Analysis of the ATW Fuel Cycle Using the REBUS-3 Code System*

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Partitioning and transmutation strategies are under study in several countries as a means of reducing the long-term hazards of spent fuel and other high-level nuclear waste. Various reactor and accelerator-driven system concepts have been proposed to transmute the long-lived radioactive nuclei of waste into stable or short-lived species. Among these concepts, the accelerator-driven transmutation of waste (ATW) system[1] has been proposed by LANL for rapid destruction of transuranic actinides and long-lived fission products (^{99}Tc and ^{129}I). The current reference ATW concept employs a subcritical, liquid metal cooled, fast-spectrum nuclear subsystem. Because the discharged fuel is recycled, analysis of ATW nuclear performance requires modeling of the external cycle as well as the in-core fuel management.

The fuel cycle analysis of ATW can be performed rigorously using Monte Carlo calculations coupled with detailed depletion calculations.[2] However, the inefficiency of this approach makes it impractical, particularly in view of (a) the large number of fuel cycle calculations needed for design optimization and (b) the need to represent complex in-core and out-of-core fuel cycle operations. To meet the need for design-oriented capabilities, tools previously developed for fast reactor calculations are being adapted for application to ATW. Here we describe the extension and application of the REBUS-3 code[3] to ATW fuel cycle analysis. This code has been extensively used for advanced liquid metal reactor design and analysis and validated against EBR-II irradiation data.

REBUS-3 is a system of programs designed for the analysis of fast reactor fuel cycles. Two basic types of analysis problems are solved: 1) the equilibrium conditions of a reactor operating under a periodically repeating fuel management scheme, and 2) the explicit cycle-by-cycle operation of a reactor under a specified periodic or non-periodic fuel management program. Reprocessing may be included in the specification of the external cycle, and discharged fuel may be recycled back into the reactor. The neutronics solution may be obtained in three spatial dimensions for Cartesian and hexagonal geometries using finite difference[4] or nodal[5] diffusion theory methods or the variational nodal transport method[6]. Search options for fresh fuel enrichment, control poison density, or reactor burn cycle time are available in REBUS-3, allowing the user to achieve a specified multiplication factor or discharge burnup without time consuming (trial and error) repetitions of the analysis.

The REBUS-3 code has recently been modified so that the existing analysis capabilities for critical reactors can be applied to accelerator-driven systems such as ATW. This was achieved by adding capabilities of constant power depletion and charged fuel enrichment search for a fixed source problem. The fuel depletion calculation can now be performed at a specified power level by scaling the independent source intensity to compensate the reactivity and source multiplication variations during an irradiation cycle. The new enrichment search capability automates the adjustment of the transuranic loading in the fresh fuel such that a specified multiplication factor is achieved for a fixed source problem at a specified point during the burn cycle.

Several verification tests have been performed to confirm the operation of the new capabilities for source-driven systems. Analyses to date have focused on 2000 and 840 MWth ATW concepts. The 2000 MWth system is similar to that described in Reference 1. Lead-bismuth eutectic is used as both the spallation target and system coolant. The target region is 55 cm high and 25 cm in radius, and is surrounded by a 15-cm thick LBE buffer. The adjacent fueled region is ~65 cm thick and 200 cm high. The 840 MWth system, which is more amenable to modularization, was obtained by a simple scale-down of the 2000 MWth system geometry. Both systems employ the metal alloy fuel composed of zirconium, transuranics (TRU), and ^{99}Tc. The flux calculations were performed with R-Z models using the finite difference diffusion theory option. The region-dependent 33-group cross sections were generated using the MC^2-2 code[7] based on ENDF/B-VI data. Fixed source calculations were performed using the spallation neutron source distribution obtained from LAHET[8] calculations. The depletion calculation utilizes burnup chains for nuclides ranging from U-234 to Cm-246. The cycle length was fixed at 100 days, and three-batch out-in refueling scheme was employed.

Core performance was evaluated for two fuel cycle scenarios. The first represents early operating cycles and employs an external feed stream of recycled LWR TRU. In the second scenario, recycle of the discharged fuel under equilibrium conditions is represented, and hence recycled LWR TRU is supplied only as a makeup for the TRU shortfall in the recycled ATW discharge. In both scenarios, (a) the depletion calculation was performed at a constant power by scaling the spallation source intensity to compensate the burnup reactivity loss, (b) the charge "enrichment" was calculated such that the reactor multiplication factor at the beginning of cycle is 0.97. The enrichment search varies the relative content of fissile material (TRU) and diluent (Zr) in the fueled zone with the Tc-99 loading fixed at ~6 atom % of the zirconium matrix composition.

Mass flow results for the startup (specified feed) and the recycle scenarios are summarized in Table 1. Since no TRU is produced due to the fertile-free ATW fuel composition, the maximum TRU destruction rate of ~1 g/MWth · day is achieved as expected. The minor actinide content in the recycled ATW TRU, at equilibrium, exceeds that in the reprocessed LWR TRU by ~10%; this increases the relative destruction rate of minor actinides in the recycle mode. The reduced ^{239}Pu mass fraction of the equilibrium/recycle TRU composition increases the TRU loading requirement by ~35%; the lower ^{239}Pu fraction is offset primarily by an increase in the ^{240}Pu fraction. As a result, the burnup reactivity loss rate is reduced by ~3%. The power peaking and peak fast fluence levels of the startup and recycle cases are nearly identical, but the increased TRU loading of the recycle case leads to reduced burnup levels. Compared to the 2000 MWth system, the 840 MWth system requires a fuel composition with somewhat larger TRU proportion (by ~20%) to preserve the subcriticality level due to the increased leakage from the core.

While the foregoing results are preliminary, they illustrate key trends in ATW performance with multiple recycle. They also demonstrate the power and versatility of the REBUS-3 code recently adapted for the fuel cycle analysis of accelerator-driven systems.

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Table 1. Core Performance Comparison for Feed Scenarios and Power Levels

Case		2000 MWth		840 MWth	
		Startup	Recycle	Startup	Recycle
Enrichment (TRU wt% in fuel)		19.9	26.9	23.6	32.0
Multiplication Factor	BOEC[1)]	0.9705	0.9700	0.9697	0.9699
	EOEC[2)]	0.8685	0.8968	0.8921	0.9146
Source Scaling Factor at EOEC		4.98	3.72	3.75	3.01
Power Peaking Factor	BOEC	2.73	2.81	2.61	2.75
	EOEC	2.80	2.91	2.61	2.77
Discharge Burnup (atom %)	Average	26.3	19.5	22.3	16.4
	Peak	56.3	44.8	45.7	36.7
Peak Fast Fluence (10^{23} n/cm^2)		2.3	2.2	1.7	1.7
External Feed (kg/cycle)	Pu	690	182	344	77
	MA[3)]	83	22	42	9
	TRU	773	204	386	86
	^{99}Tc	189	22	76	7
Recycled Feed (kg/cycle)	Pu		687		360
	MA		151		77
	TRU		837		437
	^{99}Tc		150		61
Discharged (kg/cycle)	Pu	503	685	265	359
	MA	67	153	35	78
	TRU	570	838	300	437
	^{99}Tc	162	150	68	61
Net Destruction (kg/cycle)	Pu	187	184	79	78
	MA	16	20	7	8
	TRU	203	203	86	86
	^{99}Tc	27	22	8	7

1) Beginning of equilibrium cycle
2) End of equilibrium cycle
3) Minor actinides