Advanced fuel cycles and radioactive waste management

E. Bertel *

In a new NEA publication, the effects of various advanced fuel cycles on the management of radioactive waste are assessed relative to current technologies and options, using tools such as repository performance analysis and cost studies. The results of the study show that advanced fuel cycles offer possibilities for various strategic choices regarding uranium resources and optimisation of waste repository sites and capacities, while keeping almost constant both the radiological impact of the repositories and the financial impact of the complete fuel cycle.

Reducing the volume and radiotoxicity of radioactive waste to facilitate its management and ultimate disposal is a major goal for developers of advanced nuclear systems. High-level waste (HLW) containing long-lived isotopes is the focus of this effort because it requires long-term stewardship to ensure its isolation from the biosphere. Many innovative nuclear fuel cycle schemes, at various stages of development and technology preparedness, are being considered by researchers and designers aiming at lowering the amount of HLW waste generated per unit of electricity produced. Reprocessing of spent fuel, recycling of fissile materials in light water or fast neutron reactors and eventually partitioning and transmutation of minor actinides are various options that may contribute to this goal.

A study[1] examining the impacts of advanced fuel cycles on radioactive waste management policies, carried out by a group of experts under the umbrella of the NEA Nuclear Development Committee (NDC) was published by the OECD mid-2006. The experts investigated and analysed various fuel cycle schemes (see Table 1) to assess their qualitative and quantitative impacts on the performance of different repository concepts.

Table 1. **Fuel cycle schemes analysed**

Cycles based on industrial technology and possible extensions	
1a	Once-through pressurised water reactor (PWR), reference
1b	Plutonium (Pu) recycled once in mixed-oxide fuel (MOX) for PWRs
1c	Same as 1b, adding recycling of neptunium
1d	Direct use of spent PWR fuel in Candu reactors (DUPIC)
Partially closed cycles	
2a	Plutonium burning in PWRs
2b	Plutonium and americium burning in PWRs
2c	Heterogeneous americium recycling
2cV	Storage and disposal or recycling of americium and curium
Fully closed fuel cycles	
3a	Transuranic (TRU) burning in fast reactors (FR)
3b	Pu burning in PWRs and FRs; double strata
3bV	Pu burning in PWRs and accelerator-driven systems (ADS)
3cV1	All gas-cooled fast reactor strategy with carbide fuel
3cV2	All sodium-cooled fast reactor strategy; uranium not recycled

---

** Dr. Evelyne Bertel (bertel@nea.fr) works in the NEA Nuclear Development Division.*

In addition, the study addressed natural resource requirements and economics from a broad sustainable development perspective.

The fuel cycle schemes considered include options already at the industrial and commercial development stage, as well as very innovative variants which have not yet been fully demonstrated. They pertain to three main families: existing technologies; partially closed cycles; and fully closed cycles. The reference scheme is pressurised water reactors operated with a once-through fuel cycle.

Participating experts from 13 countries provided information on existing and advanced fuel cycles. Although some processes that will be used in the most innovative schemes are at an early stage of design, it was possible to compile reasonably reliable data on mass flows for the full range of all these fuel cycles. Based on those data, estimates of waste streams for systems at an equilibrium state were calculated using validated computer codes and the outcomes were peer reviewed by the group of experts. Taking into account the uncertainties remaining on the future performance of advanced processes, ranges of values were considered for many parameters and sensitivity studies were carried out when appropriate.

Although emphasis was placed on HLW, the impacts of advanced fuel cycle schemes on low- and intermediate-level waste generation, management and disposal, are addressed briefly in the study. Results indicate that issues raised by secondary waste should not be neglected, in particular for innovative schemes leading to the generation of new types of waste with chemical and isotopic compositions different from those generated by current fuel cycles.

The HLW repositories assessed in the study cover various deep geological formations that are considered adequate for long-term isolation of radioactive waste from the biosphere. The assessment was carried out for hypothetical, conceptual repositories in granite, clay, salt and tuff formations. The parameters affecting repository performance analysed in the study include HLW isotopic composition, heat load and volume.

The indicators selected to illustrate the main results from the analyses (see Table 2) represent key aspects of the schemes in terms of their capabilities to address sustainable development goals. The metrics used in the evaluation are the ratios of the indicator values for a given scheme to their values for the reference PWR once-through scheme 1a.

A number of other parameters are evaluated and compared in the study to complement the assessment and provide a comprehensive overview of the fuel cycle schemes analysed. Those parameters include the flows of separated plutonium and the volumes of short-lived, low and intermediate waste.

Table 2. **Selected comparative assessment indicators**

Indicator	Unit
Consumption of natural uranium	kgU/TWh
Volume of conditioned HLW, including spent fuel	kg heavy metal/TWh
Transuranic losses/transfer to HLW	kgTRU/TWh
Activity of HLW after 1000 years	TBq/TWh
Decay heat of HLW after 50 years	W_{th}/TWh
Decay heat of HLW after 200 years	W_{th}/TWh
Maximum dose from HLW disposal in clay*	Sv per annum/TWh
Maximum dose from HLW disposal in granite*	Sv per annum/TWh
Maximum dose from HLW disposal in tuff*	Sv per annum/TWh
Fuel cycle cost	US$/TWh
Total cost of generating electricity	US$/TWh

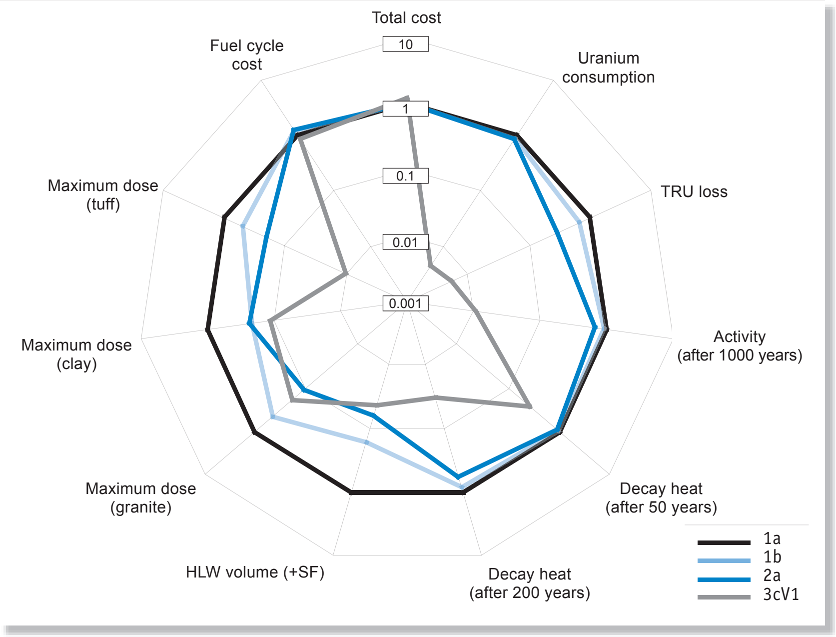
* The maximum doses calculated for disposal of HLW in salt are extremely low and differences between fuel cycle schemes in this regard are not significant enough to serve as a comparative indicator.

Uranium consumption is driven by the fraction of fast reactors included in the fuel cycle scheme; an all gas-cooled fast reactor scheme provides a theoretical potential reduction by two orders of magnitude as compared with the reference PWR once-through scheme. Transuranic losses to waste are reduced by a factor up to six with partially closed schemes, and by up to two orders of magnitude with fully closed schemes.

The activity of HLW after 1000 years is not modified significantly by partially closed schemes, but fully closed schemes can reduce it by nearly two orders of magnitude. The HLW volume is reduced significantly by any scheme, including reprocessing and recycling, with a reduction factor up to 24 for some fully closed schemes.

The decay heat of HLW after 50 years is not reduced by more than a factor of four by any scheme as compared with the reference scheme. However, the decay heat after 200 years is reduced by a factor up to 30 with schemes including minor actinide partitioning and transmutation.

Figure 1. **Comparison of selected indicators for illustrative schemes**



The repository performance assessments are based on analysing the effects of different HLW isotopic composition and heat load on repository capacity and maximum doses released. According to the approach adopted in OECD countries, all the repository concepts considered guarantee that maximum doses released to the biosphere at any time in normal conditions remain well below accepted radiation protection thresholds and authorised limits.

The comparative advantage of any scheme over the reference once-through scheme, in this context, is the additional quantity of HLW that could be disposed of in a given repository while respecting the dose limits. Heat load and waste volume are the most-affected parameters. For example, some advanced fuel schemes could allow a repository to accept waste produced from five to twenty times more electricity generation than the reference PWR once-through cycle scheme.

The analyses of the evolution of radioactivity in the waste over time illustrate the complementarities and time range of relevance of the three major courses of action in waste management: conditioning, geological disposal, and partitioning and transmutation. Partitioning followed by transmutation, storage, embedding in durable matrices, conditioning and deep geological disposal are redundant and complementary means to achieve the safe confinement of waste.

The economic analysis carried out in the study shows that the differences in total electricity generation cost between the schemes considered are not significant because waste management and disposal costs represent a very small fraction of those costs. All schemes, even the most advanced ones, may be implemented without jeopardising the competitiveness of nuclear electricity. Differences regarding fuel cycle costs are more visible, but clearly not a decisive factor to assess and compare alternative schemes.

The main results from the analysis are summarised in Figure 1. The spider web diagram displays indicators on a logarithmic scale: the closer the indicator is to the centre, the better is the performance of the scheme.

A key message drawn from the conclusions of the study is that, for all fuel cycle schemes considered, all the repository concepts analysed provide reliable and safe solutions for HLW disposal. Given the flexibility of the advanced fuel cycles under development, it is possible to design new reactor cycles that use resources more efficiently and generate less waste at acceptable costs. ■

Reference

1. NEA (2006), *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, OECD, Paris.