THE BOSTON CONSULTING GROUP

ECONOMIC ASSESSMENT OF USED NUCLEAR FUEL MANAGEMENT IN THE UNITED STATES

Report

July 2006

Prepared by the Boston Consulting Group for AREVA

NOTE TO THE READER

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EXECUTIVE SUMMARY

Governments and industry have debated several options for managing used fuel in the 40 years during which nuclear power generation has spread across the industrial world. Countries using nuclear energy have adopted different strategies — some pursuing a "recycling" strategy in which used nuclear fuel is treated and then reused as a component of new reactor fuel and some pursuing a "once-through" strategy in which untreated used fuel is stored, later to be emplaced in a permanent geological repository.

For the last 20 years, the U.S. have pursued development of a geologic repository for used fuel disposal — the once-through strategy — at Yucca Mountain in Nevada. The key benefits of that strategy are: a) capacity to handle all legacy used fuel (estimated at 54,000 metric[1] tons in 2005, currently stored at nuclear power plants); b) capacity to handle additional used fuel discharged after a period of cooling and interim storage, provided that additional repository capacity is available; and c) no further need for handling or processing of used fuel after disposal which, to that extent, makes the once-through strategy a complete lifecycle solution.

DOE 2001[2] cost estimates for a U.S. repository that is capable of storing a total quantity of 83,800 tons of commercial used fuel indicate a lifecycle investment of about $46B[3], not including costs for interim storage at power plants. Over the last decade, however, several factors have led to questions about the appropriateness of the once-through fuel cycle as an exclusive used fuel management strategy. In particular:

- Cost estimates of the once-through strategy at Yucca Mountain have significantly increased from initial estimates, in part because of increasingly stringent design requirements. Moreover, at the current rate of used fuel generation, additional repository capacity is likely to be needed for fuel discharged after 2035, even considering that Yucca Mountain capacity could be expanded to 120,000 tons.[4]
- A long-term increase in new U.S. nuclear generation is likely — beyond the currently installed 103 GW to at least 112 GW, based on incentives in the 2005 Energy Policy Act, and potentially to 160 GW, especially if significant carbon abatement legislation is enacted. Thus, strategies to manage additional used fuel must be considered.
- The underlying economics of alternative used fuel management solutions, such as recycling, have shifted, driven in part by higher uranium prices and by a deeper understanding of the long-term behavior of recycling byproducts, which leads to significant optimization of repository space.
- The recycling strategy has gained recognition through the demonstrated, long-term operational effectiveness of recycling technologies over more than 40 years of industrial experience, in combination with a higher level of confidence based on economic data from actual operations. This return of experience has also enabled some successive process and design improvements.

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[1] "Tons" always refer to metric tons for the purpose of this study.

[2] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

[3] DOE undiscounted life cycle cost estimates are reported to 2005 $ and netted of estimated cost to dispose of non-commercial nuclear waste.

[4] Estimated "Technical capacity" that could be reached at Yucca Moutain, using geologically-suitable area available within the site.

These changes make it important to further investigate recycling as part of a comprehensive nuclear waste management strategy and complementary to an exclusive once-through strategy.

In this context, BCG performed an independent study, funded by AREVA, to review the economics of the back-end of the nuclear fuel cycle and, in particular, of developing a recycling strategy in the United States. The study takes into account the specificities of the U.S. context (such as the need to handle legacy fuel) and considers possible complementarities with the current Yucca Mountain repository project. It also considers elements beyond economics, such as flows of used fuel, financing requirements and potential risk management benefits.

Those objectives were achieved using two analytical approaches. The first is a theoretical comparison of, on the one hand, the estimated long-term cost of recycling used fuel and, on the other, the possible cost of a repository to handle the same used fuel in a once-through strategy. This comparison is referred to as the “Greenfield” approach. The second approach involves comparison of, on the one hand, recycling as a solution that would complement development of the Yucca Mountain repository, termed the “Portfolio” strategy, and, on the other, a pure once-through strategy that will require additional repository capacity in the future. This second approach is referred to as the “Implementation” approach.

Where applicable, BCG leveraged AREVA know-how and proprietary data from over twenty years of nuclear recycling experience. The data from AREVA operations, supplemented by site visits and additional analyses were used by BCG as a starting point for an independent, third-party assessment of the recycling strategy. BCG triangulated on and verified key economic drivers — particularly those related to recycling — using its experience in industrial cost assessment, the value of scale, operating experience, and the like. In addition, BCG developed bottom-up estimates and triangulations for key gaps, such as transport and storage. Finally, BCG leveraged existing publicly available sources of information on repository economics, updating for known and accepted changes. The conclusions are as follows.

In the Greenfield approach, the overall discounted cost of recycling used fuel is in the order of \$520/kg, comparable to the cost of a once-through strategy, estimated at about \$500/kg, especially considering uncertainties that surround many of the variables used in the assessment, such as uranium price and repository costs.

In the Implementation approach, the cost of a portfolio strategy, based on a new integrated recycling plant opening in 2020 and handling 2,500 tons/year, combined with development of a repository (Yucca Mountain) for high-level waste from recycling (HLW-R) and untreated legacy fuel, has a total net present cost of \$48-53B. That assessment is based on a treatment process, COEX™, that does not separate pure plutonium at any point in the recycling plant. The net present cost of an exclusive once-through strategy with Yucca Mountain and an additional repository is estimated at \$47-50B. Total undiscounted life cycle cost for the recycling strategy is about \$113B, compared to about \$124-130B for the once-through strategy in which a larger portion of the cost is deferred. Once again, given the intrinsic uncertainties of the assumptions used in this study, the economics of the two strategies are comparable.

This study is aimed at back-end economics and does not enter into discussion of additional topics or criteria such as public acceptance, environmental or non-proliferation issues, even though BCG acknowledges their importance for decision makers as they weigh the merits of alternative choices. The study does not explicitly address or discuss potential legislative actions required to pave the way for a recycling strategy in the U.S.

As with all other options, the recycling strategy involves some issues that need to be addressed. In particular, successful implementation would require:

- Broad-based acceptance of recycled fuel by the nuclear industry, as recycled fuel would have to be used in a significant number of reactors.
- A positive legislative, policy, and financial environment for recycling.
- Development of optimal solutions, such as use in fast reactors or multiple recycling, to manage the relatively limited quantity of used MOX fuel, yet with flexibility on the timing.

In addition, recycling, as part of a portfolio strategy, presents a number of benefits:

- Eliminates the need for additional repository capacity, beyond the initial 83,800 ton capacity at Yucca Mountain, until 2070.
- Contributes to early reduction of used fuel inventories at reactor sites — in particular, removing newer, hotter fuel for recycling within three years of discharge and eliminating the need for additional investments in interim storage capacity.
- Relies on existing technology — with appropriate modifications — and can provide an operational transition to future technology developments such as Advanced Fuel Cycles and fast reactors.
- Shows cash flow requirements that could fit until 2030 within the current financing resources available for the once-through strategy, or even until 2050+ if acceptance of used fuel at Yucca Mountain begins only after the first years of operation of the recycling plant.
- Offers a tool for nuclear power sector to protect against potential rises in uranium prices, by providing MOX and recycled UOX fuel[5], whose production cost is independent of uranium prices and enrichment costs.

The benefits are compelling enough to warrant further consideration of recycling as a complementary approach to developing Yucca Mountain capacity.

The report is structured as follows: after a brief account of the context and methodology (section 1), the key alternatives for used nuclear fuel management are described and key economic results provided, for both the Greenfield approach and the Implementation approach (section 2). Then, more detailed results for cost analyses, fuel flows, financing and risk management are presented (section 3). Key implementation challenges that a U.S. recycling strategy would have to overcome to be successful are addressed (section 4). Finally, overall conclusions are drawn (section 5). Detailed information on specific assumptions, methodologies and key economic results are presented in the appendix.

References are footnoted at the bottom of each page. Some figures are footnoted within the figures themselves to clarify statements or assumptions that might not have been self-evident.

5 MOX and recycled UOX fuel estimated to satisfy 20-25 percent of U.S. fuel requirements.

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1. CONTEXT AND METHODOLOGY

1.1. Context

Governments and industry have debated several options for managing used fuel in the 40 years during which nuclear power generation has spread across the industrial world. Countries using nuclear energy have adopted different strategies — some pursuing a "recycling" strategy in which used nuclear fuel is treated and then reused as a component of new reactor fuel and some pursuing a "once-through" strategy in which untreated used fuel is stored, later to be emplaced in a permanent geological repository. Recycling has been adopted at some point in countries representing 30-40 percent of global installed nuclear capacity, while a strategy of storing used fuel for eventual permanent disposal has been the case in the balance of countries.

There are four operational treatment plants in the world: the first one at La Hague, France, operating in conjunction with the MOX fuel fabrication plant at Melox, and operated by AREVA, the second one at Sellafield, U.K., operated by British Nuclear Fuels, the third one in Ozersk, Russia, operated by the Russian government (Mayak plant), and the fourth one at Rokkasho-mura, Japan, operated by Japan Nuclear Fuel Limited[6]. There are currently no operational repositories for commercial used fuel, while some are currently in the development or licensing phase (e.g., Yucca Mountain, U.S., Olkiluoto, Finland).

For the last 20 years, the U.S. have pursued development of a geologic repository solution for used fuel disposal — the once-through strategy — at Yucca Mountain in Nevada. The key benefits of that strategy are: a) capacity to handle all legacy used fuel (estimated at 54,000 tons in 2005, currently stored at nuclear power plants); b) capacity to handle additional used fuel discharged after a period of cooling and interim storage, provided that additional repository capacity is developed; and c) no further need for handling or processing of used fuel after disposal which, to that extent, makes the once-through strategy a complete lifecycle solution.

DOE 2001[7] cost estimates for a U.S. repository that is capable of storing a total quantity of 83,800 tons of commercial used fuel indicate a lifecycle investment of about $46B[8], not including costs for interim storage at power plants.

Over the last decade, however, several factors have led to questions about the appropriateness of the once-through fuel cycle as an exclusive used fuel management strategy. In particular:

First, cost estimates of the once-through strategy at Yucca Mountain have significantly increased from initial estimates, in part because of increasingly stringent design requirements. Moreover, at the current rate of used fuel generation, additional repository capacity is likely to be needed for fuel discharged after 2035, even considering that Yucca Mountain capacity could be expanded to 120,000 tons.[9]

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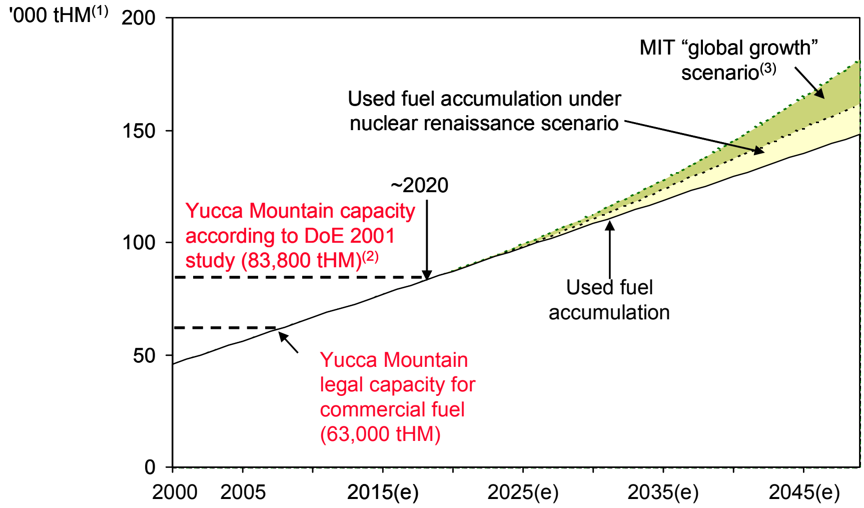
6 Rokkasho-Mura plant in Japan currently in the testing phase.

7 US DOE – *Analysis of the Total Life Cycle Cost of the Civilian Radioactive Waste Management Program* – 2001.

8 DOE undiscounted life cycle cost estimates are reported to 2005$ and netted of estimated cost to dispose of non-commercial nuclear waste.

9 Estimated "Technical capacity" that could be reached at Yucca Mountain, using geologically-suitable area available within the site.

Second, a long-term increase in new U.S. nuclear generation is likely — beyond the currently installed 103 GW to at least 112 GW, based on incentives in the 2005 Energy Policy Act, and potentially to 160 GW, especially if significant carbon abatement legislation is enacted ("nuclear renaissance" scenario). Thus, strategies to manage additional used fuel must be considered. Figure 1 shows the total estimated used fuel accumulation from nuclear power generation and the estimated timeframes during which the Yucca Mountain repository will need to be expanded to dispose of the used fuel in the once-through strategy.



(1) tHM = tons of Heavy Metal
(2) US DoE - Analysis of the total life cycle cost of the civilian radioactive waste management program – 2001. Additional Yucca Mountain capacity level considered is 105,000 tons, as reported by DOE EIS.
(3) MIT – *The future of nuclear power* – 2003, global growth scenario (300 GW installed by 2050).

Figure 1: Total estimated commercial used fuel accumulation

Third, the underlying economics of alternative used fuel management solutions, such as recycling, have shifted, driven in part by higher uranium prices and by a deeper understanding of the long-term behavior of recycling byproducts, which leads to significant optimization of repository space.

Finally, the recycling strategy has gained recognition through the demonstrated, long-term operational effectiveness of recycling technologies over more than 40 years of industrial experience, in combination with a higher level of confidence based on economic data from actual operations. This return of experience has also enabled some successive process and design improvements.

In this context, BCG performed an independent study, funded by AREVA, to review the economics of back end of the nuclear fuel cycle and, in particular, of developing a recycling strategy in the United States. The study takes into account the specificities of the U.S. context (such as the need to handle legacy fuel) and considers possible complementarities with the current Yucca Mountain repository project. It also considers elements beyond economics, such as flows of used fuel, financing requirements and potential risk management benefits.

This study is aimed at back-end economics and does not enter into discussion of additional topics or criteria such as public acceptance, environmental or non-proliferation issues, even though BCG acknowledges their importance for decision makers as they weigh the merits of alternative choices. The study does not explicitly address or discuss potential legislative actions required to pave the way for a recycling strategy in the U.S.

1.2. Methodology

This study is meant to bring an industrial perspective to recycling — synthesizing specific cost economics based on actual operating experience at existing AREVA facilities, BCG's insight into industrial cost estimates factoring in the challenges of new and existing technologies entering new markets, and BCG's assessment of the benefits of larger scale plants, feasible range of cost improvements from operating experience, and the like. From a process standpoint, BCG was able to leverage AREVA's know-how and expertise in nuclear fuel recycling from its last 20 years' operating experience in France.

For each key component, BCG analyzed data provided by AREVA and took an independent third-party view, using its expertise in industrial cost analysis to validate assumptions and, in many cases, developing specific methodologies and frameworks to triangulate on sensitive data elements or explain cost differences with previously reported data. Specifically, BCG estimated the cost of the recycling plant, which represents a significant portion of the overall cost, as BCG would estimate the cost of introducing a state-of-the-art technology in a new market, taking into account local conditions and gains from previous experience.

BCG was able to benefit from an "open-book" approach, in which AREVA provided proprietary operating and accounting data from operations at La Hague and Melox. Additionally, AREVA arranged for necessary plant visits and provided access to a variety of internal technical and economic experts in each relevant area of operation. Although this effort was not meant to be an accounting audit of the data to test its veracity, it allowed BCG to gain confidence in the underlying assumptions of the study and maintain a high level of analytical rigor.

In addition to accessing AREVA information, BCG also gathered input and feedback on key assumptions from a variety of sources external to the company. Informal interviews were conducted with experts in the energy industry, in academia, and in the Department of Energy's national laboratories. Finally, BCG conducted additional research by reviewing previous studies and analyzing existing literature. BCG made particular use of publicly available information in estimating the cost of the once-through strategy, which, unlike recycling, has not yet been deployed anywhere in the world, but for which economic studies have been performed, such as the 2001 Department of Energy Lifecycle Cost Estimates.

Throughout this engagement, BCG had complete control over the emerging results, key messages, and analytical comparisons. Under BCG agreement with AREVA, the company may publish this report in the public domain without any further alterations, unless specifically agreed to by BCG.

In terms of specific economic methodology, in order to analyze recycling strategies effectively, BCG disaggregated it into a few key components, as illustrated in Figure 2: 1) Integrated recycling plant, 2) Repository for high-level waste from recycling (HLW-R), 3) Transports of used fuel, recycled fuel and HLW-R, and 4) Credits from recycled fuel.

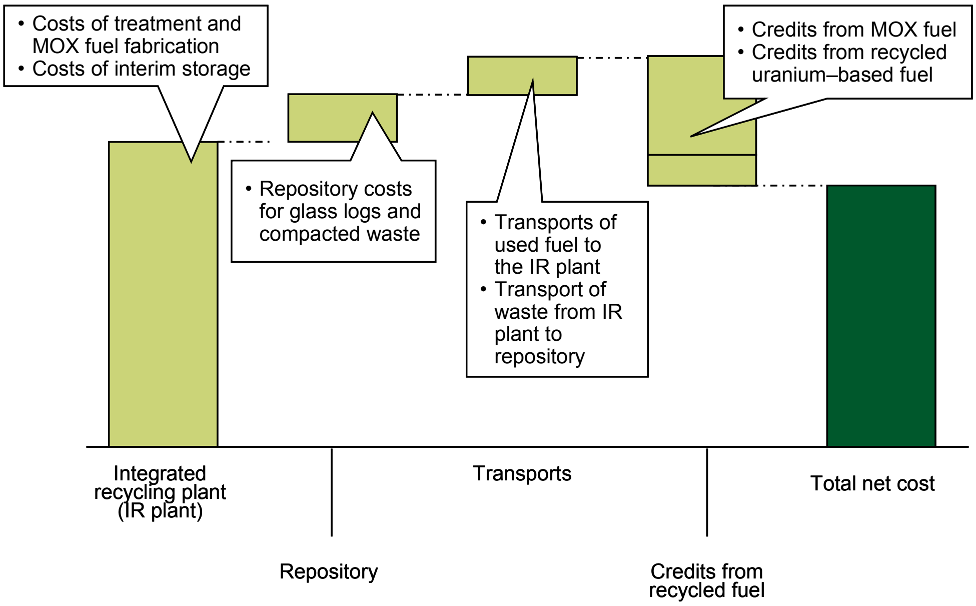


Figure 2: Cost components of recycling strategy

BCG assessed the possible introduction of recycling in the U.S., using two different analytical approaches.

1) In the *Greenfield* approach, BCG focused on analyzing the cost of a theoretical long-term recycling strategy and also provided a cost comparison of recycling vs. once-through. In the Greenfield approach, no consideration was given to existing legacy fuel stored at the utility sites. The main objective of this approach is to build up the basic economics of recycling and to enable an economic comparison with a Greenfield once-through strategy. The key economic metric is the unit cost, expressed in dollars per kilogram ($/kg).

The Greenfield approach answers the question, "How much would it cost to recycle used fuel in the U.S. over the long-term?" In this respect, the Greenfield approach lends itself well to comparisons with previous studies that have used a somewhat similar approach.[10]

2) In the *Implementation* approach, BCG assessed a possible strategy to implement recycling in the U.S. taking into account the specific U.S. context, including the existence of legacy fuel at the reactor sites and the progress toward operating a repository at Yucca Mountain. Within the Implementation approach, BCG considered a *portfolio strategy*, in which a recycling plant is an essential complement to operation of the Yucca Mountain repository.

The Implementation approach addresses economic questions such as, "How much would it cost to implement a recycling plant in conjunction with the repository?" and "What is the cost differential between a portfolio strategy and a once-through strategy in which only repositories are developed?"

[10] M. Bunn (Harvard) – *The economics of reprocessing vs. direct disposal of used nuclear fuel* – 2003.
MIT – *The future of nuclear power* – 2003.
NEA/OECD – *Les aspects économiques du cycle du combustible nucléaire* – 1994.

Within the Implementation approach, BCG looked at a broader set of assessment criteria. In addition to the economics, the Implementation approach addresses issues related to flows of used fuel, financing requirements and risk management.

The terminology for the two approaches and alternative strategies is summarized in Table 1.

	Strategy considered…	Compared to…
Greenfield approach	*Recycling* Recycling plant and repository for high-level waste from recycling (HLW-R)	*Once-through* Repository for used fuel
Implementation Approach	*Portfolio* Recycling plant operational in 2020 and full-scale repository (Yucca Mountain) for legacy fuel and high-level waste from recycling (HLW-R)	*Once-through* Yucca Mountain repository for used fuel only with a possible expansion and followed by a second repository

Table 1: Summary of two approaches used in the study

Although the two approaches discussed above build off of the same analytical components, they provide different and complementary perspectives, and are discussed separately.

2. USED NUCLEAR FUEL MANAGEMENT STRATEGIES AND KEY COMPONENTS

2.1. Used Nuclear Fuel Management Strategies

Overall strategies for the Greenfield and Implementation approaches to the nuclear fuel cycle are described further in the following sections.

2.1.1. Greenfield Approach

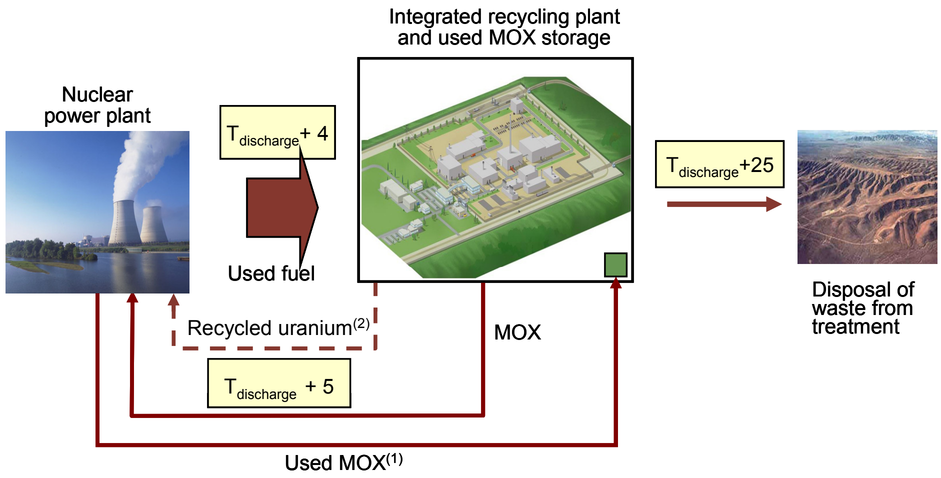
In the recycling strategy, illustrated in Figure 3, used fuel is initially discharged and cooled in pools on reactor sites for three years before being transported to the integrated recycling plant. The used fuel is further cooled for an additional year at the integrated plant site before treatment. The total cooling period is set to four years to limit the build up of americium, enhancing the efficiency of eventual disposal of high-level waste from recycling (HLW-R).

In the treatment unit, used fuel is separated into three main streams: *plutonium-uranium*[11], which is then fabricated into MOX fuel on site, in the MOX fuel fabrication unit; *recycled uranium*, which is purified, converted and re-enriched outside the integrated recycling plant and fabricated into conventional uranium-based fuel; and *fission products* and *minor actinides*, which are considered high-level waste (HLW-R).

After the MOX is used as reactor fuel, it is cooled at the reactor sites and then returned to the recycling plant, where it is stored in dedicated pools, for future use as fuel for fast reactors or in a second MOX recycle.

As part of the treatment and recycling process, specific waste (HLW-R), comprised of fission products and minor actinides, is produced and vitrified into "glass logs" contained in canisters along with compacted structural elements of fuel assemblies (hulls and end-fittings). HLW-R is stored on site at the integrated recycling plant for 21 years and then transported to a permanent repository for disposal. This duration was chosen in order to ensure a fair economic comparison with the once through strategy, where a minimum duration of 25 years' cooling of used fuel after discharge is necessary to satisfy heat constraints at disposal.

[11] Only a small portion of the total quantity of uranium available in the used fuel is co-extracted with the plutonium (COEX process). The remaining balance is recycled. The COEX process does not separate plutonium at any point in the recycling plant.



(1) Used MOX stored at integrated plant site in dedicated pools (less than 15,000 tons by 2070), for future use in fast reactors or multiple recycling.
(2) Transformed in reactor fuel outside the recycling plant.

Figure 3: Recycling strategy (Greenfield approach).

For comparison purposes, BCG also defines the once-through strategy to dispose of the same used nuclear fuel. In the once-through strategy, illustrated in Figure 4, BCG considers the opening of a repository to accommodate used fuel and considers 25 years of cooling and interim storage. Yucca Mountain lifecycle costs were used as a proxy for the cost of the repository because the only available estimates of repository costs in the United States are in reference to that project.

In the case of a once-through strategy, the used fuel is assumed to be stored at the nuclear plant site for 5 years. Once the fuel is discharged from the reactor site, it is transported and then stored at a centralized interim storage for 20 additional years. The location of the repository, from an economic perspective, does not have a material difference in the economic analysis. Further discussion on interim storage is available in appendix A7 .

The 25-year lag from the time of discharge allows the fuel to be cool enough to be ready to be disposed into the repository. This is also a comparable timetable with that of the recycling strategy.

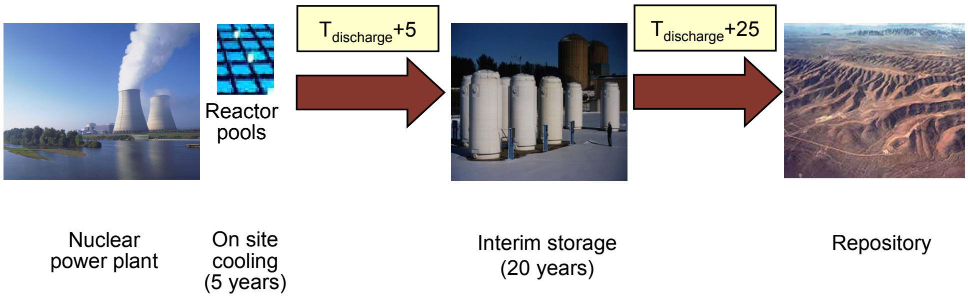


Figure 4: Once-through strategy (Greenfield approach)

The results of the economic assessment are referred back to the mid-irradiation point (~2 years before fuel discharge), since the cost of disposing the fuel, from the perspective of the power plant operator, occurs when electricity is generated.

2.1.2. Implementation Approach

In the Implementation approach, the adoption of recycling as a complementary solution in addition to the development of the Yucca Mountain repository (portfolio strategy) is compared with a pure once-through strategy that will require additional repository capacity in the future. Both strategies would manage commercial nuclear waste generated until 2070.

In the portfolio strategy, an integrated recycling plant is complementary to the Yucca Mountain repository, which would receive a significant amount of legacy used fuel, in addition to HLW-R. The recycling plant, expected to be operational by 2020, accepts all of the used fuel discharged after 2020 and a portion of the legacy fuel, which is treated in dilution with the new fuel. Over the course of the recycling plant's 50-year lifetime, about 40 percent of the legacy fuel existing in 2020 would be recycled[12], while the balance goes directly into the repository. Operation of an integrated recycling plant by 2020 is based on existing and proven technology, enhanced for known experience and optimization opportunities.

In combination, the repository and recycling plant are estimated to be capable of handling all used fuel from power generation until about 2070: about 125,000 tons of new and legacy fuel ultimately recycled and about 50,000 tons of legacy fuel disposed into Yucca Mountain. At the end of the process, about 15,000 tons of used MOX fuel is produced and initially interim stored at the plant.

[12] Net capacity of the recycling plant for this assessment was set at 2,500 tons/yr – could be adjusted to accommodate more legacy fuel.

The once-through strategy, used for reference, assumes Yucca Mountain capacity is expanded to accommodate additional used fuel — from the initial capacity of 83,800 tons[13], to the "technical capacity" of 120,000 tons. Although the exact value of the technical capacity is uncertain, estimates range from 100,000 to 150,000 tons of used fuel, BCG used 120,000 tons as the value for the possible extended capacity. With that capacity at Yucca Mountain, a second repository is needed to deal with the fuel discharged from about 2035 until 2070 and is therefore included in the once-through strategy assessment. When looking at economic models for a potential second repository, BCG refers to the Yucca Mountain model.

Figure 5 is a visual representation of the portfolio strategy, comparing it to the once-through strategy with two repositories.

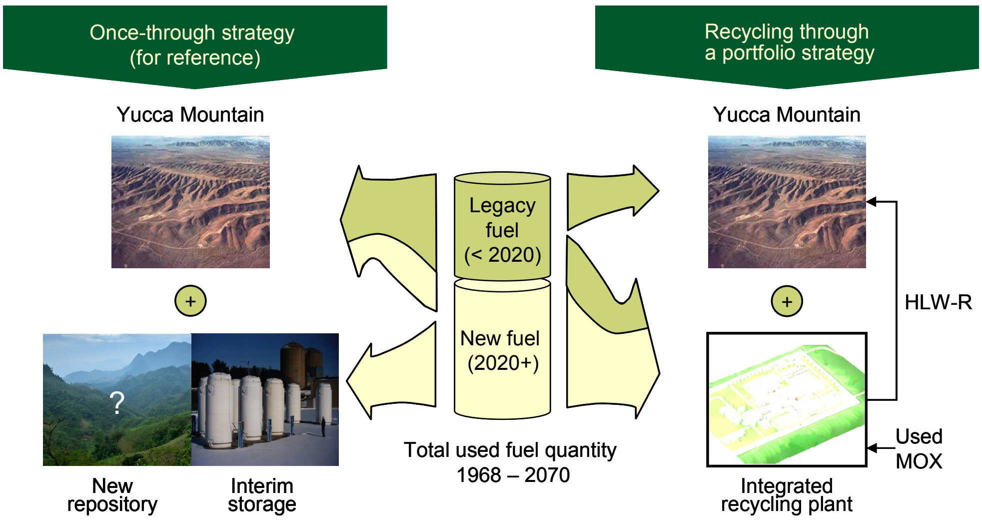


Figure 5: Portfolio vs. once-through strategy in the Implementation approach

[13] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

2.2. Key Components

Among the various inputs, two are key to building the alternative strategies: the integrated recycling plant and the geologic repository. These two components are described further in the following sections and additional information is available in appendix.

2.2.1. Integrated Recycling Plant

The recycling strategy is based on a new integrated co-extraction process, COEX^{TM}, that does not separate pure plutonium at any point in the recycling plant. The "COEX^{TM} plant", or "integrated recycling plant", is derived from existing technology and is scaled and designed according to U.S. market requirements for large volume fuel recycling. Specifically, the integrated recycling plant will be designed for a net capacity of 2,500 tons per year (300 days of operations per year), is estimated to be constructed at an overnight capital cost of $16B, and will be operated at its full net capacity. The COEX^{TM} plant is assumed to be operational by 2020.

The integrated recycling plant is based on a design that builds on existing AREVA plants at La Hague and Melox in France. It is composed of two co-located processes — the treatment and the MOX fuel fabrication processes.

In the *treatment process*, used fuel is separated into three major streams: uranium-plutonium[14], which are extracted together through the COEX^{TM} process and then turned into MOX fuel; uranium, which is sent to external facilities for purification, conversion, re-enrichment and fabrication of additional recycled fuel ("recycled UOX", or "RepU"); and fission product and minor actinides, which are vitrified into glass logs and stored on site as HLW-R and eventually disposed. In the *MOX fuel fabrication process*, the uranium-plutonium mix is turned into MOX fuel for use in light water reactors. In addition to the two main processes, the integrated recycling plant has capabilities for interim storage of used MOX, and interim storage of HLW-R.

2.2.2. Repository Facility

BCG's assumptions for the repository are based on a geologic repository similar to the one planned at Yucca Mountain and described in the 2001 DOE study. In the portfolio strategy, the recycling plant will co-exist and operate complementary to the repository.

A total of $10B had already been used as of 2005 to design and evaluate the Yucca Mountain repository and to prepare a license application to the Nuclear Regulatory Commission (NRC). In total, about $45-50B are expected to be needed for the completion of the project.

[14] Only a small portion of the total quantity of uranium available in the used fuel is co-extracted with the plutonium (COEX^{TM} process). The remaining balance is recycled. The COEX^{TM} process does not separate plutonium at any point in the recycling plant.

With respect to the overall capacity of the repository, there are three[15] possible values that can be used and to which BCG refers in this study:

- The legal capacity, which is set at 63,000 MTHM of commercial used fuel.
- The 83,800 MTHM figure set by DOE in its "Analysis of the Total Life Cycle Cost of the Civilian Radioactive Waste Management Program—2001," which has been used as a base value for the BCG assessment. All available cost estimates are tied to 83,800 MTHM, and BCG uses it as a reference.
- The technical capacity, which includes possible expansions of the current Yucca Mountain design. Estimates for that capacity vary within the range of 100,000 and 150,000 MTHM. BCG uses 120,000 MTHM as the reference point for the technical repository capacity.

Finally, when looking at economic models for a possible second repository, as part of the Implementation approach, BCG refers to the Yucca Mountain model. While there is potential for cost improvement from learning and experience in building the first repository, there is also significant uncertainty about location and geologic characteristics of another repository. BCG assumes that a new repository will require a similar level of investment as Yucca Mountain.

[15] Another potential repository capacity is the 105,000 MTHM figure, as described in the DOE Environmental Impact Statement.

3. RESULTS OF THE ASSESSMENT

As mentioned in the previous section, BCG assessed the recycling solution from two approaches: Greenfield approach, with a focus on recycling economics based on unit cost comparison and key sensitivities, and the Implementation approach, which addresses economics in terms of net present cost and includes additional criteria, including impact on fuel flows, financing requirements, and potential risk management benefits.

The main findings of the economic assessment are as follows[16]:

- In a Greenfield approach, the overall cost of recycling used fuel is in the order of $520/kg, comparable to the cost of a once-through strategy (less than 10 percent different in most sensitivities), especially considering uncertainties that surround many of the variables used in the assessment, such as uranium price and repository costs.
- In the Implementation approach, overall economics of implementing recycling as part of a portfolio strategy remains comparable to a once-through strategy considering total costs for handling all used fuel until 2070. The net present cost of the portfolio strategy is about $48-53B, is comparable to the net present cost of a pure once-through strategy, estimated at about $47-50B. Total undiscounted life cycle cost for the portfolio strategy is about $113B, compared to about $124-130B for the once-through strategy in which a larger portion of the cost is deferred.

In addition, recycling, as part of a portfolio strategy, presents a number of benefits:

- Eliminates the need for additional repository capacity, beyond the initial 83,800 ton capacity at Yucca Mountain, until 2070.
- Contributes to early reduction of used fuel inventories at reactor sites — in particular, removing newer, hotter fuel for recycling within three years of discharge and eliminating the need for additional investments in interim storage capacity.
- Relies on existing technology — with appropriate modifications — and can provide an operational transition to future technology developments such as Advanced Fuel Cycles and fast reactors.
- Shows cash flow requirements that could fit until 2030 within the current financing resources available for the once-through strategy, or even until 2050+ if acceptance of used fuel at Yucca Mountain begins only after the first years of operation of the recycling plant.
- Offers a tool for nuclear power sector to protect against potential rises in uranium prices, by providing MOX and recycled UOX fuel[17], whose production cost is independent of uranium prices and enrichment costs.

In combination, the benefits of a recycling portfolio strategy enhance risk management and provide a hedge in terms of economics, technology risks, timing risks, volumetric risks, and the like, and clearly merit further consideration and in-depth investigation by U.S. policy makers and utilities.

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[16] Based on a price of uranium of $31/lb.
[17] MOX and recycled UOX fuel estimated to satisfy 20-25 percent of U.S. fuel requirements.

The recycling strategy in the Greenfield approach and as part of a portfolio strategy in the Implementation approach, and its performance along key criteria, is further discussed in the following sections.

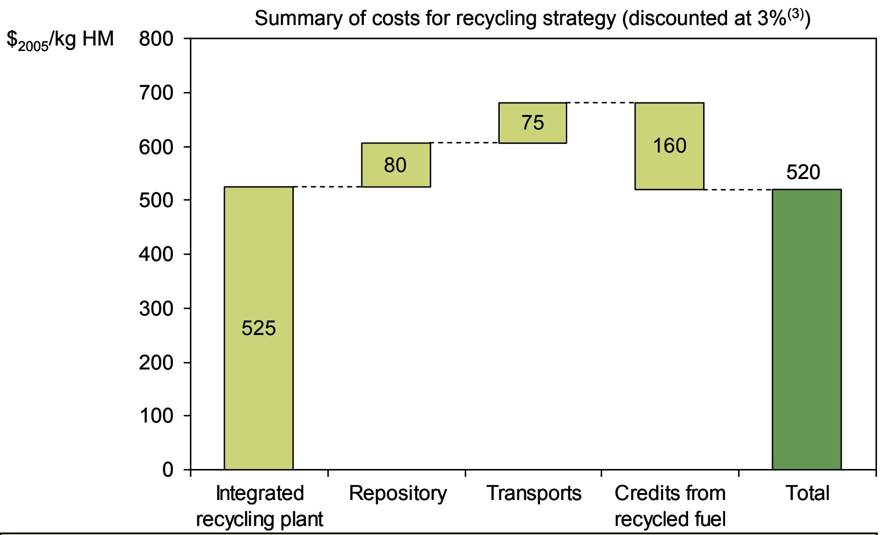
3.1. Greenfield Approach

The main result in the Greenfield approach is that the overall discounted cost of recycling used fuel is on the order of $520/kg, comparable with the cost of a once-through strategy (less than 10 percent different in most sensitivities), especially considering uncertainties that surround many of the variables used in the assessment, such as uranium price and repository costs.

In overall fuel cycle economics, back-end costs can be significant but should be viewed in the proper context. While back-end costs make up a significant portion of the fuel costs for power generators (20-30 percent in the United States), they appear to be fairly small when compared with the overall cost of electricity (<3 percent of typical bus bar cost[18]).

3.1.1. Economics

Total discounted cost of a Greenfield recycling strategy (including credits and final disposal) is estimated at around $520 per kg of used fuel, referred back to the mid-irradiation point (about two years before discharge). Unit costs are calculated from capital investments, operational, and decommissioning costs, and revenues. They are then discounted, depending on the timing of each component. The breakdown of costs, after discounting and expressed in dollars per kg of initial used fuel, is illustrated in Figure 6. Costs before discounting are also reported at the bottom of the chart.



Costs before discounting	630	175	95(1)	190(2)	710

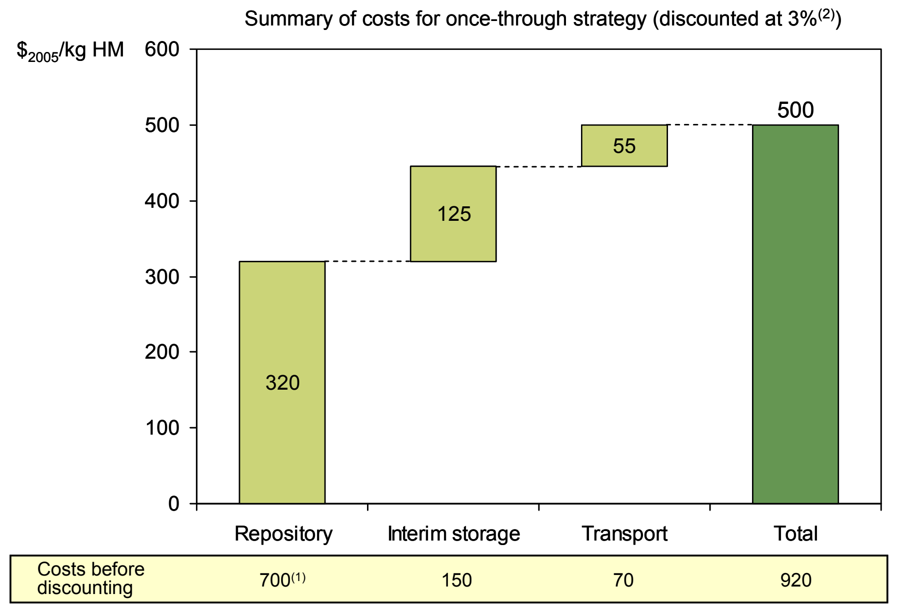
(1) $75/kg to transport the used fuel from the nuclear plant sites to the recycling plant and $20/kg to transport the HLW-R from the recycling plant to the repository.
(2) $160/kg for credits from MOX and $30/kg for credits from recycled uranium-based fuel.
(3) According to guidance from Office of Management and Budget. See US OMB, Office of Economic Policy – *Circular A-94: Main guidance for cost/benefit analysis and discount rates* – 1992 and US OMB, Office of Economic Policy – *Circular A-4: Discounting for long term projects* – 2003.

Figure 6: Cost breakdown of recycling strategy in the Greenfield approach

[18] University of Chicago – *The economic future of nuclear power* – 2004.

The discounted unit cost of the recycling strategy is comparable with that of a once-through strategy, which is estimated to be around $500 per kg of used fuel. The cost of the once-through strategy, after discounting is applied, is broken down as illustrated in Figure 7. Costs before discounting are also reported at the bottom of the chart.

Undiscounted cost of the once-through strategy is about 30 percent higher than that of the recycling strategy because the larger costs (for the repository) do not occur until 25 years after used fuel discharge.



(1) Includes $25 for the construction of a repository transportation railroad.
(2) According to guidance from Office of Management and Budget. See US OMB, Office of Economic Policy – Circular A-94: Main guidance for cost/benefit analysis and discount rates – 1992 and US OMB, Office of Economic Policy – Circular A-4: Discounting for long term projects – 2003.

Figure 7: Cost breakdown of once-through strategy in Greenfield approach

There are two key differentiating elements in the BCG assessment of recycling costs, when compared to previous assessments/studies:

- Integrated plant unit costs[19] significantly lower than previously published data.
- Repository densification factor of four, which indicates that the waste results from recycling can be packed in a geographical repository like Yucca Mountain four times more densely than used fuel.

Each of the key cost components is discussed further in the following sections and in appendix A4
.

[19] Costs of the integrated plant are based on a COEX™ process, which does not separate pure plutonium at any point in the recycling plant, and include used fuel treatment, MOX fuel fabrication costs, interim storage capacity for HLW-R and used MOX.

Integrated Recycling Plant

BCG estimated a unit cost for the integrated plant of $630/kg. That is based on the plant described in section 2.2.1 and further detailed in appendix A4 , with the following main characteristics:

- 2,500 tons per year of net capacity, based on effective throughput at 300 days per year (about 80 percent of nameplate capacity).
- Total capital investment (CapEx) of about $16B, which is mainly composed of overnight cost of construction at market price, contingencies, development[20], licensing and start-up costs; storage costs for HLW-R and used MOX are also included and decommissioning costs are considered after the closure of the plant.
- Operating costs (OpEx) of about $900M per year, which include operating expenses for both treatment and fuel fabrication, running investments, estimated taxes or taxes-equivalent, and other charges.

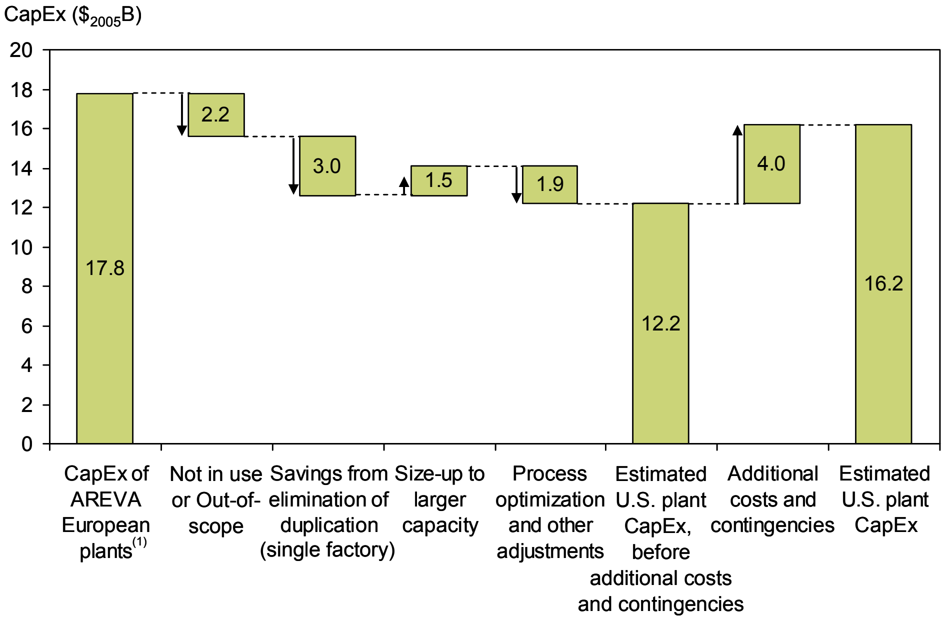
The costs outlined above are the basis for the economic assessment in both the Greenfield approach and the Implementation approach.

Reconciliation with Costs of Recycling at Existing AREVA Plants

The total capital investment required for the integrated plant is within 10 percent of the total capital investment that has been made over the years for the AREVA European plants at La Hague and Melox. Some key modifications, illustrated in Figure 8, between the existing plants and the U.S. plant are as follows:

- A few workshops not in use anymore or not in the scope of a U.S. plant.
- No duplication of similar workshops — the La Hague and Melox facilities were built “piecemeal” over time resulting in some inefficiency (La Hague for example is made of two largely independent units).
- U.S. plant larger in size to accommodate a higher volume of used fuel.
- Limited optimization for some key process steps, based on AREVA operational experience at La Hague — improvements in the vitrification and solid waste treatment.
- Additional costs and contingencies, such as costs driven by specific licensing and design requirements in the U.S., development costs, and the like.

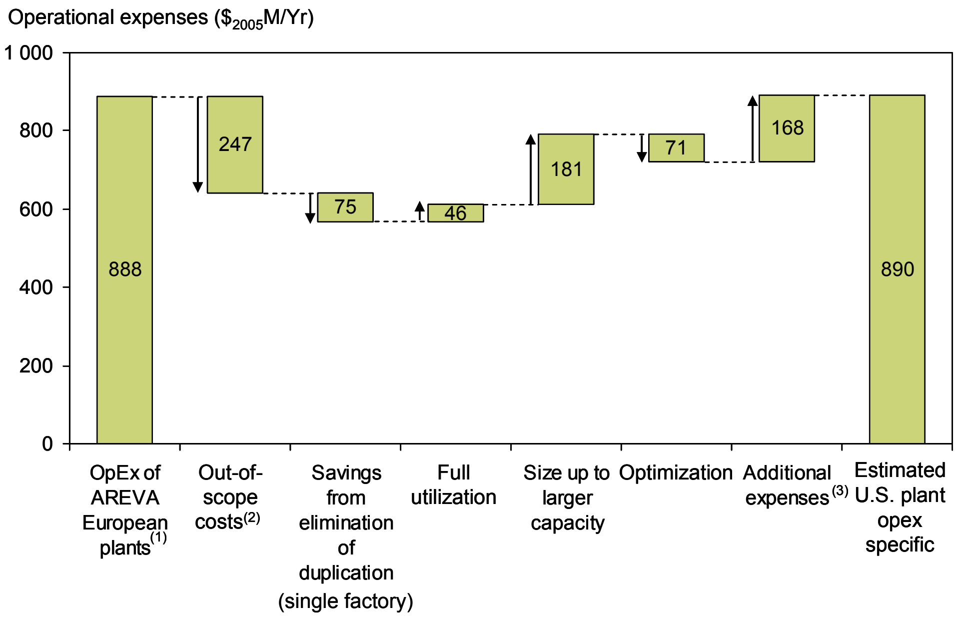
[20] Includes development costs to implement COEX™ process and some limited R&D expenses.



(1) La Hague and Melox. Refers to real actualized costs, including standard contingencies, and assumes 1€ = $1.15 (purchasing power parity).

Figure 8: Capital investments at La Hague / Melox vs. U.S. plant

BCG performed a similar analysis on operating expenses, looking at savings from elimination of out-of-scope costs, duplication and optimization, and cost increases driven by operating an integrated recycling plant at larger capacity and high utilization. The analysis, illustrated in Figure 9 shows that, after all the adjustments, the operating expenses of a U.S. plant are expected to be in line with operating expenses in La Hague and Melox.



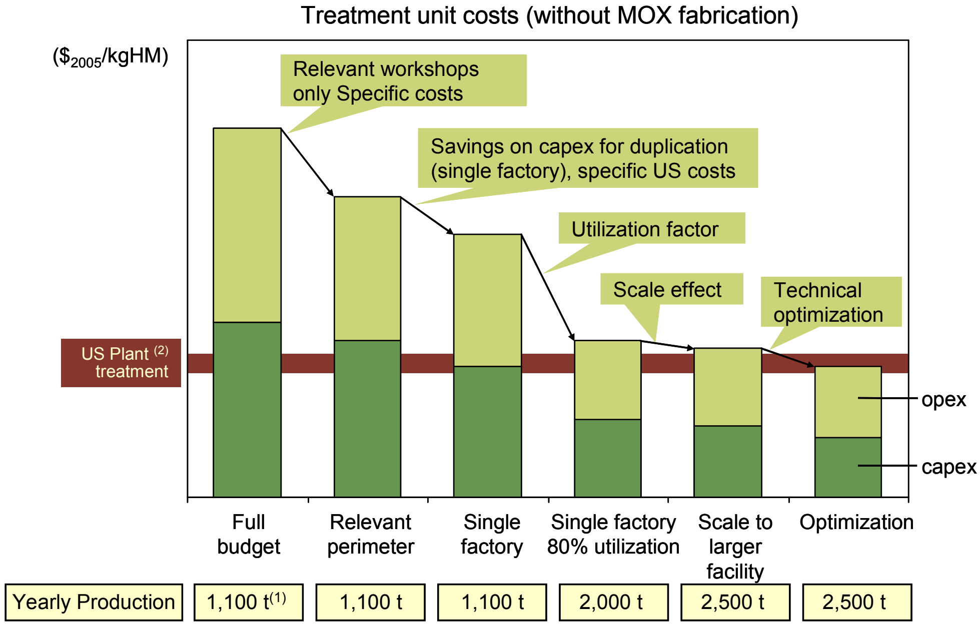
(1) La Hague and Melox, excludes non-operational expenses.
(2) Includes local taxes and other out-of-scope expenses.
(3) Includes estimated U.S. local taxes, additional running investments and additional SG&A budget items.

Figure 9: Operational expenses at La Hague / Melox vs. U.S. plant

While the capital investments and the operational expenses of the U.S. plant are comparable to those of existing European plants, a much higher used fuel throughput is expected in the U.S. plant, because of its larger size and the higher expected utilization. Utilization is expected to be at about 80 percent of the nameplate capacity, significantly higher than the current value at La Hague — higher utilization in the U.S. is guaranteed by larger volume of newly discharged fuel and existing inventory.

Thus, resulting unit cost estimates, especially for treatment, are significantly lower than the historic unit cost incurred at La Hague and Melox.

To further illustrate the point, Figure 10 shows the components that contribute to the difference between estimated and historical unit cost, in $/kg terms, for the treatment portion of the recycling plant. The treatment portion accounts for most of the difference between historical costs and expected costs of the integrated recycling plant. Data on Figure 10 have been removed upon request of AREVA.



(1) 2005 production.
(2) Including additional US costs and contingencies.
Note: WACC @3%.

Figure 10: Difference between historical and projected treatment unit costs

The considerations of unit cost and capital expenses can be summarized in relatively simple terms by saying that the integrated U.S. recycling plant is expected to have similar levels of capital investments and operational expenses as existing AREVA plants in Europe, while at the same time treating a considerably larger amount of fuel, thus resulting in lower unit costs.

Repository

Repository costs are based on the DOE 2001 study on Yucca Mountain[21], for both disposal of used fuel and HLW-R. Cash flow outlays are built directly from the cash flow profile in the DOE study, with a few relatively minor adjustments. First, the initial acceptance date was moved five years out to 2015, thus adding development time and cost. Second, BCG removed transport-related costs, which are analyzed separately (see appendix 6). Total estimated cost for disposing of commercial used fuel is about $43B, which does not include estimated repository costs for non-commercial fuel.

The calculation of the unit cost for a repository accepting only used fuel is therefore a direct application of the unit cost methodology (discussed in appendix A1), in which BCG assumed the same acceptance schedule as outlined in the DOE study. For a repository accepting only used fuel, the resulting unit cost is $700/kg. The broad sensitivities surrounding this number are discussed in detail in appendix A9 .

On the other hand, HLW-R can be packed four times more densely than initial used fuel. BCG refers to this factor of four as the “densification factor”, explained further in appendix A5 . For recycling in the Greenfield approach, the densification factor is assumed to translate directly into cost benefits. This corresponds to a theoretical situation in which the repository is either optimized upfront for HLW-R or the disposal of HLW-R is a marginal cost in the context of an existing repository. In the subsequent portfolio strategy, within the context of the Implementation approach, the economic savings from disposing HLW-R instead of used fuel are significantly smaller — in that case, BCG considers that HLW-R gets disposed in the actual Yucca Mountain, whose construction and operating costs are largely independent of whether HLW-R is disposed with used fuel or not.

Transports and Interim Storage

In the recycling strategy, used fuel is transported from reactors to the recycling plant. BCG assumed that 2,800 tons of used fuel is transported annually. That includes a portion of the legacy fuel (about 700 tons at steady state), the newly discharged fuel (about 1,800 tons), and the used MOX (about 300 tons). In addition to the used fuel, HLW-R is transported from the recycling plant to the repository after 21 years of interim storage.

The calculations for transports costs are based on estimates from the DOE study[21] and have been corroborated by estimates conducted independently using available data on AREVA’s transport experience in Europe and adjusted to account for U.S.-specific costs.

Total cost of transport for the Greenfield recycling strategy was estimated at $95/kg, before discounting. This is inclusive of $75/kg for transport of used fuel from power plant to the recycling plant and $20/kg for the transport of HLW-R from recycling plant to repository.

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[21] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

In the once-through strategy, there is a cost for storage of used fuel prior to disposal, which is estimated at ~$150/kg. Also, the cost for transporting used fuel, this time from the nuclear power plants to the repository, is $70/kg. In the once-through strategy, the used fuel is cooled for five years before being transported, instead of three years in the recycling strategy.

Detailed assumptions and calculations of transports and interim storage costs are discussed in appendix A6 and A7 .

Credits from Recycled Fuel

Recycled fuel produced from the plutonium-uranium stream and the remaining reprocessed uranium stream has a value that can offset some of the plant costs. Both the recycled fuel from the plutonium-uranium stream (MOX fuel) and the recycled fuel (recycled UOX) from the uranium stream can be used in light water reactors and are therefore comparable in value to fresh UOX of equivalent burn-up rate, after necessary adjustments for adaptation of reactors to MOX fuel use, MOX acceptance costs, and MOX transport costs as well as additional costs for conversion, enrichment, and fabrication of recycled uranium-based fuel.

The fuel value to which MOX and recycled UOX are compared is based on estimated market prices for 2020. Estimates of uranium market prices for 2020 were based on various recent studies[22] and BCG chose $31/lb U_3O_8 as the baseline assumption, which is in line with the average price in the last six months of 2005, even though prices in 2006 were exceeding $45/lb U_3O_8. Costs for enrichment were set at $110/SWU, conversion at $12/kgU, and fuel fabrication at $200/kgHM.

Results of the credit calculation yield a MOX credit of about $160/Kg (net of reactor adaptation and MOX acceptance costs, but *not* inclusive of MOX fabrication costs, which are accounted for in the integrated recycling plant) and a uranium credit of about $30/Kg (net of conversion, enrichment, and fabrication costs).

The detailed calculations, neutronic assumptions, reactor adaptation costs used to determine the credits from recycled fuel, and the like are described in further detail in appendix A8 .

Cost of Managing Used MOX

Used MOX accumulates in the recycling strategy at a rate of about 300 tons/year, and there are several solutions available for managing it. From an economic standpoint, the most beneficial is the fabrication of fuel for fast reactors[23], in which the valuable material contained in used MOX is re-used. Other possibilities include recycling MOX a second time, or multiple times, and using advanced technologies for americium removal.

Overall, the cost of managing used MOX has a limited impact on total back-end costs in terms of $/kg HM, since only about 300 tons per year is generated, or about 15 percent of the total used

[22] IAEA – Uranium 2003: resources, production and demand – 2003
[23] Such as those currently contemplated in the Gen IV forum.

fuel generated annually. BCG already factored in a cost of managing used MOX equal to the cost of managing used fuel ($520/$kg_{MOX}$).

In addition, BCG estimated that the overall impact of implementing alternative MOX management strategies is between -$50/kg HM and +$100/kg HM, respectively -10 and +20 percent of the total recycling strategy cost.

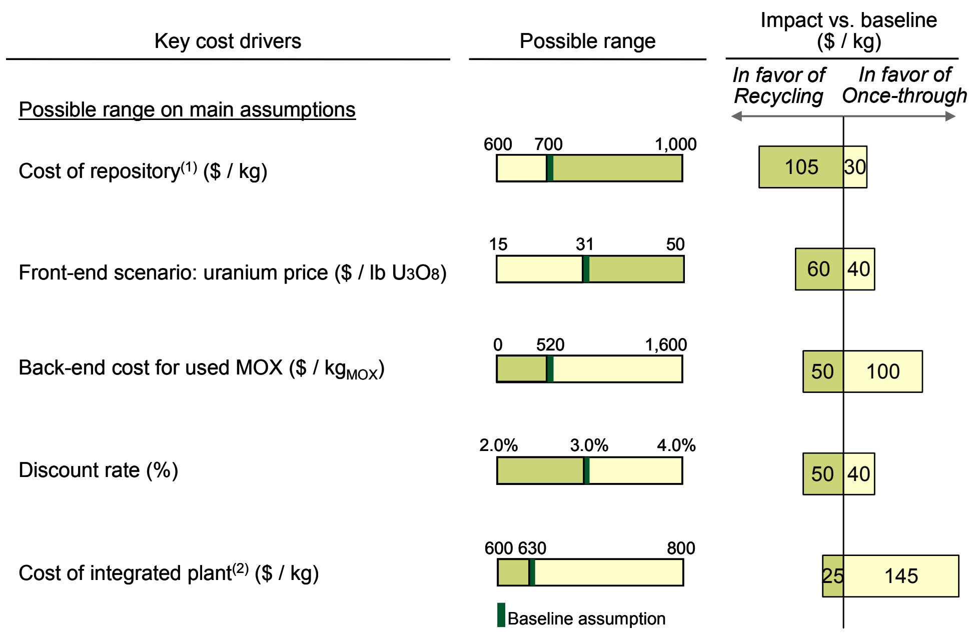
Disposal of used MOX in Yucca Mountain is not considered a viable option because it would almost entirely eliminate the repository optimization benefits gained through densification.[24]

The issue of used MOX management is discussed again in section 4 and details of the economic calculation are contained in appendix A10 .

3.1.2. Sensitivity Analysis

The cost of the recycling strategy is comparable to the cost of the once-through strategy (about 5 percent difference), considering intrinsic uncertainties encompassing the assumptions used in the study. BCG looked at several variables from the unit cost model, including repository costs, uranium prices, cost to manage used MOX, discount rate, and integrated plant costs.

The impact of each of these variables, with all other variables remaining constant, is illustrated in Figure 11.



(1) Excluding transport. lower bound: average cost of Yucca Mountain for 120,000 tons, higher bound: budget overrun at +40%.
(2) Total life cycle undiscounted cost of integrated plant is $64B (25% of which is capital investments). Lower bound of the sensitivity range equates to $61B in total life cycle costs, upper bound is $81B. CapEx/OpEx split kept constant.

Figure 11: Summary of main sensitivities in Greenfield approach

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24 However, even in the worst case scenario of direct disposal, the impact on unit cost would be expected to be less than $200/kg, about 40 percent of the total recycling strategy cost.

Selection of possible ranges for each of the variables is described in the appendix A9 . The impact of uncertainties surrounding each of these variables on the cost differential between the two strategies is in the order of or larger than 5 percent.

Two large uncertainties are the cost of the repository and the price of uranium. The effect of these two parameters on the overall difference in the cost of the recycling vs. once-through strategy is illustrated in Figure 12.

Under current assumptions, the costs of the recycling vs. the once-through strategy fall within the band of "comparable economics" (green), which indicates the cost difference is less than 10 percent. Higher repository costs and uranium prices tend to make the recycling solution more competitive. Conversely, lower repository costs and uranium prices make the once-through solution more competitive. For example, although the central estimate of unit cost for the recycling strategy is slightly higher than the expected unit cost for the once-through strategy, a uranium price above $100/kg would move the pendulum enough to make the recycling strategy less expensive than the once-through.

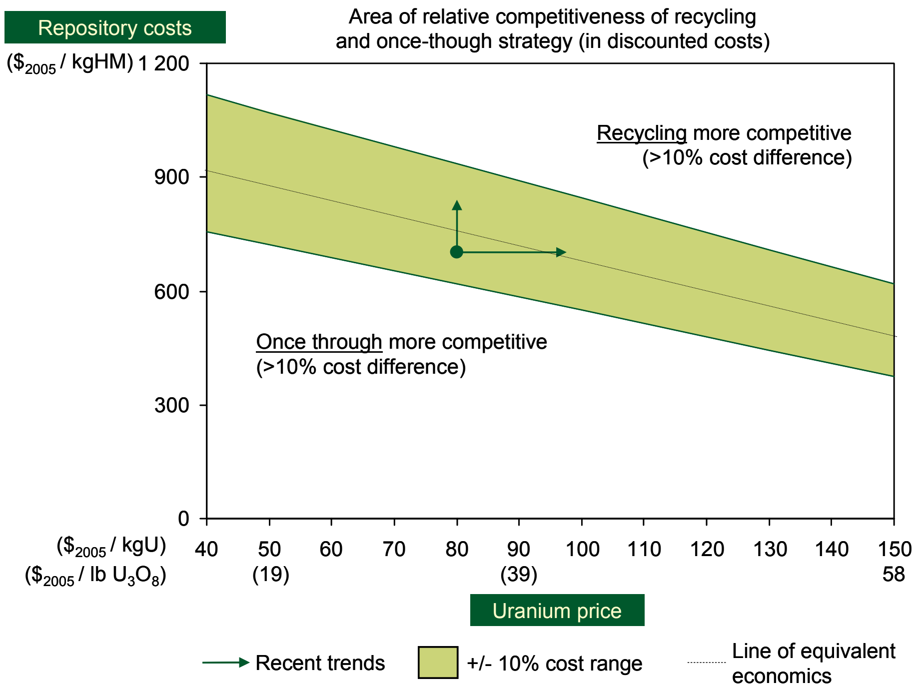


Figure 12: Effect of uranium prices and repository costs on economic comparison

Although BCG has used assumptions based on current conditions and available estimates, recent trends have indicated a potential for higher repository costs and higher uranium prices driven by a worldwide increase in nuclear fuel demand, as indicated by the arrows in Figure 12.

3.2. Implementation Approach

In this section, BCG moves away from the Greenfield approach and enters into the specificities of the U.S. context. In the Implementation approach, the adoption of recycling as a complementary solution in addition to the development of the Yucca Mountain repository (portfolio strategy) is compared with a pure once-through strategy that will require additional repository capacity in the future. Both strategies would manage commercial nuclear waste generated until 2070.

Within the Implementation approach, BCG looked at a broader set of assessment criteria. In addition to the economics, now expressed in terms of net present cost derived from expected cash flows, the Implementation approach addresses issues related to flows of used fuel, financing and risk management.

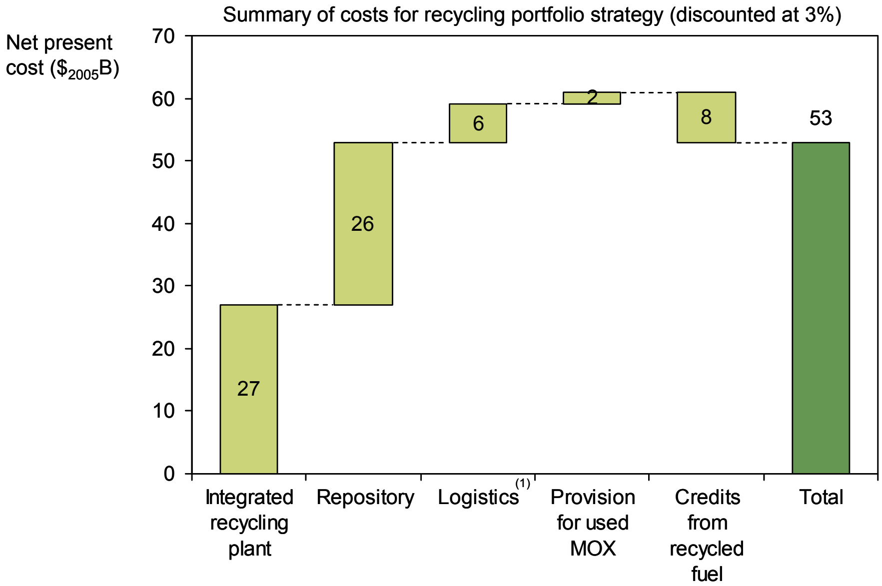
3.2.1. Economics

In the Implementation, the preferred metric for the economic analysis is the net present cost, which is derived using the methodology described in appendix 1. Although an adaptation of the unit cost methodology for the Implementation approach is also possible, it is fairly complex and not as transparent as in the Greenfield approach, because of more complex fuel flows and discounting.

Total net present cost for the recycling portfolio strategy, in which about 50,000 tons of legacy used fuel are disposed in a repository while 35,000 tons of legacy used fuel and 90,000 tons of new used fuel are recycled, is estimated at $48-53B. The range depends on the timing for beginning of waste emplacement at Yucca Mountain. In the portfolio strategy, used fuel is being moved off reactor sites by transporting it to the recycling plant starting before 2020, so it is conceivable that emplacement of used fuel in Yucca Mountain could begin after the first years of operation of the recycling plant, without any negative impact on the total amount of waste accumulated on the surface.

The breakdown of net present costs for the different components is shown in Figure 13, assuming a scenario in which emplacement at Yucca Mountain begins in 2015. The net present costs include a provision for used MOX costs, based on same back-end costs as for the initial used fuel. Figure 13 also shows the total life cycle costs, which is simply the sum of all the total costs (in constant 2005$) incurred over the life time considered.[25]

[25] Yucca Mountain costs include those for building the Nevada railroad according to the initial 2001 DOE estimate (US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001).

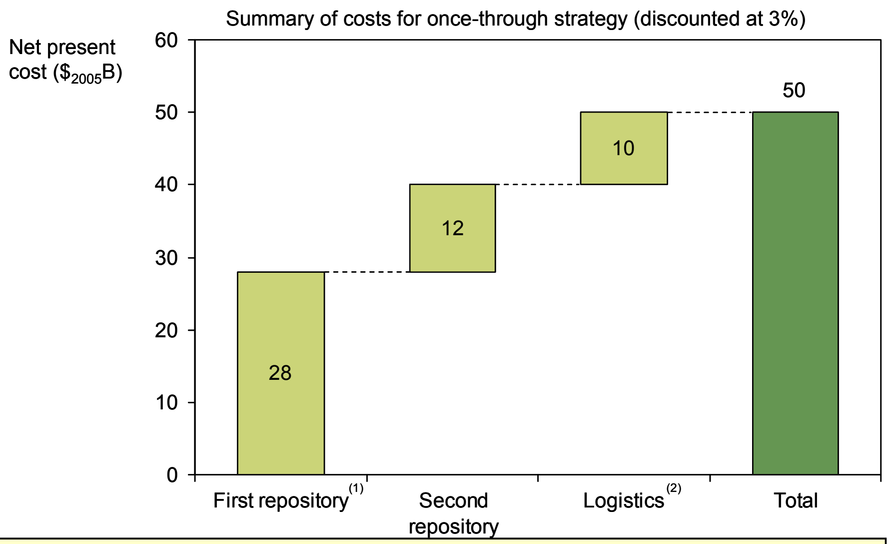


Total life cycle costs ($2005B)	64	49	16	8	24	113

(1) Includes transports.

Figure 13: Cost breakdown of portfolio strategy in the Implementation approach

The cost of the portfolio strategy is comparable with that of a once-through strategy, which is estimated to be around $47-50B. The range in this case depends whether the total capacity considered for Yucca Mountain is the baseline capacity of 83,800 tons or a technical capacity of 120,000 tons. The breakdown of net present and the total life cycle costs for the different components are shown in Figure 14, assuming a scenario in which Yucca Mountain capacity is 83,800 tons.



Total life cycle costs(1) ($2005B)	48	51(3)	31	130

(1) Adjusted for differences in volume of used fuel handled in once-through strategy vs. portfolio.
(2) Includes transport and interim storage.
(3) Cost of second repository different from first repository due to lower annual volume of used fuel emplaced. No backlog of legacy fuel results in an annual fuel flow of 2,100 tons a year (vs. 3,000 for Yucca Mountain) and a longer period of emplacement.

Figure 14: Cost breakdown of once-through strategy in the Implementation approach

Undiscounted life cycle cost of the once-through strategy is about 10-15 percent higher than that of the portfolio strategy. On the other hand, the once-through strategy is advantaged from a net present cost perspective since a significant portion of the cost is not incurred until later in the cycle, when the second repository needs to be constructed.

The results for the Implementation approach, under different scenarios, are summarized in Figure 15.

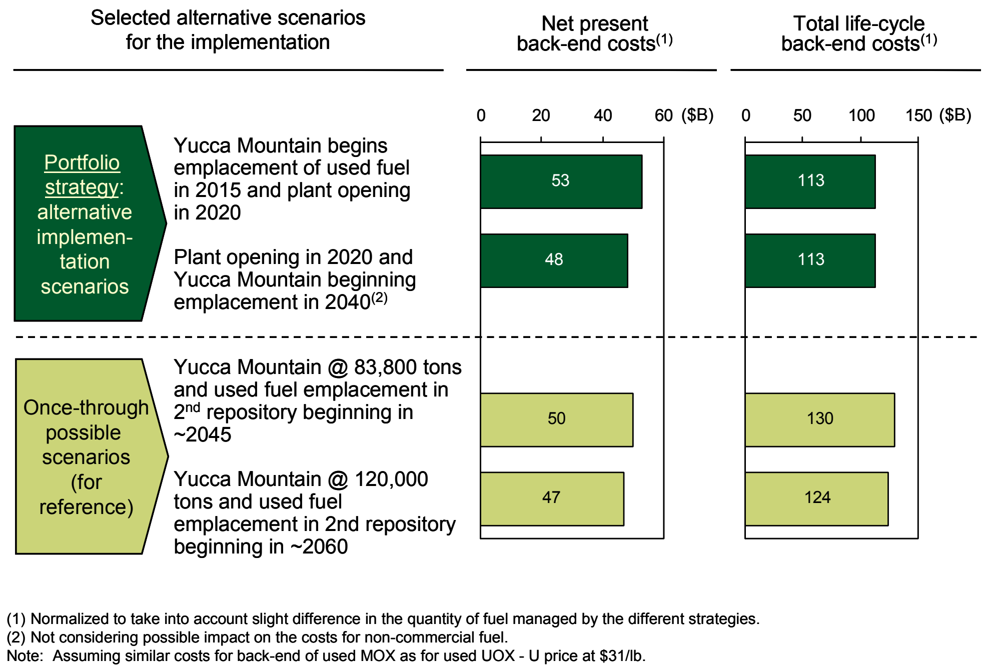


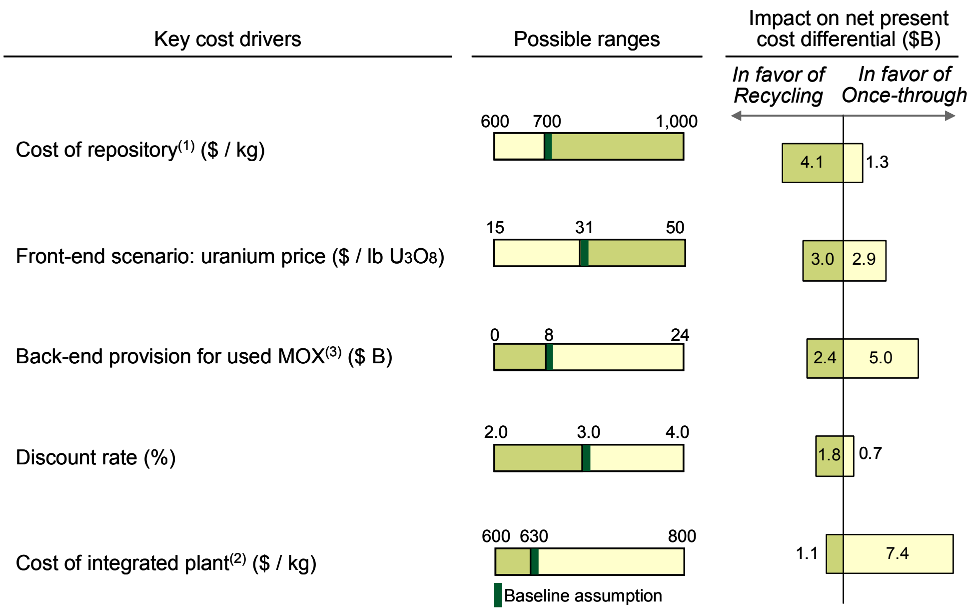
Figure 15: Net present and total life cycle costs of portfolio and once-through strategies

3.2.2. Sensitivity Analysis

As in the Greenfield approach, BCG selected a subset of the variables that are considered responsible for significant potential variability in the final results. Key uncertainties include repository costs, uranium prices, discounted cost to manage used MOX, discount rate, and integrated plant costs.

The impact of each of these variables, with all other variables remaining constant, is illustrated in Figure 16. Selection of possible ranges for each of the variables is described in appendix A9 .

As illustrated by the figure, the order of magnitude for the cost difference between the once-through and portfolio strategies (about $0-6B) is comparable to the impact of each and all of the variables.



(1) Excluding transport. lower bound: average cost of Yucca Mountain for 120,000 tons, higher bound: budget overrun at +40%.
(2) Total life cycle undiscounted cost of integrated plant is $64B (25% of which is capital investments). Lower bound of the sensitivity range equates to $61B in total life cycle costs, upper bound is $81B. CapEx/OpEx split kept constant.
(3) Baseline assumption based on a unit cost of $520/kg for disposing of used MOX, equivalent to the estimated long-term cost of disposing regular used fuel.

Figure 16: Summary of main sensitivities for Implementation approach

Selection of possible ranges for each of the variables is described in the appendix A9 .

3.2.3. Fuel Flows

An integrated plant with a net capacity of 2,500 tons, operating at full utilization, can handle all used fuel discharged after 2020 for 50 years and a large part of legacy fuel.

From a fuel flow standpoint, the portfolio strategy presents three key benefits:

- Repository capacity: eliminates the need for additional repository capacity until at least 2070.
- Used fuel on the surface: contributes to long-term reduction.
- Removes newer, hotter fuel.

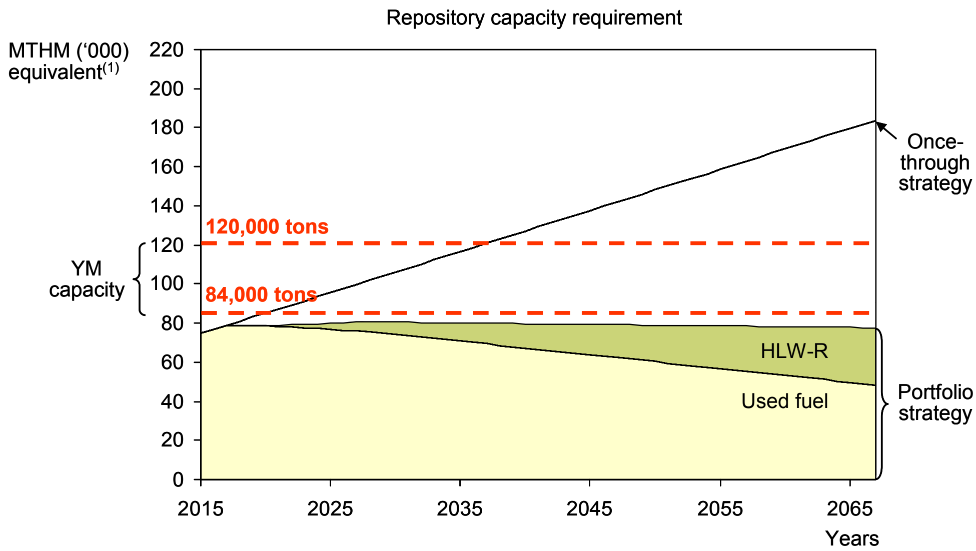
1) Repository capacity

Under current assumptions, most importantly those for discharged fuel volumes, integrated plant and densification factor, a portfolio strategy that includes recycling does not need any additional capacity at Yucca Mountain, nor a second repository, until at least 2070, as illustrated in Figure 17, which depicts the total repository capacity needed at any given year.

The light green area (used fuel) decreases slowly after 2020, as all newly discharged used fuel is recycled and a portion of legacy fuel (~700 tons/yr at steady state) is also recycled in dilution. Treating legacy fuel in dilution does not reduce the densification factor of four (see appendix A5 for a more detailed explanation on the densification factor).

The green area representing HLW-R increases slowly as 2,500 tons of fuel is recycled annually. In terms of Yucca Mountain capacity, 2,500 MTHM of used fuel treated and turned into HLW-R corresponds to about 650 MTHM of used fuel disposed directly. Therefore, total repository capacity required by the accumulated waste stays virtually flat or decreases slightly as the repository capacity freed up by treating legacy waste is almost entirely consumed by an almost equivalent quantity of HLW-R.

On the other hand, in the once-through strategy, the capacity required at Yucca Mountain by accumulated waste continues increasing at the annual rate of fuel discharged (2,100 tons/yr). An extension of Yucca Mountain, therefore, is required to dispose of fuel discharged after 2020 and an entirely new repository for used fuel discharged after 2040.



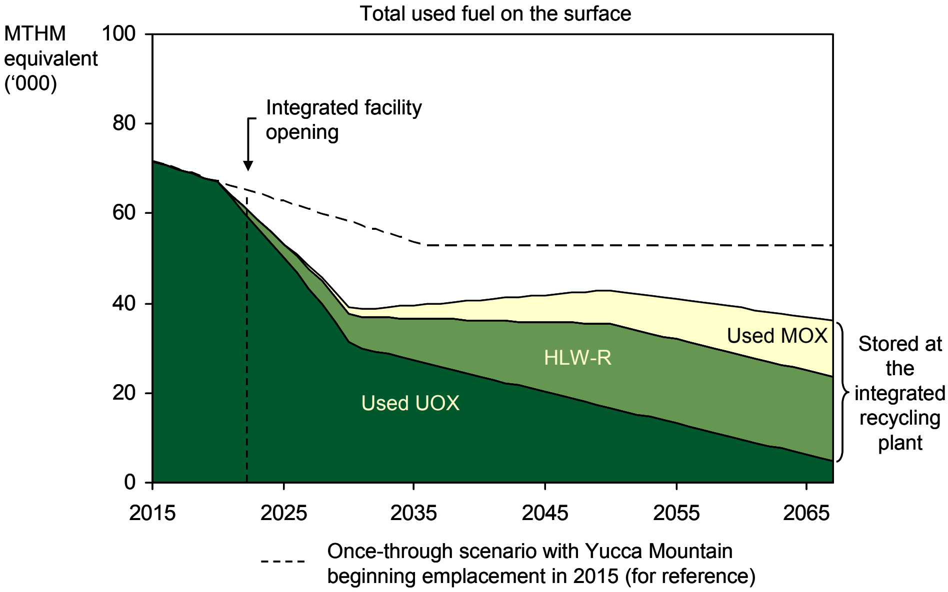
(1) Equivalent to MTHM ('000) of used fuel disposed in the repository (i.e., HLW-R takes only ¼ of the space from equivalent used fuel)

Figure 17: Total repository capacity required over the years (MTHM equivalent)

2) Accumulation of used fuel on the surface

Over the long-term, the portfolio strategy reduces the total quantity of high-level waste on the surface. Used fuel reduces significantly, as legacy waste is disposed in the repository and additional discharged used fuel is recycled. HLW-R is produced beginning in 2020 and increases in volume over time. Used MOX also accumulates starting in 2025.

Figure 18 illustrates the situation. The chart is representative of a scenario in which emplacement of used legacy fuel at Yucca Mountain begins in 2015. If emplacement of used legacy fuel were not to occur until after the first few years of operations of the recycling plant, the total waste accumulated on the surface would not decrease until legacy fuel begins to be emplaced in Yucca Mountain.



Note: HLW-R is reduced by the densification factor: HLW-R from the treatment of 1 tHM of used fuel is represented as 0.25 tHM (factor of 4). On the other hand, used MOX quantity is presented in tHM and not in densification factor, as used MOX is not intended to be disposed in Yucca Mountain (see appendix 10 for more details).

Figure 18: Total used fuel accumulated on the surface in portfolio strategy

3) Removal of newer, hotter fuel from reactors

Newly discharged fuel is hot and is stored in cooling pools, while the colder fuel is typically in dry storage. Cooling pools are considered to be a "scarce resource" at the reactor site. In the portfolio strategy, the newer and hotter fuel is removed within three years of discharge to allow for early treatment, thus eliminating the need to build additional cooling pools. On the other hand, in the once-through strategy, the older and colder fuel is more likely to be disposed of first, as detailed in DOE's acceptance priority list[26], since older and colder fuel does not need interim storage time. Thus, in the once-through strategy, new used fuel would require additional cooling pools capacity.

[26] US DoE – *Acceptance priority ranking and capacity report* – 2004

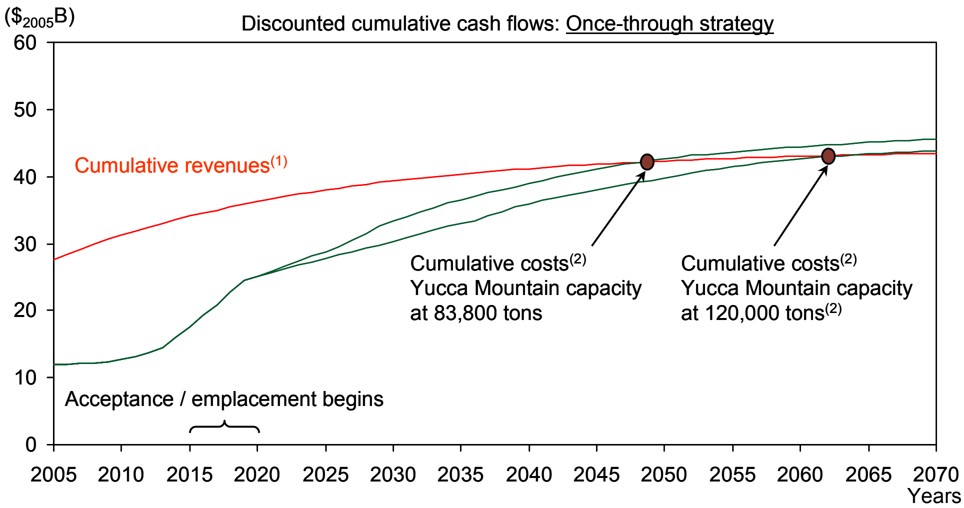
3.2.4. Financing requirements

As discussed in the previous section, the portfolio strategy provides significant benefits in the first 30-50 years of the lifecycle. However, these benefits are coupled with some early financing requirements.

To study cash requirements for each strategy, BCG compared them to the cumulative revenues of the current financing mechanism. Historically, expenditures for commercial nuclear waste management have been paid out of the federal Nuclear Waste Fund. While a detailed discussion of the current Nuclear Waste Policy Act and the use of the Nuclear Waste Fund are beyond the scope of this study, BCG makes the following assumptions for comparison purposes:

- Initial available amount is $16.3B at the end of 2004.
- No change in the current fee structure is enacted, which remains at 1 mil/KWh of electricity generated, not inflation-adjusted, according to which utilities pay into the fund annually.

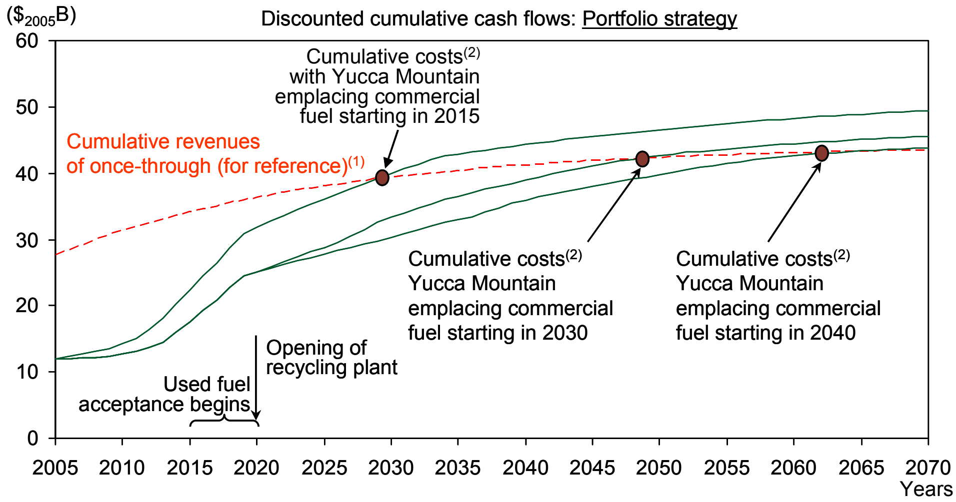
The financing requirements of the once-through strategy are shown on Figure 19 and indicate that the mil/KWh fee would be adequate until 2045 – 2060 according to the assumption on repository capacity.



(1) Assuming 2% inflation per year and fee at 1mil / KWh nominal. Assumes initial net balance of NWF to be $16.3B in 2005.
(2) Excluding cost of interim storage of legacy fuel (assumed to be directly sent to Yucca Mountain from power plants).
Note: Does not considering link with decision / costs on DoE and Navy fuel.

Figure 19: Financing outlook of once-through portfolio strategy

The analysis for the portfolio strategy shows that financing requirements would fit within the same revenues as the once-through strategy until 2030, in the case of a fully operational repository beginning emplacement of commercial fuel in 2015. Potentially this date can be extended until 2050+, if the emplacement of commercial fuel in the repository does not begin until after the first few years of operation of the recycling plant (2030-2040). The result is shown on Figure 20.



(1) Assuming 2% inflation per year and fee at 1mil / KWh nominal. Assumes initial net balance of NWF to be $16.3B in 2005.
(2) Net of credit (recycling), excluding cost of interim storage of legacy fuel (assumed to be directly sent to Yucca Mountain from power plants).
Note: Does not considering link with decision / costs on DoE and Navy fuel.

Figure 20: Financing outlook of portfolio strategy

Once again, in the portfolio strategy, used fuel is being moved off reactor sites by transporting it to the recycling plant starting before 2020, so it is conceivable that emplacement of used fuel in Yucca Mountain could begin after the first years of operation of the recycling plant, without any negative impact on the total amount of waste accumulated on the surface. The situation is illustrated in Figure 20.

3.2.5. Risk Management

Recycling as part of a portfolio strategy could reduce the risk associated with uncertainties that surround the future. Uncertainties surrounding five key areas are discussed in this section:

- Future repository costs
- Future fuel flows
- Long-term uranium supply and prices
- Pace of repository development
- Pace of deployment of advanced technologies

Uncertainty in Future Repository Costs

No cost estimates for a second repository beyond Yucca Mountain have been developed yet. Thus, absent any reliable cost estimate, the cost of the second repository in the economic assessment is assumed to be the same as the cost of Yucca Mountain.

The uncertainty surrounding future costs of a second repository is significant. On the one hand, cost reductions driven by experience are conceivable, although building a second repository in a new geologic site would likely have very different features from the Yucca Mountain project. On the other hand, the very process of finding a suitable site and opening a new political dialogue could drive costs up significantly.

In this respect, the portfolio strategy, while sensitive to factors already identified in section 3.2.2 — such as cost of the integrated recycling facility, cost of Yucca Mountain, uranium price, additional cost or credit related to management of used MOX, and discount rate — is not impacted by uncertainties surrounding the cost of a second repository, until at least 2070.

Uncertainty in Future Fuel Flows — Implication of the Nuclear Renaissance Scenario

BCG assumed a moderate increase of U.S. nuclear generation capacity by 2020 — beyond the currently installed 103 GW to at least 112 GW, based on incentives in the 2005 Energy Policy Act. A stationary model is used for generation capacity beyond 2020.

At the same time, a significant increase in nuclear power generation over the next few years is possible, even beyond what is currently included in the base case. BCG defined the case for significant increases in nuclear power as "nuclear renaissance". Under that scenario, 160 GW of installed capacity would be on line by 2030, and the level of installed capacity would stay constant after 2030. Such a significant nuclear deployment is most likely under a scenario in which stringent carbon abatement legislation is enacted and spurs replacement of an estimated 100 GW of the U.S. generation over three decades — with nuclear gaining a significant share of those builds.

An increase in nuclear power generation of that magnitude would have the effect of significantly increasing the quantity of used fuel discharged, by about 30 percent above BCG current reference scenario of 2,100 tons/year.[27]

Even under these conditions, in the portfolio strategy, the integrated plant can accommodate all of the additional used fuel by not treating legacy fuel in dilution, as it was in the reference case. More legacy fuel would now have to be disposed of in Yucca Mountain, whose capacity would need to be extended to accommodate it. However, the requirement for additional repository capacity would not exceed the technical capacity of 120,000 tons until at least 2070.

Another option available within the portfolio strategy to address the higher flow of used fuel under a nuclear renaissance scenario is to scale up the recycling plant, beyond the baseline capacity of 2,500 tons.

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[27] The increase in quantity of discharged fuel depends on the corresponding burn-up rate. With the nuclear renaissance, average higher burn-up rate are likely, driven by increase in demand.

On the other hand, the increase of volume of discharged fuel in the once-through strategy has the effect of anticipating the need for a second repository and of increasing the inventory of waste on the surface. The impact of nuclear renaissance on used fuel flows and total repository capacity needed is illustrated in Figure 21.

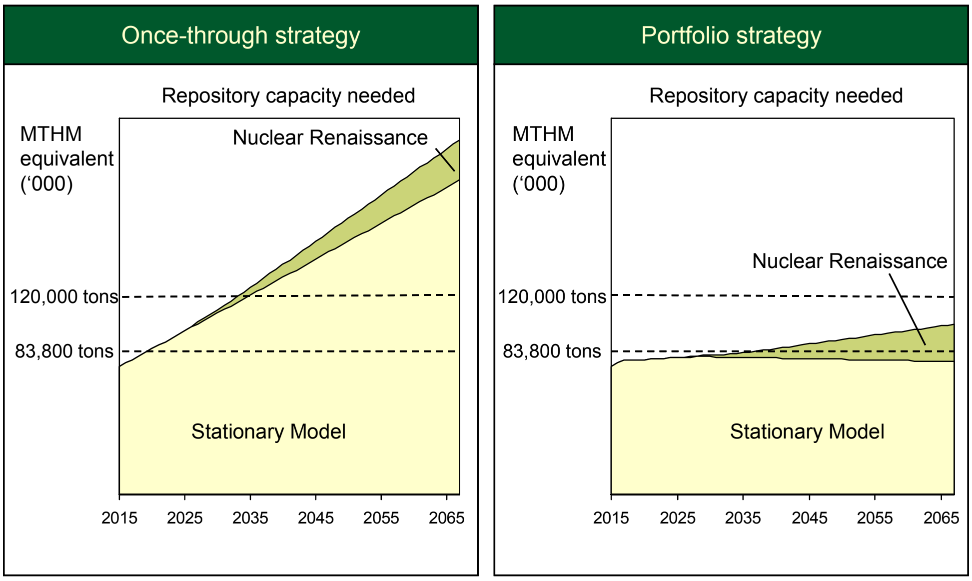

Figure 21: Impact of nuclear renaissance on repository capacity needed

Uncertainty in Long-term Uranium Prices

Both the recycled fuel from the plutonium-uranium stream (MOX fuel) and the recycled fuel (recycled UOX) from the uranium stream can be used in light water reactors and are therefore comparable in value to fresh UOX of equivalent burn-up rate, after necessary adjustments for adaptation of reactors to MOX fuel use, MOX acceptance costs, and MOX transport costs as well as additional costs for conversion, enrichment, and fabrication of recycled uranium-based fuel.

However, over the last years natural uranium prices have been increasing significantly. This recent trend in uranium prices is expected to be supported over the next few years by significant annual growth of world UOX demand (about 2% per year), primary sources expected to stay below world uranium demand, and end of secondary sources. Rising uranium prices would result in higher costs for power plant operators.

In the portfolio strategy, 20-25 percent of U.S. nuclear fuel supply is made from recycled fuel. In addition to providing a significant supply overhang and lowering dependence on foreign supply, the cost of making recycled fuel is independent of uranium prices. MOX production costs are also independent of enrichment costs. Thus, in the portfolio strategy, power plant operators could capture some of the value that the use of recycled fuel creates in when uranium prices rise, effectively protecting themselves against uranium price volatility.

Uncertainty in Pace of Repository Development

In the Implementation approach, BCG assumes that emplacement of commercial used fuel at Yucca Mountain begins in 2015.[28] At the same time, significant uncertainties surround the pace of repository development, driven by many factors, including lengthy licensing process, increasingly stringent requirements, and the like. A slower pace of development of the Yucca Mountain repository than what is currently envisioned would have a limited impact on the portfolio strategy. In particular, the total quantity of used fuel on the surface would not increase, since the integrated recycling plant begins to treat fuel by 2020. On the other hand, any delay at Yucca Mountain has a direct impact on the volume of used fuel accumulated on the surface in the once-through strategy, which relies exclusively on repository operations to reduce used fuel inventory.

Uncertainty in Pace of Deployment of Advanced Technologies

Within the time horizon that BCG considered for the integrated plant (up to 2070), two important technological evolutions could have significant impact on back-end issues: the advent of fast reactors and the development of advanced recycling techniques. Typically, fast reactor technology is associated with advanced fuel cycle technologies involving joint extraction of plutonium and minor actinides. Such a thorough extraction of radioactive material can potentially increase densification factor by much more than the factor of four considered in this assessment. Plutonium and the other minor actinides are then used to fabricate fast reactor fuel.

However, significant uncertainties surround the pace of deployment of commercial fast reactor and advanced fuel cycle technologies.

The COEX™ process that has been discussed in the context of a recycling strategy is derived from existing proven technologies. The COEX™ process is compatible with the deployment of fast reactor technologies — since the material with high energy content in used MOX could be later used to produce fuel for fast reactors — and could build valuable experience towards the development of advanced recycling technologies.

The early development of COEX™ recycling capacity can potentially "bridge the gap" between the recycling technology of today and the advanced technologies of the future, paving the way for their deployment.

[28] Alternative scenarios for dates in which emplacement of commercial used fuel at Yucca Mountain begins are used in Figures 14 and 18.

4. IMPLEMENTATION ISSUES

Implementation of recycling in the United States as a strategy to complement development of the Yucca Mountain repository presents some issues that need to be addressed. In particular, three factors need to be addressed:

- Positive legislative, policy and financial environment toward recycling.
- Broad-based industry acceptance and adaptation of U.S. reactors for use of MOX fuel
- Development of solutions to manage used MOX.

Positive Legislative, Policy and Financial Environment toward Recycling

Although legislative and regulatory considerations are beyond the scope of this study, one clear requirement for success is that enabling legislation will be needed before recycling can be moved forward.

Cost estimates for an integrated recycling plant were estimated based on a stable, positive climate in the United States towards recycling. Such a climate would ensure that the overall strategy deployment — from site selection through licensing and construction — follows timelines and regulatory approaches similar to the norm for new nuclear plant construction. An estimated seven-year construction period for a recycling plant assumes limited material interventions for licensing revisions or issues of political acceptance.

Although BCG included contingencies in recycling plant costs, BCG also assumed that a business model that brings together all the parties involved can be successfully executed for construction of the integrated plant. This could involve several creative solutions, including possible public-private partnerships, joint ventures, and other business combinations to address funding requirements, incentive-based approaches for completion, ongoing performance measures and performance-based contracting.

Broad Based Industry Acceptance and Adaptation of U.S. Reactors

The total quantity of MOX to be absorbed by U.S. reactors is estimated at ~300 tons/year. A significant number of reactors in the U.S. will have to accept MOX to make recycling a reality. Existing reactors can typically burn only up to 33 percent MOX fuel, while standard UOX fuel make up the balance. It is unclear whether future reactors will be able to burn MOX fuel at a concentration higher than 50 percent. To understand exactly what percentage of reactors would have to be adapted, BCG considered three categories that can burn different percentages of MOX:

- Current reactors with more than 20 years of remaining lifetime in 2020 could burn up to 33 percent MOX fuel with some reactor adaptation and license amendment.
- Current reactors with fewer than 20 years of remaining lifetime in 2020 could burn a lower quantity of MOX (estimated at 20 percent) with licensing-only requirements.
- Newly built reactors are likely to be able to accept higher levels of MOX fuel (~50 percent and potentially more depending on the technology).

The first category seems to represent the top candidate for reactor adaptation. If only reactors within this category were considered, 80-90 percent of them would presumably have to be available to accept MOX. If, on the other hand, the second and third categories were targeted, only 50-60 percent and 30-50 percent of the units would need to be adapted. This situation is illustrated in Figure 22.

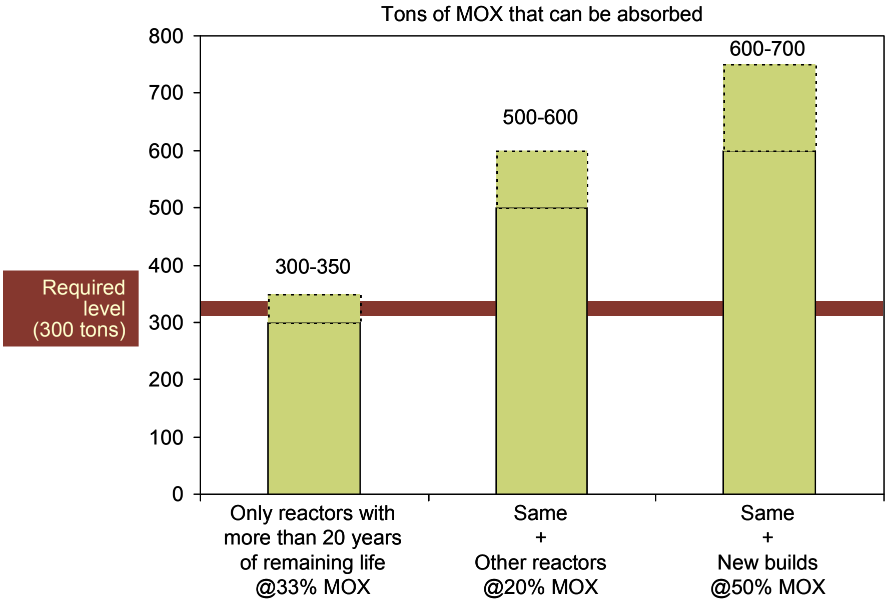

Figure 22: Reactor adaptation requirements

Broad-based acceptance of MOX by nuclear utilities is thus necessary for successful implementation of recycling in the United States. This factor was taken into account in BCG computation of credits for MOX, where a 25 percent reduction is applied to the computed value of MOX. This factor is intended to cover all the costs of introducing MOX into the system, including the less-quantifiable “MOX acceptance costs”.

Development of Solutions to Manage Used MOX

The recycling strategy, while resulting in a significant reduction in the volume of used nuclear fuel waste, is not a closed cycle or complete solution under current technology. By 2075, about 15,000 tons of used MOX will have been generated and initially stored at the recycling plant site. The recycling strategy relies on a broad range of future potential solutions to handle used MOX, with potential for negative or positive economic impact on recycling.

In a possible scenario, the portfolio strategy could leverage fast reactor and minor actinide removal technologies to limit economic impact of used MOX and to fully optimize repository space. This solution would have the effect of further reducing estimated recycling costs by 0-10 percent.

Multiple recycling of used MOX is also an alternative option. While this solution presents some technical challenges that need to be overcome, it would provide a solution in case of potential delay of fast reactor technologies. It also would have the effect of increasing total recycling costs by an estimated 10-15 percent.

Disposal of used MOX in a geologic repository is not considered a viable option, because it could increase recycling costs up to 40 percent by undermining any advantage gained on repository capacity, while also wasting valuable material with a high energy content that could be used by future generations.

More detailed calculations of the impact of used MOX on the overall economics of the portfolio strategy are included in appendix A10 .

5. CONCLUSIONS

Recycling, as part of a portfolio strategy in which an integrated recycling plant complements the Yucca Mountain repository, could be attractive for solving the long-term used fuel management requirements of the U.S. nuclear power market.

Recycling shows comparable economics to an exclusive once-through strategy, especially considering uncertainties that surround many of the variables used in the assessment, such as uranium price and repository costs.

As with all other options, the recycling strategy involves some issues that need to be addressed. In particular, successful implementation would require:

- Broad-based acceptance of recycled fuel by the nuclear industry, as recycled fuel would have to be used in a significant number of reactors.
- A positive legislative, policy, and financial environment for recycling.
- Development of optimal solutions, such as use in fast reactors or multiple recycling, to manage the relatively limited[29] quantity of used MOX fuel, yet with flexibility on the timing.

In addition, recycling, as part of a portfolio strategy, presents a number of benefits:

- Eliminates the need for additional repository capacity, beyond the initial 83,800 ton capacity at Yucca Mountain, until 2070.
- Contributes to early reduction of used fuel inventories at reactor sites — in particular, removing newer, hotter fuel for recycling within three years of discharge and eliminating the need for additional investments in interim storage capacity.
- Relies on existing technology; with appropriate modifications, and can provide an operational transition to future technology developments such as Advanced Fuel Cycles and fast reactors.
- Shows cash flow requirements that could fit until 2030 within the current financing resources available for the once-through strategy, or even until 2050+ if acceptance of used fuel at Yucca Mountain begins only after the first years of operation of the recycling plant.
- Offers a tool for nuclear power sector to protect against potential rises in uranium prices, by providing MOX and recycled UOX fuel[30], whose production cost is independent of uranium prices and enrichment costs.

The benefits are compelling enough to warrant further consideration of recycling as a complementary approach to developing Yucca Mountain capacity.

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[29] Relatively compared to the overall quantity of used fuel generated by 2070 (15,000 tons out of a total of ~200,000 tons of used fuel).
[30] MOX and recycled UOX fuel estimated to satisfy 20-25 percent of U.S. fuel requirements.

BCG recommends a range of next steps:

- Pursuing a constructive dialog among key policy makers and industry leaders on the results of this and other recent fuel cycle management initiatives. The objective of such an effort would be consensus on the possible merits of the recycling portfolio strategy and other available strategies, with identification of a limited set of issues to be addressed.
- Developing a detailed business plan for the recycling portfolio strategy that considers:
    - additional technical aspects such as development of a complete technical road map, including comprehensive deployment timeline and implied licensing/ approvals, management of used MOX fuel, and the like.
    - commercial aspects such as funding and operational mechanisms and the potential for public-private partnerships.
    - policy aspects such as non-proliferation.
- Building on the above steps and developing an overall roadmap.

APPENDIX

A1 . KEY METHODOLOGIES

In this section, we describe two key methodologies used for the economic assessment:

- The unit cost methodology, which is a standard methodology used in estimates of back-end costs and is used in the context of the Greenfield approach;
- The net present cost methodology, used in the context of the Implementation approach.

All computations are made in real 2005 dollars, using a real weighted average cost of capital (WACC).

Unit Cost

In the course of this study, the unit cost methodology is used within the Greenfield approach. Unit costs are defined as the (imaginary or real) cost of purchasing a service/product from a supplier, paid in the year the service/product is supplied. Unit costs in the study are, whenever possible, calculated using investment, operations and decommissioning lifecycle cash flows.

The unit cost calculation method used in the study is a standard average lifecycle cost calculation based on expected returns on investments. For example, in the case of an integrated recycling plant, the method seeks to identify the average revenues required over the operational lifetime of the installation such that the discounted revenues are equal to the discounted sum of all cash outflows. Specifically, we seek to solve the following equation for the unit cost (UC):

$$\sum_{i=1}^{i=a}\left[\frac{CAPEX_i}{(1+WACC)^i}+\frac{OPEX_i}{(1+WACC)^i}+\frac{DECOM_i}{(1+WACC)^i}\right]=\sum_{i=1}^{i=a}\frac{UC\cdot PROD}{(1+WACC)^i}$$

Where:

- $CAPEX_i$, $OPEX_i$ and $DECOM_i$ are the investment, operating and decommissioning costs incurred in year *i.*
- WACC is the weighted average cost of capital of the entity investing in the installation.
- PROD is the annual production of the installation in question.
- UC is the desired unit cost.

Thus, the unit cost represents the average price of service/product that a supplier would charge at any point in the lifespan of the installation.

Once the calculation of the unit cost is completed, we have a \$/kg[31] figure for each component of the cycle. Such a number needs to be further discounted depending on the timing of the expense. The mid-irradiation point is the reference point (t=0) to which all the costs are reported. Discharge occurs approximately two years after the mid-irradiation point.

For example, in the case described above, from the time of fuel discharge (t=2), the fuel would not be sent to any recycling plant until after it has been cooled at the reactor site. Therefore, the

[31] "\$" refers to 2005 dollars and "kg" refers to kilogram of used fuel discharged.

recycling unit cost needs to be discounted for the years of on-site cooling. The discount rate used for this operation is a conceptually different rate than the cost of capital originally used for the computation of the unit cost. Even though the two values could be the same, the WACC is the cost of capital for the operator of the plant, while the discount rate is the cost of capital from the perspective of the entity that has the overall responsibility on the used fuel. In the course of the study, we will often use the same value for both the WACC and the discount rate, by assuming that the Department of Energy (DOE) is effectively the owner of the fuel as well as the operator (or primary financing entity) of all the components of the fuel cycles. A more detailed discussion on the discount rate and the cost of capital is in appendix A3 .

Net Present Cost

When we move from the Greenfield to the Implementation approach, we find the use of a net present value (cost) approach, rather than a unit cost, more straightforward. Although the results from the two approaches (unit cost and net present cost) are very similar, a definition of a unit cost in the Implementation approach requires the use of assumptions that are not as transparent as in the Greenfield approach, due to the concurrent presence of legacy used fuel and new used fuel, and variable fuel flows.

The net present value is derived from the real cash flows to be expected over the course of the life time of the solution. Cash flows in the study are, whenever possible, calculated using investment, operations and decommissioning cash outlays, very similarly to what is done in the unit cost methodology. For most components, we take those cash flows directly, with a few necessary adjustments. Once the cash flows have been defined, we proceed in exactly the same way as in the unit cost methodology, only falling short of the final step in which we calculate the actual unit cost.

$$\sum_{i=1}^{i=a}\left[\frac{CAPEX_i}{(1+WACC)^i}+\frac{OPEX_i}{(1+WACC)^i}+\frac{DECOM_i}{(1+WACC)^i}\right]=NPV$$

The undiscounted cash flows represent the total life cycle cost of a given solution.
In the course of the study, wherever possible, we presented both the undiscounted and the discounted cash flows, in order to highlight the timing component of the calculation.

A2 . FUEL VOLUMES

In this section, we detail the assumptions used to calculate the amount of used fuel discharged in and after 2020.

The quantity of fuel discharged annually is an important parameter, as it drives, among other factors, the size of the integrated recycling plant, the availability of repository capacity, the quantity of MOX produced and, thus, the number of reactors that need to be adapted for the acceptance of MOX.

For our assessment, we use a stationary scenario, in which the main variables are kept constant after 2020. Although this is a simplification of future conditions, it has the advantage of being easy to test, verify and communicate and does not require the use of models and long-term estimates for the future of nuclear energy beyond 2020-2030, which go beyond the scope of this study. Two stationary scenarios are then defined:

- A base case scenario, in which we make conservative assumptions on the growth of nuclear power, based on available data.
- A nuclear renaissance scenario, in which we consider the possibility of a sharp growth in nuclear power, which, in turn, drives the annual quantity of fuel discharged.

Specifically, the quantity of fuel discharged is derived from the amount of nuclear electricity generated and the average burn-up rate. In the following two sections, we make important considerations in terms of these two key variables.

Future Nuclear Generation of Electricity

To estimate the future nuclear generation of electricity, we use the estimated installed capacity as a proxy, by assuming a constant utilization factor going forward. Although utilization factors have increased significantly since the dawn of nuclear energy, they have now reached ~90% and are expected to plateau over the next few years.

In terms of future installed nuclear generation capacity, we consider the following factors:

- Re-connection of Browns Ferry 1 expected in 2008.
- Up-rates of ~950 MW to be effective in 2005-2008 (currently under review), another ~950 expected by NRC in 2008 and ~1 GW between 2008-2020.
- New reactors for ~6 GW of capacity, driven by Energy Policy Act of 2005.
- Licenses for all reactors extended for an additional 20 years.

These factors result in an installed capacity of 112 GW by 2020, as illustrated in Figure 23. This is consistent with external studies.[32]

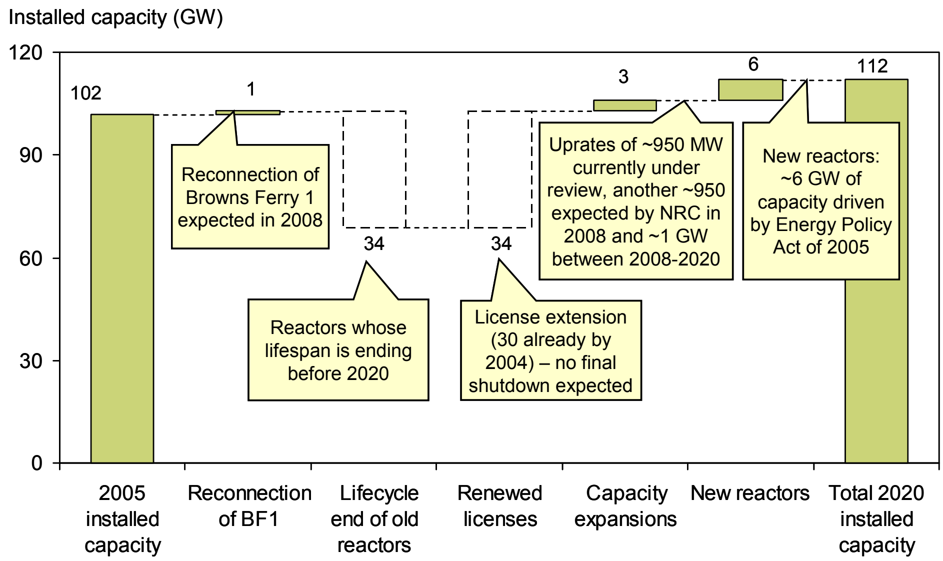


Figure 23: Expected nuclear installed capacity in 2020

In addition, we assume a steady state beyond 2020, in which old reactors that are coming off-line are substituted with new builds.

As previously discussed, we also envision a scenario in which a favorable environment towards nuclear power, driven by carbon taxation, favorable legislation, high oil and gas prices, accelerates the construction of new reactors (6 GW completed by 2015) and stimulates the construction of a second wave of reactors by 2015-2030. In order to estimate the quantity of nuclear power generation installed in 2015-2030, we looked at the existing fleet of power plants and observed that there is ~100 GW of coal production capacity, which could potentially be retired if stricter environmental regulations were enacted. In that case, we might expect that power plants based on cleaner-coal technology and nuclear would replace the retired coal plants. Assuming nuclear power accounts for a significant portion of the replaced installed capacity, we could potentially expect a total nuclear installed capacity of ~160 GW by 2030. A total installed capacity of ~160 GW is also the installed capacity for which nuclear power installed capacity grows at the same rate as projected electricity demand (~1.8%).

[32] World Nuclear Association – *The global nuclear fuel market* – 2003.

Burn-up Rate

Historically, burn-up rate is driven higher by fuel cost optimization. Main drivers for higher fuel assembly burn-ups are:

- Smaller number of fuel assemblies purchased, which, in turn, reduces used fuel storage requirements and overall fuel costs.
- Longer cycles, which drive shorter refueling outages and therefore higher utilization factors.
- Higher power plant output.

However, the legal limit of 62 GWd/t on peak rate set by NRC, bounds the potential increase in burn-up rates over the next years. The legal limit translates into an average assembly burn-up limit of 50-52 for PWR reactors, potentially stretching to 55. Other estimates call for a future burn-up rate of 53 for PWR and 49 for BWR in 2020. Such estimates are illustrated in Figure 24, along with historical burn-up rate values.

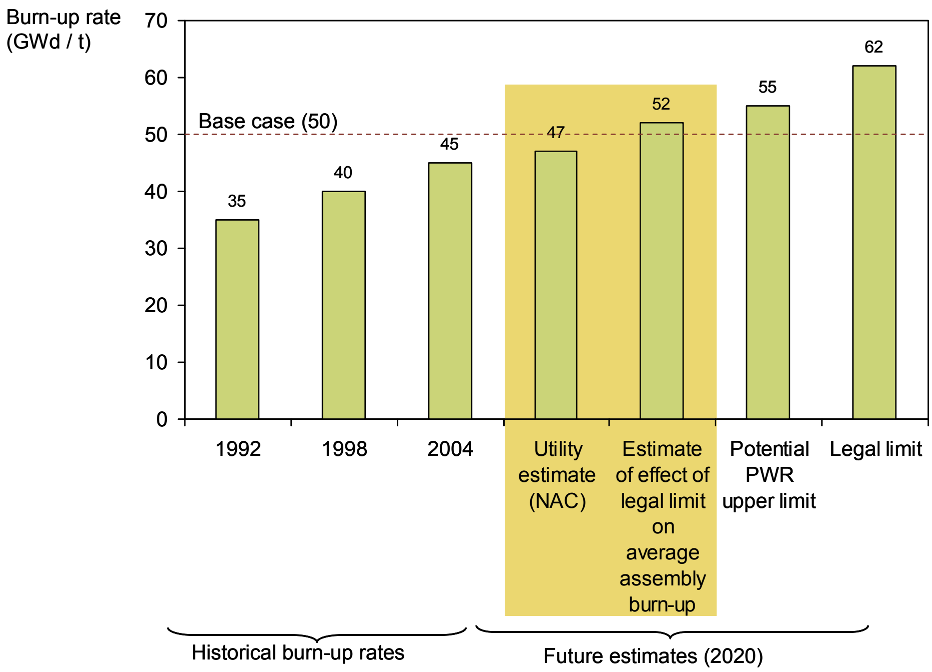


Figure 24: Burn-up rate estimates

Given the data points available, we use a central estimate on the burn-up rate of 50 GWd/t. This value is expected to remain constant after 2020, under the assumption that the 62 GWd/t legal limit is not changed.

Fuel Volumes

The estimates on future nuclear power generation and burn-up rate result in a total quantity of used fuel discharged annually of 2,100 tons/year.

In the case of the nuclear renaissance scenario, the increase in capacity installed and power generated results in a higher quantity of used fuel discharged. At the same time, the higher percentage of gen III reactors in the nuclear fleet, as a result of a higher number new builds, is expected to push the burn-up rate to higher values. The resulting quantity of used fuel discharged under the nuclear renaissance scenario is ~2,700 tons/year.

Mass Balance

In the base case scenario, annual material flows for an illustrative year under the portfolio strategy are given in Figure 25. Numbers are rounded to the closest one hundred.

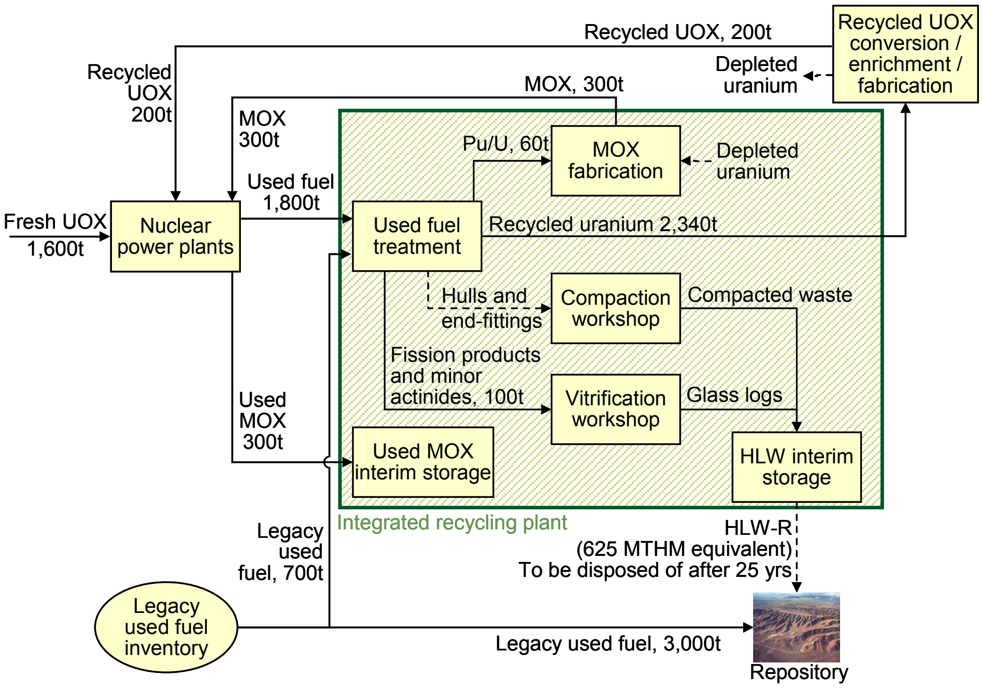


Figure 25: Annual material flows at steady state in portfolio strategy (illustrative for 2040)

At any given year, fresh fuel is loaded into nuclear power plants at a rate of about 1,600 tons. The balance of required fuel is provided by the recycled uranium-based fuel (200 tons) and MOX (300 tons), for a total of 2,100 tons. The same total tonnage of used fuel is discharged, 300 tons of which is used MOX that is sent to the recycling plant for storage and future use, either in fast reactors or in a second recycle (see section 4 and appendix A10).

The balance, 1,800 tons, is sent to the recycling plant for treatment. At the same time, 700 tons from the inventory of legacy used fuel are sent to be treated as well, in dilution.

In the treatment unit, the 2,500 tons of used fuel are separated into three main streams:

- Plutonium-uranium stream, which is then turned into MOX fuel and recycled into the system. Note that only a small portion of the total quantity of uranium available in the used fuel is co-extracted with the plutonium. The remaining balance is recycled.
- Recycled uranium stream, which is purified, converted and re-enriched outside the integrated recycling plant, fabricated into uranium-based fuel, and also recycled into the system.
- Fission products and minor actinides, which are vitrified into glass logs and, along with the compacted waste (from assembly hulls and end-fittings), stored at the integrated recycling plant site, and eventually disposed into the repository.

Finally, in the portfolio strategy, a portion of the legacy fuel is disposed directly into the repository, at a rate of ~3,000 tons/years.

A3 . DISCOUNT RATE

In this section, we detail the rationale behind the assumptions used for the discount rate.

The possible range of values for both the discount rate and the cost of capital are very broad, depending on whether we consider public or private money to be used, or a combination of both.

Throughout the study we assume that all the steps in the cycles are funded with public money, since the Department of Energy is legally responsible for the back-end of the nuclear fuel cycle. Therefore, we use the same public discount rate. However, we acknowledge that the cost of those portions of the solutions that could be managed by private entities – most notably the recycling plant, but potentially also the transport system and all interim storage facilities – could be significantly higher if a private-industry cost of capital were to be applied.

Therefore, in the next two sections, we look at the discount rate generated from public funding and from private funding (including hybrid solutions).

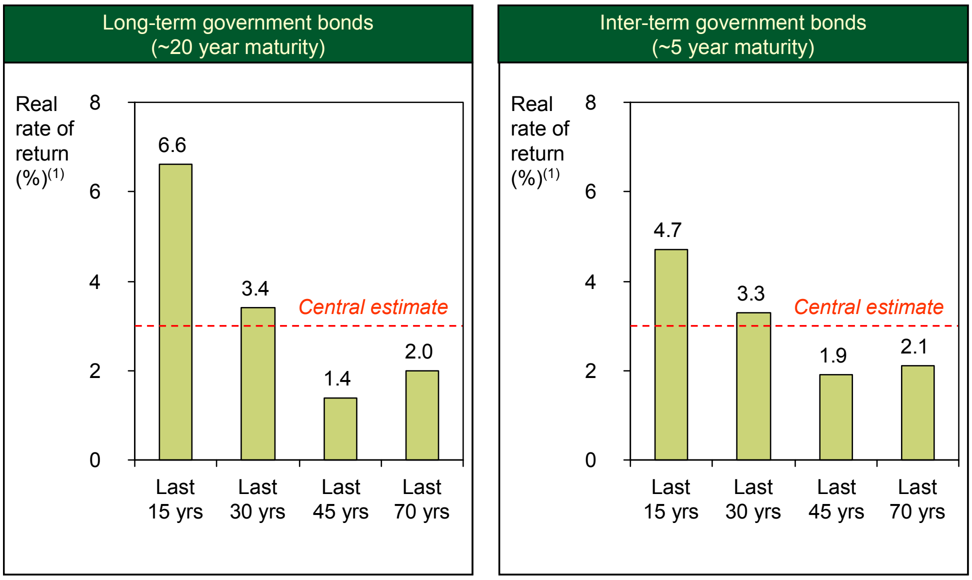
Public Funding

The value of the discount rate from public funding was triangulated based on:

- Historical real rate of return on long-term government bonds.
- Office of Management and Budget (OMB) guidance.

Fluctuations in bonds return make it such that very different average rates of return result depending on what investment interval is considered. Based on returns during the course of the last century[33], illustrated in Figure 26, a rate of return of 2-4% appears to be representative of very long periods of time, such as the ones considered in our assessment (50+ years).

[33] Ibbotson Associates – *Stocks, bonds, bills, and inflation* – 2000.



(1) Reference year is 2000.

Figure 26: Average real rates of returns for U.S. government bonds

The Office of Management and Budget (OMB) also provide guidance for the discount rate to be used when public funding is assumed, through circular A-94[34]. Appendix C[35], updated in January 2006, reads as follows: "*A forecast of real interest rates from which the inflation premium has been removed and based on the economic assumptions from the 2007 Budget is presented below (* Table 2*). These real rates are to be used for discounting real … flows, as is often required in cost-effectiveness analysis.*"

3-Year	5-Year	7-Year	10-Year	30-Year
2.5	2.6	2.7	2.8	3.0

Table 2: Real interest rates on Treasury Notes and Bonds (%)

Based on the elements above, we selected a discount rate of 3.0%, as the central assumption for our analysis. In section A9 of the appendix, the sensitivity range on the discount rate is discussed in more details.

Private Funding

In the case of a private entity, we believe an after-tax real weighted average cost of capital (WACC) of 6-7%, equivalent to ~9-10% pre-tax WACC at 35% tax rate, is reflective of an established company. Several data points corroborate this assumption.

[34] US OMB, Office of Economic Policy – *Circular A-94: Main guidance for cost/benefit analysis and discount rates* – 1992.
[35] US OMB, Office of Economic Policy – *Circular A-4: Discounting for long term projects* – 2003.

Market-driven calculations of real after-tax cost of capital for selected industries indicate a range of 5.8-6.6%. Market-driven calculations are based on current stock prices and future cash flow forecasts. Market-driven calculations are forward-looking and eliminate some of the issues that calculations based on the capital asset pricing model (CAPM) present, although actual differences between the two calculation methodologies are often immaterial. Although a detailed description of these methodologies goes beyond the scope of this study, market-driven calculations are particularly effective for peer groups. Costs of capital for selected industries are illustrated in Table 3.

	Cost of capital
Power generation	6.6%
Electric utilities	6.4%
Consumer electronics retailers	6.2%
Telecommunication	6.2%
Hospitality	6.2%
Automotive	6.2%
Oil and gas	5.8%

Table 3: Cost of capital for selected industries based on market-driven calculations

The Office of Management and Budget also provides guidance on net rate of return on private capital to be used, indicating that analyses of privately funded project should use a net real rate of return of 7.0%.

Private-public Partnerships

Hybrid models can be explored for the financing of necessary back-end investments. A typical example is a public-private partnership, a solution in which public entities provide guarantees and lower borrowing rates, while allowing private entities to invest first-hand and retain significant project management control. Such a partnership results in a cost of capital that is in between the public and the private cost of capital.

The use of private fund discount rates would have the effect of increasing unit costs significantly. Specifically, it is estimated that a private partnership at 80% public and 20% private for the recycling plant, roughly equivalent to using a 5% WACC, would result in an additional discounted unit cost of $35/kg (~6% of the discounted recycling unit cost), or in an additional undiscounted unit cost of ~$120/kg (~20%).

A4 . INTEGRATED RECYCLING PLANT

In this section, we describe three aspects of the integrated recycling plant

- Basic design and process flows of the plant.
- U.S.-specific costs.
- Comparison between the cost of a state-of-the-art large scale integrated plant in the U.S. and the historic costs of the La Hague plant.

Basic Design and Process Flows of Recycling Plant

The main flow of the plant design with the main workshops and the process lines is illustrated in Figure 27.

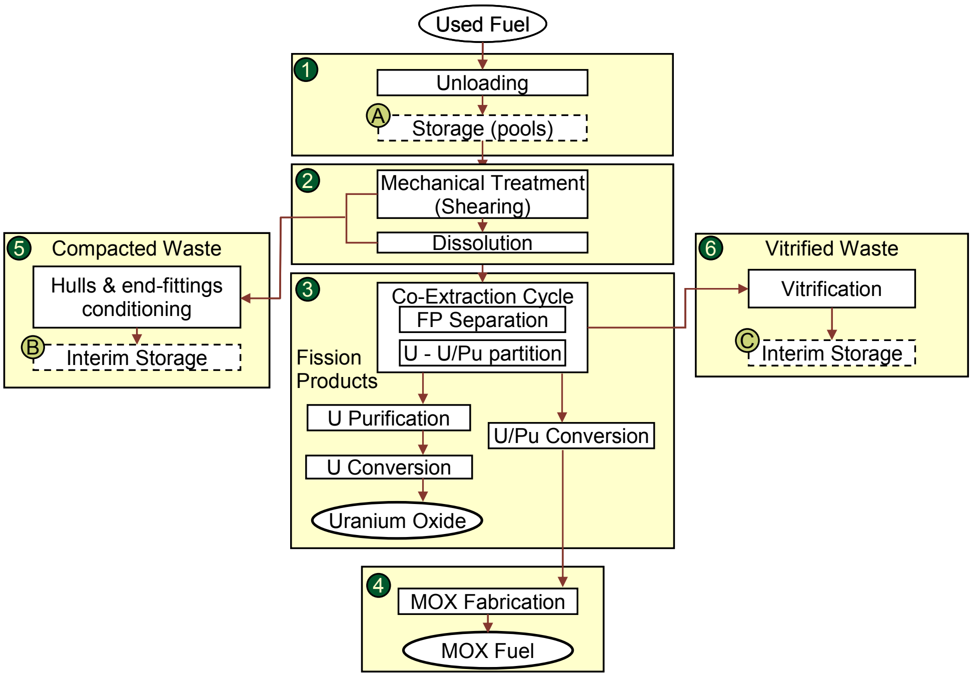


Figure 27: Schematic of the process flows within the integrated plant.

In workshop 1, the casks are unloaded (dry) and placed in pools. Three dry lines are available for this operation, plus a wet line. Once the fuel is ready, the casks are moved to workshop 2, where they undergo shearing and dissolution (three lines). The hulls and the end-fittings are sent to workshop 5, where they are compacted into cylinders (compacted waste, which is a portion of the HLW-R) and then stored at the interim storage site B. The used fuel then undergoes the chemical co-extraction process, which generates three main streams: 1) The mix of plutonium and uranium, which is sent to the MOX fabrication facility, workshop 4, where it is made into fuel for future use in light water reactors, 2) The pure uranium, which is sent to an external enrichment facility and is then fabricated into uranium-based fuel for light water reactors, 3) The fission products and the minor actinides, which are sent to the vitrification workshop 6, where they are turned into glass logs (HLW-R) and then stored at interim storage C.

Multiple lines are included in the design of the plant in order to limit operational risk and ensure availability. There is also some space available for an additional chemical line.

The plant has been dimensioned to accommodate some legacy fuel with low burn-up, which can be treated "in dilution", as previously discussed. In the treatment by dilution, the older legacy fuel, which has developed some americium content, is mixed with new fuel. As long as the ratio of older legacy fuel to new fuel is low (typically < ¼), the characteristics of the resulting glass logs and the recycled fuel are not impacted significantly, as the limiting factor is volume.

U.S.-specific Costs

The adjusted costs for treatment and fuel fabrication that are originally estimated from the real cost incurred by AREVA in Europe are converted into U.S. costs and augmented to reflect the costs that are specific to the US context, both for additional capital investments and operating expenses. For translating the cost of the integrated plant, a direct application of an exchange rate would be inappropriate, given that currency exchange is tied to market fluctuations that do not necessarily reflect the real cost of building and operating a plant in one country vs. another.

We have triangulated the overall conversion factor using a "top-down" analysis, based on publicly available conversion indices, and a "bottom-up" analysis, based on a detailed examination of the main cost line item of the integrated plant.

In the "top-down" analysis, the overall conversion factor to be applied to the original costs can be estimated using existing conversion indices, such as the purchasing power parity (PPP) index. The PPP index between France and the U.S. is 1.11[36], which indicates that it would cost $1.11 to buy the same amount of products/services that 1€ could buy in France However, if used for industrial applications, the PPP needs to be corrected for the effect of sales and value-added taxes[37]. The corrected PPP is 1.11 – 1.21. Other more specific PPP indices include a construction PPP (0.94-1.10), total goods PPP (0.87-0.96) and total services PPP (1.35-1.46)[38]. A central estimate of 1.15 is then used for the calculation. The "bottom-up", line-item analysis confirmed the validity of this estimate.

Additional U.S. costs for capital expenditures have then been included in the cost computation of the integrated plant, based on the experience obtained in U.S.-based projects. Five key components have been identified: additional protection on civil engineering, seismological impact on design, regulatory affairs, engineering requirements, and larger design of building. We estimate that these components amount to a total of ~$2B additional capital investments.

Finally, taxes (or payments-equivalent-to-taxes) on the plant could be in the order of $50M per year. This estimate is based on the analysis of the payments-equivalent-to-taxes (PETT) for Yucca Mountain outlined in the DOE 2001 TSLCC[39]. Although the exact amount of such payments for a

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[36] OECD – *Purchasing power parities and real expenditures* – 2002.

[37] Blake, Croot, Hastings (Experian Business Strategies) – *Measuring the competitiveness of the UK construction industry* – 2004.

[38] OECD – *PPP methodological manual* -- a) Chapter 6: capital goods and services and b) Annex II: classification of final expenditure on GDP – 2005.

[39] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

recycling plant is uncertain, the use of the repository figures allows for a fair comparison between the once-through and the recycling strategy. We considered insurance costs to be zero under a public ownership model (similar to Yucca Mountain).

Comparison between U.S. Plant and Historic Costs of La Hague and Melox Plants

Some important factors, especially for the treatment plant portion, should be considered when comparing the cost of a state-of-the-art large scale integrated plant in the U.S. and the historic costs of La Hague and Melox plants.

Elimination of redundant or unnecessary design components
Some of the workshops currently in operation at La Hague plant would not be relevant in the context of a recycling plant in the U.S. (such as plutonium storage, bitumen workshops, etc.). Not considering those workshops reduce construction and operation costs. Workshops included in the historical costs of La Hague and not used anymore are also excluded.

Design improvement
Significant design improvements should be considered for a plant in the U.S. The facilities in Europe were developed at different stages, over a period of time of ten years or more, and did not have benefit from an efficient "from the ground-up" design. Three important differences, which can generate significant cost savings, should be considered:

- The first difference is the use of an integrated design. Fabrication of MOX and other processes currently outside the main process flow are in line with the rest of the process, thus eliminating operational steps, such as transport and storage of work-in-progress and diseconomies of scale.
- The second difference is the use of a single treatment plant. There are currently two plants at La Hague site, UP2-800 and UP3. Combining these two plants into one would provide economies of scale, especially on buildings, utilities and other operational expenses.
- The third difference is the use of each portion of the plant at full capacity thanks to a focused debottlenecking.

Overall scale effects
The net capacity of a plant in the U.S., given expected flows of used fuel, should be in the order of 2,500 tons per year. The net capacity is based on 300 days of operation and allows for routine shut-downs and maintenance. This is significantly larger capacity than the plants currently operating in Europe. The $/kg economics of the larger plant does therefore benefit from economies of scale, typical of large industrial plants.

Technical optimization
Based on the last 20+ years of experience in the European facilities, AREVA considered that some technical optimizations could be implemented in a plant in the U.S. by 2020. The three most important technical optimizations considered relate to vitrification process, management of solid waste, and laboratories organization and design.

The economic impact of these factors were discussed in section 2.2.1.

Job Creation

While we did not include the creation of jobs as an economic criteria in our assessment, it is important to note it, as it would have a significant impact on the surrounding communities of a potential recycling plant. In fact, on-going operational activities of the plant would create ~5,000 highly compensated jobs that require significant skills. The total number of people indirectly employed as a result of the presence of the plant would be six times as high. The large number of indirect jobs is a result of: a) the impact of the plant's large scale of investment activity (nearly all of which is sub-contracted); b) the significant level of operational procurement (including contracted out services); c) the employment impact of the spending power of those employed in the industry and its suppliers.

A5 . REPOSITORY

In this chapter, we delve into four areas related to the repository

- Key assumptions, where we re-iterate and detail some important inputs to the cost analysis.
- Calculation of the densification factor, which is an important cost driver in the cost of recycling in the Greenfield approach.
- Translation of the densification factor into cost savings.
- Clean storage solution recently proposed by DOE and rationale for not including this potentially viable repository design option in our estimates.

Key Assumptions

As a reference for the repository, we use Yucca Mountain, in particular referring to the economic and physical parameters delineated in the DOE 2001 study[40]. While we understand that some of the parameters in the DOE study could be outdated at the time of this study, given recent developments concerning the repository licensing process, we believe that the source is adequately representative and can be used as a starting point. To partially alleviate the issue described above, in the sensitivity analysis portion of the economics, we have looked at the impact of major uncertainties (see appendix A9).

The repository is composed of surface and subsurface facilities. As part of the surface facility, a significant area is devoted to the receipt of waste. The largest part of the subsurface facilities is the actual drifts. Waste for disposal is packaged into special waste packages, made of corrosion-resistant material and stainless steel. In addition, at the time of repository closure, titanium drip shields are installed to further reduce corrosion rates and protect waste packages from rock falls.

In terms of *capacity* of the repository, we use 83,800 tons of used fuel as the reference point. We also assume that the acceptance rate of Yucca Mountain is 3,000 tons/year. We assume that the capacity of the repository can potentially be extended to reach the technical capacity, which is estimated to be at 120,000 tons.

In addition to used commercial fuel, Yucca Mountain is also designed to accommodate used DOE and Navy fuel, and a portion of the cost is allocated for those types of non-commercial fuel. In the course of this study, we always look exclusively at the commercial portion, which constitutes about 73% of the expected total cost of the repository.[40]

As far as the opening date of Yucca Mountain, defined as the earlier date at which nuclear waste begins to be emplaced underground, the 2010 opening date (i.e. the date in which used fuel begins to be emplaced underground) in the DOE study[40] does not seem any longer valid under current U.S. conditions. We therefore move the opening date to 2015, thus adding five years of development. We assume that, during the additional five years of development, DOE would spend annually the average cost originally expected in the 2000-2005 timeframe.

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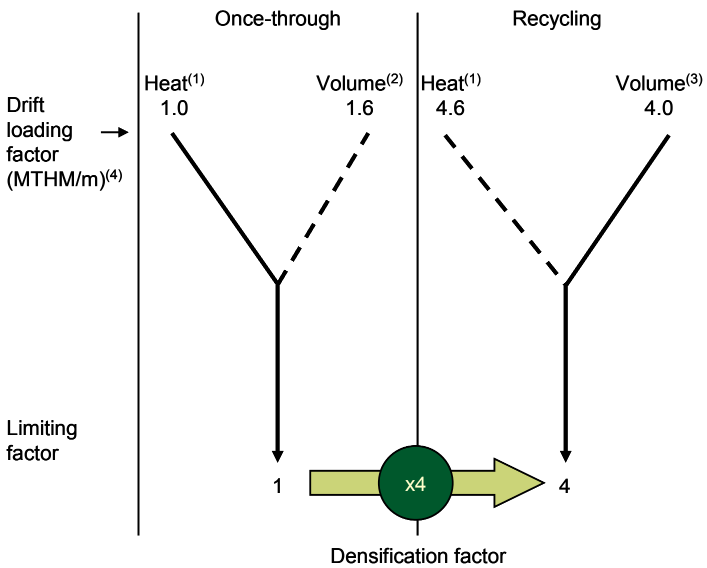
[40] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

Densification Factor

In the recycling strategy, the repository is expected to accept high-level waste from recycling (HLW-R). Since HLW-R has lower heat content and is more compacted than used fuel, it is conceivable that a higher quantity of HLW-R, in terms of metric tons of initial heavy metal (MTHM), can be disposed of within the same physical constraint of the repository. There is, therefore, a “densification factor”.

The quantity of HLW-R or used fuel that can be disposed per unit length of Yucca Mountain is further referred to as the “drift loading factor” and is expressed in MTHM/m_{YM}. In the terminology used in this study, the *densification factor* is the ratio of the *drift loading factor* of HLW-R to the *drift loading factor* of used fuel.

In order to calculate the drift loading factors, we need to look at two potential constraints that can limit the amount of waste that can be disposed into the repository: volume and heat. Calculations of the heat-constrained drift loading factors are based on a thermal modeling tool developed by AREVA. The results of the calculations are a drift loading factor of 3.8-4.2 MTHM/m_{YM} for HLW-R and of 1.0-1.1 MTHM/m_{YM} for used fuel. The resulting densification factor is ~4, as illustrated in Figure 28.



(1) Assumes 50 GWd/TU burn-up -For HLW: 3 years of cooling before treatment and 21 years of interim storage; For used fuel: total cooling time of 25 years.
(2) For new used fuel volume constraint, assumes 8.45 MTHM per waste package and 5.2 $m_{Yucca\ Mountain}$ / waste package.
(3) For HLW-R volume constraint, assumes 1.3 - 1.4 canisters / MTHM, 28 canisters / waste package, 5.2 $m_{Yucca\ Mountain}$ / waste package (volume-driven).
(4) Defined as the quantity of equivalent initial heavy metal that can be disposed of per linear meter of Yucca Mountain drifts.

Figure 28: Densification factor calculation

<u>Volume constraint for high-level waste from recycling (HLW-R)</u>: in the integrated recycling plant, 1.3-1.4 canisters of vitrified and compacted HLW-R are generated per MTHM (used fuel). Considering that 28 canisters can be loaded into a waste package, that implies that ~20-22 MTHM per waste package. Since a waste package is ~5.2 m long, the quantity of HLW-R that can be disposed per linear meter of Yucca Mountain, or drift loading factor, is in the order of 3.8-4.2 MTHM/m.

Volume constraint for used fuel: each used PWR fuel assembly is ~0.4 MTHM. Each waste package can contain 21 PWR assemblies. The same assumption of 5.2 m for the length of a waste package results in a drift loading factor for used fuel of ~1.6 MTHM/m. In the case of BWR assemblies, this number could be similar or potentially even higher, since more, but lighter, assemblies can be loaded into a waste package.

The calculation of the heat constraints is based on two temperature constraints at Yucca Mountain: the temperature of the drift wall has to be below 200° C and the temperature in between drifts has to be less than 96° C, in order to guarantee the geologic integrity of the repository at any point in time. In addition, 75 years of drift ventilation are provided, after which the ventilation system is shut off.

Each of the actinides and the fission products contribute to a portion of the heat generated, which results in temperature peaks. The two major peaks occur at the ventilation shut-off time, driven by short-lived products, such as cesium (^{137}Cs) and strontium (^{90}Sr), and around 1600 years after disposal, driven by long-lived actinides such as plutonium (^{239}Pu and ^{240}Pu) and americium (^{241}Am). The contribution of each component to the total decay heat is illustrated in Figure 29.

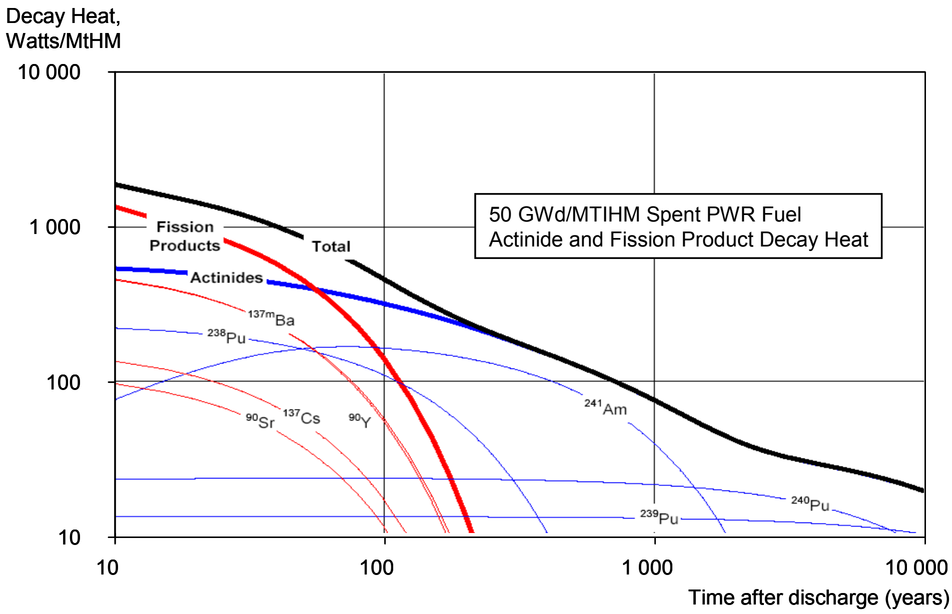


Figure 29: Contribution of each component of used fuel to the decay heat

Heat constraint for used fuel: In the case of used fuel, the long-term peak, driven by ^{239}Pu, ^{240}Pu and ^{241}Am is the key limiting factor and results in a maximum quantity of fuel by linear meter of gallery of 1.0-1.1 MTHM/m, which is lower than the drift loading factor from simple volume considerations.

Heat constraint for HLW-R: In the case of HLW-R, plutonium and americium are present only in minimal quantities. Early treatment of fuel ensures very limited americium build-up. In the thermal model developed by AREVA and used for this study, a cooling time of four years coupled with an interim storage duration of 21 years results in a drift loading factor of 4.6 MTHM/m, which is higher than the drift loading factor from simple volume consideration.

A detailed description of the thermal model used in the calculation of the heat-constrained drift loading factors goes beyond the scope of this report. However, a description of similar thermal models can be found in available literature.[41,42]

The results show that the disposal of used fuel is constrained by heat, while the disposal of high-level waste is constrained by volume. The ratio of the HLW volume-constrained to the used fuel heat-constrained drift loading factors is ~4, which is the densification factor we sought to compute.

In the Implementation approach, legacy fuel is treated in dilution with fresh fuel and a quantity of americium is introduced in the HLW-R glass logs. The americium drives long-term heat in the waste and has the effect of decreasing the drift loading factor. As we consider the treatment of 700 tons of legacy used fuel annually, the resulting HLW-R drift loading factor decreases, even interim storage of HLW-R longer than 21 years in the Implementation approach partially offsets the negative effect of the presence of Americium in the waste. The drift loading factor, even considering dilution, remains above the volume-constrained drift loading factor and, thus, the densification factor is not impacted. Treatment of a larger quantity of legacy used fuel in dilution could negatively impact the densification factor.

Finally, it is important to consider that compacted waste is not considered a high-level waste and has very low thermal output (1/100 that of glass logs). Thus, the disposal requirements on compacted waste are much less stringent and could be met without using a deep geologic repository. If compacted waste were not disposed of in the geologic repository and if the duration of interim storage of vitrified waste is increased to 60 years – which can be accomplished with virtually no additional cost and this option has been considered for the Implementation approach – the resulting densification factor could be as high as 8.

Repository Cost Calculation in Greenfield Recycling Strategy

To calculate the cost of a repository in the recycling strategy, in the Greenfield approach, we go back to the definition of the unit cost and we leverage the findings from the densification factor analysis.

The unit cost is intended as the price that a hypothetical repository operator would charge to dispose of the fuel. This will be depending on the amount of waste that can de disposed of per linear unit. In the case of HLW-R, a densification factor of 4 implies that 4 times more waste (in terms of metric tons of initial heavy metal) can be disposed per linear unit of repository. Considering the linear capacity of the drift as the "scarce resource" of the repository, a densification factor of four effectively implies a 75% discount on unit cost compared to the reference point. Thus, in the Greenfield approach, we capture 100% of the potential cost benefits deriving from the densification factor. In the portfolio strategy in the Implementation approach,

[41] Wigeland (ANL), Bauer (ANL) – *Repository benefits of partitioning and transmutation* – 2004.
[42] Wigeland (ANL), Bauer (ANL), Hill (ANL), Stillman (ANL) – *Repository impact of limited actinide recycle* – 2005.

because we are disposing of legacy fuel as well, we capture only a small fraction of the potential benefits that a densification factor could potentially provide.

A second and more complex approach to estimate the repository cost in a Greenfield recycling strategy could take into consideration the possibility of building a HLW-R-only repository. We went through a simplified analysis in which we estimate the cost of designing and building such a facility and we found similar result as the ones obtained applying a straight densification factor. However, given the major drawbacks and undue complications of such an analysis, and given that current repository plans in the U.S. include the disposal of used fuel, at least the legacy fuel, from-the-ground-up" HLW-only repository re-designs go beyond the scope of the study and are not included in this study.

Clean Storage Solution

The Department of Energy has recently advocated a "clean storage solution". The clean storage solution would require the power plant operators to "canisterize" the used fuel with multi-purpose canisters, known as TADs (Transport, Aging, Disposal), which can be directly disposed of without being transferred into a separate waste package. In this way, no bare fuel would need to be exposed at any point in time during unloading operations at Yucca Mountain. This solution is likely to reduce the cost of the surface plant at Yucca Mountain, but a large portion of the cost would in practice be shifted to the power plant operators and the overall cost of the system might not be reduced. In fact, there is a potential for higher cost for the whole system, as new waste packages would be significantly more expensive to be able to serve multiple purposes.

Significant uncertainties around this solution in terms of timing and cost (DOE contractors evaluating cost of this option at the time of publication of this report) make it impossible to meaningfully take this new design into account within this study.

A6 . TRANSPORT

In this chapter, we detail some of the assumptions behind the calculation of the transport costs. There are four main sections

- Transport of used fuel, from the nuclear power plant to the integrated recycling plant (for the recycling and the portfolio strategy).
- Transport of the high-level waste from recycling (HLW-R) from the integrated plant to the repository after the necessary period of interim storage. The costs resulting from the assumptions in the first and the second section make up for the transport cost in the recycling and portfolio strategy.
- Transport of used fuel from the nuclear power plants to the repository directly (once-through strategy only).
- Transport of MOX fuel from the recycling plant back to the nuclear power plants, which is used in the calculation of the MOX credits.

Transport of Used Fuel from Power Plants to Recycling Plant (Recycling/Portfolio Strategy)

The transport of used fuel begins after three years from discharge. After three years, the fuel is transported to the integrated recycling plant.

The cost of transporting used fuel to the recycling plant was calculated on the basis of internal information from AREVA experience on transporting freshly discharged fuel. Considerations on distances, cask capacities and other specificities of the U.S. situation are also taken into account. Also, the initial capital expenditures occur in the first year and the lifetime of the transport system is in line with the lifetime of the integrated plant, at 50 years.

<u>Capital investments</u> include the cost to acquire the casks, the railcars, the road transport systems, the security and maintenance systems. Since the lifetime of casks, railcars and road transport systems is 25 years, the expenditures for these items will be repeated once over the course of 50 years.

To calculate type and number of casks necessary for the transport system, we observe that only ~60% of the utilities in the U.S. are equipped to handle the heavy 5.4-ton cask, while the remaining ~40% of the utilities can only use 2.7-ton casks. Given the quantity of used fuel displaced and an assumed turnaround time of 6 weeks, ~160 casks are needed.

A number of railcars equivalent to the number of casks is also needed. In addition, an investment for the security system is applied, as well as a cost of for the road transport system and for the maintenance system.

The resulting capital investments are in the order of $1.0B, repeated after 25 years.

<u>Operational expenses</u> represent the annual costs that are necessary to operate the fleet of casks and reactors and transport the used fuel. Four main drivers are responsible for operational expenditures: cask capacity (in tons of used fuel), casks per railcars, railcars per shipment,

turnaround time. The average cask payload is ~4 tons of used fuel, which is a blended average of larger and smaller casks. Assuming 12 casks/train, the resulting operating costs are ~$120M per year for a total of 2,500 tons/year.

Decommissioning costs are applied at the end of the lifetime of the equipment. 10% of the initial capital cost is applied at 25 years and 50 years after discharge.

The resulting unit cost is ~$75/kg.

Transport of High-Level Waste from Recycling (HLW-R) (Recycling/Portfolio Strategy)

We also estimated the cost of transporting high-level waste based on AREVA experience in Europe, adapted to the U.S. context, similar to what was done for the transport of used fuel. The specific assumptions differ from those used for the used fuel in that:

- Special casks for vitrified waste are used. These casks are more expensive than regular casks and hold 28 canisters of vitrified waste or 36 canisters of compacted waste.
- Transport begins after 21 years of interim storage, thus capital is not invested until much later in the future.
- Additional security system investments are not needed for HLW-R, given that security systems built for used fuel can be used.
- Based on AREVA experience, turnaround time for HLW-R transport could be significantly longer than used fuel, potentially as high as 18 weeks.

The resulting unit cost for transporting HLW-R from the recycling plant to the repository is $20/kg (kg of initial used fuel).

Transport of Used Fuel from Power Plants to Repository

As a base line for the cost of transporting used fuel from the nuclear power plants to the repository, we use the transport cost estimates performed by DOE in the 2001 TSLCC report.[43] In that study, details are provided for the Waste, Acceptance, Storage and Transport portion of the repository (WAST). We exclude all the costs that are specific to the repository, such as all the waste acceptance costs (from development to operations) and the Nevada railroad costs (from engineering and construction), which account for a unit cost of ~$25/kg and are included in the cost of the repository. The non-civilian portion of the costs is also excluded. In addition, four years of costs additional development are added to initial TSLCC estimates to account for additional development time to reflect changes since 2001.

The $70/kg unit cost estimate resulting from this calculation is consistent with “bottom-up” estimates performed by AREVA on the basis of its own operational experience.

This is a slightly lower estimate than the cost of transporting used fuel from the nuclear power plants to the recycling facility. The small difference between the two cases, in the order of $5/kg,

[43] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

can be explained by the fact that, in the first case, the fuel is moved five years after cooling in storage pools (consistent with the requirements power plant operators have over used fuel), while, in the second case, the fuel is moved only three years after being discharged by the power plants, in order to undergo early treatment that limits americium build-up. The difference in cooling time translates into slightly different packaging requirements.

Transport of MOX

Transport costs for MOX were once again based on AREVA estimates. External sources are not available. Although estimates for MOX fuel transport costs carry a high level of uncertainty, we used the following assumptions and data as a starting point:

- Transport begins after five years from discharge, after the used fuel has been treated and MOX has been fabricated.
- Investments include transport casks, which can hold ~4 tons of used MOX.
- Since 1 kg of used fuel generates ~120 g of MOX or, conversely, there is a conversion factor of ~8 between used fuel and MOX, each cask carry the equivalent of 32 tons of initial heavy metal.

Note that the transport cost for MOX is accounted for in the plutonium credit calculation. It is applied against the revenue as part of the cost of using MOX.

A7 . INTERIM STORAGE

In the case of the recycling strategy, interim storage is carried out at the recycling plant site for high-level waste from recycling operations (HLW-R, vitrified and compacted waste) and for used MOX and is included in the overall cost of the integrated plant. This section focuses on the cost storing the used fuel at a centralized storage facility, which is a key component of the cost of the once-through strategy.

We used an external study[44] as a starting point for the interim storage cost and we adjusted it to take into account the specificities of the once-through strategy as defined in this study. The key differences are as follows:

- The maximum capacity assumed in our base case is 50,000 tons (not 67,200, as in the external study[44]), based on 20 years of interim storage at 2,500 tons per year.
- Scale effects exist when moving from a larger plant to a smaller plant, i.e. a larger plant has a lower cost per unit stored than the smaller plant. However, in this case, scale effects are not very pronounced given the inherent "modularity" of a storage plant. Therefore, for the capital investments, we considered that 80% of the costs are variable and 20% of the costs are fixed. For operational expenditures, we considered the cost to be fully variable.

The adjusted values are outlined in Table 4.

Key Costs	**Centralized Interim Storage**
Initial capital investment ($M)	421
Marginal capex ($/kg)	60-80
Operation expenditures ($M)	114
Other Assumptions	
Annual fuel flow (tons/yr)	2,500
Max capacity (tons)	50,000
Duration (yrs)	20
Discount rate	3%

Table 4: Adjusted interim storage assumptions

It should be noted that three options are available for the interim storage location, in the Greenfield approach. Beside the option selected for the base case (centralized interim storage co-located with repository), the interim storage could be placed either at the power plant's location or in a centralized location, but not co-located with the repository. Each of the three solutions could be deemed unsuitable for different reasons: while co-location with the repository is not viable under the current legislative framework, long interim storage at the plant site is not a preferred option from the perspective of the plant operators, who want the used fuel off their site after a five-year window; finally, although a centralized interim storage not co-located with the repository appears to

[44] Macfarlane (MIT) – *Interim storage of used fuel in the United States* – 2001.

be a theoretically feasible solution, in reality it has been very difficult to find a suitable site in the U.S. In conclusion, we looked at sensitivities surrounding costs of the three different options and concluded that differences in costs are fairly small and one choice vs. another would not impact the overall economics of the solution.

Finally, we consider the following:

- For centralized storage, operations begin at year 5 (fuel cools for 5 years on-site).
- Initial capital expenditures are allocated evenly across the first four years before operations.
- For centralized storage, fuel is accepted for 20 years and remains in storage for 20 years.
- Fuel storage levels peak and then begin to decrease after fuel is no longer accepted.

The result is an interim storage unit cost of $150/kg, of which ~$80/kg driven by capital expenditures and $70/kg driven by operating expenses.

A8 . CREDITS FROM RECYCLED FUEL

The recycled fuel (both the MOX and the uranium-based recycled fuel, or recycled UOX) has a value and can provide a credit to offset some of the other costs.

MOX and recycled UOX can be used in light water reactors and are therefore comparable in value to UOX from mined uranium ore, after necessary adjustments for reactor adaptation costs, MOX acceptance costs and/or additional fuel enrichment, conversion, and fabrication costs.

We divide this chapter in three sections:

- Estimate of the value of UOX fuel, to which MOX and recycled UOX need to be compared to.
- Calculation of the value of MOX, which includes estimates for reactor adaptation, MOX acceptance and other costs.
- Calculation of the value of recycled UOX, which includes estimates for additional cost of enrichment, conversion and fabrication of recycled UOX.

Value of Fresh Fuel

The value of UOX fuel, to which MOX and recycled UOX are compared, is based on estimated value in 2020 of the various components required to fabricate UOX fuel: natural uranium ore, conversion, enrichment and fuel fabrication. The assumptions used are in line with market prices observed in the last six months of 2005, as listed in Table 5.

Front-end fuel cycle component	Estimated cost
Uranium ore	\$80/kgU (\$31/lb U_3O_8)
Enrichment (including tail management)	\$110/SWU
Conversion	\$12/kgU
Fuel fabrication	\$200/kgHM

Table 5: Main front-end assumptions

These four key drivers of the value of UOX fuel are discussed in detail in the next two paragraphs. After that, the neutronic parameters and the production factors necessary to complete the calculation of the value of UOX fuel are discussed.

Uranium Prices

Over the last years natural uranium prices have been increasing to a level of ~$36/lb U_3O_8 by the end of 2005, which is not yet at the same level as the historical peak price of ~$110/lb U_3O_8 (in real dollars), which was reached in 1975-1980. This recent trend in uranium prices, shown in Figure 30, is expected to be supported over the next few years by three key elements:

- Significant annual growth of world UOX demand expected (~2% per year).
- Existing primary sources of uranium expected to be stable and below world uranium demand.
- End of secondary sources of uranium, such as the Russian HEU contract, slated to end in 2013.

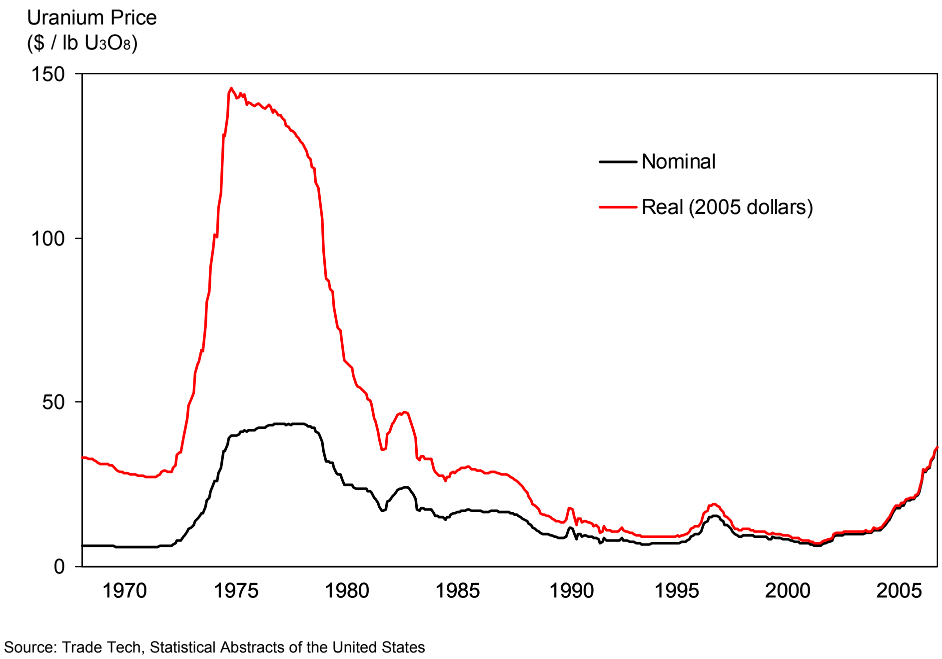


Figure 30: Historical prices of uranium price ore

At the same time, there are three factors that partially compensate for the price-rising factors, although materializing at different time horizons:

- Drive towards lower tails assay – as uranium prices increase, the fuel fabricants are pushed to reduce natural uranium feed by lowering the enrichment tails assay (retroaction effect), thus depressing demand.
- Development of new mining facilities might become attractive under these new market conditions, thus increasing supply.
- Availability of additional secondary sources through recycling in the longer term, also increasing supply.

Our current best estimates, resulting from the combination of all of these factors, call for potential steady growth of uranium prices of ~1.5-2% per year until 2020. For the purpose of this study, however, we used a conservative estimate of $31/lb U_3O_8, which is lower than present prices and future expected values, but more in line with historical values.

Any detailed forecast of future prices, especially over such a long-term horizon and with such a high variability, goes beyond the scope of the study. In appendix A9 , uncertainties and potential bounds on uranium prices are discussed in the context of a sensitivity analysis.

Enrichment, Conversion and Fabrication Costs

In the case of enrichment, conversion and fabrication costs, it is very difficult to estimate the direction of future prices. Several factors play a role. While, on the one hand, fuel demand growth and end of HEU contract will increase demand for enrichment and conversion, thus pushing prices higher, on the other hand new cost-effective technologies are likely to offset these increase.

In the end, we believe that rising demand for enrichment is offset by cost improvements and additional capacity coming on line, likely resulting in stable or slowly rising enrichment costs. Conversion and fabrication costs are also assumed to stay at 2005 levels.

Neutronic Parameters and Production Factors of Fresh Fuel

The next step in the calculation of the value of the fuel is the definition of the neutronic parameters, such as the burn-up rate and its enrichment in ^{235}U isotope. The fabrication parameters such as the optimal tails assay, the uranium feed and the enrichment SWU need is deduced from an economic optimization. In the case of UOX fuel, for a burn-up rate estimate of 50 GWd/T (see appendix A2), neutronic parameters are assumed as follows:

Main neutronic parameters	
Burn-up (GWd/t)	50
Required enrichment in ^{235}U(%)	4.1
Natural enrichment in ^{235}U (%)	0.7
Production factors	
Optimal tails assay (%)	0.25
U feed (kgU/kgUOX)	8.3
SWU need (SWU/kgUOX)	6.1

Table 6: Main neutronic parameters and production factors for UOX fuel

All the assumptions outlined above result in a central value of UOX fuel of $1,635/kg, broken down as follows in terms of $/kg:

- Fabrication: $200/kg
- Enrichment: $672/kg
- Conversion: $100/kg
- Uranium feed: $663/kg

The value of $1,635/kg is the starting point for the calculation of the credits for the plutonium/uranium stream (MOX) and for the pure uranium stream (recycled UOX).

Value of MOX

The ratio of the fissile plutonium content in MOX vs. used fuel is ~8, or, conversely, from a kg of used fuel, only about ~120 g of MOX can be fabricated by concentrating the plutonium at the same burn-up as the initial fresh fuel.

Data on costs of using MOX were made available to BCG from experience in the U.S., France, Germany, Switzerland, Belgium and Japan and discussions with utilities involved in MOX programs. We have used these data as the basis of our estimates.

The value of MOX differs from the value of UOX fuel in three key factors.

First, there are additional costs a power plant would incur in using MOX instead of UOX fuel. Direct reactor costs are estimated at about 6% of the initial value of MOX. In addition to the cost of moxification of reactors, we also take into account transport costs and some other overhead and management costs, estimated at about 4% of the initial value of MOX, resulting in a total cost of 10%.

Secondly, operation with MOX fuel is similar to operation with UOX fuel. Nonetheless, we account for a "MOX acceptance cost" to take into account all costs related to additional adaptation steps, both for the utility and for the fuel vendors. These costs are above and beyond the costs that are directly quantifiable and are driven by the following factors: a) Use of MOX comes along with issues of political acceptance and potential indirect risks taken by power plant operators, which also need to be rewarded; b) Other “softer” costs are expected, but not explicitly included in the moxification costs considered here, such as the cost of managing multiple fuel suppliers and the indirect additional cost for the uranium feed (uranium penalty). The MOX acceptance cost is set at 15%.

Thus, the total “discount” for the value of MOX is 25%, which means that the value of a given quantity of MOX is equivalent to ~75% of the value of fuel made from fresh uranium, before capital cost adjustments.

Finally, MOX is readily available once produced in the integrated plant, while UOX needs to be fabricated 6 months to 2 years in advance. This results in a capital cost gain that increases the value of MOX.

All the factors above result in a value of MOX of $1,360/kg. However, only ~120g of MOX are fabricated for each kg of initial used fuel (factor of ~8), given the ratio of initial fissile plutonium content (from the used fuel) to target fissile plutonium content at 50 GWd/t, as outlined in Table 7. Thus, the actual value of MOX, is ~$160/kg (kg of initial used fuel).

Plutonium content in used UOX fuel	
Pu total in used fuel (%)	1.2
Pu fissile in used fuel (%)	0.8
Plutonium content in MOX fuel	
Pu total in MOX (%)	10.1
Pu fissile in MOX (%)	6.5

Table 7: Main neutronic parameters for MOX

It is important to note that the MOX fabrication costs are not included in the $160/kg figure. The MOX fabrication costs are included in the recycling costs, as part of the integrated plant.

Value of Recycled UOX

Recycled uranium-based fuel is also expected to replicate the performance of UOX fuel (iso-burn-up equivalence). Since recycled uranium comes from used uranium, some of the target neutronic parameters and production factors are different than those of UOX fuel. Specifically:

Main neutronics parameter of used UOX fuel	
Burn-up (GWd/t)	50
Used fuel ^{235}U content (%)	0.7
Recycled uranium ^{235}U content (%)	0.8
Main neutronics parameters of recycled UOX	
Burn-up (GWd/t)	50
Target re-enrichment in ^{235}U (%)	4.7
Production factors	
Optimal tails assay (%)	0.4
RepU feed (kg RepU / kg of recycled UOX)	12.1
SWU need (SWU/kgUOX)	5.2

Table 8: Main neutronic parameters and production factors for recycled UOX

A particularly important parameter is the uranium feed factor, which is 12.1 based on an economic optimization of production costs. Since only 93.5% of the original used fuel is utilized for fuel recycling, effectively 1 kg of used fuel generates ~80 g of recycled UOX.

In addition, enrichment, conversion and fabrication costs are higher for recycled fuel than UOX fuel. Conversion cost could triple due to the necessity to build a dedicated conversion plant. Enrichment and fabrication could increase by respectively 15% due to additional re-enrichment to compensate neutronic losses and tails management and 7% due to radiological constraints.

In summary, from the point of view of the fuel provider, the fuel cost structure is slightly different from that of UOX fuel. While the cost of uranium ore is eliminated, the conversion, enrichment and fabrication costs are higher than UOX fuel costs. Once these cost increases are factored in, the total fuel cost to manufacture recycled fuel comes to $1,260/kg. This is still lower than the total value of 1 kg of fuel, which is $1,635. The difference of $375/kg is the value that can be extracted. However, since only 80g of recycled fuel is fabricated from an initial kg of used fuel, the value in terms of $ per kg of used fuel is ~$30/kg.

Value of Recycled Fuel in the Context of Volatile Uranium Prices and Enrichment Costs

In the portfolio strategy, 20-25 percent of U.S. nuclear fuel supply is made from recycled fuel. In addition to providing a significant supply overhang and lowering dependence on foreign supply, the cost of making recycled fuel is independent of uranium prices. MOX production costs are also independent of enrichment costs. Thus, in the portfolio strategy, power plant operators could potentially capture some of the value that the use of recycled fuel creates in when uranium prices rise, effectively protecting themselves against uranium price volatility.

Figure 31 shows how potential value is generated (or destroyed) for a power plant operator under a few front-end scenarios, on fuel purchased, on an annual basis. The chart assumes that the power plant operator uses MOX for 30% of its fuel needs, 20% recycled UOX and 50% is supplied by fresh UOX at market price. Note that this is a different way of looking at the same sensitivity on uranium prices, as the one described and illustrated in section 3.1.2 and appendix A9 , where a broader system view was taken. In this case, the value created by using MOX and recycled UOX in the context of higher uranium prices and enrichment costs is put in the perspective of the plant operator and the potential value that it could capture.

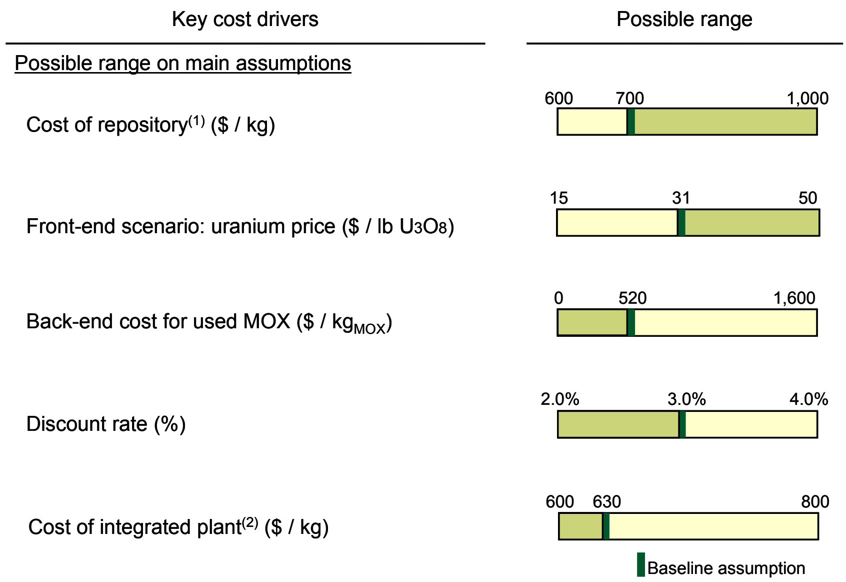
Front-end value created for 200 tons of fuel purchased annually (~10 GW installed capacity)

Enrichment price ($ / SWU) (Low → High) \ Uranium price ($ / lb U3O8) (Low → High)	20	31	39	50
150	+$2M	+$26M	+$43M	+$67M
130	($7M)	+$13M	+$29M	+$54M
110	($15M)	Base case	+$16M	+$41M
90	($23M)	($8M)	+$3M	+$28M

Figure 31: Value available to power plant operators under different front-end scenarios

A9 . UNCERTAINTY ON MAIN ASSUMPTIONS

In this chapter, we review some of the figures used for the sensitivity analysis. The summary of the outcome of the sensitivity analysis is reported in the figure below.



(1) Excluding transport. lower bound: average cost of Yucca Mountain for 120,000 tons, higher bound: budget overrun at +40%.
(2) Total life cycle undiscounted cost of integrated plant is $64B (25% of which is capital investments). Lower bound of the sensitivity range equates to $61B in total life cycle costs, upper bound is $81B. CapEx/OpEx split kept constant.

Figure 32: Summary of main sensitivities

In the next four sections, we analyze the rationale behind the sensitivity ranges used in each of the assumptions, with the exception of the cost of used MOX, which is discussed more in depth as a separate section (appendix A10).

Cost of repository

There are significant uncertainties surrounding the repository costs.

Although many factors come into play, three key uncertainties have been modeled:

- Acceptance rate below the originally expected 3,000 tons per year (to ~2,000 tons per year).
- Repository capacity higher than 83,800 tons (120,000 tons).
- Additional development time (10 extra years of active investments).

In addition, the TSLCC analysis[45], which we have used as a starting point for our cost estimates, has been referred to[46], by the DOE contractors more closely involved in the development of the repository site, as “an order of magnitude estimate, with an associated uncertainty range of plus or minus 40%.” In fact, since 2001, many design factors of the repository have been revised, as well

[45] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.
[46] Bechtel/SAIC – *Total system life cycle cost for site recommendation letter report* – 2002.

as some key cost estimates, e.g. the estimated cost of the Nevada railroad was more than doubled, from ~$1B to ~$2B.

The suggested range for the sensitivity analysis is between $600/kg and $1,000/kg, as illustrated in Figure 33.

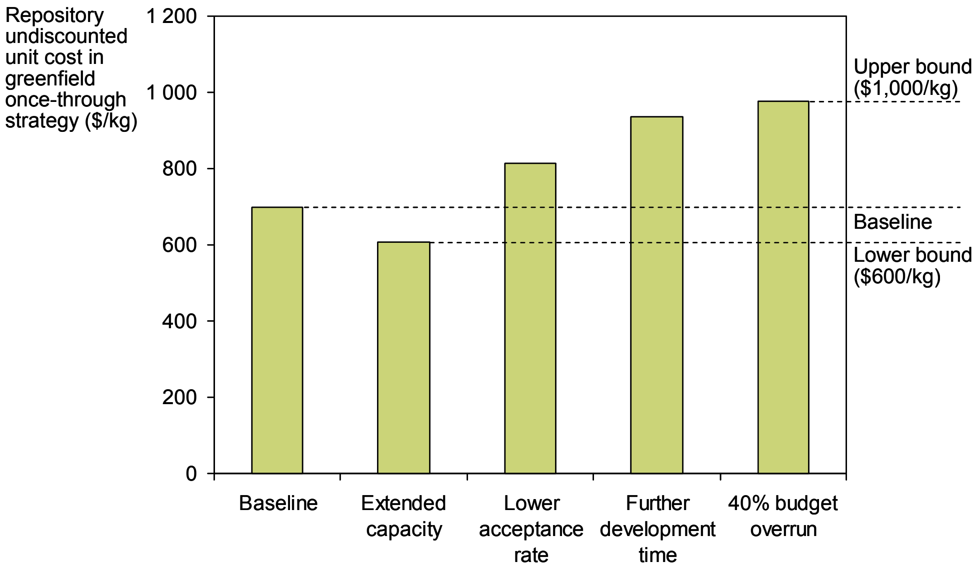
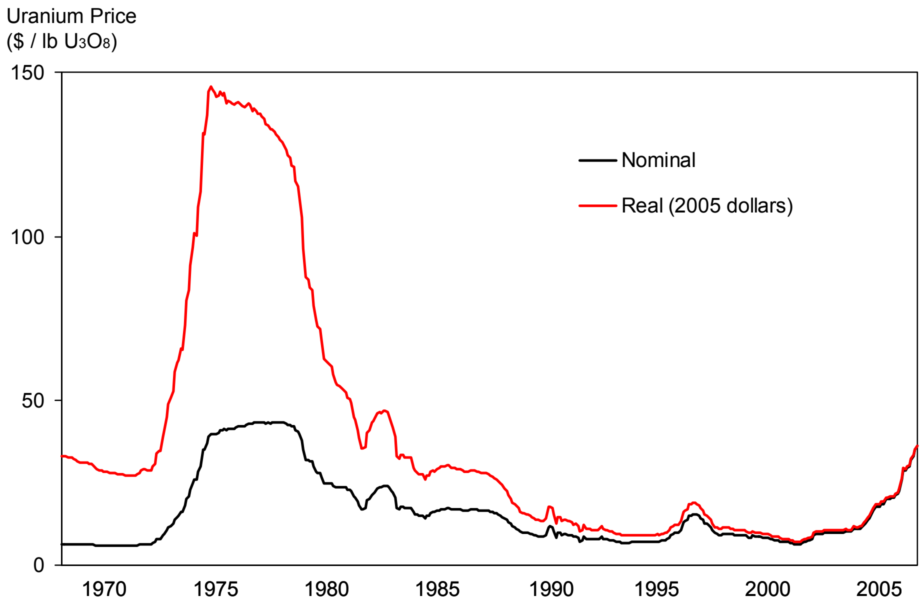


Figure 33: Sensitivity range for repository costs

Finally, as a reference point, over the course of the last twenty years, the Department of Energy has updated its cost estimates for the repository several times, as directed under legislative guidelines. Cost estimates have shown an upward trend, which seems to indicate that additional budget overruns are possible, as cost estimates are reviewed with the benefit of updated and more detailed information and considering design updates. In real dollars, the 1998 DOE estimate was 15-25% higher than the 1995 estimate and the 2001 estimate was 15-25% more expensive than the estimate in 1998.

Uranium Prices

As previously discussed (appendix A8), uranium prices have shown a high degree of volatility since the inception of nuclear power. They were very high at the end of the 70's, up to almost three times the prices at the end of 2005 (in 2005$). Prices experienced a very sharp drop throughout the 80's and stayed low in the 90's.



Source: Trade Tech, Statistical Abstracts of the United States.

Figure 34: Uranium prices historical trends and sensitivity range

A potential sensitivity range is difficult to define. We believe that using the lowest and the highest historical value for uranium prices would be too broad.

Therefore, we look at average prices over two periods of time: a period of high prices (1970-1985) and a period of low prices (1985-2000). The average price during the high-price period was ~$50/lb U_3O_8 ($130/kgU) and we use this value as the high sensitivity range, while the average price during the low-price period was ~$15/lb U_3O_8 (or $40/kgU) and this is the low end of the sensitivity range. Although we acknowledge that the definition of the sensitivity range is open to different interpretations of the available data, we believe that the ranges illustrated in Figure 34 and the sensitivities in Figure 30 can provide a good sense of the economics under different uranium price scenarios.

Overall Integrated Plant Costs

The uncertainty around the cost of the integrated plant is expected to be lower than that surrounding a repository. A few factors contribute to narrow the sensitivity range considered for the integrated plant, especially the availability of detailed cost estimates on an existing plant and the knowledge gained by AREVA on potential cost uncertainties during the 20+ years of recycling experience.

Existing estimates are believed to be accurate within 30% on potential overruns and 5% on potential savings from current estimates. For the purpose of the sensitivity analysis, we assume that the cost of the integrated plant could be between $600 and $800/kg.

Recent occurrences in which U.S. contractors have attempted to replicate European plants in the U.S. have shown that cost overruns can be significant. While, based on the AREVA experience in US-based project, we acknowledge that a significant risk of cost over-run is always present, we considered the following factors:

- A significant portion of the cost over-runs observed is attributable to political uncertainties surrounding any specific project; in section 4, we briefly discuss how a positive climate toward recycling will be necessary for a successful implementation in the U.S..
- A significant portion of potential cost overruns is already captured in the cost of the integrated plant. This portion includes additional licensing costs, additional protection on civil engineering, seismological impact on design, regulatory affairs costs, additional U.S.-driven engineering requirements, larger building design, R&D expenses, which account for an additional ~$4B in capital investments for the integrated plant.

Discount Rate

The discount rate used throughout the study is based on the expected cost of public capital, as discussed in appendix A3 . Based on the analysis of available information and following the Office of Management and Budget guidance, we concluded that 3% should be used as central estimate for our calculations. At the same time, we acknowledge that some uncertainty surrounds this number, as it is possible that the cost of capital will change significantly over the course of the timeline we consider. A higher discount rate has the effect of penalizing strategies that require early investments, while a lower discount rate preserves the importance of future cash flows.

For the low end of the sensitivity range, a meaningful data point is provided by today's rates for Treasury Inflation-Protected Securities (or TIPS). TIPS are representative of real risk-free return of securities going forward. The rate of return on these securities at the end of 2005 was ~2% and we use this as the lower end of the discount rate sensitivity range. 2% is also the average real rate of return for long-term government bonds over the last 70 years.

We suggest using a symmetric range for the sensitivity on the discount rate, therefore making 4.0% the high end of the range. This is also consistent with an analysis performed by DOE on the adequacy of the nuclear waste fund fee[47], in which the range of returns considered is between 2.6% and 4.2%.

Finally, in the case of projects involving very long time horizons and many generations (such as the one considered in the study) a very low discount rate could be used, potentially as low as zero or even negative, to reflect a premium that should be charged to the current generation when a cost is passed on to future generations. The effect of using a zero discount rate would be to put more emphasis on additional repositories that would have to be built in the future, thus making the once-through strategy more expensive when compared to the recycling strategy. However, an economic-sociological discussion of long-term discount rates goes beyond the scope of the study and is therefore not considered further.

[47] US DoE – *Nuclear waste fund fee adequacy: an assessment* – 2001.

A10 . MANAGEMENT OF USED MOX

In this chapter, we identify and discuss four possible routes to manage used MOX, which accumulates in the recycling strategy at a rate of ~300 tons/year:

- *Dispose of used MOX in Yucca Mountain* – although we do not consider this as a viable option, since disposing of used MOX would almost entirely eliminate the benefits gained through the densification factor, we do attribute an economic cost to it and use this cost as an upper bound for the potential cost of managing used MOX.
- *Perform multiple-recycling* – within this option, used MOX is recycled one or many more time to extract the plutonium/uranium to make "MOX2" and potentially MOX3, MOX4, and the like.
- *Remove americium and perform multiple-recycling* – similar to the previous option with the exception that americium is removed during the used MOX recycling process, thus reducing the long-lived actinides in the resulting HLW-R.
- *Recycle used MOX in fast reactors* – within this option, fast reactor fuel is fabricated from used MOX and employed to generate electricity.

Overall, the cost of managing used MOX has a limited impact on the total back-end costs, in terms of $/kg, since only a relatively small quantity of MOX is generated (~300 tons/year, ~15% of the total used fuel generated annually).

We estimate this impact to be between -$50/kg and +$100/kg. Even in the worst case scenario (direct disposal), which we believe not to be viable, the impact on the unit cost is expected to be less than $200/kg (~40%).

The detailed results from the analysis on used MOX are discussed in the following sections.
For each of the four options that we analyze for the management of used MOX, we calculate the cost differential between the cost of managing used MOX and the back-end cost of used fuel in the recycling option (~$530/kg).

Direct Disposal

The heat content of used MOX is very high. If used MOX were to be directly disposed into the repository after 20-25 years of interim storage, due to the temperature constraints in the repository, it would not be disposed as densely as used regular fuel. In this case, the densification factor for used MOX is ~0.15, which means that 150g of used MOX would take up as much space in the repository as 1 kg of used fuel. The cost of the repository, previously calculated at ~$340/(kg of initial used fuel), would now be ~$2,240/(kg of used MOX). Leaving other costs at the same level, disposal of used MOX is ~$1,900/(kg of MOX) more expensive than disposal of used fuel.

However, two factors contribute to lower this estimate dramatically:

- The disposal of used MOX does not occur until 9 additional years after the corresponding disposal of used fuel, since used fuel is cooled for ~4 years, processed (~1 year) and then used in reactors for ~4 years – that gives the used MOX the benefit of an additional 9 years of discount (~20% discount at 3% discount rate);
- Used MOX is in much smaller quantity than used fuel. For 1kg of used fuel, only 120g of used MOX are generated, thus the cost in terms of $ / (kg of initial used fuel) is ~8 times less than the cost in terms of $/(kg of used MOX).

The results of the calculation suggest that the additional cost of used MOX, if directly disposed in the repository, can be less than $200/kg (or less than 40% of the total cost of the recycling strategy). We consider this figure to be the upper bound for our estimates, but we do not include this figure in the sensitivity range, since disposal of used MOX is not considered to be a viable option.

Multiple Recycling

In the case of multiple recycling, used MOX is recycled again. Plutonium is extracted and fuel is fabricated, similarly to what happened with the used fuel in the first part of the cycle.

The used MOX is treated 10 years after discharge, due to technical constraints. From 1 kg of used MOX, about 600 g of MOX_2 can be produced. During the recycling process, high-level waste in the form of glass logs and compacted waste is generated. Since the resulting waste from treating used MOX has a higher content of highly radioactive products when compared to the waste produced from used fuel, the densification factor for HLW-R from used MOX is only ~0.5, which is much lower than the densification factor of four obtained for HLW-R from uranium-based used fuel. Thus, the disposal cost of HLW-R for used MOX is ~8 times higher than the cost of disposal in the base case recycling strategy.

While having a higher cost of repository, recycling used MOX has the benefit of providing additional credits from MOX_2. Assuming that 600 g of MOX_2 can be fabricated from 1 kg of initial used MOX (compare to 120g of MOX from 1 kg of initial fuel) and that a 50% discount would be applied to MOX_2 vs. MOX (due to quality and multi-fuel management issues), the additional credit is about ~$150/kg.

Once again, factoring an additional 9 years in discounting the costs, and reporting the costs back into $/(kg of initial used fuel), the additional cost from recycling used MOX a second time is in the order of $0-50/kg. In the case of multiple recycling, occurring every ~15 years, the additional cost remains in the order of $0-50/kg.

Even if we were to assume that no credits can be obtained from the sale of MOX_2, the additional cost of managing used MOX would increase, but would stay within $50-100/kg. We consider $100/kg to be the upper bound for the sensitivity analysis.

The option described above for the management of used MOX is subject to technical developments, since a second MOX cycle has not been fully operational yet and some technical questions remain to be addressed.

Multiple Recycling with Americium Removal

In the case of multiple recycling with americium removal, the computation is similar to that of a simple multiple recycling. However, if americium is removed, two things occur:

- The resulting HLW-R has a lower content of long-lived actinides and thus enjoys a densification factor of ~2.8, which is less than 4.0 (from used fuel), but more than 0.5 (HLW-R from used MOX without americium removal).
- Americium has to be disposed in a separate repository.

While the first factor can be quantified easily, resulting in a net benefit from the used MOX of $0-50/(kg of initial used fuel), the second factor is more difficult to quantify. No data is available on the potential cost of an Americium-only repository. It is conceivable that, given the very small quantity of Am generated through the process, the costs in terms of $/(kg of initial used fuel) might be relatively small, but we have not attempted to produce any cost estimate. Any additional cost for an americium-only repository would have to be added.

Used MOX as Fuel for Fast Reactors

In this section, we briefly discuss the option of using used MOX to fabricate fuel for fast reactors. The uncertainties surrounding the development of fast reactors are broad and the economic considerations for long-term technologies cannot be conclusive and have not been fully tested as part of this study. However, in order to estimate the order of magnitude of the potential use of used MOX as input for fast reactor fuel, we attempt to develop initial assumptions. In the course of the next few years, further work will need to be performed to refine and test these assumptions, and to fully develop a comprehensive economic assessment on this specific issue.

If fast reactors are deployed, used MOX becomes more valuable as its high plutonium-content makes it a good candidate for being recycled into fast reactor fuel. A simplified calculation of what would be the benefit of using recycling used MOX into fast reactors considers a key factor: the fissile plutonium content of used MOX is much higher than the content of used fuel (3.9% instead of 0.8%), thus, if Pu is to be used in fast reactors, credits from the sale of plutonium would be almost 5 times as high as the credits resulting from used fuel, or ~$600/kg$_{MOX}$ more. This is almost exactly offset by the loss in densification factor on the HLW-R. Therefore, the resulting additional cost from recycling used MOX in fast reactors is ~$0/kg of initial used fuel. The cost of managing used MOX is similar to the cost of managing uranium-based used fuel, which we used as a base case.

However, there are two additional factors that could increase/decrease this cost estimate:

- If americium is also removed during the process, the HLW-R would benefit from a much higher densification factor, thus resulting in a net positive benefit from having MOX, in the order of $0-50/kg of initial used fuel. The $50/kg benefit (expressed in terms of dollars per kilogram of initial used fuel) is effectively equivalent to a real "zero" cost of used MOX ($0/kgMOX), i.e. in which the used MOX is a resource that can be used and for which its value offsets the fuel fabrication and other costs – we used a $50/kg benefit as the lower bound of our sensitivity range.
- If fast reactors prove to be uneconomical, it is conceivable, although unlikely, that the back-end system of the nuclear fuel cycle could bear some of the additional costs necessary to make fast reactor technology viable and absorb the plutonium, which in the recycling strategy, has not been buried underground. If we assume that ~10-15 reactors are needed to absorb the plutonium stock and that fast reactors might cost 20% more than current reactors, the additional total cost is in the order of $7-12B, or about $50-100/kg of initial used fuel.

In summary, while strategies for the management of used MOX need to be deployed, the costs of such strategy could reasonably be expected not to exceed $50-100/kg of initial used fuel, which is equivalent to an additional 10-20% on top of the initial cost of recycling. Even, in the worst case (direct disposal of MOX), the additional cost for disposing of used MOX would burden the overall cost of a recycling strategy by less than 40%.

A11 . ECONOMICS IN THE IMPLEMENTATION APPROACH

In this chapter, we illustrate the cash profiles for the portfolio strategy and for the once-through strategy. The cash flow profiles are the key inputs to the calculation of the net present costs, included in section 3.2.1. Two sections are included in this chapter:

- Cash flow profiles and contributions from each component.
- Assumptions that are used in the Implementation approach and that were adjusted from Greenfield approach assumptions.

Cash Flow Profiles

The overall cash flow profile for the recycling strategy is shown in Figure 35. To draw the chart we assume that commercial used fuel begins to be emplaced underground in the repository after the first years of operation of the recycling plant (in 2030), with the understanding that there is a significant degree of flexibility on such a date, indicated with the red arrow. For the economic comparison, we have considered the year of first emplacement in Yucca Mountain to be between 2015 and 2040.

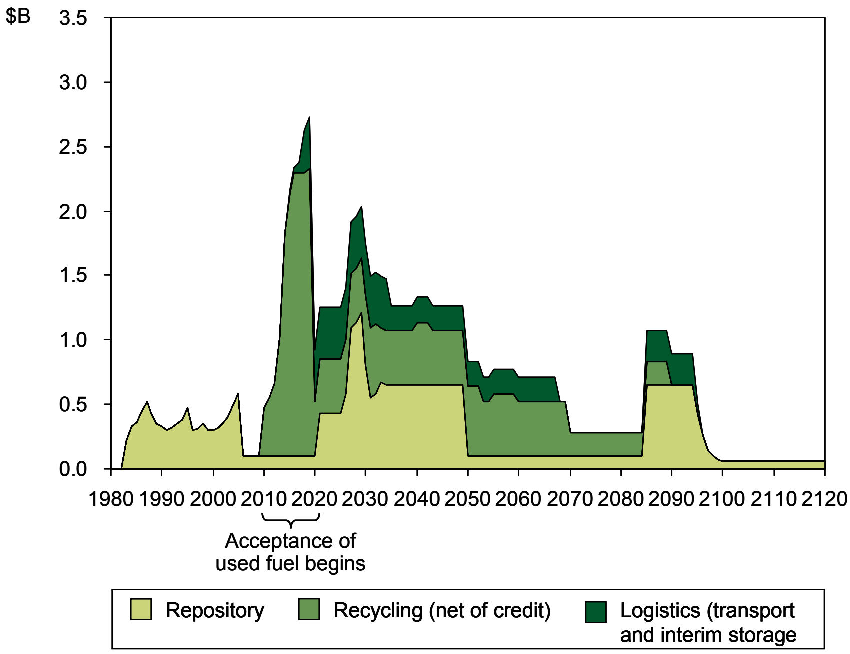


Figure 35: Cash flow profile for portfolio strategy (emplacement in Yucca Mountain in 2030)

In the portfolio strategy, the largest cash expense occurs in the 2015-2020 timeframe, which coincides with the construction period of the recycling plant. A second lower peak occurs at the time of opening of the repository. After that, the cash flow remains fairly high, but constant, while the legacy fuel is disposed at the same time as the new used fuel is recycled. At the end of the disposal period the cash flow decreases significantly, while only the recycling plant is fully operational. After ~2070 the cash expenses are very modest, requiring only decommissioning of the plant, monitoring of the repository and interim storage of HLW-R at the recycling plant. Eventually, the HLW-R is disposed into the repository during a period of time of ~10 years, which represents the last important cash expense.

The repository accepts 3,000 tons per year, according to the stated acceptance rate at Yucca Mountain[48], until the inventory of legacy fuel destined to the repository is depleted or about 20 years after acceptance begins. The repository is at that point temporarily shut down, waiting for the disposal of high level waste from recycling (HLW-R). HLW-R starts being produced in 2020, but because HLW-R is interim-stored at the integrated plant site for 20-25 years or more, it does not become available until 2045 or later. From that point on, there is a constant stream of a relatively small quantity of HLW-R coming available for disposal every year, which could be either shipped to the repository every year in small quantity or could be stored at the integrated plant site and then shipped in larger annual quantities within the course of fewer years. The latter option allows for optimization of Yucca Mountain operations and we choose it for the cash flow. The economic impact of "spreading" the cash flow outlays from HLW-R disposal over a longer period of time would not be material, also considering that it occurs very far out in the future.

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[48] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

The once-through strategy exhibits a very different profile. In the once-through strategy, there is a first peak requirement around 2015, in conjunction with the opening of the first repository. After the first peak, the cash flow outlays remain sustained, as expenses are necessary to operate the repository and to transport and store the new used fuel. Around 2030-2035, the development and evaluation period of the second repository begins, requiring additional cash expenditures, which eventually peak around 2060-2065. As the first repository ceases full operations around 2065, the cash flow requirements ease up. The last important cash expense is represented by the operation of the second repository (until ~2100). The cash flow profile for the once-through strategy is illustrated in Figure 36.

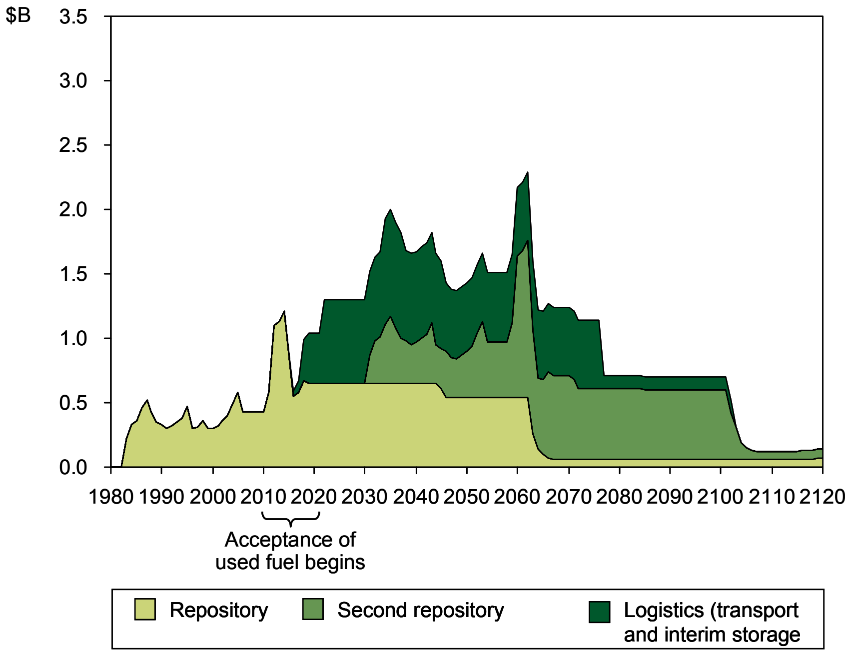

Figure 36: Cash flow profile for once-through strategy

Note that most of the assumptions used are identical or very similar to the ones used in the Greenfield approach, as we build off of the same analyses. However, a few specific assumptions and some adjustments are needed in order to match cash flow profile to timing and quantities of fuel discharged. In the next section, we discuss these specific assumptions.

Assumptions Specific to the Implementation Approach

1) The cost of the integrated recycling plant is based on the capital investments (CapEx) and operational expenditures (OpEx) figures presented in section 2.2.1. The distribution of the CapEx over time is based on the typical cash flow profile for the construction of an industrial plant based on AREVA experience. The OpEx is constant throughout the course of the operations.

2) The cash flow profile for the repository is mostly derived from the DOE TSLCC[49], with the same few adjustments as the ones described in appendix A5 . In the U.S. context for the once-through strategy, there is a period of time for which the quantity of fuel available for disposal is lower than the maximum acceptance rate. For that period of time we lowered the operational cost of Yucca Mountain by considering 60% of the costs as variable and 40% as fixed.

3) In the once-through strategy, we consider the construction of a second repository. The uncertainties around the potential cost of a second repository are enormous and significantly higher than the already-large uncertainties on the first one, as already discussed in section 3.2.5. A new site would have to be selected and a new political dialogue would have to begin. The cost of such a feat is extremely difficult to predict. On the one hand, some lessons-learned from the Yucca Mountain experience could be successfully applied, thus reducing the potential cost. On the other hand, the selection of the site might be more complicated than the first time around, as the preferred site is not available any more. Also, the concept of experience curve might not apply in the case of repositories, which appear to be one-of-a-kind projects. Given these considerations, the only possible assumption to be taken for the second repository is that the cost would be similar to the cost of the first one.

4) Credits are applied at the time the recycled fuel (recycled UOX and MOX) is sold to the power plant operators.

5) Transport costs are applied using the unit cost information from the Greenfield approach and applying the unit cost against the quantity and timing of fuel discharged.

6) For interim storage, we distinguish between CapEx and OpEx. The CapEx is spread over 4 years at the beginning of the fuel acceptance period to build the necessary interim storage capacity. The OpEx is then applied throughout the life time of the interim storage plant (20 years). We also assume that a second interim storage plant is built for the second repository, with the exact same cost and cash flow profile of the first one. In both strategies, we do not include any interim storage cost for fuel already stored at plant sites.

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[49] US DoE – *Analysis of the total life cycle cost of the civilian radioactive waste management program* – 2001.

GLOSSARY

Discounting	Process of reducing the relative weight of costs that are incurred in the future, applying a discount rate or a cost of capital.
Burn-up rate	Quantity of energy that can be (or has been) extracted from a unit of nuclear fuel. It is expressed in GWd/t.
Co-extraction (COEX^{TM})	Treatment process whereby uranium and plutonium are extracted together from the used fuel.
Fast reactors	Advanced reactor technologies expected to eventually replace next generation technologies currently being commercialized (Gen III). Fast reactors can burn actinides effectively.
Greenfield approach	Perspective in which only new used fuel discharged after 2020 is considered.
Densification factor	Ratio of the drift loading factor of HLW-R to the drift loading factor of used fuel. It is indicative of how much more densely waste from recycling operations (HLW-R) can be packed compared to used fuel.
Drift loading factor	Quantity of waste that can be disposed per linear meter of repository capacity. It is expressed in MTHM/m.
Interim storage	Process of aging nuclear waste (either used fuel of high-level waste from recycling) to allow for some radioactive decay to occur.
Legacy fuel	Used fuel that is discharged before 2020.
MOX fuel	Mixed-oxide fuel fabricated from recycled plutonium and uranium.
Reactor adaptation	Process of adaptation of nuclear reactors to the use of MOX.
Portfolio strategy	Strategy in which a recycling plant is developed in conjunction with a repository for the disposal of HLW-R and legacy waste.
RepU	Recycled uranium.
Retroaction effect	Effect by which, as uranium prices increase, optimum tails assay decreases, thus reducing demand for uranium.
Tails assay	A measure of the amount of fissile uranium (U^{235}) remaining in the waste stream from the uranium enrichment process.
Unit cost	The (imaginary or real) cost of purchasing a service/product from a supplier, paid in the year the service/product is supplied.
Implementation approach	Perspective in which a comprehensive analysis of the nuclear fuel cycle in the U.S. is performed, considering legacy fuel and existing investments. The portfolio strategy is defined in the context of this approach.

ACRONYMS

AFC	Advanced Fuel Cycle (advanced recycling techniques)
AFCI	Advanced Fuel Cycle Initiative
BCG	The Boston Consulting Group
CAPEX	Capital expenditures
COEX^{TM}	Co-extraction process
DOE	Department of Energy
FR	Fast reactors
HLW-R	High-level waste resulting from recycling operations (compacted waste and glass logs)
HM	Heavy metal (initial used fuel)
IR	Integrated Recycling Plant
MOX	Mixed oxide fuel
MTHM	Metric tons of (initial) heavy metal
NRC	Nuclear Regulatory Commission
NWF	Nuclear Waste Fund
OCRWM	Office of Civilian Radioactive Waste Management
OPEX	Operational expenditures
PPP	Purchasing power parity
UOX	Uranium oxide fuel
SWU	Separative Work Unit
WACC	Weighted average cost of capital

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