USING VITRIFIED AND COMPACTED WASTES TO OPTIMIZE REPOSITORY USE

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ABSTRACT

Traditionally, political choices made with respect to the value of spent nuclear fuel (SNF) have been associated with a single corresponding technical option for dealing with the back-end of the nuclear fuel cycle: judging spent fuel as valuable material was invariably a decision to reprocess and recycle, while assessing fuel as waste implied a decision in favour of direct disposal. However, difficulties encountered throughout the nuclear world in establishing high-level waste repositories and the consequent need to optimize the use of those that are built have created doubts about the viability of the direct disposal option, especially in a future world where nuclear power is an important part of global energy provisions. Waste management solutions today must therefore be evaluated not only on the difference in cost between new and recycled fuel, but also with the value of another potentially scarce resource in mind: repository capacity.

This paper summarizes the preliminary results of studies performed to examine, from an economic point of view, the viability of SNF treatment as a means to deal with a SNF management challenge similar in size and scope to the current US situation. The first part of the study, detailed in this paper, examines the potential scope of the waste management challenge in a future where nuclear energy accounts for an important part of electricity production. The ability of direct disposal and SNF treatment options to deal with the challenge outlined are discussed.

INTRODUCTION

There is considerable evidence throughout the world that the development of geological repositories for the disposal of high-level nuclear wastes is a difficult, expensive and slow process, despite general scientific consensus that geological repositories offer the best available disposal method for high-level nuclear wastes [1]. 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 of each nation for the construction of a geological repository. In the case of Yucca Mountain, opposition from the State of Nevada and the difficult characterisation of the site has significantly slowed the project, so much so that it has been delayed by at least twelve years and won't begin receiving wastes before 2010. Costs are also important – in 2001, the Office of Civilian Radioactive Waste Management, the agency responsible for managing the Yucca Mountain program, reported that approximately $6.7 Billion had already been spent on site selection and characterisation, and that the program would require an additional $49.3 Billion (constant 2000 dollars) through 2119. In the US, the difficulties with establishing a repository at Yucca Mountain have resulted in calls to use the site as efficiently as possible; many smaller nations, meanwhile, with small amounts of waste have investigated the possibility of sending wastes to an international repository [2].

In the meantime, worldwide stocks of spent nuclear continue to grow, highlighting the need for eventual disposal facilities. In 2002, approximately 150,000 metric tons of heavy metal (MTHM) of SNF were stored in pools and dry storage installations, while another 25,000 MTHM of spent fuel equivalent were stored in vitrified waste storage facilities across the globe. Further, over 11,000 MTHM are being unloaded from reactors every year, and it seems unlikely that this figure will decrease in the future as nuclear energy continues to prove itself as a carbon-free and reliable source of electricity. In the US, the National Energy Policy Group headed by the Vice-President encouraged the President in a 2001 report to support the expansion of nuclear power as part of the nation's energy policy [3]. More recently, a major 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].

In this context, there is sufficient reason to consider SNF treatment as a means of reducing waste volumes and maximizing repository use, whether considering open or closed fuel cycles. In fact, the characteristics of the waste forms produced by treatment render such an option technically desirable for several reasons, including the immobilization of fission products and minor actinides at the molecular level, significant reduction of waste volumes, packaging of wastes in standardized containers and the possibility of cost-effectively and safely storing wastes for at least one hundred years. On the other hand, such an option should be shown to be economically competitive compared to direct disposal if it is to be considered a serious alternative. In this paper, we first resume previous studies showing at what unit cost SNF treatment is cost-competitive with direct disposal for a given set of assumptions and conditions. Evolutions in the prospects of nuclear energy, notably the possibility of an important increase in nuclear capacity in the US, have forced us to revise our initial assumptions, particularly in terms of the amounts of SNF requiring suitable management. The rest of the paper therefore summarizes our efforts to characterize the magnitude and scope of the SNF management challenge that could be faced should nuclear energy continue to play an important role in electricity provisions in the US. We also comment on the suitability of two SNF management options, direct disposal and SNF treatment to deal with the challenge. These results will be used in future work to again analyse the conditions for which SNF treatment is economically attractive compared to direct disposal for the revised set of assumptions and conditions.

REPROCESSING TO MAXIMIZE REPOSITORY USE

Given 1) the expense and difficulty of establishing repositories, and 2) the real possibility of continued use of nuclear energy, there is a clear need to optimize the use of those repositories that are constructed. The existence of this need has long been recognized in France where SNF treatment and recycling of spent fuel allows the reduction of wastes requiring disposal. It is being increasingly acknowledged in the US as well, as witnessed by the advent of the Advanced Fuel Cycle Initiative in 2002 within the Department of Energy.

SNF treatment today provides a means of significantly reducing the volume of high-level waste that requires disposal in a geological repository by separating spent fuel into four components: uranium, plutonium, fission products and hulls and end pieces. The thermal output of SNF can also be better managed through separation of select actinides and/or fission products, depending on repository design and constraints. The majority of the volume reduction comes with the removal of uranium, which makes up approximately 95% of the spent fuel assembly. It is generally accepted that this separated uranium, relatively pure, cool and not very radioactive need not occupy space within a geological repository, and should certainly not be subject to the same requirements for containment that apply for fission products and minor actinides.

In previous studies, we calculated the required economic performance of reprocessing that would render it economically competitive with direct disposal. Specifically, we compared two cases involving the management of 120,000 MTHM of spent fuel either by 1) direct disposal in two repositories or 2) SNF treatment and placement of all waste in one repository.

For the direct disposal option, we envisioned a scenario where a Yucca Mountain-type repository is constructed and begins operation in 2010. The timing of emplacement, monitoring and closure operations was estimated based on guesses and whatever was available in the literature.

For the SNF treatment case, we developed a hypothetical scenario where spent fuel was first delivered to a reprocessing facility for treatment and conditioning, preferably on the site of the repository. In that study, we chose to adhere to the current US policy regarding the recycling of plutonium; in other words, the plutonium extracted by the treatment was not recycled, but rather immobilized in ceramic form for placement in canisters containing vitrified fission products. After sufficient cooling, the canisters would be disposed of in a single repository. We chose a cooling time for the canisters such that the capacity of Yucca Mountain was effectively doubled while respecting the waste package thermal limits currently outlined in the Yucca Mountain program plan. Specifically, we calculated the thermal output of the vitrified wastes that allowed twice as much equivalent tons of spent fuel to fit in a standard Yucca Mountain waste package (WP21) while not exceeding the thermal loading limit of those packages, assumed to be 11.53 kW [5].

After determining the timelines required for each SNF management solution, we calculated the unit cost of treatment at which treatment of all fuel, and then emplacement in a single repository was equal to the cost of building two repositories. We concluded that for a SNF treatment cost of up to 620 $/kg, treatment and disposal in one repository was competitive with direct disposal in two repositories without taking into account the heavy, potentially infinite political cost that a second repository would entail, or the qualitative advantages of dealing with vitrified and compacted wastes. This figure, we said, was not an unrealistic goal for the industry to attempt to attain in the coming years and decades.

Recent developments regarding the prospects of nuclear energy have required a revision of several assumptions that served as the basis for the study described above. In particular, recent optimism about the potential for nuclear energy to continue and even expand its role in energy production, especially in the United States has required rethinking about the quantities of SNF requiring safe, effective and efficient management. Whereas before we sought to compare two solutions for the management of 120,000 MTHM of SNF (the total discharges of today's US reactor fleet with license extensions), any significant 're-birth' of nuclear energy will require the management of considerably more important quantities of SNF.

The goal of our work remains the same: examine, from an economic point of view, the circumstances and conditions in which spent fuel treatment is a cost competitive alternative to direct disposal. The study comprises three parts: 1) Energy production scenario and SNF management need, 2) Management Option Scenarios, 3) Cost comparisons. Here we present and comment the energy production scenario retained for analysis and the subsequent SNF management need, as well as our first efforts at developing realistic SNF management options.

In the last few years, the scope of the SNF management issue in the United States has greatly evolved, if not actually, at least provisionally. In 2001, when the DOE last performed an adequacy assessment of the funding for the Yucca Mountain Project, it based its estimates on the need to dispose of approximately 83,800 MTHM of SNF. This figure was based on discharge estimates for today's US nuclear fleet with expected lifetimes of 40 years. Today, however, it is expected that almost the entire fleet of reactors will seek, if they have not already done so, license renewals extending plant operational lifetimes to sixty years. The consequent impact on total amount of SNF, from today' reactors, requiring some form management by 2050 has therefore increased to approximately 120,000 MTHM. Further, there has been recent recognition from both government and academic institutions that nuclear energy could play an important role in future electricity provisions, especially if reductions in overall carbon emissions are required.

The renewed development of nuclear energy will require the management and disposal of significantly increased quantities of wastes. Any serious attempt at increasing nuclear capacity in the United States by government, industry or both will require that the choices made for SNF management are suitably adapted for the size and scope of the job. How much nuclear energy? How much SNF? What's the most suitable SNF management and waste disposal option? All are questions that must be addressed simultaneously to help overcome potential opposition to reactor projects, foster public confidence in the industry, and assure that sustained development of the nuclear option remains possible.

To quantify the amounts of SNF requiring management that a significant renewal of nuclear energy would entail, we simulated the growth in nuclear capacity required for two growth scenarios: 1) a "medium" scenario where nuclear energy provides 20% of US electricity supply (keeping its current share) 2) a "high" scenario where nuclear energy provides 30% of US electricity supply beginning in 2020. We assumed a generic growth of electricity that follows the US DOE's Energy Information Administration forecasts until 2025, increasing at an annual rate of 2% thereafter. In our analysis, we assumed the entire current reactor fleet was operated for sixty years, and then retired. New, "third" generation nuclear capacity is added as necessary to maintain the given nuclear generation market share. It is further assumed that beyond 2040, required additional nuclear capacity is supplied by fourth generation fast reactors. The capacity and generation required for the two scenarios in 2050 is shown in Table I and compared to the results obtained in the MIT report.

Table I Nuclear generation share

	COGEMA		MIT Report	
Scenario	Medium	High	Low	High
Nuclear Share of Generation	20%	30%	30%	50%
Generation (TWhe)	1,917	2,875	2,505	4,174

Figure 1 below shows, for both the medium and high growth scenarios, trends for the retirement of existing capacity and the addition and retirement of new third generation capacity, as well as the addition of fast reactor capacity after 2040. For both scenarios, new capacity must be added by about 2010 to keep nuclear energy's current 20% generation share. For the high growth scenario, capacity will have to be added at an increasing rate after 2020 to increase, then maintain, a 30% share for nuclear energy.

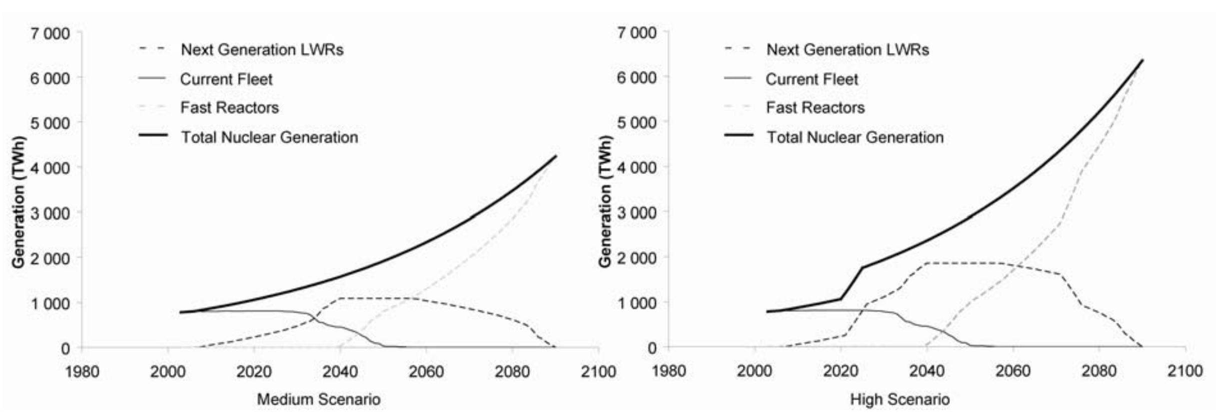

Fig. 1 Nuclear generation growth scenarios

With suitable hypotheses for plant efficiencies and fuel burn-up, generation can be converted to quantities of spent fuel discharged. In both cases, an assumption is made that overall, plant efficiencies for modern reactors increase from approximately 32% to 35% as the fleet of reactors is renewed. Further, it is assumed that fuel burn-ups, thanks to various improvements, are gradually increased from 40GWd/MTHM today to 70GWd/MTHM by 2070.

Figure 2 shows the cumulative quantities of SNF discharged for the medium and high growth scenarios for first, second, and third generation light water reactors only. It is assumed, for simplicity, that fast reactor fuel is reprocessed, recycled, with very little in the way of wastes requiring final disposal compared to light water reactors. As such, these fast reactor wastes can be imagined as requiring a particular disposal solution potentially quite different (and further away in the future) than for LWRs.

Figure 2 clearly shows the magnitude of the spent fuel management challenge that could be faced should nuclear energy continue to play an important role in the nation's energy provisions. For the medium growth scenario, the total amount of SNF discharged by 2050 is more than 165,000 MTHM, exceeding 215,000 MTHM by 2080. For the high growth scenario, SNF discharges amount to over 200,000 MTHM by 2050 and 285,000 MTHM by 2080.

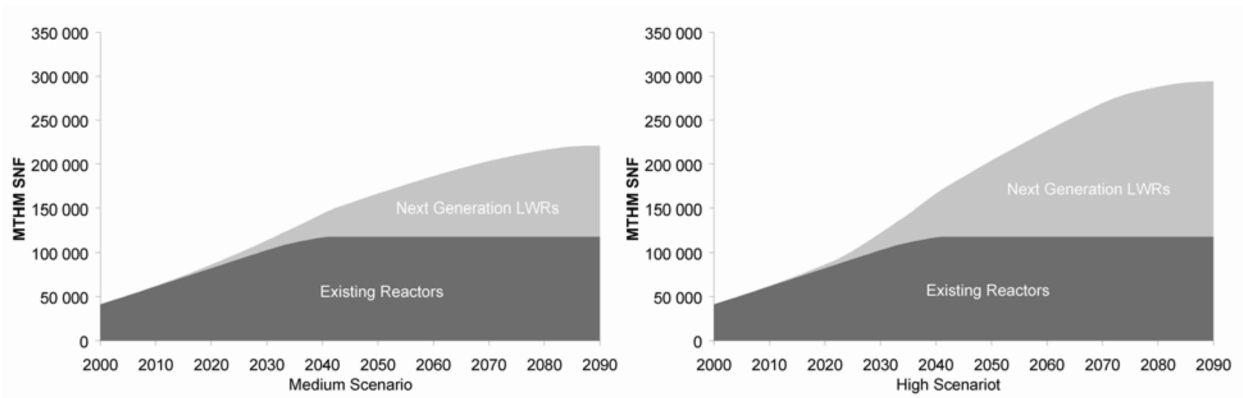

Fig. 2 Wastes generation

Two alternative strategies for managing the significant amounts of SNF discharged in any nuclear growth scenario are considered here: 1) direct disposal in one or multiple repositories, 2) some from of SNF treatment, either with or without recycling, with eventual disposal of waste products.

For direct disposal, the adequacy and viability of the option will depend on the availability of repository capacity at reasonable cost. In the United States today, there is little evidence that that is, or will be, the case. The Yucca Mountain repository in Nevada is already planned to open more than a decade behind schedule, and is still facing aggressive opposition from the State of Nevada. In addition, the site today is legally limited to a capacity of no more than 63,000 MTHM of civilian SNF (and another 7,000 MTHM of military waste), a capacity even insufficient for the amount of SNF expected to be discharged from today's reactors, without considering the impact of license extensions. If this limit is effectively applied, and assuming other repositories could be sited and constructed, almost 3.5 repositories of similar size would be required by the end of the century for the medium nuclear growth scenario for LWR fuel only, and 4.5 repositories would be required for the high growth scenario. In other words, a Yucca Mountain type repository would be required every 11 to 14 years between now and 2060, when the last repository for LWR fuel might be required ready for operations. Considering that characterization work at Yucca Mountain began in earnest in the mid-1980's, the challenges associated with the direct disposal option seem daunting.

It has been suggested that the "true" capacity of Yucca Mountain is considerably larger than 63,000 MTHM. For instance, the MIT report states in a footnote: "The 70,000 MTHM capacity limit at Yucca Mountain was politically determined, and according to some knowledgeable observers the physical storage capability of the site would be at least twice as large." [4] Despite these assertions, the DOE has published little in the way of evidence that significantly more space is available at the site. In its 2001 Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, the DOE wrote: "The primary area consists of an area bounded on the east by the Ghost Dance Fault, and on the west by the Solitario Canyon Fault. Expansion areas are potentially available; however, additional characterization activities would be required. These areas lie west of the Solitario Canyon fault."[6] Thus, whatever extra space is available, a geological fault would have to be crossed and additional characterization performed.

The SNF treatment option, which may or may not include recycling of actinides, would also need to overcome various obstacles to become a viable option, but it presents several advantages as well. In general, the attractiveness of this solution is the ability to optimize repository use by conditioning wastes such that only the minimum quantity of material requiring long-term disposal is placed in the repository. As a result, the capacity of a repository in terms of equivalent tons of SNF can be increased several-fold. Of course, defining the "minimum" quantity of waste requiring disposal is both a technical and political issue. Materials to be conditioned and disposed of must be suitably selected to maximize volume reduction and minimize short and long term heat loads. Wigeland et al. have shown that SNF treatment with subsequent recycling of actinides first as MOX fuel and then as fuel for fast reactors can increase the capacity of Yucca Mountain, while respecting its current volume and thermal constraints, by a factor of 3.2 [7]. Others have suggested that the recycling of actinides combined with the separation and surface storage of the short-lived heat producing fission products cesium and strontium, repository capacity can be increased by a factor of at least 50 [8]. Processes must also be chosen that can reduce the perceived proliferation risk of SNF treatment, while simultaneously reducing effluent streams and total costs.

In order to treat the significant amounts of SNF expected to be discharged in the medium and high growth scenarios described above, a very significant deployment of treatment capacity will be required. Considering that the cumulative tons of LWR SNF treated at the COGEMA La Hague and BNFL Thorp plants to date amount to less than 25,000 MTHM, the magnitude of challenge cannot be understated. Sufficient treatment capacity would need to be added incrementally to overcome the backlog of existing SNF stocks and to deal with new LWR SNF discharges.

CONCLUSIONS

The prospects for the future of nuclear energy are promising. Within the United States, there is increasing recognition of the atom's ability to assure abundant and cheap energy supplies while simultaneously reducing carbon emissions. At the same time however, doubts are rising about the suitability of direct disposal as a sustainable waste management option. The repository being developed at Yucca Mountain has been plagued by opposition, delays, and difficulties with site characterization and is in any case not even designed to handle the amount of fuel expected to be discharged from today's operational reactors, an amount totalling approximately 120,000 MTHM.

If nuclear energy keeps its share of the nation's electricity generation, up to 215,000 MTHM of LWR spent fuel will require some form of management, and if the nuclear energy increases its generation share from today's 20% to 30%, the total amount of LWR spent fuel requiring management will be above 285,000 MTHM. These amounts do not even consider discharges from fast reactors, which, in this study, are assumed to be deployed beginning in 2040. These amounts of wastes would require a total of 3 to 5 Yucca Mountain-sized repositories between 2010 and 2060. Given the history of the Yucca Mountain project, the siting, characterization, licensing, construction and operation of so many repositories seems unlikely.

An alternative waste management solution is spent nuclear fuel treatment; in other words, the conditioning of wastes for disposal. Treatment technology has the possibility to, among other things, reduce waste volumes and reduce the thermal power of waste packages, ultimately increasing repository capacity compared to direct disposal by several factors. SNF treatment, however, would require a significant deployment of treatment capacity in the next several decades.

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