SAFETY ASPECTS OF RADIOACTIVE WASTE MANAGEMENT IN DIFFERENT NUCLEAR FUEL CYCLE POLICIES, A COMPARATIVE STUDY

A.A. Gad Allah

National Center for Nuclear Safety and Radiation Control,
Atomic Energy Authority, Nasr City-P.O. Box 7551, Cairo, Egypt,

ABSTRACT

With the increasing demand of energy worldwide, and due to the depletion of conventional natural energy resources, energy policies in many countries have been devoted to nuclear energy option. On the other hand, adopting a safe and reliable nuclear fuel cycle concept guarantees future nuclear energy sustainability is a vital request from environmental and economic point of views. The safety aspects of radioactive waste management in the nuclear fuel cycle is a topic of great importance relevant to public acceptance of nuclear energy and the development of nuclear technology. As a part of nuclear fuel cycle safety evaluation studies in the department of nuclear fuel cycle safety, National Center for Nuclear Safety and Radiation Control (NCNSRC), this study evaluates the radioactive waste management policies and radiological safety aspects of three different nuclear fuel cycle policies. The once-through fuel cycle (OT- fuel cycle) or the direct spent fuel disposal concept for both pressurized light water reactor (PWR) and pressurized heavy water reactor (PHWR or CANDU) systems and the "self-generated" or recycling fuel cycle concept in PWR have been considered in the assessment. The environmental radiological safety aspects of different nuclear fuel cycle options have been evaluated and discussed throughout the estimation of radioactive waste generated from spent fuel from these fuel cycle options. The decay heat stored in the spent fuel was estimated and a comparative safety study between the three fuel cycle policies has been implemented.

Key Words: Nuclear Fuel Cycles Safety/Nuclear waste management/Spent Fuel Management / Recycling Concepts /Nuclear Fuel Cycles Environmental Safety

1. Introduction

The nuclear fuel cycle (NFC), is a series of industrial processes which involve the production of nuclear fuel for nuclear reactors either for research or power generation (Fig.1).The development and improvement of safety aspects of radioactive waste management for nuclear fuel cycle policies in countries having nuclear power plants for electricity generation play an important role in the enhancement of nuclear technology and in the magnitude of public acceptance to nuclear power. To ensure the radiological safety of nuclear fuel cycle installations, basic safety objectives, concepts and principles are defined in situations which could potentially result in a release of radioactive material from its designated location with the consequent risk of radiation exposure to personnel. These safety objectives or principles include technical safety measures and administrative or procedural measures (radiation protection objectives).The technical safety aspects in conjunction with administrative and procedural safety measures ensure defense against hazards due to exposure to radiation. In order to achieve the previous safety objectives in the design and operation of a nuclear fuel cycle installation, comprehensive safety analyses should be carried out to identify all sources of exposure and to evaluate radiation doses that could be received by the public and by workers at the installation, as well as potential effects of radiation on the environment.

Among the different sources of exposure which could potentially result in a release of radioactive material are the nuclear or radioactive wastes arising during various processes of the nuclear fuel cycle. In the framework of the nuclear fuel cycle safety, radioactive wastes as well as the spent nuclear fuel are considered issues of special concern within the scope of nuclear fuel cycle safety analysis studies [1,2]. In the present study, types and volumes of radioactive wastes arising from water- cooled reactor NFC alternatives PWR-OT, PHWR-OT and PWR with MOX fuel, that having the same generating electrical capacity: 1.0 GWe(1000 MWe), have been assessed, evaluated and compared. Concerning the safety aspects, the study is focusing on the decay heat, activity, and radio-toxicity which could be a measure for the effectiveness of waste management and the environmental effect for various nuclear cycles. The decay heat and activity properties could be used for the design of transportation cask, interim storage, final disposal facility and their treatment systems.

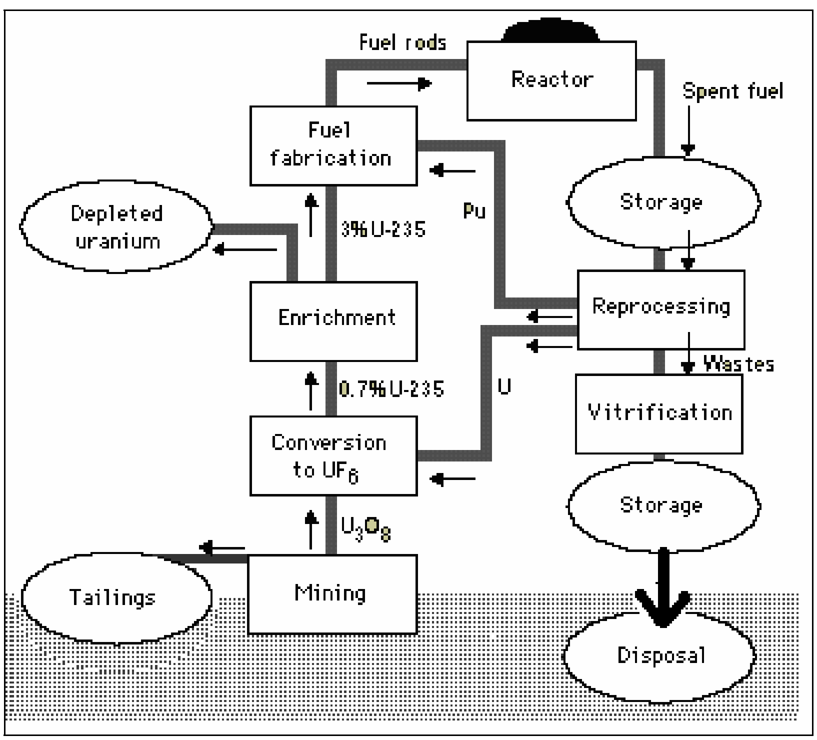

Fig 1. A generalized nuclear fuel cycle schematic

2. Calculation Procedure

2.1. Reference input data and assumptions

The reference PWR and PHWR reactor parameters are initially chosen, and their fuel cycle characteristics *(e.g.*, initial enrichment and discharge burn up) need to be defined. These inputs are used to estimate the material flow balance requirements for each fuel cycle throughout ENFCE code and radioactive wastes generated by applying ORIGEN2 codes [(2,3)]. For practical purposes, a reactor power of 1000 MWe (1 GWe), has been taken as reference reactor for both PWR and PHWR systems for the purpose of radioactive waste assessment. Also, It was assumed that LEU (Low Enriched Uranium) PWR fuels and mixed oxide (MOX) fuels were operating at a burn up values of 33,000 MWd/MTU and 8000 MWd/MTU for PHWR (nuclear fuel burn up unit is expressed in Mega Watt day per Metric Ton Uranium: MWd//MTU). Table (1) depicts the reference reactor systems and the characteristic parameters of each fuel cycle which are used as input data for determining each fuel cycle material balance and radioactive wastes generated. The calculation procedure flow diagram throughout ENFCE and ORIGEN2 codes, with inputs and output parameters is shown in Fig. (2).

Table (1): Reference reactors and NFC data

Reactor &NFC parameters	Reference Values	
Reactor type	PWR	PHWR
Electric power (MWe)	1000	1000
Thermal efficiency (%)	34	33
Thermal power (MWt)	2940	3030
Specific power (MWt/ton U)	40.2	25.5
Capacity factor (%)	80	90
Fuel Loading per core (MTU)	69.5	84.7
Burn up (MWd/MTU)	33000	8000
Initial fuel enrichment (%)	5.0	0.711

3. Results and Discussions

3.1. Radioactive wastes generated from the NFC front-end

To evaluate all radioactive wastes generated in various fuel cycles, they are firstly classified according to their activity level and half-life.The classification of radioactive wastes management programs are different from country to another. In this study, the radioactive wastes are classified into five categories, which can be handled, stored and disposed of differently. The first type is the spent fuel itself, which is discharged directly from the reactor and may be included in high-level waste class in some countries. The second type is the high-level waste (HLW), which is a stream of waste (liquid or solidified form) after reprocessing or dirty scrap and collective volatiles and semi volatiles during reprocessing plant operation. The third type is the intermediate-level waste (ILW) which is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and a total concentration of such radionuclides in excess of 0.1 Ci per metric ton of waste. The fourth one is low- level waste (LLW),

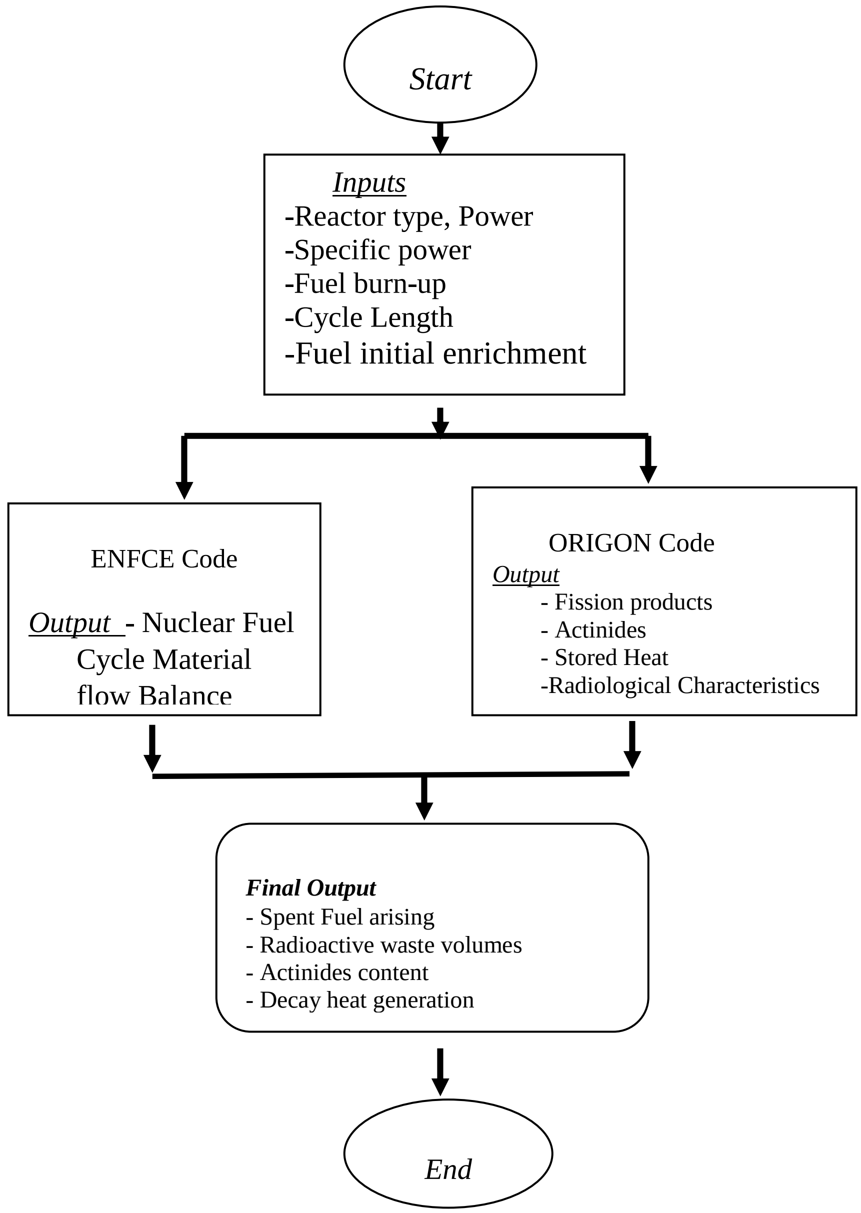

Fig.(2): Calculation procedure flow diagram

which is generated in all steps of the fuel cycles. The last one is mill tailings, which is ore residues from milling after uranium extraction [(1)].

In the beginning of nuclear fuel cycle processes, during mining and milling stage, uranium ore concentrate (U_3O_8) or yellow cake is extracted from the ore by chemical processing techniques.

The ore residues containing chemical effluents and waste rocks containing naturally occurring radioactive materials or NORM (particularly Ra isotopes and radon) are called mill tailings. They are normally stabilized and disposed of at or close to the mine of origin. As these wastes contain natural long-lived radio-nuclides, they must be disposed of in a way that affords long-term protection to personnel and the environment. During conversion, enrichment and fabrication stages, radioactive wastes are also generated. For example; there are scrap materials still containing uranium and enrichment tailings containing depleted uranium. During reactor operation, ILW/LLW are generated both as liquid and as solid. The liquid wastes are in the form of contaminated water from different parts of the reactor system and from the plant. Purification or concentration of this water gives rise to slurries that are mixed with cement or asphalt to form a stable waste form. Fig (3) shows the estimated material balance requirements for PWR and PHWR fuel cycle policies for a reactor power of 1000 MWe calculated by ENFCE computer programme [(2)].

During and after power reactor operations, radioactive waste remains in three sources. The first is fission products resulting from nuclear fission taken place in reactors. Typical long-life nuclide fragments with the highest radioactivity are ^{137}Cs,^{90}Sr, and their daughters. The second source is actinides which are uranium and transuranic (TRU) elements mainly neptunium, plutonium, americium and curium. The third source of radioactivity is activation products such as those resulting from neutron irradiation of structural material and impurities. The ORIGEN2 codes [(3)], has been used to estimate the fission products, radioactive wastes and radioisotope decay heat output of spent fuels in NFC options.

3.2. Radioactive wastes in the back-end of the NFC

3.2.1. Once –through NFC option (OT-or direct disposal option)

Inventories of spent fuel (SF) from nuclear power plants are growing. By the end of 2002, about 250, 000 -270,000 t HM of spent fuel had been discharged globally. Approximately 80,000-90,000 t HM of spent fuel had been sent to reprocessing. The remaining quantity of spent fuel (about 170,000 t HM) is currently in storage [(4,5)] . After a period of cooling ranges between 30 to 50 years, fuel assemblies may be encapsulated directly or be disassembled using remote handling techniques so that the fuel pins can be packed together more closely prior to encapsulation. The encapsulation process involves placing the spent fuel in a canister of metal, such as copper, steel or titanium, or of ceramic material. After that, the canister is tightened e.g. by welding a lid. Intermediate storage and encapsulation results in 0.2 m^3 of medium level radioactive waste per ton of uranium [(6-9)].

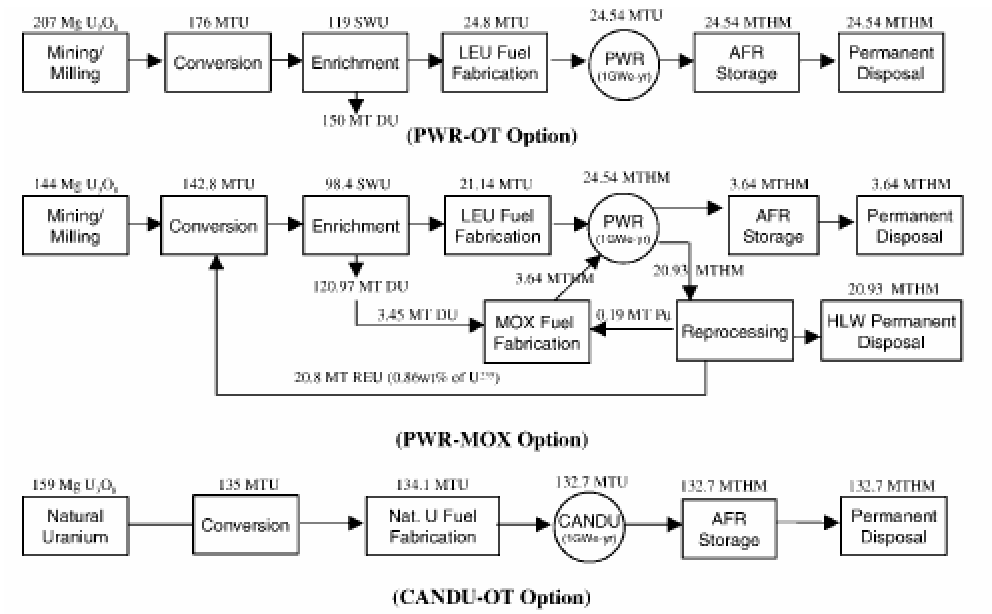

Fig (3): Material balance requirements for 1 GWe PWR and PHWR - NFC policies

When spent fuel is in pool storage or packaged in casks or canisters for dry storage, ILW and LLW are generated. Values of: 2 m^3/GWe.yr for LLW and 0.2 m^3/GWe.yr for ILW from spent PWR and MOX fuel storage and from their packaging process have been used. These values are equivalent to 0.077 m^3/MTHM for ILW and 0.008 m^3 /MTHM for LLW, from spent PWR and MOX fuels [(10)].

3.2.2. Reprocessing policy

In the PWR-MOX fuel cycle policy, the plutonium recovered from reprocessing of LEU spent PWR fuel is made into MOX fuel, which is re-burnet in a PWR and then the discharged spent MOX fuel is disposed of. Many radioactive elements of different intensities and half-lives are generated through the back-end nuclear fuel cycles. For example, during reprocessing, spent fuel is dissolved and uranium and plutonium are separated for recycling. The main waste product is the heat-generating high-level waste solutions containing the bulk amount of fission products from the spent fuel. Some of the reprocessing waste contains a substantial amount of long-lived nuclides and these will require the same degree of isolation from man's environment as spent fuel. ILW/LLW is also generated at a reprocessing plant [(11)].

The main waste products during reprocessing are the high level waste solutions containing most of fission products from the spent fuel, these wastes are vitrificated for final disposal. ILW/LLW is also generated at the reprocessing plant and these wastes are treated as solidified slurries in cement or asphalt, compacted waste, incinerated ash or packaged solid waste. After reprocessing the liquid high-level waste can be calcined (heated strongly) to produce a dry powder which is incorporated into borosilicate (Pyrex) glass to immobilize the waste. The glass is then poured into stainless steel canisters, each holding 400 kg of glass. The radioactive wastes from a 1000 MWe reactor is contained in 5 tones of such glass, or about 12 canisters 1.3 meters high and 0.4 meters in diameter (12). These can be readily transported and stored, with appropriate shielding. Approximate nuclear wastes volumes arising from different operating reprocessing facilities in Europe and Japan are shown in Table (2).

Table (2): Nuclear Waste volumes arising from reprocessing facilities(12)

Waste Types	Waste volume in m^3/GWe.yr		
	LLW	**ILW**	**HLW**
Range of waste volumes arising	70-95	20-45	2-4

For the estimation of LLW and ILW volumes, reference values of 0.008 m^3/MTHM and 0.2m^3/MTHM are used, while the volumes of spent fuel and HLW to be disposed of, are assumed to be 1.5 m^3/MTHM and 0.115 m^3/MTHM, respectively (13). In a geological repository, the heat generated by the disposed spent fuel and HLW will determine the actual space that the waste occupies and is not considered here. The PWR-MOX fuel cycle has the smallest mill tailings which is ~30% lower than that for the PWR-OT fuel cycle. The estimated total waste volumes arising from all stages of nuclear fuel cycle policies are estimated from the unit volumes are documented in Table (3). The different types of wastes are expressed in terms of m^3/GWe-yr.

Table (3): Types and quantities of radwastes for NFC options in m^3/GWe.yr

Fuel Cycle Concept	Waste Type				
	Tailings	**LLW**	**ILW**	**HLW**	**SF**
PWR-OT	**52.57**	**522**	**33**	**-**	**37**
PHWR-OT	**40.4**	**580.5**	**69.5**	**-**	**200**
PWR-MOX	**36.6**	**557.5**	**68**	**5**	**5**

In practice, there are large uncertainties in the waste volumes. For example, the radwaste volumes arising depend strongly on the prevailing country's environmental regulations: i.e. more stringent regulations may result in larger waste volumes during routine operations. Also, if one is willing to spend more money, one can further reduce or compact the waste volumes. In spite of all these uncertainties, our comparison should still be meaningful, because it is quite probable that factors would affect all waste volumes in similar ways. When regulations are tight, all waste volumes are likely to take higher values, regardless of fuel cycle option and of fuel cycle steps [(13)]. The wastes volume generated per GWe.year from reprocessing, storage, conditioning (including vitrification in case of HLW) and disposal have been assessed using five different references values. Approximate ranges of 2.7-3.7 m^3/MTHM for LLW, 0.77-1.73 m^3/MTHM for ILW, and 0.08-0.15 m^3/MTHM for HLW respectively, have been adopted [(14)].

As shown from Table (3), the PWR-MOX fuel cycle has the smallest mill tailings which is ~30% lower than that for the PWR-OT fuel cycle. Also, the PWR-MOX option has the highest ILW volume among the options, mainly due to the wastes generated in the reprocessing plant. The ILW of PWR-OT option is the lowest, however HLW is generated in the reprocessing plant for the PWR-MOX option. The volume of the waste of HLW and spent fuel is not a critical measure for waste disposal. The decay heat and the resulting disposal area are dominant factors to control the efficiency for overall waste management

3.3. Radiological safety considerations

3.3.1. Decay heat generation from spent fuel

Heat generation by decay of radionuclides is a significant characteristic mainly restricted to highly radioactive wastes from nuclear energy production. For most of the quantitatively dominating radioisotopes, it declines relatively fast, facilitating the waste management after some decades already. For the final disposal of the waste, however, the ongoing heat production may cause long-term problems due to the potential influence on the host rock properties that have to be evaluated carefully. The heat generated by radioactivity decay in a sealed waste repository will raise rock temperatures to a maximum from a few decades to about 300 years after repository closure and then gradually releases subside. This decay heat affects disposal waste spacing and then disposal cost. In fact, a very long-term decay heat is not important for repository. It depends on the spacing of canisters in the repository, and the thermal conductivity of the host rock [(15)].

To quantify the environmental safety effect of the waste management policy in a given nuclear fuel cycle such as storage and disposal of spent fuels, the decay heat generated in wastes should be measured on both short and long term basis. Generally, for low level wastes, the key cost driver is the waste volume but the key cost driver in spent fuels and high level wastes (HLW) is the decay heat. The decay heat generally affects dry storage or disposal waste spacing. This spacing is important in disposal process, because it affects the number of spent fuel canisters that can be placed in the repository of a given size and thus the disposal cost [(16,17)].

Table (4) shows a comparison of the decay heat output (in terms of Watt per Metric Ton of spent fuel: W/MTSF) of radioisotopes contained in spent fuel after 50 and 300 years of cooling time for direct disposal and reprocessing options as derived from ORIGEN2 computer code calculations. The first column lists the decay heat generated by seven isotopes that are producing almost all of heat in the fuel cycles. As can be seen from the table, the decay heat of MOX spent fuel is the highest at both 50 years and 300 years. It could be seen also that, at 50 years of cooling time, the decay heat of the PWR spent fuels is governed by ^{90}Sr and ^{137}Cs. On the other hand, the decay heat of the MOX spent fuel is governed by ^{241}Am. The decay heat of PWR-OT spent fuel option is 20 % ~ 35 % of the decay heat of the PWR-MOX spent fuel. The main difference between the two spent fuels is the decrease of fission products (^{90}Sr and ^{137}Cs). Also, it could be depicted that, for 50 year to 300 year, the PWR-MOX option has the total highest decay heat output during the first 300 years than other cases, while the CANDU-OT fuel cycle option has the total lowest decay heat output. Quantitatively, the PWR-MOX option has about 3 and 15 times higher decay heat output compared to the PWR-OT and CANDU-OT fuel cycle options respectively after 50 years of storage and twice these values after 300 years.

Table (4): Decay heat output of radioisotopes in spent fuels (W/MTSF)

FC-option	**PWR Spent Fuel**		**CANDU Spent Fuel**		**MOX Spent Fuel**	
Years/ Isotope	**50**	**300**	**50**	**300**	**50**	**300**
^{90}Sr*	**160**	**0**	**34**	**0**	**74**	**0**
^{137}Cs*	**166**	**1**	**37**	**0**	**168**	**1**
^{238}Pu	**64**	**9**	**1**	**0**	**387**	**56**
^{239} Pu	**10**	**10**	**5**	**5**	**15**	**15**
^{240} Pu	**16**	**15**	**7**	**7**	**47**	**46**
^{241}Am	**123**	**91**	**21**	**16**	**647**	**476**
^{242}Cm	**11**	**0**	**0**	**0**	**165**	**0**
Residue	**4**	**1**	**0**	**0**	**23**	**12**
Total	**555**	**128**	**106**	**29**	**1526**	**606**

* Included daughter products

4. Conclusion

This study estimates and compares wastes generated from water-cooled reactors NFC alternatives: PWR-OT, PWR with MOX fuel and PHWR-OT (CANDU) concepts that generates the same amount of electricity. The different types of wastes are expressed in terms of m^3/GWe-yr. It was found that the PWR-MOX option has the lowest tailings and spent fuel volumes among the options, but the option has high volume of intermediate level waste (ILW) and high-level waste (HLW). PWR-OT option has the lowest LLW and ILW volume among the options, but has high mill tailings and spent fuel volume. The radwaste volumes obtained in this study could be helpful for assessment of environmental effect and waste management cost in various fuel cycle alternatives. Concerning the safety aspects, the study is focusing on the decay heat, activity, and radio-toxicity which could be a measure for the effectiveness of waste management and the environmental effect for various nuclear cycles. The decay heat and activity properties are essential safety factors for the design of transportation cask, interim storage, final disposal facility and their treatment systems.

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