MULTI-SCENARIO ANALYSIS OF USED NUCLEAR FUEL MANAGEMENT OPTIONS

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ABSTRACT

Robust increases in energy demand, improvements in the performance of existing nuclear power plants, renewed interest in assuring domestic energy supply and concern about climate change have recently provided arguments for renewing and further expanding the use of nuclear energy in the United States. Such an evolution will likely require implementation of a spent nuclear fuel management system in addition to the prospects that encapsulated spent fuel disposal at Yucca Mountain offer today.

The first step in addressing the challenge of managing the nuclear fuel cycle for an expanded nuclear reactor fleet must include a thorough analysis of the different options available to the nuclear industry. Support tools are required to evaluate the advantages and disadvantages of the different spent fuel management options associated with evolutions in energy demand, fuel supply, technological alternatives and other such factors. Looking ahead, the opportunities offered by *and* the conditions necessary for the deployment of advanced spent nuclear fuel (SNF) treatment and generation four (GEN IV) technologies must be considered.

To answer this need, AREVA has developed a software tool capable of simulating a wide-range of SNF management scenarios. In the first part of this paper, the analysis tool is described, including its overall structure and the fuel cycle models used. The second part summarizes some initial results obtained using the tool. Specifically, material flows for different scenarios corresponding to various separation technologies are presented. In this first analysis, material flows from currently envisioned SNF management options and one proposed by the Advanced Fuel Cycle Initiative are compared. The results provide an idea of the size and throughput of the production facilities required. The economic comparisons, involving cost estimates for many non-industrialized or even non-existing technologies, are the subject of on-going work.

INTRODUCTION

Over the last several years, nuclear energy has proved itself a key part of the US energy supply, and holds the promise to play an even more important role in coming years. The Nuclear Energy Institute reports that virtually all US nuclear plants have or will seek 20-year extensions to their operating licenses, suggesting the viability and reliability of existing reactors [1]. Although the US nuclear fleet only accounts for 10.9% of installed generating capacity, it nevertheless provided 20% of the nation's electricity in 2003 [2]. As for the future, concerns about assuring domestic energy supplies, combined with increasing awareness of global warming issues, make nuclear energy an attractive source of energy for the coming decades. In 2001, the National Energy Policy Group headed by the Vice-President encouraged the President to support the expansion of nuclear power as part of the nation's energy policy [3]. More recently, a study performed at the Massachusetts Institute of Technology recognized the importance of keeping the nuclear option available as a means of securing future carbon-free energy supplies [4].

What is the most suitable SNF management and waste disposal option? Experience in the US and throughout the world show that the development of geological repositories for the disposal of high-level nuclear waste is an expensive and slow process, despite general scientific consensus that geological repositories offer the best available disposal method for high-level nuclear wastes [5]. Although many nations with civilian nuclear reactors have programs in place to develop geological repositories, few have advanced beyond preliminary site investigations. The most advanced programs are those in the US, France, Finland, Sweden, and Germany, but only the Yucca Mountain site in the US and the Olkiluoto site in Finland have been officially approved by the respective governments for the construction of a geological repository. In the case of Yucca Mountain, difficulties have delayed the project by about twelve years and it won't begin receiving wastes before 2010.

In this context, there is a rationale to consider SNF treatment as a means of maximizing repository capacity, which is clearly a rare resource. Wigeland et al. at Argonne National Labs have shown how the performance of a repository – and thus its specific capacity – is impacted by the radioisotopes contained in wastes headed for geological disposal. They explain for example, that the removal of actinides from wastes can increase repository capacity by a factor of 3.2 [6].

On the other hand, the use of treatment as key component of the SNF management policy must make economic sense, and separated materials must be managed appropriately. Given the importance of decisions to be made, there is a clear need for analysis detailing the advantages, disadvantages and costs of various options for SNF management. AREVA has therefore developed a software tool aiming for this purpose. It is composed of several modules corresponding to SNF management steps (fuel unloading, interim storage, reprocessing, interim storage of the reprocessing products, potential recycling, storing of final waste). Each module contains modifiable parameters (dates, capacities, separation processes, recycling options), which taken together define a scenario (a scenario here is defined as the implementation of a given SNF management strategy within a given energy demand context). The different material flows are then defined. Combined with costing models, such material flows lead to an economic evaluation of a given scenario. The analytical tool allows comparisons on the basis of several criteria, such as perceived technological risk and complexity, quantities of different materials requiring management, or global cost.

The tool is first described in the following sections, and then simulations of three scenarios involving different SNF management options are described.

SNF MANAGEMENT SIMULATION TOOL

The AREVA SNF Management Simulation Tool was designed to quickly evaluate material flows and costs associated with different types of SNF management options, including the comparison of different separation technologies.

The tool consists of several interdependent modules. The modules represent individual systems or steps associated with the nuclear fuel cycle, including SNF production, storage, treatment, etc. Variables within each module allow the user to quickly define the key parameters of a given system, which can include temporal, performance or engineering/science inputs. For example, the module regarding SNF production requires user definition of electricity demand in 2002 (base year), the yearly increase in electricity demand, percent of demand supplied by nuclear reactors, start-up year of GEN IV reactors, etc. Basic reactor performance parameters are also adjustable. Once the variables are set, the tool generates an array of data providing key information for each year beginning in 2002 and running through 2100.

Spent fuel is divided into different categories in the model, corresponding to the types of fuel expected to be used throughout the century. These include UOX SNF types, corresponding to burn-ups between 40 and 75 GWd/tU, and MOX fuels. This classification of fuels serves mostly to keep track of actinide and fission product inventories, either as isotopes contained in used fuel or as separated material following treatment. The isotopic composition of a given type of fuel is set by the burn-up and a 10-year cooling period.

The SNF treatment module allows the user to choose between various separation technologies (or none), as well as the start-up date and capacity of the treatment facilities. The types of separations considered include: U only, U - Pu, U – Pu/Np, U – Pu/Np – Cs/Sr, U – Pu/Np - Cs /Sr - Cm/Am, and grouped actinide extraction (GANEX). Elements not separated are assumed to go to waste stream. In the recycling module, the tool allows the user to choose, whether separated materials are recycled or not, and whether priority for recycling of materials should be given to producing MOX fuel or fuel for GEN IV reactors. Other modules follow the flow of materials all the way to the final disposal step.

Facility start-up and shut-down dates, calculated materials flows and additional cost models provide the necessary information to perform economic analysis of a given scenario. In general, the tool has been programmed with a cash-flow approach to required capital, operation and dismantling costs. Taken together, the information provides an estimation of the profile and magnitude of cash flows required to implement a given SNF management strategy in a given energy-demand context. This global cash flow, discounted to a given year, is used to compare different scenarios.

USING THE TOOL

To illustrate the potential use of the tool, we present and compare key elements for three scenarios. The first involves the implementation of a SNF storage, encapsulation, and direct disposal strategy. The second and third implement closed fuel cycles: in the second scenario, a uranium and plutonium separation process is considered; in the third, an advanced separation process is assumed where U is extracted and the pairs Pu/Np, Cs/Sr and Am/Cm are co-extracted. We limit the presentation of our results to material flows. The idea is to identify how much material must be managed at a given point of time throughout the following decades. The associated economic comparisons, requiring cost estimates for many non-industrialized or even non-existing technologies, are the subject of on-going work.

In all three scenarios, the same energy consumption and nuclear energy demand profile is used. This profile is modeled after current US data and historical trends. Electric consumption is set at 3,800 TWh in 2002, growing at a modest annual rate of 1.5%. Nuclear energy is programmed to continually provide 20% of electricity consumed, thus requiring new generating capacity to satisfy increasing demand and to eventually replace today's reactors. GEN IV reactors are assumed to begin service in 2050, at which point LWR capacity is decreased at a fixed rate of 2.5% annually. Thus, the last discharge of fuel from an LWR occurs around 2090. In the three scenarios considered, we focus on tracing SNF and separated materials from LWRs.

In the first scenario, SNF is assumed to be stored on reactor sites, and then transported to a final repository for encapsulation and disposal. Here, over 225,000 metric tons of heavy metal (MTHM) of SNF will be discharged by 2090, requiring disposal in several repositories. The opening date of a first repository is set for 2010, and its capacity is set to 100,000 MTHM. This is significantly above Yucca Mountain's current legislated capacity of 63,000 MTHM of civilian waste constituently with the current discussions and uncertainties associated with the final capacity of Yucca Mountain. Subsequent repositories will be required for the remaining SNF. We can either assume two additional repositories of 60,000 MTHM, or a single second repository capable of accepting 120,000 MTHM. The first of these repositories will need to be operational by 2045 if SNF transport rates are set to 3,000 MTHM/year and deliveries to disposal sites are continuous. A third repository will be required before the end of the century, and additional repositories will be required for waste products originating from GEN IV reactor fuel.

In the second scenario, SNF is sent to treatment facilities in order to reduce waste volumes and remove major actinides from waste contents, thus increasing the specific capacity of Yucca Mountain. As already mentioned, Wigeland and al. have shown that eliminating all actinides from wastes can increase the capacity of Yucca Mountain by approximately a factor of 3.2. Removing only the uranium and plutonium will reduce this effect – we assume the capacity of Yucca Mountain is increased by a factor of 2.

Pu is recycled as MOX fuel in the LWR reactor fleet. Fission products and minor actinides are conditioned in glass logs, which are then stored before disposal in Yucca Mountain. The extracted U can be safely stored at surface facilities and/or recycled to manufacture new fuel. For the same amount of energy produced in the direct disposal scenario presented above, 205,000 MTHM of UOX fuel is required for the LWR fleet compared to 225,000 MTHM in the first scenario. The difference is made up by the recycled MOX fuel. In this second scenario, we assume discharged MOX is stored while either awaiting treatment and recycling of actinides in GEN IV reactors, or disposal in a repository.

There are many possible combinations of treatment facilities start-up dates and throughput that can make this scenario industrially viable. We have selected for the exercise a phased approach with 1,000 MTHM/year by 2025, 3,000 MTHM/year by 2035 and 5,000 MHTM/year by 2050.

The tool allows rapid analysis of the closed fuel cycle trade-offs including the balance between: 1) quantities of SNF stored at reactors sites; 2) SNF transport rates; 3) and SNF storage pool capacities at the treatment facilities can be quickly studied. For example, with SNF transport rates limited to a maximum of 3,000 MTHM/year, it turns out that interim SNF storage capacity at a treatment site would need to be sized a maximum of 50,000 MTHM in order to allow the treatment plant to run at full capacity. However, if SNF transports can be increased to achieve a maximum of 5,000 MTHM/year, then the maximum interim storage of SNF at treatment plant can be reduced to 10,000 MTHM.

The third scenario is similar to the second, with an advanced separation technology permitting the extraction of U and co-extraction of Pu/Np, Am/Cm and Cs/Sr. Removal of the pairs Am/Cm and Cs/Sr from ultimate waste streams can significantly increase repository capacity thanks to the removal of long and short-term heat sources. Referring again to studies showing that removal of actinides can increase repository capacity by a factor of 3.2, it is assumed that the additional removal of Cs/Sr will increase this gain to at least a factor of 5.

While the significant increase in repository capacity is attractive, the implementation of such an advanced separation technology raises additional questions about the management and recycling of separated materials. The Cs/Sr pair, both with short half-lives, could be stored in surface facilities while their heat output decreases. They can then be disposed of in a repository without impinging on thermal constraints and adding little volume. However, it is worth noting that there seems to be no real consensus in the nuclear community on how to best package Cs/Sr waste. The actinides Am/Cm are another issue. Such actinides can hardly be efficiently used in LWR fuel. They are of course, more adapted to use in most GEN IV reactor concepts. And there is little point in immobilizing them in some waste form for disposal, since their presence in a repository will negate any benefit of separating them from ultimate waste streams in the first place. Management of stocks of Am/Cm is thus restricted to interim storage until required for GEN IV reactor fuel fabrication.

Table I provides the balance of materials generated by the three SNF management strategies considered above at the retirement of the very last LWR, which occurs here in 2089 (the last LWR reactor is put in service in 2049 after which replacement capacity is supplied by GEN IV reactors).

Table I. Balance of Materials Generated by the SNF Management Strategies at Retirement of Last LWR.

	Scenario 1 *Direct Disposal*	**Scenario 2** *U-Pu Separation*	**Scenario 3** *Advanced Separations*
Discharged UOX fuel (MTHM)	225,058	203,530	203,290
Treated UOX fuel (MTHM)	-	203.530	203,290
UOX Fuel Based Waste (MTHM)	225,058	12,777	11,180
Repositories Required for UOX Fuel Based Waste	Yucca Mountain + 1 or 2 repositories	Yucca Mountain	Yucca Mountain
Discharged MOX (MTHM)	-	21,529	21,768
Separated Am/Cm (MT)	-	-	331
Separated Cs/Sr (MT)	-	-	1048 (mostly Cs)

From the table it can be drawn that direct disposal of used nuclear fuel is hardly desirable should LWRs continue to provide 20% of the US electricity supply considering the cost, time and complexity to license multiple repositories.

On the other hand, the simulation shows that Yucca Mountain could indeed handle most if not all wastes generated from UOX-based fuel discharged from LWR reactors with U-Pu separation technologies. The additional removal of Am, Cm, Cs and Sr does little to reduce the actual mass of waste destined for high-level disposal, but nevertheless permits an increase in repository capacity through optimal thermal loading, so much so as to decrease the required size of Yucca Mountain, or considerably increase its lifetime.

While proven U-Pu as well as advanced separation technologies can increase the loading of ultimate wastes in repositories like Yucca Mountain, separated actinides and other elements must ultimately be managed. In Scenario 2, plutonium is recycled as MOX in the LWR fleet, and the entire stock of discharged MOX is limited to 22,000 MTHM by 2090. We can imagine two options for managing this inventory. First, assuming GEN IV reactors come into operation by 2050, the used MOX fuel can serve as a strategic source of plutonium and other actinides for GEN IV reactor fuel fabrication. Since most GEN IV reactors concepts are inherently associated with closed fuel cycles and can accommodate burning of actinides, the management of ultimate wastes is greatly simplified once GEN IV reactors are operational. If GEN IV reactors are not placed into service and no new reactors are built after 2050, an alternate scheme for managing inventories of used MOX will be required. However, only 22,000 MTHM of spent fuel will be ultimately accumulated by 2090. Between now and then, sufficient time will be available to develop alternative MOX disposal technologies.

Scenario 3 is more complicated. Separated actinides will require interim storage for 30 to 40 years until they can be recycled in GEN IV reactors. How and where to store them are legitimate questions, even if, as Table I shows, their quantities are relatively small. Similar questions apply to the interim storage of separated Cs and Sr, although the heat-generating isotopes of these elements only have half lives on the order of 30 years. After several tens of years of surface storage, stocks of remaining Cs and Sr and their products can probably be disposed of in a repository without imposing a relevant thermal load or taking up much space. The necessity of temporarily storing these elements, however, brings up the question of the interest of separating them in the first place. Since ultimate waste forms resulting from spent fuel treatment can be easily and safely stored for at least a hundred years, Cs and Sr could be left incorporated with the other vitrified waste. Such a possibility has the added benefit of buying time for the final repository.

The added benefit of implementing an advanced separation technology (such as increased repository loading or reduced repository size) must be weighed against the technical uncertainties and costs associated with the management of separated materials.

CONCLUSIONS AND FUTURE WORK

AREVA has developed a tool to assist in the evaluation of different SNF management scenarios. We have illustrated the results obtained on three scenarios where nuclear energy continues providing 20% of the US electricity supply. With the assumptions made, results show that a direct disposal approach would lead to require additional repository capacity beyond what Yucca Mountain can accept.

On the other hand, a SNF management strategy featuring the separation of major actinides from other waste materials could sufficiently optimize repository capacity. In this model all waste resulting from UOX-based fuel could be disposed of at Yucca Mountain while complying with the current volume and thermal constraints. In such a scheme, plutonium would be recycled a first time as MOX fuel, and then recycled again in GEN IV reactors. In a worst-case scenario where GEN IV reactors are not placed in service, only a limited amount of about 22,000 MTHM of MOX fuel would require to be disposed of by 2090.

Advanced separation technologies provide the possibility to significantly increase the waste capacity of Yucca Mountain through optimal thermal loading, enough to decrease the required size of the repository or to expand its life time. However, such technologies remain to be developed and additional storage facilities would be required to interim store separated elements before disposal (for fission products) or recycling (for minor actinides). The costs associated with these uncertainties and extra facilities needs to be weighed against the savings provided by the volume reduction of waste to be stored in the final repository.

Current work is focusing on "translating" information about SNF management facilities and material flows established in our scenarios into economic data for comparisons. The framework exists in the software tool, but raw data is still being collected and estimated (for example – how much does it cost to store Cs or Sr?). Work is also under way on a repository "thermal" module that should help understand the appropriate scheduling of shipments to Yucca Mountain as a function of isotopes contained in materials being disposed of, and the desired thermal loading of repository tunnels.

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