors [1].

Assuming constant power generation, the burnup of the fuel can be found as;

$$\int^{B_d} [\rho(B) - \rho_L] dB = 0 \tag{2.1}$$

where B : Burnup (MWd/tU)

B_d : Discharge Burnup (MWd/tU)

ρ_L : Leakage Reactivity

$\rho(B)$: Reactivity at Burnup B

In non-linear reactivity model, reactivity is a higher order polynomial function of burnup. In this study, a second order polynomial is used to determine reactivity as a function of burnup.

$$\rho(B) = A_0 + A_1 B + A_2 B^2 \tag{2.2}$$

For n=3 batches reactor, equation 2.1 can be written as;

$$\frac{\rho(B_d) + \rho(2B_d) + \rho(3B_d)}{3} = \rho_L \tag{2.3}$$

$$\frac{14}{3} A_2 B_d^2 + 2A_1 B_d + \left(A_0 - \rho_L\right) = 0 \tag{2.4}$$

The root of the equation 2.4 is the discharge burnup B_d.

2.3. Burnup-Enrichment Calculation

MONTEBURNS computer code is used to calculate leakage reactivity (ρ_L) of reference reactor (ρ_L=0.127332). A short description of MONTEBURNS code is presented in Appendix A.

For different UO_2 fuel enrichments in the range of 3.3 wt % to 5 wt %, MONTEBURNS code is used to obtain reactivity change with fuel burnup. By using the non-linear reactivity model for n=3 batches (Equation 2.4), discharge burnup values are calculated. Discharge burnup of different enrichments are shown in Figure 2.1.

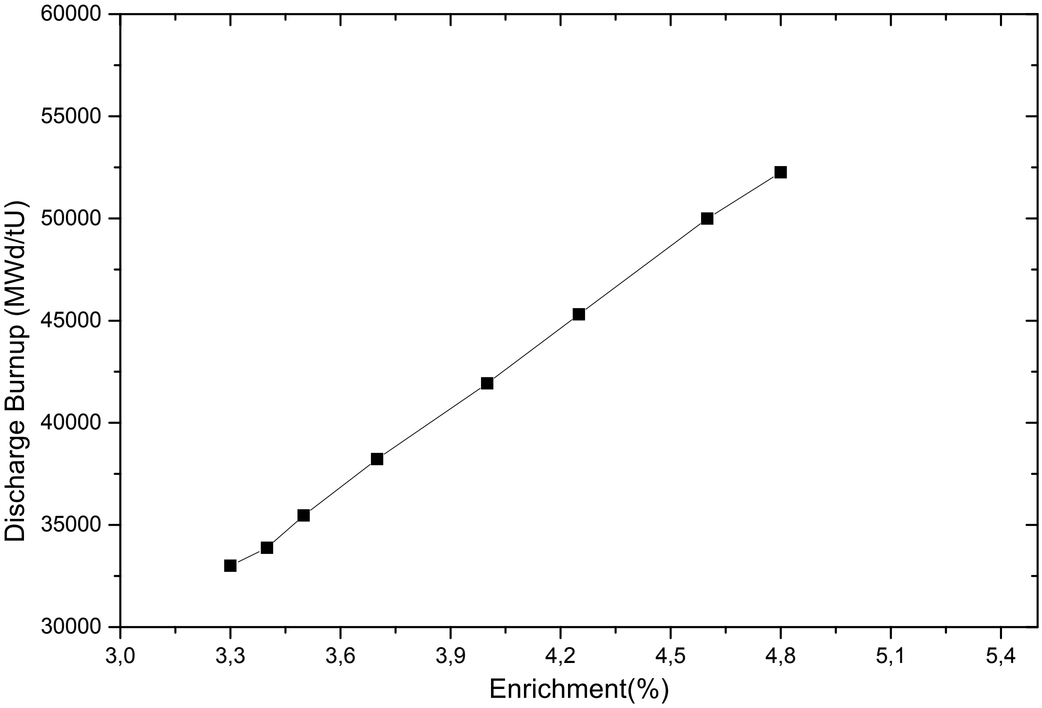

Figure 2.1. Discharge burnup of UO_2 fuels with different enrichments

By fitting this curve, a linear relationship between enrichment (ε) and discharge burnup (B_d) is found:

$$B_d = 12982\varepsilon - 9991,2 \tag{2.5}$$

where B_d in MWd/tU, and ε in % enrichment.

In the cost analysis; 33000 MWd/tU, 40000 MWd/tU, 50000 MWd/tU burnup values are used and fuel enrichments needed to reach these burnups are calculated from Equation 2.5. These enrichment values are given in Table 2.2.

Table 2.2. Fuel enrichments needed to reach selected burnup values

Burnup (MWd/tU)	Enrichment (wt %)
33000	3.30
40000	3.85
50000	4.63

2.4. Calculation of Equivalent MOX Composition

Because of the existence of poisonous isotopes of uranium and plutonium in SF, the fissile content of MOX fuel must be higher than that of the fresh fuel used.

In this section, for different fuel cycle cases, total fissile content of MOX fuels which are equivalent to the fresh UO_2 fuels with enrichments 3.3 wt %, 3.85 wt % and 4.63 wt % are determined by discharge burnup calculations using the non-linear reactivity model.

Cases:

SRNU: Standard reprocessing using natural uranium as fertile makeup material

SRRU: Standard reprocessing using recovered uranium as fertile makeup material

CCEU: Complete coprocessing using enriched uranium as fissile makeup material

CCPu: Complete coprocessing using plutonium from standard reprocessing as fissile makeup material

2.4.1. Method of Calculation

Schematic view of calculation steps of equivalent MOX composition is presented in Figure 2.2.

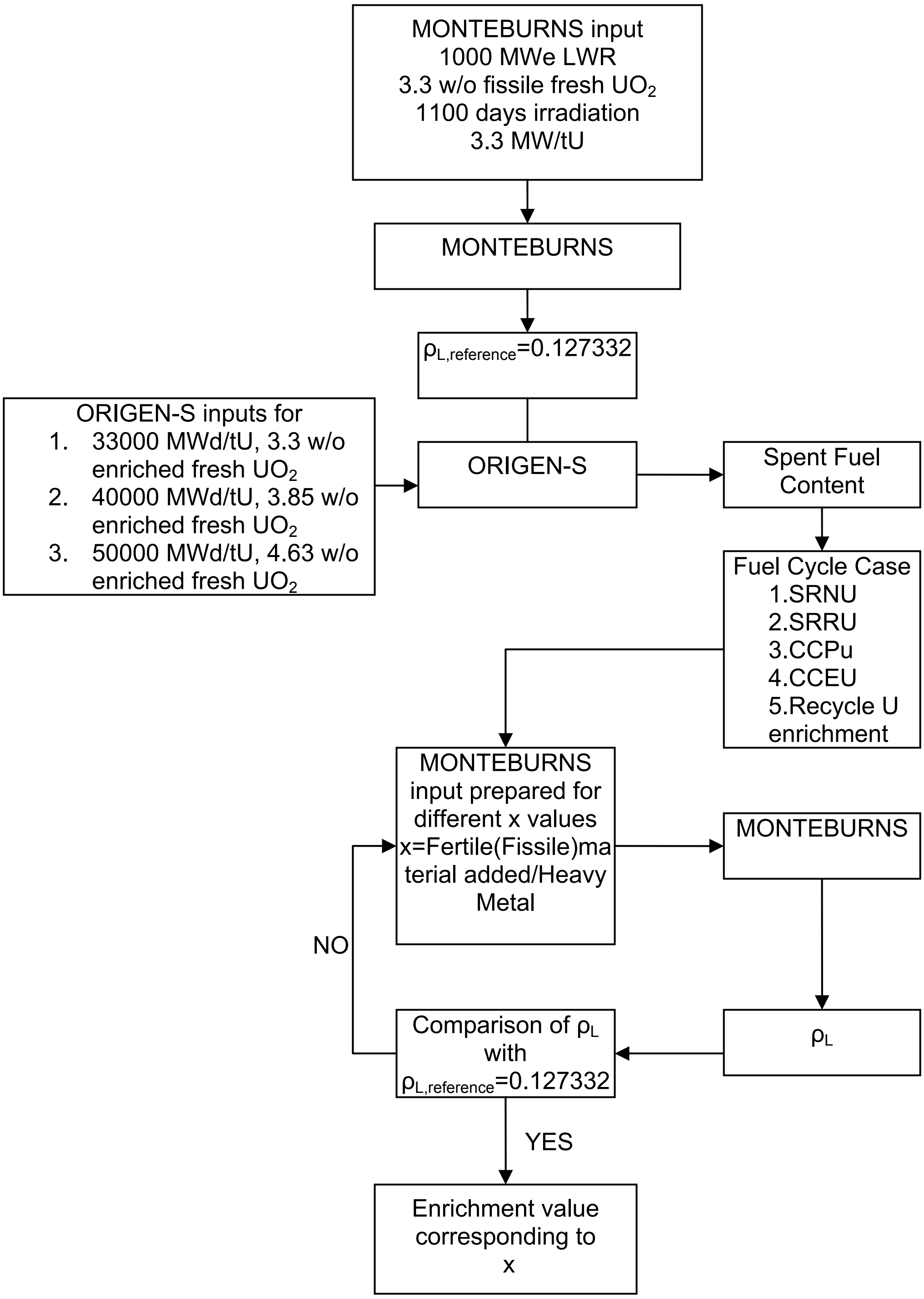

Figure 2.2. Schematic view of calculation steps of equivalent MOX composition

Reference reactor power (1000 MWe) is kept constant and compositions of SFs exposed to burnups of 33000 MWd/tU, 40000 MWd/tU, 50000 MWd/tU and cooled for 5 years are calculated using the ORIGEN-S depletion code. A short description of ORIGEN-S is presented in Appendix A. Uranium and Plutonium isotopes in SFs of burnups 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU are shown in Table 2.3.

Table 2.3. U and Pu Isotopes in SFs of Burnups 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU

Nuclide	Burnup (MWd/tU)		
	33000	40000	50000
U233 (gr)	5.59312E-03	5.92917E-03	6.305179E-03
u234 (gr)	1.29484E+02	1.20885E+02	1.121643E+02
u235 (gr)	8.19263E+03	7.87974E+03	7.251146E+03
u236 (gr)	4.52078E+03	5.46242E+03	6.756121E+03
u237 (gr)	2.41501E-05	2.68658E-05	2.972513E-05
u238 (gr)	9.43358E+05	9.35063E+05	9.231404E+05
Total U (gr)	9.56201E+05	9.48526E+05	9.372599E+05
Pu236 (gr)	4.21146E-04	6.22680E-04	1.005632E-03
Pu238 (gr)	1.60462E+02	2.36805E+02	3.681465E+02
Pu239 (gr)	5.25989E+03	5.26583E+03	5.256023E+03
Pu240 (gr)	2.14843E+03	2.27115E+03	2.387643E+03
Pu241 (gr)	7.96745E+02	8.86338E+02	9.806718E+02
Pu242 (gr)	3.40289E+02	4.35734E+02	5.664184E+02
Total Pu (gr)	8.70582E+03	9.09586E+03	9.558902E+03
Fissile U (%)	0.85679	0.83074	0.77365
Fissile Pu (%)	69.56998	67.63704	65.24489
FissileU+Pu (%)	1.47675E+00	1.46529E+00	1.42454E+00

For all fuel cycles, these SF contents are used to produce MOX fuels which are equivalent to fresh UO_2 fuels. By using different fertile or fissile makeup material ratios x (x=Added fertile or fissile material/Total Heavy Metal), new fuel compositions are prepared. For these compositions, MONTEBURNS code is used to obtain reactivity change with fuel burnup. By using the non-linear reactivity model for n=3 batches (Equation 2.4), discharge burnup values are calculated. For four cases

SRNU, SRRU, CCEU, CCPu with 33000 MWd/tU burnup, discharge burnups are plotted versus x and given in Figures 2.3, 2.4, 2.5 and 2.6 respectively.

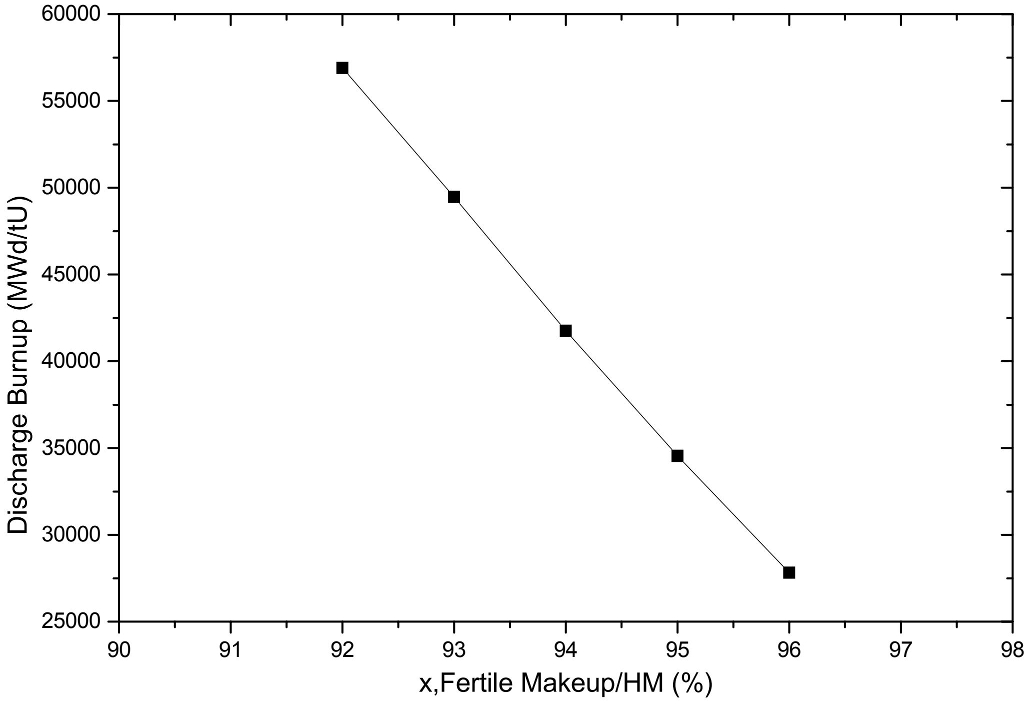

Figure 2.3. Discharge burnup vs. x, 33000 MWd/tU SRNU case

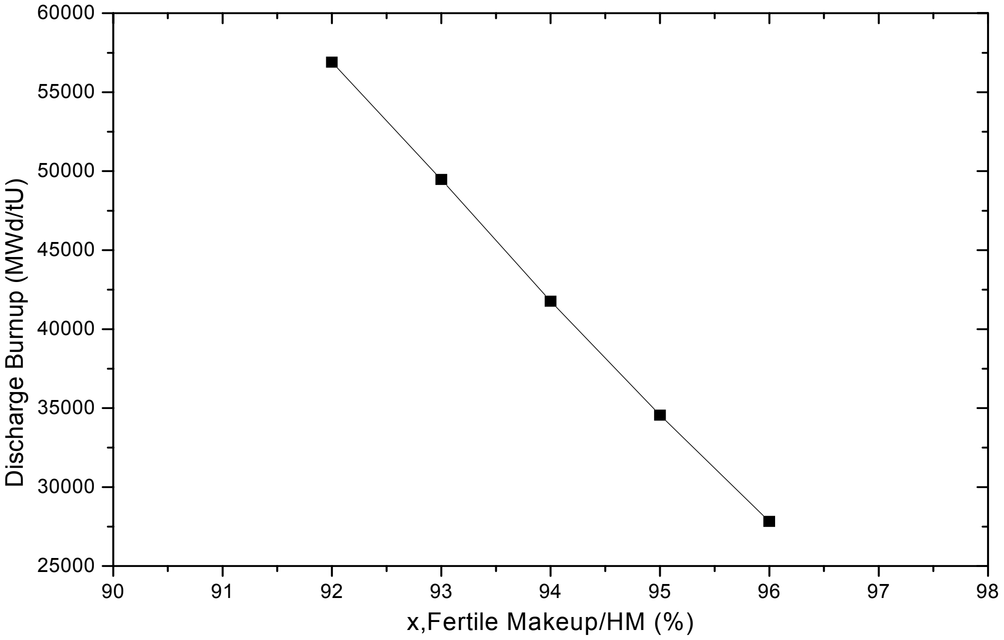

Figure 2.4. Discharge burnup vs.x, 33000 MWd/tU SRRU case

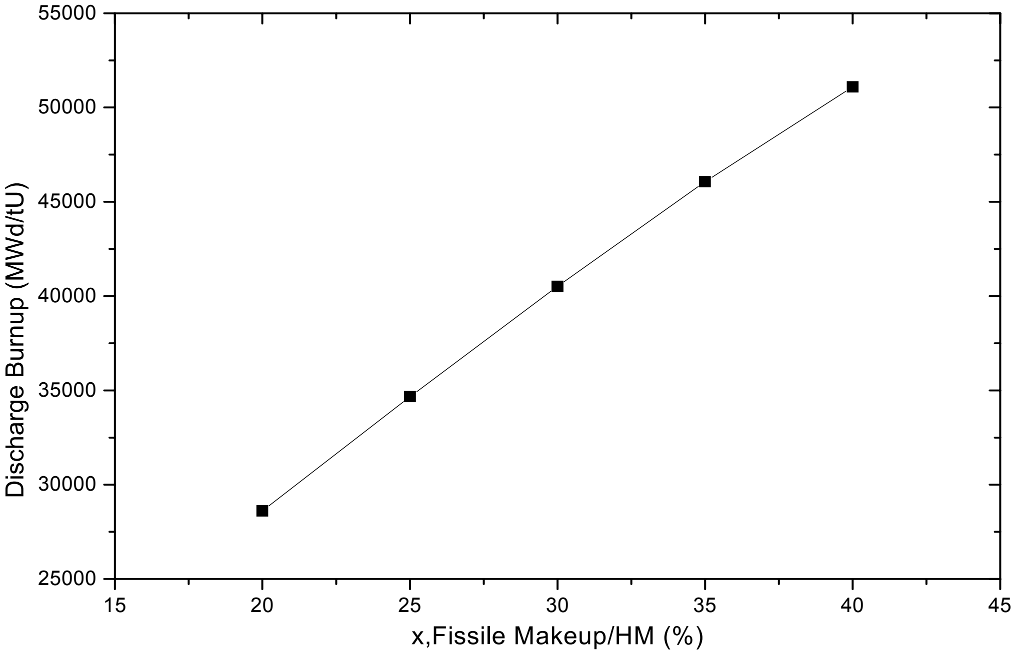

Figure 2.5. Discharge burnup vs.x, 33000 MWd/tU CCEU case

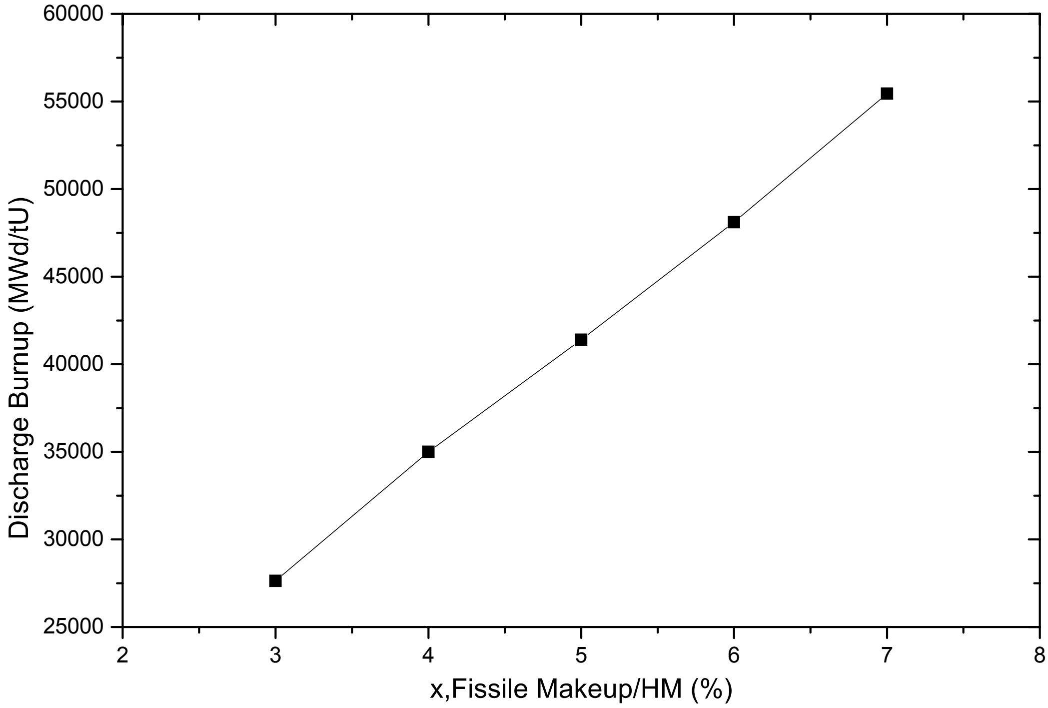

Figure 2.6. Discharge burnup vs. x, 33000 MWd/tU CCPu case

For cases SRNU, SRRU, CCEU, CCPu with 40000 MWd/tU and 50000 MWd/tU burnups, plots of x versus discharge burnups are given in Appendix B.

By fitting these curves, a linear relationship between x and discharge burnup (B_d) is obtained for all fuel cycle cases. These relationships are in the form of $B_d = a_0\chi + a_1$ and a_0 and a_1 coefficients for each case are presented in Table 2.4.

Table 2.4. a_0 and a_1 coefficients for each fuel cycle case

Burnup MWd/tU	Fuel Cycle Case							
	SRNU		SRRU		CCEU		CCPu	
	a_0	a_1	a_0	a_1	a_0	a_1	a_0	a_1
33000	-7541.6	751708	-7307.4	728998	1127.8	6354.2	6872.7	7154.5
40000	-7170.8	715337	-6467.3	647409	1150.5	5188.3	7046.6	5486.4
50000	-6558.0	655060	-6201.9	619817	1138.4	4992.3	6945.3	4850.7

These linear equations are used to calculate x values needed to obtain MOX fuels which are equivalent to fresh UO_2 fuels, and with the x values at hand, MOX enrichments are calculated. Equivalent MOX enrichments for each case are presented in Table 2.5.

Table 2.5. Equivalent MOX enrichment for each fuel cycle case

Burnup	Fuel Cycle Case			
MWd/tU	SRNU	SRRU	CCEU	CCPu
33000	3.95	4.12	3.49	4.04
40000	4.72	5.04	4.07	4.81
50000	5.71	6.01	4.82	5.86

These MOX enrichments are used in fuel cycle cost analysis.

2.5. Recycle Uranium Enrichment Calculation

Recovered uranium from SF will differ from natural uranium because of the presence of isotope U-236. Due to the presence of U-236 isotope, which is a strong neutron absorber, recycle uranium is reenriched to a U-235 fraction higher than that required with natural uranium feed.

In this section, the fissile contents of recycle uranium equivalent to 3.3 wt %, 3.85 wt % and 4.63 wt % enriched fresh uranium are estimated by discharge burnup calculations using the non-linear reactivity model. Discharge burnup vs. ε graphs are obtained for 33000 MWd/tU, 40000 MWd/tU, 50000 MWd/tU burnup values, and these graphs are presented in Figures 2.7, 2.8 and 2.9, respectively.

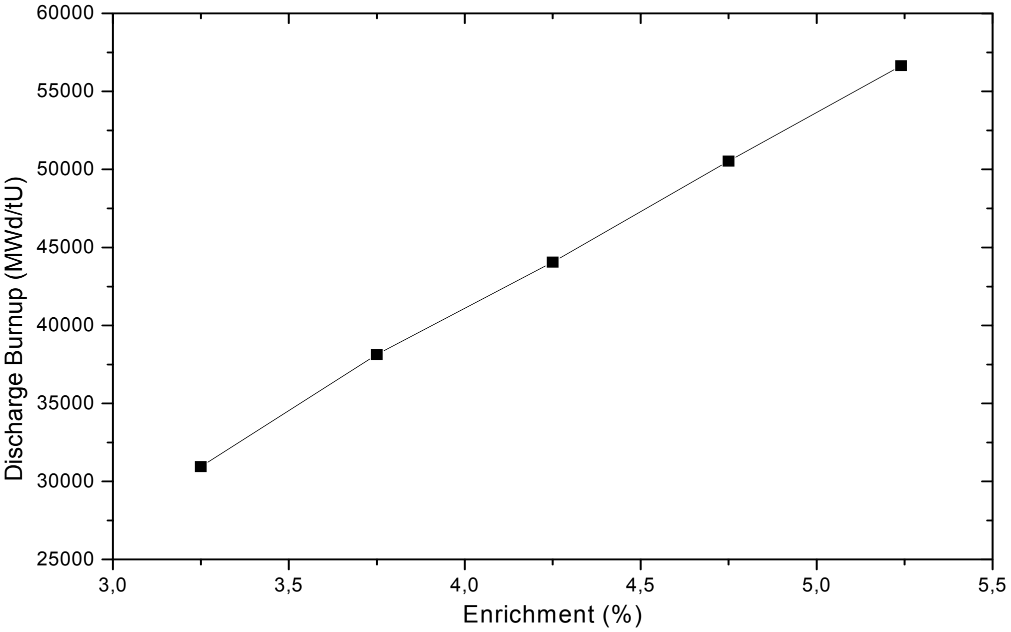

Figure 2.7. Discharge burnup vs. enrichment of recycle uranium obtained from SF burned to 33000 MWd/tU

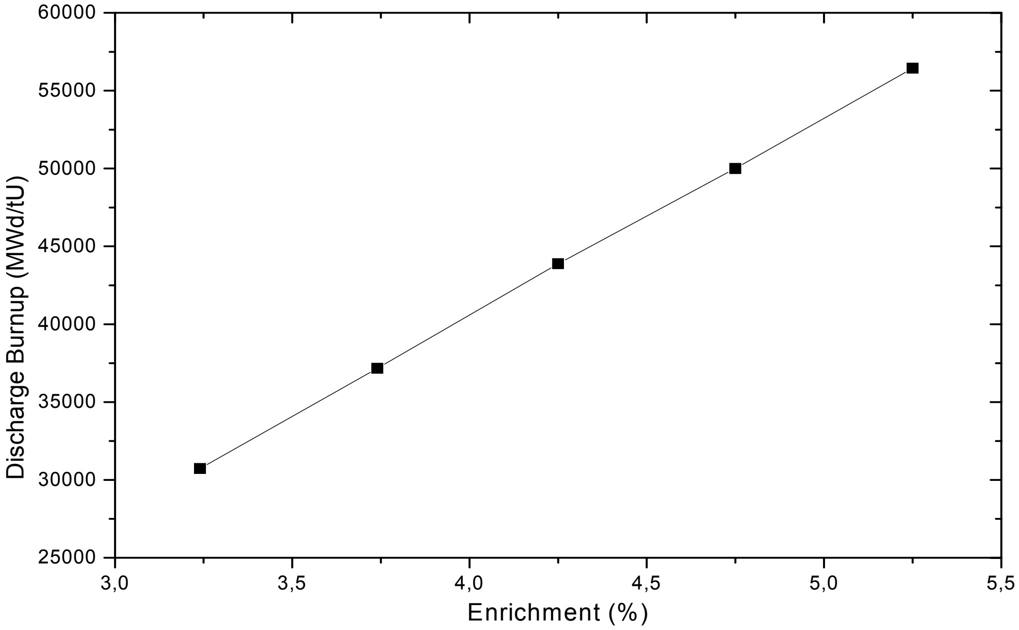

Figure 2.8. Discharge burnup vs. enrichment of recycle uranium obtained from SF burned to 40000 MWd/tU

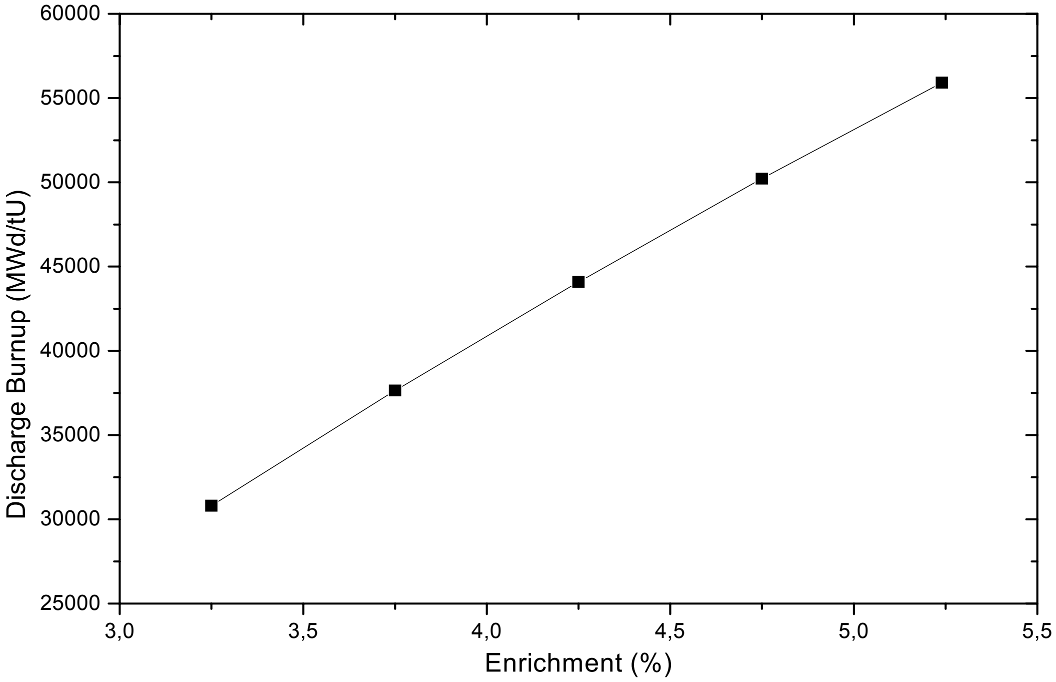

Figure 2.9. Discharge burnup vs. enrichment of recycle uranium obtained from SF burned to 50000 MWd/tU

By fitting these curves, linear relationships between recycle uranium enrichment and discharge burnup (B_d) are obtained. These relationships are in the form of $B_d = a_0\varepsilon + a_1$, and a_0 and a_1 coefficients are presented in Table 2.6.

Table 2.6. a_0 and a_1 coefficients for recycle uranium case

Burnup (MWd/tU)	Recycle Uranium Case	
	a_0	a_1
33000	12811	-10356
40000	12779	-10613
50000	12609	-9832

These linear equations are used to calculate recycle uranium fissile content equivalent to 3.3 wt %, 3.85 wt % and 4.63 wt % enriched fresh uranium. Equivalent recycle uranium enrichments are presented in Table 2.7.

Table 2.7. Equivalent recycle uranium enrichments

Burnup (MWd/tU)	Fresh Fuel Enrichment (wt %)	Recycle Uranium Enrichment (wt %)
33000	3.30	3.383
40000	3.85	3.931
50000	4.63	4.750

These recycle uranium enrichments are used in cost analysis.

The fissile content of the multiple recycled uranium equivalent to 3.3 wt % enriched fresh uranium is also investigated and results are presented in Table 2.8

Table 2.8. Multiple recycled uranium enrichments for 33000 MWd/tU

Uranium Recycling number	Equivalent Enrichment
1	3.383
2	3.434
3	3.457
4	3.531
5	3.660
6	3.688
7	3.781

2.6. Multiple Recycled MOX Fuel Enrichment Calculation

Multiple recycling of the spent MOX fuel from SRNU cycle is considered here. In this case, the spent MOX fuel is reprocessed to recover plutonium and this plutonium is used to produce fresh MOX fuel with fissile content equivalent to 3.3 wt% enriched fresh UO_2 fuel. Equivalent compositions are calculated for multiple recycled MOX fuel by using the same method described in section 2.4. The fissile contents of the multiple recycled MOX fuels equivalent to 3.3 wt % enriched fresh UO_2 fuel are presented in Table 2.9.

Table 2.9. Multiple recycled MOX fuel enrichments for SRNU with 33000 MWd/tU

MOX Recycling number	MOX enrichment
MOX disposal	-
MOX recycled once	3.95
MOX recycled 2nd	5.01
MOX recycled 3rd	5.99
MOX recycled 4th	6.84
MOX recycled 5th	7.39

The increment in equivalent MOX fuel enrichment is decreases with recycling number. This decrease can be observed from Figure 2.10.

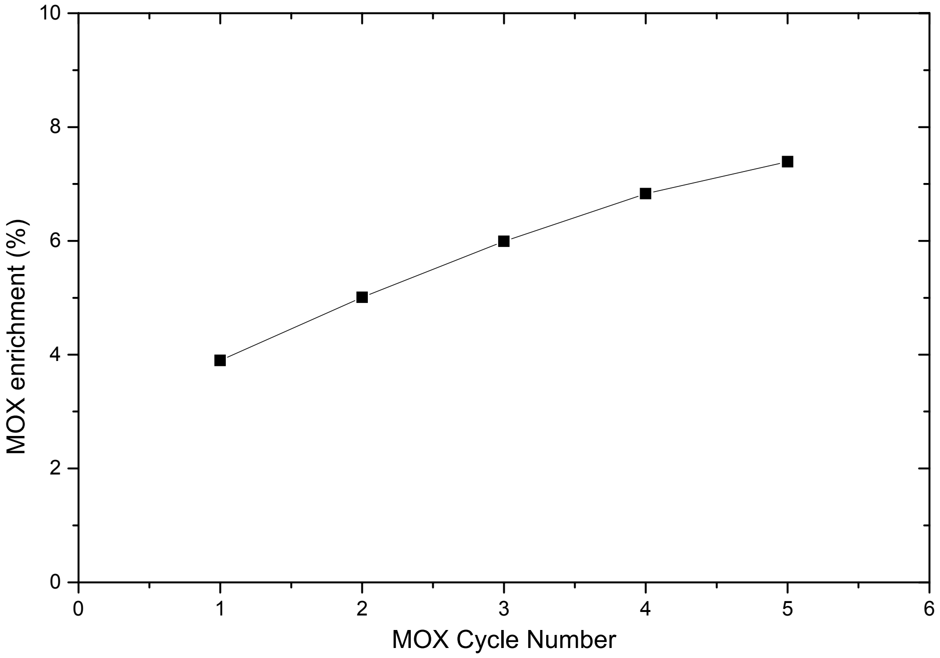

Figure 2.10. MOX enrichment change with recycling number

As shown in Figure 2.11, isotopic content of plutonium in spent MOX fuels change with recycling number.

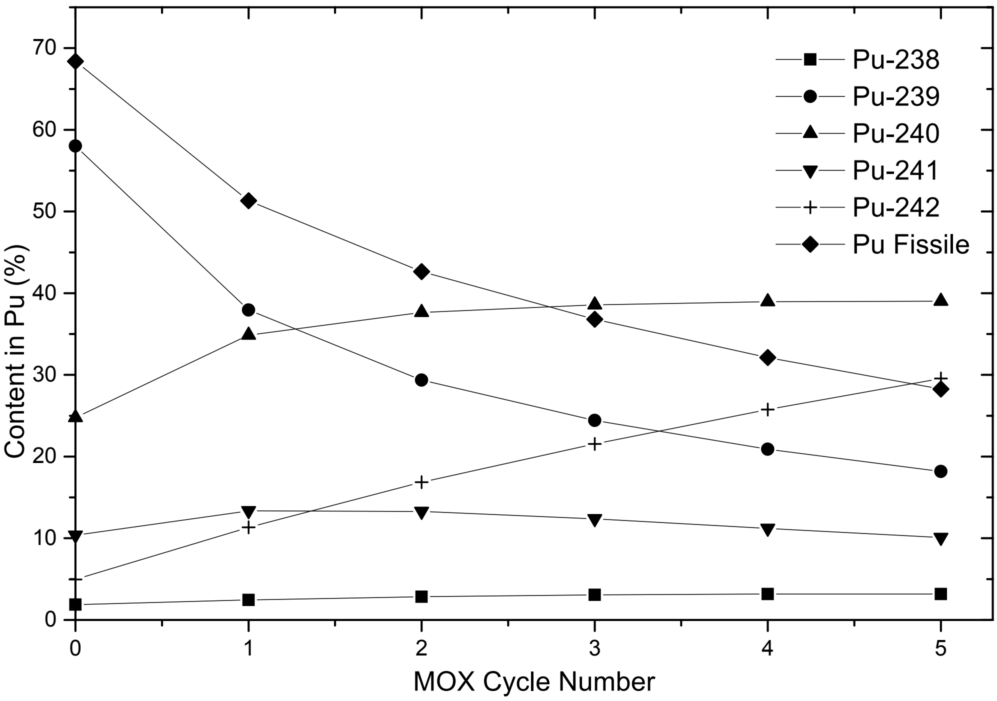

Figure 2.11. Change of isotopic content of Pu in SF with MOX recycling

Total fissile Pu content of spent MOX fuel decreases with MOX recycling, and fraction of parasitic isotopes Pu-240 and Pu-242 increase. Because of penalties mainly resulting from these isotopes, total fissile content of MOX that makes it equivalent to the 3.3 wt% enriched fresh U fuel increases with cycle number.

3. FUEL CYCLE COST ANALYSIS

Fuel cycle cost analyses are performed using the NFCCOST code which is written using FORTRAN programming language. Figure 3.1 shows the flow diagram of NFCCOST code.

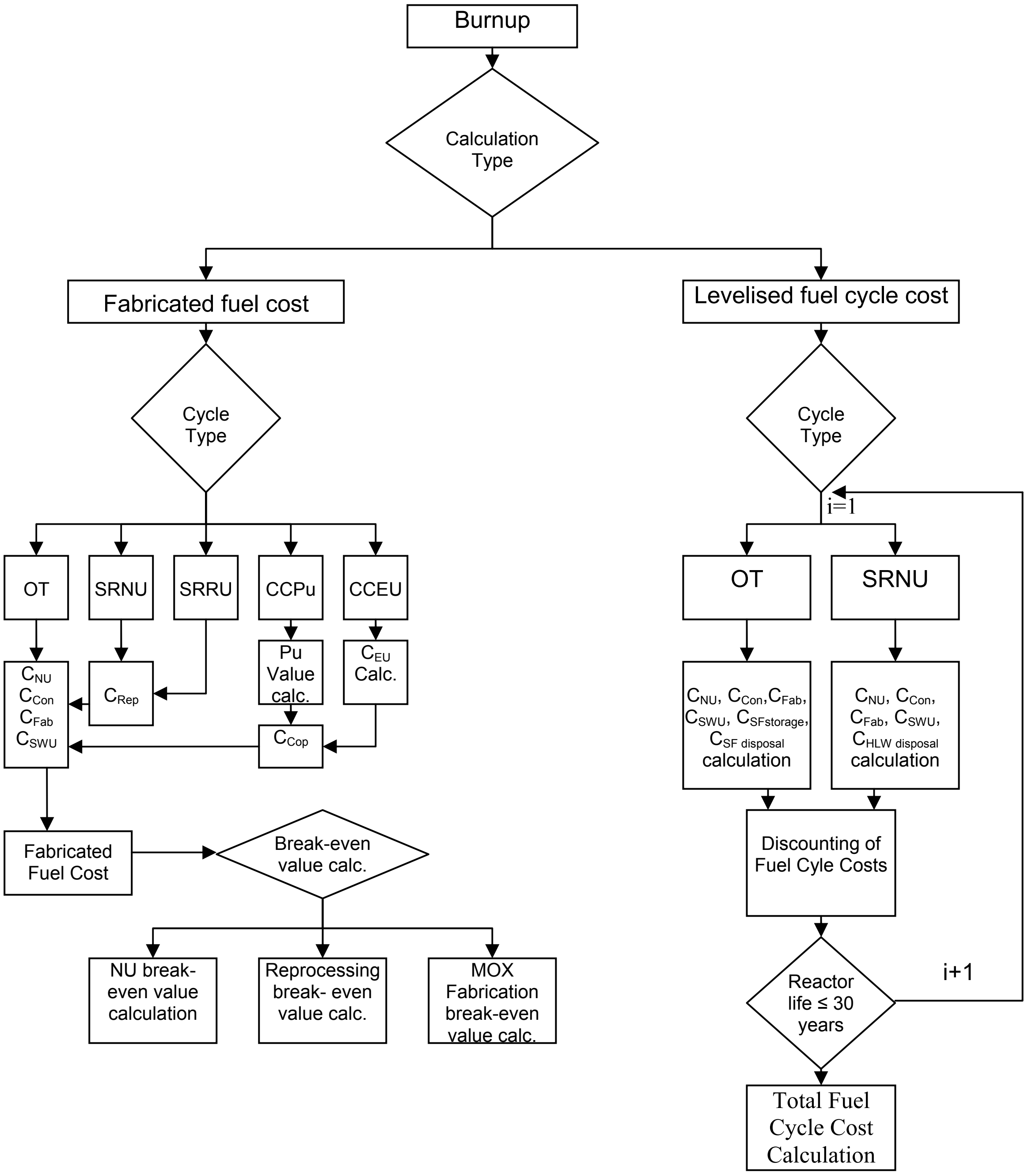

Figure 3.1. Flow diagram of NFCCOST code

In this chapter, nuclear fuel cycle costs for once-through, standard reprocessing and coprocessing cycles are evaluated. Cost analysis are made for 1000 MWe LWRs fueled with 3.3 wt %, 3.85 wt % and 4.63 wt % enriched UO_2 fuels. Cost analyses of closed cycles are based on one ton of SF and contents of SFs for each case are given in Table 3.1.

Table 3.1. Spent fuel contents used in cost analysis

Burnup (MWd/tU)	Enrichment (%)	Plutonium content (kg)	Uranium content (kg)	Fissile Pu (%)	Fissile U (%)
33000	3.3	8.71	956.2	69.57	0.85
40000	3.85	9.10	948.5	67.64	0.83
50000	4.63	9.56	937.3	65.24	0.77

3.1. Fuel Cycle Costs

3.1.1. Once-through Cycle

Unit costs for natural uranium purchase, conversion, enrichment, and fabrication stages of once-through cycle are added together in order to calculate unit cost of enriched and fabricated fuel ready to feed into reactor. Unit cost of fabricated fuel in once-through cycle can be given by the relation [2]:

$$C_{OT} = (C_{NU} + C_{Con})\left(\frac{M_{NU}}{M_{EU}}\right) + C_{SWU}\frac{M_{SWU}}{M_{EU}} + C_{Ufab} \tag{3.1}$$

where,

C_{OT}=unit cost of fabricated U fuel for once-through cycle ($/kg U)

C_{NU}=unit cost of natural uranium ($/kg U)

C_{Con}=unit cost of conversion ($/kg U)

M_{NU}=amount of natural uranium required to enrich uranium (kgU)

M_{EU}=amount of enriched uranium (kgU)

C_{SWU}=unit cost of Separative Work Unit ($/kg SWU)

M_{SWU}=amount of Separative Work Unit required to enrich uranium (kg SWU)

C_{Ufab}=unit cost of uranium fabrication ($/kg U)

3.1.2. Closed Cycle with Standard Reprocessing

3.1.2.1. Standard Reprocessing Using NU as Makeup Material (SRNU)

In the SRNU cycle, recovered plutonium is blended with natural uranium in order to produce MOX with an appropriate fissile content and recovered uranium is reenriched and recycled (RcU). Unit cost of fabricated fuel in SRNU can be calculated by adding average unit cost of fabricated fuel (RcU+MOX) and reprocessing [2].

Average unit cost of fabricated fuel (RcU+MOX) in SRNU cycle can be calculated by:

$$C_{(RcU+MOX)-SRNU} = \frac{\left[(M_{MOX-SRNU}C_{MOX-SRNU}) + (M_{RcU-SRNU}C_{RcU-SRNU})\right]}{M_{MOX-SRNU} + M_{RcU-SRNU}} \qquad (3.2)$$

where,

$C_{(RcU+MOX)-SRNU}$=average unit cost of fabricated fuel (RcU+MOX) ($/kg HM)
$M_{MOX-SRNU}$=amount of MOX produced in standard reprocessing with NU per t SF
$C_{MOX-SRNU}$=unit cost of fabricated MOX in SRNU ($/kg HM)
$M_{RcU-SRNU}$=amount of RcU produced in standard reprocessing with NU per t SF (kgU)
$C_{RcU-SRNU}$=unit cost of fabricated RcU in SRNU ($/kg U)

$C_{MOX-SRNU}$:

Unit cost of MOX fabricated in SRNU ($C_{MOX-SRNU}$) can be calculated from:

$$C_{MOX-SRNU} = C_{NU}\left(\frac{M_{NU}}{M_{MOX-SRNU}}\right) + C_{MOXfab} \qquad (3.3)$$

where,

$C_{MOX-SRNU}$=unit cost of fabricated MOX in SRNU ($/kg HM)
C_{NU}=unit cost of natural uranium ($/kg U)
M_{NU}=amount of natural uranium required as makeup (kgU)
$M_{MOX-SRNU}$=amount of MOX produced in SRNU (kg)
C_{MOXfab}= unit cost of MOX fabrication ($/kg HM)

Material balances for MOX production in SRNU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.2.

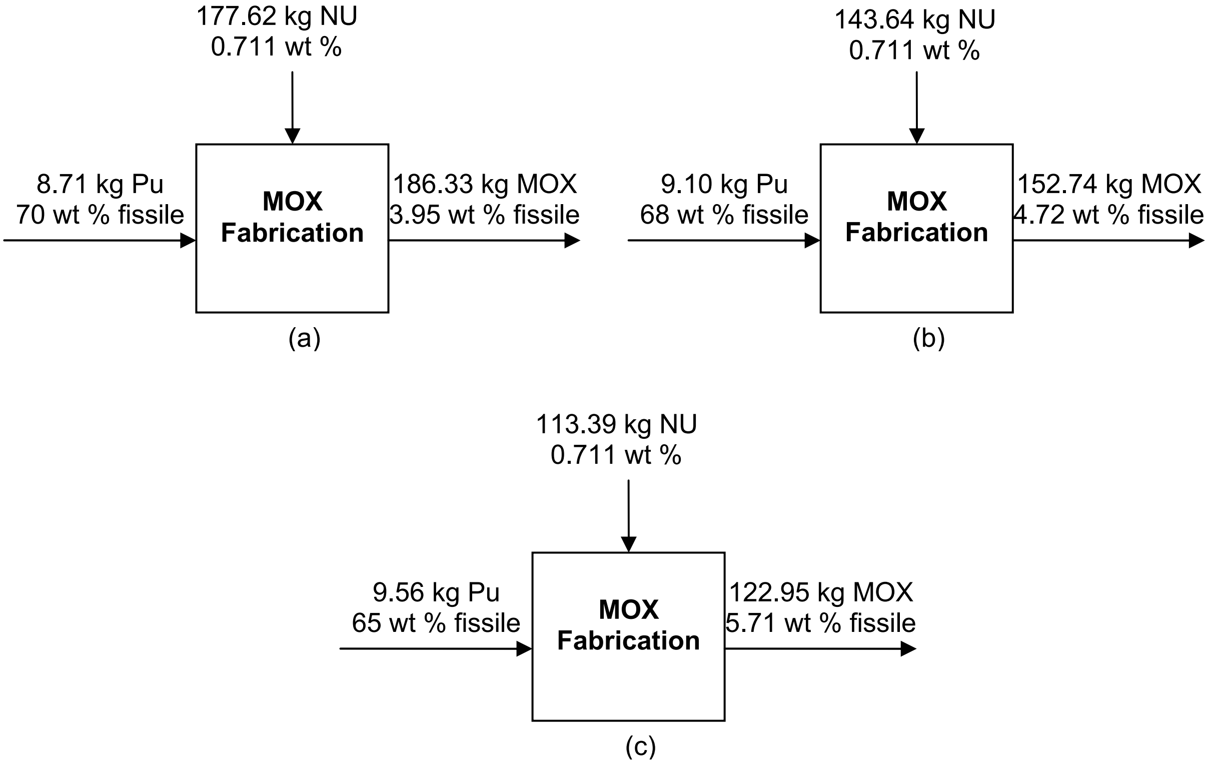

Figure 3.2. Material balances for MOX production in SRNU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

<u>$C_{RcU-SRNU}$:</u>

Unit cost of RcU fabricated in SRNU ($C_{RcU-SRNU}$) can be calculated from:

$$C_{RcU-SRNU} = C_{SWU}\left(\frac{M_{SWU}}{M_{RcU-SRNU}}\right) + C_{Ufab} \tag{3.4}$$

where,

$C_{RcU-SRNU}$=unit cost of fabricated RcU (\$/kg U)
C_{SWU}=unit cost of Separative Work Unit (\$/kg SWU)
M_{SWU}=amount of Separative Work Unit required to enrich uranium (kg SWU)
$M_{RcU-SRNU}$=amount of RcU produced in SRNU per t SF.
C_{Ufab}=unit cost of uranium fabrication (\$/kg U)

Material balances for production of recycle uranium (RcU) fuel in SRNU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.3.

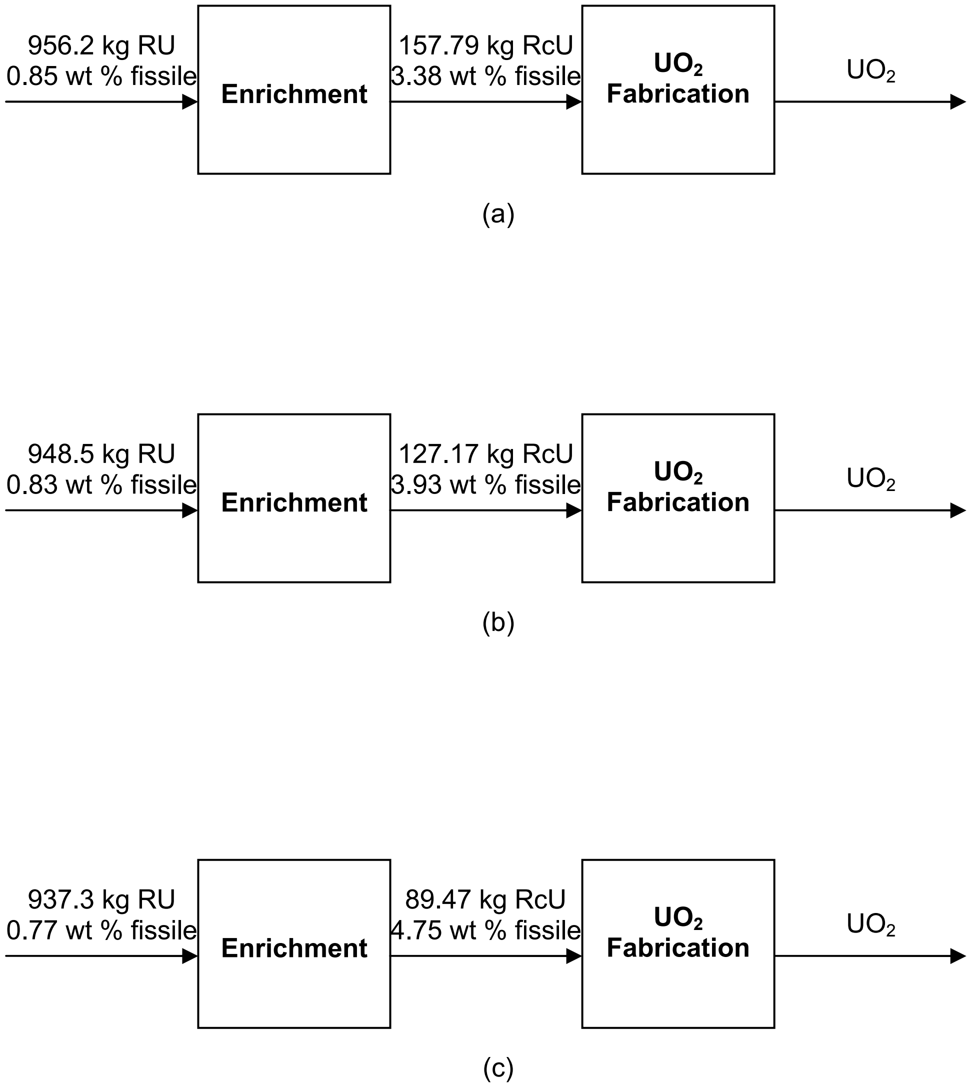

Figure 3.3. Material balances for RcU production in SRNU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

Equations 3.3 and 3.4 are inserted into equation 3.2 and standard reprocessing cost is added to this new equation to obtain the relation which is giving the unit cost of fabricated fuel in SRNU:

$$C_{SRNU} = (C_{NU}(\frac{M_{NU}}{M_{MOX}}) + C_{MOXfab})\frac{M_{MOX-SRNU}}{M_{MOX-SRNU} + M_{RcU-SRNU}} + (C_{SWU}\frac{M_{SWU}}{M_{RcU-SRNU}} + C_{Ufab})\frac{M_{MOX-SRNU}}{M_{MOX-SRNU} + M_{RcU-SRNU}} + \frac{M_{SF}C_{rep}}{M_{MOX-SRNU} + M_{RcU-SRNU}} \tag{3.5}$$

where,

C_{SRNU}=unit cost of fabricated fuel in SRNU (\$/kg HM)
M_{SF}= Heavy Metal in SF reprocessed (kg)
C_{rep}= unit cost of reprocessing (\$/kg HM)
($M_{MOX-SRNU}$+$M_{RcU-SRNU}$)=total amount of products in SRNU (kg HM)

3.1.2.2. Standard Reprocessing using RU as Makeup Material (SRRU)

In the SRRU cycle, recovered plutonium is blended with recovered uranium (RU) in order to produce MOX with an appropriate fissile content and remaining recovered uranium is reenriched and recycled (RcU). Unit cost of fabricated fuel can be calculated by adding up average unit cost of fabricated fuel (RcU+MOX) and reprocessing [2].

Average unit cost of fabricated fuel (RcU+MOX) in SRRU cycle can be calculated by:

$$C_{(RcU+MOX)-SRRU} = \frac{[(M_{MOX-SRRU}C_{MOX-SRRU}) + (M_{RcU-SRRU}C_{RcU-SRRU})]}{M_{MOX-SRRU} + M_{RcU-SRRU}} \tag{3.6}$$

where,

$C_{(RcU+MOX)-SRRU}$=average unit cost of fabricated fuel (RcU+MOX) (\$/kg HM)
$M_{MOX-SRRU}$=MOX produced in standard reprocessing with RU per t SF (kg)
$C_{MOX-SRRU}$=unit cost of fabricated MOX in SRRU (\$/kg HM)
$M_{RcU-SRRU}$=RcU produced in standard reprocessing with RU per t SF (kgU)
$C_{RcU-SRRU}$=unit cost of fabricated RcU (\$/kg U)

$C_{MOX-SRRU}$:

Unit cost of MOX fabricated in SRRU ($C_{MOX-SRRU}$) is directly equal to unit cost of MOX fabrication since unit cost of RU used as makeup is taken to be zero.

$$C_{MOX-SRRU} = C_{MOXfab} \tag{3.7}$$

Material balances for MOX production in SRRU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.4.

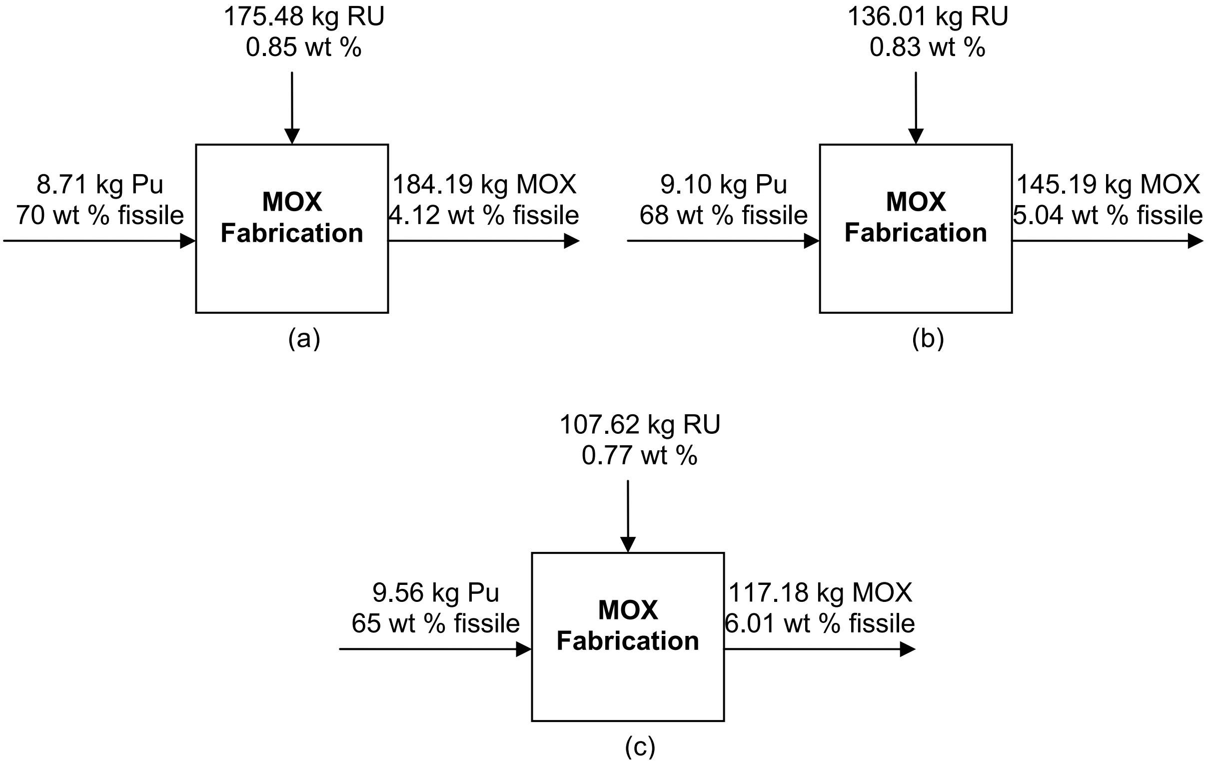

Figure 3.4. Material balances for MOX production in SRRU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

$C_{RcU-SRRU}$:

Unit cost of RcU fabricated in SRRU ($C_{RcU-SRRU}$) can be calculated from:

$$C_{RcU-SRRU} = C_{SWU}\left(\frac{M_{SWU}}{M_{RcU-SRRU}}\right) + C_{Ufab} \tag{3.8}$$

where,

$C_{RcU-SRRU}$=unit cost of fabricated RcU in SRRU ($/kg U)

C_{SWU}=unit cost of Separative Work Unit ($/kg SWU)

M_{SWU}=amount of Separative Work Unit required to enrich uranium (kg SWU)

C_{Ufab}=unit cost of uranium fabrication ($/kg U)

Material balances for production of recycle uranium (RcU) fuel in SRRU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.5.

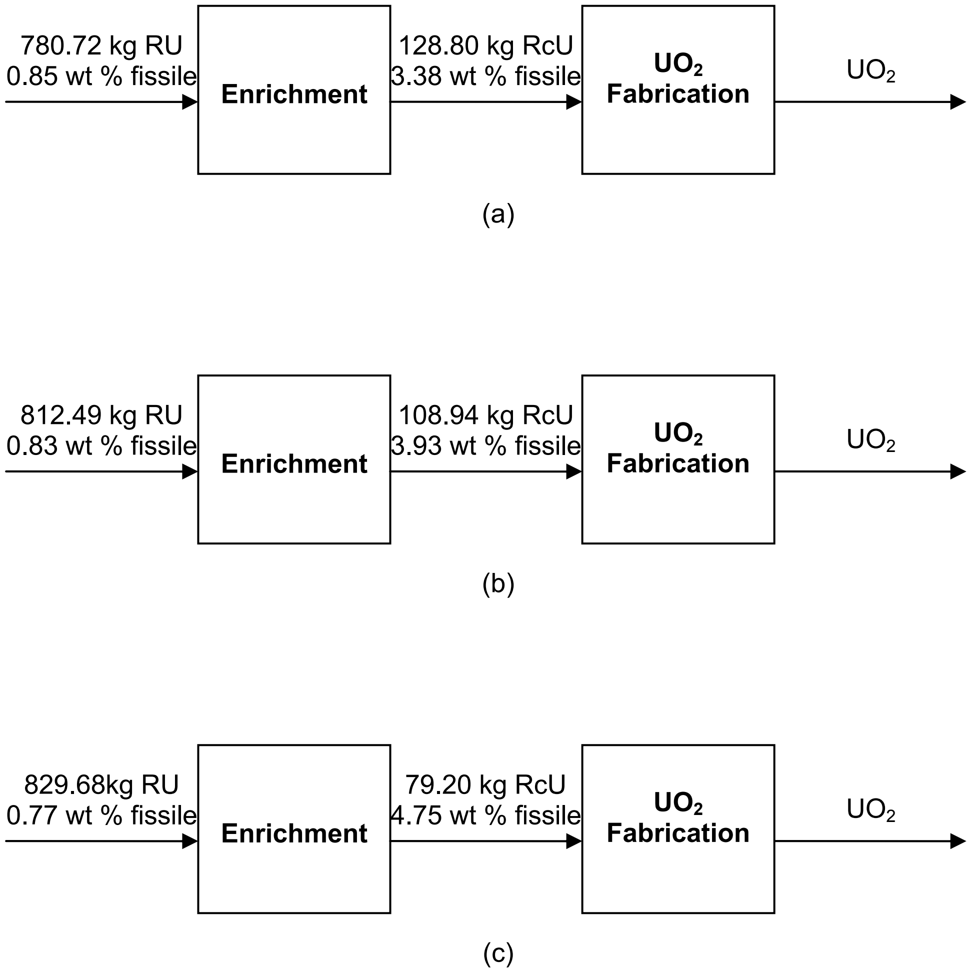

Figure 3.5. Material balances for RcU production in SRRU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

Equations 3.7 and 3.8 are inserted into equation 3.6 and standard reprocessing cost is added to this new equation to obtain the relation which is giving the unit cost of fabricated fuel in SRRU:

$$C_{SRRU} = (C_{SWU}\frac{M_{SWU}}{M_{RcU-SRRU}} + C_{Ufab} + C_{MOXfab})\frac{M_{MOX-SRRU}}{M_{MOX-SRRU} + M_{RcU-SRRU}} + \frac{M_{SF}C_{rep}}{M_{MOX-SRRU} + M_{RcU-SRRU}} \tag{3.9}$$

where,

C_{SRRU}=unit cost of fabricated fuel in SRRU ($/kg HM)
M_{SF}= Heavy Metal in SF reprocessed (kg)
C_{rep}= unit cost of reprocessing ($/kg HM)
($M_{MOX\text{-}SRRU}$+$M_{RcU\text{-}SRRU}$)=total amount of products in SRRU (kg HM)

3.1.2.3 Standard Reprocessing using DU as Makeup Material (SRDU)

In the SRDU cycle, recovered plutonium is blended with depleted uranium in order to produce MOX with an appropriate fissile content and recovered uranium is reenriched and recycled (RcU). Unit cost of fabricated fuel in SRDU can be calculated by adding average unit cost of fabricated fuel (RcU+MOX) and reprocessing.

Average unit cost of fabricated fuel (RcU+MOX) in SRDU cycle can be calculated by:

$$C_{(RcU+MOX)-SRDU} = \frac{[(M_{MOX-SRDU}C_{MOX-SRDU}) + (M_{RcU-SRDU}C_{RcU-SRDU})]}{M_{MOX-SRDU} + M_{RcU-SRDU}} \tag{3.10}$$

where,

$C_{(RcU+MOX)\text{-}SRDU}$=average unit cost of fabricated fuel (RcU+MOX) ($/kg HM)
$M_{MOX\text{-}SRDU}$=amount of MOX produced in standard reprocessing with DU per t SF
$C_{MOX\text{-}SRDU}$=unit cost of fabricated MOX in SRDU ($/kg HM)
$M_{RcU\text{-}SRDU}$=amount of RcU produced in standard reprocessing with DU per t SF (kgU)
$C_{RcU\text{-}SRDU}$=unit cost of fabricated RcU in SRDU ($/kg U)

$C_{MOX\text{-}SRDU}$:

Unit cost of MOX fabricated in SRDU ($C_{MOX\text{-}SRDU}$) can be calculated from:

$$C_{MOX-SRDU} = C_{MOXfab} \tag{3.11}$$

where,

$C_{MOX-SRDU}$=unit cost of fabricated MOX in SRDU (\$/kg HM)
C_{MOXfab}= unit cost of MOX fabrication (\$/kg HM).

Material balances for MOX production in SRDU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.6.

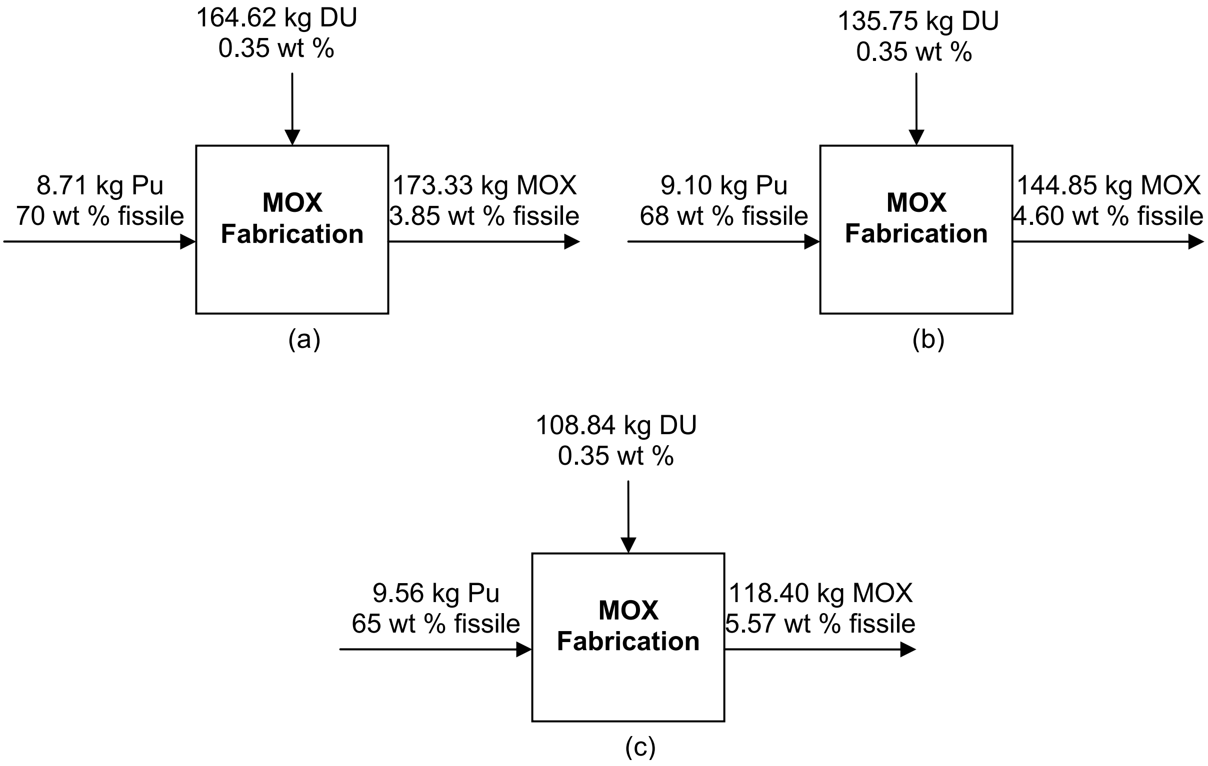

Figure 3.6. Material balances for MOX production in SRDU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

$C_{RcU-SRDU}$:

Unit cost of RcU fabricated in SRDU ($C_{RcU-SRNU}$) can be calculated from:

$$C_{RcU-SRDU} = C_{SWU}\left(\frac{M_{SWU}}{M_{RcU-SRDU}}\right) + C_{Ufab} \tag{3.12}$$

where,

$C_{RcU-SRDU}$=unit cost of fabricated RcU (\$/kg U)
C_{SWU}=unit cost of Separative Work Unit (\$/kg SWU)

M_{SWU}=amount of Separative Work Unit required to enrich uranium (kg SWU)
$M_{RcU\text{-}SRDU}$=amount of RcU produced in SRDU per t SF.
C_{Ufab}=unit cost of uranium fabrication ($/kg U)

Material balances for production of recycle uranium (RcU) fuel in SRDU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are same as the SRNU case.

Equations 3.11 and 3.12 are inserted into equation 3.10 and standard reprocessing cost is added to this new equation to obtain the relation which is giving the unit cost of fabricated fuel in SRDU:

$$C_{SRDU} = (C_{SWU}\frac{M_{SWU}}{M_{RcU-SRDU}} + C_{Ufab} + C_{MOXfab})\frac{M_{MOX-SRDU}}{M_{MOX-SRDU} + M_{RcU-SRDU}} + \frac{M_{SF}C_{rep}}{M_{MOX-SRDU} + M_{RcU-SRDU}} \tag{3.13}$$

where,

C_{SRDU}=unit cost of fabricated fuel in SRDU ($/kg HM)
M_{SF}= Heavy Metal in SF reprocessed (kg)
C_{rep}= unit cost of reprocessing ($/kg HM)
($M_{MOX\text{-}SRDU}$+$M_{RcU\text{-}SRDU}$)=total amount of products in SRDU (kg HM)

3.1.3. Closed Cycle with Complete Coprocessing

3.1.3.1. Complete Coprocessing using EU as Makeup Material (CCEU)

The product of complete coprocessing is a mixed uranium and plutonium solution. In the CCEU cycle, this product is blended with enriched uranium (10 wt %) in order to produce MOX with an appropriate fissile content. Unit cost of fabricated fuel in CCEU cycle can be calculated by adding unit cost of fabricated MOX fuel and unit cost of coprocessing.

$C_{MOX\text{-}CCEU}$:

Unit cost of MOX fabricated in CCEU ($C_{MOX\text{-}CCEU}$) can be calculated from:

$$C_{MOX-CCEU} = C_{EU}\left(\frac{M_{EU}}{M_{MOX-CCEU}}\right) + C_{MOXfab} \tag{3.14}$$

where,

$C_{MOX\text{-}CCEU}$=unit cost of fabricated MOX in CCEU ($/kg HM)
C_{EU}=unit cost of enriched uranium used as makeup ($/kg U)
M_{EU}=amount of enriched uranium required as makeup (kgU)
$M_{MOX\text{-}CCEU}$=amount of MOX produced in CCEU (kg)
C_{MOXfab}= unit cost of MOX fabrication ($/kg HM).

Material balances for MOX production in CCEU cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.7.

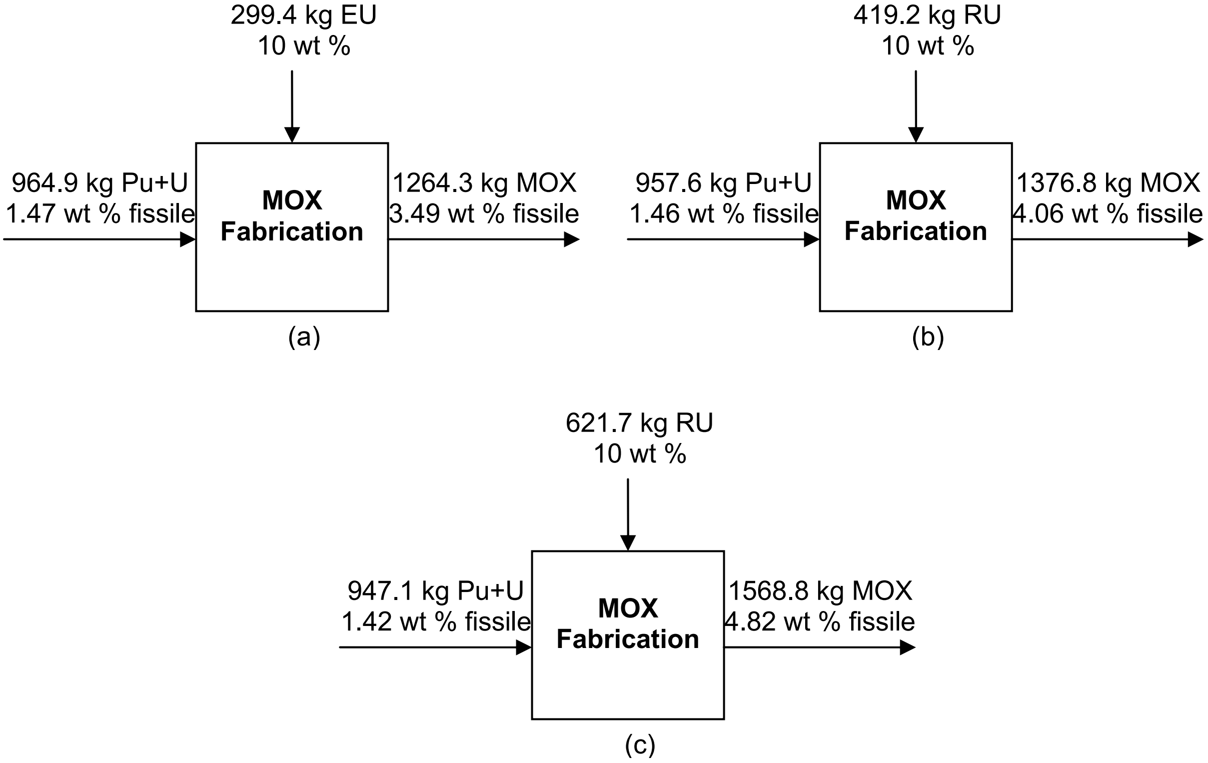

Figure 3.7. Material balances for MOX Production in CCEU

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

Unit cost of fabricated fuel in CCEU cycle can be given by the relation:

$$C_{CCEU} = C_{EU}\left(\frac{M_{EU}}{M_{MOX-CCEU}}\right) + C_{MOXfab} + \frac{C_{Cop} M_{SF}}{M_{MOX-CCEU}} \tag{3.15}$$

where,

C_{CCEU}=unit cost of fabricated fuel in CCEU ($/kg HM)

C_{Cop}=unit cost of coprocessing ($/kg HM)

M_{SF}= Heavy Metal in SF reprocessed (kgHM)

3.1.3.2. Complete Coprocessing using Pu as Makeup Material (CCPu)

In the CCPu cycle, mixed Pu+U product is blended with fissile Pu from standard reprocessing in order to produce MOX with an appropriate fissile content. Unit cost of fabricated fuel in CCPu cycle can be calculated by adding unit cost of fabricated MOX fuel and unit cost of coprocessing.

<u>$C_{MOX-CCPu}$:</u>

Unit cost of MOX fabricated in CCPu ($C_{MOX-CCPu}$) can be calculated from:

$$C_{MOX-CCPu} = \frac{V_{Puf} M_{Puf}}{M_{MOX-CCPu}} + C_{MOXfab} \tag{3.16}$$

where,

$C_{MOX-CCPu}$=unit cost of fabricated MOX in CCPu ($/kg HM)
V_{Puf}=Plutonium value ($/g fissile)
M_{Puf}=fissile Pu required to produce MOX (g)
$M_{MOX-CCPu}$=amount of MOX produced in CCPu (kg)
C_{MOXfab}= unit cost of MOX fabrication ($/kg HM)

<u>Plutonium Value Calculation:</u>

Pu recovered by reprocessing LWR spent fuel, can be used as fresh fuel. Plutonium value is calculated by the indifference method. By using that method, the plutonium value is settled as the economic break-even point of MOX fuels to the fresh enriched uranium fuels. As calculating Pu value, Pu is assumed to be diluted with NU before producing MOX, then, amount of MOX and its cost compared with amount of fresh U to be replaced by that MOX :

$$V_{Puf} = \frac{M_{MOX}(C_{fresh} - C_{MOX}) - M_{NU} C_{NU}}{x_{Pu} M_{Pu}}$$

where,

V_{Puf}=Plutonium value ($/g fissile)

M_{MOX}=amount of fabricated MOX fuel produced by diluting Pu (kg)

M_{NU}=amount of added Natural Uranium (kg)

M_{Pu}=amount of Pu (g)

C_{fresh}=Cost of fabricated fresh fuel ($/kg)

x_{Pu}= fissile material weight fraction in Pu

Material balances for MOX production in CCPu cycles with 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU burnups are shown in Figure 3.7.

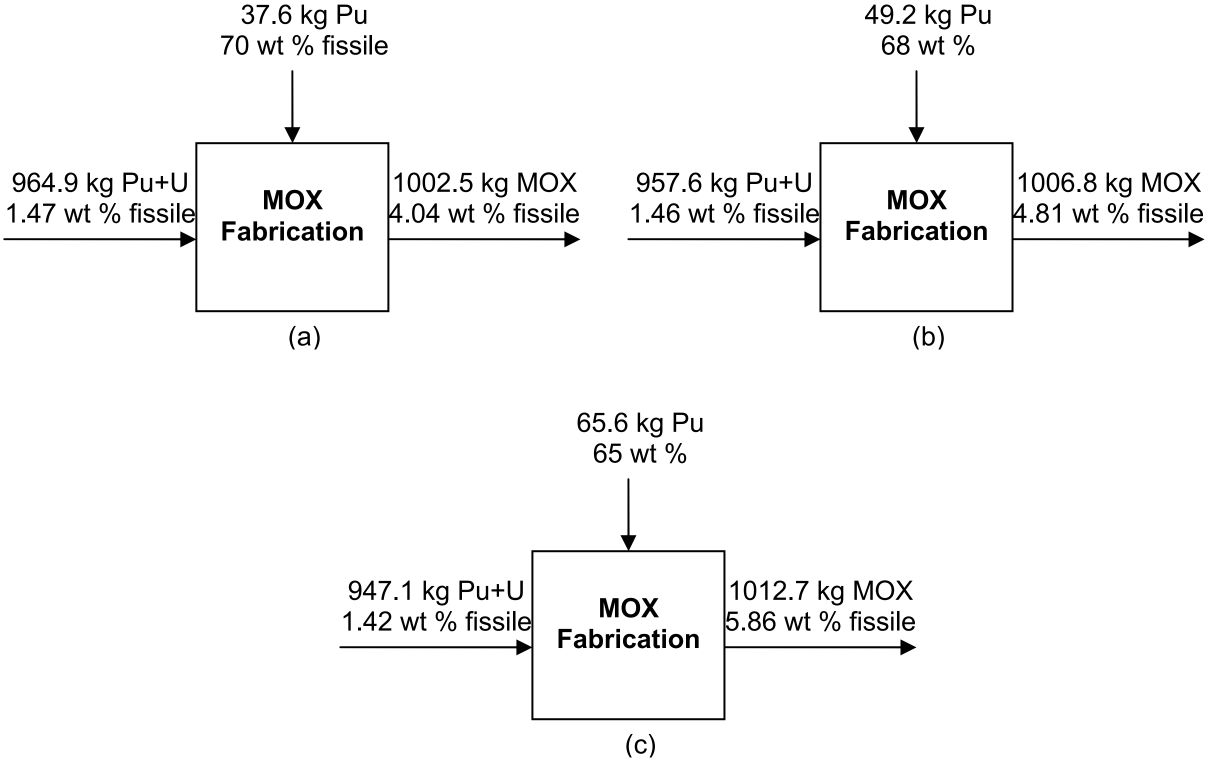

Figure 3.8. Material balances for MOX production in CCPu

(a) 33000 MWd/tU (b) 40000 MWd/tU (c) 50000 MWd/tU

Unit cost of fabricated fuel in CCPu cycle can be given by the relation:

$$C_{CCPu} = \frac{V_{Puf} M_{Puf}}{M_{MOX-CCPu}} + C_{MOXfab} + \frac{C_{Cop} M_{SF}}{M_{MOX-CCPu}} \qquad (3.17)$$

where,

C_{CCPu}=unit cost of fabricated fuel in CCPu ($/kg HM)

C_{Cop}=unit cost of coprocessing ($/kg HM)

M_{SF}= Heavy Metal in SF reprocessed (kg)

3.2. Unit Costs

The unit costs for the different stages of the fuel cycle are necessary to evaluate unit cost of fuel ready to be loaded into reactor. The unit costs obtained from different sources are presented in Table 3.2.

Table 3.2. Unit costs obtained from different sources

Unit Costs	Reference								
	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Natural Uranium ($/kgU)	16.5	25	50	83.2	20	85	70	40	50
Conversion ($/kgU)	7	5.5	8	6	8	5	6	4	4
Enrichment ($/SWU)	108	105	110	130	90	110	130	80	100
U fabrication ($/kgU)	-	240	275	190	250	130	190	190	250
MOX fabrication ($/kgHM)	-	-	-	-	600	500	760	-	-
U reprocessing ($/kgU)	-	-	720	550	800	500	750	-	800
MOX reprocessing ($/kgHM)	-	-	-	-	800	500	900	-	-
HLW disposal ($/kgHM)	-	-	90	150	-	-	150	250	-
SF disposal ($/kgU)	-	-	610	150	300	150	-	-	-

Since unit costs of conversion (C_{Con}), enrichment (C_{SWU}) and uranium fabrication (C_{Ufab}) show small changes between sources given in Table 3.2 , these unit costs are taken to be constant in fuel cycle cost analysis and C_{Con}=6 \$/kgU, C_{SWU}=110 \$/kgSWU and C_{Ufab}=200 \$/kgU. Unit costs of natural uranium (C_{NU}), MOX fabrication (C_{MOXfab}) and reprocessing (or coprocessing)[C_{rep} or C_{cop}] are lie in the ranges 11.5-85 \$/kgU, 500-760 \$/kgHM and 500-800 \$/kgHM respectively. In fuel cycle cost analysis, these unit costs are taken to be variable in specified ranges.

3.3. Methodology of Break-even Cost Analysis

The " break-even cost " is the unit cost of a process that makes the unit cost of fabricated fuel produced in one cycle exactly equal to that in the other cycle.

Break-even values of variable unit costs C_{NU}, C_{MOXfab} and C_{rep} (or C_{cop}) are calculated for all fuel cycle cases given in section 3.1. As evaluating break-even cost of any of these processes, the unit cost of process which we looking for its break-even value is taken as variable in the ranges determined from Table 3.2 and other two are fixed at their lowest, less high, average, more high and highest values. When not used as variable, lowest, less high, average, more high and highest values of each unit cost are given in Table .3.3.

Table 3.3. Fixed values of unit costs used in break-even value calculations

Unit Costs	Fixed unit cost values				
	Lowest	Lower	Average	Higher	Highest
C_{NU} (\$/kgU)	10	30	50	70	90
C_{rep} (or C_{cop}) (\$/kgHM)	100	300	500	700	900
C_{MOXfab} (\$/kgHM)	300	400	500	600	700

Combinations of fixed values of unit costs are used to indicate the most favorable, more, average, less and least favorable cost conditions for closing the cycle. Cost conditions for each break-even cost calculation [C_{NU}, C_{MOXfab} and C_{rep} (or C_{cop})] are given in Table 3.4.

Table 3.4. Cost conditions for closing cycle

Variable unit cost	Cost Condition for Closing the Cycle				
	Least Favorable	Less Favorable	Average	More Favorable	Most Favorable
C_{NU} (\$/kgU)	$C_{rep}(C_{cop})$=900	$C_{rep}(C_{cop})$=700	$C_{rep}(C_{cop})$=500	$C_{rep}(C_{cop})$=300	$C_{rep}(C_{cop})$=100
	C_{MOXfab}=700	C_{MOXfab}=600	C_{MOXfab}=500	C_{MOXfab}=400	C_{MOXfab}=300
C_{rep}(or C_{cop}) (\$/kgHM)	C_{NU}=10	C_{NU}=30	C_{NU}=50	C_{NU}=70	C_{NU}=90
	C_{MOXfab}=700	C_{MOXfab}=600	C_{MOXfab}=500	C_{MOXfab}=400	C_{MOXfab}=300
C_{MOXfab} (\$/kgHM)	C_{NU}=10	C_{NU}=30	C_{NU}=50	C_{NU}=70	C_{NU}=90
	$C_{rep}(C_{cop})$=900	$C_{rep}(C_{cop})$=700	$C_{rep}(C_{cop})$=500	$C_{rep}(C_{cop})$=300	$C_{rep}(C_{cop})$=100

3.3.1. Break-even Natural Uranium Costs (C_{NU})

Unit costs of fabricated fuels for each fuel cycle are calculated for varying natural uranium unit costs and for cost conditions given in Table 3.4. Unit costs of fabricated fuels for each fuel cycle are plotted versus natural uranium unit cost and cost lines for each fuel cycle are obtained. Intersections of any two of these lines indicate break-even natural uranium cost for the two cycles.

Cost lines for SRNU, SRRU and SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus natural uranium cost and these lines are shown in Appendix C.

As observed from these figures cost lines for SRNU, SRRU and SRDU cycles have same characteristics. Therefore, it will be appropriate to obtain only SRNU cost lines to compare break-even natural uranium costs for SRNU, SRRU and SRDU cycles with the break-even natural uranium costs for other cycles (OT, CCPu and CCEU).

B=33000 MWd/tU

Cost lines and break-even values for NU cost for the four cycles are shown in Figures 3.9, 3.10, 3.11, 3.12 and 3.13 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

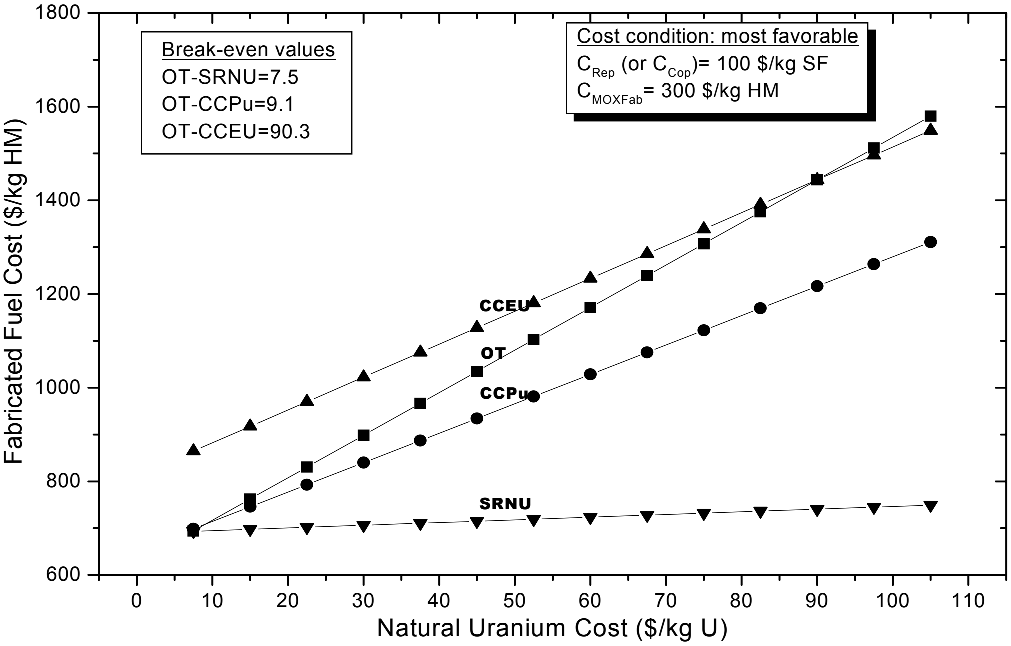

Figure 3.9. Break-even C_{NU} values for most favorable condition (33000 MWd/tU)

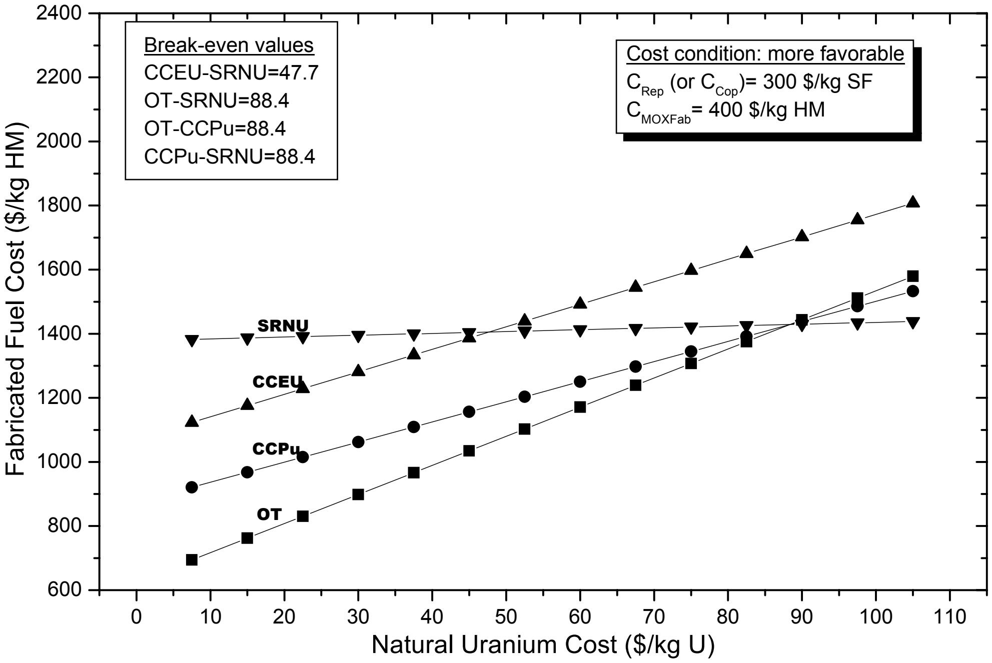

Figure 3.10. Break-even C_{NU} values for more favorable condition (33000 MWd/tU)

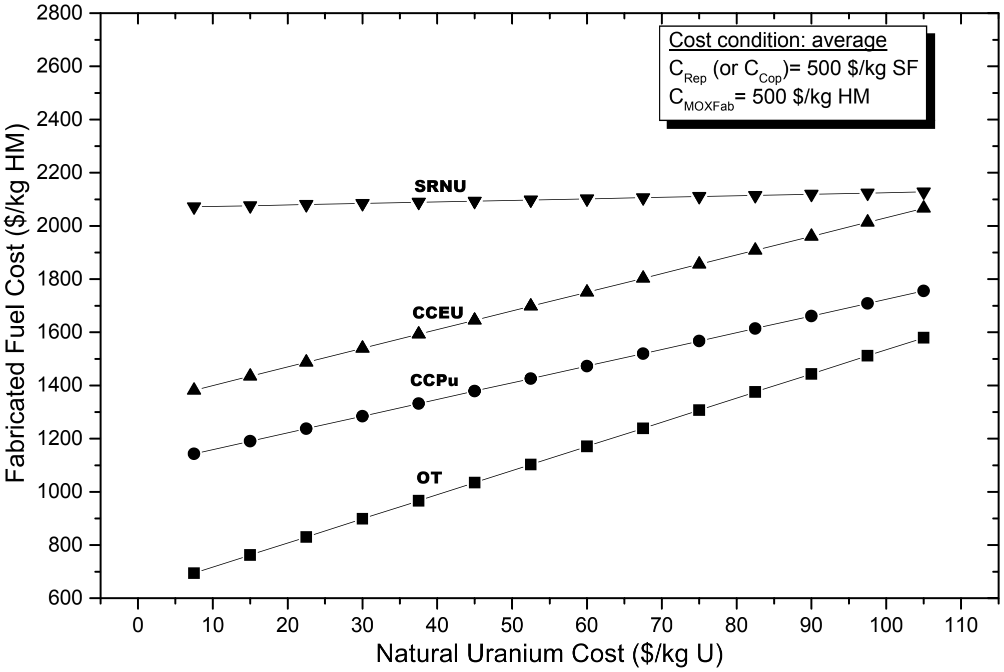

Figure 3.11. Break-even C_{NU} values for average cost condition (33000 MWd/tU)

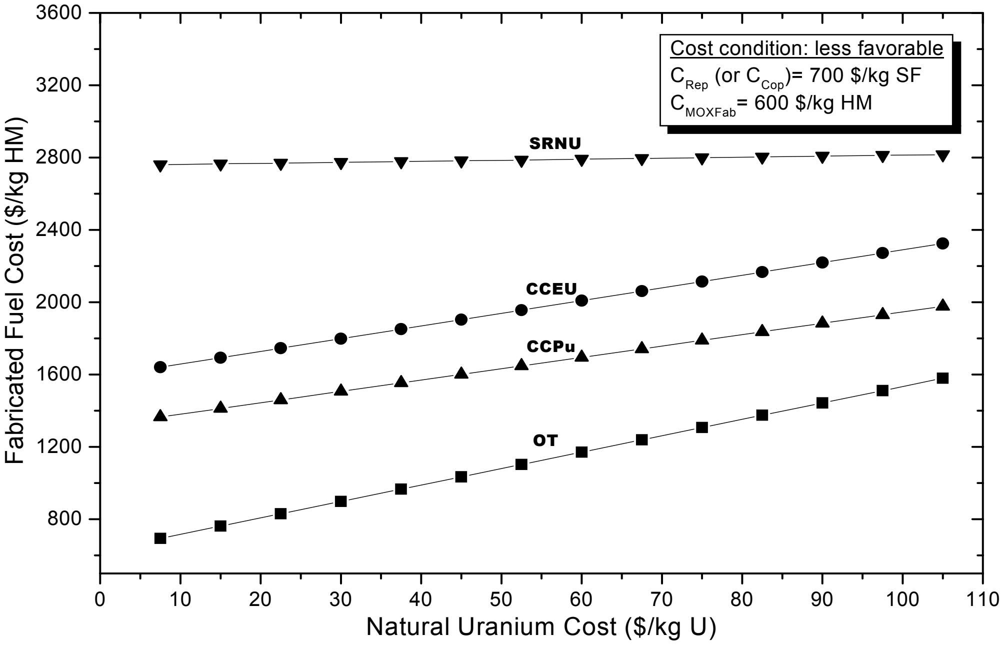

Figure 3.12. Break-even C_{NU} values for less favorable condition (33000 MWd/tU)

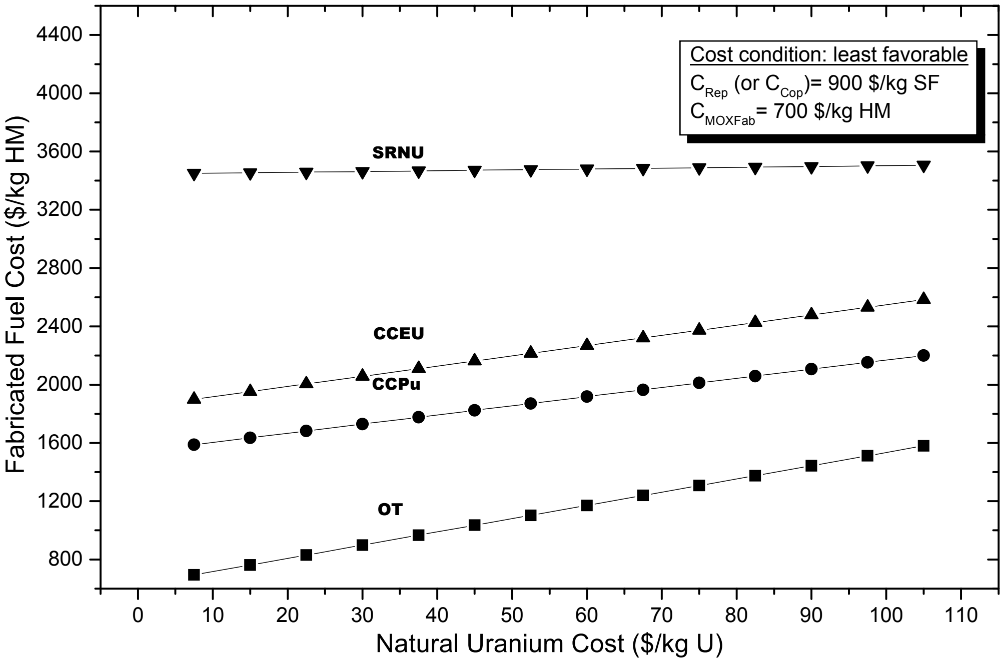

Figure 3.13. Break-even C_{NU} values for least favorable condition (33000 MWd/tU)

For the most favorable conditions (C_{Rep}=100 $/kg and C_{Moxfab}=300 $/kg), OT cycle is the most sensitive to unit cost of NU since its cost line slope is the largest. SRNU cycle is the best choice for unit cost of NU higher than 7.5 $/kg. CCEU is more expensive than other cycles for NU price lower than 90.3 $/kg and OT becomes the most expensive cycle for NU price higher than 90.3 $/kg.

For the more favorable conditions (C_{Rep}=300 $/kg and C_{Moxfab}=400 $/kg), OT cycle is the most sensitive to unit cost of NU and the most economical case for NU price less than 88.4 $/kg, above which SRNU cycle is the best choice.

For the average favorable conditions (C_{Rep}=500 $/kg and C_{Moxfab}=500 $/kg), less favorable conditions (C_{Rep}=700 $/kg and C_{Moxfab}=600 $/kg) and least favorable conditions (C_{Rep}=900 $/kg and C_{Moxfab}=700 $/kg), OT cycle is the most sensitive to unit cost of NU and there is no break-even value for NU unit cost.

B=40000 MWd/tU

Cost lines and break-even values for NU cost for the four cycles are shown in Figures 3.14, 3.15, 3.16, 3.17 and 3.18 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

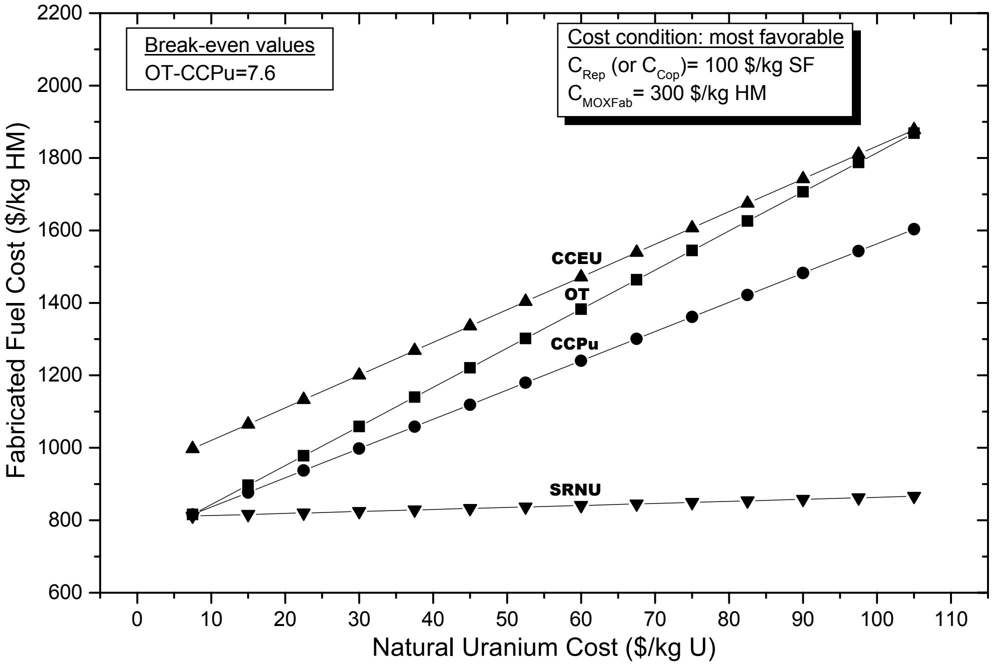

Figure 3.14. Break-even C_{NU} values for most favorable condition (40000 MWd/tU)

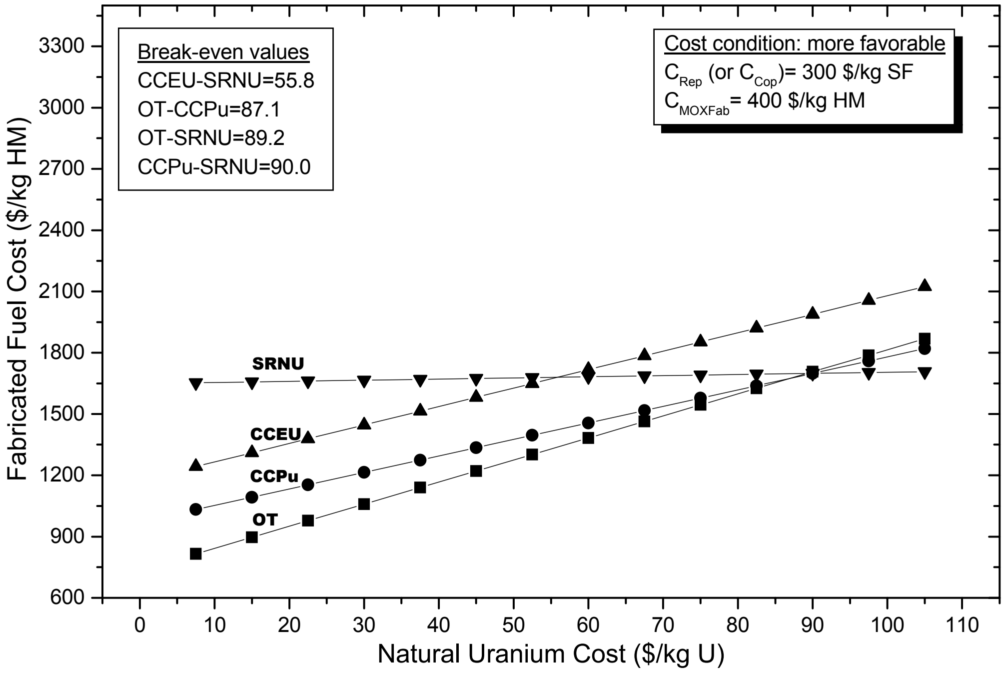

Figure 3.15. Break-even C_{NU} values for more favorable condition (40000 MWd/tU)

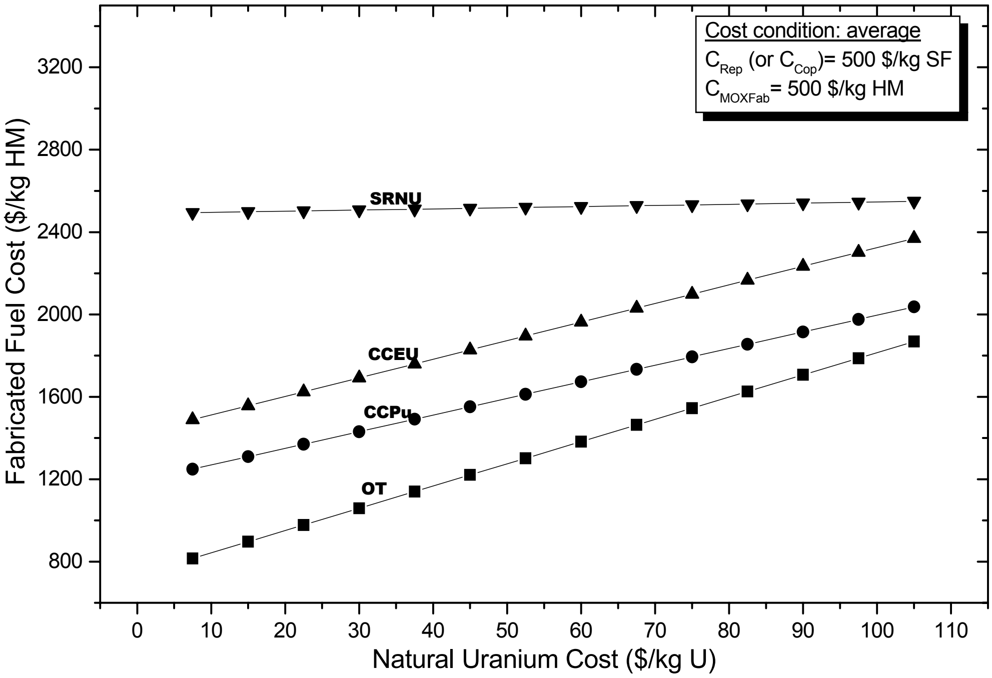

Figure 3.16. Break-even C_{NU} values for average condition (40000 MWd/tU)

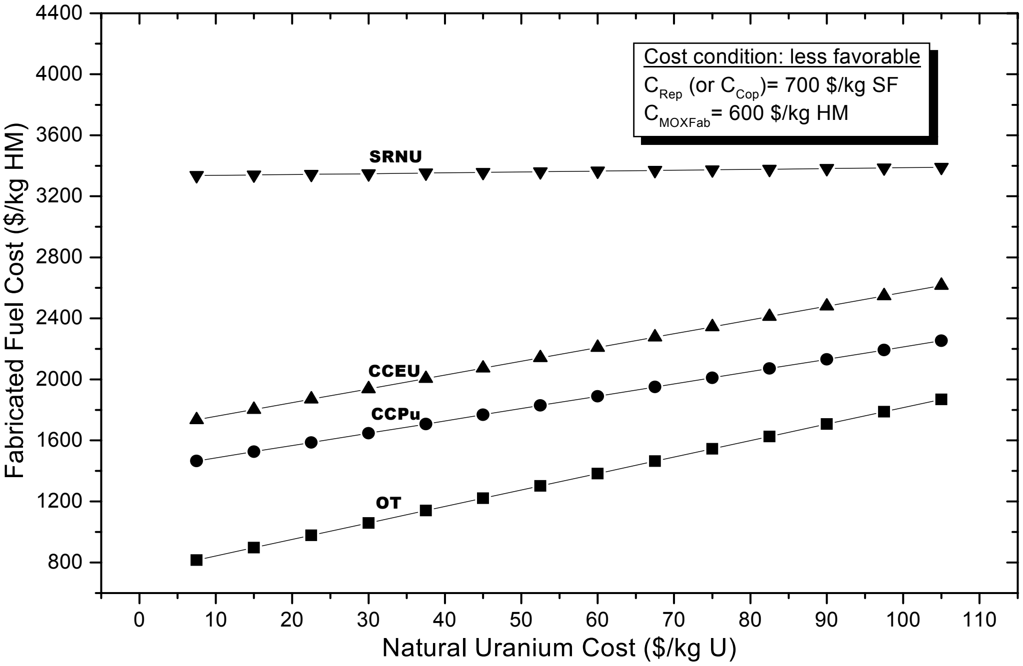

Figure 3.17. Break-even C_{NU} values for less favorable condition (40000 MWd/tU)

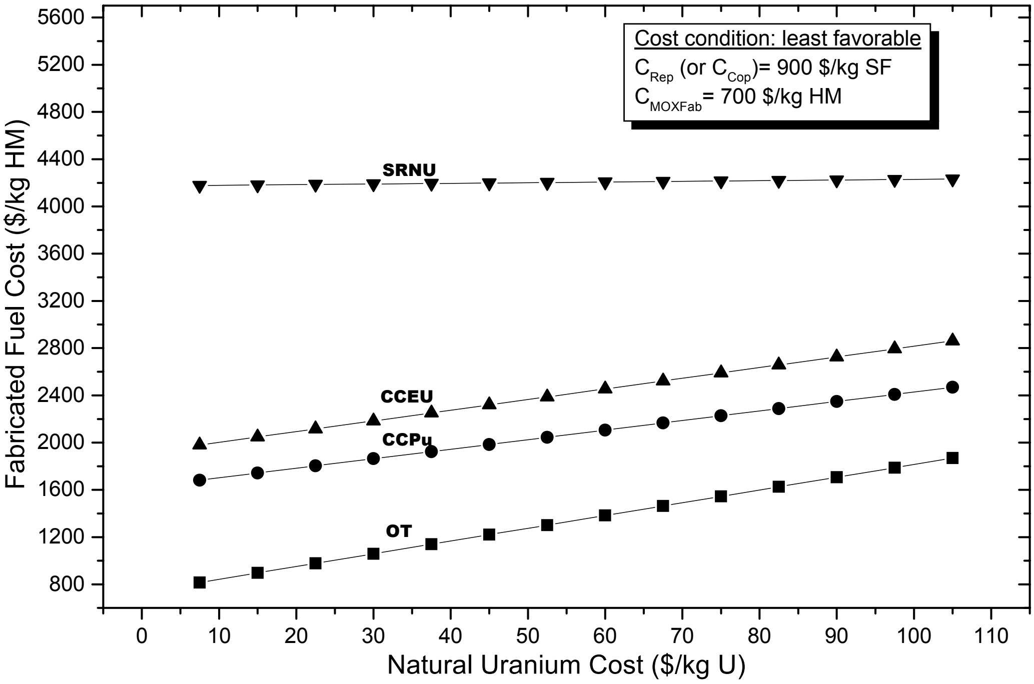

Figure 3.18. Break-even C_{NU} values for least favorable condition (40000 MWd/tU)

For all cost conditions, OT cycle is the most sensitive to unit cost of NU and for the average, less and least favorable cases it is the most economical cycle.

For the most favorable cost conditions SRNU cycle is the cheapest and CCEU cycle is always more expensive than other cycles.

For more favorable cost conditions, OT cycle is economically most advantageous for NU prices less than 87.1$/kg. For NU prices higher than 90 $/kg SRNU is the cheapest cycle.

B=50000 MWd/tU

Cost lines and break-even values for NU cost for the four cycles are shown in Figures 3.19, 3.20, 3.21, 3.22 and 3.23 for the most, more, average, less and the least favorable cost conditions for closing the cycle respectively.

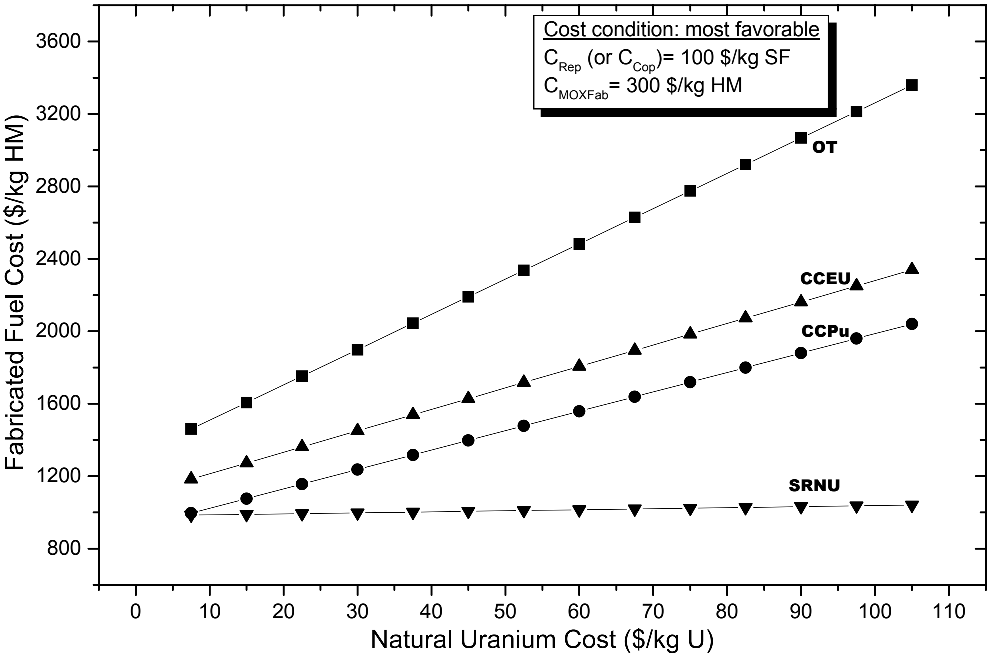

Figure 3.19. Break-even C_{NU} values for most favorable condition (50000 MWd/tU)

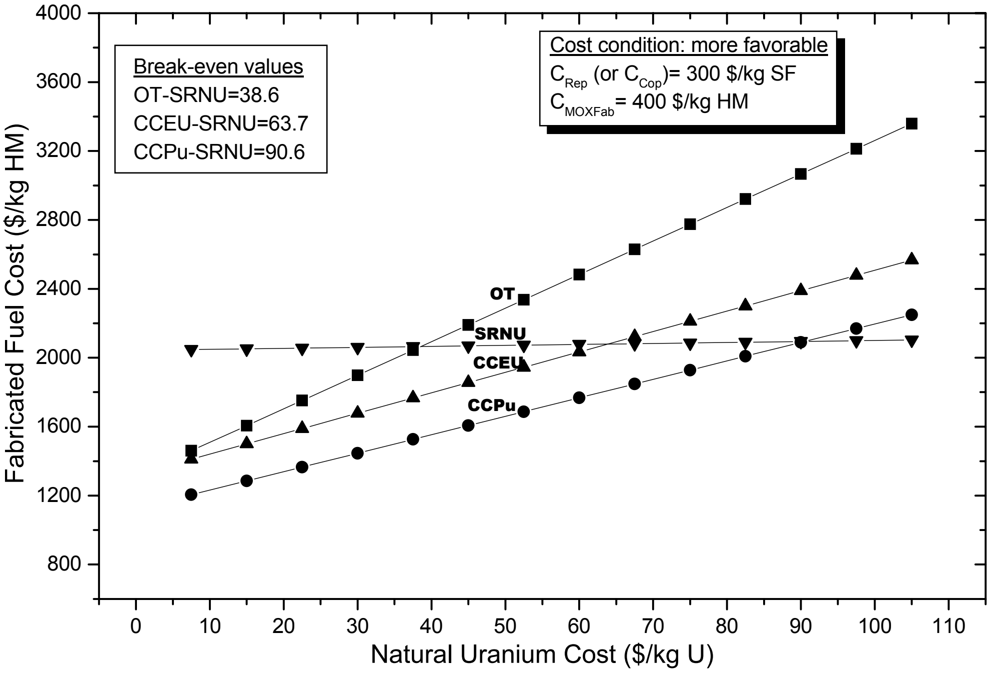

Figure 3.20. Break-even C_{NU} values for more favorable condition (50000 MWd/tU)

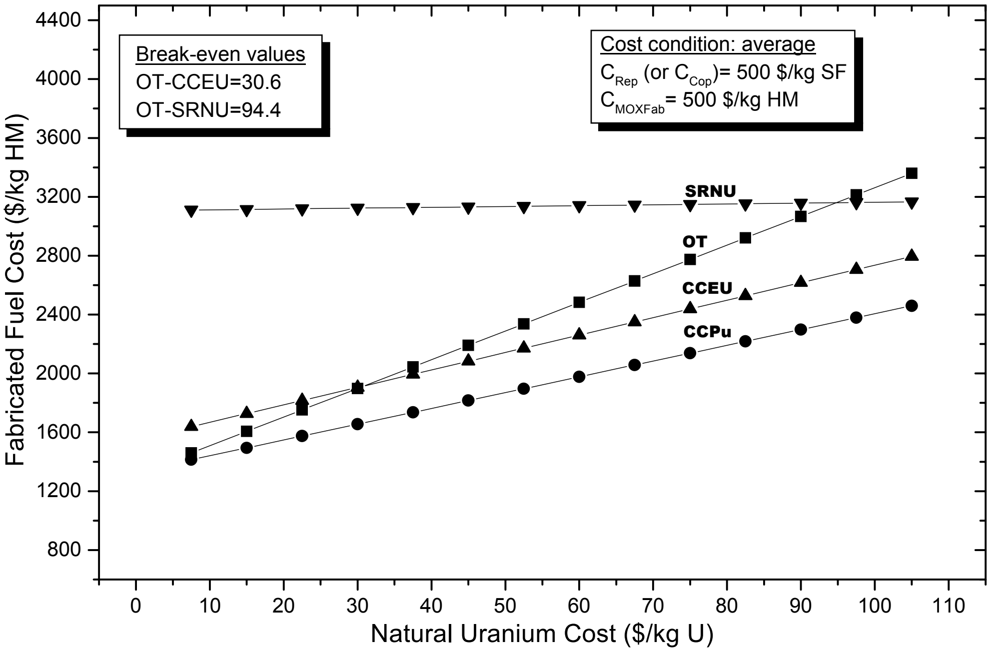

Figure 3.21. Break-even C_{NU} values for average condition (50000 MWd/tU)

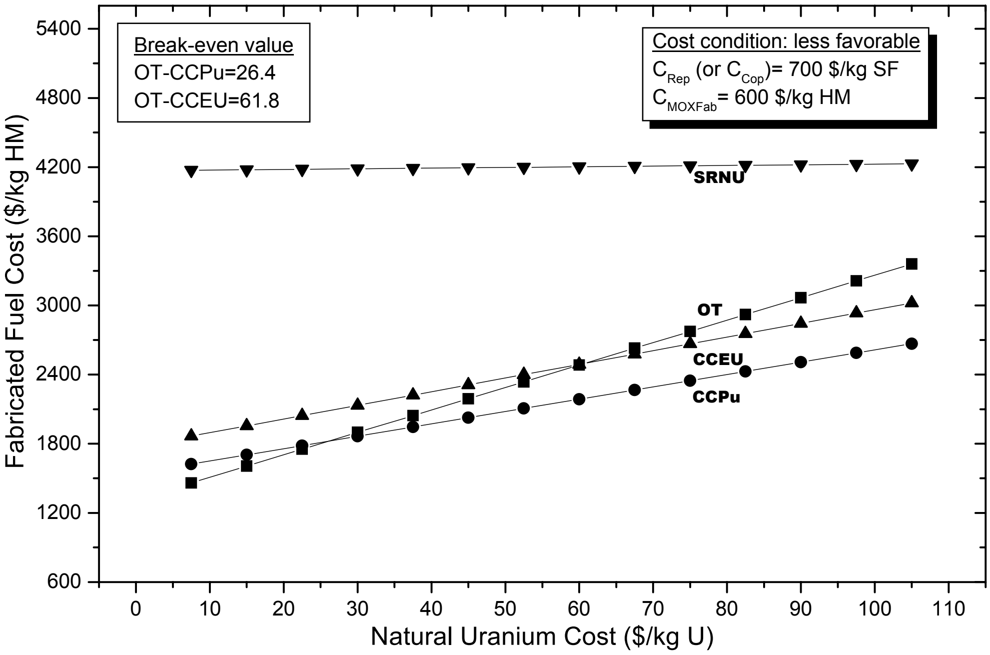

Figure 3.22. Break-even C_{NU} values for less favorable condition (50000 MWd/tU)

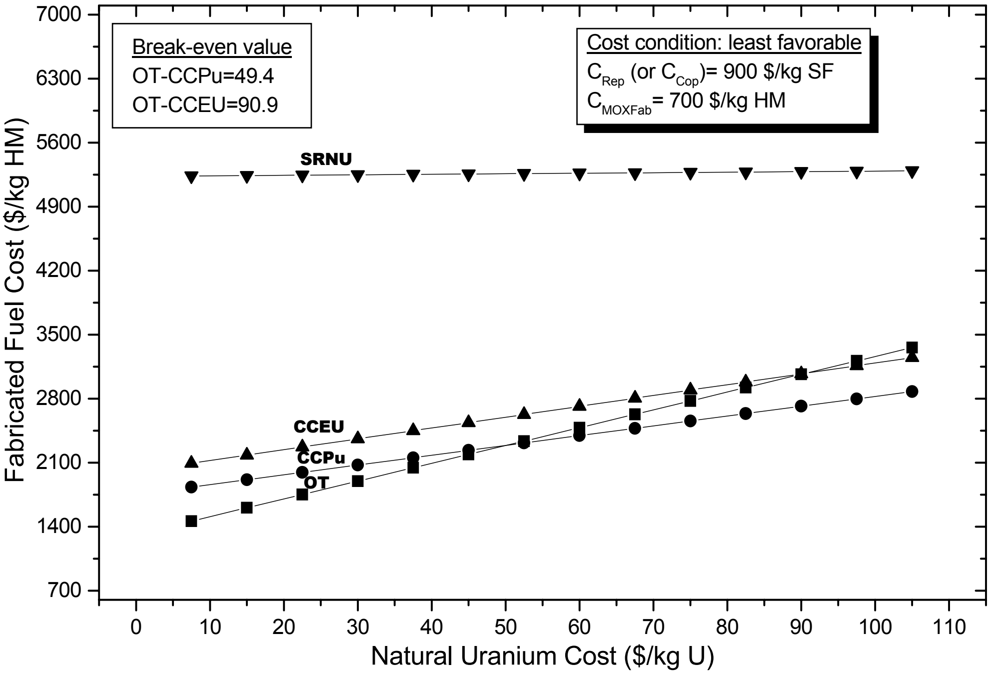

Figure 3.23. Break-even C_{NU} values for least favorable condition (50000 MWd/tU)

For all cost conditions, OT cycle is the most sensitive to unit cost of NU.

For the more favorable conditions, CCPu cycle is the most advantageous case.

For average case, CCPu cycle is always the cheapest case and SRNU is almost always the most expensive cycle.

For less favorable cost conditions, OT cycle is economically most advantageous for NU prices less than 26.4$/kg above which, CCPu is the cheapest cycle.

For least favorable cost conditions, OT cycle is the most economical cycle for NU price lower than 49.4 $/kg and SRNU cycle is always the most expensive case.

3.3.2. Break-even Reprocessing (or Coprocessing) Costs (C_{Rep} or C_{cop})

Unit costs of fabricated fuels for each fuel cycle are calculated for varying reprocessing costs and for cost conditions given in Table 3.4. Unit costs of fabricated fuels for each fuel are plotted versus reprocessing unit cost and cost lines for each fuel cycle are obtained. Intersections of any two of these lines indicate break-even reprocesssing cost for the two cycles.

Cost lines for SRNU, SRRU and SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus reprocessing cost and these lines are shown in Appendix C.

As observed from these figures cost lines for SRNU, SRRU and SRDU cycles have same characteristics. Therefore, it will be appropriate to obtain only SRNU cost lines to compare break-even reprocessing costs for SRNU, SRRU and SRDU cycles with the break-even reprocessing (or coprocessing) costs for other cycles (OT, CCPu and CCEU).

B=33000 MWd/tU

Cost lines and break-even values for reprocessing cost for the four cycles are shown in Figures 3.24, 3.25, 3.26, 3.27 and 3.28 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

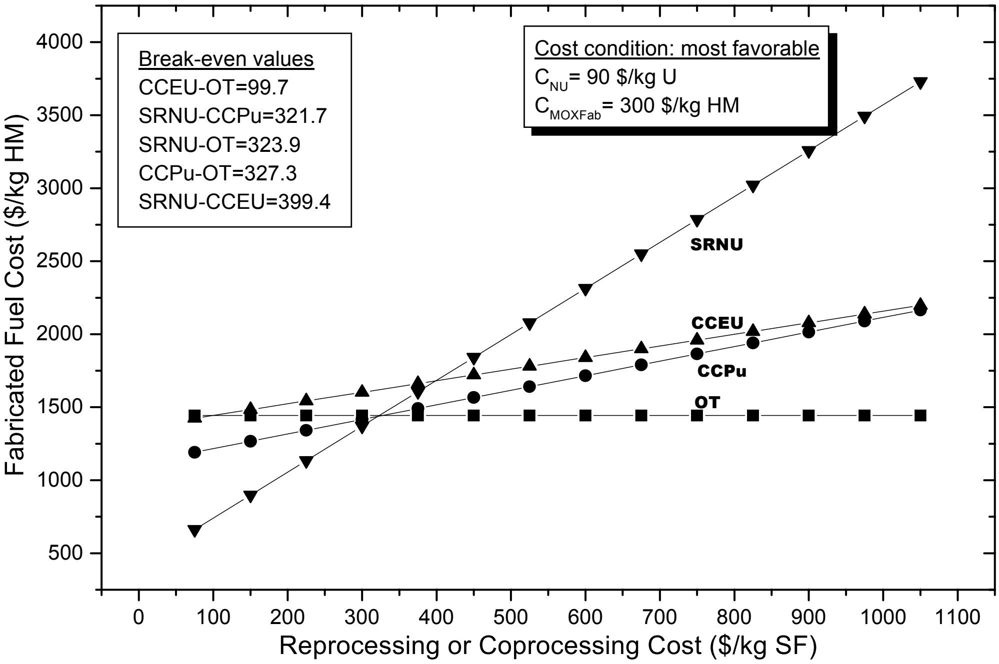

Figure 3.24. Break-even C_{Rep} values for most favorable condition (33000 MWd/tU)

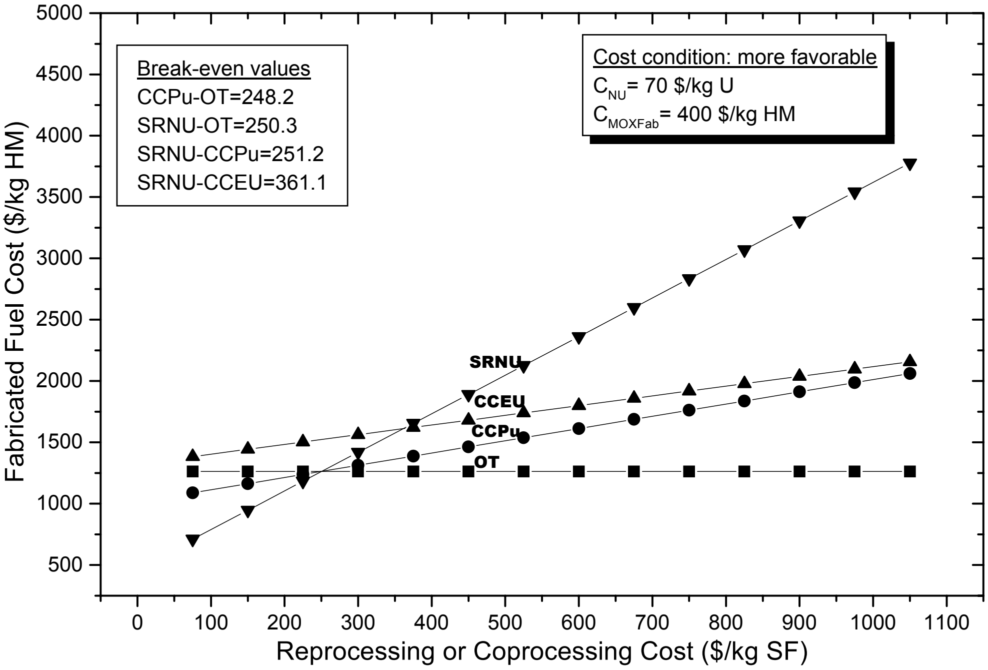

Figure 3.25. Break-even C_{Rep} values for more favorable condition (33000 MWd/tU)

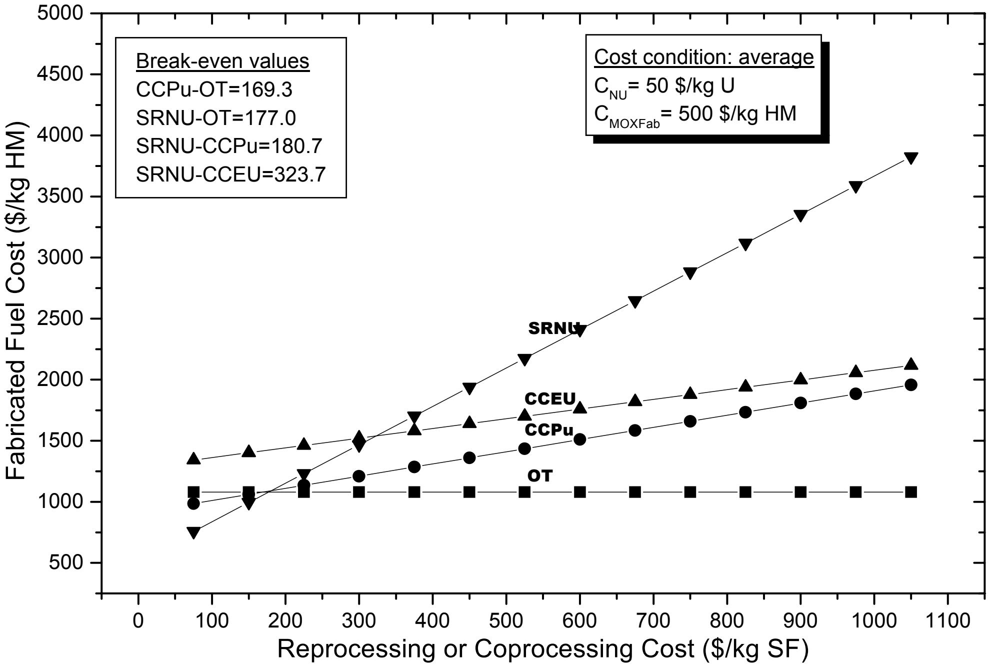

Figure 3.26. Break-even C_{Rep} values for average condition (33000 MWd/tU)

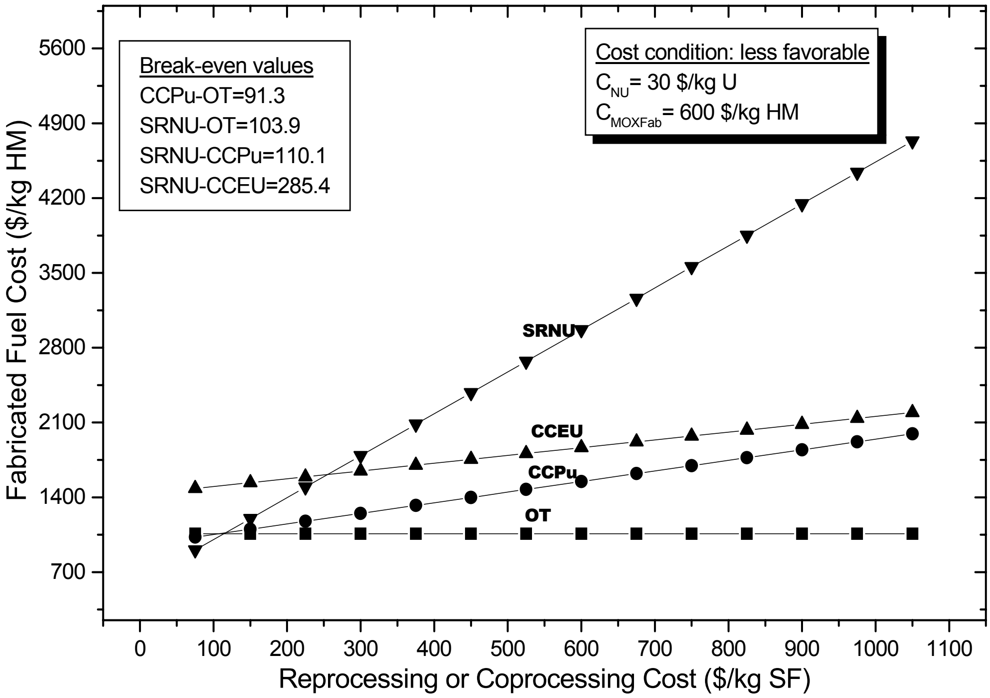

Figure 3.27. Break-even C_{Rep} values for less favorable condition (33000 MWd/tU)

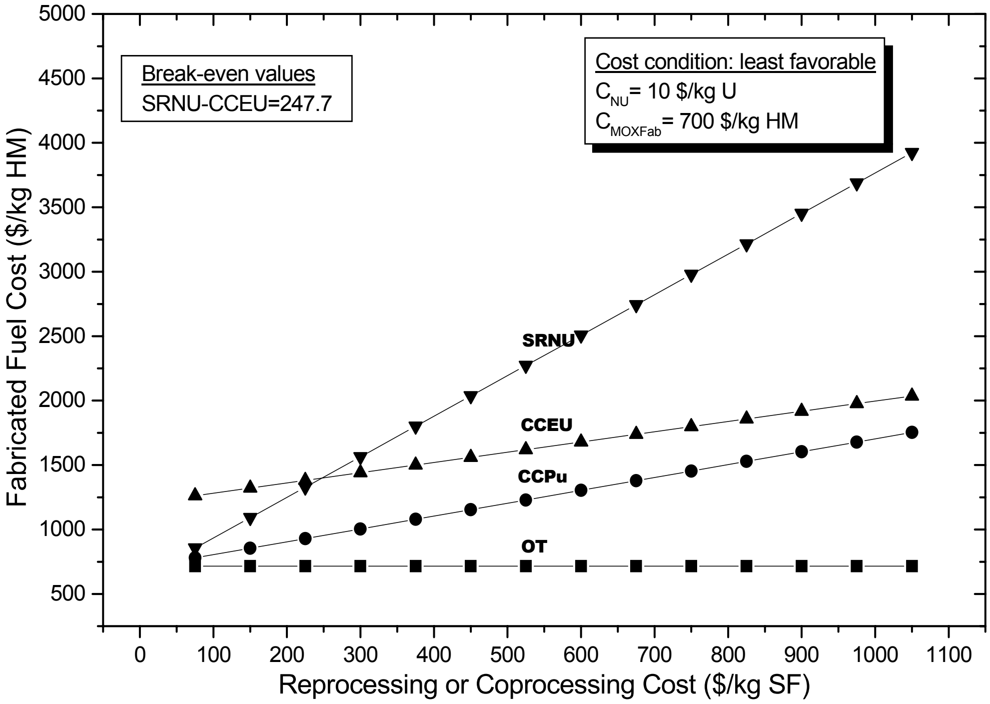

Figure 3.28. Break-even C_{Rep} values for least favorable condition (33000 MWd/tU)

The SRNU cycle is the most sensitive to unit cost of reprocessing in all conditions. For the most favorable conditions (C_{NU}=90 $/kg and C_{MOXfab}=300 $/kg), a reprocessing unit cost less than 321.7 $/kg makes the SRNU cycle the most economical case and C_{rep} greater than 327.3 $/kg makes the OT cycle the cheapest. For the more favorable cost conditions (C_{NU}=70 $/kg and C_{MOXfab}=400 $/kg), SRNU is the best choice for reprocessing costs lower than 250.3 $/kg. For C_{rep} unit costs higher than 251.7 $/kg OT becomes the most economical. For the average favorable cost conditions, (C_{NU}=50 $/kg and C_{MOXfab}=500 $/kg), SRNU is the most advantageous cycle for low reprocessing costs. For the less favorable (C_{NU}=30 $/kg and C_{MOXfab}=600 $/kg), and least favorable (C_{NU}=10 $/kg and C_{MOXfab}=700 $/kg), OT is almost always the most economical cycle.

B=40000 MWd/tU

Cost lines and break-even values for reprocessing cost for the five cycles are shown in Figures 3.29, 3.30, 3.31, 3.32 and 3.33 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

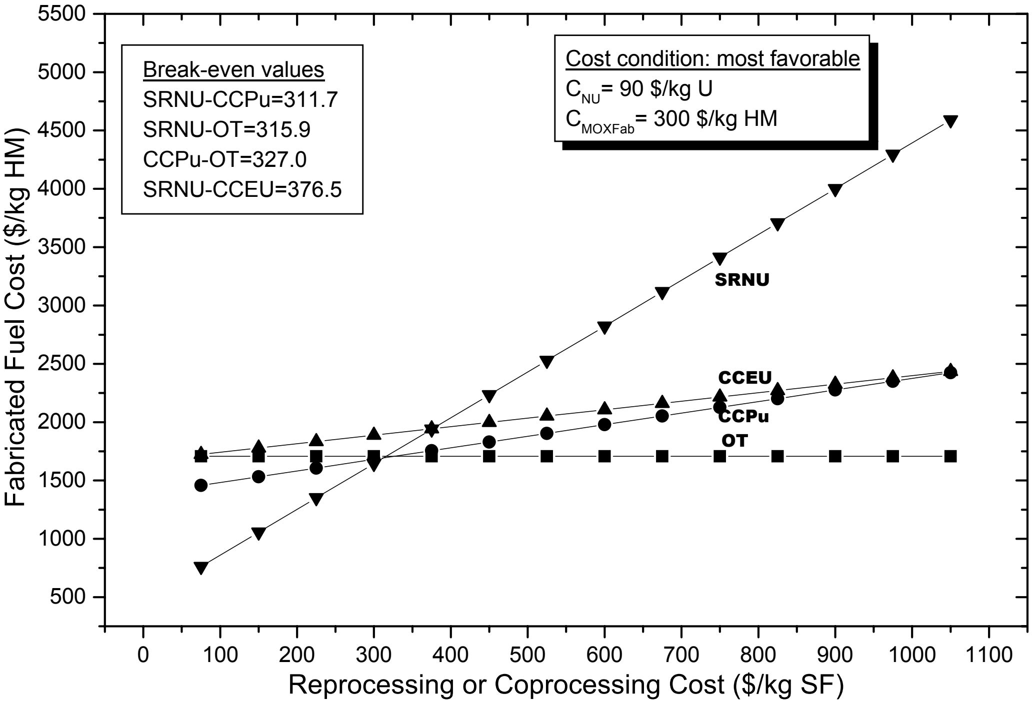

Figure 3.29. Break-even C_{Rep} values for most favorable condition (40000 MWd/tU)

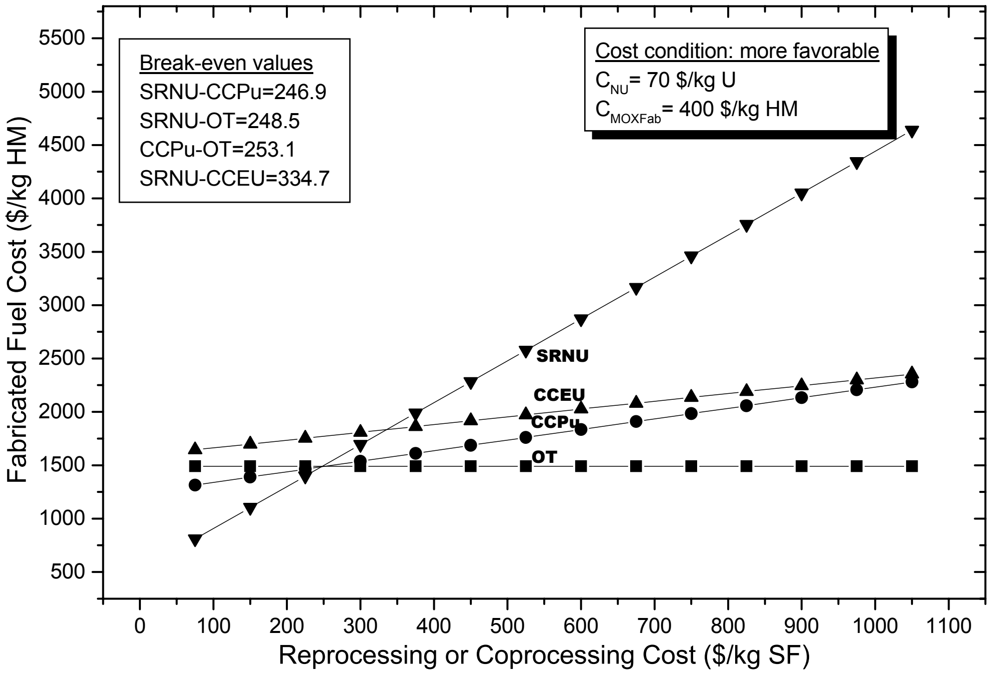

Figure 3.30. Break-even C_{Rep} values for more favorable condition (40000 MWd/tU)

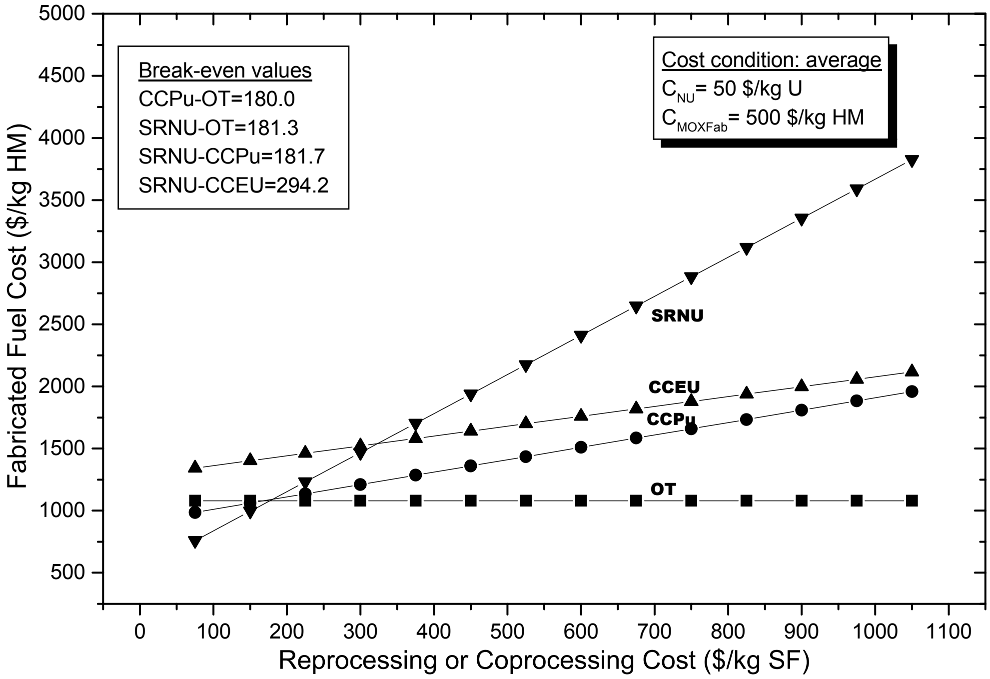

Figure 3.31. Break-even C_{Rep} values for average condition (40000 MWd/tU)

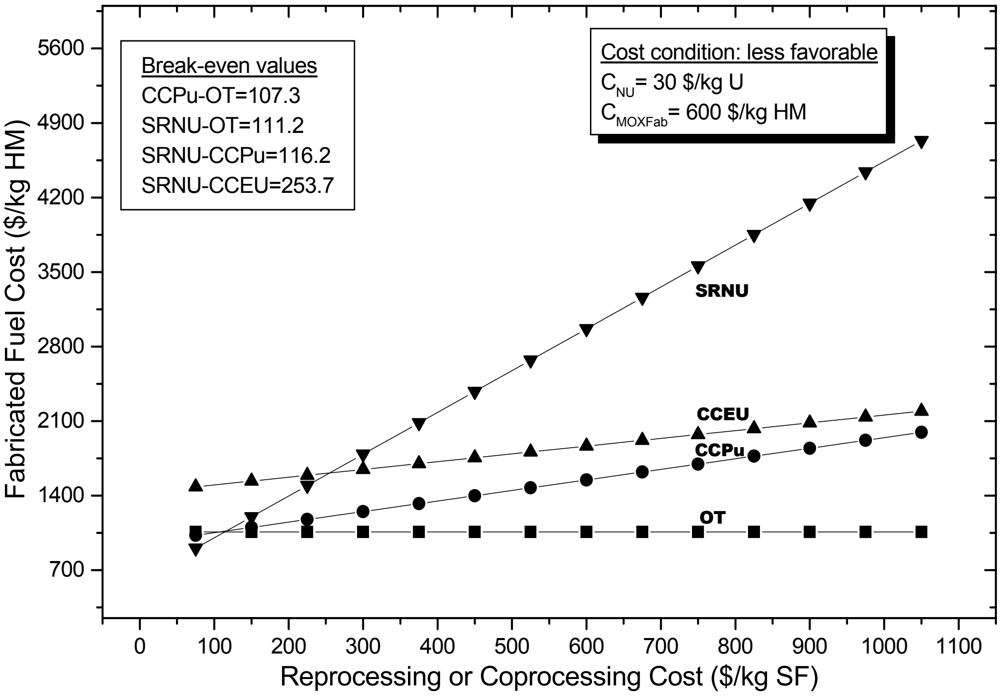

Figure 3.32. Break-even C_{Rep} values for less favorable condition (40000 MWd/tU)

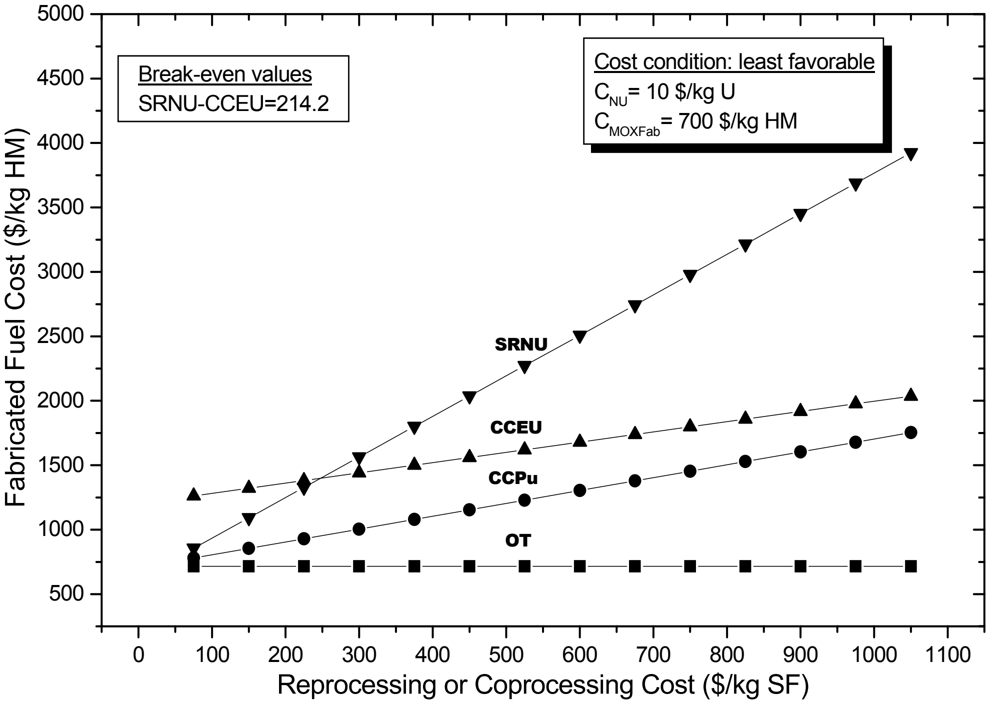

Figure 3.33. Break-even C_{Rep} values for least favorable condition (40000 MWd/tU)

The SRNU cycle is the most sensitive to unit cost of reprocessing in all conditions. For the most favorable conditions, SRNU is the most economical cycle for reprocessing unit costs less than 311.7 $/kg and OT cycle becomes the cheapest choice for reprocessing costs higher than this value. For the more favorable cost conditions, SRNU is the best choice for reprocessing costs lower than 246.9 $/kg, above which OT becomes the most economical. For the average favorable cost conditions, SRNU is the most advantageous cycle for reprocessing costs lower than 181.3 $/kg. For the less favorable and least favorable, OT is almost always the most economical cycle and SRNU is always the most expensive case for high reprocessing costs.

B=50000 MWd/tU

Cost lines and break-even values for reprocessing cost for the four cycles are shown in Figures 3.34, 3.35, 3.36, 3.37 and 3.38 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

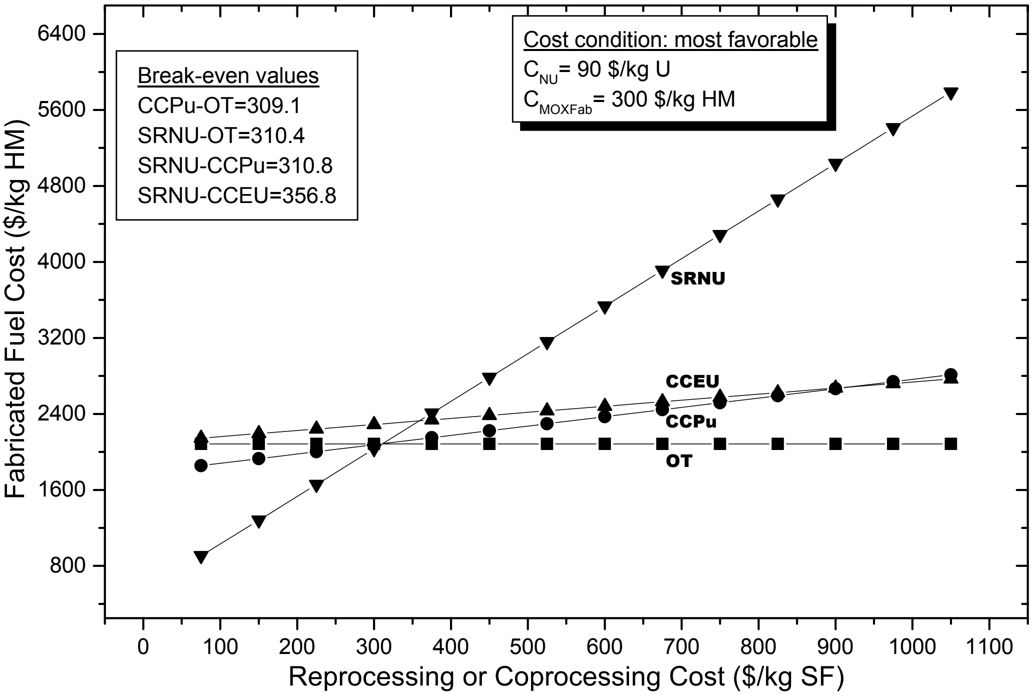

Figure 3.34. Break-even C_{Rep} values for most favorable condition (50000 MWd/tU)

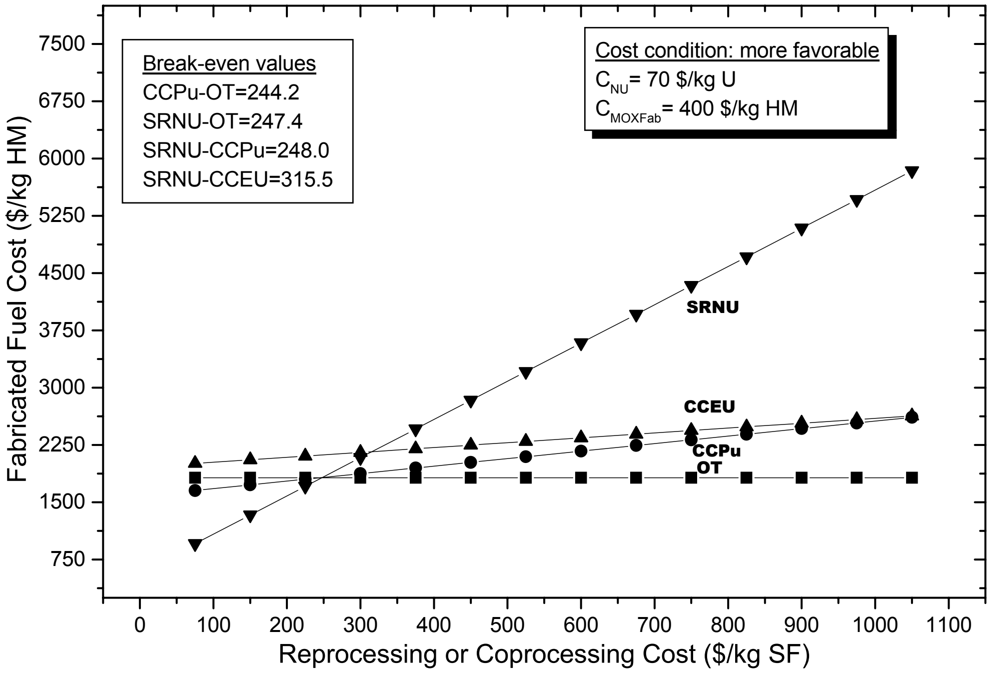

Figure 3.35. Break-even C_{Rep} values for more favorable condition (50000 MWd/tU)

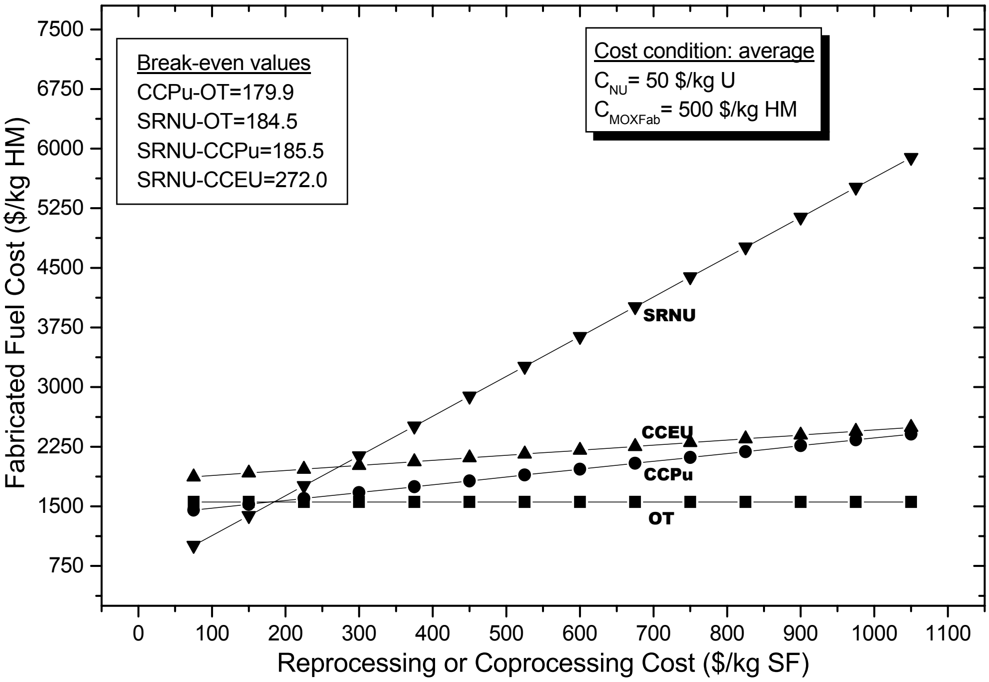

Figure 3.36. Break-even C_{Rep} values for average condition (50000 MWd/tU)

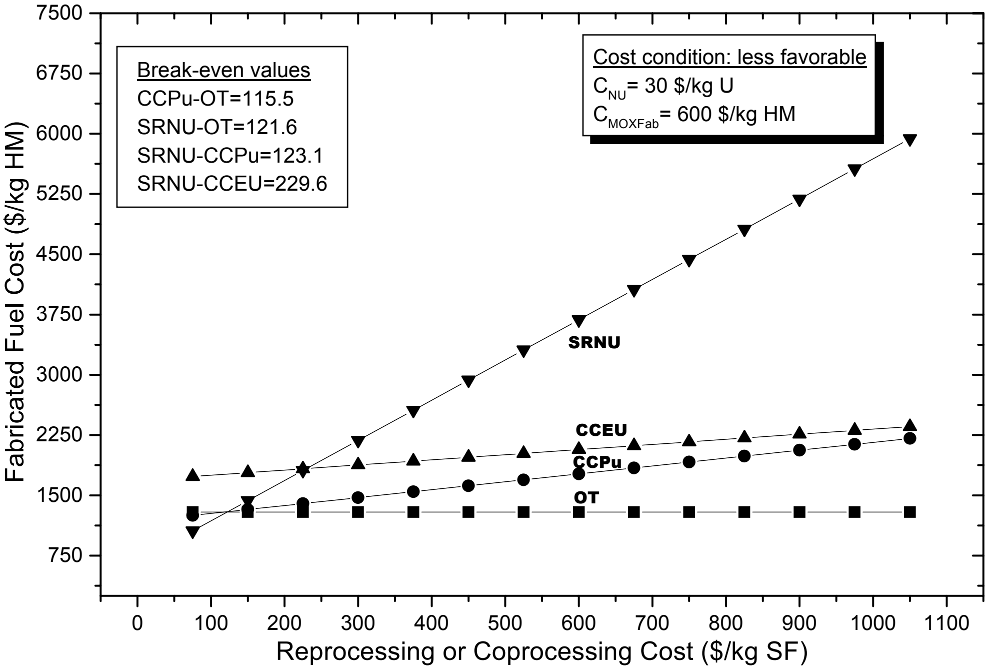

Figure 3.37. Break-even C_{Rep} values for less favorable condition (50000 MWd/tU)

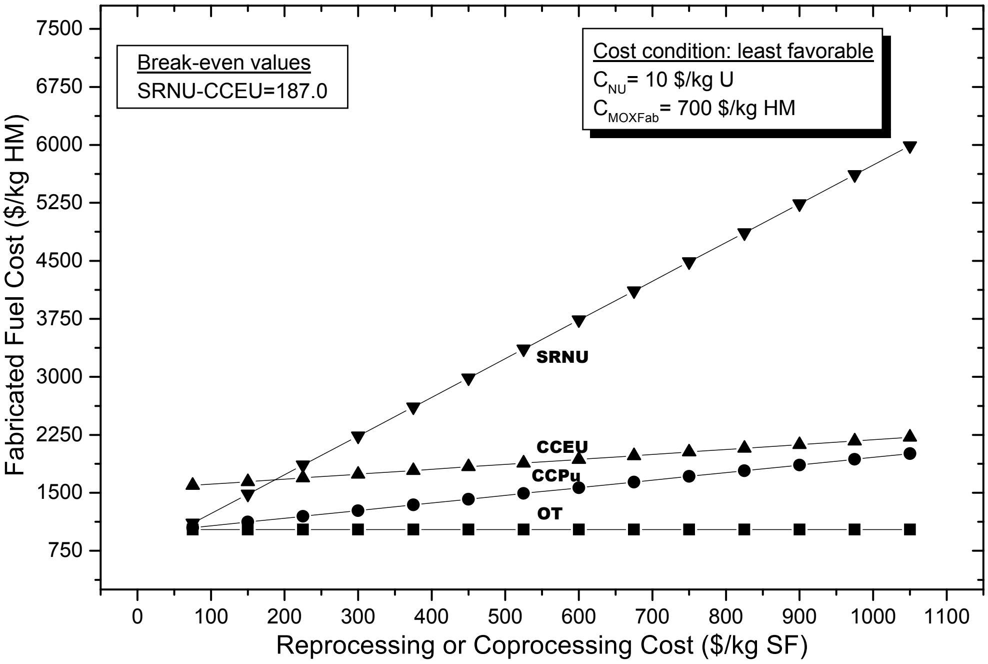

Figure 3.38. Break-even C_{Rep} values for least favorable condition (50000 MWd/tU)

The SRNU cycle is the most sensitive to unit cost of reprocessing in all conditions. For the most favorable and more favorable conditions, SRNU is the most economical cycle for reprocessing unit costs less than 310.4 and 244.2 $/kg respectively. For the more favorable cost conditions, OT is the cheapest cycle for reprocessing costs greater than 247.4 $/kg. For the less favorable and least favorable, OT is almost always the best choice.

3.3.3. Break-even MOX Fabrication Costs (C_{MOXfab})

Unit costs of fabricated fuels for each fuel cycle are calculated for varying MOX fabrication costs and for cost conditions given in Table 3.4. Unit costs of fabricated fuels for each fuel are plotted versus MOX fabrication unit cost and cost lines for each fuel cycle are obtained. Intersections of any two of these lines indicate break-even MOX fabrication cost for the two cycles.

Cost lines for SRNU, SRRU, SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus MOX fabrication cost and these lines are shown in Appendix C.

As observed from these figures cost lines for SRNU, SRRU and SRDU cycles have same characteristics. Therefore, it will be appropriate to obtain only SRNU cost lines to compare break-even MOX fabrication costs for SRNU, SRRU and SRDU cycles with the break-even MOX fabrication costs for other cycles (OT, CCPu and CCEU).

B=33000 MWd/tU

Cost lines and break-even values for MOX fabrication cost for the four cycles are shown in Figures 3.39, 3.40, 3.41, 3.42 and 3.43 for the most favorable, more favorable, average, less favorable and the least favorable cost conditions for closing the cycle.

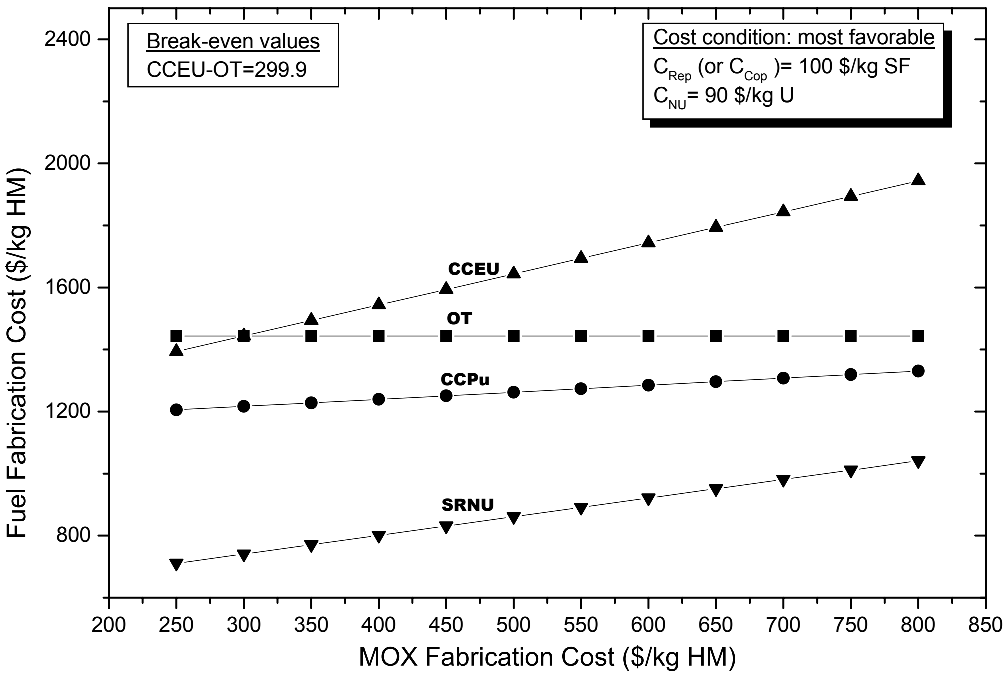

Figure 3.39. Break-even C_{MOXfab} values for most favorable condition (33000 MWd/tU)

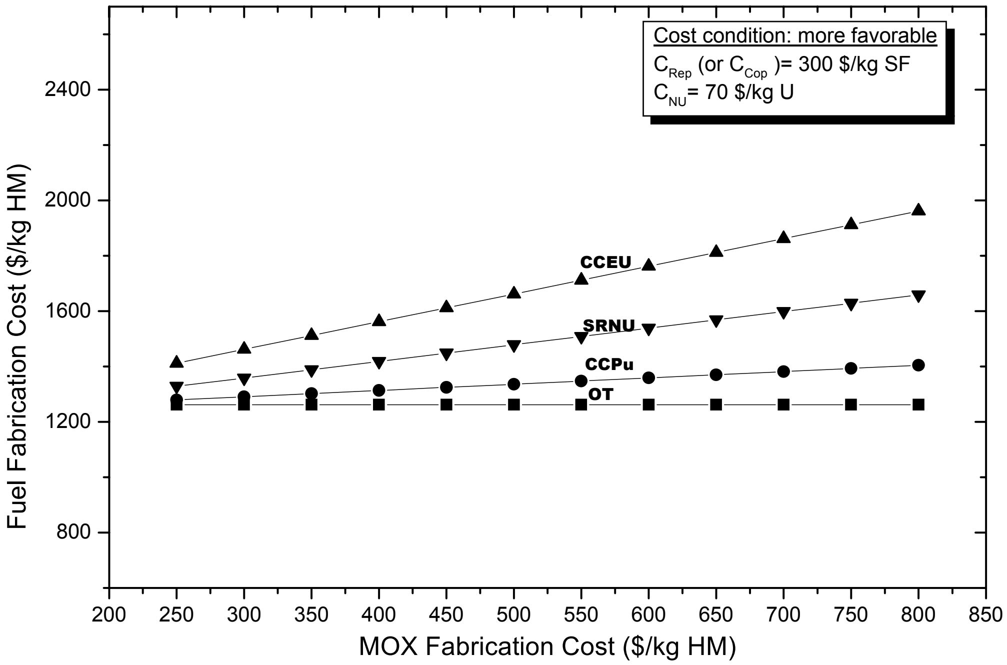

Figure 3.40. Break-even C_{MOXfab} values for more favorable condition (33000 MWd/tU)

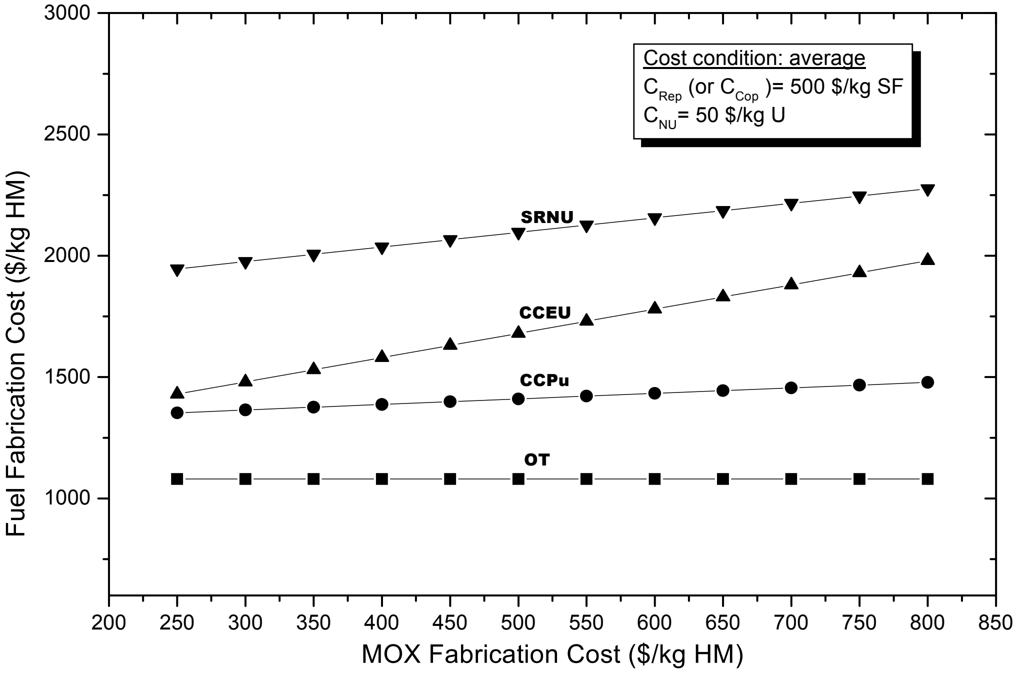

Figure 3.41. Break-even C_{MOXfab} values for average condition (33000 MWd/tU)

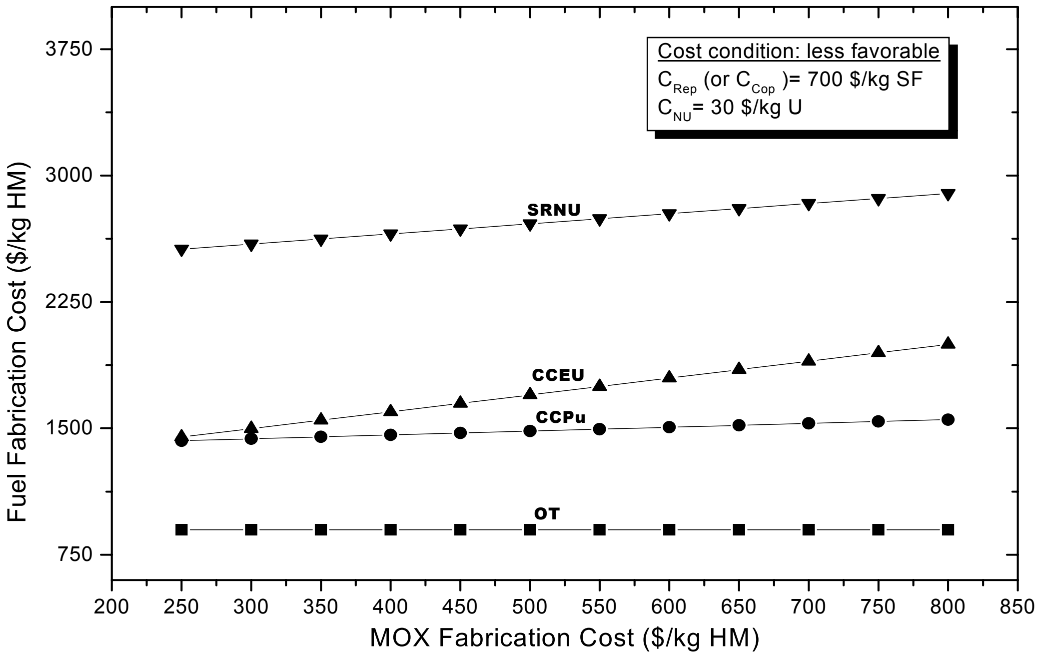

Figure 3.42. Break-even C_{MOXfab} values for less favorable condition (33000 MWd/tU)

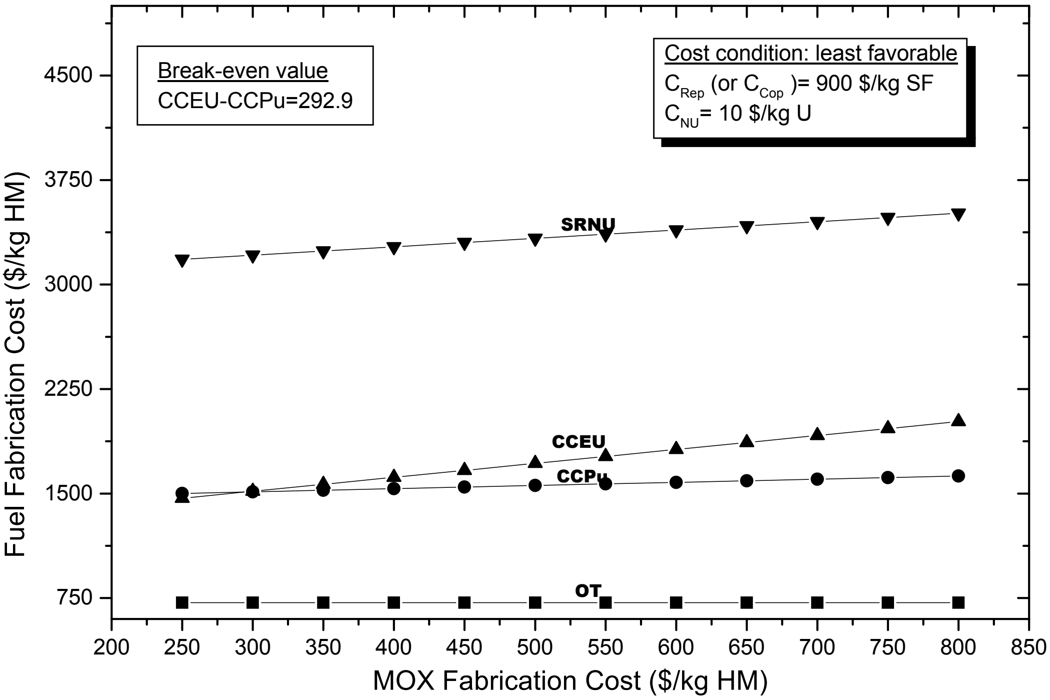

Figure 3.43. Break-even C_{MOXfab} values for least favorable condition (33000 MWd/tU)

For the most favorable cost conditions (C_{NU}=90 \$/kg and C_{rep}=100 \$/kg), SRNU is the cheapest cycle and there is only one break-even value, 299.9 \$/kg abow which CCEU is the most expensive. For the more favorable (C_{NU}=70 \$/kg and C_{MOXfab}=300 \$/kg), average (C_{NU}=50 \$/kg and C_{MOXfab}=500 \$/kg) and less favorable (C_{NU}=30 \$/kg and C_{MOXfab}=700 \$/kg) cost conditions there is no break-even value and OT is always the most economical. For the least favorable cost conditions (C_{NU}=10 \$/kg and C_{MOXfab}=900 \$/kg), there is one break-even value 292.9 \$/kg, below which CCEU cycle is more economical than CCPu cycle.

B=40000 MWd/tU

Cost lines and break-even values for MOX fabrication cost for the five cycles are shown in Figures 3.44, 3.45, 3.46, 3.47 and 3.48 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

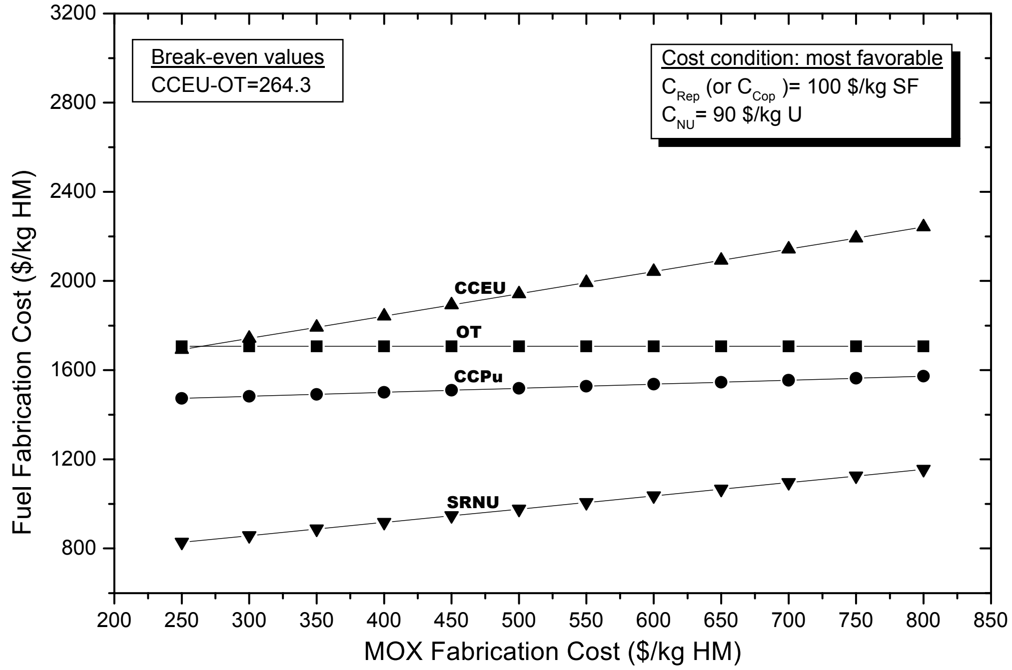

Figure 3.44. Break-even C_{MOXfab} values for most favorable condition (40000 MWd/tU)

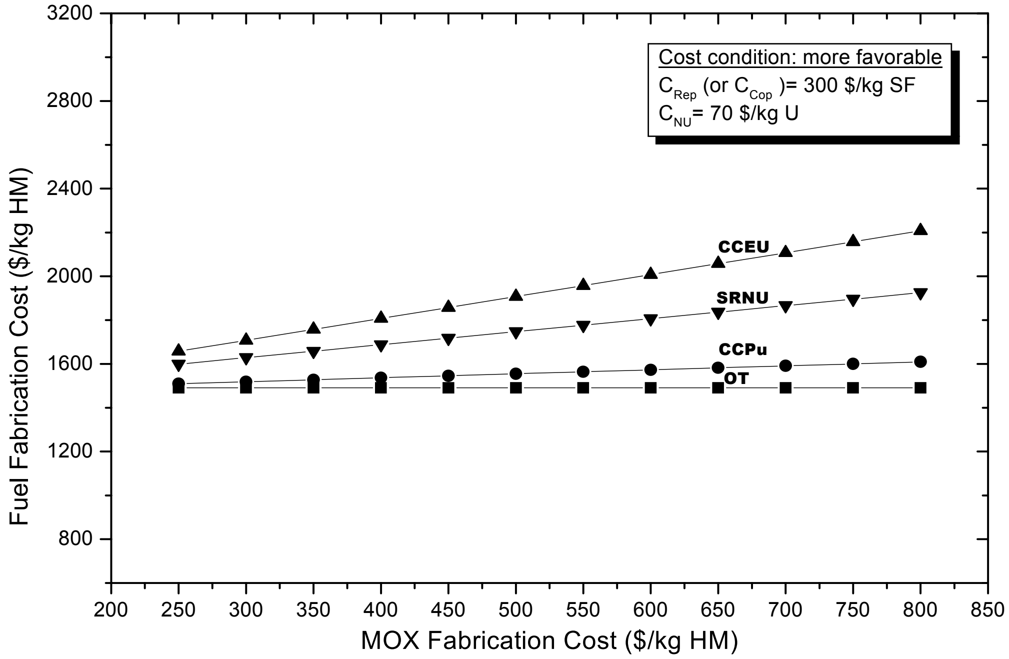

Figure 3.45. Break-even C_{MOXfab} values for more favorable condition (40000 MWd/tU)

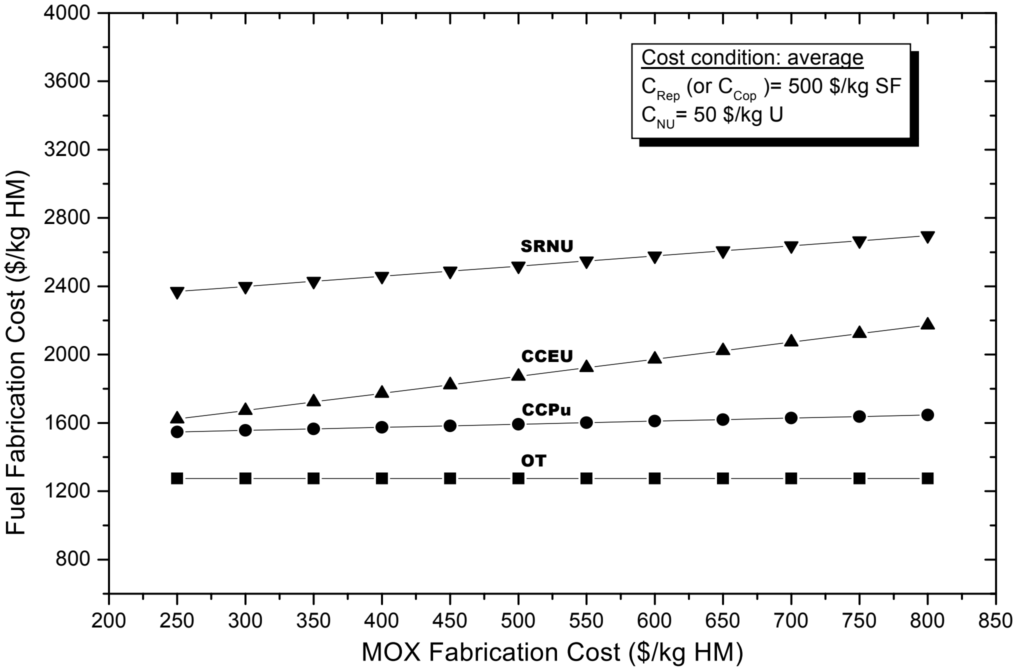

Figure 3.46. Break-even C_{MOXfab} values for average condition (40000 MWd/tU)

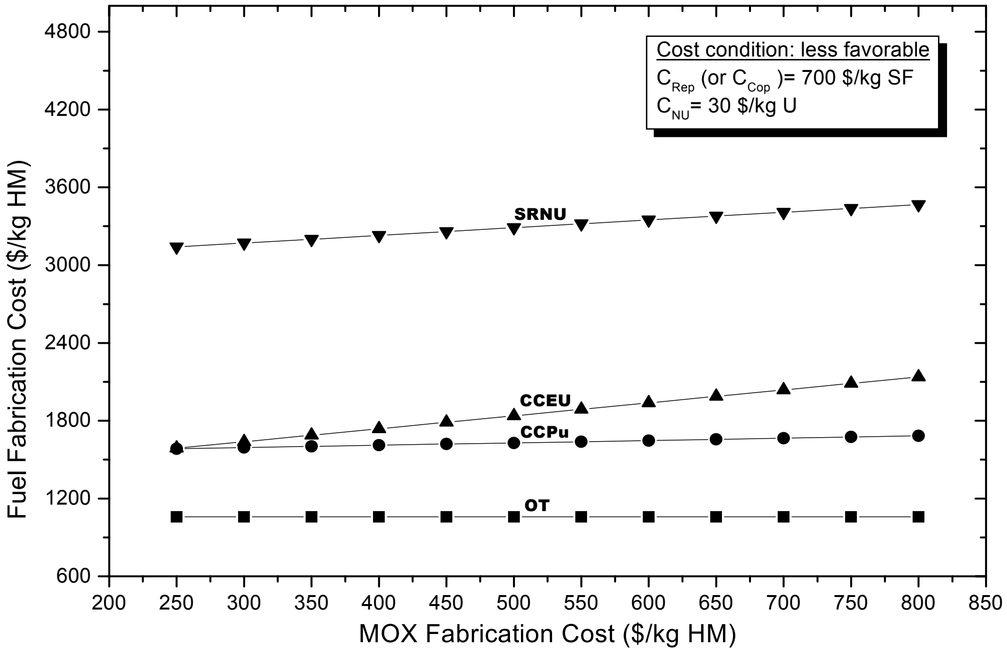

Figure 3.47. Break-even C_{MOXfab} values for less favorable condition (40000 MWd/tU)

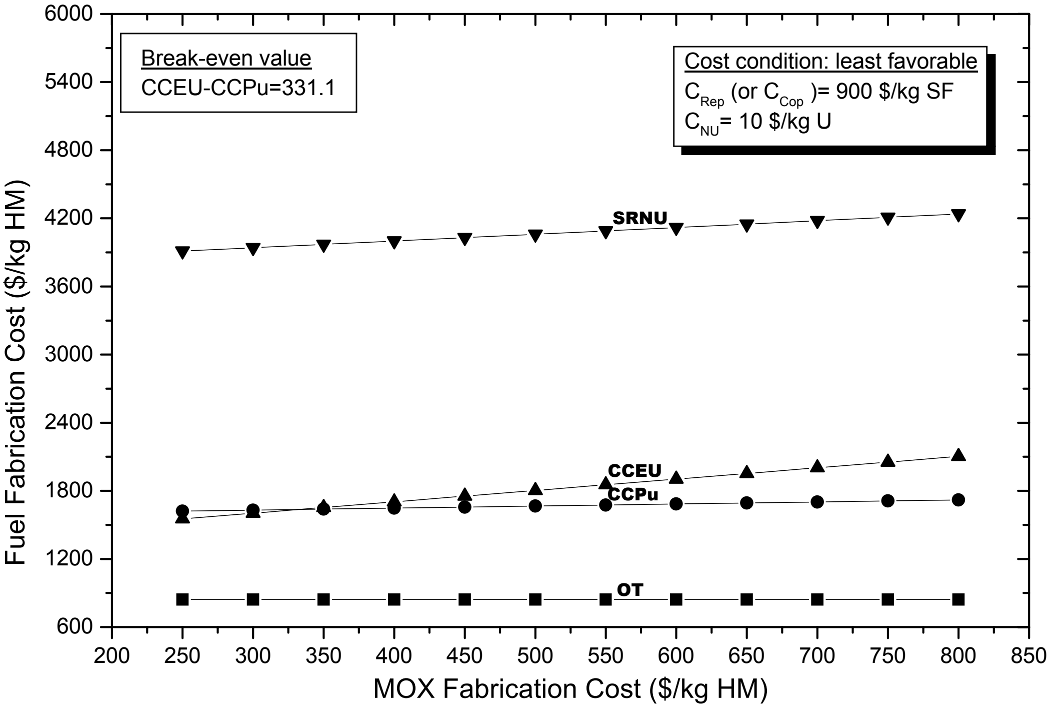

Figure 3.48. Break-even C_{MOXfab} values for least favorable condition (40000 MWd/tU)

OT is the best choice for all conditions except the most favorable cost condition. For most favorable cost condition, SRNU is the most economical case. CCEU is the most sensitive to unit MOX fabrication cost. For the least favorable cost conditions, CCPu is more expensive than CCEU for MOX fabrication costs lower than 331.0 $/kg.

B=50000 MWd/tU

Cost lines and break-even values for MOX fabrication cost for the four cycles are shown in Figures 3.49, 3.50, 3.51, 3.52 and 3.53 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

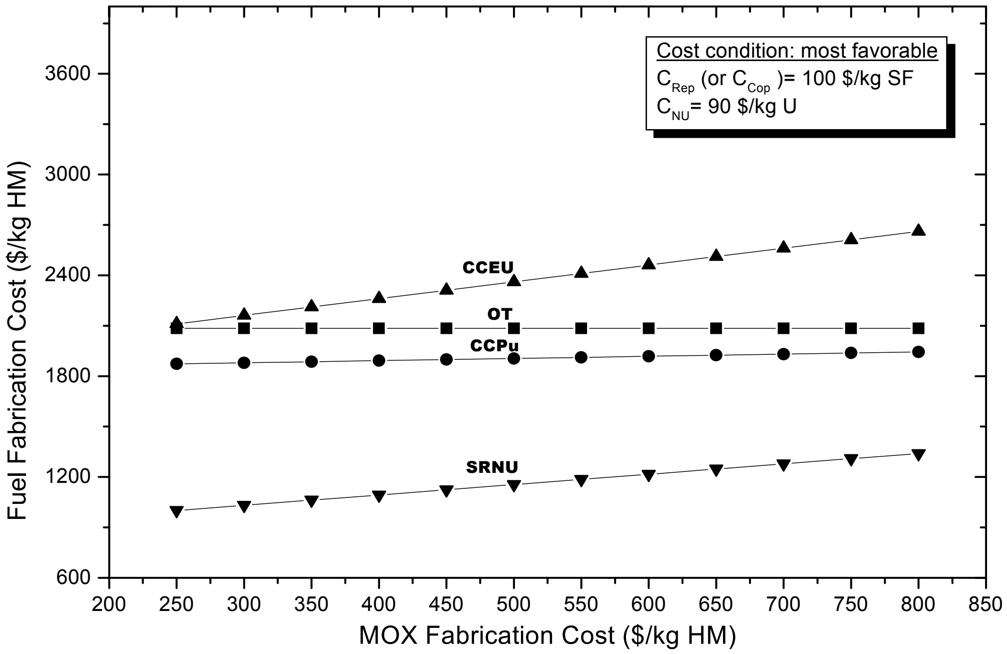

Figure 3.49. Break-even C_{MOXfab} values for most favorable condition (50000 MWd/tU)

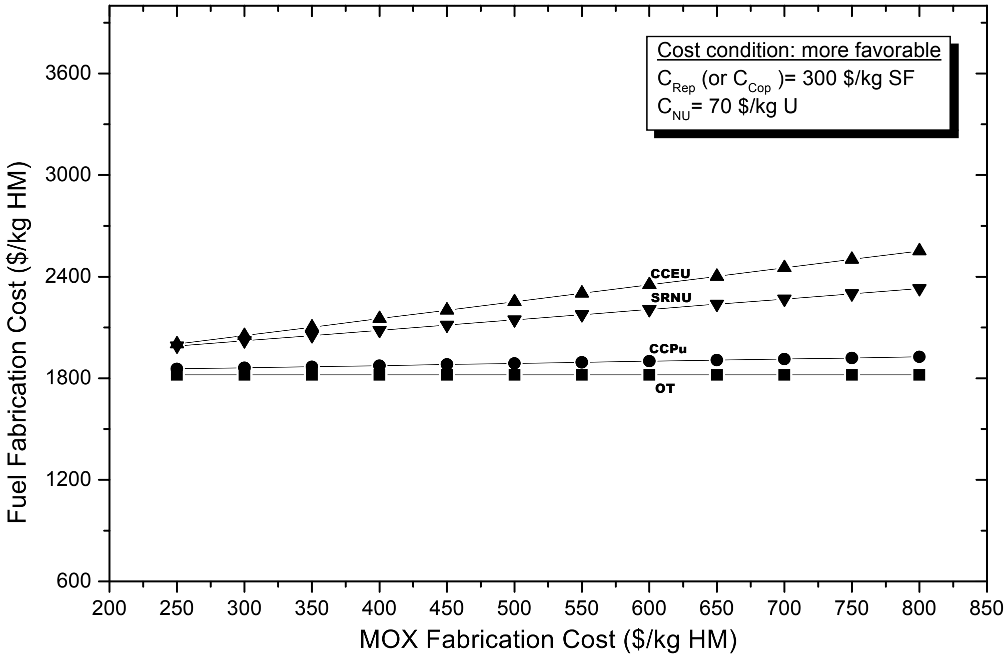

Figure 3.50. Break-even C_{MOXfab} values for more favorable condition (50000 MWd/tU)

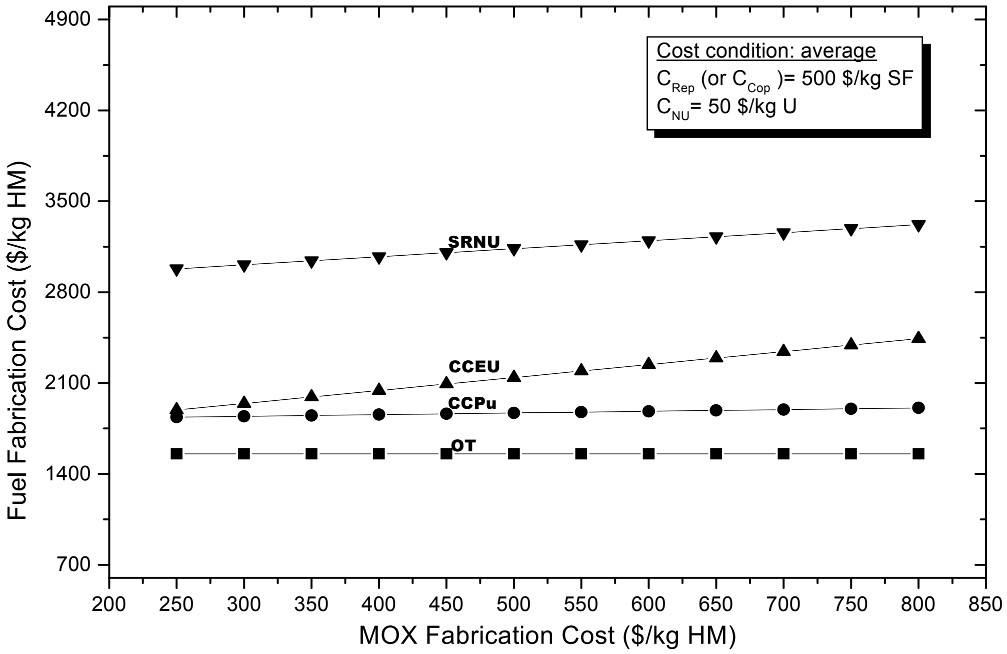

Figure 3.51. Break-even C_{MOXfab} values for average condition (50000 MWd/tU)

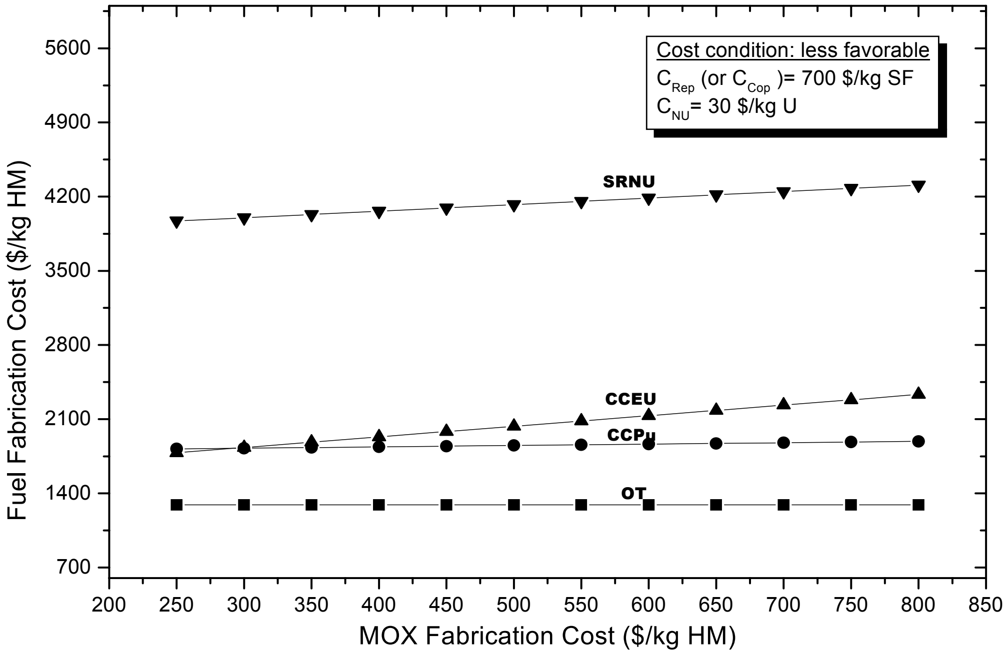

Figure 3.52. Break-even C_{MOXfab} values for less favorable condition (50000 MWd/tU)

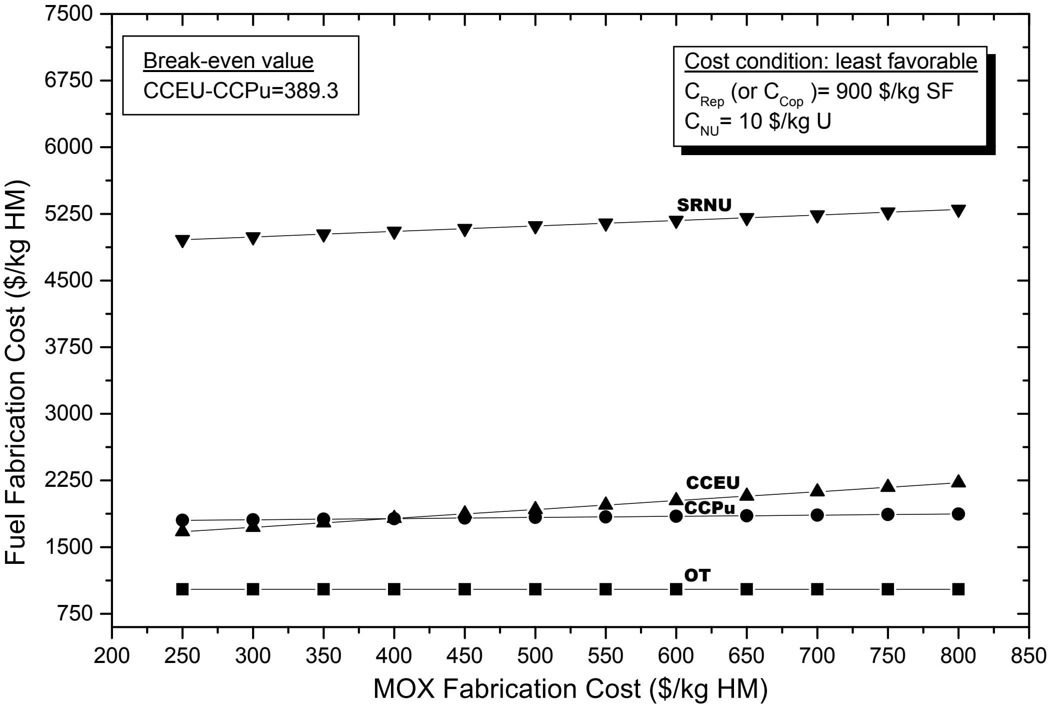

Figure3.53. Break-even C_{MOXfab} values for least favorable condition (50000 MWd/tU)

For most favorable cost conditions, SRNU is the cheapest cycle and CCEU is the most expensive. For more favorable cost conditions, CCEU is the most expensive case and OT is the best choice. For average, less and least favorable cost conditions SRNU is the most expensive and OT is the most economical.

4. LEVELISED FUEL CYCLE COST ANALYSIS

For OT and SRNU cycles, the lifetime levelised fuel cycle cost calculations are performed by using NFCCOST computer program.

4.1. Method of Calculation

Discount Rate: The discount rate is the interest rate used in determining the present value of future cash flows.

Present Value: Present value is a way of comparing the value of money now with the value of money in the future. A dollar today is worth more than a dollar in the future, because inflation erodes the buying power of the future money, while money available today can be invested and grow.

Present value can be calculated by the formula:

$PV=FV/(1+r)^{-n}$

Future value can be calculated by the formula:

$FV=PV/(1+r)^{n}$

where,
PV: Present value
FV: Future value
r: Discount rate
n: Time period

The unit costs for different stages of the fuel cycle are discounted to a selected base date and added together in order to arrive a total fuel cycle cost in present value terms. In order to obtain the levelised fuel cycle cost, total fuel cycle cost is divided to net electricity generated over the reactor lifetime.

4.1.1. Total Fuel Cycle Cost

In order to calculate the overall fuel cycle cost, cost of each fuel cycle component is calculated and added together. Costs of each fuel cycle component can be written as:

Cost of NU:

$$P_1 = \sum_{ts}^{rl} M_{ann}(t).C_{NU}(1+r)^{t-lu-t_b}$$

where,

P_1: Total NU cost ($)

$M_{ann}(t)$: Mass of NU feed per year (kg)

C_{NU}: Unit cost of NU ($/kgU)

r: Discount rate (in percentage)

t_b: Base date of monetary unit

lu: Lead time for NU

rl :Reactor lifetime

ts:Initial loading time

Lead time is the term referring to the date at which materials are obtained, services are performed and payments for front-end components occur, prior to the date of loading fuel into the reactor.

Cost of Conversion:

$$P_2 = \sum_{ts}^{rl} M_{ann}(t).C_{Con}(1+r)^{t-lc-t_b}$$

P_2: Total conversion cost ($)

C_{Con}: Unit cost of NU conversion ($/kgU)

lc: Lead time for conversion

Cost of Enrichment:

$$P_3 = \sum_{ts}^{rl} M_S(t).C_{SWU}(1+r)^{t-le-t_b}$$

P_3: Total enrichment cost ($)

$M_S(t)$: Mass of SWU needed to enrich NU (kg)

C_{SWU}: Unit cost of SWU ($/kgSWU)

le: Lead time for enrichment

Cost of Uranium Fabrication:

$$P_4 = \sum_{ts}^{rl} M_U(t).C_{Ufab}(1+r)^{t-lf-t_b}$$

P_4: Total Uranium fabrication cost ($)

$M_U(t)$: Annual Uranium loading (kg)

C_{Ufab}: Unit cost of Uranium fabrication ($/kgU)

lf: Lead time for Uranium fabrication

Cost of Reprocessing:

$$P_5 = \sum_{ts}^{rl} M_{SF}(t).C_{\mathrm{Re}\,p}(1+r)^{t-t_b}$$

P_5: Total reprocessing cost ($)

$M_{SF}(t)$: Mass of fuel discharged from reactor (kg)

C_{Rep}: Unit cost of reprocessing ($/kgU)

Cost of MOX Fabrication:

$$P_6 = \sum_{ts}^{rl} M_{MOX}(t).C_{MOXfab}(1+r)^{t-t_b}$$

P_6: Total MOX fabrication cost ($)

$M_{MOX}(t)$: Mass of MOX fuel charged in reactor (kg)

C_{MOXfab}: Unit cost of MOX fabrication ($/kgHM)

Cost of HLW Disposal:

$$P_7 = \sum_{ts}^{rl} M_{HLW}(t).C_{HLW}(1+r)^{t-t_b}$$

P_7: Total HLW disposal cost ($)

$M_{HLW}(t)$: Mass of HLW (kg)

C_{HLW}: Unit cost of HLW disposal ($/kgHM)

Cost of SF Storage:

$$P_8 = \sum_{ts}^{rl} M_{SF}(t).C_{Storage}(1+r)^{t-t_b}$$

P_8: Total SF storage cost ($)

$M_{SF}(t)$: Mass of SF (kg)

$C_{Storage}$: Unit cost of SF storage ($/kgHM-year)

Cost of SF Disposal:

$$P_9 = \sum_{ts}^{rl} M_{SF}(t).C_{SF}(1+r)^{t-t_b}$$

P_9: Total SF disposal cost ($)

$M_{SF}(t)$: Mass of SF (kg)

C_{SF}: Unit cost of SF disposal ($/kgHM)

Total fuel cycle cost over the reactor lifetime rl is:

$$P_{tot} = \sum_{i=1}^{9} P_i$$

Levelised fuel cycle cost can be written as:

$$luc = \frac{P_{tot}}{\sum_{ts}^{rl} E(t)}$$

where E(t) is the yearly net electrical output and is given by :

E(t)=(Electrical Power).(Capacity Factor).8760hr/yr

4.2. Reference Reactor and Fuel Cycle Data

The reference reactor is a typical PWR with a thermal output of 3000 MW giving an electrical output of 1000 MWe. Reference reactor assumed to be in operation in the year 2005 and reactor lifetime is 30 years. Table 4.1 exhibits all the reactor and fuel cycle data:

Table 4.1.Reference reactor and fuel cycle data

Reactor Type	PWR
Fuel Enrichment (wt %)	3.3
Power (MWe)	1000
Thermal Efficiency (%)	32.5
Capacity Factor (%)	80
Fuel Exposure Time (day)	1100
Burnup (MWd/tU)	33000
Initial Loading Time	2005
Reactor Lifetime (yr)	30
Lead Time for Uranium Purchase (months)	24
Lead Time for Conversion (months)	18
Lead Time for Enrichment (months)	12
Lead Time for Fabrication (months)	6
Reprocessing Period (year)	1

It is assumed that spent fuel will be stored on site for 35 years and then it will disposed of.

4.3. Cost Parameters

Base date of monetary unit is 2000 and discount rate is 5 percent. Reference unit cost values of fuel cycle components are given in Table 4.2.

Table 4.2 Fuel cycle component unit costs

Component	Reference Price
Uranium Purchase ($/kgU)	30
Conversion ($/kgU)	6
Enrichment ($/kgSWU)	110
U Fabrication ($/kgU)	200
MOX Fabrication ($/kgHM)	400
Reprocessing ($/kgU)	600
HLW Disposal ($/kgU)	250
SF Storage ($/kgHM-year)	5
SF Disposal ($/kgHM)	250

Since the natural uranium prices today are high, unit cost of natural uranium is taken as 30 $/kgU. Unit cost of MOX fabrication is assumed to be 2 times that of uranium fuel fabrication which is taken as 200 $/kgU [12].

4.4. Results

Based on reference prices and assumptions, the lifetime levelised fuel cycle costs for OT and SRNU fuel cycle cases are evaluated. These calculations are performed for discount rates 0 and 5 percents.

r=0 (constant dollar) :

The levelised fuel cycle cost for the OT cycle is 5.162 mills/kWh. Table 4.3 shows the contribution of each fuel cycle component for the initial core and refuels in the total fuel cycle cost.

Table 4.3 Levelised fuel cycle cost for the OT cycle, r=0

Component	luc (mills/kWh)		
	Initial Core	Reloads	Total
Uranium Purchase	0.095	0.953	1.048
Conversion	0.019	0.191	0.210
Enrichment	0.155	1.544	1.699
U Fabrication	0.078	0.777	0.855
Front-End total	**0.347**	**3.465**	**3.812**
SF Storage	-	0.379	0.379
SF Disposal	-	0.971	0.971
Back-End total	**-**	**1.350**	**1.350**
Total cost	**0.347**	**4.815**	**5.162**

Shares of each component on total cost are given in Figure 4.1. As shown in Figure 4.1. enrichment cost has the greatest contribution to total fuel cycle cost (33%).

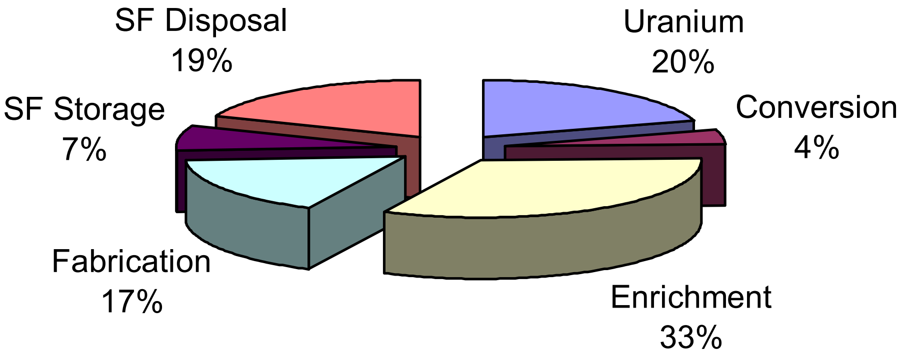

Figure 4.1 Share of component cost for the OT cycle, r=0

The levelised fuel cycle cost for the SRNU cycle is 5.764 mills/kWh. Table 4.4 shows the contribution of each fuel cycle component for the initial core and refuels in the total fuel cycle cost.

Table 4.4 Levelised fuel cycle cost for the SRNU cycle, r=0

Component	luc (mills/kWh)		
	Initial Core	Reloads	Total
Uranium Purchase	0.095	0.732	0.827
Conversion	0.019	0.162	0.181
Enrichment	0.155	1.342	1.497
U Fabrication	0.078	0.669	0.747
MOX Fabrication	-	0.253	0.253
Front-End total	**0.347**	**3.158**	**3.505**
Reprocessing	-	2.040	2.040
HLW Disposal	-	0.030	0.030
SF Storage	-	0.051	0.051
SF Disposal	-	0.138	0.138
Back-End total		**2.259**	**2.259**
Total cost	**0.347**	**5.417**	**5.764**

Shares of each component on total cost are given in Figure 4.2. As shown in Figure 4.2. reprocessing cost has the greatest contribution to total fuel cycle cost (36%).

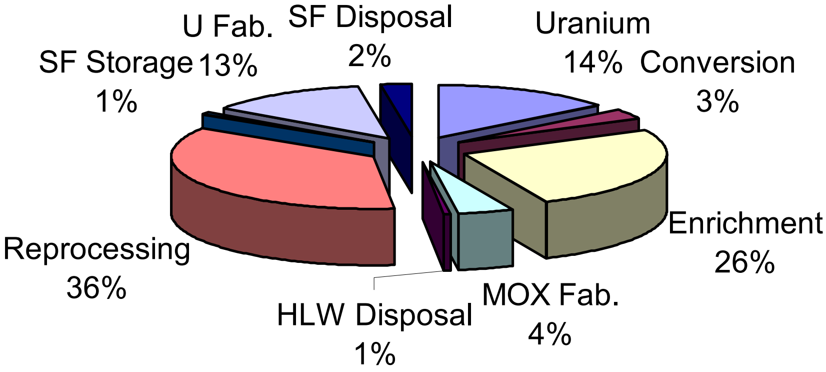

Figure 4.2 Share of component cost for the SRNU cycle, r=0

Table 4.5 presents levelised OT and SRNU fuel cycle costs for various C_{NU}, C_{Rep} and C_{MOXfab} values.

Table 4.5 Levelised fuel cycle costs for OT and SRNU cycle (r=0)

C_{NU} ($/kgU)	C_{Rep} ($/kgHM)	C_{MOXfab} ($/kgHM)	OT (mills/kWh)	SRNU (mills/kWh)
20	500	300	4.798	5.074
20	500	400	4.798	5.137
20	500	500	4.798	5.201
20	600	300	4.798	5.414
20	600	400	4.798	5.477
20	600	500	4.798	5.541
20	700	300	4.798	5.754
20	700	400	4.798	5.818
20	700	500	4.798	5.881
30	500	300	5.161	5.361
30	500	400	5.161	5.424
30	500	500	5.161	5.488
30	600	300	5.161	5.701
30	600	400	5.161	5.764
30	600	500	5.161	5.828
30	700	300	5.161	6.041
30	700	400	5.161	6.104
30	700	500	5.161	6.168
40	500	300	5.499	5.627
40	500	400	5.499	5.691
40	500	500	5.499	5.754
40	600	300	5.499	5.967
40	600	400	5.499	6.031
40	600	500	5.499	6.094
40	700	300	5.499	6.302
40	700	400	5.499	6.371
40	700	500	5.499	6.434

r=0.05 (spent dollar) :

The levelised fuel cycle cost for the OT cycle is 18.243 mills/kWh. Table 4.6 shows the contribution of each fuel cycle component for the initial core and refuels in the total fuel cycle cost.

Table 4.6 Levelised fuel cycle cost for the OT cycle, r=0.05

Component	luc (mills/kWh)		
	Initial Core	Reloads	Total
Uranium Purchase	0.110	2.564	2.674
Conversion	0.023	0.538	0.561
Enrichment	0.188	4.366	4.554
U Fabrication	0.097	2.310	2.407
Front-End total	**0.418**	**9.778**	**10.196**
SF Storage	-	1.535	1.535
SF Disposal	-	6.512	6.512
Back-End total	**-**	**8.047**	**8.047**
Total cost	**0.418**	**17.825**	**18.243**

Shares of each component on total cost are given in Figure 4.3. As shown in Figure 4.3. SF Disposal cost has the greatest contribution to total fuel cycle cost (36%).

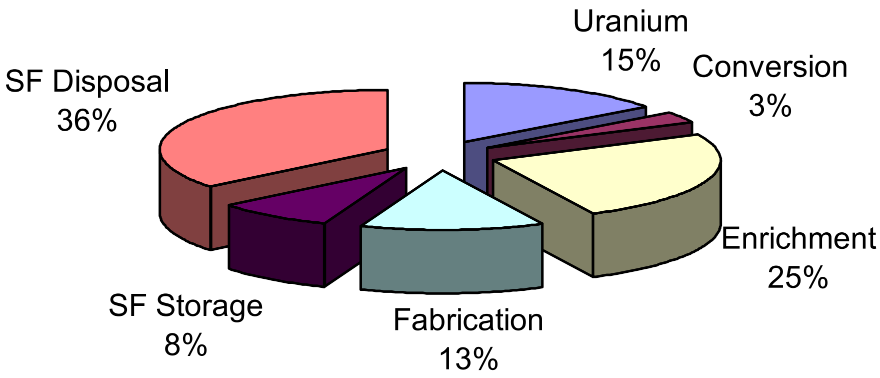

Figure 4.3 Share of component cost for the OT cycle, r=0.05

The levelised fuel cycle cost for the SRNU cycle is 27.386 mills/kWh. Table 4.7 shows the contribution of each fuel cycle component for the initial core and refuels in the total fuel cycle cost.

Table 4.7 Levelised fuel cycle cost for the SRNU cycle, r=0.05

Component	luc (mills/kWh)		
	Initial Core	Reloads	Total
Uranium Purchase	0.110	3.622	3.732
Conversion	0.023	0.874	0.897
Enrichment	0.188	7.243	7.431
U Fabrication	0.097	1.716	1.813
MOX Fabrication	-	1.351	1.351
Front-End total	**0.418**	**14.806**	**15.224**
Reprocessing	-	10.874	10.874
HLW Disposal	-	0.085	0.085
SF Storage	-	0.231	0.231
SF Disposal	-	0.972	0.972
Back-End total	**-**	**12.162**	**12.162**
Total cost	**0.418**	**26.968**	**27.386**

Shares of each component on total cost are given in Figure 4.4. As shown in Figure 4.4. reprocessing cost has the greatest contribution to total fuel cycle cost (39%).

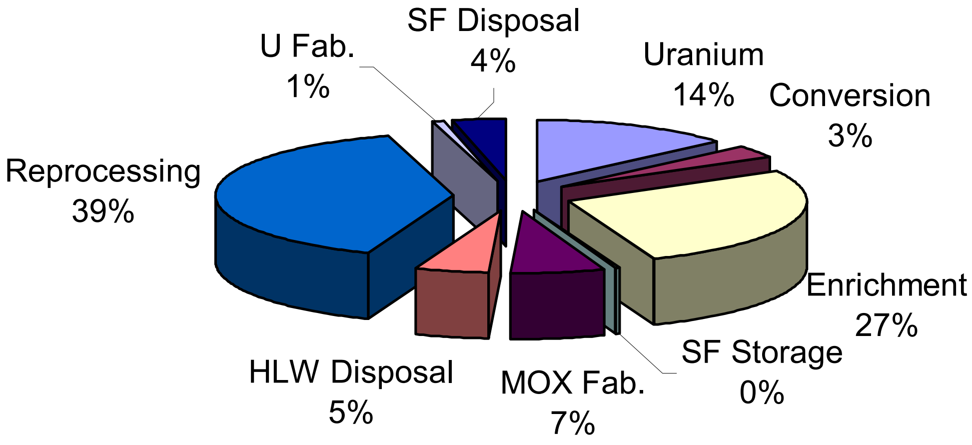

Figure 4.4 Share of component cost for the SRNU cycle, r=0.05

Table 4.8 presents levelised OT and SRNU fuel cycle costs for various C_{NU}, C_{Rep} and C_{MOXfab} values.

Table 4.8 Levelised fuel cycle costs for OT and SRNU cycle (r=0.0)

C_{NU} ($/kgU)	C_{Rep} ($/kgHM)	C_{MOXfab} ($/kgHM)	OT (mills/kWh)	SRNU (mills/kWh)
20	500	300	17.307	23.921
20	500	400	17.307	24.259
20	500	500	17.307	24.596
20	600	300	17.307	25.734
20	600	400	17.307	26.071
20	600	500	17.307	26.409
20	700	300	17.307	27.546
20	700	400	17.307	27.884
20	700	500	17.307	28.221
30	500	300	18.244	25.236
30	500	400	18.244	25.574
30	500	500	18.244	25.912
30	600	300	18.244	27.049
30	600	400	18.244	27.386
30	600	500	18.244	27.724
30	700	300	18.244	28.861
30	700	400	18.244	29.199
30	700	500	18.244	29.536
40	500	300	19.115	26.464
40	500	400	19.115	26.802
40	500	500	19.115	27.139
40	600	300	19.115	28.276
40	600	400	19.115	28.614
40	600	500	19.115	28.952
40	700	300	19.115	30.099
40	700	400	19.115	30.426
40	700	500	19.115	30.764

4.5. Sensitivity Analysis

Sensitivity calculations are made to analyze the impact of variations in the unit costs on the total fuel cycle cost.

4.5.1. Once-through Cycle

Effects of variation from reference NU purchase, Enrichment and Uranium fabrication unit costs are analyzed. Figures 4.5 and 4.6 shows the effects of unit costs on the OT fuel cycle as discount rate r=0 and r=0.05 respectively.

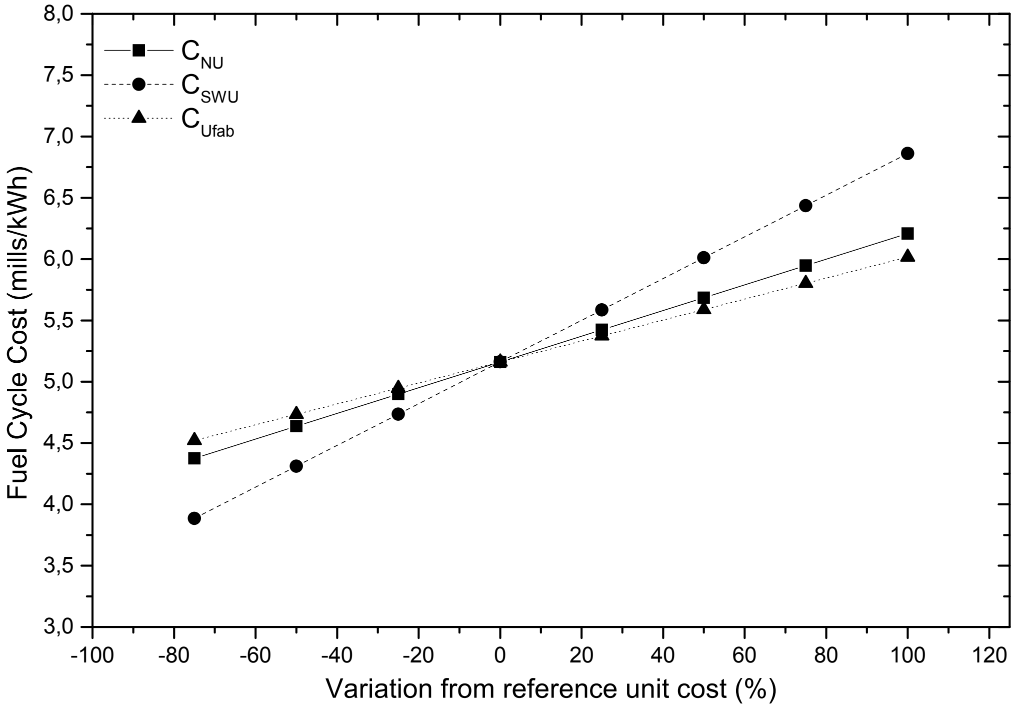

Figure 4.5 OT fuel cycle cost sensitivity to price variations, r=0

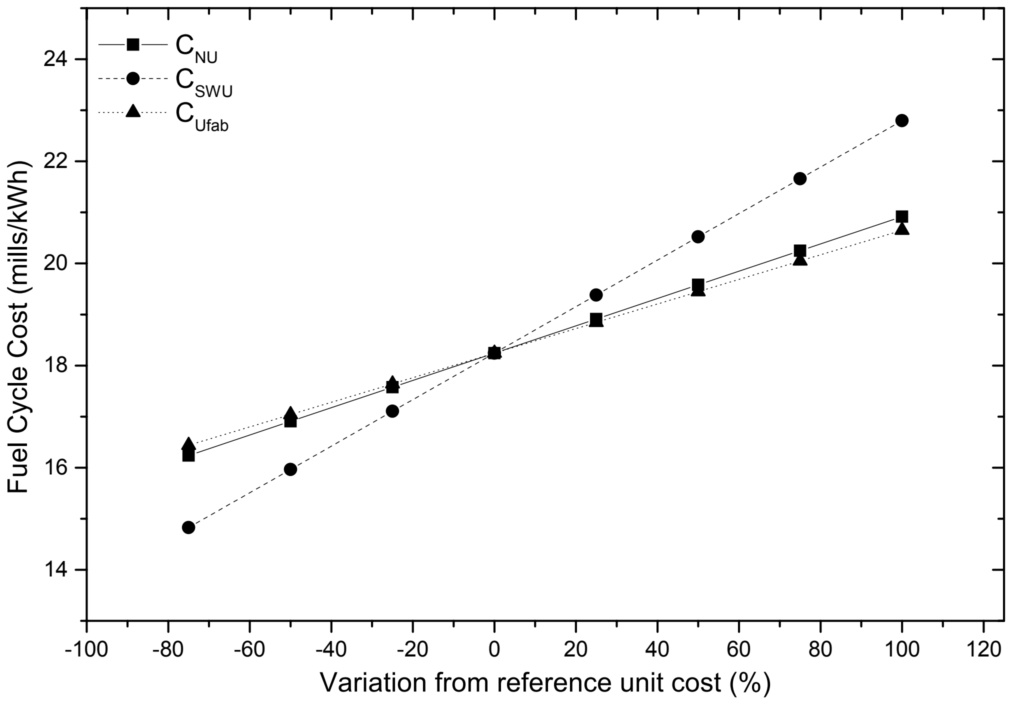

Figure 4.6 OT fuel cycle cost sensitivity to price variations, r=0.05

As observed from Figures 4.5 and 4.6 OT fuel cycle is the most sensitive to enrichment price.

4.5.2. SRNU Cycle

Effects of variation from reference NU purchase, Enrichment, MOX fabrication and Reprocessing unit costs are analyzed. Figures 4.7 and 4.8 show the effects of unit costs on the SRNU fuel cycle as discount rate r=0 and r=0.05 respectively.

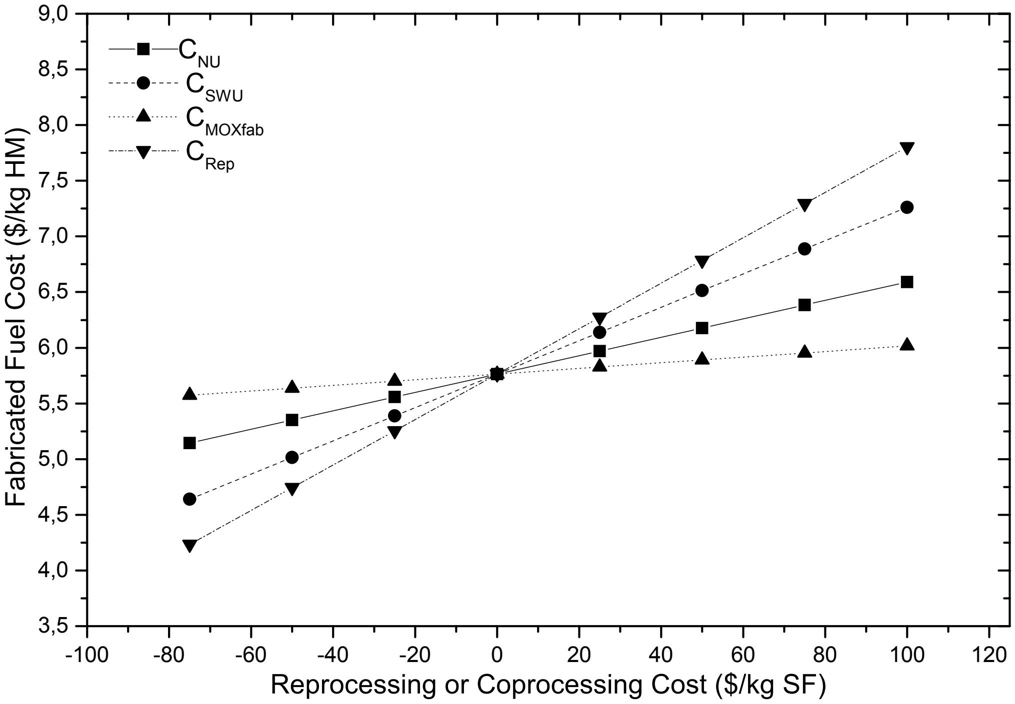

Figure 4.7 SRNU fuel cycle cost sensitivity to price variations, r=0

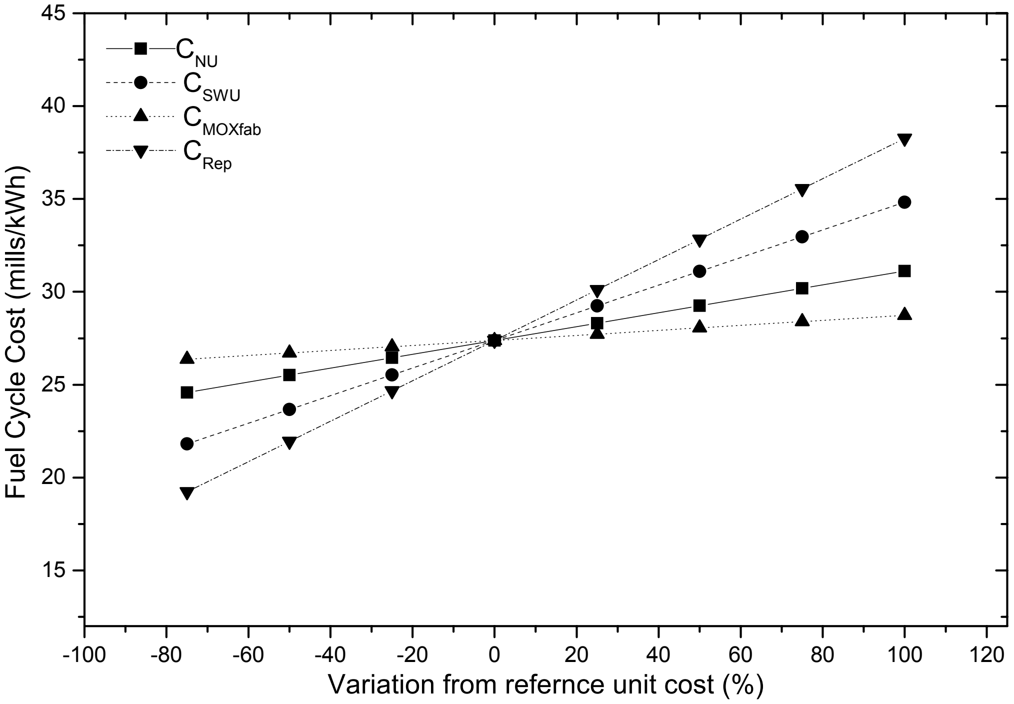

Figure 4.8 SRNU fuel cycle cost sensitivity to price variations, r=0.05

As observed from Figures 4.7 and 4.8 SRNU fuel cycle is the most sensitive to reprocessing cost.

5. COMPARISON OF RESULTS AND CONCLUSION

Unit costs of fabricated products for OT, SRNU, SRRU, CCEU and CCPu cycles are calculated for different unit prices and break-even C_{NU}, C_{MOXfab} and C_{Rep} unit cost values are evaluated for five cost conditions (most favorable, more favorable, average, less favorable and least favorable). These calculations are performed for 3 burnup values: 33000 MWd/tU, 40000 MWd/tU and 50000 MWd/tU.

When C_{NU} is considered as variable, OT cycle is the most economical cycle in all conditions except for most favorable cost conditions. For most favorable cost conditions SRNU is the best choice.

SRNU cycle is the most sensitive cycle to unit cost of reprocessing in all conditions and most advantageous cycle for low reprocessing costs. CCEU cycle is the most sensitive cycle to $C_{MOXfab.}$

Levelised fuel cycle cost analysis are made for OT and SRNU cycles and sensitivity analysis are included to observe effects of variations in unit prices. Levelised fuel cycle cost for OT is slightly lower than SRNU cycle. OT cycle is the most sensitive to enrichment unit cost as SRNU cycle is the most sensitive to reprocessing unit cost.

APPENDIX A. CODES

A.1. MONTEBURNS

MONTEBURNS is a fully automated tool that links the Monte Carlo transport code MCNP with the radioactive decay and burnup code ORIGEN2. MONTEBURNS produces a large number of criticality and burnup results based on various material feed/removal specifications, power(s) and time intervals. The program processes input from the user that specifies the system geometry, initial material compositions, feed/removal specifications and other code-specific parameters. Various results from MCNP, ORIGEN2 and other calculations are then output successively as the code runs. The principle function of MONTEBURNS is to transfer one-group cross-section and flux values from MCNP to ORIGEN2, and then transfer the resulting material composition (after irradiation and/or decay) from ORIGEN2 back to MCNP in a repeated, cyclic fashion[13].

A.2. ORIGEN-S

ORIGEN-S computes time-dependent concentrations and source terms of a large number of isotopes, which are simultaneously generated or depleted through neutronic transmutation, fission, radioactive decay, input feed rates and physical or chemical removal rates [14]. The calculations may pertain to fuel irradiation within nuclear reactors, or storage, management, transportation, or subsequent chemical processing of removed fuel elements.

The original version of the ORIGEN program was developed by the Chemical Technology Division of ORNL for use in computing the compositions and radioactivity of fission products, cladding materials, and fuel materials in LWRs, LMFBRs, MSBRs and HTGRs. The primary advantage of ORIGEN over earlier burnup codes is its capability to treat the full isotopic transition matrix rather than a limited number of transmutation changes.

The version of ORIGEN applied in the SCALE system, ORIGEN-S, has several improvements over the original program.

APPENDIX B. CALCULATION OF EQUIVALENT MOX COMPOSITON

B.1. Calculation of Equivalent MOX Composition for 40000 MWd/tU

For four cases SRNU, SRRU, CCEU, CCPu with 40000 MWd/tU burnup, discharge burnups are plotted versus x and given in Figures B.1, B.2, B.3 and B.4, respectively.

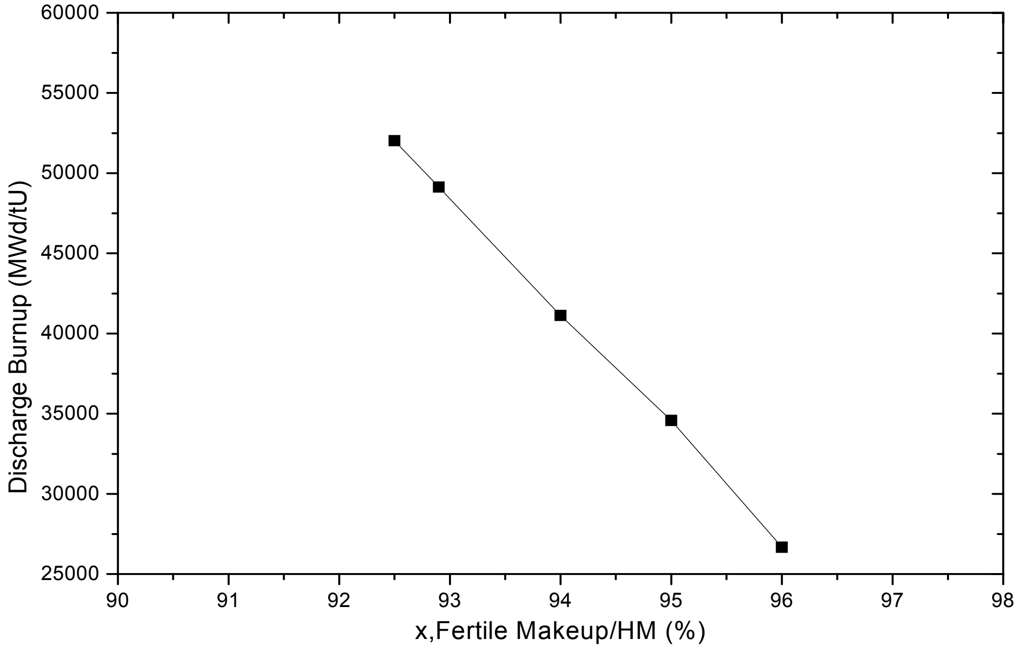

Figure B.1. Discharge burnup vs. x, 40000 MWd/tU SRNU case

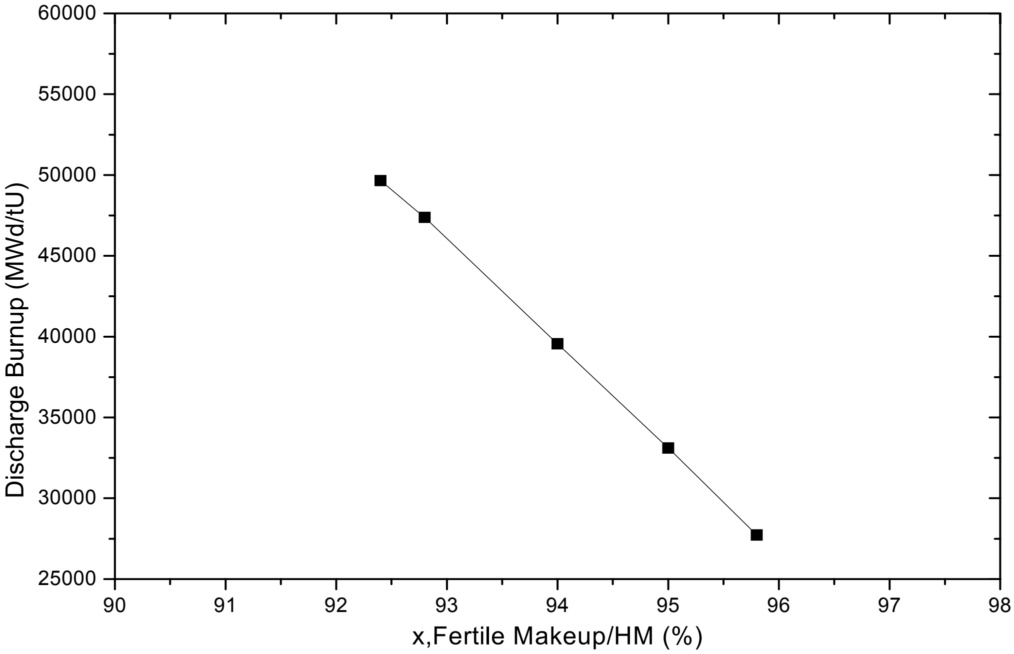

Figure B.2. Discharge burnup vs. x, 40000 MWd/tU SRRU case

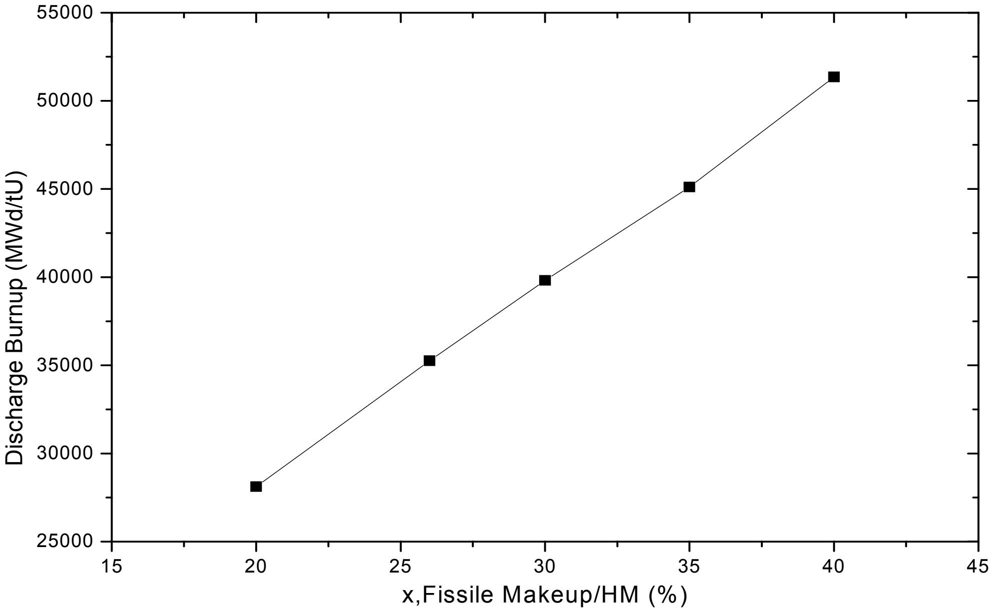

Figure B.3. Discharge burnup vs. x, 40000 MWd/tU CCEU case

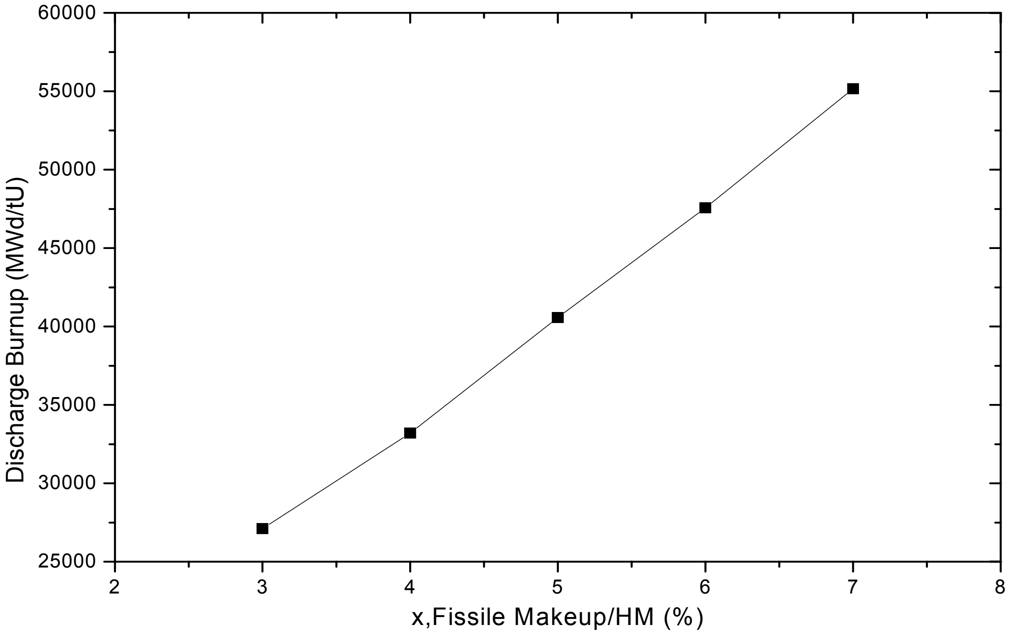

Figure B.4. Discharge burnup vs. x, 40000 MWd/tU CCPu case

B.2. Calculation of Equivalent MOX Composition for 50000 MWd/tU

For four cases SRNU, SRRU, CCEU, CCPu with 50000 MWd/tU burnup, discharge burnups are plotted versus x and given in Figures B.5, B.6, B.7 and B.8.

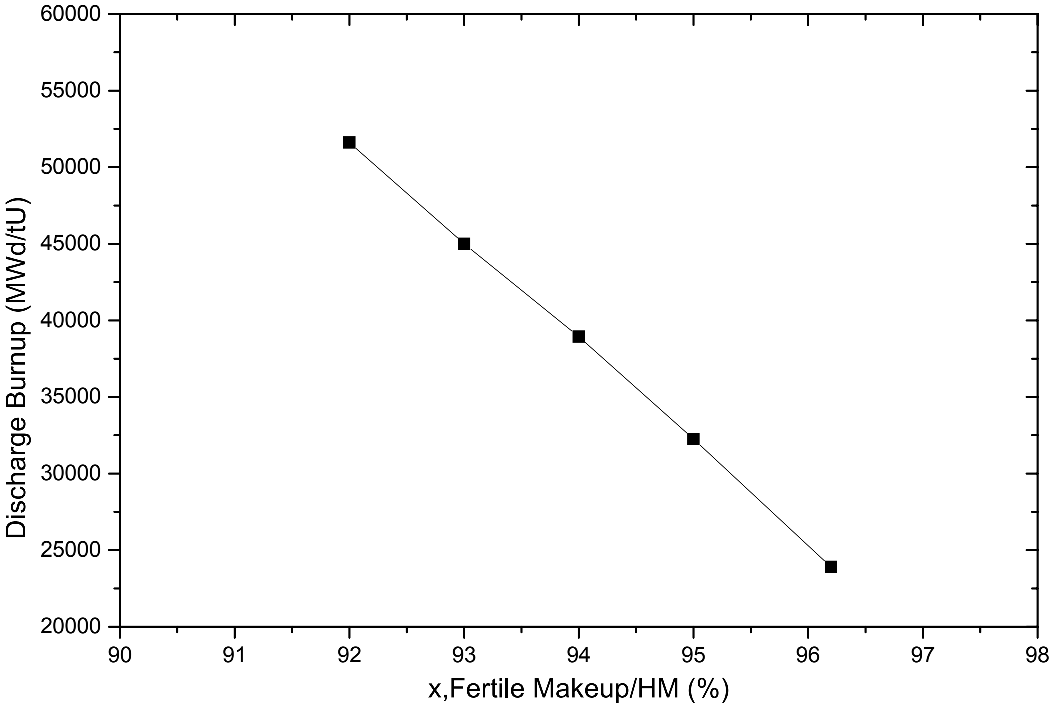

Figure B.5. Discharge burnup vs. x, 50000 MWd/tU SRNU case

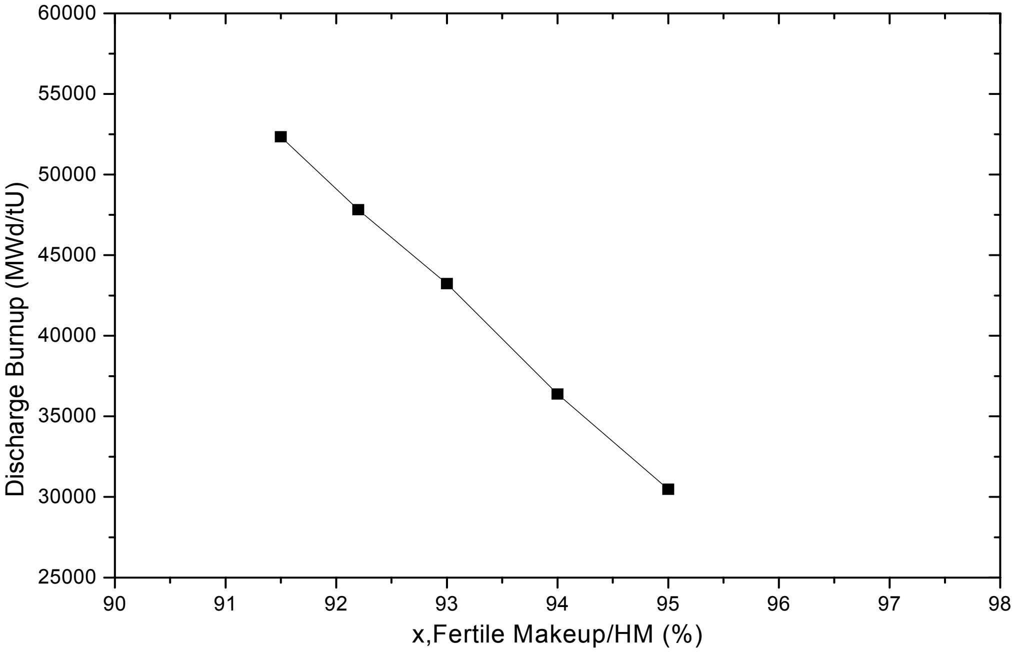

Figure B.6. Discharge burnup vs. x, 50000 MWd/tU SRRU case

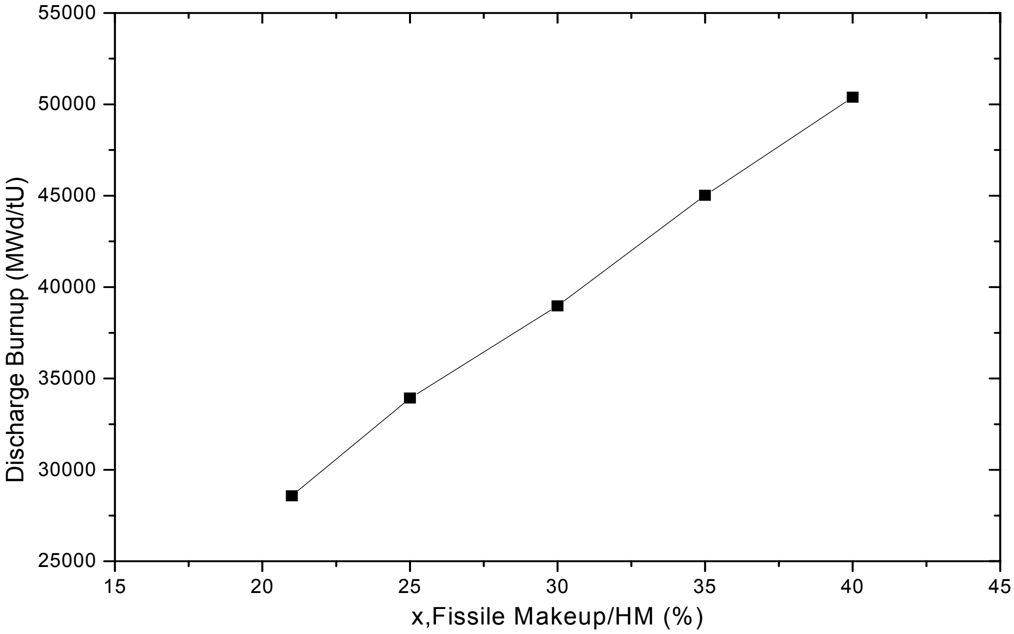

Figure B.7. Discharge burnup vs. x, 50000 MWd/tU CCEU case

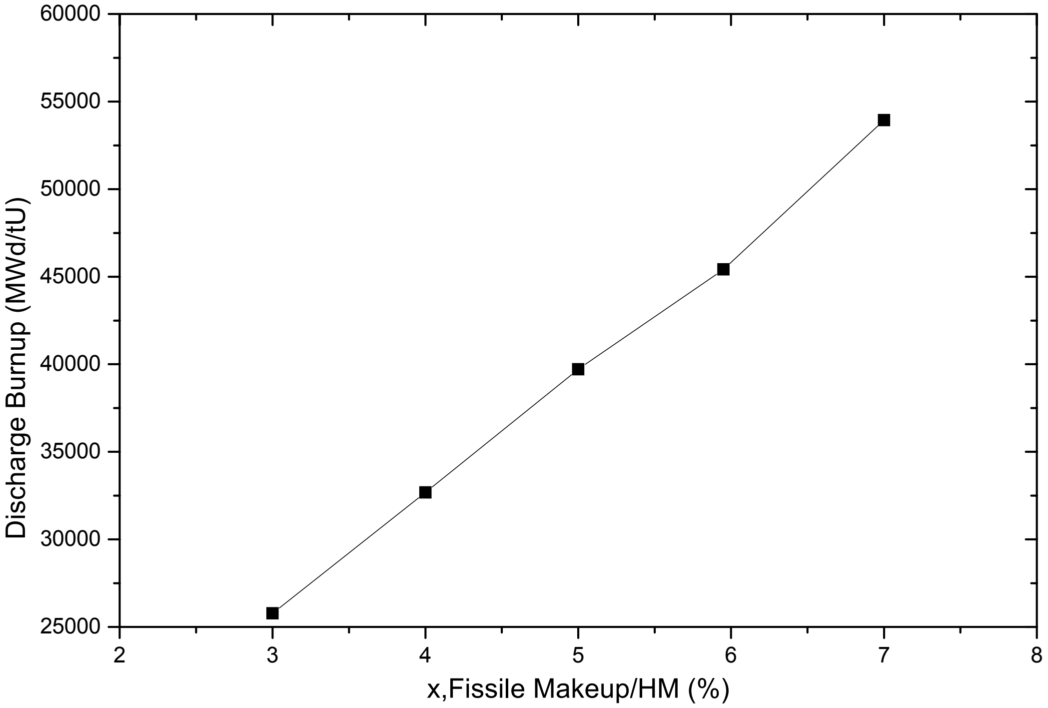

Figure B.8. Discharge burnup vs. x, 50000 MWd/tU CCPu case

APPENDIX C. BREAK-EVEN COSTS FOR SRNU, SRRU AND SRDU

C.1. Comparison of Break-even C_{NU} costs for SRNU, SRRU and SRDU cycles

Cost lines for SRNU, SRRU, SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus natural uranium cost and these lines are shown in Figures C.1, C.2, C.3, C.4 and C.5 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

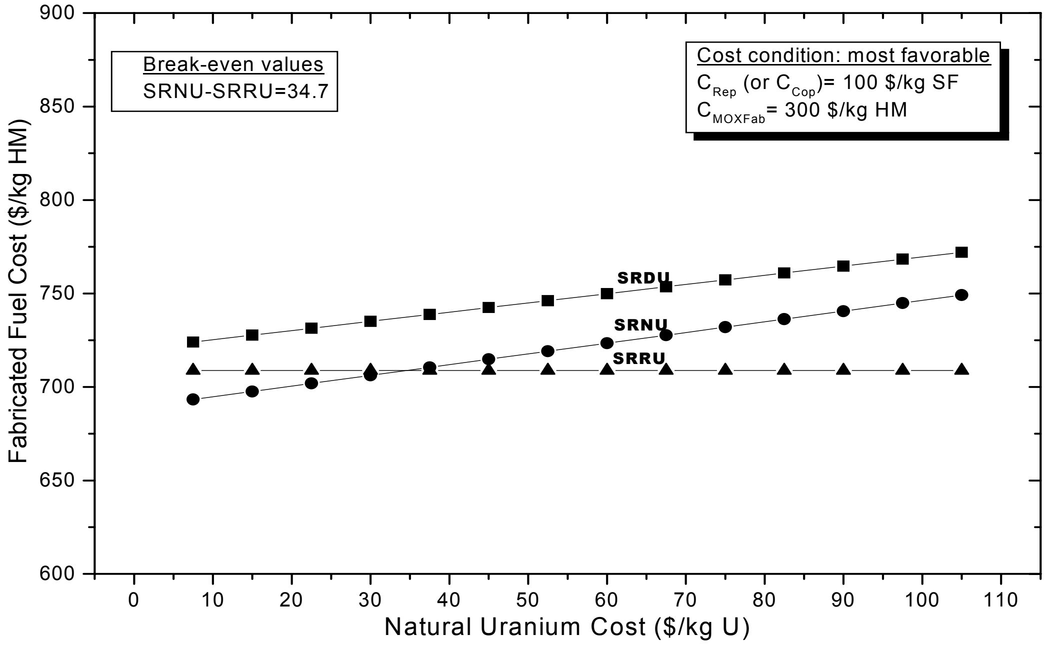

Figure C.1. Break-even C_{NU} for SRNU, SRRU and SRDU for most favorable case

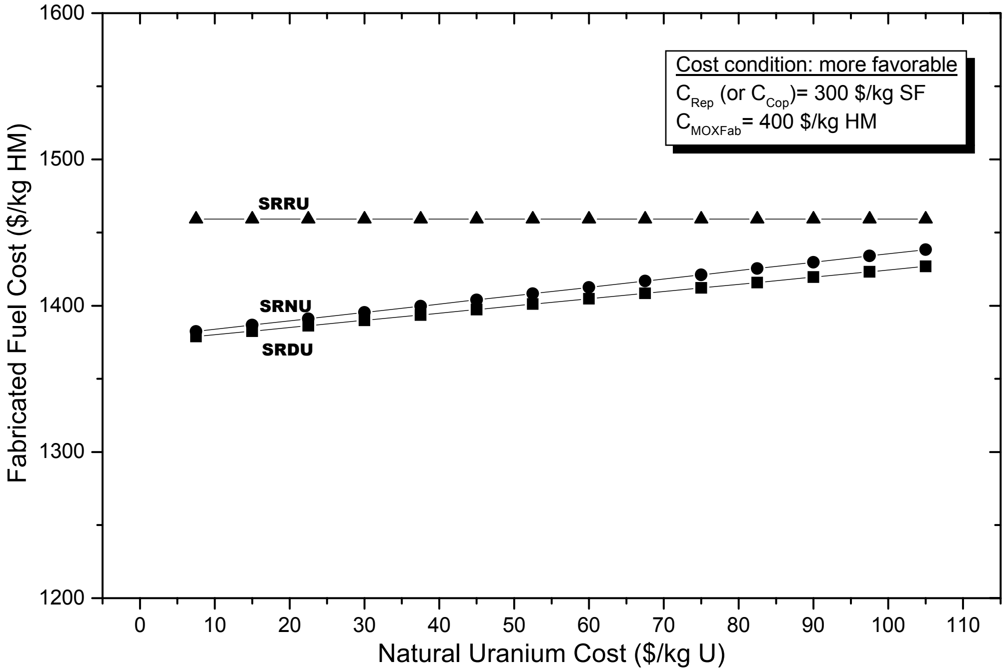

Figure C.2. Break-even C_{NU} for SRNU, SRRU and SRDU for more favorable case

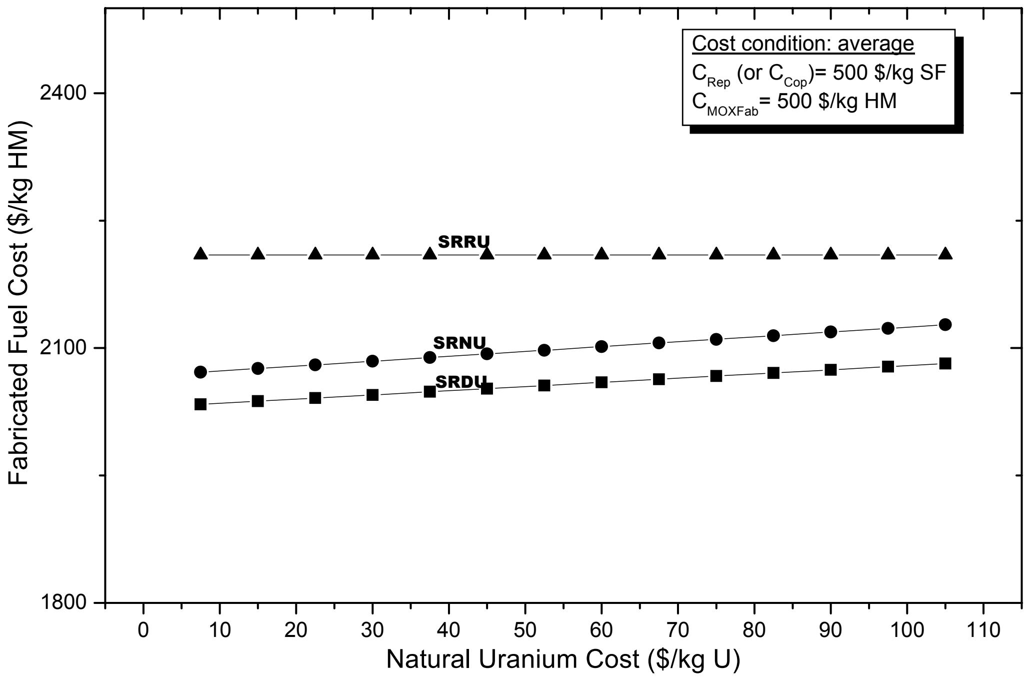

Figure C.3. Break-even C_{NU} for SRNU, SRRU and SRDU for average case

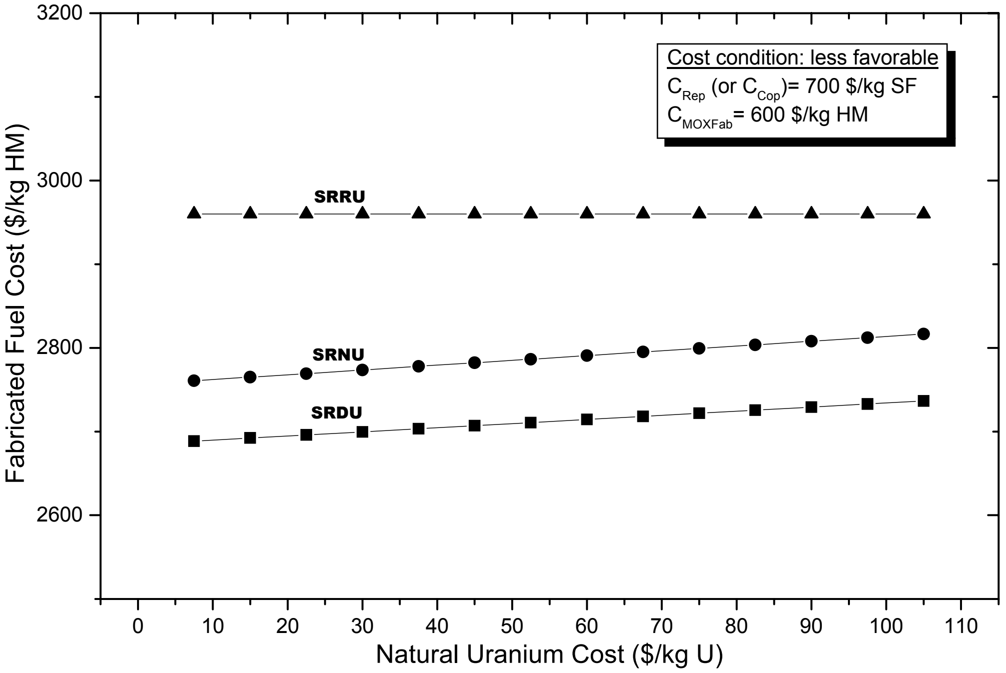

Figure C.4. Break-even C_{NU} for SRNU, SRRU and SRDU for less favorable case

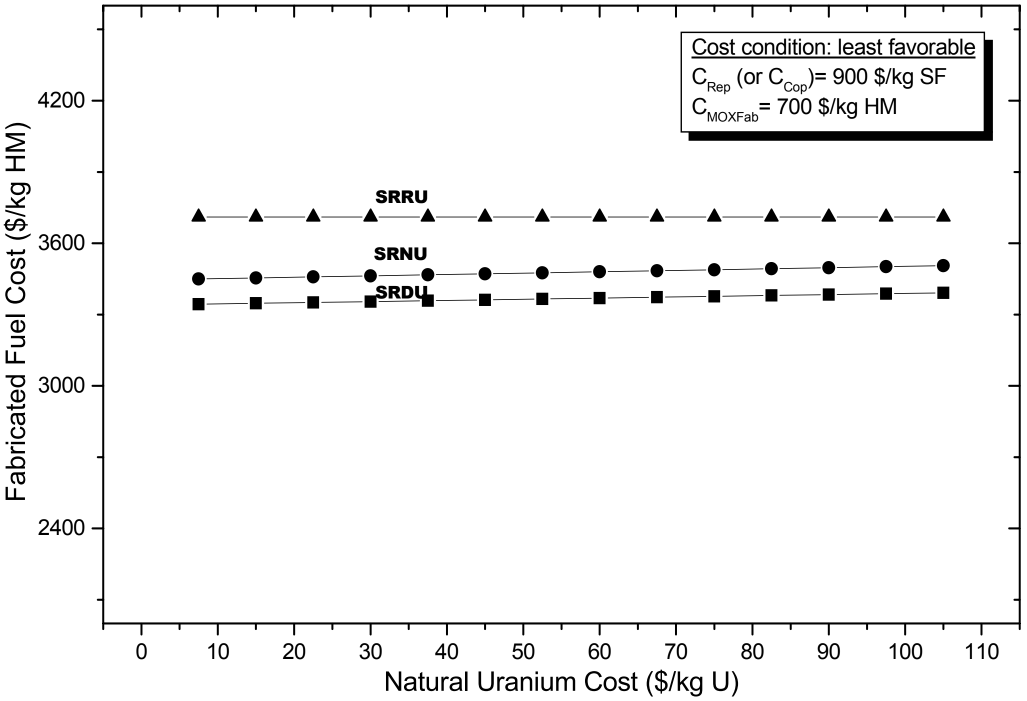

Figure C.5. Break-even C_{NU} for SRNU, SRRU and SRDU for least favorable case

C.2. Comparison of break-even C_{Rep} costs for SRNU, SRRU and SRDU cycles

Cost lines for SRNU, SRRU, SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus reprocessing cost and these lines are shown in Figures C.6, C.7, C.8, C.9 and C.10 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

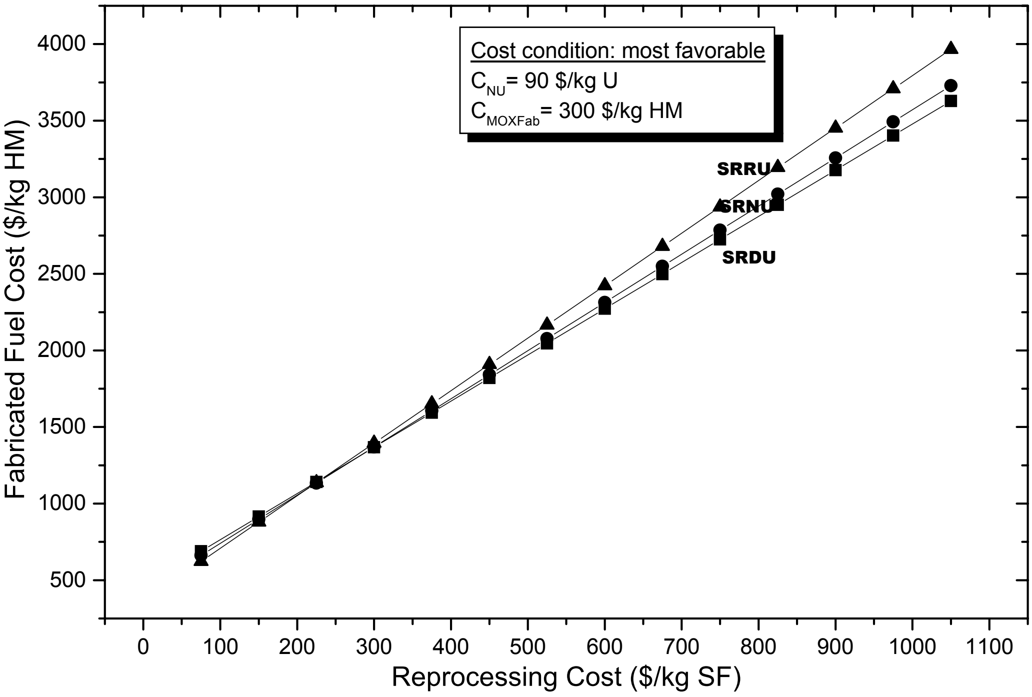

Figure C.6. Break-even C_{Rep} for SRNU, SRRU and SRDU for most favorable case

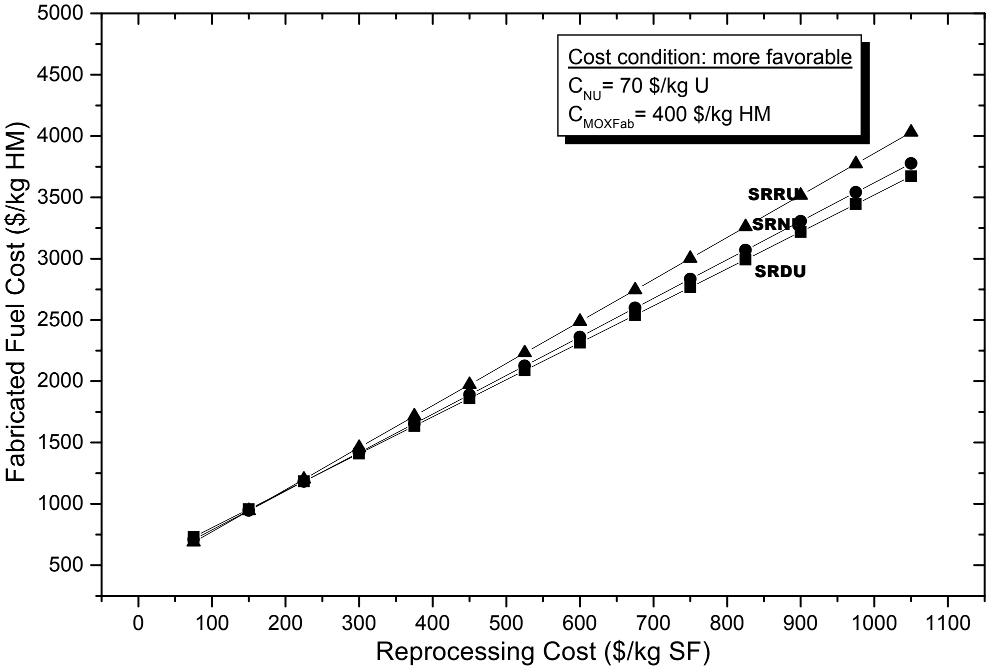

Figure C.7. Break-even C_{Rep} for SRNU, SRRU and SRDU for more favorable case

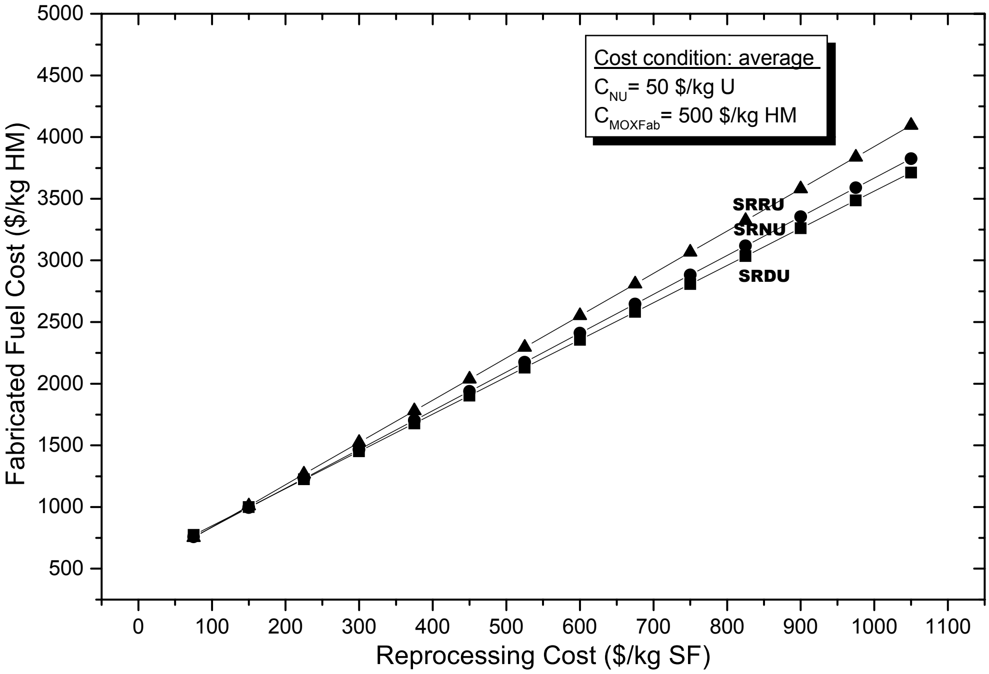

Figure C.8. Break-even C_{Rep} for SRNU, SRRU and SRDU for average case

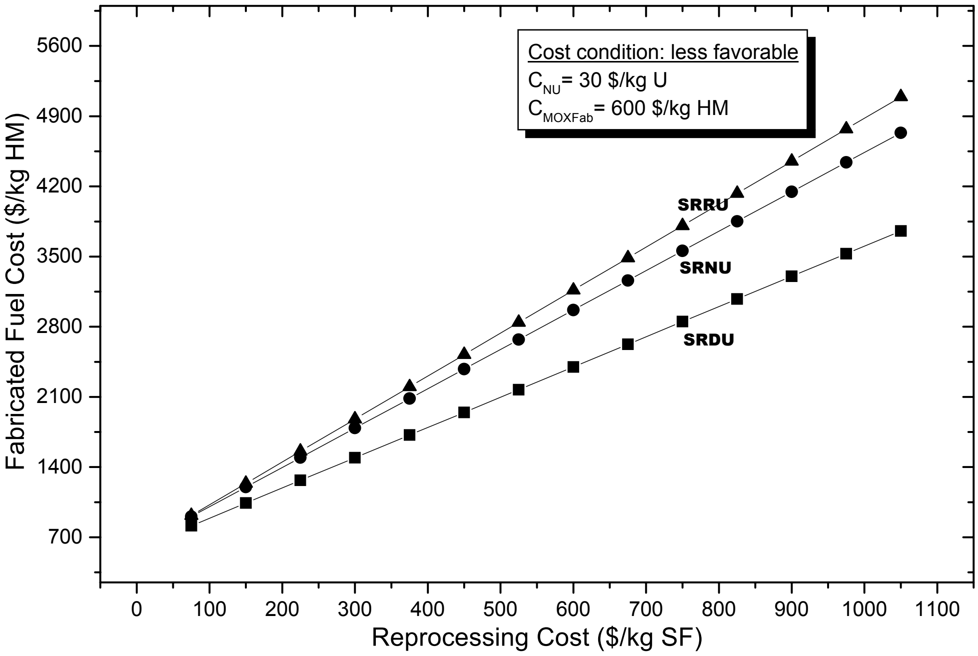

Figure C.9. Break-even C_{Rep} for SRNU, SRRU and SRDU for less favorable case

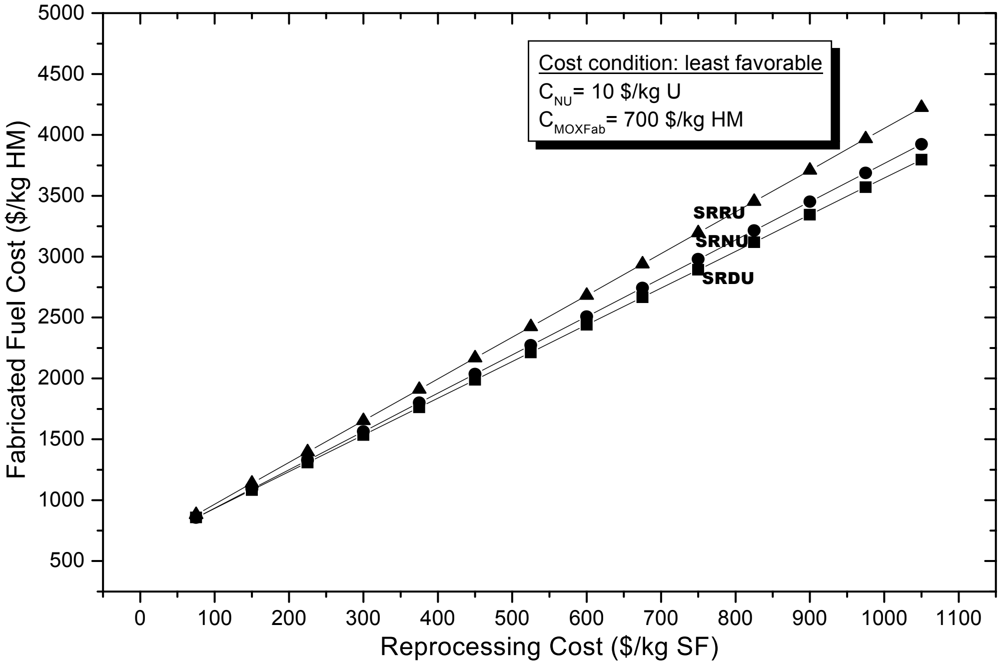

Figure C.10. Break-even C_{Rep} for SRNU, SRRU and SRDU for least favorable case

C.3. Comparison of break-even C_{MOXfab} for SRNU, SRRU and SRDU cycles

Cost lines for SRNU, SRRU, SRDU cycles with 33000 MWd/tU are obtained by plotting unit fabricated fuel cost versus MOX fabrication cost and these lines are shown in Figures C.11, C.12, C.13, C.14 and C.15 for the most, more, average, less and the least favorable cost conditions for closing the cycle.

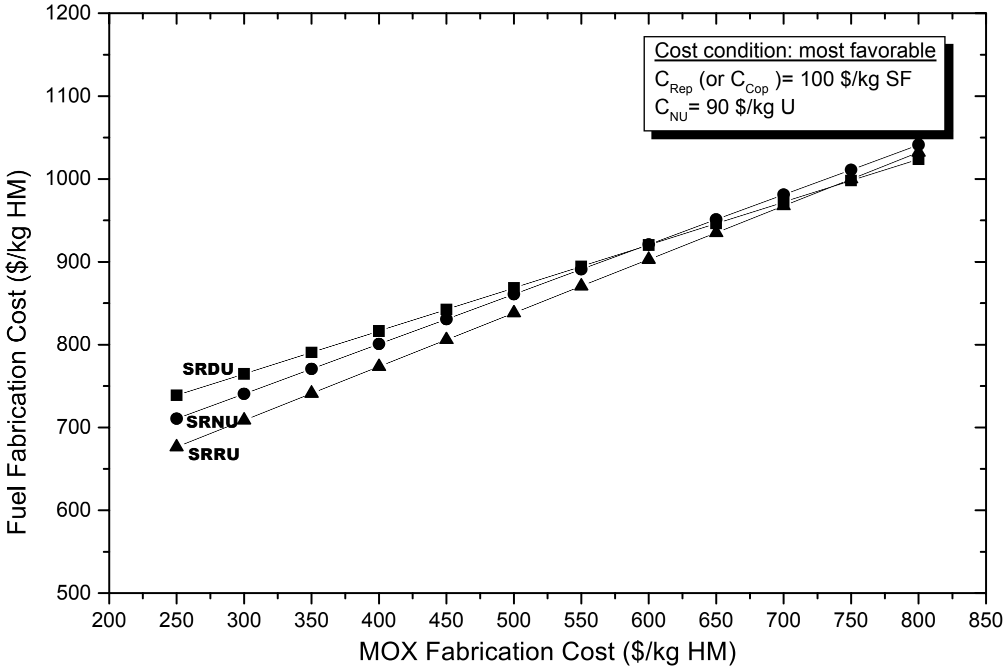

Figure C.11.Break-even C_{MOXfab} for SRNU, SRRU and SRDU for most favorable case

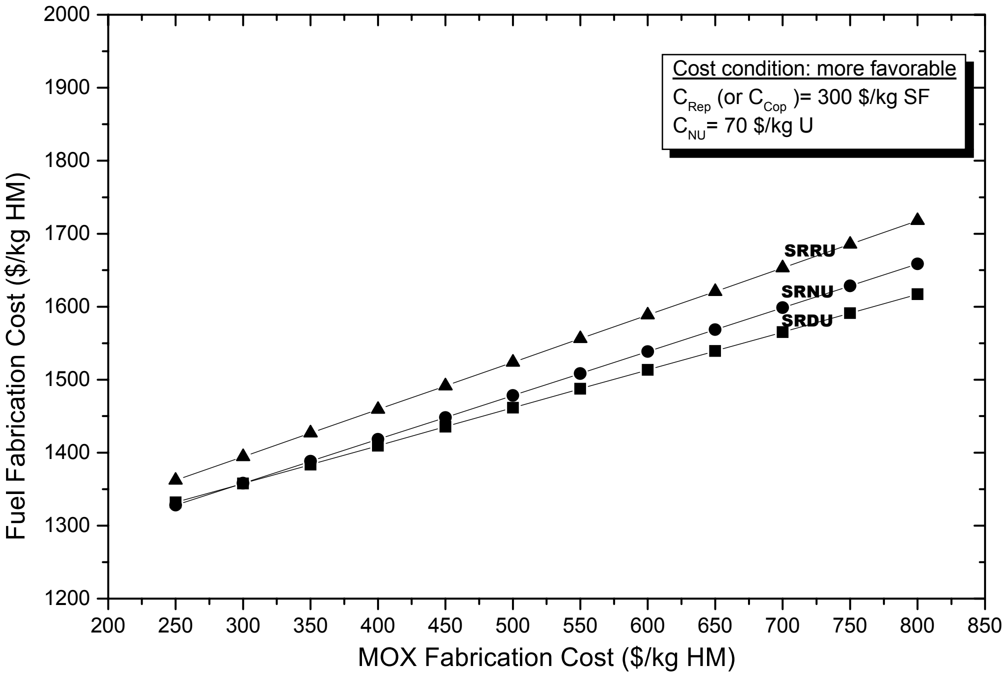

Figure C.12. Break-even C_{MOXfab} for SRNU, SRRU and SRDU for more favorable case

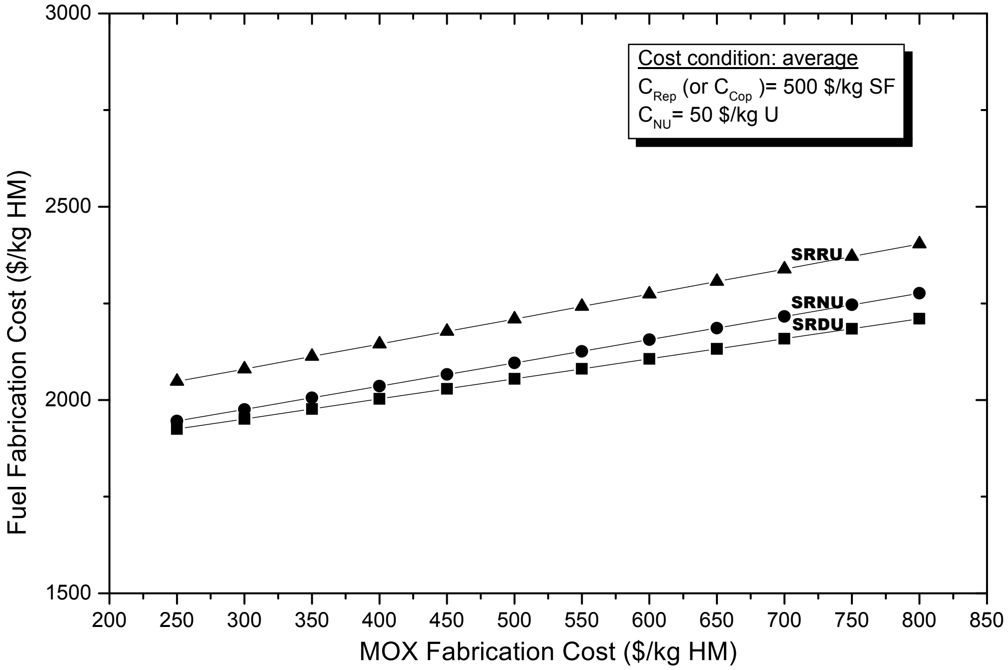

Figure C.13. Break-even C_{MOXfab} for SRNU, SRRU and SRDU for average case

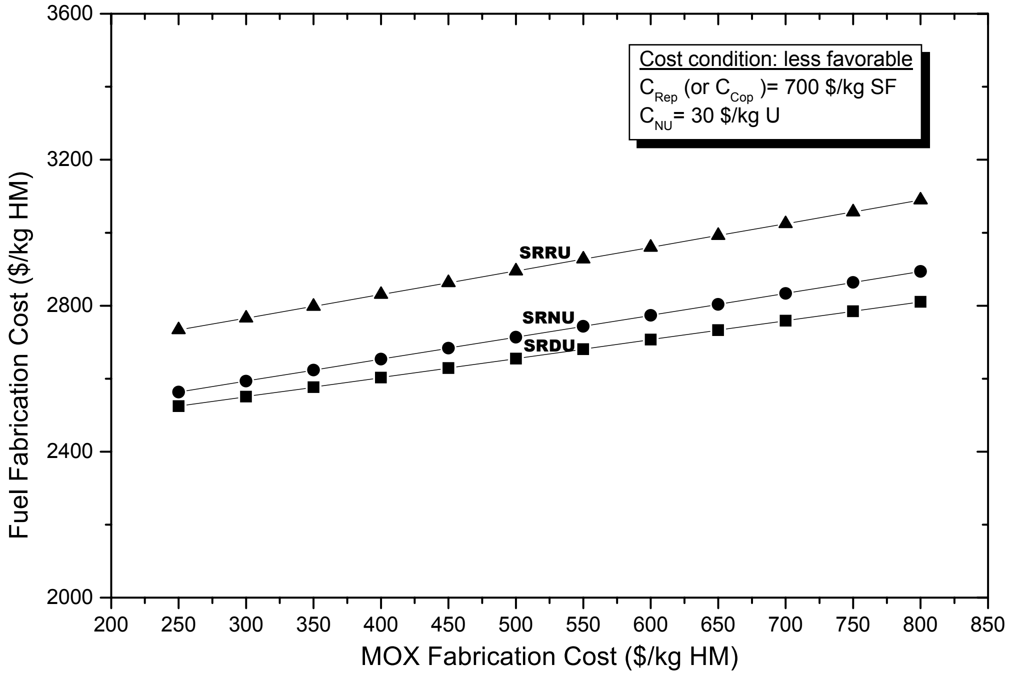

Figure C.14. Break-even C_{MOXfab} for SRNU, SRRU and SRDU for less favorable case

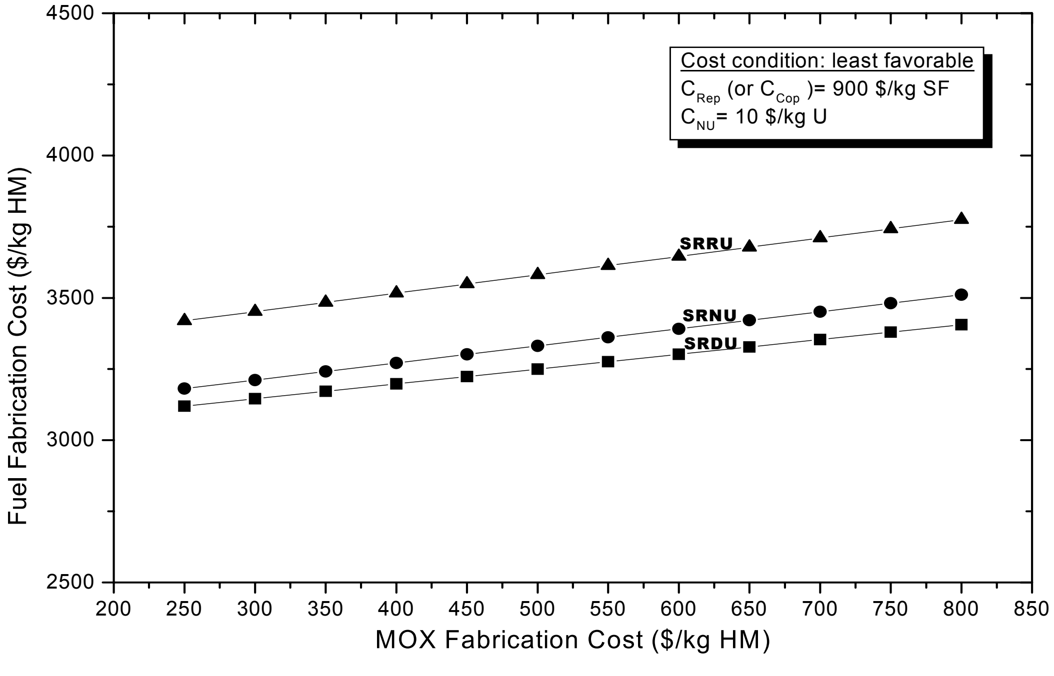

Figure C.15.Break-even C_{MOXfab} for SRNU, SRRU and SRDU for least favorable case

BIBLIOGRAPHY

[1] Drisscoll, M. J., Downar, T. J., Pilatt E. E., 1990, Linear Reactivity Model for Nuclear Fuel Management, American Nuclear Society,Illinious.

[2] Ozdemir, L., 2003, A Nuclear Fuel Cycle with Complete Coprocessing of Uranium and Plutonium in Spent fuel:Flow Sheet and Cost Analysis.

[3] Historical Ux Month-End Spot Prices, 2005, The Uxc Consulting Company.

[4] Nuclear Issue Briefing Paper 8, October 2003, Uranium Markets.

[5] OECD, Paris, 1993, The Economics of Nuclear Fuel Cycle, Nuclear Energy Agency.

[6] OECD, Paris, 1985, The Economics of Nuclear Fuel Cycle, Nuclear Energy Agency.

[7] Nuclear Issue Briefing Paper 8, August 2003, Uranium Markets.

[8] JUHANNI, V., 1981, Optimization of Nuclear Fuel Cycle Strategies Under Uncertainty, Technical research Centre of Finland Nuclear Engineering Laboratory.

[9] WATANABE, S., 1987, Incentives for Recycling Fissile Materials in Thermal and Fast reactors in Japan.

[10] Cochran, R. G., and Tsoulfanidis, N., 1990, The Nuclear Fuel Cycle: Analysis and Management, American Nuclear Society.

[11] IAEA, Vienna, 1988, The Nuclear Fuel Cycle Information System.

[12] IAEA, 1998, Economic Evaluation of Bids for Nuclear Power Plants.

[13] Poston, David I., and Trellue, Holly R., 1999, User’s Manual, Version 2.0 for Monteburns, Version 1.0.

[14] Hermann, O. W., and Westfall, R. M., 1998, Origen-S User’s Manual.

RESUME

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