ANNEX II.

COMPARATIVE ASSESSMENT OF COLLABORATIVE FUEL CYCLE OPTIONS FOR INDONESIA

II-1. INTRODUCTION

II-1.1. Background

Under the long term energy development plan for Indonesia, the growth of energy demand is projected to increase very rapidly. Meeting the increased domestic energy demand presents a major challenge to the country, as existing resources are limited. Selection of energy supply options shall be sought and deliberated from various aspects, including energy availability and security, technology, safety, social economic and environment.

To guide the development of sustainable energy supply, Presidential Decree Number 5 on National Energy Policy (2006) has been enacted. The policy addresses the national primary energy mix in 2025, in which the share of oil supply shall be reduced only up to 20%, natural gas increases to 30%, coal should be more than 33%, bio-fuel up to 5%, geothermal up to 5%, other renewable sources (bio-mass, nuclear energy, hydro, solar cell, and wind) up to 5%, and liquefied coal up to 2%.

The introduction of nuclear power in Indonesia is not only to reach an optimum energy mix considering costs and environment, but also to relieve the pressure arising from the increasing domestic demand for oil and gas (so that oil and gas resources can be used for export and feed stocks). Thus, the role of nuclear power is to stabilize the supply of electricity, conserve strategic oil and gas resources and protect the environment from harmful pollutants that result from use of fossil fuels.

In the context of the civil use of nuclear energy, Indonesia has enacted Act No. 10 of 1997 on Nuclear Energy, which underscores the importance of nuclear energy for our welfare and the need for its safe applications. The national commitment to implementing a nuclear power program is stated in Act No. 17 Year 2007 on Long Term National Energy Planning 2005 – 2025.

The inclusion of nuclear power in the energy mix sets the ground for the need of sustainable planning of the country's nuclear power plant (NPP) program into the future. The aim of the current study is to analyses a range of fuel cycle options from the perspective of their effect on the utilization of natural Uranium resources and the radioactive waste generated (i.e. spent fuels). This is intended to support the sustainable of NPP program development in Indonesia.

The results of feasibility study for the first NPP in Indonesia support plans for a 1000 MW(e) class of PWR operating in an open fuel cycle with extended interim storage of spent fuel. This is considering the spent fuel still possesses economic value and long term strategic value. If economically feasible, nuclear fuel element fabrication is planned to be conducted in Indonesia and the national uranium resources will be used as substitutions. Meanwhile, enrichment services will be obtained from international market.

The concept of spent fuel take-back to the country of origin can be implemented if economically beneficial, in particular at the initial stage of NPP introduction. This concept is judged to be able to increase public acceptance with respect to NPP option.

The projected energy generation (MWyear) for CO_2 limitation scenario and the role of nuclear in the energy mix calculated by MESSAGE is given in Fig. II-1. It can be seen that with the above low carbon scenario, nuclear will enter into the energy scenario in 2024 with

an installed capacity of 2,000 MW(e) and then be anticipated to grow up to 36,000 MW(e) by 2050.

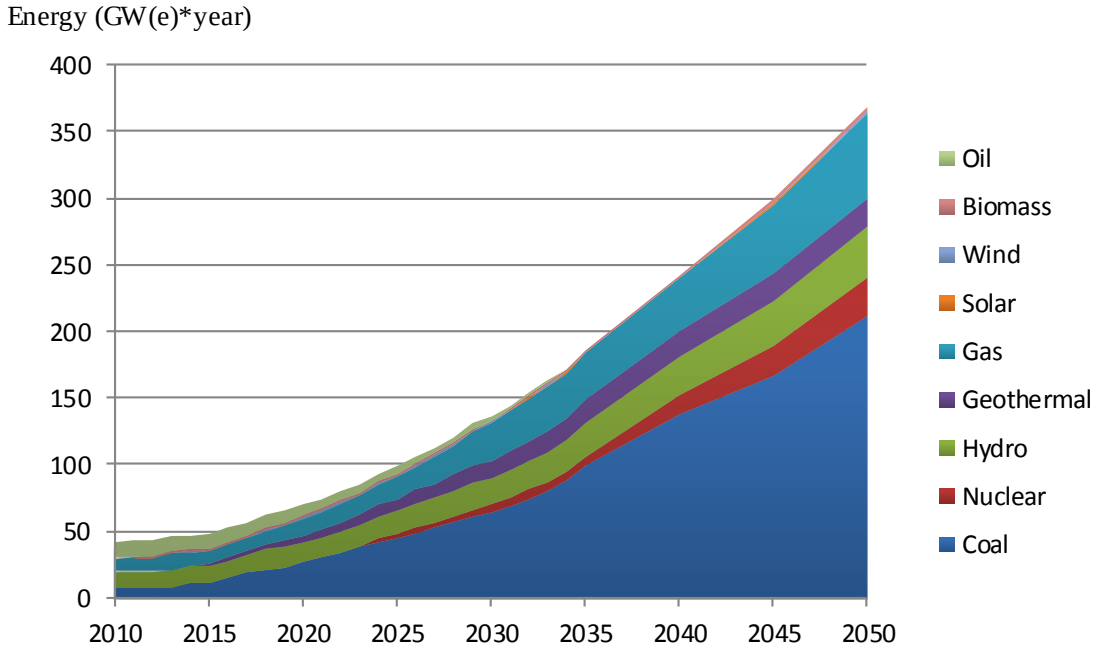

FIG. II-1. Projected energy generation until 2050 based on CO_2 limitation scenario.

II-1.2. Objectives

The objectives of this study are to assess the most viable option of fuel cycle strategies to support the sustainability of nuclear power plants implementation in Indonesia, and to identify potential national, regional, and international arrangements for the fuel cycle.

The assessment results could be used to support the preparation of nuclear fuel cycle policy, to develop awareness of long term issues surrounding the nuclear power program, and to support strategic planning and decision making for the development and deployment of NPP program in a sustainable manner.

Safe, secure, economical and publically acceptable nuclear power with security of supply and that maximizes the usable energy produced from natural resources while minimizing the waste resulting from the nuclear energy system is required conditions necessary for Indonesia to deploy nuclear power plants.

II-2. METHODOLOGY

The comparison of different nuclear fuel cycle options was used in this study. Various fuel cycle options will then be compared to a reference once-through fuel cycle. The evaluation metrics were used to evaluate and compare include: resource utilization, waste production, proliferation risk, and fuel cycle cost.

For the purpose of this study, resources utilization is measured as the mass of natural uranium (or thorium) required per unit energy generated (tons/GW(e)year). Waste production is measured using two metrics, i.e. the mass of transuranics and the mass of fission products discharged per unit energy generated (kg/GW(e)year). The proliferation risk posed any given fuel cycle are difficult to quantify. Therefore, to avoid these difficulties, the inventories plutonium and transuranics per unit energy generated (kg/GW(e)) are used in this study. A

fuel cycle cost metric is used to capture the impact of advanced fuel cycles on the cost of fuel alone.

A literature review is conducted to identify fuel cycles that are currently generating interest, present attractive features to reduce natural uranium required and less waste (spent fuel) per-unit energy generated. For each fuel cycle, mass flow calculations are performed based on data available in the literature [II-1 - II-8].

Analysis of nuclear fuel cycle however, requires a detailed modelling as it includes a set of processes to make nuclear fuel from natural uranium, to generate electricity from nuclear reactor and to manage spent fuel discharged from the reactor. For simplicity, only equilibrium conditions are considered in the study.

The equilibrium model focuses on a batch study with the assumptions that the whole system is in a steady state and that the mass flow as well as electricity production throughout the fuel cycle is in an ideal equilibrium state, which calculates the material flow for the production of a certain amount of electricity. The equilibrium model enables a clear and direct comparison to suggest which optimized system should be complemented in the future.

Five options of nuclear fuel cycles were evaluated in order to support the sustainability nuclear power program in Indonesia. These fuel cycles include:

(1) Once-Through Fuel Cycle. This open fuel cycle assumes for the electricity production of 1000 MW(e)year of Pressurized Water Reactors (PWR) with conventional uranium oxide (UO_2) fuel of medium burnup (51 GWday/tHM), and the direct disposal of spent nuclear fuel (SNF) in a geologic repository.

(2) Plutonium Recycle with MOX Fuel in PWR (Pu Mono-Recycle). This fuel cycle assumes conventional reprocessing of LWR fuel, similar to current fuel cycle schemes being used in some European and Asian counties. This Pu recycle scheme assumes the use of 1000 MW(e) PWRs using UO_2 fuel. The spent UO_2 fuel is processed with conventional PUREX reprocessing and the separated plutonium (Pu) is recycled in the form of uranium-Pu mixed oxide (MOX) fuel in PWRs. This fuel cycle assumes disposal of the resulting high-levelradioactive waste (HLW) from the PUREX reprocessing step as well as direct disposal ofMOX SNF in a geologic repository.

(3) Direct Use of PWR Spent Fuel in CANDU Reactor (DUPIC).This fuel cycle is based upon dry thermal and mechanical processes to directly fabricate CANDU (Canada Deuterium Uranium) fuel from spent PWR fuel material without separating the fissile material and fission products. This concept was proposed and termed the “DUPIC” fuel cycle in a joint development program involving KAERI (Korea Atomic Energy Research Institute), AECL (Atomic Energy Canada Limited) and the US Department of State in 1991. Since then, KAERI, AECL and the United States, with the participation of IAEA, have been engaged in a practical exercise to verify the concept.

(4) Synergistic Fuel Cycle of LWR–FR: A fast reactor utilizes fast neutrons of which a higher energy can burn both ^{235}U and TRUs. This aspect makes it possible to transmute the TRUs and extract energy at the same time. The spent fuels of PWR are to be reprocessed (advanced PUREX) to obtain TRU-bearing fuels for FRs, while the remaining uranium partitioned from the spent fuel of PWR would be disposed of as low- and intermediate-level radioactive waste. The TRU fuel after burning in FR would be repeatedly reprocessed through pyro-processing, and the recovered TRUs would be recycled into an FR to close the fuel cycle.

(5) Once-Through Th-U Fuel in Light Water Reactor (PWR). The use of thorium fuel in a current PWR with a once-through fuel cycle remains an attractive option due to potential advantages, such high conversion ratio in connection

with extended burnup and low initial fissile material inventory. Furthermore, thorium fuel cycles could have the potential to improve waste generation issues, operational safety, economics, and proliferation resistance. The use of thorium as a fertile material can reduce minor actinide generation and the radiotoxicity of spent fuel.

The data used in the study regarding processes and material flows for each fuel cycle scheme considered are drawn from published literature. The main input data used in the study is summarized in Table II-1 (reactor and fuel specifications) and Table II-2 (fuel cycle service unit costs).

For fuel cost analysis, simplicity model of MIT study is used. In this model, the amount of fuel passing through a certain step multiplied with the unit cost of the specific material offers the fuel cost of a single step and combined with the additional cost assosiated with the operation. By summarizing the costs of all components of an fuel cycle, and then divided by electric power generated, the overall costs of the fuel cycle can be obtained.

The aim of advanced fuel cycles is to improve the sustainability of nuclear energy by enhancing the effectiveness of natural resource utilization and by reducing the volume and long-term radio-toxicity of high-level waste while the costs of energy products, for example electricity, stay economically viable. This is due to the fuel cycle cost is only a small fraction of total nuclear electricity generation cost.

TABLE II-1. REACTOR AND FUEL SPECIFICATIONS

Items	PWR UOX (OTFC)	PWR MOX (Pu Mono Recycle)	PHWR (DUPIC Fuel Cycle)	FR (TRUs Burner)	PWR (U-Th fuel)
Fuel discharge burnup (GWday/tHM)	51	51	14	140	*)
Reactor thermal efficiency (%)	34	34	33	40	34
Fresh fuel composition	UO_2 4.3% U235	MOX 8.1% Pu 91.9% DU	UOX from spent fuel of PWR	33.16% TRU 66.84% U	Seed: UO_2, 20% U235 Blanket: 87% ThO_2, 13% UO_2, 10% ^{235}U
Spent fuel composition	1.197% Pu 0.51% MA 5.264% FP 93.439% U	5.52% Pu 0.54% MA 5.15% FP	0.8379% Pu 0.12% MA 6.7091% FP 0.9233% U	59.94% U 26.46% TRU 14.1% FP	Seed: 1.97% TRU 1.56% Pu 14.5% FP Blanket: 0.51% TRU 0.45% Pu 8.8% FP

*) Reactor generates 1.570 GW(e)year (18 months cycle length), UO_2 fuel is replaced every cycle (7.703 tHM), and $(Th-U)O_2$ fuel is replaced every 9 cycles (58.997 tHM).

TABLE II-2. FUEL CYCLE SERVICE UNIT COSTS

Items	PWR UOX	PWR MOX	DUPIC	FR (TRUs)	PWR (U-Th fuel)
Fuel cost – Front end					
– Natural uranium ($/kgHM)	80	-	-	-	80
– Conversion ($/kgHM)	10	-	-	-	10
– Uranium enrichment ($/kgSWU)	120	-	-	-	120
– Fuel fabrication ($/kgHM)	275	1500	850	2500	275
Fuel cost – Back end					
– SF storage and disposal ($/kgHM)	250	-	250	-	250
– SF reprocessing ($/kgHM)	-	1000	-	-	-
– Advance PUREX ($/kgHM)	-	-	-	1000	-
– Pyro-reprocessing ($/kgHM)	-	-	-	2500	-
– HLW storage and disposal ($/kgHM)	-	200	-	200	-
Fuel service – Lead iime					
– Nat. uranium purchase (months)	24	-	-	-	24
– Conversion service (months)	20	-	-	-	20
– Enrichment service (months)	18	-	-	-	18
– Fuel fabrication (months)	12	-	12	12	12
– Reprocessing	-	24	-	24	-
Fuel service – Lag time					
– SF storage (years)	5	5	5	5	5

Notes: Reprocessing losses of 0.1% are assumed for all fuel types reprocessing methods; ^{235}U in natural uranium is 0.007114; Tail assay in enrichment serviceis 0.3; No material losses in uranium conversion and fuel fabrication; SF cooling time prior to reprocessing is 5 years; and carrying charge factor is 0.1 per year.

II-3. ANALYSIS OF FUEL CYCLES

II-3.1. Once through fuel cycle in PWR

The current PWRs operate on either of two fuel cycles, i.e. once-through or single pass plutonium recycle. The once-through fuel cycle consists of the following steps: mining and milling of uranium ore, U_3O_8 purification and conversion to UF_6, enrichment, fuel fabrication, irradiation in the reactor, storage of irradiated fuel for cooling, and direct disposal of spent fuel.

Resources utilization. Assuming a fuel burnup of 51 GWday/tHM, thermal efficiency of 34%, and fuel enrichment of 4.3% ^{235}U, then the mass of fuel that needs to be irradiated for the production of 1 GW(e)year of electricity is 21.05 tons of enriched uranium or 204.66 tons of natural uranium. The Separative Work Unit for uranium enrichment process is 123.02 tons SWU. The depleted uranium as by-product of enrichment process is 183.61 tons (assuming a tail assay of 0.3%).

Waste production. From the above data can be obtained that the spent fuel to be discharged from reactor is about 21.05 tHM/GW(e)year. This spent fuel 51 MWday/kgU contain up to 93.439 weight % (wt.%) of uranium, 1.197 wt.% of plutonium, 0.1 wt.% of minor actinides, and 5.264 wt.% of fission products. It can be concluded that the mass of transuranics discharged is about 0.27 t/GW(e)year, the mass of plutonium discharged is about 0.252 t/GW(e)-year and the mass of fission products discharged is about 1.1 t/GW(e)year.

Proliferation risk. The PWR once through fuel cycle has favorable characteristics of proliferation resistance. The front end of fuel cycle requires enrichment to levels that are far

below the threshold where proliferation concerns are raised (20%). The direct disposal of spent fuel eliminates reprocessing operations where component of spent fuel can be separated. Illicit retrieval of plutonium or actinides is more difficult due to the presence of highly radioactive fission product in the spent fuel (providing barrier against proliferation).

Fuel cycle cost. Based on the results of mass flow analysis such as described in Fig. II-2, and by using the data listed in Table II-2, the overall costs of PWR once through fuel cycle per unit electric power generated was determined, i.e. 6.347 mills[1]/kW(e)h. This cost came from 2.663 mills/kW(e)h of the natural Uranium purchase, 0.325 mills/kW(e)h of the UF_6 conversion service, 2.317 mills/kW(e)h of the Uranium enrichment service, 0.876 mills/kW(e)h of the fuel assemblies fabrication, and 0.165 mills/kW(e)h of spent fuel assemblies storage and disposal.

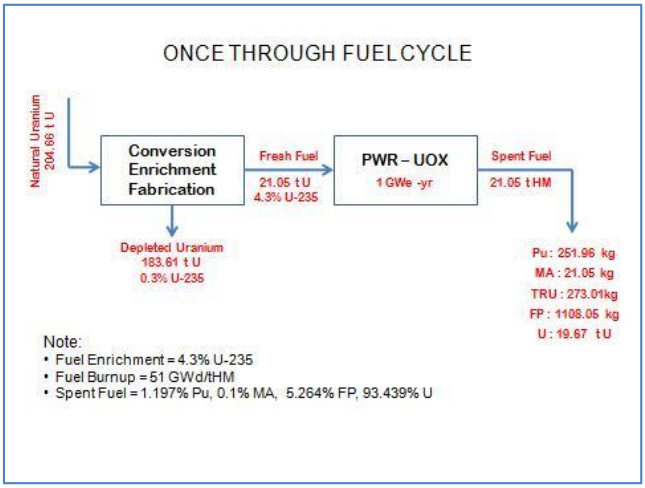

FIG II-2. Mass balance of PWR once through fuel cycle (all quantities are per GW(e)year).

II-3.2. Plutonium recycle with MOX fuel in PWR (Pu–mono recycle, Fig. II-3)

The plutonium contained in spent fuel can be recycled as fissile material in new nuclear fuel. Recycled plutonium is mixed with natural uranium or depleted uranium to make MOX fuel (MOX – mixed oxide). Because of its detrimental effect on reactor control, the cores of the most current PWR cannot be loaded fully with MOX fuel. Typically only 1/3 of the core can be loaded with MOX fuel.

The fresh MOX contains of plutonium up to 8.1 wt.% and depleted uranium up to 91.9 wt.%. In this study all UOX spent fuel discharged from reactors is reprocessed for plutonium recycle but none of the MOX spent fuel. The irradiated MOX fuel up to 51 GWday/tHM contain of 88.79 wt.% uranium, 6.06 wt.% transuranic elements, 5.52 wt.% plutonium, 0.54 wt.% minor actinides, and 5.15 wt.% fission products.

It is assumed that all spent UOX is reprocessed for plutonium recycle, and the ratio of UOX based to MOX based capacity is determined by requiring that the amount of plutonium discharged in spent UOX be equal to the amount of plutonium required for MOX fabrication. During the PUREX process, it is assumed that 0.1% of the uranium and plutonium cannot be recovered and ends up in the HLW.

Resources utilization. Using mass balance equation can be obtained that the power derived from UOX fuel is 87% and the power derived from MOX fuel is 13%. The mass of

[1] 1 mill is 1/1000 of the US dollar or 1/10 of the US dollar cent.

fuel that needs to be irradiated for the production of 1 GW(e)year of electricity is 18.34 tons UOX fuel (enriched up to 4.3% ^{235}U) and 2.71 tons MOX fuel. The required natural uranium for UOX fuel is about 178.34 tons. The separative work unit for enrichment process is 107.20 tons SWU and depleted uranium is 160 tons. MOX fabrication requires 0.219 tons of plutonium, and 2.49 tons of depleted uranium. If compared to the once through fuel cycle, the recycling of Pu in the MOX fuel can save up to 13% of required natural uranium.

Waste production. The waste produced in this fuel cycle is composed of high level waste (HLW) and separated irradiated uranium from reprocessing operations and spent MOX fuel. The HLW is composed of all of the fission products and minor actinides in spent UOX fuel, i.e. 5.2 wt.% of fission products, 0.12 wt.% of minor actinides, 0.093 wt.% of uranium, and 0.0013 wt.% of plutonium. Therefore the waste discharge in HLW is 965.56 kg/GW(e)year of fission products, 18.34 kg/GW(e)year of minor actinides, and 0.22 kg/GW(e)year of plutonium. Spent MOX fuel to be discharged from reactor is 2.71 tHM/GW(e)year. The content of irradiated MOX fuel up to 51 GWday/tHM is 88.79 wt.% of uranium, 6.06 wt.% of transuranic elements, 5.52 wt.% of plutonium, 0.54 wt.% of minor actinides, and 5.15 wt.% of fission products. Mass balance analysis indicates that the spent MOX fuel to be discharged from reactor is 2.71 tHM/GW(e)year. Therefore, the content of spent MOX fuel is 2.40 t/GW(e)year of uranium, 164.04 kg/GW(e)year of transuranic elements, 149.43 kg/GW(e)year of plutonium, 14.62 kg/GW(e)year of minor actinides, and 139.41 kg/GW(e)year of fission products. Finally, the waste discharged from plutonium recycle in PWR consists of 182.61 kg/GW(e)year of transuranic elements and 1.105 t/GW(e)year of fission products. If compared to the once through fuel cycle, the recycling of Pu in the MOX fuel can reduce to 6.8% of considered waste (i.e. transuranic elements and fission products).

Proliferation risk. The PUREX process raises serious proliferation concern because its produces separated plutonium. Assuming a separated plutonium storage time of 6 months, the plutonium to be held in storage at any given time (inventory) is about 109.78 kg/GW(e), since the total plutonium mass flow is 219.56 kg/GW(e)year. In reality, there is a fundamental problem with balanced fuel material in mix fuel cycles, i.e. a specific ratio between various fuels is difficult to achieve in practice. This may lead to some undesirable consequences, i.e. the accumulation of separated plutonium in storage.

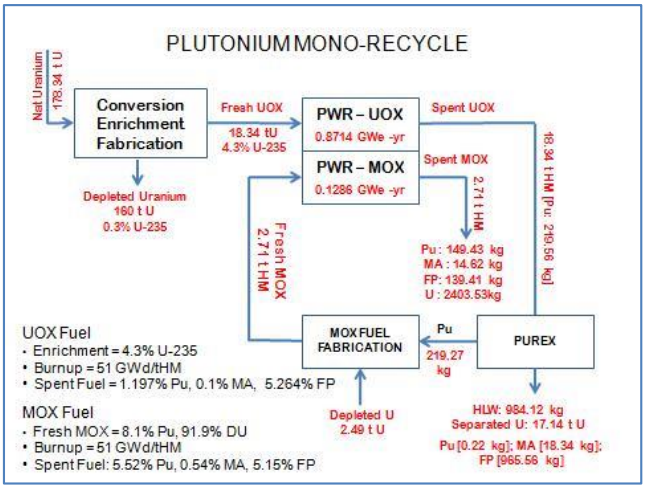

FIG II-3: Mass balance of PWR with plutonium mono-recycle
(all quantities are per GW(e)year).

Fuel cycle cost. The fuel cycle cost of nuclear park consist of 0.8714 GW(e)year PWR with UOX fuel and 0.1286 GW(e)year PWR with MOX fuel (Pu-mono recycle) is about

8.481 mills/kW(e)h. This cost in higher up to 33.6 % compared to the fuel cycle cost of PWR UOX once through fuel cycle. The fuel cycle cost of PWR MOX (Pu-mono recycle) is about 22.943 mills/kW(e)h. And the main contribution of this cost came from the reprocessing cost of PWR-UOX spent fuel. The fuel cycle cost of PWR-MOX consist of credit for PWR-UOX spent fuel is about -5.793 mills/kW(e)h, reprocessing cost of PWR-UOX spent fuel is about 23.171 mills/kW(e)h, fabrication cost of MOX fuel assemblies is about 4.776 mills/kW(e)h, cost of HLW storage and disposal is about 0.624 mills/kW(e)h, and cost of MOX spent fuel storage and disposal is about 0.165 mills/kW(e)h.

II-3.3. DUPIC fuel cycle (Fig. II-4)

The DUPIC (direct use of spent PWR fuel in CANDU) is intended to extract more energy from PWR fuel without increasing initial enrichment. The basic idea of this fuel cycle is that the spent PWR fuel contains enough fissile materials to be burnt in CANDU reactors, by direct re-fabrication without separating the residual of fissile materials via a dry reprocessing process known as OREOX (oxidation and reduction of oxide fuel). The DUPIC fuel cycle may offer a good alternative to other conventional options, such as plutonium recycle with MOX fuel.

Due to excellent neutron economy in CANDU reactors, it is possible to make spent PWR fuel, which typically has a fissile content of about 1.5%, to sustain criticality in a CANDU reactor up to a burnup of 10 to 20 GWday/tHM. After irradiation in a CANDU reactor, the spent DUPIC fuel is sent to storage and disposal.

Resources utilization. It is assumed that PWR fuel enriched to 4.3% and irradiated to 51 GWday/tHM is directly recycled into DUPIC fuel for further irradiation up to 14 GWday/tHM in CANDU reactor for total burnup of 64 GWday/tHM. If the thermal efficiencies of the PWR (34%) and CANDU reactor (32%) is taken into account, the mass of spent DUPIC fuel to be discharged from reactor is 16.70 tHM/GW(e)year. And the required natural uranium of DUPIC nuclear energy system is about 162.71 tHM/GW(e)year. This means that the DUPIC fuel cycle will save the natural uranium requirement per unit energy generated up to 20.5%.

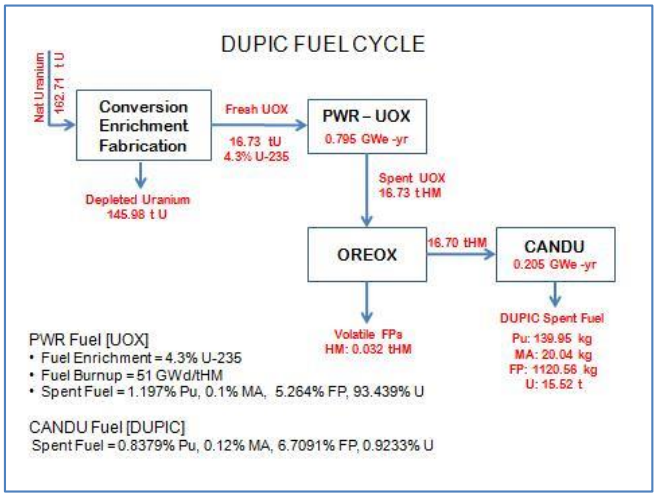

FIG. II-4. Mass balance of DUPIC fuel cycle
(all quantities are per GW(e)year).

Waste production. In balanced DUPIC fuel cycle, PWRs account for 79.5% of the nuclear installed capacity, while CANDU account for 20.5%. The mass of spent DUPIC fuel is about 16.70 tHM/GW(e)year. It is contain approximately 159.99 kg/GW(e)year of transuranic elements, 139.95 kg/GW(e)year of plutonium, 20.04 kg/GW(e)year of minor

actinides, and 1.12 t/GW(e)year of fission products. In this case the DUPIC fuel cycle could reduce the mass of spent fuel per unit energy generated up to 20.7%.

Proliferation risk. Because reprocessing of spent PWR fuel is not dissolved and none of fuel component are extracted other than volatile fission products, the DUPIC fuel cycle presents minimal proliferation risk. In addition, the mass of plutonium discharged per unit energy generated in irradiation DUPIC fuel is also lower than in once-through fuel cycle of PWR. The plutonium discharge is about 44.5% lower than for PWRs once-through fuel cycle at 51 GWday/tHM.

Fuel cycle cost. The fuel cycle cost of this DUPIC nuclear energy system, 79.5% PWR and 20.5% CANDU/PHWR, is about 6.648 mills/kW(e)h. This cost is higher up to 5% compared to the once through fuel cycle of PWR – UOX.

II-3.4. Synergistic fuel cycle of LWR – FR (Fig. II-5)

In this fuel cycle scheme, the spent fuels of PWR are to be reprocessed (advanced PUREX) to obtain TRU-bearing fuels for FRs, while the remaining uranium partitioned from the spent fuel of PWR would be disposed of as low- and intermediate-level radioactive waste. The TRUs fuel after burning in FR are repeatedly reprocessed through pyro-processing, and the recovered TRUs are recycled into an FR to close the fuel cycle.

Resources Utilization. Using mass balance equation can be obtained that the power derived from PWR-UOX is about 61.65% and the power derived from FR-TRUs fuel is 38.35%. The mass of fuel that needs to be irradiated for the production of 1 GW(e)year of electricity is 12.98 tons PWR - UOX fuel (enriched up to 4.3% ^{235}U) and 2.5 tons FR – Metallic TRUs fuel. The required natural uranium of this nuclear energy system is about 126.17 tons. The separative work unit for enrichment process is 75.84 tons SWU and depleted uranium is 113.2 tons. TRUs fuel fabrication requires 828.87 kg of TRUs, and 1.67 tons of depleted uranium. If compared to the once through fuel cycle, this nuclear energy system can save up to 38.4% of required natural uranium.

Waste production. The waste of this nuclear energy system come from reprocessing of PWR – UOX fuel (advanced PUREX) and reprocessing of FR – metallic TRUs fuel (pyro-processing). The waste discharge in HLW is 0.83 kg/GW(e)year of transuranic elements, 1.036 kg/GW(e)year of fission products, 12.13 tons of uranium, and 1.486 of depleted uranium. If compared to the once through fuel cycle, this nuclear energy system can reduce the TRUs content in the discharged HLW up to 99.7%.

Proliferation risk. The total mass of spent fuel reprocessed in this nuclear energy system is about 15.48 ton/GW(e)year. No separated plutonium is produced in this nuclear energy system, but a considerable amount of transuranics must be held in inventory between reprocessing and fuel fabrication. Assuming a storage time of 6 months, the working inventory is 414.44 kg. The quantity of transuranics going to waste is about 0.83 kg/GW(e)year. Assuming that 85% of this amount is plutonium, the plutonium discharge for this nuclear energy system is 0.706 kg/GW(e)year.

Fuel cycle cost. The fuel cycle cost of this synergistic PWR - FR nuclear energy system, 61.65% of PWR and 38.35% of FR, is about 7.699 mills/kW(e)h. This cost is higher up to 20% compared to the once through fuel cycle of PWR.

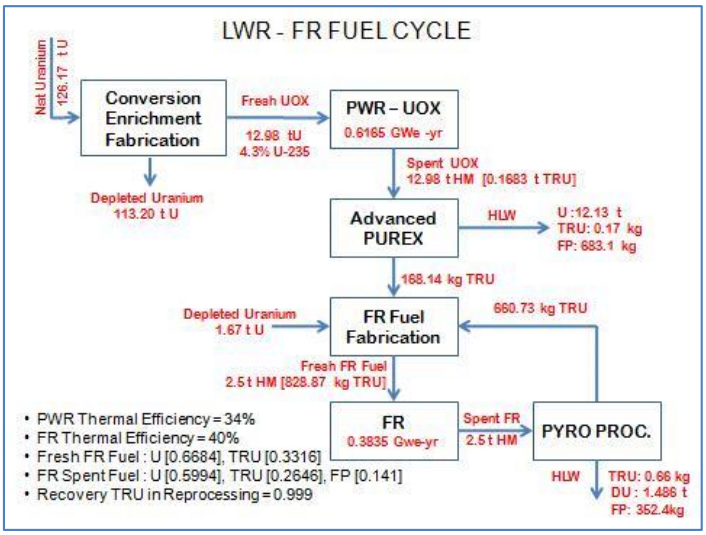

FIG. II-5: Mass balance of synergistic PWR - FR fuel cycle (all quantities are per GW(e)year).

II-3.5. Once through TH-U fuel cycle in PWR (Fig. II-6)

The natural abundance of thorium in comparison to uranium, its chemically inert nature, superior thermal conductivity of ThO_2 over UO_2 and advanced neutron characteristics make thorium based fuel cycles attractive. Thorium fuel may be utilized either in a once-through manner (also called an open fuel cycle), i.e. by producing ^{233}U in a fuel element and in parallel burning it up in the same element, or in a mode with spent fuel reprocessing, i.e. in a closed fuel cycle. Thorium and ^{233}U utilization is technically feasible in most existing and prospective reactor designs, including LWRs, HWRs, fast breeders (FBRs) and molten salt reactors.

The reactor core (PWR) for once through Th-U fuel is divided into two regions, i.e. the seed and the blanket. The seed contains fissile material (^{235}U or ^{239}Pu) and the blanket contains fertile material (^{232}Th). The different in-core fuel management scheme is used for the two regions. The blanket will remain in core for a long period of time, allowing significant breeding and in-situ burning of ^{233}U, while the seed will be replaced more frequent to maintain reactivity. In this study, the concept of whole assembly seed and blanket (WASB) is used. The WASB calls for two types of homogeneous assemblies, i.e. seed assembly containing only seed fuel pins, and blanket assembly containing only blanket fuel pins. WASB concept is based on a Westinghousen1150 MW(e) PWR. A positive feature of this WASB concept is fully compatible with the existing power plants.

In the WASB concept, the seed pins contain uranium oxide enriched to 20% ^{235}U, and the blanket pins contain 87% thorium oxide and 13% contain uranium oxide enriched to 10% ^{235}U. Under the proposed in-core fuel management scheme for WASB, one-third of the seed assemblies (7.703 tHM) are discharged and replaced every cycle, while the blanket (58.997 tHM) will be discharged and replaced only once every 9 cycles. The duration of a cycle is 18 months, over which reactor generated 1570 GW(e)year (the assumed capacity factor is 91%). Thus the discharge rate for the seed is 5.01 tHM/GW(e)year, and for the blanket is 4.26 tHM/GW(e)year.

Resources utilization. To generate energy of 1 GW(e)year, the seed needs about 4.91 tHM of uranium oxide enriched to 20% ^{235}U, and the blanket needs about 0.543 tHM of uranium oxide enriched to 10% ^{235}U. Thus to generate energy of 1 GW(e)year, the reactor needs about 247.74 tHM of natural uranium and about 3.622 tHM of thorium oxide.

Waste production. The composition of plutonium, transuranics, and fission product in the spent WASB seed fuel is 1.56 wt.%, 1.97 wt.%, and 14.5 wt.%; while in the spent WASB blanket fuel is 0.45 wt.%, 0.51 wt.%, and 8.8 wt.%. Thus the total mass of plutonium, transuranics, and fission products is 95.33 kg/GW(e)year, 117.95 kg/GW(e)year, and 1.078 t/GW(e)year. And the total spent fuel discharged is 9.085 tHM/GW(e)year. It shows that the transuranics and plutonium discharge rate for WASB are about 3 times lower than for a conventional once-through fuel cycle.

Proliferation risk. High proliferation resistance is the most important argument used in of seed and blanket proposals. The plutonium discharge for WASB is about 95.33 kg/GW(e)year compared with 251.96 kg/GW(e)year for conventional PWR at 51 GWday/tHM. Besides that, the plutonium from spent seed and blanket fuel is less attractive than the plutonium from conventional spent fuel because of its higher heat generation rate.

Fuel cycle cost. The fuel cycle cost of this nuclear energy system is about 8.054 mills/kW(e)h. This cost is higher up to 26.9% compared to the once through fuel cycle of PWR.

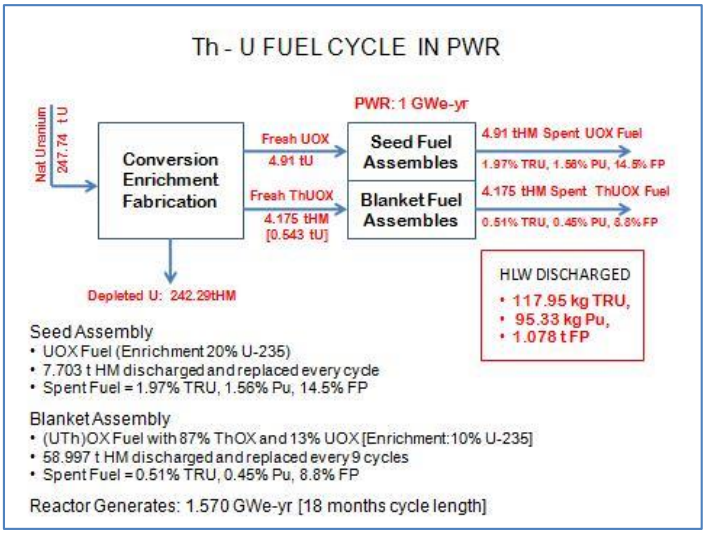

FIG. II-6. Mass balance of synergistic PWR - FR fuel cycle (all quantities are per GW(e)year).

II-4. COMPARATIVE ASSESSMENT

II-4.1. Resources utilization

PWRs on the once through UOX fuel cycle utilize uranium resources poorly compared with single pass plutonium recycling MOX fuel in PWRs, DUPIC cycle and PWR – FR nuclear energy system. While once through Th-U fuel cycle in PWR consumes uranium resources higher compared with other fuel cycle. The PWR – FR nuclear energy system most efficient utilize uranium resources compared the other fuel cycle. Due to the CANDU reactors in DUPIC cycle to have a better neutron economy compared with PWR reactors, the DUPIC cycle consumes fissile materials more efficient compared PWR. But DUPIC (and also PWR – FR) cycle until now is not yet available in commercial market (still under development).

Considering uranium utilization, it can be concluded until the mid-century (2050) the once through UOX fuel cycle in PWR is the most viable options to support NPP program in Indonesia in a sustainable manner. If uranium availability becomes a concern and significant uranium utilization are required, the implementation of single pass plutonium recycling MOX

fuel should be introduced. Proven technology to recycle plutonium in the spent UOX fuel is available in the commercial market now and may be much cheaper in the future.

It should be noted that uranium resources are sufficient to support the moderate deployment of NPP until the mid-century (according to the GAIN study). The significant reduction of natural uranium demand could be performed by incorporating fast reactors into the reactor mix; the reduction would correspond approximately to the percentage of fast reactors in the mix. Considering the current size of the depleted uranium stock, any fast reactors which could be constructed in this century would not depend on the availability of natural uranium.

II-4.2. Waste production

The impact of nuclear waste on the environment is difficult to evaluate. The long-term impact on the environment and the public from nuclear waste repositories is due to the radioactive isotopes that have the highest mobility in the geologic environment of the repository. In a general rule, the radiotoxicity of fission products is at least 2 orders of magnitude below that of the actinides after a few hundred years, but they are much more mobile. As a result, the dose to the public from a nuclear waste repository is dominated by fission products for the first million years or so after closure.

From the waste production point view, the synergistic PWR-FR scenario is the best choice among thefuel cycles considered. This fuel cycle dischargestransuranic elements and fission productsat a much lower rate per unit energy generated (electricity). The DUPIC cycle is expected to discharge more transuranic elements and fission products per unit energy generated due to extended burnup of UOX fuel in CANDU reactors. Although both the single-pass plutonium recycling MOX fuel and once-through cycle of U-Th are expected to have modest discharges of transuranic elements and fission products per unit energy generated, there is no clear advantage for fission product transmutation (i.e., no fuel cycle is clearly superior in minimizing fission product discharge rates).

The fission product discharge rate for synergistic PWR-FR fuel cycle is slightly lower than that of PWR-OTFC because the fast reactors contribute to increased thermal efficiency of the fleet. However, reductions in fission product discharge rates through increased thermal efficiency are limited because thermal efficiencies are not likely to go beyond 50%, which means that fission product discharge rates could be at best reduced by a factor of 1.5 as compared to current PWRs.

If commericial availability must be considered, the synergistic PWR-FR fuel cycle is the best option based on the rate of transuranic elements and fission products discharged per unit energy generated. This fuel cycle is also the best option if utilization of uranium resources is a strong consideration in the selection process. However, if residual uranium is not considered as a resource for future fast reactors, its long-term radiological impact has to be considered as an integral part of waste management,due to the fact that uranium decay products always dominate global radiotoxicity in the very long term.

Between thermal reactors, the use of once through Th-U fuel cycle in PWR is the best choice among others fuel cycle considered, from the waste production point view. This fuel cycle produce the much lower of transuranic elements and fission product per unit energy generated (electricity) due to the much lower of ^{238}U in the fresh fuel. The DUPIC cycle to have much higher transuranic elements and fission product discharged per unit energy generated. This is due to extended burnup of UOX fuel in CANDU reactors. The single pass plutonium recycling MOX fuel to have modest transuranic elements and fission product discharged per unit energy generated.

If commericial availability must be considered, the synergistic PWR-FR fuel cycle is the best option based on the rate of transuranic elements and fission products discharged per unit energy generated. This fuel cycle is also the best option if utilization of uranium

resources is a strong consideration in the selection process. However, if residual uranium is not considered as a resource for future fast reactors, its long-term radiological impact has to be considered as an integral part of waste management,due to the fact that uranium decay products always dominate global radiotoxicity in the very long term.

Decay heat is a major input for the design of underground repositories. HLW arising from advanced fuel cycle schemes generates considerably less heat than the spent fuel arising from the reference PWR once-through scheme. This lower thermal output of HLW allows a significant reduction in the total length of disposal galleries needed.

II-4.3. Proliferation risk

It should be noted that no nuclear fuel cycle is free from proliferation risk. However, the separation of plutonium from spent fuel is viewed as the most dangerous activity associated with commercial nuclear fuel cycles from aproliferation risk perspective. The single-pass plutonium recycling fuel cycle requires a plutonium working inventory of up to 219.27 kg/yearat any given time. To put in perspective, a 1000 MW(e) PWR would produce aquantity of plutonium sufficient to make about 22 nuclear weapons.

The plutonium discharge to the repository also raises proliferation concern. A PWR operating on the once-through fuel cycle sends 251.96 kg/GW(e)year of plutonium to the repository. This quantity is enormous compared to the 10 kg plutonium needed to make a weapon.

Fuel cycles such as single-pass plutonium recycling, and even the Radkowsky thorium reactor as a once-through cycle of U-Th fuel in a PWR, do not reduce the plutonium discharge rate by even a single order of magnitude. These fuel cycles cannot be said to offer a significant advantage in this regard. It should be noted that the evaluation metrics used in this study do not take into account the isotopic composition of plutonium. Generally, the plutonium discharged from high burnup fuels is less suitable for nuclear weapons because it contains more isotopes, in particular ^{238}Pu, a prolific neutron emitter and a significant decay heat source.

Fuel cycles involving multi-pass recycling of tranuranics (PWR-FR) would send only very small amounts of plutonium to the repository (< 1 kg/GW(e)year of TRU). The plutonium is thus extremely dilute in the HLW and extraction of a significant quantity would require processing large amount of radioactive waste, a difficult task for an illicit group. Furthermore, the isotopic composition of this plutonium is highly degraded due to the multiple high burnup irradiations. Hence, the proliferation risk associated with the repository is greatly reduced in such a fuel cycle. However, this must be weighed against the fact that these fuel cycles require actinide partitioning, thus producing proliferation risk in the short term.

The volume of HLW to dispose of is a driving factor to determine the total capacity of a given repository site. This volume is reduced significantly by closed fuel cycle schemes as compared with the reference PWR once-through scheme. Differences in heat load and waste volume may have a major impact on the detailed concept of the repositories.

II-4.4. Fuel cycle cost

Once-through fuel cycles that rely on conventional reactors (PWR with UOX fuel) present the lowest fuel cost. The DUPIC fuel cycle is also relatively attractive economically because it relies on the type of recycling process involved is projected to be less costly than aqueous reprocessing or pyro-processing. The price of natural uranium, which is an important factor in fuel cost for the reference cycle (once-through fuel cycle), has a moderate impact on fuel cycle cost for schemes involving reprocessing and recycling.

It should be noted that the fuel cost is small relative to the total cost of nuclear electricity generation. Fuel cycle costs range from 10 to 20 percent of total with waste

management accounting for only 1 to 5 percent of the total. While waste management costs vary significantly among strategies, their contribution to total generation costs is small enough to prevent it from being a major driving factor in decision making.

The fuel cost of a PWR-FR fuel strategy could be competitive with the once-through option of PWR if the price of uranium is high and if optimistic assumptions are made regarding the cost of reprocessing, FR fuel fabrication, and HLW disposal.

The lower spent fuel and plutonium discharge rates and degraded plutonium isotopic afforded by the use of thorium in PWRs are not rewarded under the current system of nuclear waste management. There is no incentive for NPP operators to incur the expenses associated with developing thorium fuels and refitting PWR cores to accommodate seed and blanket assemblies. The benefits from these fuel cycles are insufficient to change the prospects for nuclear energy considerably.

Fuel cycle cost is only a small fraction of total nuclear electricity generation cost. Nuclear power is a capital intensive technology and the investment cost – associated with building, refurbishing and eventually dismantling the reactor – exceeds by far the fuel cycle cost. Therefore, the impact of various fuel cycle schemes on the economics of nuclear electricity remains marginal under any set of assumptions.

Table II-3 provides summary of the numerical data used in comparative analysis.

TABLE II-3. SUMMARY OF ANALYSIS RESULTS (COMPARATIVE TABLE)

Fuel cycle metrics	**PWR OTFC**	**PWR Pu mono-recycle**	**DUPIC fuel cycle**	**PWR – FR fuel cycle**	**PWR Th-U fuel cycle**
Resources utilization : – Natural uranium consumption (tHM/GW(e)year)	204.66	178.34	162.71	126.17	247.74
Waste [HLW]: – TRU discharge (kgHM/GW(e)year) – FP discharge (kgHM/GW(e)year)	273.01 1108.05	182.61 1104.97	159.99 1120.56	0.83 1035.5	117.95 1078.0
Proliferation: – Pu discharge (kgHM/GW(e)year) – Separated Pu (kgHM/GW(e)year) – TRU discharge (kgHM/GW(e)year) – Reprocessing rate (tHM/GW(e)year)	251.96 - 273.01 -	149.65 219.27 182.61 18.34	139.95 - 159.99 (16.73)	NC *) - 0.83 15.48	95.33 - 117.95 -
Economic: – Fuel cost of NPP park (mill$/kWh)	6.347	8.481	6.648	7.699	8.054

*) NC: Not calculated

II-5. CONCLUDING REMARKS

While the deployment of an NPP operated on the once-through fuel cycle will not represent the most efficient use of uranium resources, this is not likely to become a concern before the middle of the 21st century. Furthermore, the once through fuel cycle does not require any reprocessing of spent fuel and therefore poses minimal proliferation risk. The greatest liability of the once through fuel cycle is that it sends large quantities of plutonium and minor actinides to the repository. It also can be argued that the repository presents a significant proliferation risk since it contains large amounts of plutonium.

The single pass recycling of plutonium in MOX fuel offers modestly-attractive uranium resources savings. Also, the waste production per unit energy generated is lower than waste production in the once-through UOX fuel cycle. However, this fuel cycle poses greater the proliferation risk due to working with inventories of separated plutonium. Coupled with fast reactors, this fuel cycle may become more attractive in the future.

The DUPIC fuel cycle is a plausible mid-century candidate as it offers attractive advances in waste management. The mass of spent fuel discharged by a PWR/PHWR nuclear park is 3 times lower in the DUPIC cycle. The most significant hurdle for DUPIC is the development of the OREOX process. It should be noted that DUPIC deployment will be limited to countries that have both PWRs and PHWRs.

Since reprocessing followed by multiple recycles and actinide burning (PWR-FR fuel cycle] reduces the volume and long term toxicity of nuclear wastes, it could be used in conjunction with other storage options to mitigate or defer capacity constraints. If compared to the once through fuel cycle, this nuclear energy system can reduce the TRUs content in the discharged HLW up to 99.7%, and can save up to 38.4% of required natural uranium. Pyro-processing separates actinides (uranium plus transuranics) from fission products present in spent fuel. The mixture of actinides produced results in an unusable form for weapons applications (low proliferation risk)

The use of Th-U in PWR with the seed blanket concept is attractive due to the lower spent fuel and plutonium discharge rates and degraded plutonium isotopic. However, this fuel cycle requires much more natural uranium than the once through UOX fuel cycle. The once through Th-U fuel cycle in PWR is only viable if there is no burden regarding uranium resources.

A central goal of sustainable development is to maintain or increase the overall assets (natural, man-made and human or social assets) available to future generations. The aim of advanced fuel cycles is to improve the sustainability of nuclear energy by enhancing the effectiveness of natural resource utilization and by reducing the volume and long-term radiotoxicity of high-level waste while the costs of energy products, for example electricity, stay economically viable.

Advanced fuel cycles address among others the problem of long-term radiotoxicity of HLW by burning the majority of the long-lived MA. Reducing the amount of actinides to be disposed of does not facilitate the short and medium term waste management issues, because the problem of the heat produced by the fission products remains as an important issue.

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