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Dynamic Analysis of the Thorium Fuel Cycle in CANDU Reactors

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본 보고서를 2006 년도 “건식 재가공 핵연료 노심특성 평가 기술개발” 과제의 기술 보고서로 제출합니다.

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ABSTRACT

The thorium fuel recycle scenarios through the Canada deuterium uranium (CANDU) reactor have been analyzed for two types of thorium fuel: homogeneous ThO_2UO_2 and ThO_2UO_2-DUPIC fuels. The recycling is performed through the dry process fuel technology which has a proliferation resistance. For the once-through fuel cycle model, the existing nuclear power plant construction plan was considered up to 2016, while the nuclear demand growth rate from the year 2016 was assumed to be 0%. After setting up the once-through fuel cycle model, the thorium fuel CANDU reactor was modeled to investigate the fuel cycle parameters. In this analysis, the spent fuel inventory as well as the amount of plutonium, minor actinides and fission products of the multiple recycling fuel cycle were estimated and compared to those of the once-through fuel cycle.

From the analysis results, it was found that the closed or partially closed thorium fuel cycle can be constructed through the dry process technology. Also, it is known that both the homogeneous and heterogeneous thorium fuel cycles can reduce the SF accumulation and save the natural uranium resource compared with the once-through cycle. From the material balance view point, the heterogeneous thorium fuel cycle seems to be more feasible. It is recommended, however, the economic analysis should be performed in future.

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I. Introduction

The thorium fuel has been studied as an alternative to conventional nuclear fuels in the pressurized water reactor (PWR) as well as Canada deuterium uranium (CANDU) reactor to save the uranium resources and to provide a great degree of energy self-reliance. The thorium fuel cycle has proliferation resistance characteristics which is a main goal of the Generation-IV (Gen-IV) reactors [1].

Many studies have been performed for the thorium fuel cycle of the CANDU reactors [2-4]. In these studies, both the once-through and recycling fuel cycle were investigated through the various fuel management simulations. Recently, the feasibility study was carried out for the multiple recycling fuel cycle by a dry reprocessing technology [5]. The previous studies have show that the thorium fuel cycle of the CANDU reactor is feasible in the physics as well as economic point of view.

This study investigates the multiple recycling thorium fuel cycle scenarios in the CANDU reactor through a dynamic analysis method. The multiple recycling is modeled by the dry process technology. The dry process considered in this study is “dry reprocess” developed for transmutation of actinides in the oxide fuel [6-8] or “thermo-mechanical process” developed for the direct use of spent PWR fuel in CANDU reactors (DUPIC) fuel cycle dry process technology [9-11]. The thorium fuel cycle model is incorporated into the Korean once-through nuclear fuel cycle. This study estimates the spent fuel inventory as well as the amount of other important nuclear materials. The results of this study will provide important data for the design analysis of the repository and selection of reactor strategy in the future. First, the dynamic fuel cycle modeling was described in Section II. Second, the fuel cycles are analyzed and the results are compared to those of the once-through fuel cycle calculation in Section III. Finally, Summary and conclusion are given in Section IV.

II. Dynamic Fuel Cycle Modeling

The reactor systems considered in this study are typical 1000 MWe PWR and 713 MWe CANDU (CANDU-6) reactors. Table I gives the reactor data for both PWR and CANDU-6 reactors. In CANDU-6 reactor, there are 380 fuel channels and each channel contains 12 fuel bundles. The standard fuel bundle has 37 fuel elements as shown in Fig. 1, while the CANDU flexible fueling (CANFLEX) fuel bundle has dual size 43 fuel elements. From the physics view point, however, these two fuel bundles do not have much different characteristics each other.

In this study, the DYMOND code [1,12] which adopts the dynamic analysis method has been modified for dry reprocess modeling. The DYMOND code was developed by Argonne National Laboratory (ANL) for Gen-IV roadmap study [1]. The DYMOND code employs the "ITHINK" platform [13] to assess the long term fuel cycle scenario. In the DYMOND, it is assumed that the reactor system evolves over time. Based on the energy demand model, the reactor and fuel cycle scenario such as the number of reactor to be built, operating reactor and capacity of each reactor type can be determined. Through time-evolving analysis of the candidate fuel cycles, the most appropriate fuel cycle can be chosen, considering the technical and economic impacts over time.

II.1 Homogeneous Thorium-Uranium Recycling

The homogeneous thorium-uranium (ThO_2-UO_2) fuel was considered to construct a closed fuel cycle as schematically shown in Fig. 2. In this fuel cycle model, the thorium and uranium are homogeneously mixed within the 43-element CANFLEX fuel bundle. In this model, the required amount of uranium and thorium are calculated as follows:

$$\mathrm{M}_{Th} = \mathrm{R}_{Th-U} \cdot \mathrm{F}_{Th} \tag{1}$$

$$\mathrm{M}_{U} = \mathrm{R}_{Th-U} \cdot \mathrm{F}_{U} \tag{2}$$

where $R_{Th\text{-}U}$ is a ThO_2-UO_2 fuel request, and F_{Th} and F_U are ThO_2 and UO_2 fractions in the fresh fuel, respectively.

The feed is the difference between the required and recovered amount as follows:

$$\mathrm{FD}_{Th} = \mathrm{M}_{Th} - \mathrm{RC}_{Th} \tag{3}$$

$$\mathrm{FD}_{U} = \mathrm{M}_{U} - \mathrm{RC}_{U} \tag{4}$$

where RC_{Th} and RC_U are the recovered amount of ThO_2 and UO_2, respectively. The recovered amount can be calculated as follows:

$$\mathrm{RC}_{Th} = \mathrm{D}_{Th-U} \cdot (1-\mathrm{L}) \cdot \mathrm{S}_{Th} \tag{5}$$

$$\mathrm{RC}_{U} = \mathrm{D}_{Th-U} \cdot (1-\mathrm{L}) \cdot \mathrm{S}_{U} \tag{6}$$

where $D_{Th\text{-}U}$ is a amount of dry processed, L is a loss factor of dry process, and S_{Th} and S_U are the THO_2 and UO_2 fraction in the spent fuel, respectively. In this homogeneous recycling model, the fission products are assumed to be removed completely from the spent fuel through the dry process and feed a 20 wt% slightly enriched uranium (SEU) and thorium for the further fuel cycle. In this way, it is possible to keep most of the irradiated actinides in the reactor system throughout the plant life time.

II.2 Heterogeneous Thorium-DUPIC Recycling

The heterogeneous thorium-DUPIC fuel designed to burn the PWR spent fuel in the CANDU reactor. The fuel bundle has both the thorium and DUPIC fuel elements in a 37-element standard CANDU fuel bundle. The thorium fuel is located in the inner 7 fuel elements and continuously recycled. The DUPIC fuel is located in the outer 30 fuel elements and replaced after each fuel cycle. This fuel cycle is a partially closed fuel cycle as shown in Fig. 3. In this model, the required amount of uranium and thorium are calculated as follows:

$$\mathrm{M}_{Th} = \mathrm{R}_{Th-DUP} \cdot \mathrm{F}_{Th-U} \cdot \mathrm{F}_{Th} \tag{7}$$

$$\mathrm{M}_{U} = \mathrm{R}_{Th-DUP} \cdot \mathrm{F}_{Th-U} \cdot \mathrm{F}_{U} \tag{8}$$

$$\mathrm{M}_{DUP} = \mathrm{R}_{Th-DUP} \cdot (1-\mathrm{F}_{Th-U}) \tag{9}$$

where $R_{Th\text{-}DUP}$ is a thorium-DUPIC fuel request, and $F_{Th\text{-}U}$ is a ThO_2UO_2 fraction in thorium-DUPIC fuel, and F_{Th} and F_U are ThO_2 and UO_2 fractions in fresh thorium fuel, respectively.

The feed is the difference between the required and recovered amount as follows:

$$FD_{Th} = M_{Th} - RC_{Th} \tag{10}$$

$$FD_U = M_U - RC_U \tag{11}$$

where RC_{Th} and RC_U are the recovered amount of ThO_2 and UO_2, respectively. The recovered amount can be calculated as follows:

$$RC_{Th} = D_{Th-DUP} \cdot (1 - L) \cdot S_{Th-U} \cdot S_{Th} \tag{12}$$

$$RC_U = D_{Th-DUP} \cdot (1 - L) \cdot S_{Th-U} \cdot S_U \tag{13}$$

where $D_{Th\text{-}DUP}$ is a amount of dry processed, L is a loss factor of dry process, and $S_{Th\text{-}U}$ is the ThO_2UO_2 fraction in the spent fuel. And, S_{Th} and S_U are the THO_2 and UO_2 fraction in the spent ThO_2UO_2, respectively. In this heterogeneous recycling model, the rare earth fission products are assumed to be removed by 30% from the ThO2UO2. The DUPIC part is not recycled. In this case, the natural uranium (NU) and thorium are fed for the next fuel cycle.

III. Fuel Cycle Analysis Results

III.1 Once-Through Fuel Cycle

From the long-term energy supply plan of the Korea [14], the nuclear power is expected to grow from 13.716 GWe in 1999 to 25.2 GWe in 2015. In this study, the nuclear power growth rate was assumed to be 0% from the year 2016 to the year 2100. For the reactor information of the once-through fuel cycle, current operating reactors are considered which are 12 PWRs and 4 CANDUs. The reactor life times were assumed to be 40 and 30 yrs for the PWR and CANDU, respectively. In this scenario, all of the CANDU reactor was assume to be shutdown after its life time and there will be no more CANDU construction [14].

Fig. 4 shows the nuclear demand variation with time, which indicates that the nuclear power demand model in the DYMOND code predicts the nuclear demand well. Fig. 5 and Fig. 6 show the deployment of fuel cycle services and reactor needed to meet the energy demand. The deployed capacity which is determined by the capacity fraction of each reactor type varies with the demand, but it is not exactly the same as demand because an already deployed reactor capacity does not exactly match to the demand curve. Once all CANDUs are shutdown, the electricity generation is dominated by PWR after 2030. The number of operating PWR in 2100 is expected to be ~25 for the reactor power of 1.0 GWe.

The spent fuel (SF) inventory, as shown in Fig. 7, gradually increases with time and the total SF will be ~64.6 kt in 2100. After 2030, the CANDU SF remains constant at the value of ~8.7 kt because no more spent fuels are produce from the CANDU. The total amount of Pu, minor actinides (MA) and fission products (FP) in the SF will be 0.78 kt, 0.08 kt, 3.34 kt, respectively.

III.2 Homogeneous Thorium-Uranium Recycling Fuel Cycle

In the homogeneous fuel cycle model, the closed fuel cycle is achieved by the multiple recycle of the thorium fuel. For the homogeneous cycle model, the thorium fuel CANDU reactor is deployed from 2020 by the capacity of 30%. The volume fraction of UO_2 considered in this study is 9% with an initial 235U enrichment of 20wt%. The discharge burnup is estimated to be 14000 MWd/t. The calculation assumptions are made as follows:

- The CANDU-6 reactor was used as a reference core for thorium fuel recycling.
- The 43-element fuel bundle was chosen.
- The fuel material is the mixture of ThO_2 and UO_2.
- The enrichment of uranium feed is 20wt%.
- By the dry process, all the actinides are recycles, while the fission products are removed. The fuel mass is kept constant by feeding thorium and uranium fuel.

Fig. 8 shows the capacity fraction of each reactor to meet the nuclear demand. The thorium-CANDU reactor fraction increases from 2030 and it becomes ~30% from 2075. While the fraction of the PWR decreases from 2030 with the increasing of the thorium-CANDU capacity. With the above capacity fractions, the number of operating PWR and thorium-CANDU will be 19 and 12, respectively in 2100.

With the thorium-CANDU reactor deployment as above, the annual amount of the natural uranium mined is shown in Fig. 9. The mined uranium for PWR decreases slowly with increasing the thorium-CANDU reactor capacity, and the mined uranium for the CANDU reactor decreases and eventually becomes to zero in 2030. The mined uranium for thorium-CANDU reactor increases from 2030 to 2040, and it decreases rapidly after recycling starts. The uranium mining for CANDU reactor decreases and becomes zero after 2030. The total uranium mining is compared between once-through and thorium cycle in Fig. 10. It can be seen that the uranium mining is low after 2040 compared to that of the once-through cycle. The total amount of uranium mining until 2100 will be 455 kt and 389 kt for once-through and thorium cycle, respectively. Fig. 11 shows the feed of enriched uranium and thorium fuel. Both enriched uranium and thorium feed increase from around 2030 to 2040, but they decrease rapidly after recycling starts.

Fig. 12 shows the accumulated SF from each reactor. The SF from the PWR increases continuously and becomes ~45 kt in 2100, while the SF from CANDU reactor remains constant after 2030 by ~9 kt. In the homogeneous thorium fuel cycle, there is no SF from thorium-CANDU reactor since all the thorium-based SF is recycled. The total SF of the thorium cycle is compared with that of the once-through cycle in Fig. 13. It can be seen that the total SF from the thorium fuel cycle is 9% smaller compared with that of the once-through cycle.

The inventory of the Pu, MA and FP are shown in Fig. 14. The Pu inventory in 2100 is 0.71 kt which is ~9% smaller compared to that of the once-through, as shown in Fig. 15. The inventory of MA and FP are compared with the once-through cycle in Fig. 16 and 17, respectively. It can be seen that the amount of MA and FP are 8% and 7% smaller, respectively compared to those of the once-through cycle.

III.3 Heterogeneous Thorium-DUPIC Recycling Fuel Cycle

For the heterogeneous fuel cycle, two kinds of fuel rods are considered: the thorium fuel and DUPIC fuels. In the 37-element standard CANDU fuel bundle, the outer 30 fuel rods are loaded with the DUPIC fuel, while the inner 7 fuel rods are loaded with the thorium fuel for multiple recycling. In the heterogeneous thorium fuel cycle, the DUPIC fuel is used for the drive fuel for maintaining a chain reaction since the thorium fuel does not contain the fissile isotopes. For this fuel cycle model, it is assumed that the uranium fraction in ThO_2UO_2 is 10% and the rare earth fission products removal rate is 30% in the DUPIC fuel. The discharge burnup is 19000 MWd/t. In this case, the natural uranium is used as a feed material.

The capacity fraction depending on the reactor type is same as the homogeneous recycling case as described in Sec. III.2. In the heterogeneous thorium fuel cycle, as shown in Fig. 18, the mined uranium for PWR and CANDU reactor are same as those of the homogeneous thorium fuel cycle, since the PWR and CANDU reactor deployment scenario is same for both fuel cycles. The mined uranium for thorium-DUPIC CANDU reactor is very small compared to that of the homogeneous cycle since low fraction of natural uranium is used in the heterogeneous cycle. The uranium mining for CANDU reactor decreases and becomes zero after 2030. The total uranium mining is compared between once-through and thorium cycle in Fig. 19. It can be seen that the uranium mining is low after 2040 compared to that of the once-through cycle. The total amount of uranium mining until 2100 will be ~380 kt which is ~16% and ~2% lower compared with that of the once-through and homogeneous cycle, respectively. Fig. 20 shows the feed of the natural uranium and thorium fuel. Both enriched uranium and thorium feed increase from around 2030 to 2040, but they decrease rapidly after recycling starts. Also, the amount of the uranium and thorium feed are very small compared with those of the homogeneous cycle.

Fig. 21 shows the accumulated SF from each reactor. The SF from the PWR increases slowly and becomes ~32 kt in 2100, while the SF from CANDU reactor remains constant after 2030 by ~9 kt. Unlike the homogeneous thorium cycle, some SF is produced from heterogeneous thorium-DUPIC cycle since DUPIC part of the SF is not recycled. The total SF of the thorium cycle is compared with that of the once-through cycle in Fig. 22. It can be seen that the total SF from the heterogeneous thorium fuel cycle is ~18% smaller compared with that of the once-through cycle. The SF is also ~10% smaller compared with that of the homogeneous cycle.

As shown in Fig. 23, the amount of the Pu, MA and FP in 2100 will be 0.59kt, 0.06 kt and 3.42 kt, respectively. The inventory of the Pu in 2100 is ~24% smaller compared to that of the once-through, as shown in Fig. 24. As seen in Fig. 25, the MA inventory is ~25% smaller compared to that of the once-through cycle. Fig. 26 shows that the FP inventory is a little larger compared with that of the once-through cycle because some of the rare-earth fission products are removed during the dry process.

IV. Summary and Conclusion

The multiple homogeneous and heterogeneous thorium recycling fuel cycle in the CANDU reactor has been modeled and applied to the Korean nuclear fuel cycle. After setting up the once-through model, the thorium fuel cycle were analyzed from viewpoints of the material flow.

From the comparison between the once-through and homogeneous fuel cycle, it can be summarized as follows:

- The amount of uranium mining can be reduced by 15%.
- The amount of total SF is reduced by 9%.
- The amount of Pu, MA and FP in the SF are reduced by 9%, 8%, and 7%, respectively.

From the comparison between the once-through and heterogeneous fuel cycle, it can be summarized as follows:

- The amount of uranium mining can be reduced by 16%.
- The amount of total SF is reduced by 18%.
- The amount of Pu and MA in the SF are reduced by 24% and 25%, respectively.
- The amount of FP is slightly higher.

From the above results, it was found that the closed or partially closed thorium fuel cycle can be constructed with a small amount of feed of uranium and thorium. Furthermore, both thorium fuel cycles can reduce the SF accumulation. From the material balance view point, the heterogeneous thorium fuel cycle seems to be more feasible. It is recommended, however, the economic analysis should be performed in future.

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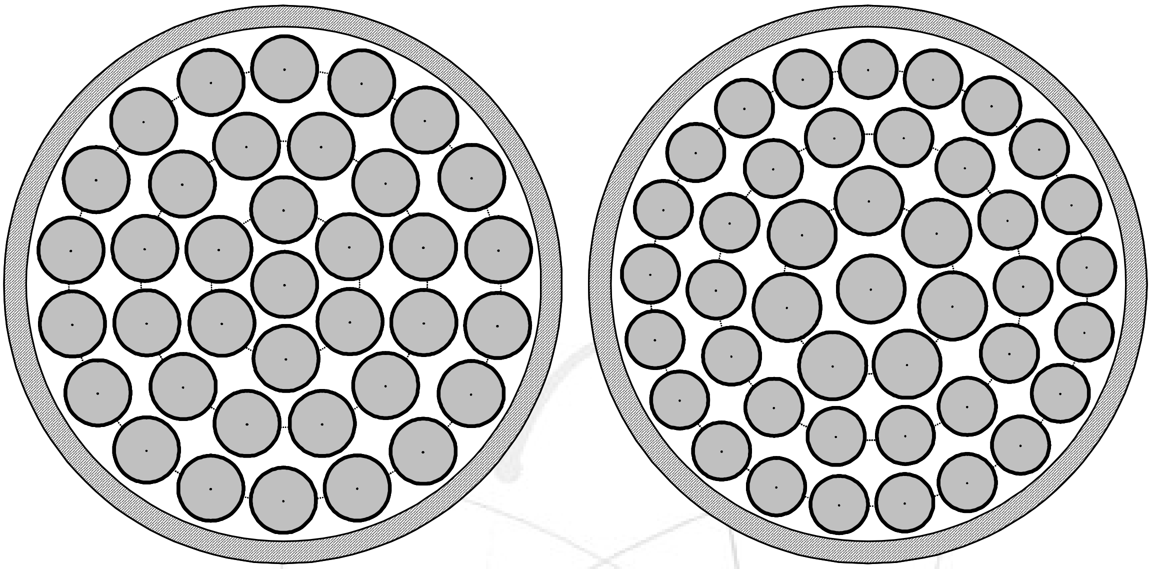
Table I Reactor Specifications

	PWR	CANDU	CANDU-Th
Power, GWe	1.0	0.71	0.71
Burnup, GWd/t	40	7.5	14(Homogeneous) 19(Heterogeneous)
U Enrichment, %	4	0.71	20(Homogeneous) 0.71(Heterogeneous)
Life Time, yr	40	30	40
Thermal efficiency, %	35	35	35
Load Factor	0.85	0.85	0.85



37-Element Standard Fuel Bundle 43-Element CANFLEX Fuel Bundle

Fig.1 CANDU fuel bundles

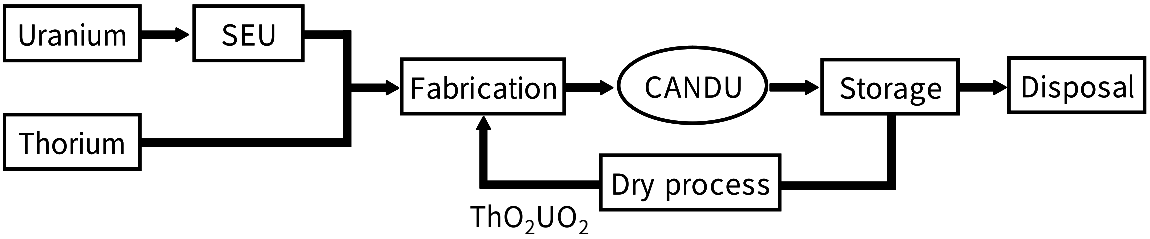


Fig. 2 A Closed thorium fuel cycle (Homogeneous recycle)

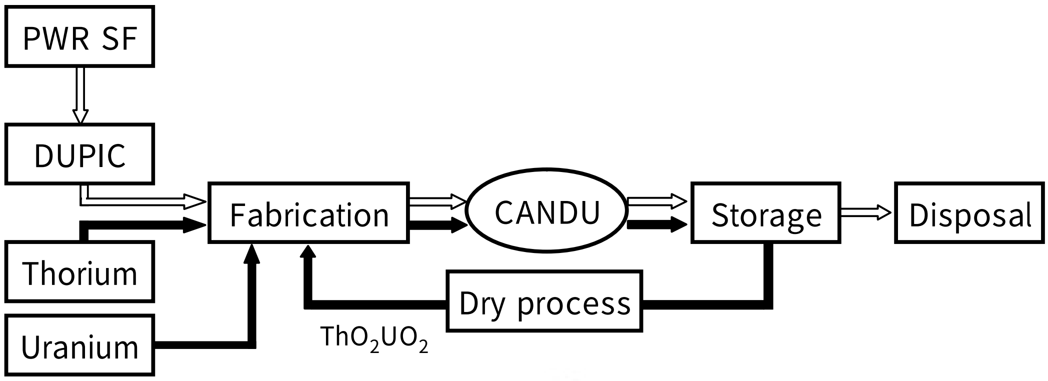


Fig. 3 A partially closed thorium fuel cycle (Heterogeneous recycle)

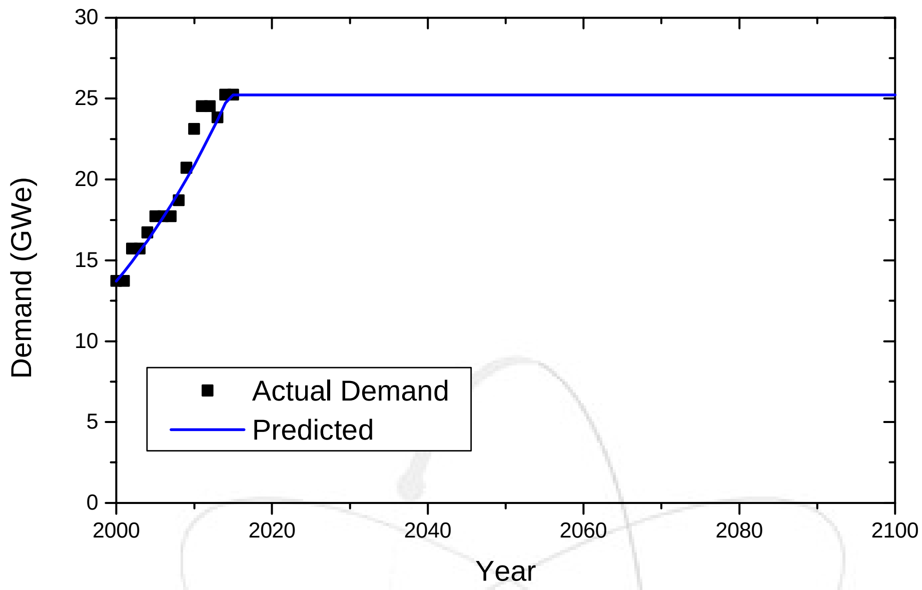


Fig. 4 Comparison of actual and predicted nuclear power demand

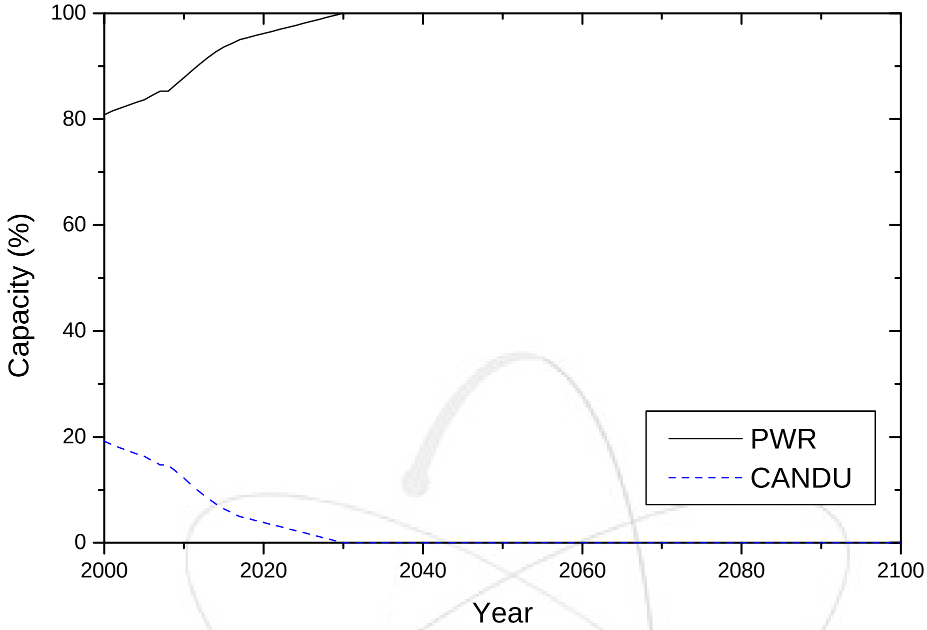


Fig. 5 Variation of reactor capacity (Once-through cycle)

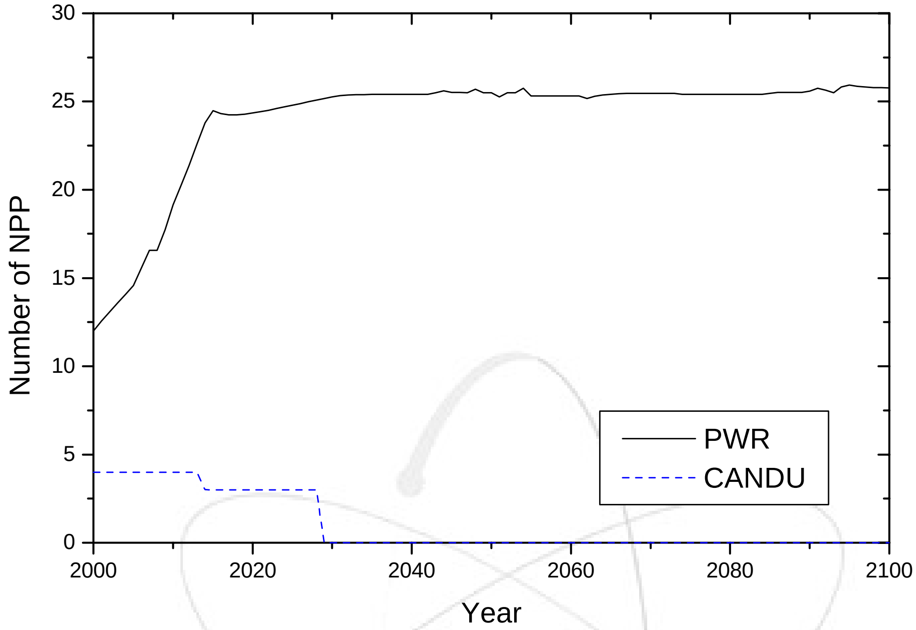


Fig. 6 Number of nuclear power plant (Once-through cycle)

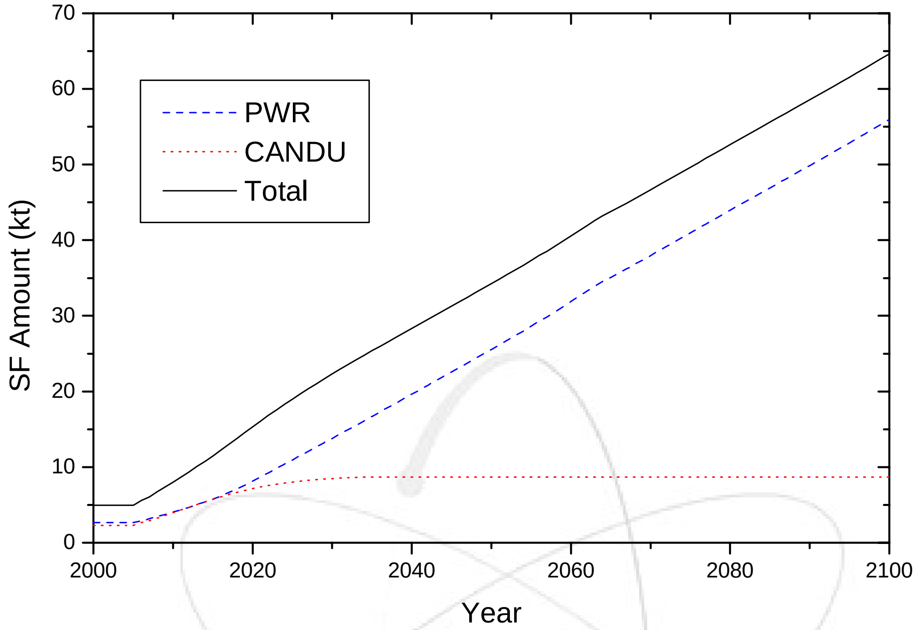


Fig. 7 Accumulation of spent fuel (Once-through cycle)

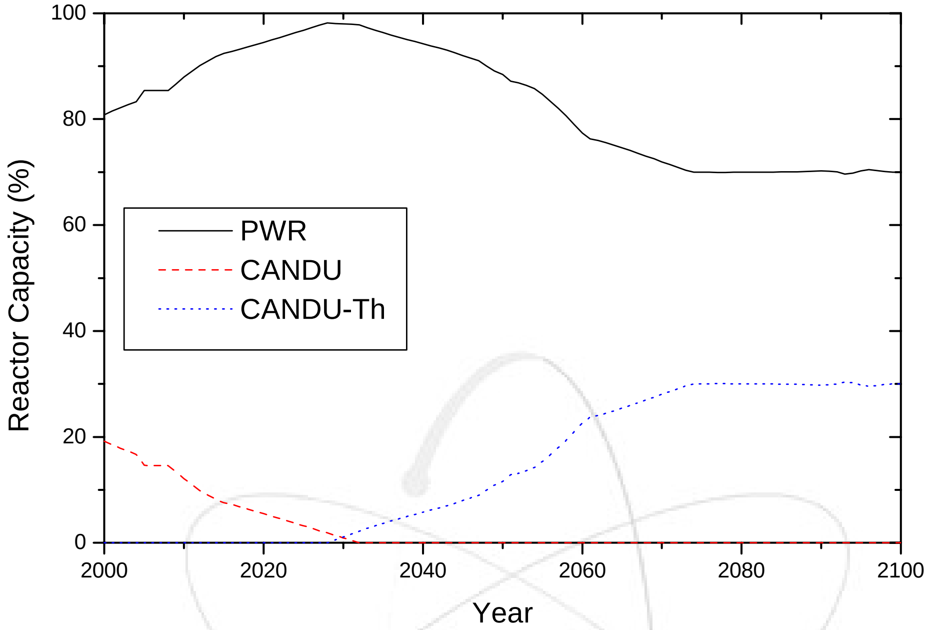


Fig. 8 Variation of reactor capacity (Thorium cycle)

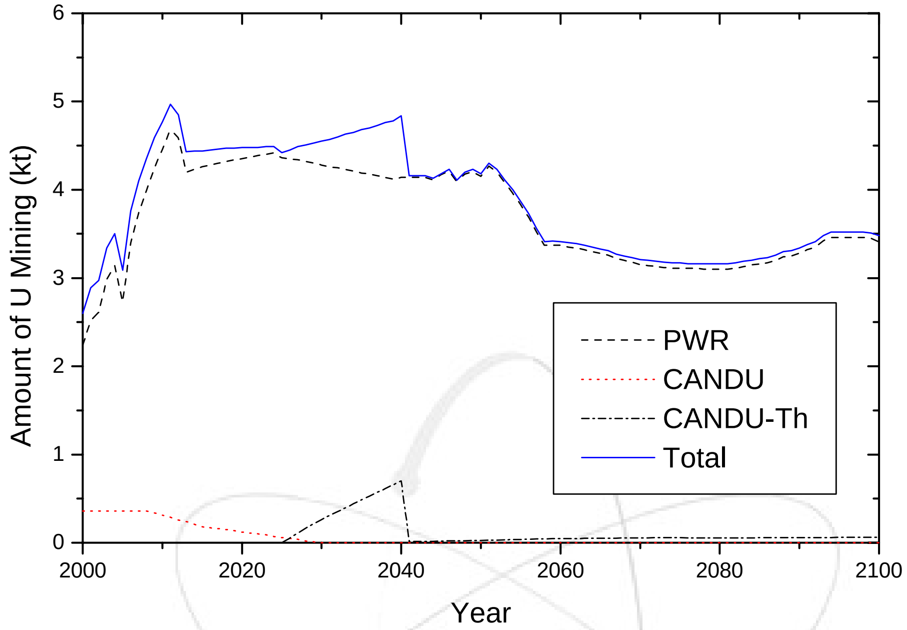


Fig. 9 Amount of annual uranium mining (Homogeneous thorium cycle)

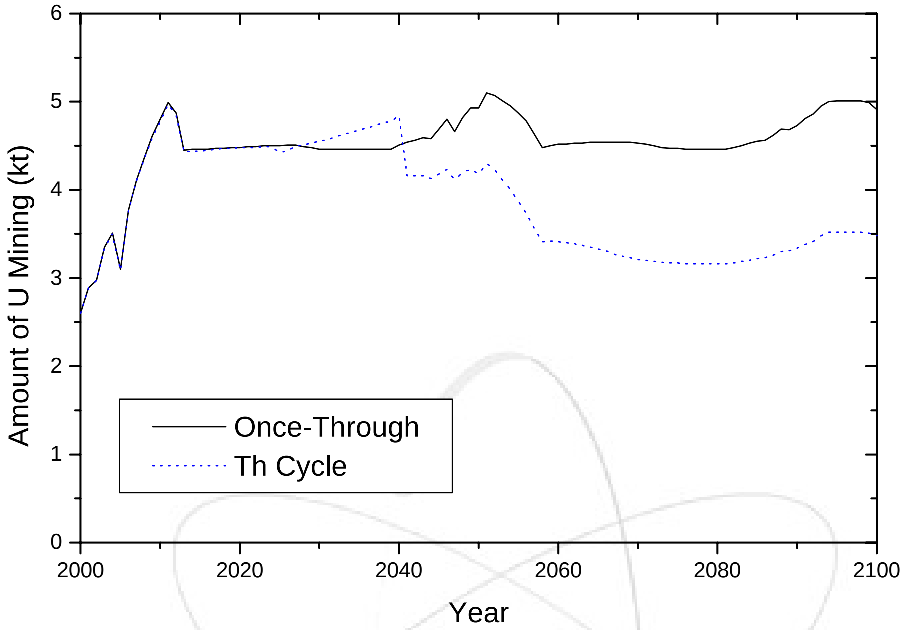


Fig. 10 Comparison of annual uranium mining (Homogeneous thorium cycle)

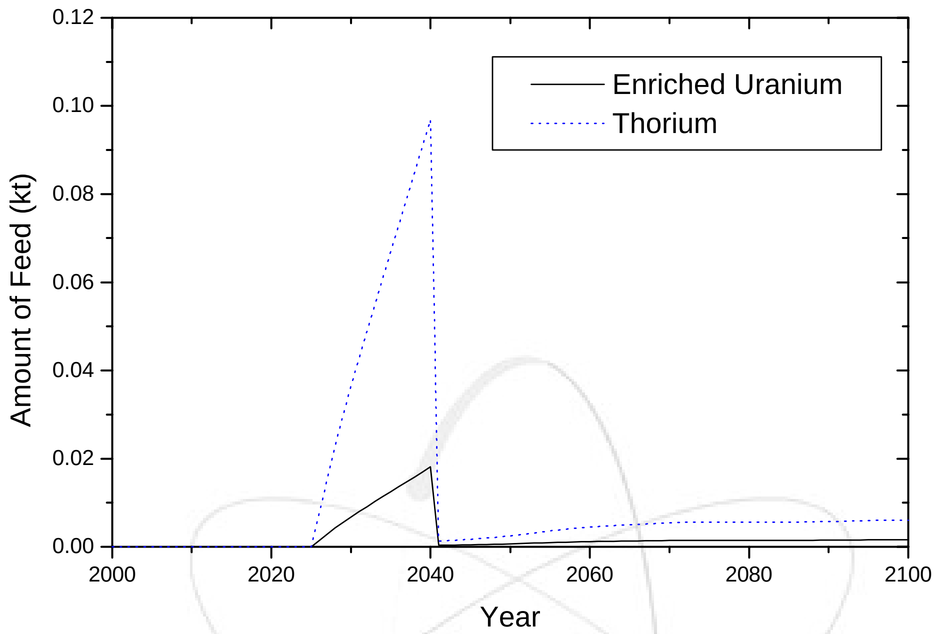


Fig. 11 Amount of annual feed of uranium and thorium (Homogeneous thorium cycle)

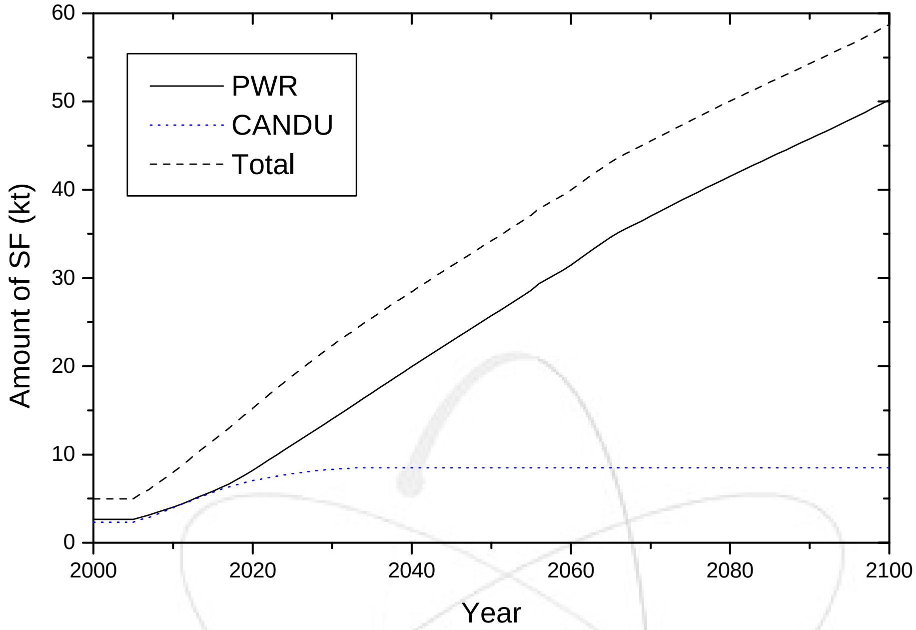


Fig. 12 Accumulation of spent fuel (Homogeneous thorium cycle)

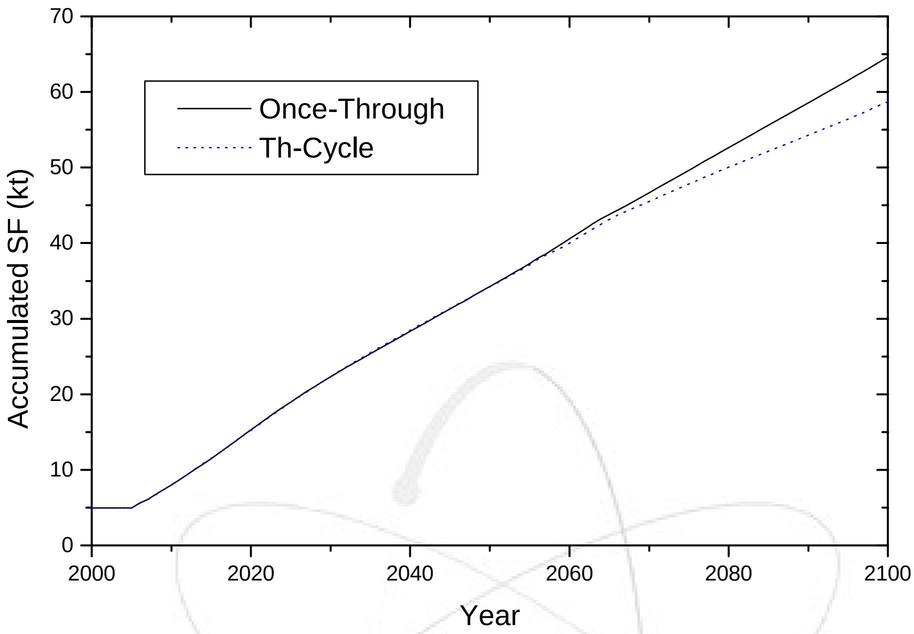


Fig. 13 Comparison of spent fuel inventory (Homogeneous thorium cycle)

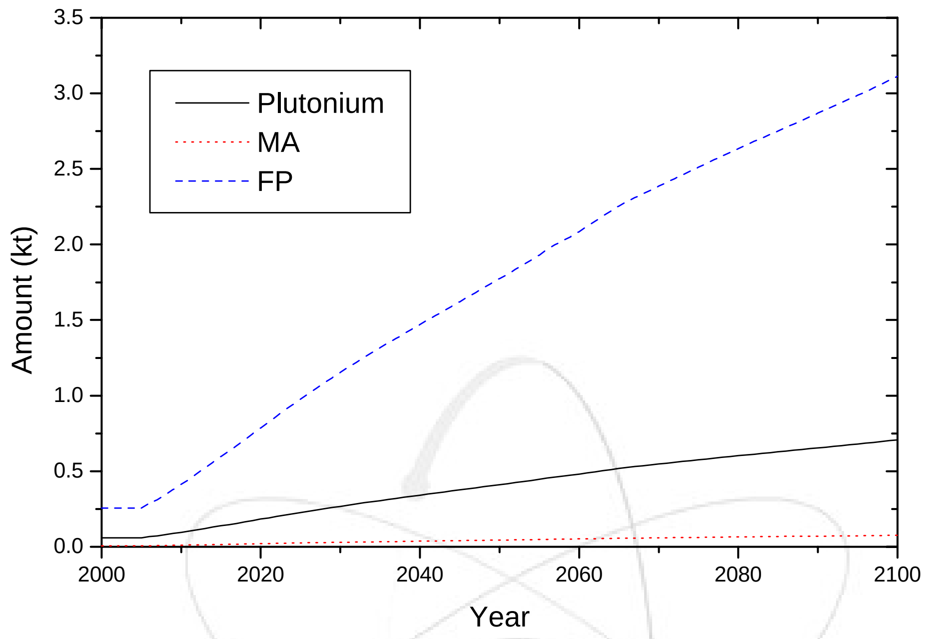


Fig. 14 Accumulation of heavy elements and fission products (Homogeneous thorium cycle)

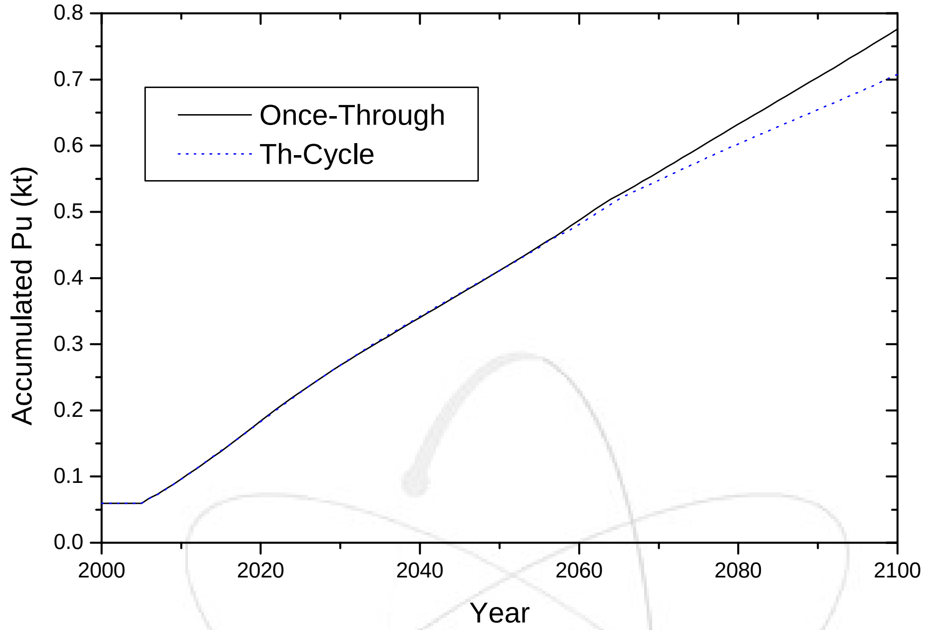


Fig. 15 Comparison of plutonium inventory (Homogeneous thorium cycle)

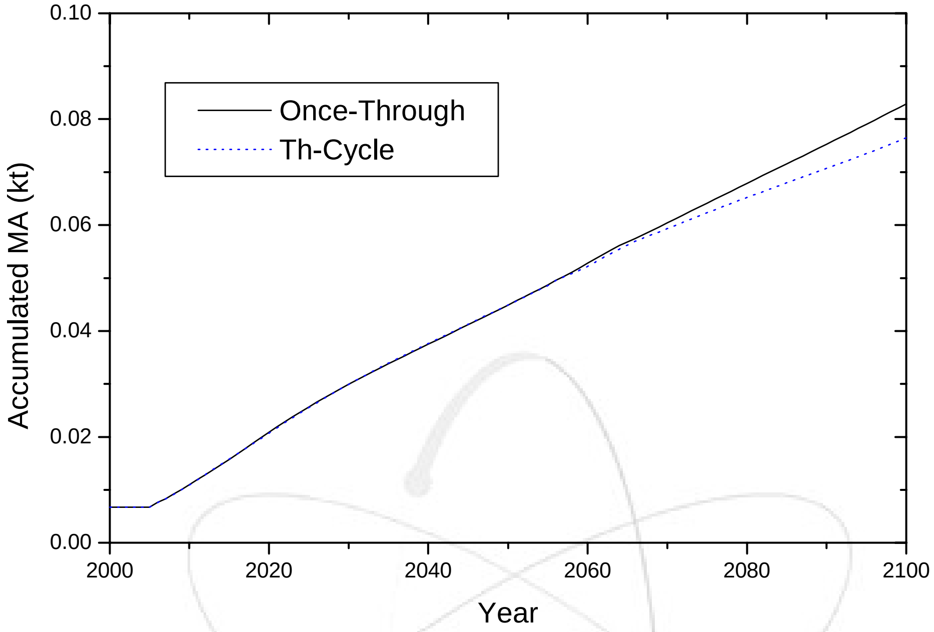


Fig. 16 Comparison of minor actinides inventory (Homogeneous thorium cycle)

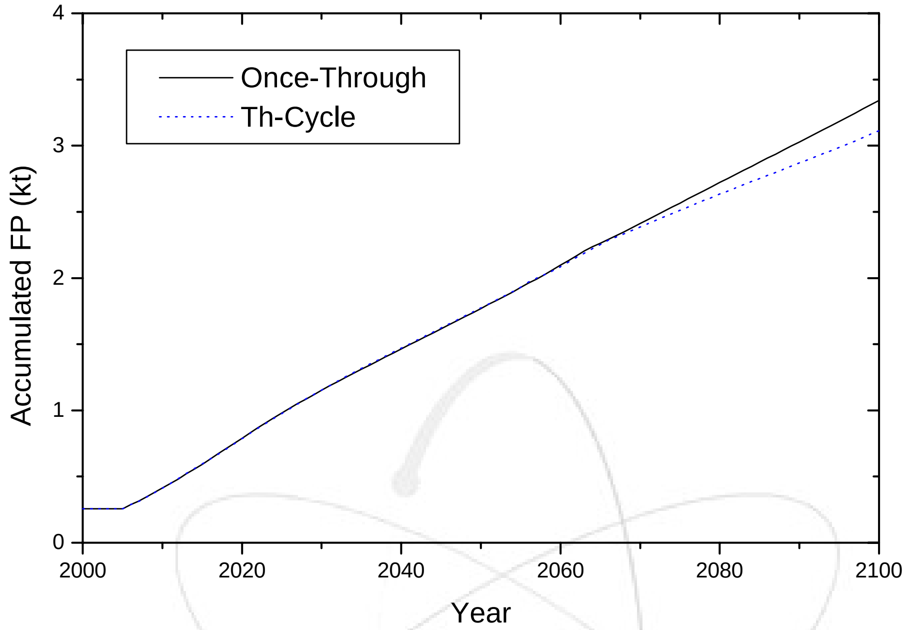


Fig. 17 Comparison of fission products inventory (Homogeneous thorium cycle)

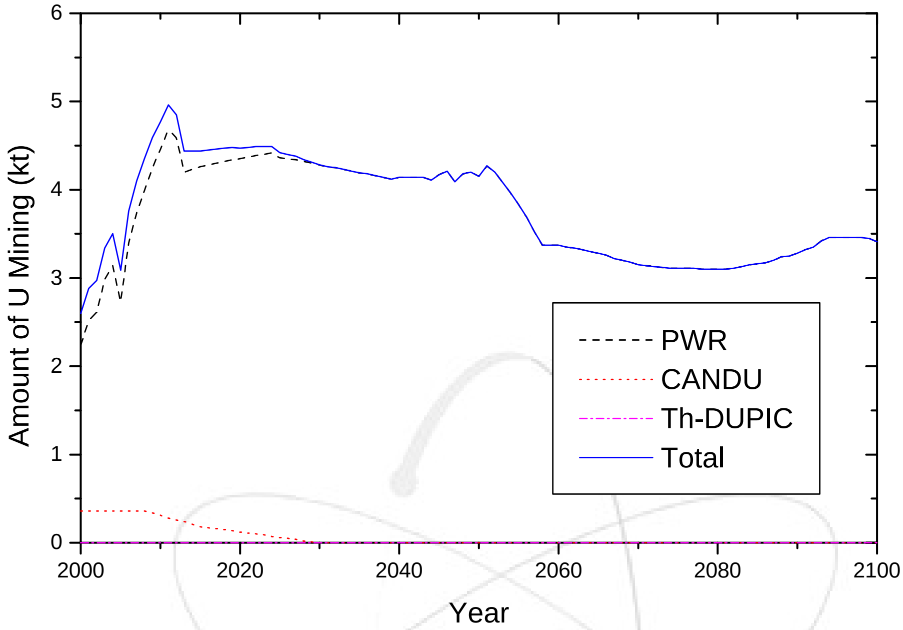


Fig. 18 Amount of annual uranium mining (Heterogeneous thorium cycle)

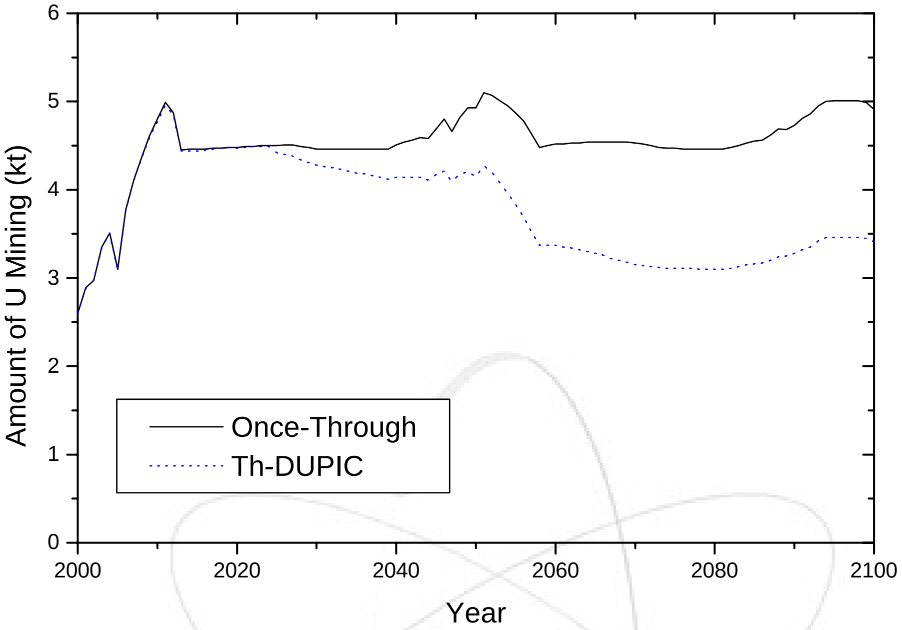


Fig. 19 Comparison of annual uranium mining (Heterogeneous thorium cycle)

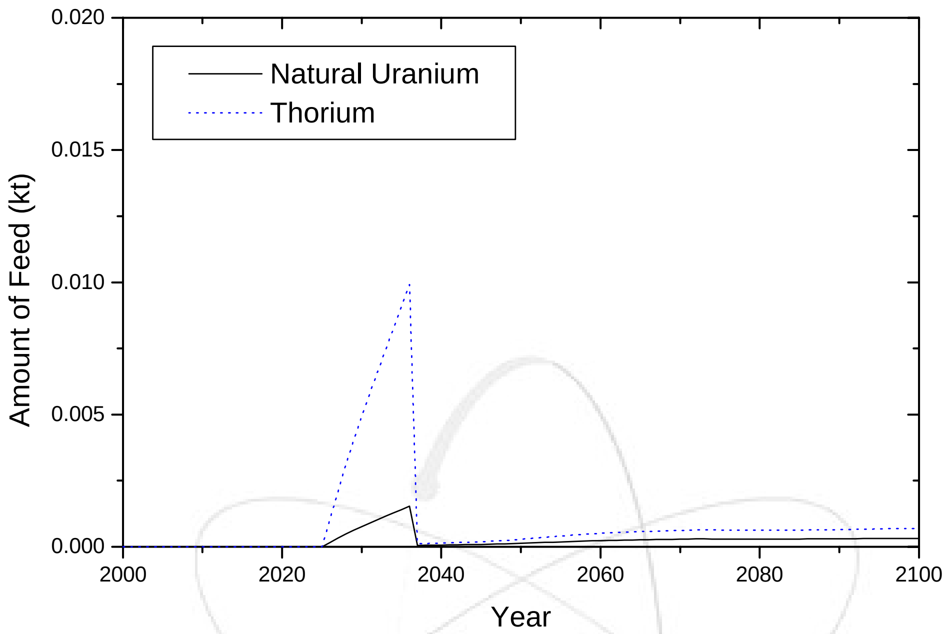


Fig. 20 Amount of annual feed of uranium and thorium (Heterogeneous thorium cycle)

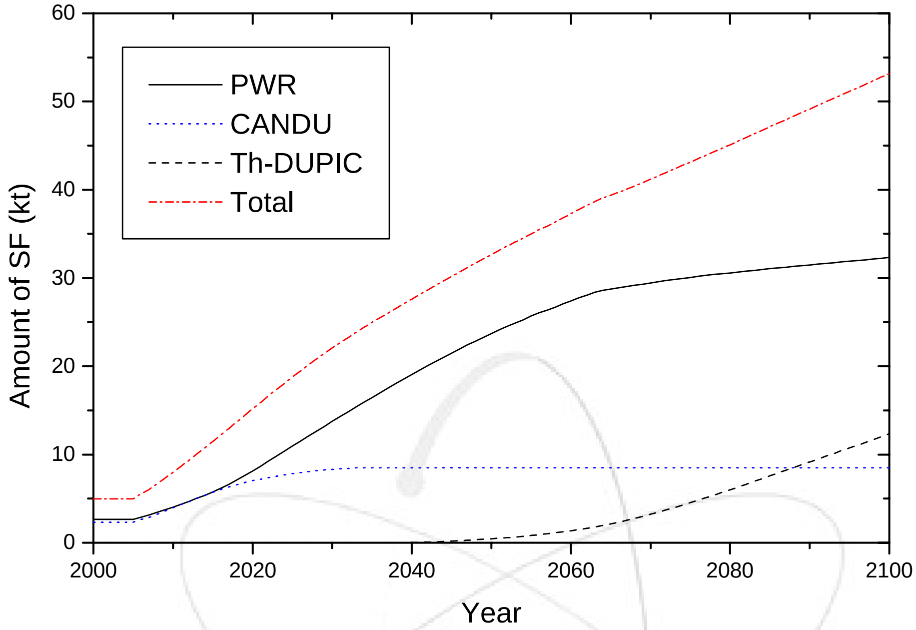


Fig. 21 Accumulation of spent fuel (Heterogeneous thorium cycle)

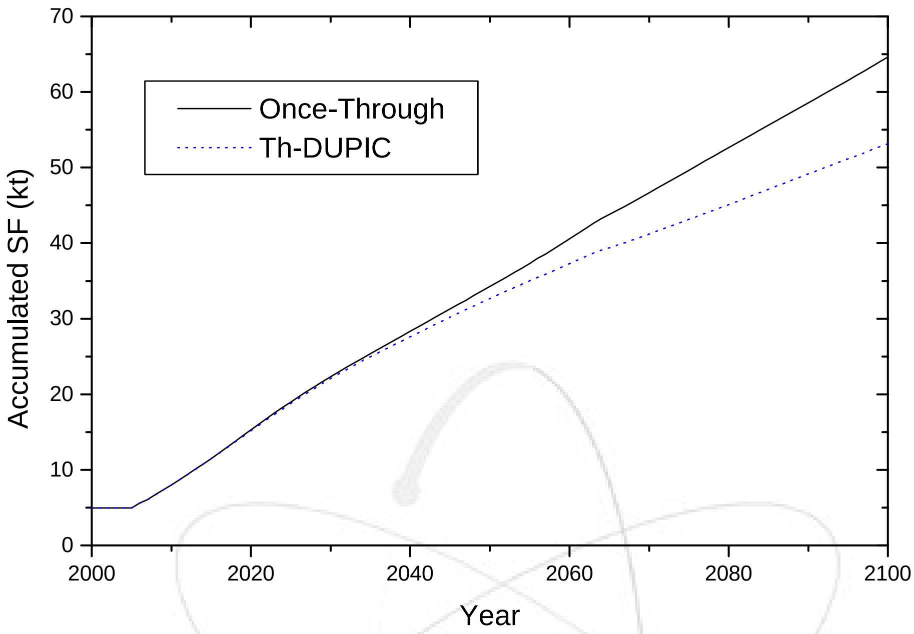


Fig. 22 Comparison of spent fuel inventory (Heterogeneous thorium cycle)

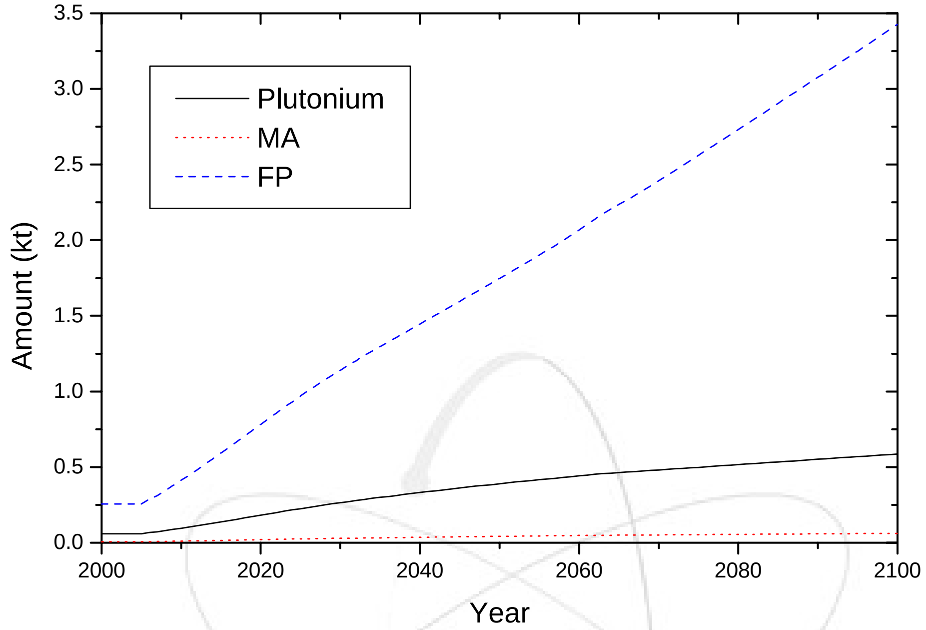


Fig. 23 Accumulation of heavy elements and fission products (Heterogeneous thorium cycle)

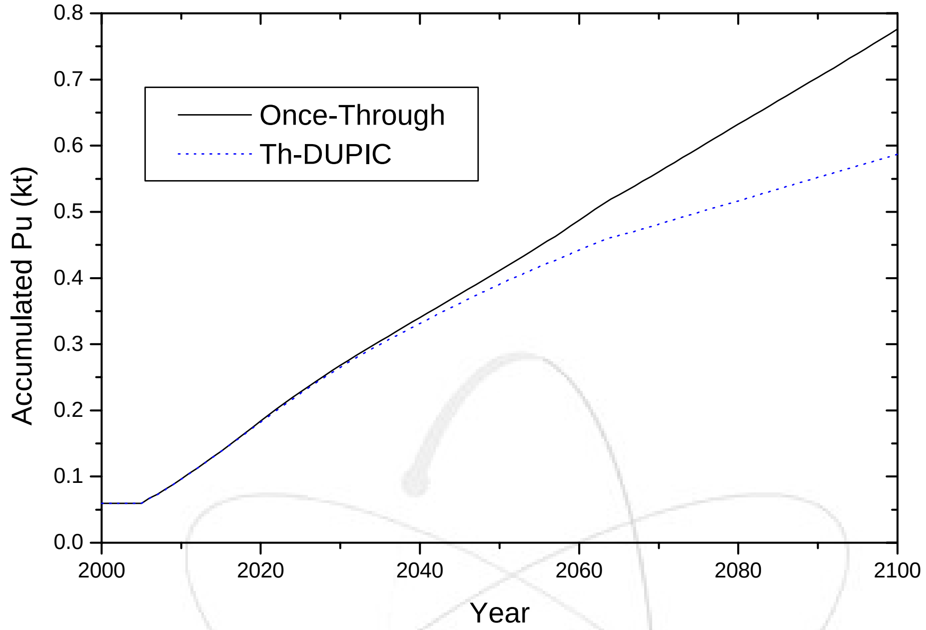


Fig. 24 Comparison of plutonium inventory (Heterogeneous thorium cycle)

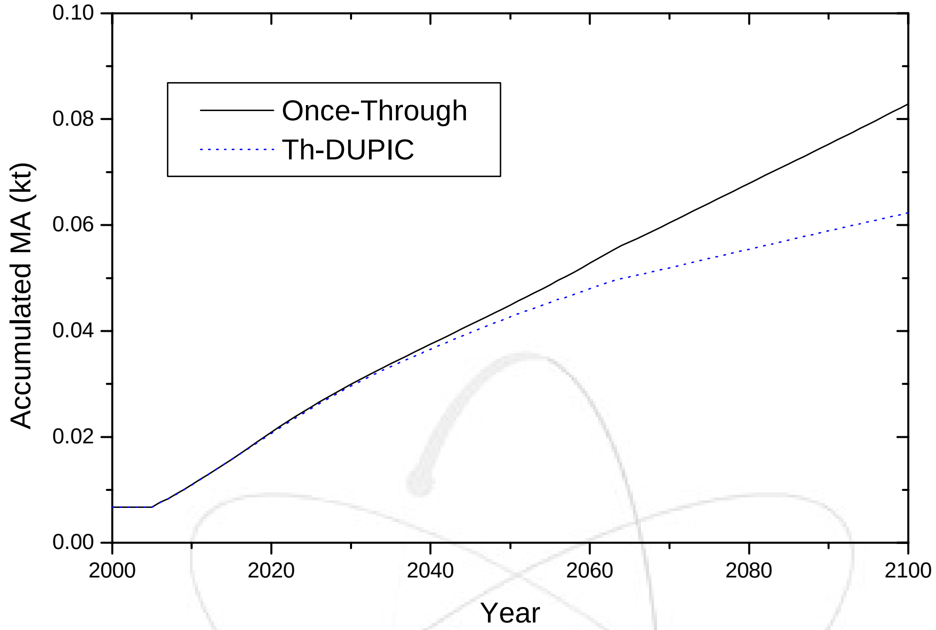


Fig. 25 Comparison of minor actinides inventory (Heterogeneous thorium cycle)

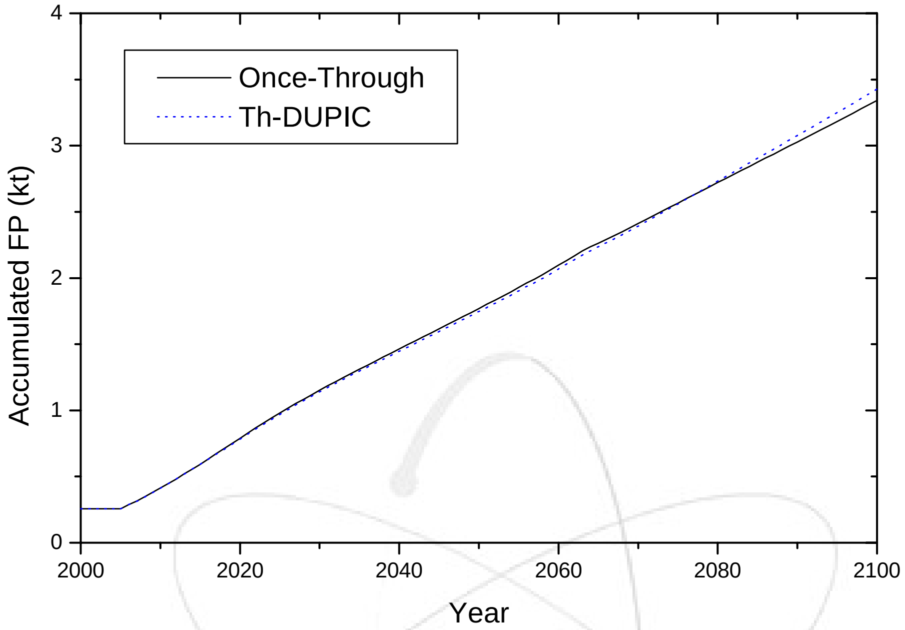


Fig. 26 Comparison of fission products inventory (Heterogeneous thorium cycle)

서 지 정 보 양 식

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제목/부제	Dynamic Analysis of the Thorium Fuel Cycle in CANDU Reactors
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연구위탁기관		계약 번호			

초록 (15-20줄내외)

CANDU 원자로를 이용한 토륨 재순환 핵연료 주기를 2 가지 핵연료 즉, 균질 ThO_2UO_2 및 비균질 ThO_2UO_2-DUPIC 핵연료에 대해서 분석하였다. 사용후 핵연료 재순환은 핵비확산성을 가지는 건식공정에 의해 이루어진다. 비순환 주기 모델에서 2016 년까지의 원전 건설 계획을 고려하였고, 2016 년 이후에는 원자력 요구 증가량이 0%라고 가정하였다. 비순환 주기 모형화 후 토륨 핵연료 장전 CANDU 원자로 주기를 모형화 하였다. 핵연료 주기 분석에서는 사용후 핵연료 재고량과 사용후 핵연료 내 플루토늄, minor actinide 및 핵분열 생성물 양을 계산하여 비순환 주기와 비교 하였다. 핵연료 주기 분석 결과, 건식 처리 공정을 통하여 폐쇄 및 부분적 폐쇄 토륨 핵연료 주기의 성립이 가능하다는 것을 알 수 있었다. 또한, 균질 및 비균질 토륨 핵연료 주기는 사용후 핵연료 발생양을 감소시키고 천연 우라늄 자원을 절약할 수 있는 것으로 나타났다. 물질 흐름 관점에서 비균질 토륨 핵연료 주기가 더욱 타당성이 있는 것으로 나타났지만 향후 경제성 분석이 필요할 것으로 판단된다.

주제명키워드 (10단어내외)	토륨 핵연료 주기. CANDU 원자로, 비순환 주기, 사용후 핵연료 , 플루토늄, minor actinide, 핵분열생성물, 건식 처리

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Abstract (15-20 Lines)

The thorium fuel recycle scenarios through the Canada deuterium uranium (CANDU) reactor have been analyzed for two types of thorium fuel: homogeneous ThO_2UO_2 and ThO_2UO_2-DUPIC fuels. The recycling is performed through the dry process fuel technology which has a proliferation resistance. For the once-through fuel cycle model, the existing nuclear power plant construction plan was considered up to 2016, while the nuclear demand growth rate from the year 2016 was assumed to be 0%. After setting up the once-through fuel cycle model, the thorium fuel CANDU reactor was modeled to investigate the fuel cycle parameters. In this analysis, the spent fuel inventory as well as the amount of plutonium, minor actinides and fission products of the multiple recycling fuel cycle were estimated and compared to those of the once-through fuel cycle.

From the analysis results, it was found that the closed or partially closed thorium fuel cycle can be constructed through the dry process technology. Also, it is known that both the homogeneous and heterogeneous thorium fuel cycles can reduce the SF accumulation and save the natural uranium resource compared with the once-through cycle. From the material balance view point, the heterogeneous thorium fuel cycle seems to be more feasible. It is recommended, however, the economic analysis should be performed in future.

Subject Keywords (About 10 words)	thorium fuel, CANDU reactor, once-through cycle, spent fuel, plutonium, minor actinide, fission products, dry process