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Material Flows of Several Nuclear Fuel Cycles

Fanxing Gao, Won Il Ko*, Sung Ki Kim
Korea Atomic Energy Research Institute
1045 Daedeokdaero, Yuseung-gu, Daejon 305-353, Republic of Korea
**Corresponding author : nwiko@kaeri.re.kr*

1. Introduction

Nuclear power is a promising solution to meet the increasing energy demand by offering cheap and reliable energy meanwhile, especially, eliminating the CO_2 emit. A complete and well-organized nuclear fuel cycle system is the basis for sustainable power generation. In general, a typical nuclear fuel cycle system consists of a number of components from mining to geological disposal. Some components may have several variants, e.g., fuels, enrichment, reactors, back-end treatment, etc. Therefore, theoretically, by a flexible combination of selected components, it is possible to form various fuel cycle alternatives, and therefrom, it is critical to carry out a comparative analysis to answer such a seemingly simple question: which option is better?

Almost all the countries planning nuclear power have performed systematical studies, so there are numerous reference materials [1][2][3][4][5]. However, the key concerns, e.g., the objectives, the technology readiness, social acceptance, and politics, are different from country to country, so an indiscriminate study should therefore be avoided. Hence, an equilibrium model was selected to perform a general study which focused on a batch study [6] [7][8][9][10].

Material flow is the basis of nuclear fuel cycle system analysis which provides important information, e.g., uranium consumption, waste generation, actinide inventory, etc. Uranium consumption has a close relationship with resource security and affects nuclear fuel cycle cost, and then, finally affects the nuclear power sustainability [8][9][10]. Waste generation indicates the burden on waste management that is a main constraint limits the nuclear development from environment point of view. This paper evaluates the material flows quantitatively, mainly focusing on resource utilization and waste generation.

2. Methods

2.1 Model Setup

One is equilibrium model and the other is dynamic model. Equilibrium model focus on the batch study with the assumptions that the whole system is in a steady state and mass flow as well as the electricity production all through the fuel cycle is in equilibrium state, which calculates the electricity production within a certain period and associated material flow to obtain several criteria for assessment of the sustainability of nuclear power, e.g., resource utilization, waste generation, environment affects. Dynamic model takes the time factor into consideration to simulate the actual cases. Compared with the dynamic analysis model, the outcome of equilibrium model is more theoretical which may offer relatively clear and direct comparisons, especially with regard to the large uncertainty of the development of the pyro-technology evaluated. In this study equilibrium model was built to calculate the material flow on a batch basis.

2.2 Fuel Cycle Cost

In this work, seven main types of options have been evaluated as shown in Fig. 1.

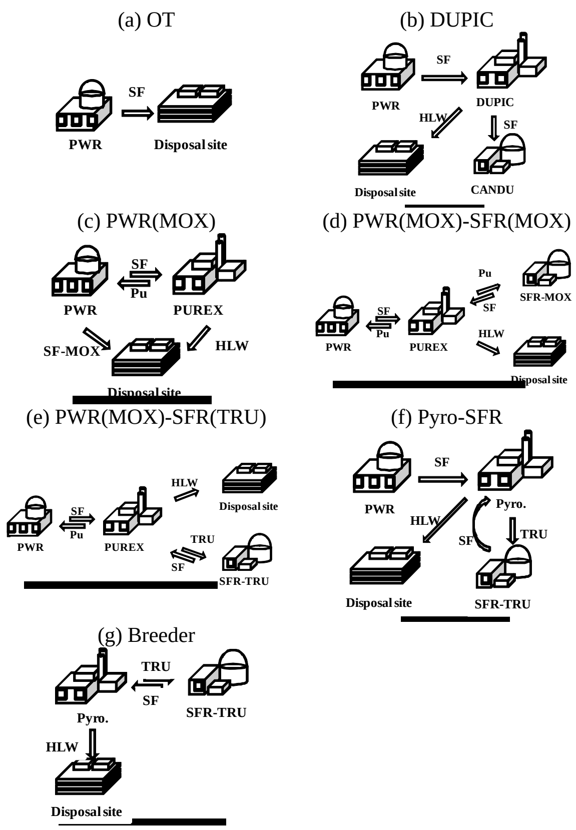

Fig.1 Schematic description of fuel cycle options

3. Results and Discussion

Table 1 summarizes a quantitative comparison of uranium utilization and waste generation based on OT. Setting the OT Cycle as a basis, for the DUPIC Recycling, it burns 92% of the uranium needed by OT to produce 1 TWh of the electricity, by introducing 155% of LILW-SL, 155% of LILW-LL, and 120% of HLW. In the PWR(MOX) case, it produces 124% of LILW-SL, 178% of LILW-LL, and 21% of HLW, by using 87% of uranium. On the whole, SFR-involved recycling shows clear advantages in controlling radioactive waste generation as well as uranium consumption, particularly with higher CRs.

Table 1 Resource and waste generation compared with OT

	Uranium	HLW	Spent fuel	Pu	Excavation volume
OT	100.0%	100.0%	100.0%	100.0%	100.0%
DUPIC	91.8%	120.4%	116.8%	73.0%	53.7%
PWR(MOX)	86.6%	20.8%	13.4%	61.6%	89.8%
Pyro-SFR(0.36)	82.2%	1.9%	0.0%	0.1%	13.5%
Pyro-SFR(0.71)	59.9%	1.7%	0.0%	0.3%	31.2%
Pyro-SFR(1.00)	8.6%	1.2%	0.0%	0.5%	72.1%
PWR(MOX)-SFR(MOX,0.35)	71.9%	7.6%	0.0%	0.2%	58.1%
PWR(MOX)-SFR(MOX,0.7)	69.7%	7.4%	0.0%	0.3%	54.2%
PWR(MOX)-SFR(MOX,1.00)	54.8%	5.8%	0.0%	0.3%	52.1%
PWR(MOX)-SFR(TRU,0.35)	77.8%	7.0%	0.0%	0.3%	50.3%
PWR(MOX)-SFR(TRU,0.7)	71.5%	7.0%	0.0%	0.3%	48.5%
PWR(MOX)-SFR(TRU,1.0)	48.9%	6.0%	0.0%	0.4%	41.8%
Breeder (1.2)	0.8%	2.3%	0.0%	0.8%	28.4%

4. Conclusions

Material flows of thirteen fuel cycle options, covering three reactors and two reprocessing techniques, were quantitatively investigated employing an idealized equilibrium model, mainly focusing on the consumption of uranium resources and waste generation.

Setting the OT Cycle as a basis, several key data were derived for a comprehensive comparison, e.g., spent fuel inventory, waste generation (i.e. LILW-SL, LILW-LL, HLW), Pu inventory, and excavation volume of underground repository. On the whole, SFR-involved recycling options shown clear advantages in reducing the generation of radioactive waste as well as controlling the consumption of uranium, particularly with higher CRs, i.e., Pyro-SFR(1.00) option burned 8.6% of the uranium needed by OT to produce 1 TWh of electricity by introducing 54.2% of LILW-SL, 26.0% of LILW-LL, 1.2% of HLW and no spent fuel inventory with a requirement of 72.1% of the excavation volume.

However, with regard to the status of the selected options, the development of SFR, the R&D concerning the pyroprocessing, and the deployment of underground repository, inevitably affect the realization of the promising advantages of Pyro-SFR Recycling. Continuous effort is therefore still intensely needed. Moreover, it should be notified, other factors besides resource utilization and wastes generation, e.g., economic analyses, proliferation resistance assessments, and technology availability, also play considerably important role in comprehensive analysis of various nuclear fuel cycles, so based on the findings of this study, further studies concerning other key factors would be performed to pursue a promising fuel cycle strategy for a nuclear power sustainability.

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