THE IMPORTANCE OF A REPOSITORY TO ADVANCED NUCLEAR FUEL CYCLES

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INTRODUCTION

Considerable interest and effort are being focused on the development of advanced fuel cycles involving new reactor designs, reprocessing and recycling technologies, and waste forms. Some of these will have a beneficial impact on high-level waste management requirements, by reducing - perhaps greatly - the quantity of long-lived radionuclides requiring disposal and producing high-performance waste forms. This has led some to argue that development of repositories can be deferred, perhaps indefinitely. However, history indicates that this is an error of significant proportions. The low priority that the Atomic Energy Commission gave to waste management compared to reactor development was an important cause of the evolution of "the waste management problem" as an obstacle to the nuclear power option.[i] Nuclear power systems must be understood and approached as integrated systems, from cradle to grave. Development of permanent repositories for disposal of waste from advanced fuel cycles and/or waste treatment technologies should be viewed as an integral part of the effort to develop those technologies. This paper discusses the key policy and technical interdependencies between a repository and the rest of the nuclear fuel cycle.

DISCUSSION

Implications of Advanced Nuclear Fuel Cycles for a Geologic Repository

While advanced fuel cycle and waste treatment technologies could ease the high-level waste disposal problem, there are no waste treatment technologies on the horizon that can eliminate or even delay the need for a geologic repository.[ii] They can at best reduce or delay the need for a second repository. Advanced fuel cycle technologies involve reprocessing the spent nuclear fuel from reactors yielding three basic products: short- and long-lived fission products and transuranics. The collective disposition of these products – through recycling, transmutation, or disposal – will define the relationship between the fuel cycle and repository.

Insight into the possible impact of the Advanced Fuel Cycle Initiative can be gained by examining the five-phase process for implementation of advanced nuclear fuel cycles in the U.S. described by Laidler and Bresee.[iii]

- Phase 0, running past 2020, is the current once-through cycle in which spent fuel would be stored and ultimately sent for direct disposal in a repository.
- Phase 1, starting in the 2020s, would involve reprocessing spent fuel to remove uranium for separate disposal as low-level waste, strontium and cesium for long-term storage until they have decayed, with the remaining transuranics and fission products going to the repository for disposal.
- Phase 2, starting after 2030, would be similar to phase 1 except that plutonium and neptunium would be separated for recycling in light water reactors.
- Phase 3, starting around 2040, would be similar to phase 2, except that all of the transuranics would be removed for destruction in dedicated burner (fast) reactors, and the uranium would be recycled.
- Phase 4, starting after 2040, would implement generation IV reactors and all of the actinides would be recycled through those reactors.

Laidler and Bresee conclude that given conservative or reasonable nuclear growth rates, a single Advanced Fuel Cycle Initiative spent fuel processing facility with an annual throughput of 2,000 MTHM might be sufficient for Phases 1-3. At that capacity, this facility would merely keep up with the nominal annual rate of spent fuel generated by light water reactors and would only be capable of addressing inventories beyond the 70,000 MTHM statutory limit of Yucca Mountain. Therefore, planning for direct disposal of at least the first 70,000 MTHM of spent fuel is prudent because any beneficial impacts of advanced fuel cycles on waste management would apply primarily waste generated after those cycles are implemented. This would substantially reduce the need for additional geologic disposal capability above the initial 70,000 MTHM limit for Yucca Mountain.

Consequently, it is most productive at this time to think of waste management benefits of treatment technologies for light water reactor spent nuclear fuel and future Advanced Fuel Cycle Initiative waste forms beyond the initial 70,000 MTHM planned for Yucca Mountain. Such consideration is consistent with the current waste management and disposal policy authorized by the Nuclear Waste Policy Act, which contains a provision for the Secretary of Energy to address the need for a second repository by reporting to Congress by 2010. The Department of Energy addressed this point in the Advanced Fuel Cycle Initiative program's 2003 report to Congress:

> "Similarly, it is far too early to rely on this emerging technology to plan for the future. For this reason, DOE believes that all analyses regarding the future of nuclear power in the United States should assume the continued use of current fuel cycle technology and the application of a deep geologic repository early in the next decade. While we recommend no change in current planning at this time, we do recognize that if nuclear power continues to operate in this country for the long term, it will continue to produce significant quantities of spent nuclear fuel. This fact presents long-term challenges that must be addressed."[iv]

These considerations have led to a near-term focus by the Advanced Fuel Cycle Initiative program on providing information for the statutorily required report to Congress on the need for a second repository to be delivered by DOE between 2007 and 2010. With that perspective, there are a number of ways that advanced fuel cycle and waste treatment technologies could ease the high-level waste disposal problem, even though they could not eliminate it. Advanced reactor concepts involving some form of radionuclide recycling have the potential to transmute waste products both in the existing spent nuclear fuel and the fuel designed for those reactors. This could substantially reduce the volume, toxicity, and heat output of the wastes requiring disposal. With any advanced technology that involves some form of processing of spent nuclear fuel prior to disposal, there is also the opportunity to use a high-performance (e.g. low-solubility) waste form that might improve repository performance.

Impacts of Advanced Fuel Cycle Initiative on the Need for Future Repositories

Wigeland et al. note that repository area is a scarce resource, so that efforts to conserve it by reducing the area required for disposal of the waste from a unit amount of nuclear electricity generation would be advantageous.[v] There are two ways to do this – reduction of the physical volume of the waste, and reduction of the heat output. This analysis is relevant as applied to potential expansion of a Yucca Mountain repository or the need for a second repository, in either case to manage the waste beyond the 70,000 MTHM statutory limit.

Waste volume reduction

In phase 1 of the advanced fuel cycle deployment scenario described by Laidler and Bresee, the only material that would be separated from the spent fuel during reprocessing would be the uranium, to be reused in fuel or disposed of as low-level waste. Since uranium represents the great majority of the volume of the fuel, this separation would provide the major potential reduction in waste volume. However, the net decrease in volume will depend on the waste loading that is achievable for the high-level waste form. As discussed further below, whether reduced waste volume also translates into a reduced requirement for repository area depends first and foremost on the removal of heat-generating radionuclides, not uranium, since disposal area is determined by the heat output of the waste.

rmal output reduction

The greatest potential impact for reduction in the area required for high-level waste disposal comes from removal of the principal heat-generating radionuclides. Two thermal design objectives in the proposed Yucca Mountain repository are key: a 96^{o}C maximum temperature for the center of the pillars between disposal drifts, and a 200 ^{o}C maximum drift wall temperature. Keeping the center of the pillars below boiling is intended to ensure that water mobilized by the heat from the waste can drain downward between the pillars instead of pooling above the drifts. Wigeland et al. showed that in the case of once-through spent fuel, the mid-pillar temperature limit is the binding constraint because of the long-term integrated heat output from the long-lived major actinides, primarily americium and plutonium.[vi] They showed that removal of the plutonium and americium for separate disposition would have the potential of reducing the size of a repository at Yucca Mountain for 70,000 MTHM of commercial spent nuclear fuel by a factor of 4.3 to 5.4. Once those long-lived heat sources are removed, the 200 ^{o}C drift wall temperature limit becomes the binding constraint because of the temperature peak soon after closure caused by the heat output of strontium-90 and cesium-137 – two principal fission products with half-lives of approximately 30 years. Removal of the strontium and cesium for separate disposition – in addition to removal of the plutonium and americium – could allow a further reduction in area, up to a total factor of 40. With all of these radionuclides removed, some short-lived fission products and minor actinides (e.g., curium) become the dominant heat source, making the 200^{o}C drift wall temperature limit the binding constraint at the time of emplacement of the waste (instead of soon after closure, as in the case of strontium and cesium). Removal of these radionuclides would have the potential for further reductions in disposal area.

The ability to achieve these potential reductions in disposal area depends on several important factors. First, there must be some means of destroying or otherwise disposing of these materials somewhere else.[vii] The option that is frequently suggested for disposition of the cesium and strontium is separate storage for perhaps 300 years (10 half-lives), until they have decayed to a fraction of their current level. At that point they might be disposed of as low-level waste or emplaced in a high-level waste repository with little thermal impact and little long-term impact on dose. Such storage might be done in a separate surface storage facility or in the repository during an extended period of open operation, perhaps in a remote section with relaxed thermal constraints because the relatively short length of the thermal pulse and the rapid decay of the source term would render thermal impacts less important. Storage for a period of several centuries is likely to be technically feasible. However, it raises new policy issues that have not yet been debated. Centuries-long monitored storage has not yet been accepted as a waste management option in the U.S. It is unclear whether current regulations would allow for dependence on institutional control beyond 100 years or so. An appropriate regulatory framework for long-term storage dependent on institutional control might need to be developed.

Finally, the ability to realize the full benefit from removal of heat generating radionuclides in terms of reduction in disposal area will depend upon the ability to produce heavily-loaded waste forms.[viii] Once the heat generators are removed, the limit to the amount of waste that can be placed in a drift becomes the number and dimensions of disposal packages, which depend on the volume of the loaded waste form, not the volume of the high-level waste itself. The currently-planned high-level waste loading for borosilicate glass is on average about 30 percent – meaning that the volume of the waste form is about 3 times the volume of the high-level waste to be disposed of. With an advanced fuel cycle, improved waste forms with a higher fractional waste loading might be possible. In addition, there could be an opportunity to consider whether larger and/or differently configured high-level waste canisters than the current designs could reduce the amount of unused space in the waste packages, allowing an increased waste loading per package and hence an increased linear waste loading in the drifts.

Reduction in dose

In addition to reducing the heat output of the waste, separation of certain radionuclides for separate treatment and disposition could reduce the dose resulting from additional wastes beyond the initial 70,000 MTHM. This could allow disposal of more waste in a repository for a given dose standard. The importance of such a reduction depends on the dose standard that the repository must meet. As Wigeland et al point out, the currently projected dose from a Yucca Mountain repository is so far below the vacated 15 millirem standard during the first 10,000 years that additional reductions through separations and transmutation would have little relative benefit for performance in that time period. However, this may not be the case with a standard applied at the time of peak dose, several hundred thousand years into the future, when long-lived radionuclides such as technecium-99, iodine-129, neptunium-237, and the various isotopes of plutonium are modeled in the DOE Yucca Mountain Environmental Impact Statement to have reached the accessible environment, although not at dose levels considered harmful to public health and safety. A peak dose standard may be required by the July 2004 federal court decision that directed EPA to issue a new regulation consistent with the NAS 1995 recommendation that compliance at the time of peak dose be assessed.

DOE’s long-term dose calculations in the Yucca Mountain Environmental Impact Statement show that the dominant contributor is neptunium-237. The primary source of neptunium-237 is americium-241, which is principally produced by plutonium-241 decay. Consequently, the most significant impact on peak dose in the long term would result from removal of these principal actinides – americium and plutonium – for separate transmutation. Importantly, that step would also reduce or essentially eliminate the long-term integrated heat output from the waste – the necessary first step for achieving a significant reduction in the amount of disposal area required per unit of nuclear electricity generation. Again, destruction – not simply separation – of these radionuclides would be needed to achieve these benefits.

Implications of Repository Development for Advanced Fuel Cycle Initiative

The discussion so far has focused on implications of implementation of advanced fuel cycles for a Yucca Mountain repository. As noted, these impacts are relevant to operation of the repository after the 70,000 MTHM statutory limit has been reached. The implications of the development of a Yucca Mountain repository for implementation of advanced fuel cycles could be more immediate.

It is important to recognize that the legal framework governing the development of a Yucca Mountain repository, the Nuclear Waste Policy Act as amended, is fully compatible with implementation of advanced fuel cycles involving waste processing technologies. In fact, the Act is essentially fuel cycle-neutral. A repository developed under the Act must be capable of disposal of both spent fuel and high-level waste from reprocessing. The discussions preceding passage of the Act included consideration of whether the repositories should be only for high-level radioactive waste from reprocessing spent fuel (as originally expected), or for spent fuel as well. Some argued that reprocessing and recycling of the plutonium was advantageous for safe long-term waste disposal, and that spent fuel should not be disposed of since it was a valuable energy resource.[ix] Others argued that separation and reuse of plutonium heightened the risk of proliferation of nuclear weapons, and that spent fuel could be disposed of safely without reprocessing.[x] Several studies had supported the conclusion that reprocessing of spent fuel is not required for safe isolation of the waste.[xi,xii] Reflecting this conclusion, the Act provides for repositories for the disposal of both high-level waste and spent fuel. At the same time, it reflects the disagreement about the possible future reuse of spent fuel – a disagreement that remains unresolved today – in the fact that it refers only to "such spent fuel as may be disposed of" and requires retrievability of spent fuel (but not of high-level waste) for possible economic reasons.

The Nuclear Waste Policy Act is a forcing function for the development of the repository and the regulations that it must meet. Successful licensing and development of a Yucca Mountain repository as directed by the Act would resolve many waste management uncertainties that would affect decisions concerning the development of advanced fuel cycles. It is important to know the repository site and design, the regulatory performance criteria, and what is required to demonstrate compliance with them in order to assess the importance of the potential waste management benefits of advanced fuel cycles and to develop waste-management-based design criteria for advanced fuel cycle facilities and processes.

Timely licensing and operation of a repository would facilitate siting, constructing, and operating the facilities needed for advanced nuclear fuel cycles or waste treatment by allaying fears that those sites would become *de facto* long-term high-level waste repositories for lack of any place else to send the waste. Efforts to site both high- and low-level radioactive waste management facilities have encountered substantial, and often insurmountable, difficulties in gaining public acceptance. A 1992 review of public acceptance issues associated with transmutation noted that surveys since the Three Mile Island accident show strong public resistance to siting nuclear facilities in general, and nuclear waste facilities in particular, near where they live.[xiii] Any advanced fuel cycle would require siting a number of new nuclear facilities. Such facilities might be subject to the same siting difficulties that have faced other nuclear facilities, including repositories, in the past. Continued progress on a high-level waste repository is likely to be needed to provide assurance that any "interim" sites for waste processing and storage remain truly "interim."[xiv]

CONCLUSION

As the National Academy of Sciences recommended in 1996, advanced nuclear fuel cycles and waste treatment technologies should be pursued as a potential long-term complement to the expeditious development of a geologic repository, not as an alternative.[xv] That prudent policy is embedded in the current Department of Energy Strategic Plan, which includes two key strategies for management of high-level radioactive waste and spent nuclear fuel.[xvi]

1. Take the necessary steps to establish a permanent geologic repository for high-level waste and spent nuclear fuel at the Yucca Mountain, Nevada, site.
2. Lead an international long-term research program on advanced technology options to promote future waste-management alternatives, which could significantly reduce the amount of future spent nuclear fuel requiring disposal."

Well over 70,000 MTHM will have been discharged by existing reactors by 2020. This suggests that for a reasonable nuclear development scenario, planning for direct disposal of at least the first 70,000 MTHM of spent fuel is prudent. As a result, any beneficial impacts of advanced fuel cycles on waste management would be relevant to waste generated after those cycles are implemented, and would affect the need for and impact of additional geologic disposal capability beyond the initial 70,000 MTHM limit for Yucca Mountain. Consequently, it is most productive at this time to think of waste management benefits of treatment technologies for light water reactor spent nuclear fuel and future Advanced Fuel Cycle Initiative waste forms beyond the initial 70,000 MTHM planned for Yucca Mountain. Such consideration is consistent with the current waste management and disposal policy authorized by the Nuclear Waste Policy Act, which contains a provision for the Secretary of Energy to address the need for a second repository by reporting to Congress by 2010.

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xiv. "Continued visible progress toward the establishment of such permanent waste facilities — providing some confidence that "interim" facilities will not become "permanent"—is likely to be essential to gaining political acceptance for the establishment of adequate interim storage." Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective near-Term Approach to Spent Fuel Management, A Joint Report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy, June 2001. Authors: Matthew Bunn, John P. Holdren, Allison Macfarlane, Susan E. Pickett, Atsuyuki Suzuki, Tatsujiro Suzuki, Jennifer Weeks. See also Massachusetts Institute of Technology (MIT). (2003) *The Future of Nuclear Power: An Interdisciplinary MIT Study*. Cambridge, Mass.: Massachusetts Institute of Technology, July.

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xvi. The Department of Energy Strategic Plan, "Protecting National, Energy, and Economic Security with Advanced Science and Technology and Ensuring Environmental Cleanup, " Draft: August 6, 2003, p. 28: "The President's budget for the Department's repository program supports the completion of work needed for the submission of a license application to the Nuclear Regulatory Commission (NRC) in 2004 and the development of a repository and associated transportation capabilities needed to initiate repository operations by 2010. The Department will pursue two strategies to accomplish this goal. The Department will:

1. Take the necessary steps to establish a permanent geologic repository for high-level waste and spent nuclear fuel at the Yucca Mountain, Nevada, site.
2. Lead an international long-term research program on advanced technology options to promote future waste-management alternatives, which could significantly reduce the amount of future spent nuclear fuel requiring disposal."