Impact of Nuclear Energy Futures on Advanced Fuel Cycle Options

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Abstract

The Nuclear Waste Policy Act requires the Secretary of Energy to inform Congress before 2010 on the need for a second geologic repository for spent nuclear fuel. By that time, the spent fuel discharged from current commercial reactors will exceed the statutory limit of the first repository. There are several approaches to eliminate the need for another repository in this century. This paper presents a high-level analysis of these spent fuel management options in the context of a full range of possible nuclear energy futures. The analysis indicates the best option to implement varies depending on the nuclear energy future selected.

The first step in understanding the need for different spent fuel management approaches is to understand the size of potential spent fuel inventories. A full range of potential futures for domestic commercial nuclear energy is considered. These energy futures are as follows:

1. Existing License Completion - Based on existing spent fuel inventories plus extrapolation of future plant-by-plant discharges until the end of each operating license, including known license extensions.
2. Extended License Completion - Based on existing spent fuel inventories plus a plant-by-plant extrapolation of future discharges assuming all operating plants having one 20-year extension.
3. Continuing Level Energy Generation - Based on extension of the current ~100 GWe installed commercial base and average spent fuel discharge of 2100 MT/yr through the year 2100.
4. Continuing Market Share Generation – Based on a 1.8% compounded growth of the electricity market through the year 2100, matched by growing nuclear capacity and associated spent fuel discharge.
5. Growing Market Share Generation - Extension of current nuclear capacity and associated spent fuel discharge through 2100 with 3.2% growth, equivalent to continuing the average market growth of last 50 years for an additional 100 years.

Five primary spent fuel management strategies are assessed against each of the energy futures to determine the number of geologic repositories needed and how the first repository would be used. The geologic repository site at Yucca Mountain, Nevada, has the physical potential to accommodate all the spent fuel that will be generated by the current fleet of domestic commercial nuclear reactors, even with license extensions. If new nuclear plants are built in the future as replacements or additions, the United States will need to adopt spent fuel treatment to extend the life of the repository. Should a significant number of new nuclear plants be built, advanced fuel recycling will be needed to fully manage the spent fuel within a single repository.

Introduction

The U.S. Secretary of Energy is required by the Nuclear Waste Policy Act (NWPA) [1] to provide to Congress the Department's recommendation concerning the need for a second geologic repository for spent nuclear fuel (SNF). This recommendation is required "…on or after

January 1, 2007, but no later than January 1, 2010." By 2010, the spent fuel discharged from current commercial reactors will exceed the statutory limit of the first repository[1].

The Department of Energy's Advanced Fuel Cycle Initiative (AFCI) is charged with research and development of advanced fuel cycle approaches. The Senate Report on the Energy and Water Development Appropriations Bill for 2004 [2] included the following requirement for the AFCI program:

> *"The initiative shall assist the Secretary with development of alternative technology options that may influence the Secretary's 2007 statutorily required recommendation for the need to develop a second repository."*

With this charge from Congress, the AFCI Systems Analysis group proceeded to bound the repository question. This paper summarizes that effort.

Problem Formulation

There is no single answer to the question asked by the NWPA. Instead, the answer is dependent on a combination of market factors driving the amount of spent fuel produced along with the options for managing that material. Different levels of nuclear energy generation will result in different amounts of SNF. Different management approaches for the SNF result in different amounts of material that go to geologic disposal.

This approach of assessing different levels of SNF inventories and management approaches is represented conceptually in Table 1. The columns in the table indicate increasing levels of SNF discharged from commercial reactors. The rows indicate increasingly aggressive management approaches to limit the disposed material. The entries in the table indicate the answer to the NWPA question under each combination of SNF level and management approach. It should be noted that under the current management approach of a "once through" fuel cycle with direct disposal of the SNF without reprocessing, the projected SNF always exceeds the statutory limit of the 1st repository and a second repository is needed. This is shown in the first row of Table 1. In each additional row the more aggressive management approach is assumed to "handle" an additional column of SNF generation.

Given this conceptual approach, we now develop the columns and rows of the table. First, we assess the range of plausible nuclear futures for the remainder of the century. Next, we identify primary SNF management approaches. Finally, we compare the nuclear futures versus the management approaches to build the table.

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[1] Per the NWPA, commercial nuclear power plant operators pay the U.S. Government $0.001 per kilowatt-hour of electricity produced. In return, the Government agrees to take ownership of the commercial SNF. The NWPA authorizes the development of a geologic repository for the SNF, but limits the disposal quantity to 70,000 metric tons initial heavy metal (MTiHM) until a second repository is opened. Initial heavy metal refers to the initial uranium content of the fresh fuel prior to irradiation. 7,000 MT of the repository capacity has been set aside for government spent fuel and high level waste from defense activities, leaving 63,000 MT for commercial SNF.

Table 1 - Conceptualization of the second repository question

Is Second Repository Needed? (yes/no)	Commercial SNF Total #1	Commercial SNF Total #2	Commercial SNF Total #3	Etc.
Current Approach	Yes	Yes	Yes	Yes
Mgmt Approach A	No	Yes	Yes	Yes
Mgmt Approach B	No	No	Yes	Yes
Mgmt Approach C	No	No	No	Yes
Etc.	---	---	---	---

Alternative Nuclear Futures

The first step in understanding the need for a second repository is to understand the size of potential spent fuel inventories. A full range of potential futures for domestic commercial nuclear energy is considered. For each energy future, the total amount of SNF fuel discharged through the end of the century was calculated. The calculation of these baseline SNF quantities assumed the use of current power plant designs and fuel burn-up levels.

These energy futures are as follows:

Alternative 1. Existing License Completion
Alternative 2. Extended License Completion
Alternative 3. Continuing Level Energy Generation
Alternative 4. Continuing Market Share Generation
Alternative 5. Growing Market Share Generation

Alternative 1: Completion of Existing Licenses

This case assumes all existing reactors operate until the end of their current licenses, with no extensions beyond the 26 already granted [3]. No new plants are constructed. The total amount of used nuclear fuel produced in this case is dependent on several factors, including average plant availability, capacity uprates, and fuel burn-up durations. All these factors are assumed constant for estimating this case.

This case is intended as a practical lower bound. It results in a total projected inventory of commercial used nuclear fuel of ~100,000 MTiHM when the final reactor license expires in 2046.

The likelihood of <u>at least</u> this amount of used nuclear fuel being produced is very high, since it only assumes completion of existing licenses and the related contracts for the government to dispose of the used nuclear fuel produced.

Alternative 2: Completion of Extended Licenses

This case is designed to be an upper bound for the existing commercial infrastructure. It assumes all existing reactors apply for and are granted one 20-year license extension but no new plants are ordered (and no second extensions are sought).

This case results in a total projected inventory of commercial used nuclear fuel of ~120,000 MTiHM[2]. The last reactor license would expire in 2055.

The probability of every existing reactor applying for and being granted license extensions is fairly low, since there are a few older, smaller reactors that the owners may not wish to extend. However, roughly 3/4th of all reactors have already either been granted extensions (26), have extension applications filed (18), or have announced that applications are under development (18 specifically named plus an additional 11 unnamed) [3]. Thus it is likely that 90 % or more of the total current generating capacity may eventually be granted extensions. It is also possible that some owners may apply for second extensions.

Alternative 3: Continuing Level Nuclear Generation

This is the first case that considers construction of new plants, but only as replacement for existing plants that are retired. A total used nuclear fuel inventory is not calculated, since generation is assumed to be ongoing indefinitely. Instead, the inventory in the year 2100 is used as an arbitrary point of measure. Note that this restates the question from "Is a second repository needed?" to "Is a second repository needed this century?"

Several factors affect the used nuclear fuel generation rate at a level energy generation rate. Burn-up levels are expected to continue to increase, reducing the amount of used nuclear fuel produced per unit of energy produced. Replacement plants may use new designs that are more or less efficient. Timing of replacement plant construction is dependent on license extensions. Given the uncertainty of these variables, the approximate current generation rate of 2,100 MT/yr is conservatively used for projections. It results in cumulative used nuclear fuel generation by 2100 of ~250,000 MTiHM.

For this future case to occur, new plants must eventually be ordered to replace those that are retired. Thus, a key **trigger event** for this case is announcement of a new plant order.

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[2] It should be noted that the high case used by the Yucca Mountain FEIS [4] differs from the high case used in this document due to the assumption on duration of license extensions. The FEIS states, "For conservatism, these data were derived from the Energy Information Administration "high case" assumptions. The high case assumes that all currently operating nuclear units would renew their operating licenses for an additional 10 years (DIRS 103493-DOE 1997, p. 32)." Since 1997, all license extensions granted or applied for have been for 20 years, so we use that value here.

Alternative 4: Increasing Electricity Generation with Level Nuclear Share

Nuclear energy currently provides ~20 % of U.S. electricity [5]. This future case assumes maintaining this market share while overall domestic electricity grows. The growth rate is achieved through a combination of plant extensions, replacements, and additional new plant construction.

The Energy Information Administration (EIA) 25 year projection for domestic electricity growth is 1.8%. We use this rate and extend the projection to 2100. This results in cumulative used nuclear fuel generation by 2100 of ~600,000 MTiHM.

The 1.8 % growth rate compares favorably with other growth scenarios. By 2020, it results in ~140 GWe of domestic nuclear capacity, compared to the 150 GWe recommended by nuclear utilities [6]. By 2050, it results in ~240 GWe, compared to 300 GWe used by MIT in their low case growth scenario [7].

For this case to occur, new plants must be added soon. While these plants are under construction, growth must come from continued operational improvement and uprates of existing plants. Again, a key trigger event is the announcement of a new plant order, preferably followed soon after by additional orders.

While there are currently 103 operating reactors in the U.S., no new plants have been ordered since 1978. However, the spate of license extensions has been accompanied by a dramatic increase in uprates. Starting in 1998, plant owners have started performing major equipment changes that are resulting in "extended" uprates of up to 20% [8]. The equivalent of several power plants has been added through these efforts (see Figure 1). Thus, nuclear growth is occurring without new plants being ordered. In addition, a major refurbishment of the Browns Ferry plant is underway to restart this facility in 2007. Finally, new plant orders may be just around the corner - three groups applied for new nuclear plant site permits in 2003.

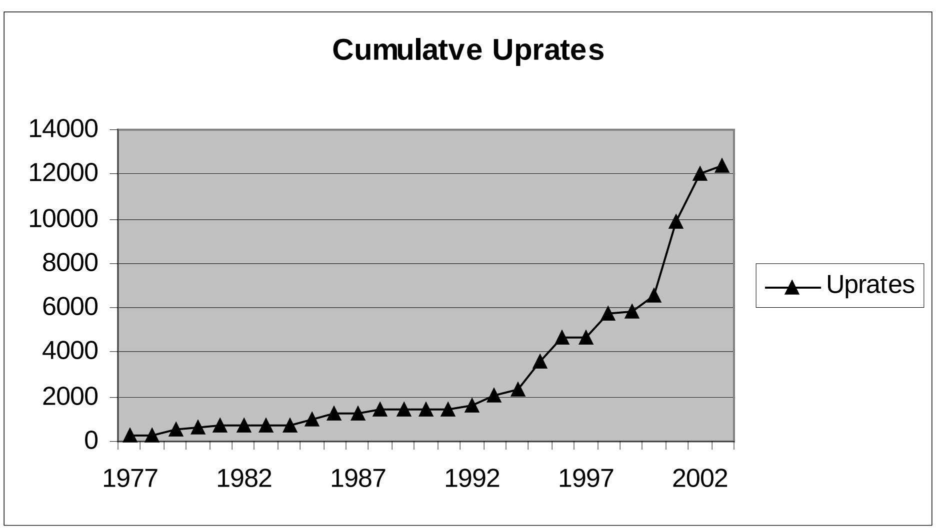

Figure 1 - Cumulative commercial reactor uprates in MWs of thermal output.

Alternative 5: Increasing Energy Generation with Increasing Nuclear Share

Nuclear energy has been the fastest growing domestic energy source over the last 50 years. While this growth has leveled off in the last ten years, several factors could contribute to a renewed growth period:

- Increasing natural gas prices
- Growing concern over carbon emissions
- Development of alternate fuels for the transportation sector
- Increasing use of bulk heat in industrial processes

This case is intended as an upper bound. It assumes the ~20 % electricity market share gain of the last 50 years is continued, doubling by 2050 and redoubling by 2100. To achieve this growth rate, nuclear energy needs to grow at an annual rate of 3.2%. This will result in an unlikely 80% market share if all the energy is used to generate electricity. However, a significant share of the energy is assumed to be for other applications such as hydrogen generation. This is especially true in the last half of the century when world oil and natural gas reserves are projected to be depleted.

Since some of the growth will be in energy areas other than electricity, the share of total energy is also considered. Nuclear energy currently represents 8.4% of total domestic energy use. The EIA rate projection for average energy growth across all sectors is 1.5%, with the fastest growth in transportation and electricity. The 3.2% nuclear growth rate would result in nuclear energy supplying between 40-45% of total energy, roughly equivalent to oil's current market share.

The 3.2% growth rate results in cumulative used nuclear fuel production by 2100 of ~1,500,000 MTiHM.

The 3.2 % growth rate results in ~470 GWe of installed capacity in 2050, which compares favorably with the MIT high growth scenario of 477 GWe. It is much lower that the growth rate recommended by six Department of Energy National Laboratories [9]. The National Laboratory growth is based on achieving the objective of "50 percent of U.S. electricity and 25 percent of U.S. transportation fuels produced by nuclear energy by 2050", which results in the equivalent of over 700 GWe installed capacity in 2050.

This case would appear to have low likelihood at first glance. Certainly, with no plants currently under construction the growth rates are not obtainable in the first ten years. To stay on the growth curve 2 or 3 new plants are needed initially each year. But when compared to the historical record this rate does seem sustainable [10]. During the 1970s an average of 4 plants were completed per year. By 2040 most existing plants would need to be replaced and an additional 10 new plants would be needed per year. Fifteen new plants were completed in both 1974 and 1975.

While construction rates may be obtainable, other areas would also be stressed. Uranium prices are very stable at ~$10-12 a pound, and have been declining for 20 years [10]. However, during the prior building boom uranium prices were almost $40 a pound. Fuel is a small, but still significant portion of the total cost of nuclear energy. Repository space could also be limiting. The projected cumulative used nuclear fuel in 2100 is >20 times the statutory capacity of the first repository.

Other Alternatives

The high growth rate of Alternative 5 seems to provide an upper bound for the repository analysis. Certainly an even higher domestic growth rate seems very unlikely. However, there is a possible nuclear future that could result in even higher SNF quantities. This case involves the development of an international provider-user arrangement whereby the U.S. and other existing nuclear weapons states "lease" fuel to non-weapons states to reduce proliferation potential. The provider states perform all front end enrichment and all back end SNF management, eliminating the need for the user states to develop these parts of the fuel cycle. Such an arrangement has been suggested [11, 12] to address world energy demand and the environmental impacts of fossil fuels. In a provider-user arrangement, the total SNF managed by the U.S. could surpass the Alternative 5 quantities.

Summary of Nuclear Futures

As shown in Table 2 below, five different nuclear futures have been defined in this section providing reasonable bounding of the range of cumulative spent commercial nuclear fuel that may be expected by 2100. The first two futures assume no new plants, while the remaining three assume new plants to replace existing plants and provide overall growth of nuclear energy output.

Table 2 - Summary of Nuclear Futures and cumulative SNF

Nuclear Futures	Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative SNF in 2100 (MTiHM)	100,000	120,000	250,000	600,000	1,500,000

Alternative Management Approaches

The next step in understanding the need for a second repository is to assess the technical options for SNF management. Five primary spent fuel management strategies are assessed against each of the energy futures to determine the number of geologic repositories needed and how the first repository would be used.

Current Approach

The current SNF management approach involves one pass through a light water reactor followed by storage until the geologic repository is opened. At that time, the stored SNF will be shipped for disposal. Newly discharged fuel will be stored for several years to cool before shipping. The SNF is disposed without any additional treatment or separation. Repository capacity for commercial SNF is legally limited to a total of 63,000 MTiHM.

Under this approach, a second repository is needed for every postulated nuclear future. The only way to avoid the need for a second repository would be to revoke the operating licenses of all 103 commercial plants before 2010. This would result in an immediate loss of 20% of U.S. electricity production.

Partition to Reduce Disposal

This approach involves reprocessing of the SNF to remove the spent uranium, significantly reducing the heavy metal content to be disposed. This approach is currently precluded by an executive branch policy against reprocessing of SNF established during the Carter Administration in an attempt to lead other countries away from reprocessing methods that separate plutonium. The French and British reprocessing facilities in place at that time have since both been expanded and the Japanese have built a similar facility that is near operability.

Reversing the no reprocessing policy would not change repository needs for two reasons. First, the NWPA bases the legal capacity on the initial heavy metal in the fresh fuel instead of the heavy metal disposed. Thus, removal of the uranium would make no legal difference in the capacity calculation. Second, the limiting factor on repository performance is the long-term heat load, which is dominated by americium and plutonium. Even if the NWPA was changed by Congress to be based on disposed heavy metal, the removal of the uranium would not change the heat load.

Because this approach provides no net benefit to repository capacity versus the current approach it is not considered further as part of this scoping study. Separation of the uranium would provide other benefits related to the handling of the SNF and the operation of the repository, but it would not change the need for a second repository.

Expanded Repository Capacity

The capacity limit of the first repository is a legal limit, not a physical limit. If Congress changed the NWPA to base the capacity on the technical capacity of the Yucca Mountain site, more SNF could be disposed. The total technical capacity of the site has not been published, but two documents provide a lower limit. The Yucca Mountain Final Environmental Impact Statement [4] included two cases with 105,000 MT of commercial fuel and increased amounts of defense and other wastes. The Yucca Mountain Science and Engineering Report [13] included discussion of a technical capacity of at least 119,000 MT. This would provide a minimum of 112,000 MT for commercial SNF (plus the 7,000 MT for defense SNF and HLW).

For simplicity, we assume a physical capacity of 120,000 MT for commercial fuel, matching the supply from our first two nuclear futures. The 112,000 MT value above is a minimum and the additional 8,000 MT can be achieved in two ways. First, a review of the science and engineering evaluation suggests the technical capacity may be higher. Second, trends in fuel burn-up could make up the difference. Figure 2 shows the past history of burn-up rates [14], showing significant increase in burn-up levels in the last 20 years. A 12% additional increase in burn-up would result in an 8,000 MT reduction in the future SNF generated in Alternative 1.

While it would require the Congressional action of a change in the NWPA, the expansion of the capacity of the first repository would be sufficient to address all SNF generated by the current fleet of commercial reactors. This includes both the SNF projected to be generated based on the existing licenses, as well as the additional SNF that would be produced if all these reactors were granted 20 year license extensions.

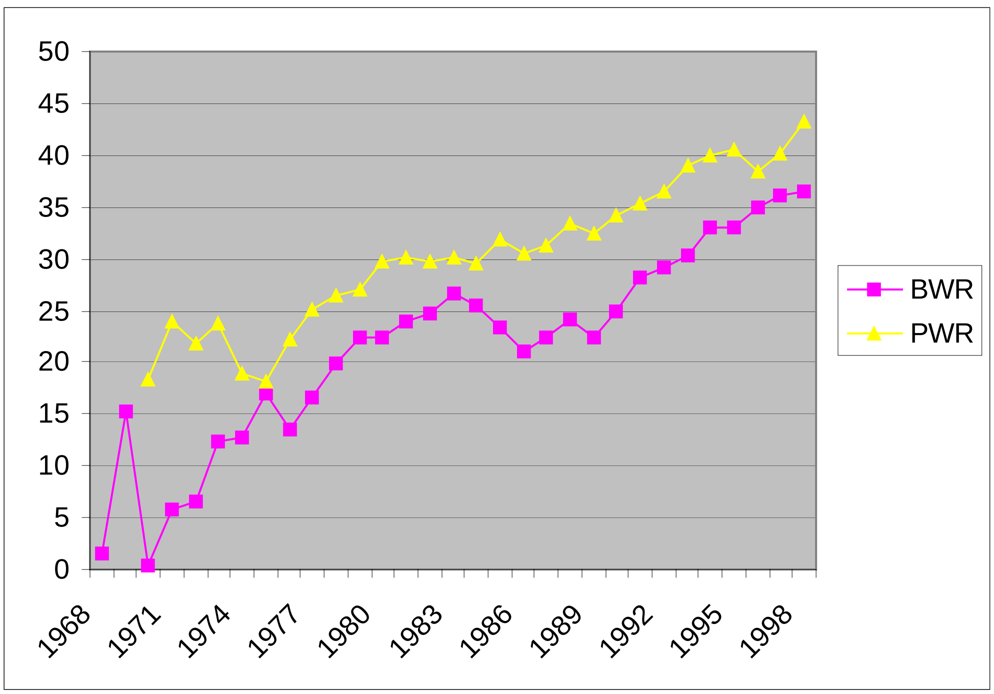

Figure 2 - Historic fuel burn-up levels for Boiling Water Reactors and Pressurized Water Reactors

Separations, Limited Thermal Recycle, Repository Capacity Expansion

While repository expansion alone is sufficient to address the first two nuclear futures, this management approach will not be sufficient if additional reactors are constructed, either as replacements for the current fleet or to support nuclear growth. A more aggressive management approach is required.

As mentioned previously, separation of the SNF to remove the uranium provides some benefits to repository operation but no net improvement in capacity due to the presence of decay heat from americium and plutonium. To increase the capacity, these elements must also be removed. However, unlike uranium that can be disposed as low-level waste, these elements must instead be destroyed. The easiest way to accomplish this with the existing nuclear infrastructure is to recycle these elements in the current thermal reactors and their replacements. The key isotopes to destroy are Am-241 and its precursor Pu-241. Destruction of these isotopes removes most of the heat generated between 1000 and 10,000 years, the time of projected peak temperatures in the repository rock between waste drifts at Yucca Mountain [15]. There are several approaches to thermal recycle that result in destruction of a portion of the Am-241 and Pu-241 with each additional pass through the reactor. In addition, the short-term heat load must be reduced. Either extending the period of forced ventilation of the repository past the planned 75 years or removing cesium and strontium from the fuel can accomplish this. The cesium and strontium can be stored until they decay, and then disposed as low level waste.

Recycle in thermal reactors is limited by a buildup of non-fissile higher actinide isotopes that tend to absorb neutrons during reactor operation. Each successive pass results in more of these isotopes, requiring higher fuel enrichment to provide enough neutrons to sustain the nuclear reaction. After only a few passes the enrichment levels necessary become impractical. This limits the destruction of Am-241 and Pu-241 and the effective overall reduction in long-term heat generation by the SNF. This limit has not been completely determined, but appears to provide no better than a 50% reduction in heat load[3]. This reduction, combined with repository capacity expansion is sufficient to address the 250,000 MT of SNF generated in the level energy generation nuclear future through 2100.

Separations, Repeated Combined Thermal and Fast Recycle

The limitations of thermal recycle can be addressed by burning the non-fissile higher actinides in fast spectrum reactors. The higher energy neutrons in fast reactors are able to affect the fission of these isotopes. Using a combined strategy of both thermal and fast reactors allows for continuous recycle of plutonium, neptunium, americium, and curium until these elements are totally destroyed. In this SNF management approach, the only quantities of these elements that end up in the repository are trace amounts left with the fission products during separations. The net impact, assuming at least 99.9% separation efficiency, is a 50-fold decrease in long-term heat load [15]. An additional benefit is at least an order of magnitude decrease in the source term contributing to long-term waste toxicity.

This management approach sufficiently reduces the effective load on the repository to allow the equivalent of over 3,000,000 MT to be disposed within the 63,000 MT legal capacity of the first repository, as long as the NWPA is changed by Congress to be based on the disposed heavy metal. This eliminates the need for a second repository in this century under all postulated nuclear futures.

Separations, Repeated Fast Recycle

The final management approach examined is to separate the SNF and recycle only in fast reactors. This approach has the same impact on repository capacity as the previous case. The

[3] While 50% appears to be an upper bound, the practical limit may be lower. We round the value for purposes of this scoping study, resulting in a factor of 2 impact on repository capacity.

added benefit of this approach is in the sustainability of the fuel cycle. In the high growth scenario, the fissile U-235 that makes up only 0.7% of natural uranium may become scarce. Fast reactors can be converted from net actinide burners to net actinide producers by modifying their operation. This allows these reactors to also be operated as breeder reactors, allowing full utilization of U-238, which makes up the other 99.3% of natural uranium, extending the fuel supply by a factor of 75-100.

Summary of SNF Management Approaches

The geologic repository site at Yucca Mountain, Nevada, has the physical potential to accommodate all the spent fuel that will be generated by the current fleet of domestic commercial nuclear reactors, even with license extensions. If new nuclear plants are built in the future as replacements or additions, the United States will need to adopt spent fuel treatment to extend the life of the repository. Should a significant number of new nuclear plants be built, advanced fuel recycling will be needed to fully manage the spent fuel within a single repository.

Table 3 summarizes these results. It expands the nuclear future columns of Table 2 by adding rows for the fuel management strategies. An additional column is added to the left side of the table for reference, showing the existing legislative limit of the repository. The second repository question is answered by showing the number of Yucca Mountain equivalents that would be needed under each combination of nuclear future and SNF management approach.

Table 3 is divided into quadrants by two thick lines. The vertical line indicates the change from existing reactors to the inclusion of new reactors. The construction of new reactors was identified as a key trigger event that enables the futures on the right side of the table.

The horizontal line on Table 3 indicates the key change in policy and the law to allow commercial spent fuel reprocessing in the U.S. and allow the benefits of material recycling to be realized in the legal definition of repository capacity. As can be seen from the table, this change is required to accomplish management of SNF from new reactors if a second repository is to be avoided.

It should be noted that an assessment of the tradeoffs in political and economic capital between additional repositories and advanced fuel cycles is beyond the scope of this paper. The authors only point out the conditions that could drive the need to complete such an assessment and make a spent fuel management decision.

Of paramount interest is where we stand in Table 3. As indicated by its title, the U.S. is currently on the first row of the table. Although the AFCI and the Generation IV Nuclear Energy Systems Initiative are researching the advanced separations, fuels, and reactors needed for lower rows, there is no authorization at this time to develop full-scale separations facilities.

But which column are we in? In 1998, the EIA projection for 2020 included a significant reduction in the number of operating commercial reactors in the country, equivalent to a position between the first and second columns. Since 1998, the EIA projection has moved solidly into the third column [16]. Figure 3 shows this change in projected nuclear energy levels. With 3 site license applications pending [17], movement to the fourth column may be imminent.

Table 3 - Nuclear Futures versus Management Options Table

	Nuclear Futures	Legislative Limit	Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
	Cumulative discharged fuel in 2100 (MTiHM)	63,000	100,000	120,000	250,000	600,000	1,500,000
		Existing Reactors Only <-----			-----> Existing and New Reactors		
	Fuel Management Approach	**Number of Repositories Needed**					
<------ No Recycle	Current Management Approach (under existing repository legislation)	1	2	2	4	9	22
	Expanded Repository Capacity	1	1	1	3	5	13
Reprocess and Recycle ------>	Separations, Limited Thermal Recycle, Repository Capacity Expansion	1	1	1	1	3	7
	Separations, Repeated Combined Thermal and Fast Recycle	1	1	1	1	1	1
	Separations, Repeated Fast Recycle	1	1	1	1	1	1

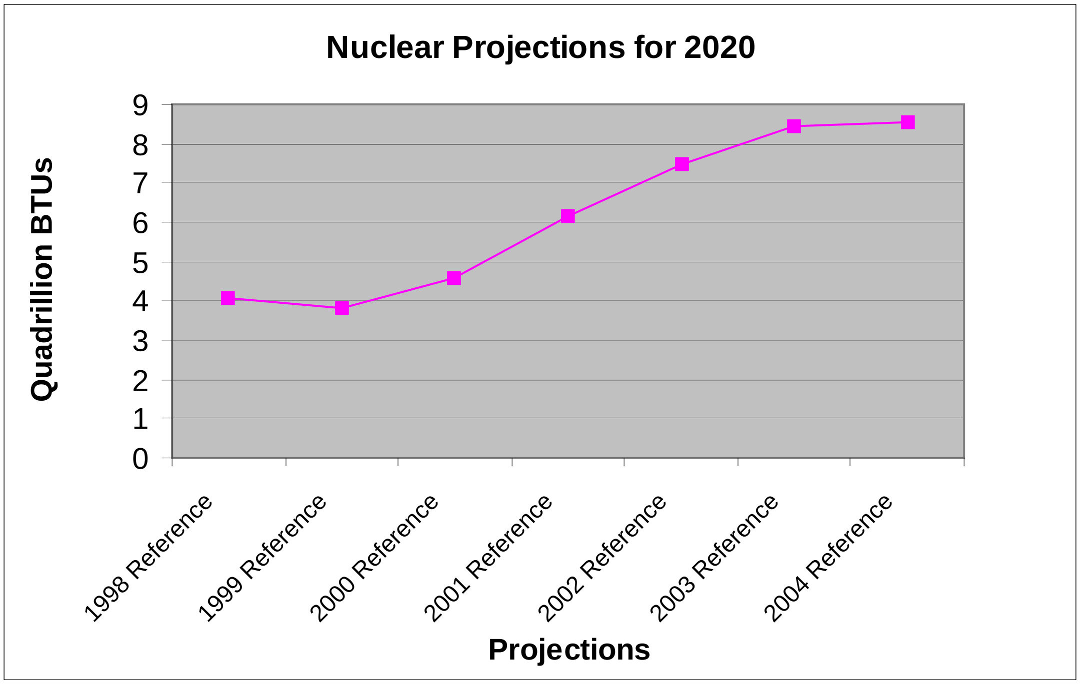

Figure 3 - Changes in EIA future nuclear energy projections from 1998 to 2004

Conclusions

Whether a second geologic repository is needed in the United States is dependent on a combination of the market forces driving the generation of spent fuel and the management approach applied to the spent fuel. This paper has examined a range of alternatives for both of these aspects and determined that a second repository can be avoided in this century if the right management approach is selected and the associated technology and infrastructure developed. Whether additional repositories are more or less desirable than these management approaches from the perspectives of politics and economics has not been assessed. However, industry trends in the last 5 years suggest such an assessment may need to be made in the near future.

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