Advanced Fuel Cycles and Impacts On The Yucca Mountain Repository

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ABSTRACT

One of the goals identified for advanced fuel cycles, such as that proposed by the Global Nuclear Energy Partnership, is to reduce the volume of wastes that would ultimately have to be disposed in a geologic repository. Besides reducing volume, techniques that recycle the vast majority of actinides along with the removal of key fission products also reduce the inventory of radionuclides that must ultimately be disposed and the thermal output of the wastes. Advanced recycling techniques may also generate waste forms having different characteristics than those that have been considered for disposal in a repository at Yucca Mountain to-date. These all have a potential impact on several aspects of a repository, such as the proposed repository at Yucca Mountain, including surface and subsurface facility design, pre-closure and post-closure safety analyses, and ultimately licensing. These changes would all have to be performed in accordance with the requirements at 10 CFR 63 and approved by the U.S. Nuclear Regulatory Commission in a license amendment prior to the disposal of any wastes from an advanced fuel cycle.

INTRODUCTION

The Global Nuclear Energy Partnership (GNEP) aims to “recycle nuclear fuel using new proliferation-resistant technologies to recover more energy and reduce waste” [1]. The Nation’s decision to recycle commercial spent nuclear fuel in an advanced nuclear fuel cycle, such as that being considered under the GNEP, would require changes to the approach of nuclear waste management and disposal currently being developed at Yucca Mountain. As discussed in this paper, changes to the waste forms associated with recycling could present benefits to waste disposal as compared to the current once-through fuel cycle. These benefits could allow increased flexibility in nuclear waste management and disposal while potentially reducing the risks associated with geologic disposal.

The development of a repository at Yucca Mountain is proceeding in accordance with the Nuclear Waste Policy Act [2]. The current design of the proposed repository emplaces 63,000 MTIHM of commercial spent nuclear fuel and 7,000 MTIHM-equivalent of Department of Energy-owned spent nuclear fuel and high level nuclear waste. Efforts are underway to complete pre-closure and post-closure safety analyses based on this design, in accordance with 10 CFR 63. The current design and the safety analyses will be included in a license application for construction of the repository that is currently planned to be submitted to the U.S. Nuclear Regulatory Commission (NRC) no later than June of 2008 [3].

After construction authorization is granted, initial construction would begin. The license application and subsequent revisions to the application, made in response to NRC requests for additional information, would be updated to reflect any new or more detailed information and submitted to the NRC in support of receiving a license. Waste emplacement would begin following NRC approval to receive and possess waste, currently planned to occur in 2017 [3].

Full-scale deployment of advanced fuel cycles and the need to dispose of associated wastes is not expected to occur before 2020 [4]. This is after commercial spent nuclear fuel and DOE-owned spent nuclear fuel/high level nuclear waste would begin to be emplaced at Yucca Mountain. In addition, while an advanced fuel cycle could likely recycle all of the existing commercial spent nuclear fuel, some commercial spent nuclear fuel may still be directly disposed after advanced fuel cycle facilities are deployed. DOE-owned spent nuclear fuel and high level nuclear waste would still need to be disposed. Thus, development of the Yucca Mountain repository needs to proceed on-track to design, license, and construct a repository for the disposal of these waste forms.

The disposal of wastes from an advanced fuel cycle could be implemented later. Work under the Advanced Fuel Cycle Initiative (AFCI) has shown the potential to reduce both the volume and thermal density of nuclear waste that would require geologic disposal, as compared to the direct disposal of commercial spent nuclear fuel. This results from the separation of actinides and key fission products from commercial spent nuclear fuel combined with recycling of actinides and surface decay-storage of fission products. Volume and thermal reduction could result in improved utilization of sub-surface repository area. The removal of the actinides and key fission products from the waste stream could reduce the risk to the public, measured in terms of radiation dose, of operations at a repository and following closure of the repository after waste emplacement. Realizing these potential benefits for the Yucca Mountain repository would require design modifications, updated pre-closure and post-closure safety analyses, submittal of an amendment to the license (in accordance with 10 CFR 63.44), and approval by the NRC. This paper summarizes the potential benefits that may be realized from an advanced nuclear fuel cycle and discusses what information would need to be collected and the types of analyses/calculations that would need to be completed to support and complete the development of such an amendment and obtain NRC authorization to dispose of wastes from an advanced fuel cycle.

REPROCESSING/RECYCLING CONCEPTS

The radionuclide inventory in the waste and the amount of waste that is ultimately disposed are the fundamental variables that drive all aspects of repository performance ranging from thermal response to the dose that could potentially be received by the public following closure of the repository. As discussed above, the current design and operating mode of a repository at Yucca Mountain is based on disposing commercial spent nuclear fuel and DOE-owned wastes. The GNEP may propose to change the radionuclide inventory of waste that would require disposal by achieving the following goals [4]:

- Separation and recovery of transuranic (TRU) elements (plutonium, neptunium, americium, and curium) at better than 99 percent efficiency;
- Separation and recovery of two fission products, cesium and strontium, each at better than 99 percent efficiency; and
- Separation and recovery of the uranium at high purity, at better than 99.9 percent efficiency.

The separation processes that have been shown at laboratory scale to meet these criteria are the UREX+ family of aqueous separations processes and pyrochemical processing [5]. The UREX+ family is a suite of aqueous solvent extraction processes for partitioning light water (LWR) oxide fuels and pyrochemical processing is an electrorefining process primarily for the recycling of metal fuels discharged from fast reactors. The process flow sheets for each are shown in Figure 1 [6].

Although these separation goals have been achieved at the laboratory scale, it has not been demonstrated that they can be achieved at the larger scales needed for full GNEP deployment. Operations at the LaHague reprocessing plant have demonstrated that 99.9% of the uranium and plutonium can be recovered [7], giving some confidence that the GNEP actinide separation goals can be achieved for the UREX+ process. The proposed GNEP technology development program calls for the construction and operation of a Consolidated Fuel Treatment Center (CFTC) and an Advanced Fuel Cycle Facility (AFCF) that would provide the ability to develop and demonstrate aqueous and pyroprocessing separations technologies, transmutation fuel fabrication technologies, and state-of-the-art safeguards instrumentation and monitoring systems [4], in support of GNEP system deployment beyond 2020.

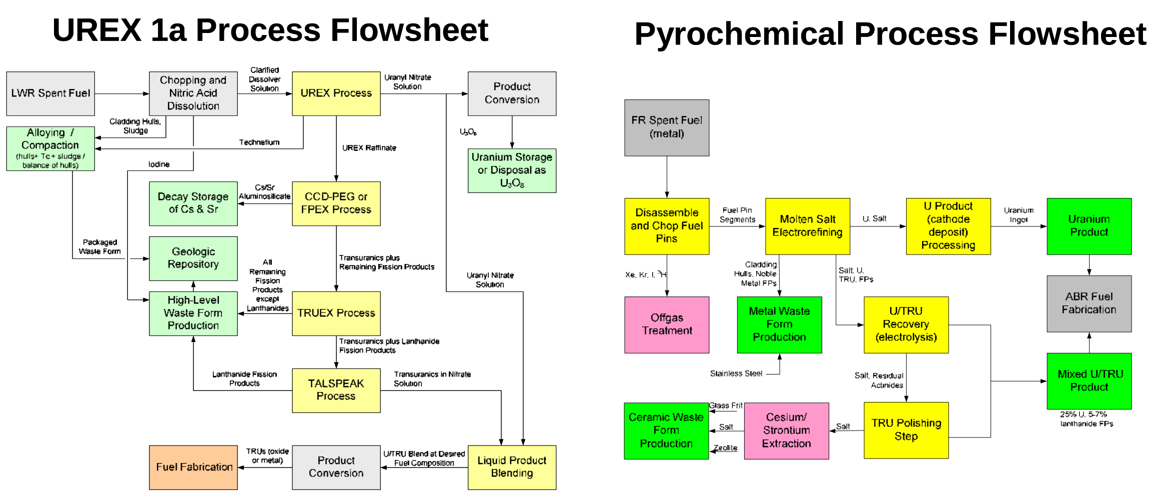

Fig. 1. UREX+ and pyrochemical process flowsheets [6]

The waste forms that would be generated by an advanced fuel cycle are not currently known and would depend on the separation method(s) ultimately chosen and waste form development activities at the AFCF. As shown in the process flowsheets shown in Figure 1, UREX+ and pyroprocessing have different waste streams with different disposition pathways, including geologic disposal, being considered. These include noble off-gas capture and decay-storage, Cs and Sr capture and decay-storage prior to disposal to allow these heat producing radionuclides to decay, and the capture and immobilization of fission products and trace actinides for geologic disposal. Several waste forms are under consideration for geologic disposal including glass (i.e., borosilicate- and phosphate-based), ceramic (e.g., Synroc, titanates, zirconates), hydroceramic, metallic, and glass-bonded zeolite (with the later two from pyroprocessing). Of these, only borosilicate glass has been sufficiently characterized for disposal in a proposed repository at Yucca Mountain. The properties of any waste forms generated by an advanced fuel cycle would have to be determined before they could be disposed, including:

- Waste form loading (MTIHM-equivalent/canister)
- Thermal density (kW/MTIHM-equivalent)
- Radionuclide inventory
- Waste form composition
- Degradation rate
- Degradation products
- Chemical environment

POTENTIAL EFFECTS ON REPOSITORY DESIGN

Repository Sub-Surface Facilities

As shown in Figure 2, the thermal density of commercial spent nuclear fuel is dominated by the heat generated mainly by the decay of fission products for the first 60 yr and from actinide elements thereafter. The current design of the sub-surface facilities at a proposed repository at Yucca Mountain is driven by the thermal density and has been chosen to satisfy thermal criteria related to the overall long-term performance of the repository (thermal aspects of design are not regulatory requirements). These criteria are [8]:

- Maximum center temperature between emplacement drifts of 96°C to ensure that the pillars between the emplacement drifts are free draining.
- Maximum cladding temperature of 350°C.
- Maximum waste package surface temperature of 300°C.
- Emplacement drift wall temperature below 96°C during the pre-closure period so as not to preclude cooler operating modes.
- Emplacement drift wall temperature below 200°C during the post-closure period to avoid potential mineralogical changes in the host rock.

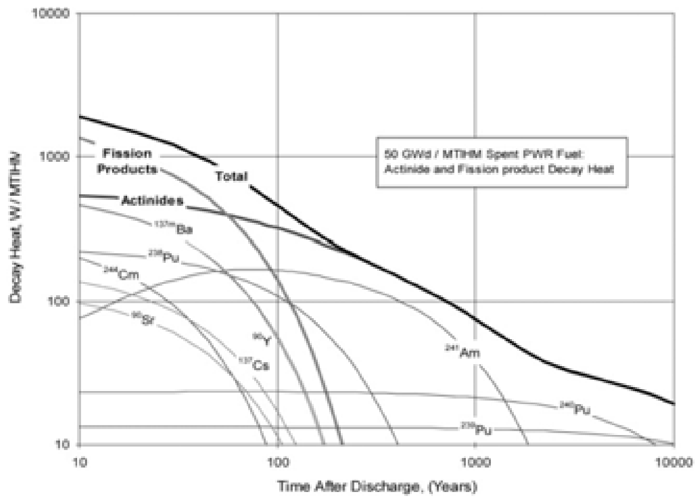

Fig. 2. Dominant decay heat contributors in spent PWR fuel irradiated to 50 GWd/MTIHM [9]

The variables associated with thermally optimizing the sub-surface repository design are illustrated in Figure 3. The thermal response of the repository depends on:

- The waste form thermal density profile (kW/equivalent MTHM) which is a function of the waste form types, quantities, and half-lives of the immobilized radionuclides.
- The waste package thermal output (kW), which is directly proportional to the amount of waste contained in a waste package.
- The emplacement drift linear heat rate (kW/m), which is controlled by the waste package thermal output and the waste package spacing.
- The emplacement drift spacing (which combined with the amount of waste contained in each waste package and the waste package spacing dictates the areal loading of the repository).

Changing these variables through design modifications and/or different operational parameters directly impacts the repository thermal regime. This methodology was used, given the thermal density of commercial spent nuclear fuel and the thermal constraints listed above, to guide the sub-surface design of the proposed repository at Yucca Mountain. This process resulted in the current sub-surface repository design being comprised of the following [8]:

- Drift spacing of 81 meters.
- Waste package spacing of 0.1 meters.
- Average emplacement drift line load of 1.45 kW/m.
- Maximum waste package thermal output of 11.8 kW.
- Ventilation flow rate of 15 m^3/s.
- Duration of waste emplacement of 23 years followed by 50 years of forced ventilation following emplacement of the last waste package.

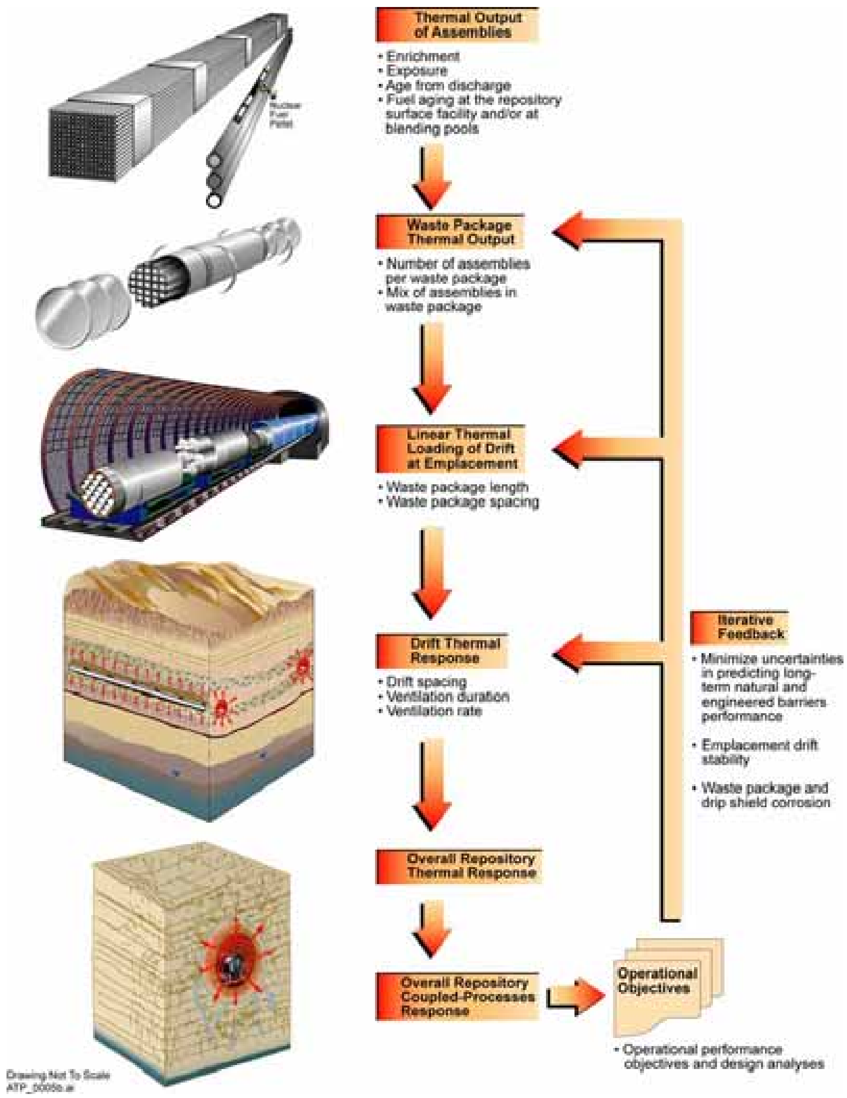

Fig. 3. Variables affecting the thermal performance of the repository [10, Figure 2-8]

The first variable shown in Figure 3, thermal output of assemblies, is equivalent to the thermal output of a waste form generated from an advanced fuel cycle. The waste form thermal output would depend on the thermal density which depends on the separation efficiency and the amount of waste that could be loaded into the waste form. This is shown schematically in Figure 4. Reducing the waste form thermal output allows increased flexibility in the design and operation of a repository by reducing one of the key variables affecting the repository thermal behavior.

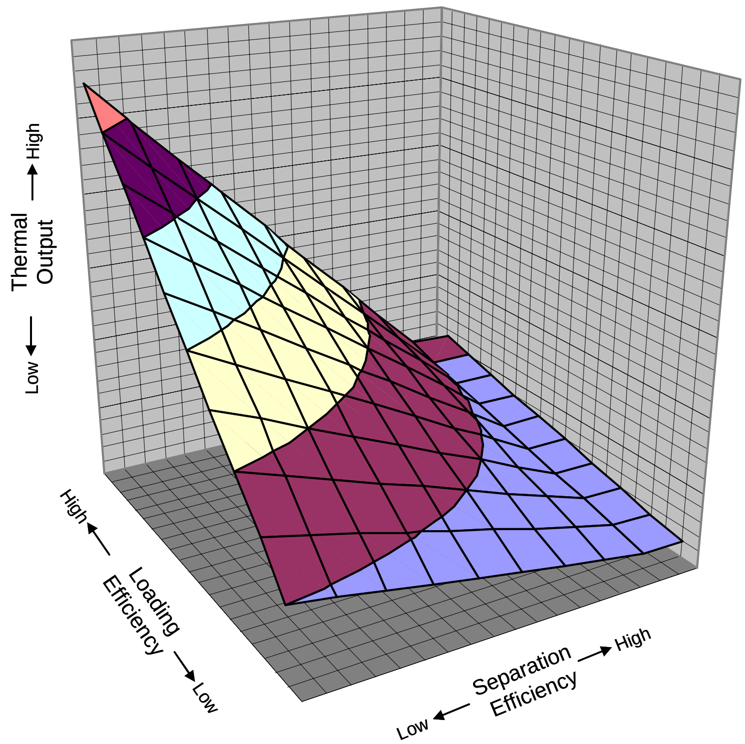

Fig. 4. Schematic showing dependence of waste form thermal output, separation efficiency, and waste form loading efficiency

Because the recycling technology still needs to be demonstrated and the waste form characteristics have yet to be determined, it is not currently possible to conduct such optimization analyses. Thus, the amount of waste that could be emplaced in a given area, under an advanced nuclear fuel cycle cannot presently be determined. However, analyses have been conducted to bound the thermal benefit that could be realized with recycling [9]. These bounds provided separations targets which if ultimately achieved would maximize the potential benefit, in terms of utilization of repository space, which could be realized. The analyses utilized two-dimensional thermal models of emplacement drifts spaced 81 meters apart with active ventilation at 15 m^3/s assumed to be operating for a 50 year period following emplacement of the last waste package.

The amount of waste that could be disposed in an emplacement drift was determined for recycling spent pressurized water reactor fuel with varying separation efficiencies (90%, 99%, 99.9%) by evaluating the thermal response against the thermal criteria listed above. The amount of waste that <u>hypothetically</u> could be disposed per meter of emplacement drift for each of these cases was determined by comparing the thermal response against the thermal criteria presented above. The results shown in Figure 5 show the hypothetical increase in waste that could be loaded per unit length of an emplacement drift, as compared to the direct disposal of spent pressurized water reactor fuel, for the different cases analyzed.

These results should not be construed as meaning that if separation efficiencies greater than 99% can be achieved, increases in the utilization of repository space by factors greater than 100 could be achieved. Rather, these results demonstrate that a large thermal benefit could be realized if such efficiencies are realized. Again, both the separation efficiencies and the waste form loading densities need to be determined such that the waste form thermal output can be quantified and the sub-surface repository design optimized.

For example, operation of the LaHague reprocessing plant indicates that waste volume reductions on the order of a factor of 4 are routinely achieved [7]. Such a volume reduction combined with separation efficiencies greater than 99% would result in a waste form with a very low thermal density, leading to low linear heat rates within the emplacement drifts. Optimization of the sub-surface repository design could then consider: 1) moving the emplacement drifts closer together, and/or 2) lessening the ventilation requirements for those drifts (rate and duration) while maintaining thermal performance within the thermal criteria presented above. Ultimately, drift spacing may be constrained by the mechanical and structural properties of the rock. These waste forms could also be co-located with any commercial spent nuclear fuel that would be disposed, analogous to the manner in which the current co-disposal waste packages are planned to be emplaced in the proposed repository [8].

The question as to whether a repository that would dispose wastes from an advanced fuel cycle would be constrained by volume or by thermal output cannot be answered at present and could only be known once sufficient information is known to optimize the subsurface repository design. This information includes waste form characteristics (i.e., waste form types, thermal density, loading density) and the total amount of waste that would ultimately be disposed in the repository.

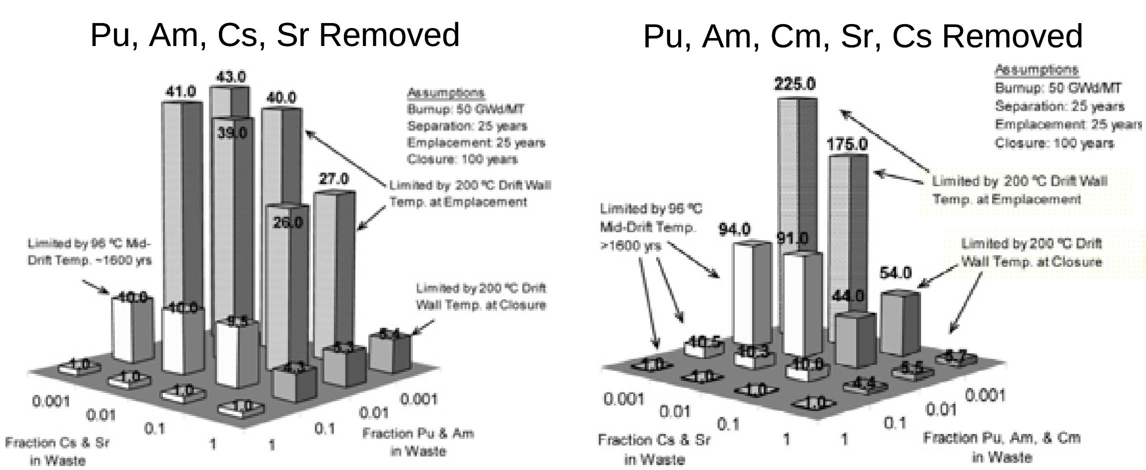

Fig. 5. Increase in the amount of waste that could hypothetically be placed in an emplacement drift for different separation efficiencies [9, Figures 7 and 8]

Volume limitations and thermal constraints should not be thought of as two independent constraints because the ultimate capacity of the repository would be constrained by both. Given complete relaxation of a specific inventory limit (e.g., 70,000 MTHIM), the total capacity would ultimately be limited by volume because only a finite amount of waste could be emplaced in the physically available space. Part of this physical volume would be used to dispose of DOE owned spent nuclear fuel/high level waste and Navy spent nuclear fuel that would not be recycled in an advanced fuel cycle. Wastes from recycling commercial spent nuclear fuel in an advanced fuel cycle having lower thermal densities could be emplaced with higher areal loadings while meeting thermal constraints allowing an increase in the total amount of wastes that could be disposed within the physical capacity.

Repository Surface Facilities

The surface facilities for the proposed repository at Yucca Mountain are being designed to be capable of processing individual commercial spent nuclear fuel assemblies and canisterized spent nuclear fuel assemblies, DOE-owned spent nuclear fuel, and DOE-owned high level nuclear waste into waste packages for ultimate disposal. It is expected that any waste forms generated by advanced fuel cycle processing facilities would be canisterized for transport to and disposal in a repository. Either the current facility designs could be modified to be capable of processing these waste forms or additional facilities could be designed and constructed, depending on waste disposal throughput requirements. Ultimately, an optimization of the repository surface facilities would be needed, once the characteristics of the advanced fuel cycle waste forms were determined. These characteristics include waste form types, canister sizes, and quantities.

The design of additional facilities or the revision of existing surface handling facility designs for processing waste forms from an advanced fuel cycle would be able to take advantage of the design analyses and calculations for both the current Yucca Mountain repository facilities and the waste handling processes in an advanced fuel cycle facility. It is likely that several of the facility functions and process steps will have undergone NRC review and approval. New and unproven design concepts would likely not have to be used, making any re-design effort simpler. Inherent in such an optimization and surface facility design effort is integration with the pre-closure safety analysis, which is discussed below.

PRE-CLOSURE REPOSITORY SAFETY

The design and operation of the repository must be shown to meet the preclosure performance objectives at 10 CFR 63.111 by conducting a preclosure safety analysis in accordance with 10 CFR 63.112. The preclosure safety hazard analysis involves identifying the natural and human-induced hazards at the geologic repository operations area, the development of potential event sequences, screening the event sequences based on frequency of occurrence, and a consequence analysis for those event sequences that need to be included.

Because the facilities that would process wastes from an advanced fuel cycle would likely be very similar to the current facility designs, the hazards and event sequences are expected to be similar. These hazards relate primarily to dropping, bumping, and/or tipping of fuel assemblies, canisters, and/or waste packages. The removal of the actinides and key fission products in an advanced fuel cycle would lessen the material at risk, potentially reducing the consequences of event sequences involving advanced nuclear fuel cycle waste forms. Consequence analyses conducted in support of the Yucca Mountain Site Recommendation indicate that several of the radionuclides, actinides in particular, that would be separated and recycled in an advanced fuel cycle contribute significantly to off-site doses for event sequences involving commercial spent nuclear fuel assemblies [11].

Additional factors could potentially reduce the risk associated with operations of the repository when considering waste forms from an advanced fuel cycle. For example:

- The design of the canisters that contain wastes from an advanced fuel cycle may be such that they would not breach under any credible event sequence.
- The waste forms from an advanced fuel cycle may be more durable than commercial spent nuclear fuel, resulting in a lower release of radionuclide-bearing respirable particles from any breached canisters.

Pre-closure safety analysis would be iterative and evolve as the design evolves and would provide feedback into the facility design effort. Ultimately, the facility designs would advance to the level where a pre-closure safety analysis that meets the requirements at 10 CFR 63 could be developed, supporting an amendment to a license. New data would have to be gathered regarding the advanced fuel cycle waste forms to support the pre-closure safety analysis effort, including:

- Waste form types and quantities
- Waste form loading densities
- Canister design
- Waste form behavior during accident scenarios

The pre-closure safety analysis for facilities that would handle waste forms from an advanced fuel cycle would be able to take advantage of the pre-closure safety analyses for both the current Yucca Mountain repository facilities and safety analyses for the waste handling processes in an advanced fuel cycle facility. The safety analyses for an advanced fuel cycle facility will be similar to those that would be conducted for repository handling facilities and would require similar data needs. However, as will be discussed later, the data would have to be able to support a pre-closure safety analysis that would be developed in accordance with 10 CFR 63 and Yucca Mountain quality assurance requirements.

POST-CLOSURE REPOSITORY SAFETY

Removing the actinides from commercial spent nuclear fuel in an advanced fuel cycle may potentially reduce the potential effective dose to the public if the actinides were recycled and remaining wastes were disposed in a repository at Yucca Mountain, as compared to the direct disposal of the commercial spent nuclear fuel [12]. Figure 6 shows a comparison over a one-million year period between the direct disposal of 70,000 MTIHM of commercial spent nuclear fuel and the disposal of processing waste from 70,000 MTIHM with 99.9% removal of all actinides. Note that these figures have been normalized to the peak of the estimated mean annual dose rate for the direct disposal of 70,000 MTIHM of PWR spent fuel. These results show the potential for either reducing the risk to the public for disposing 70,000 MTIHM-equivalent of high level nuclear waste or increasing the amount of waste that can be disposed while keeping the level of risk equivalent to or less than that for the direct disposal of commercial spent nuclear fuel [12].

These results, although preliminary and at a scoping level, demonstrate that a potential benefit exists. However, it must be recognized that the models used were simplified and far-removed from those that would be required to demonstrate compliance with post-closure performance requirements at 10 CFR 63. The entire systematic performance assessment process would ultimately have to be repeated in accordance with the requirements at 10 CFR 63.

A long-term performance assessment, some times referred to as a total system performance assessment (TSPA), is a systematic process for evaluating repository performance [13]. It begins with the identification of a comprehensive set of features, events, and processes (FEPs) that could potentially affect repository performance. These are then screened, based on probability or consequence, to determine those FEPs that need to be considered in a performance assessment. Detailed models of the FEPs, or combination of FEPs, are developed and the results of these detailed models are used to develop simplified representations for implementation into a total system model. The process is iterative with the results of performance assessment feeding back into data collection and design activities. The performance assessment model evolves as additional information is collected and the design evolves. This iterative and integrated process has been followed by the Yucca Mountain Project as is evident by the multiple TSPA analyses that have been completed over the last two decades.

It is not likely that disposing of wastes from an advanced nuclear fuel cycle would result in additional FEPs having to be included in a long-term performance assessment. However, a comprehensive re-evaluation of the FEPs would have to be completed to demonstrate that all FEPs important to long-term repository performance are considered in the performance assessments. The next step involves the development of detailed process-level models and abstraction-level models for inclusion in the performance assessment. It is these models that would change.

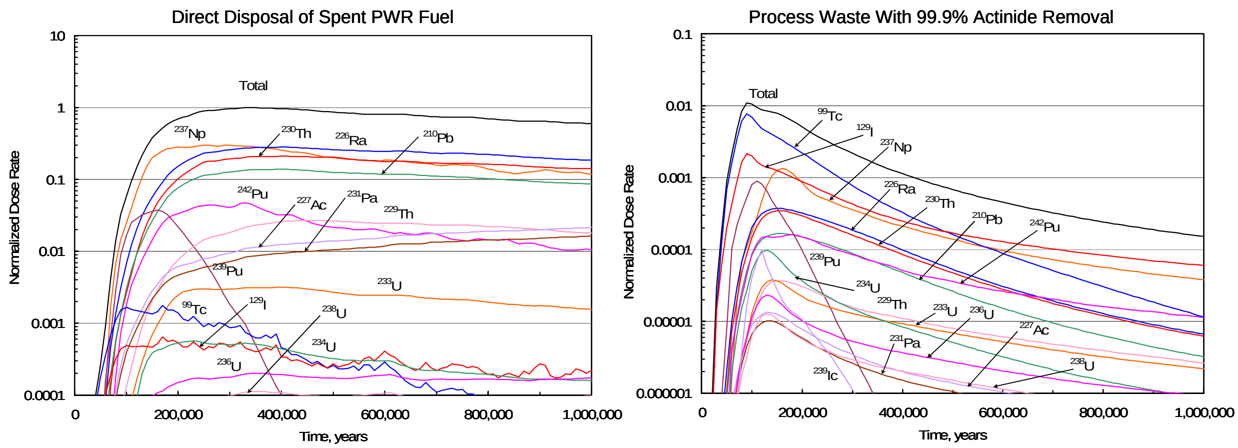

Fig. 6. Comparison of projected mean annual dose rates for the direct disposal of 70,000 MTIHM of commercial PWR spent fuel and the disposal of 70,000 MTIHM of process wastes with 99.9% actinide removal [12]

Revising the performance assessment to include waste forms from an advanced fuel cycle is not as simple as implementing new waste form models into the performance assessment because several of the FEPs are coupled. As discussed above, the removal of actinides and key fission products would reduce the thermal density of the waste and allow for an optimization of the repository design. This, combined with the total amount of waste that would be disposed and the volume of the waste, could result in a different sub-surface repository configuration. The unsaturated zone flow and radionuclide transport models would have to be revised to appropriately reflect a different repository configuration. The coupled thermal-hydrologic model would have to be modified to include both new thermal characteristics of the waste and a modified unsaturated zone flow regime. The thermal response would then impact waste package and waste form degradation rates. The manner and rates that the waste forms degrade would affect the chemical environment within a breached waste package, which could in turn affect the degradation rate. The waste form degradation rate, the in-package chemical environment, and the degradation products all affect the rate that radionuclides would be released.

This discussion points out some of the coupled models that would need to be developed and/or revised to implement additional waste forms from an advanced fuel cycle into the long-term performance assessment. All models would have to be reviewed and developed and/or revised to ensure that all couplings are appropriately captured. Any newly developed or revised models would ultimately have to satisfy the acceptance criteria in the Yucca Mountain Review plan (YMRP) [14]. These acceptance criteria will be used by the NRC in its review of the post-closure safety case and include criteria for model integration, data sufficiency, and uncertainty treatment and propagation.

The foundation of a performance assessment and the detailed process-level modeling is data collected through site investigations or experimental measurements. The inclusion of additional waste forms from an advanced fuel cycle could potentially require additional site investigation and would surely require experimental information about the durability of the waste forms themselves. Much of this needed information is identical to that discussed above. The gathering of additional experimental information, and any needed site investigation data, should be focused by modeling needs to satisfy the YMRP acceptance criteria.

As discussed above, the performance assessment process is iterative with the results of performance assessment feeding back into data collection and design activities, followed by evolution of the performance assessment model. This integrated and iterative process will need to be continued as efforts proceed to develop and characterize waste forms that would be generated by an advanced nuclear fuel cycle.

QUALITY ASSURANCE ASPECTS

The YMRP establishes the technical criteria the NRC will use in evaluating the pre-closure and post-closure safety analyses for a repository at Yucca Mountain. Quality assurance requirements, contained in the Quality Assurance Requirements and Description (QARD) [15] document, must also be met. The QARD establishes quality assurance requirements designed to meet 10 CFR 63, Subpart G, Quality Assurance including requirements for software, data, models, scientific analyses, scientific notebooks, and engineering calculations. These requirements are implemented into procedural requirements. Anything supporting an ultimate safety case for the demonstration of compliance with regulatory requirements must be done in accordance with these requirements and deemed qualified. All activities related to the ultimate disposal of advanced nuclear fuel cycle waste forms in a repository at Yucca Mountain should be performed, as much as practicable, in accordance with the QARD requirements from the onset to ensure that everything developed is available for use in future evaluations of compliance with 10 CFR Part 63. This includes data collection (experimental and/or site investigation), software development, model development, calculations, and analyses.

CONCLUSION

The discussion above demonstrates that recycling commercial spent nuclear fuel with the separation and recovery of actinides and key fission products could prove beneficial in terms of managing and disposing of nuclear waste. The discussion also points out that the ultimate disposition of recycling wastes involves a potentially complex regulatory process that will ultimately require revisions to the pre-closure and post-closure safety analyses and amendments to a repository license. Integration between all involved, including those responsible for developing the waste forms, the processing facilities, and the disposal system is essential. This integration should occur from the onset to ensure that an optimal solution is ultimately achieved.

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REFERENCES

1. *Global Nuclear Energy Partnership Fact Sheet*. U.S. Department of Energy (2006). Available at http://www.gnep.energy.gov/pdfs/06-GA50506-01.pdf.
2. Nuclear Waste Policy Amendments Act of 1987. Public Law No. 100-203. 101 Stat. 1330.
3. E.F. Sproat (2006). U.S. Department of Energy Testimony before the Subcommittee on Energy and Air Quality Committee on Energy and Commerce, U.S. House of Representatives, July 19, 2006.
4. Spent Nuclear Fuel Recycling Plan, Report to Congress, U.S. Department of Energy (May, 2006). Available at http://www.gnep.gov/pdfs/snfRecyclingProgramPlanMay2006.pdf.
5. Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2006 Update, U.S. Department of Energy (July 2006)
6. J.J. Laidler, "Development of Spent Fuel Processing Technologies in the United States", OECD/NEA 9th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Nimes, France (September 2006).
7. J. Thomasson, S. Barithel, A. Cocaud, P. Derycke, P. Pierre, "The Universal Canister Strategy in Spent Fuel Reprocessing: UC-C a Real Industrial Improvement", WM'04 Conference (February 2003).
8. P. Harrington (U.S. Department of Energy), "Project Operational Thermal Management Strategy", presentation to the U.S. Nuclear Waste Technical Review Board (February 2005).
9. R.A. Wigeland, T.H. Bauer, T.H. Fanning, and E.E. Morris, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository." Nuclear Technology, Vol. 154 (April 2006).
10. Yucca Mountain Science and Engineering Report. DOE/RW-0539, Rev. 1. U.S. Department of Energy (2002).
11. Design Basis Event Frequency and Dose Calculation for Site Recommendaiton, CAL-WHS-SE-000001 REV 01 ICN 02, Bechtel SAIC LLC (December 2001).
12. R.A. Wigeland, E.E. Morris, T.H. Bauer, "Criteria Derived For Geologic Disposal Concepts", OECD/NEA 9th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Nimes, France (September 2006).
13. Yucca Mountain Site Suitability Evaluation, DOE/RW-0549, U.S. Department of Energy (February 2002).

14. Yucca Mountain Review Plan, NUREG-1804 Rev. 02, U.S. Nuclear Regulatory Commission (July 2003).

15. Quality Assurance Requirements and Description Rev. 18, DOE/RW-0333P, U.S. Department of Energy (October 2006). Available at http://www.ocrwm.doe.gov/documents/qard/48027/48027.pdf.