Technical Meeting on Back End of the Fuel Cycle
Considerations for Small Modular Reactors

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Direct Recycling of SMR Spent Fuel for Uranium Utilization Improvement and Reduction of High Level Nuclear Waste

Nader M. A. Mohamed

Reactors Department, Egyptian Atomic Energy Authority, Egypt

Introduction

- Due to their flexible designs, Small Modular Reactors (SMRs) promise flexible power generation for a wide range of users and applications.

- SMRs designs are ranged from down scales of exciting reactors to generation IV reactors.

- Around 70 SMR projects have been identified by the IAEA, the majority of these reactors are in the development stage.

- SMRs in the type of LWRs are potentially deployed in the near term.

- Because of its small core volume, SMR cores have higher neutron leakage than that of the large scale reactors. It follows that, SMRs will discharge the spent fuel with higher residual of the fissile materials which would:

1. Degrade the uranium utilization,
2. Increase the high level nuclear waste and
3. Enhance the quality of plutonium which decrease the proliferation resistance.

Recycling of spent fuel

1. Chemical reprocessing

- The extraction of the fissile isotopes from the spent fuel through the chemical reprocessing and recycling them in the reactors was proposed early when the commercial power plants were built.

- Since three or four decades, some countries like USA stopped reprocessing as a political consideration of weapons proliferation.

- Also, chemical reprocessing has not important impact on reducing the high level waste.

Recycling of spent fuel (cont.)

2. Dry processing

- The alternative recycling process is direct use of the spent fuel by dry processing technique.
- Direct Use of Spent PWR Fuel In CANDU Reactors (DUPIC) which is originally proposed in Korea is an example of dry processing.
- The general method of DUPIC is re-fabricating the PWR spent fuel for CANDU bundles.
- An addition fuel burnup of around 12 GWd/t can be obtained of recycling a typical Westinghouse PWR spent fuel in CANDU-6 reactor.
- The complex DUPIC processing facility and the transportation of highly radioactive materials from the PWR to this facility and from this facility to the CANDU reactor makes the estimation of the economics of DUPIC cycle difficult.
- However, recycling the spent fuel from the PWR-SMR makes the DUPIC cycle more attractive because of the high residual fissile material in the spent fuel.

Case Study

- As a case study recycling of the spent fuel of NuScale SMR in CANDU-6 reactor was investigated.

- The NuScale Power Module™ (NPM) is a small pressurized-water reactor with thermal power of 200 MWth and electrical power of 60 MWe.

- The core configuration of the NPM consists of 37 fuel assemblies with effective length of 200 cm.

- The fuel assembly design is modelled from a standard 17 x 17 PWR fuel assembly with 24 guide tube locations for control rod and a central instrument tube.

- The equilibrium loading consists of assemblies with 4.05 % and 4.55 % enriched U-235, the latter contains Gd_2O_3 in 16 rods in the fuel assembly.

- The core cycle is 24 calendar month and discharge the spent fuel with average burnup of around 40 GWd/t.

NPM vs. Typical PWR

Parameter	NuScale Power Module™ (NPM)	Typical “Parent” PWR
Thermal power (MWth)	200	3411
Electrical power (MWe)	60	1150
Fuel assembly	Standard 17 x 17 PWR	Standard 17 x 17 PWR
Assembly length (cm)	200	366
Number of assemblies	37	193
Fuel Enrichment (% U-235)	< 5	<5
Burnable poisons	Gd_2O_3 in some assemblies	IFBA (boron)
Core cycle (month)	24	18
Burnup (GWd/t)	40.4	51.7
Reflector	Heavy (stainless steel)	Light water

Simulation

- MCNPX computational code based on the ENDF/B-VII was used in the calculations.

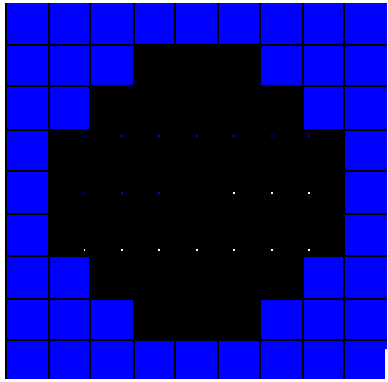
- In order to evaluate the leakage effect, the infinite and effective multiplication factors of the standard and NPM reactors are calculated. In the calculations, the enrichment was adjusted such that the effective multiplication factor of the standard PWR is around unity.

- In the burnup calculations, the lattice cell of the standard and NPM poisons-free and poisoned fuel assemblies were modeled.

- A criticality calculation (KCODE calculations) with the BURN cards is used to calculate the system criticality and the burnup of the fuel and fuel inventory after each time interval (defined in the BURN cards).

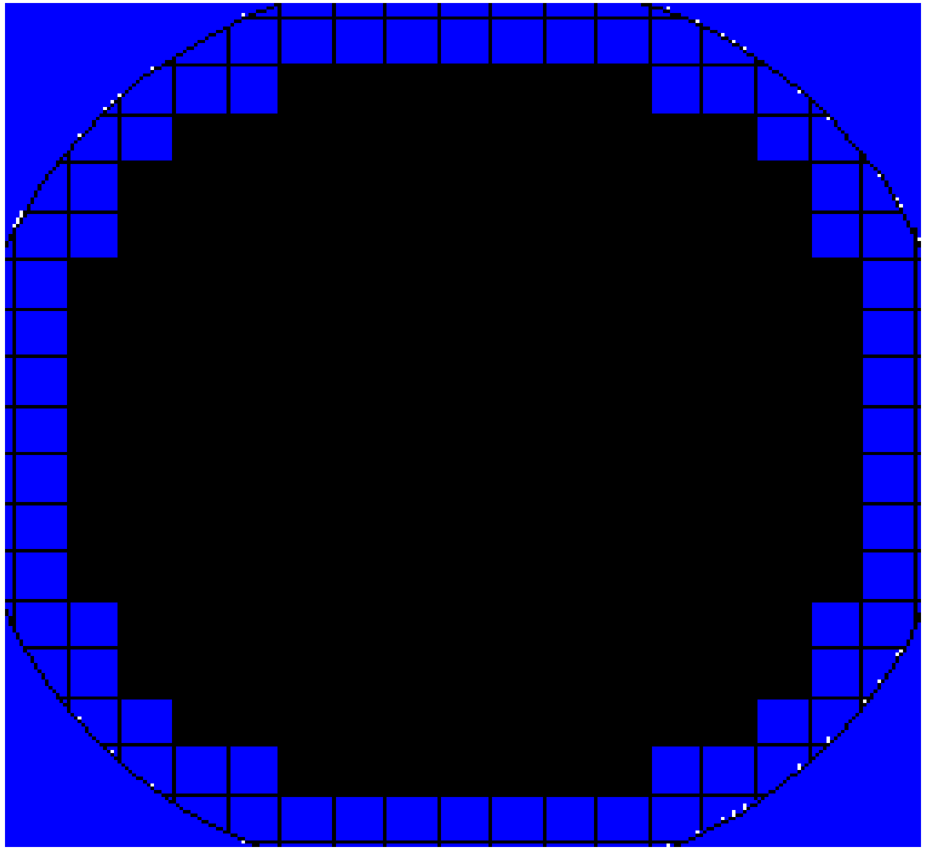
Leakage effect

NPM: 37 assemblies Assembly length =200 cm
Reflected by stainless steel



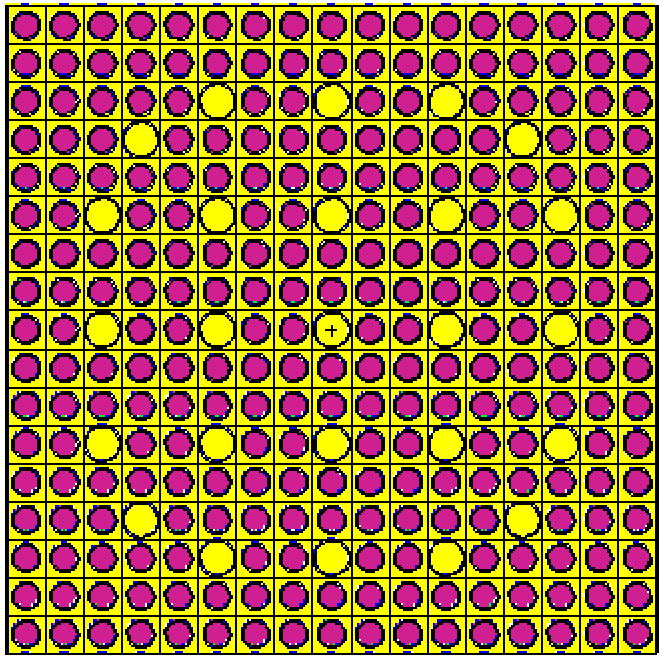
Calculated leakage	
NPM	Typical PWR
~ 6 %k	~ 2 %k

Typical PWR: 193 assemblies
Assembly length = 366 cm
Reflected by light water

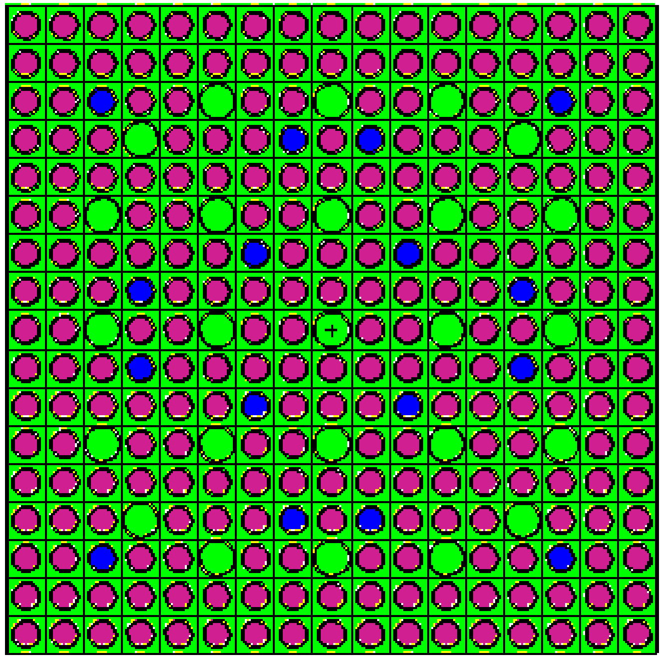


MCNPX lattice model of NPM

Poisons-free assembly

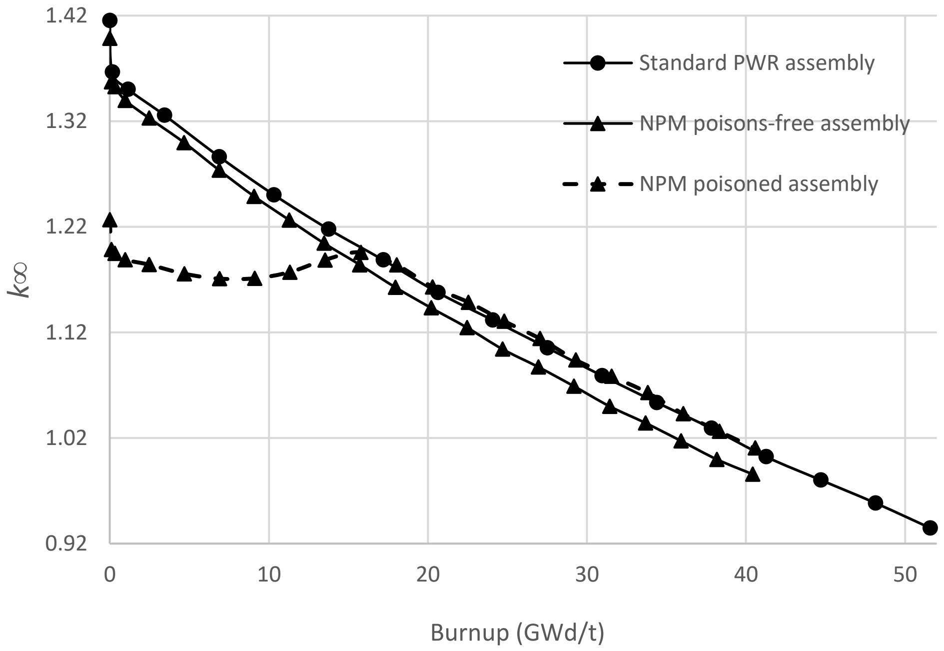


Poisoned assembly



Burnup

- The standard and NPM reactors employ three batch core fuel strategy.
- At the fuel discharge, the infinite multiplication factors are 0.9348, 0.98566, and 1.01049 for the standard and the NPM poisons-free and poisoned fuel lattice cells, respectively



Depletion histories of the standard and the NPM fuels

Residual fissile materials

The differences between the standard fuel assembly reactivity and that of NPM at the discharge is due to the higher residual amounts of the fissile materials in the NPM which would compensate the higher leakage of the NPM core.

Main Fissile nuclides concentrations (a/b-cm) in the fuel at the loading and at the discharge

Nuclide	At loading			At discharge		
	Standard	NPM poisons-free	NPM poisoned	Standard	NPM poisons-free	NPM poisoned
U-235	0.001048	0.000943	0.001055	0.0001789	0.0002274	0.0003025
Pu-239	-	-	-	0.0001279	0.0001243	0.0001311
Pu-241	-	-	-	0.0000376	0.0000314	0.0000318
Total	0.001048	0.000943	0.001055	0.0003444	0.0003831	0.0004654

Direct recycling

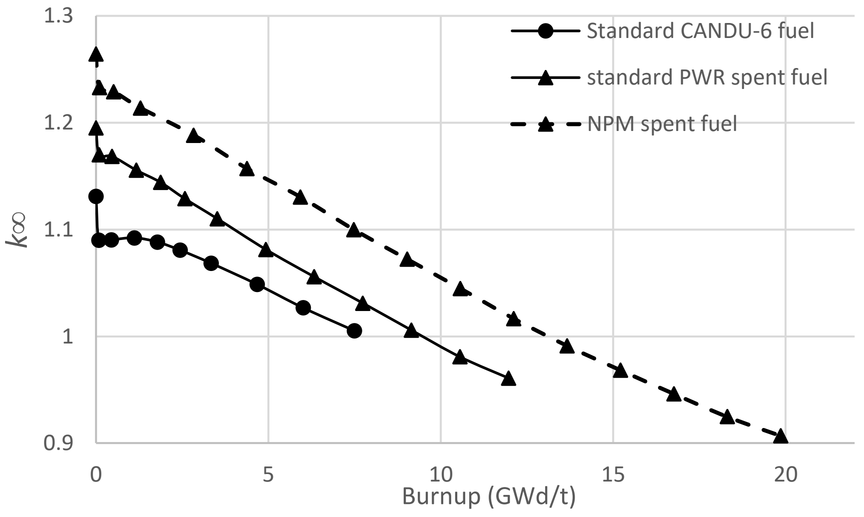
- In recycling of NPM spent fuel in CANDU-6 reactor, it was assumed:

1. Three-fourth of the fuel is that originally poisons-free (4.05 % U-235) and one-fourth was originally poisoned with Gd_2O_3 with enrichment of 4.55 % U-235.
2. The standard PWR fuel is recycled in the standard CANDU-6 fuel bundle while NPM fuel is recycled in the CANFLEX fuel bundle that can withstand higher fuel burnup.
3. One year of cooling time.

- The material inventories of the standard PWR and NPM spent fuel were input in the CANDU-6 standard and CAFLEX fuel bundles, respectively for the lattice cells calculations.

Burnup of recycled fuel

- The equilibrium CANDU core contains fuel with different burnups: from fresh to exit-burnup since it is fueled on-power. Therefore, the lattice cell infinite reactivity, ρ_∞ can be calculated from:
- $\rho_\infty = \dfrac{\int_0^{\text{exit}} \rho_\infty(B)dB}{B_{\text{exit}}}$
- Where, $\rho_\infty(B)$ is the lattice cell infinite reactivity at burnup B and B_{exit} is the burnup at the discharge. CANDU-6 discharges the fuel at about 7.5 GWd/t, Using Eq. 1 and the figure, ρ_∞ was calculated for the CANDU-6.



Depletion histories of the standard CANDU-6 fuel and the standard PWR and NPM spent fuels.

In order to find the discharge burnup of the recycled fuel, the integration of Eq. 1 was carried out over the burnup until ρ_∞ decreases to that of CANDU-6.

Burnup of recycled fuel (cont.)

- The standard PWR is loaded with 4.5% U-235 and discharges the spent fuel with burnup of 51.6 GWd/t and if it is recycled in CANDU-6, the spent fuel will be burnt to 12 GWd/t and the total burnup will be 63.6 GWd/t with an increase of around 23%.

- In the case of NPM, the fuel has average enrichment of 4.175 % U-235 and discharges it with burnup of 40.4 GWd/t. If the NPM spent fuel is recycled in CANDU-6, it will give additional burnup of 20 GWd/t and the total burnup will be 60.4 GWd/t with an increase of around 50%.

- Also, the high level nuclear waste will be reduced by the same percentage i.e 23% and 50% reduction of the nuclear waste of the standard PWR and NPM reactors, respectively.

Summary of calculation results

Reactor type	Average Enrichment (% U-235)	Total burnup (GWd/t)		% increase of burnup and reduction in the nuclear waste
		Without recycling	With recycling	
Standard PWR	4.5	51.6	63.6	23
NPM	4.175	40.4	60.4	50

Thank you for your attention