AVOIDING NEED FOR MULTIPLE REPOSITORIES IN A NUCLEAR GROWTH SCENARIO

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ABSTRACT

Nuclear energy growth in the U.S. can be accommodated in coming decades, without a second high level waste repository, and without buildup of large spent fuel inventories if a vigorous start on closing the fuel cycle is made now. We think it is a mistake to rely on the open once-through fuel cycle for the next 50 years, as the 2003 MIT report (the Future of Nuclear Power) recommends. There are difficulties and costs (and proliferation risks) associated with multiple repositories dotted all around the world, which is the inevitable future if nuclear power grows and the once-through fuel cycle is relied upon exclusively. Instead we project here a future in which the US moves forward quickly with electrochemical or aqueous processing technology for LWR spent fuel. All alternative technologies must be evaluated by cost, safety, and proliferation-resistance criteria. Argonne has proven many of the elements of electrochemical process technology by operating the EBR-II spent fuel treatment process on a pilot scale of a ~2.4 MT/yr processing plant, coupled with Argonne's experience with a 20 MWe sodium cooled passively safe power plant (EBR-II, operated for 30 years). Pre-conceptual designs of a 100 MT/yr fuel recycle plant and a 300 MWe fast-burner power plant have been completed which could (perhaps) achieve operation in 2008 and 2014.

Nuclear energy, growing at an assumed rate of 2% per year from 2010 forward without closing the fuel cycle, implies that total U.S. spent-nuclear fuel would reach the legislated capacity of Yucca Mountain (63,000 metric tons heavy metal) in 2011, and the technical capacity (120,000 tons) in ~2033. If instead the fuel were processed in an evolutionary 500 MT/yr processing plant operational by 2014, and three further plants of 1500 MT/yr deployed in 2021, 2028, and 2035, a second repository won't be needed until the end of the century. The plutonium and minor actinides would be used to fuel fast burner reactors, so that plutonium inventories are controlled; the plutonium that would exist would be commingled with minor actinides, and neither plutonium nor minor actinides would go to the repository. Rather, to a good approximation, only fission-product waste would be sent to the repository. With 20 years cooling time (roughly, the current average age of spent fuel), and with transuranics removed (the major long term decay heat contributor), repository capacity can be increased by a factor of ~5 with no increase in repository thermal management.

The 2%/yr increase in US nuclear power starting in 2010 would result in 215 GWe in 2050, 141 GWe from advanced LWRs and 74 GWe from advanced fast burner reactors with a base- case conversion ratio (CR) of 0.5. The split depends on this conversion ratio. The stored plutonium peaks at just under 900 tons in 2028, then is reduced to 2000 levels (~450 tons) by mid-century. Without processing and recycle, the plutonium in spent fuel would rise to over 2000 tons by 2050. It is assumed that the Yucca Mountain repository will begin receiving LWR spent fuel when it is licensed, but because LWR spent fuels will be retrievable from Yucca Mountain for many decades after it opens, eventually all the spent fuel waste emplaced could be retrieved and processed, and indeed this must be done if the factor of five increase in repository capacity is to be realized.

INTRODUCTION

In this paper we report conclusions of nuclear fuel cycle systems studies conducted over the past two years. The main conclusion is that it is possible to accommodate nuclear energy growth in the U.S. in coming decades, without need for a second high level waste repository, and without buildup of large spent fuel inventories. However, this is a very difficult problem, and if it is to be overcome, a vigorous start on closing the fuel cycle must be made fairly quickly.

In this matter we disagree with the conclusion of the 2003 MIT study, The Future of Nuclear Power [1], to rely solely on thermal reactors and a once through fuel cycle, until at least mid-century. We agree with many of the study's recommendations including the important observation that nuclear plant construction needs to start now to meet the U.S. power needs and reduce global carbon emissions. However, we believe it is a mistake to rely solely on the open once-through fuel cycle for the next 50 years or more. Further, while it is very important, as the MIT report recommends, to develop proliferation-resistant closed nuclear fuel cycles (that use fast reactors to destroy all the actinides), we think it is important as a policy matter to move forward on this now. A good deal of this work has already been developed by Argonne, with electrochemical pyroprocessing, the basic elements of which have reached a scale of ~2.5 MT/yr, but the features are known and could be implemented in existing facilities at a prototype scale of 5 MT/yr. A 20 MWe sodium cooled passively safe power plant (EBR-II) was operated for 30 years. Preconceptual designs of a 100 MT/yr fuel processing plant [2] and a 300 MWe sodium cooled passively safe fast reactor plant [3] were completed with aggressive start up dates of 2008 and 2014 respectively. The fuel processing milestone, of course, is very difficult to envision. Nevertheless, these two demonstration plants are a necessary bridge to the capacity needed for production plants.

The implication of nuclear energy growing at a rate of 2% per year from 2010 forward is that total U.S. spent-nuclear fuel would reach the legislated capacity of Yucca Mountain (63,000 metric tons heavy metal) in 2011, and the technical capacity (~120,000 tons) in ~2033. Even if the 120,000 tons storage capacity is achievable, the nuclear energy growth rate would be impacted well before 2033. Who would opt for a new nuclear plant if we were to be back in the high-level waste disposal debate long before the middle of a new plant's useful life? With fuel processing, a rate of processing beginning with a 500 MT/yr reprocessing plant operational by 2014; and three evolutionary plants of 1500 MT/yr deployed in 2021, 2028, and 2035, the need for a second repository can be avoided until at least mid-century, and with periodic deployment of additional capacity, until the end of the century, and all without great buildups of spent fuel. To do this, one must process spent fuel from the thermal-spectrum reactors, recover essentially all of the actinide elements, and send only fission-product wastes to the repository. With about 20 years cooling before processing, the repository capacity can be increased by a factor of 4 to 5. Much of today's spent fuel has been out of the reactor for 20 years already and with the timing of processing plant construction, it is easy to envision a minimum 20 year cooling period for before all spent fuel were scheduled for processing..

An aggressive pace is necessary to have the assumed 500 MTHM/yr plant in operation by 2014. In the base case, with the constraint of a single repository, waste quantities up to the "technical capacity" of Yucca Mountain are allowed, but not exceeded. The technical capacity of Yucca Mountain, 119,000 MTHM, is based on maximum use of the area of the Project, the "area of the Total System Performance Assessment model domain" (Yucca Mountain Science and Engineering Report [4]).

The 2%/yr increase in the US starting in 2010 would result in 215 GWe in 2050. It is of two types. The principal capacity is based on present LWR technology (or advanced LWRs, or even HTGRs), but includes advanced technology: fast burner reactors. The precise split depends on the conversion ratio of the fast burners. For clarification purposes, we take conversion ratio (CR) of 0.5 as the base case to illustrate the effects of deployment of these reactors on the repository. LWR spent fuel, processed by any of today's candidate technologies, leaves a waste product containing considerably less than 1 percent of the transuranics (TRU) originally present. These transuranics (~90% plutonium) are responsible for long-term decay heat that determines the amount of waste that can be stored if the spent fuel is not processed.

By excluding the TRU from the repository, one can increase the waste loading of the repository significantly. The factor of 5 increase in waste from LWR fuel is possible without affecting the thermal management strategy of the repository. An even larger factor might be possible, deriving from the much shorter time the fission products wastes require confinement (and so corrosion is likely a less serious problem, waste package temperatures might be increased etc.), but such a further increase is a longer-term issue suited to further study and repository dynamics.

The time-dependent deployment of the new nuclear capacity is assumed to begin in 2010. Plants based on present technology gradually increase their capacity from 97 GWe in 2010 to 141 GWe in 2050; while the actinide-fueled ("fast burner") reactor deployment rises to 74 GWe at 2050. Direct disposal of spent LWR fuel commits the entire technical capacity of Yucca Mountain by 2033. However, with processing, the "HME Stored" (that is, the equivalent space taken up and heat rejection) totals 80,000 MTHM (equivalent) by 2050, with still room in Yucca Mountain for nearly another 40,000 MTHM(equivalent).

The stored plutonium (actually TRU) peaks at just less than 900 tons in 2028, and then is reduced to 2000 levels (~450 tons) by mid-century. Note that, if no LWR processing and recycle were done, the plutonium in spent fuel would rise to over 2000 tons by 2050 for the 2% power growth assumed in this scenario. Because wastes (including LWR spent fuels) will be retrievable from Yucca Mountain for many decades after it opens, if it were desired to further reduce the plutonium and minor actinides in the repository, additional LWR fuel processing capacity, beyond that assumed in this scenario, could be deployed. In this way it would be possible to realize any reduction in repository transuranic inventory that might be desired.

The constraining issue in nuclear energy growth for the next fifty years is not likely uranium resources, but rather finding land where the public will allow disposal of the spent fuel. This is evident from the difficulty in opening a single repository at Yucca Mountain. We do not believe it is prudent to assume that a second repository will be any easier to site than the first. Thirty year interim central storage facilities or bore holes recommended by the MIT report may also be difficult to site. Nuclear plants operated once-through will not be sustainable if the spent fuel issue is not adequately addressed. Processing the spent fuel so that actinides as a group are removed, are never separated and are destroyed in fast burner reactors, extends the technical capacity of the Yucca Mountain repository significantly without increasing the potential long-term exposure from radionuclide release.

Strategy for a US Nuclear Energy Future

Model development and extensive parameter studies previously reported on in Reference [5] laid the basis for arriving at a reasonable strategy for the US Nuclear Energy Future with reprocessing, and this future is described in this section. There are of course other processing technology alternatives. At Argonne we consider the following scenario to be possible, but very aggressive:

- U.S. nuclear power growing at a 2% annual growth rate from 2010 onward, resulting in 215 GWe capacity at mid-century.

- Timely availability of the Yucca Mountain repository, initially for placement of intact LWR spent fuel, and later for placement of processed waste (fission products only) from LWR spent fuel. Politically, and to support the U.S. nuclear industry, it is imperative that emplacement of spent LWR fuel in the repository begin as soon as Yucca Mountain is available.

- Elimination of any second repository until well after 2050, even with the substantial reactor deployments cited above. Key to this is processing a portion of the LWR spent fuel inventory, producing a waste free of transuranics for storage in the repository, and committing the recovered transuranics to fuel fast burner reactors.

- More specifically, a key element is a sequence of advanced fuel processing plants for LWR spent fuels. A first demonstration production plant of 100 metric tons of heavy metal per year (MTHM/yr) should come online in 2008 (the most aggressive assumption of all, but it could be slipped by a few years, pushing the schedule for everything out a few years, without impacting the main conclusions), followed by a 500 MTHM/yr plant in 2014, and in a baseline scenario plants of 1500 MTHM/yr would then follow in 2021, 2028, and 2035. The timing of processing plant construction is crucial to eliminating need for a second repository.

- Avoiding accumulation of processed product, by having full-scale (several hundred MWe plants or modules) fast spectrum reactors ready to accept this fuel in the 2017-2019 period. The stage for this would be set with a government-funded 300 MWe fast-spectrum demonstration production reactor assumed to begin operation in 2012; fueled with TRU obtained from the 100 MT/yr processing plant.

- Incorporation of integrated safeguards and maximum transparency, by design, for both reactor and fuel cycle plants.

- Encouraging by example a global nuclear energy regime in which those countries having substantial nuclear energy infrastructures can follow the U.S. model. For states not having suitable infrastructure, seek an internationalized fuel cycle regime, wherein processing of spent fuel is provided, and fresh low-enriched uranium fuel supplied in its place, with actinide-free HLW returned to the generating country.

- On a more measured pace, development of other advanced reactor technologies to address hydrogen production. This should be a part of the system architecture, so that transition to a hydrogen-based economy is facilitated when it is deemed necessary.

Systems Model and Preliminary Results

A "base-case" scenario was developed in examining the implications of a range of nuclear energy futures upon electricity generation and waste management demands. This is not intended as a rigid recommendation, but rather an example of the sort of nuclear energy future that is reasonable and possible.

An aggressive pace is necessary to have the assumed 500 MTHM/yr processing plant in operation by 2014. The specific reactor technology is assumed to emerge from an enhanced, accelerated Gen IV program to assure that recycle can take place in reactors appropriate to it.

In order to avoid a second waste repository, it will be necessary to place more waste in Yucca Mountain than its "legislated capacity" (63,000 MTHM for commercial spent fuel). We note many studies in the literature, including many issued by the Department, which contain such an assumption. We recognize that under current legislation, the legislated capacity noted above cannot be exceeded until a second repository is in operation. These policy and political matters are beyond the scope of this paper. In the base case, with the constraint of a single repository deemed very important, waste quantities up to the "technical capacity" of Yucca Mountain are allowed, but not exceeded. As mentioned previously, the technical capacity of Yucca Mountain, 119,000 MTHM, is based on maximum use of the area of the Project, the "area of the Total System Performance Assessment model domain."

The 215 GWe in 2050 is of two types. The capacity is based on the most current LWR technology as well as fast burner reactors. As shown in Table I, the precise split depends on the conversion ratio of the fast burners:

Table I Capacity Totaling 215 GWe @ 2050 by Reactor Type

Present-Technology Capacity	Conversion Ratio	Actinide-Fueled Capacity
164 GWe	0.0	51 GWe
154	0.25	61
141	0.50	74
98	1.0	117

For clarification purposes, we take conversion ratio, CR, to be 0.5 as the base case to illustrate the effects of deployment of these reactors on the repository. LWR spent fuel, processed by electrochemical technology, leaves a waste product containing considerably less than 1 percent of the transuranics (TRU) originally present. These transuranics are responsible for long-term decay heat that determines the amount of waste that can be stored. By excluding the TRU from the repository, one can increase the waste loading of the repository significantly. The waste from about five times as many processed spent fuel assemblies compared to unprocessed can be stored without increasing the thermal management loading of the repository. This benefit was corroborated by the National Academy Committee on Separations Technology and Transmutation Systems in 1996 [6] which stated:

> "The removal of actinides from the material being emplaced in the repository allows 4 to 5 times more waste to be emplaced in a given area of the repository"

An even larger factor might be possible, deriving from the much shorter time the fission products wastes require confinement (and so corrosion is likely a less serious problem, waste package temperatures might be increased etc.), but such a further increase is a longer-term issue suited to further study of the repository dynamics.

Figure 1 presents the time-dependent deployment of the new nuclear capacity, assumed to begin in 2010 for CR=0.5. LWR Plants gradually increase their capacity from 97 GWe in 2010 to 141 GWe in 2050; while the actinide-fueled ("fast burner") reactor deployment rises to 74 GWe at 2050. When a new plant is needed, the selection of a fast reactor or thermal plant is based upon TRU fuel availability. The model places a thermal plant in service if not enough TRU fuel has been manufactured from processing. If sufficient TRU is available, then a fast burner reactor is placed in service. Hence, the number of fast reactor plants is limited by the amount of TRU fuel available which is determined by the total reprocessing capacity available at that time.

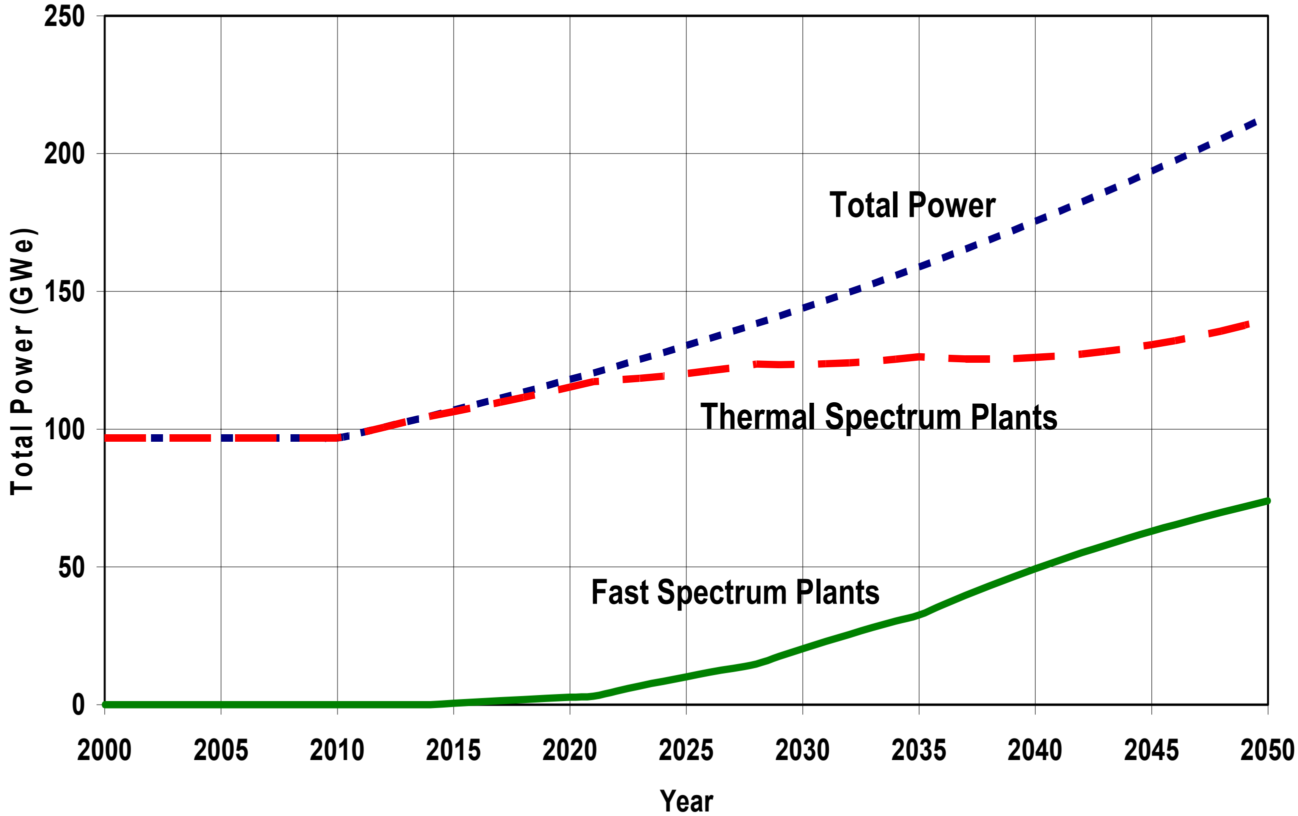

Fig. 1 Capacity deployment; 2000-2050 *(CR=0.5)*.

Figure 2 compares metric tons of heavy metal (equivalent), using the five-for-one credit on processed waste, in the two relevant scenarios. Direct disposal of spent LWR fuel commits the entire technical capacity of Yucca Mountain by 2033. On the other hand, the "HME Stored"- the stored "heavy-metal equivalent"- totals 80,000 MTHM(equivalent) at 2050, with still room in Yucca Mountain for nearly 40,000 MTHM or MTHM(equivalent).

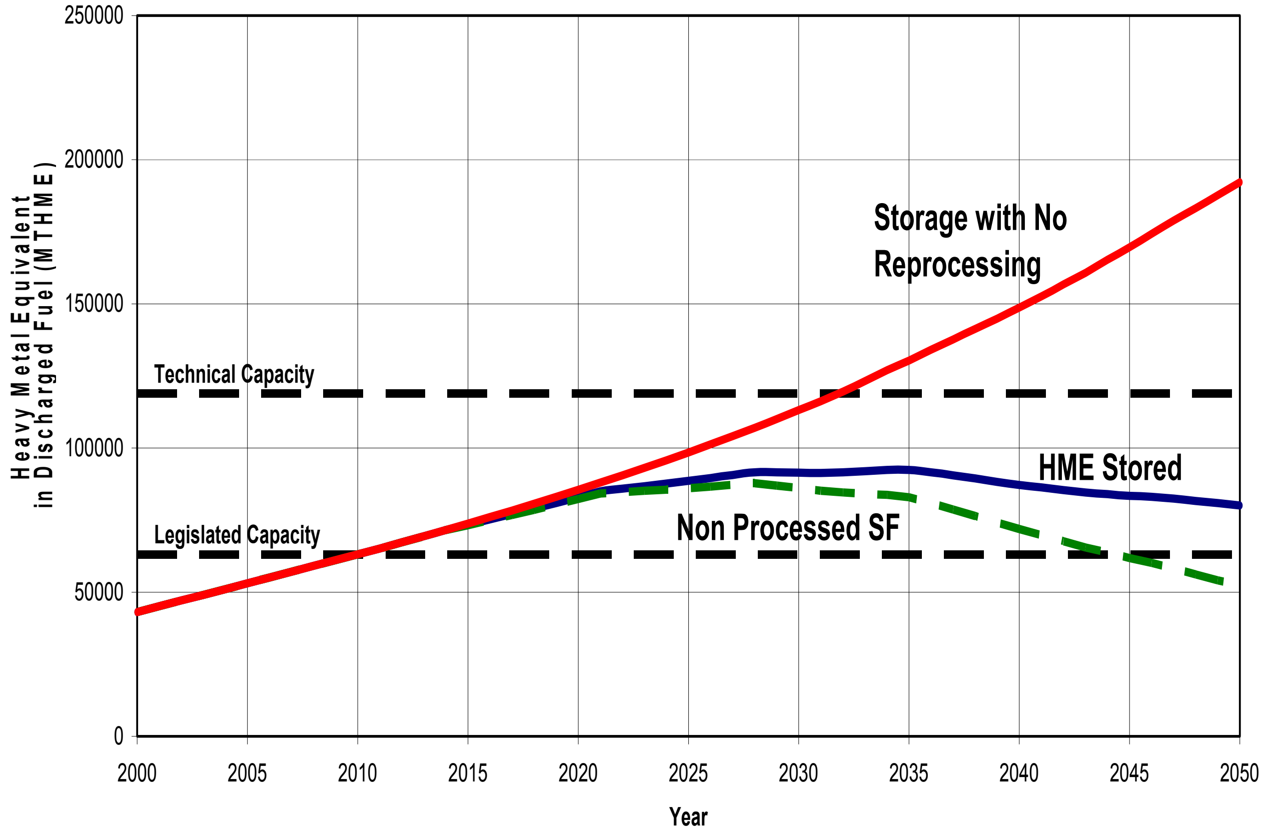

Fig. 2 Repository heavy metal or heavy metal equivalent

Finally, Figure 3 shows the amount of plutonium in U.S. spent fuel, i.e. the plutonium that is outside the reactors, as a function of time. Note that the stored plutonium peaks at just under 900 tons in 2028, then is reduced to 2000 levels (~450 tons) by mid-century. Note that, if no LWR processing and recycle were done, the plutonium in spent fuel would rise to over 2000 tons by 2050 for the growth assumed in this scenario. Because wastes (including LWR spent fuels) will be retrievable from Yucca Mountain for many decades after it opens, unprocessed fuel already stored would be retrieved to reduce the plutonium and minor actinides in the repository. After 2050 additional LWR fuel processing capacity would be needed to keep the actinide inventory decreasing. In this way it will be possible to use the current repository to almost the end of the century. The amount of reprocessing needed will depend upon the actual growth of nuclear power.

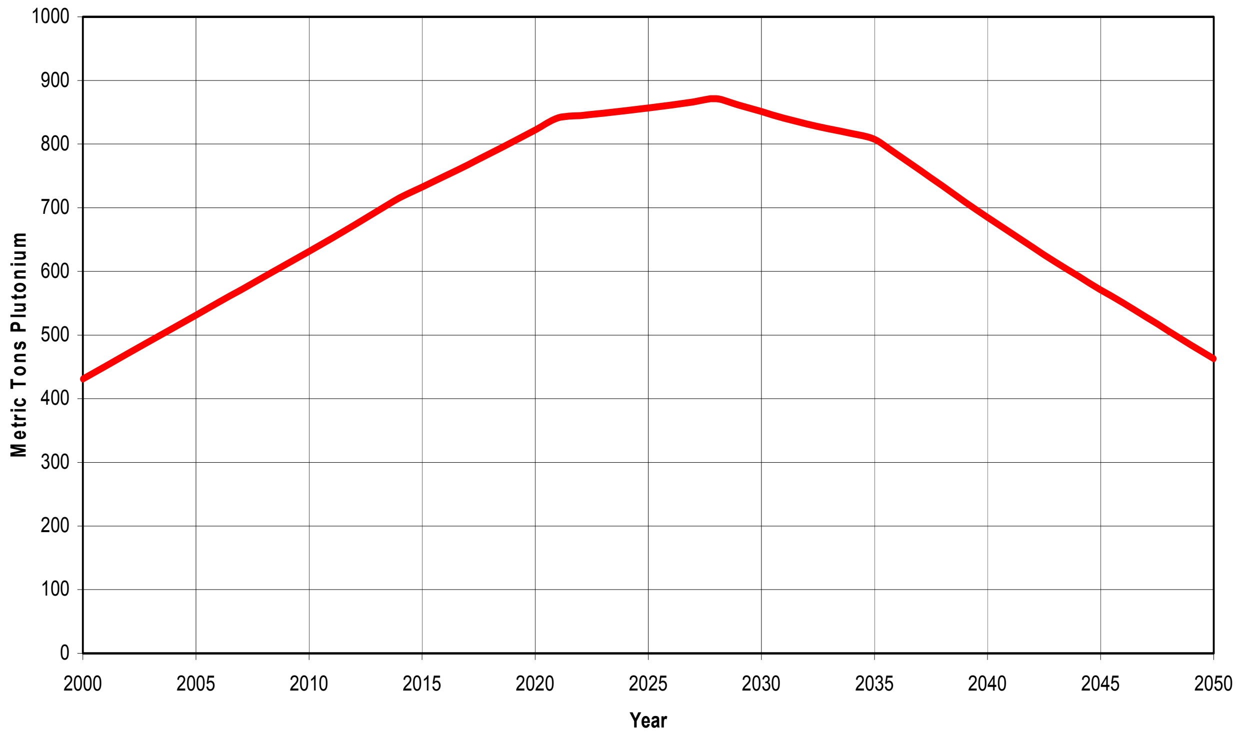

fig. 3 plutonium Inventory in Spent Fuel Destined for the Repository

In summary, the initiative allows significant U.S. nuclear electricity in 2050, LWR spent fuel processing beginning in 2014 to allow all wastes generated to be placed in the first repository, and the development of reactors to utilize (as opposed to storing, long-term) the transuranics, the most important of which is plutonium.

Creating Energy and Economic Security

The goal of this initiative is bold: to create a future of U.S. nuclear power growth, underpinning energy and economic security, while avoiding the seemingly insurmountable obstacle of requiring a second HLW repository. Bold measures are needed to achieve the goal. In this section we gather up all the arguments for advocating such an aggressive move, repeating some things briefly, and expanding upon others.

We noted before that a robust U.S. nuclear power future with only a single repository can be achieved only by processing some portion of the LWR spent fuel inventory, and removing the transuranics.

(a) Without processing, and without Yucca Mountain capacity expansion, operation of the current U.S. nuclear plant fleet creates wastes that reach the legislated limit for commercial spent fuel (63,000 MTHM) in the repository in 2011. Under these conditions, "orphan" high level wastes--wastes that have no assured disposition path, would then once more be generated. Orphan wastes have plagued nuclear power in the U.S. for the last 30 years or more, and returning to this condition would be a huge disincentive for U.S. nuclear plant expansion from that point forward, here encountered soon after the Administration's Nuclear Power 2010 initiative might reach fruition.

(b) Without processing, but with expansion of Yucca Mountain capacity, the nuclear power potential is only modestly better. Above we assumed a growth scenario for U.S. nuclear power: capacity flat at ~100 GWe to 2010, and growing at 2% annually after that. The wastes reach the Yucca Mountain technical capacity, as noted, in 2033. The disincentives above in (a) are present here too, they just appear a number of years later. Utilities could not rationally be expected to commit to nuclear expansion in 2010, if the nuclear waste disposal issue were known to be coming back in 2033, well before the useful lifetime of the plants is over.

(c) By processing the entire LWR spent fuel inventory, removing TRU, disposing of only fission products, and assuming the decay-heat efficiency improvement factor of 5, the equivalent wastes placed into Yucca Mountain would reach legislated capacity much later. The dates are 2077, 2065, and 2058; for U.S. nuclear power growth from 2010 onward of 2, 3, and 4%, respectively.

(d) By processing the entire LWR spent fuel inventory, again assuming an efficiency improvement of 5, but now escalating to the technical capacity of Yucca Mountain, these equivalent wastes would reach the limit in 2107, 2087, 2074; again for U.S. nuclear plant growth from 2010 onward of 2, 3, and 4%. Note that in the 2% growth case, we have a 100-year nuclear waste management solution.

It seems clear, from the timing constraints outlined above, that a U.S. commitment to such a path cannot be deferred for very long. The credibility of the commitment will lie both in its early timing, and in its magnitude.

The Argonne system uses a phased approach where the separations technology is demonstrated for its economics and proliferation resistance characteristics using an initial ~500 MTHM/yr LWR processing plant starting in 2014. With this experience, a sequence of larger plants will be deployed beginning in about 2021. This strategy requires a substantial near-term processing commitment.

Given that spent LWR fuel is about 1% TRU (plutonium and minor actinides), whether the processing plant is 2000 MTHM/yr beginning in 2015, or 500 MTHM/yr beginning a year earlier, the scenario is for multi-ton quantities of TRU to be extracted annually. For the processed product there are three options:

(a) Simply store it, presumably as self-protected, low attractiveness-level , remotely-handled material,

(b) Recycle it to U.S. LWRs, which because of time constraints imply it would likely be in a MOX monorecycle mode, or

(c) Accelerate the solution that must ultimately be implemented in any case: recycle it as fast-burner reactor fuel.

Storing the product in large quantities could involve more safeguards and security concerns than allowing orphan LWR spent fuel to build up indefinitely, and we do not evaluate this option in this study. We turn to the reactor options.

MOX monorecycle to LWRs can certainly be done, but its real effect is mainly to park the processed product, first in the LWR, and afterward in spent fuel storage. The bulk of the minor actinides build up in storage, awaiting the ultimate fast reactor solution. Only about 25% of the plutonium is consumed in its LWR residence, and the minor actinide mixture is increased such that the long-term radiotoxicity of the MOX spent fuel is little different than the original UOX spent fuel. Moreover, the MOX monorecycle path is costly: it is front-end loaded with MOX fuel fabrication facilities that would only be operated until the fast reactor solution was in hand. Conventional MOX fuel fabrication requires that the processing step produce a relatively pure plutonium product, which has unanswered questions about its consistency with the U.S. nonproliferation policy. Unconventional MOX fuel fabrication, i.e. remote fabrication of a contaminated product, is relatively untested. For all these reasons, MOX monorecycle is a stop-gap measure, and a costly one at that. The Nation should proceed down this path only if the fast-burner reactor development and deployment schedule were very uncertain or protracted in time.

That leaves the third option. We believe that the prospects for success of an accelerated fast reactor development schedule are, in fact, excellent. We see no reason why a government-funded demonstration production fast reactor could not be operating ~2012-2013. This would be a combination prototype and test facility, demonstrating the revolutionary passive safety benefits that are possible with fast-spectrum machines, allowing the development of fuels with greater net TRU consumption, and expediting the licensing of the follow-on industrial plants. The first industrial-sized plants could then follow in about 2017-2019.

On this schedule, the fast-spectrum reactors can keep pace with the needed LWR spent fuel process facilities' output, which themselves avoid the repository constraints. The TRU used as fuel in the fast reactors will be observed and safeguarded far better than it could ever be in a repository.

Improving Repository Performance with Processed Waste Forms

The benefits of the High Level Waste (HLW) that stem from either advanced aqueous processes (vitrified glass) or the pyroprocess (glass-bonded sodalite and a stainless steel-zirconium metal alloy) cannot be fully realized under the present Yucca Mountain waste disposal constraints and criteria. These constraints were developed for irradiated spent oxide fuel rods with full loadings of plutonium, minor actinides, and fission products.

With waste containing only 0.1% to 1.0% of the transuranics, repository design and operation is amenable to considerable simplification. The area loadings could be greatly increased and the 10,000 year survival of engineered barriers, imposed for LWR spent fuel, is not required. Concerns about corrosion, which at present may drive project design to lower temperatures, lower area loadings and lower total repository capacity, are greatly ameliorated if the engineered barriers need survive only 500 years, as may well be the case for the new waste forms. The leach rate and transport characteristics of the new candidate waste forms are also vastly better than those of oxide spent fuel. A sustained substantial program to capitalize on the intrinsic properties of the HLW forms in this initiative is warranted.

Integrated Safeguards and Transparency

Existing industrial recycle technologies primarily rely on extrinsic barriers like physical security, time to detect, access control, and materials accountability. The safeguards systems for these technologies were developed early as they were ready for deployment. Advanced recycle technologies, such as the pyroprocess, provide barriers more intrinsic to the process that derive from the chemical, radiological, and isotopic characteristics of the materials in process. The total safeguards system is a central part of the development and the demonstration of the recycle technology.

Intrinsic characteristics may to some degree conflict with current extrinsic systems: the higher radiation fields for plutonium and other TRU products, for example, may lead to further development work on the sensor and detector systems used in extrinsic barriers. The prototype projects, reactor and fuel cycle, are the development and demonstration test-beds for integrated safeguards and for transparency.

Methodologies for assessing the combined benefits of both intrinsic and extrinsic safeguards are needed early. Much of the discussion of safeguards and its role in nonproliferation is somewhat subjective but intrinsic safety barriers are clearly superior to extrinsic since they are failsafe.

Internationalization of a New Nuclear Energy Regime

There are presently 34 countries plus Taiwan that need to dispose of spent fuel intact or as HLW. As more countries elect to build nuclear power plants in the future, spent fuel stores will accumulate in more and more countries, unless efforts to develop regional spent fuel repositories are successful. The willingness of one country to accept another's spent fuel is anything but certain, and even if it were certain, it would have non-proliferation implications.

Internationalization of civilian nuclear fuel cycle services, possibly on a regional basis, has been recognized as possessing certain advantages for many decades. Generally the model has been to suggest that nations with small nuclear programs, or developing nations, forego closing the fuel cycle, in exchange for guaranteed access to low-enriched uranium fuel. Discharged from the reactor, the fuel assemblies would be shipped to Fuel Cycle Centers located in the established weapons states, or those with large nuclear infrastructures. There the recovered TRU would be committed to reactors in the host States.

Focusing on the smaller nuclear power states, there is about 88 GWe nuclear power capacity deployed in these states today, and it can be estimated that they have accumulated about 37,000 MTHM of spent thermal-reactor fuel. These totals are remarkably close to those of the U.S. today (about 100 Gwe, with ~44,000 MTHM accumulated spent fuel). The U.S. scenarios that we study in this exercise thus apply almost exactly to what might be termed the "rest of the world" (ROW) in this context.

The U.S. scenarios can be applied more or less directly. Placement of the LWR fuel processing plants, and the reactors in which the transuranic fuel is to be recycled, would exist only in the large-infrastructure nuclear nations with solid nuclear nonproliferation credentials. Fresh uranium fuel supply comes from these nations, who have sunk investments in the technology. Spent fuel is returned to those nations, processed under international control, the TRU committed to reactors within their borders, under international control. The TRU-free HLW from the spent fuel is returned to the client countries for disposal. But note: the client-country repositories carry no long-term burden due to transuranics. Note more importantly: there are no "plutonium mines".

A sustainable global nuclear energy future will ultimately require measures such as these. Effectiveness will require Russian participation. It will take time, perhaps a long time, to develop both the technologies and the institutions to affect such a Fuel Cycle Center and client arrangement. The U.S. and Russia need to work together on this common goal.

CONCLUSION

This initiative starts the U.S. on an exciting new energy-security path. At mid-century, hundreds of GWe of clean, safe nuclear capacity could be deployed, with a single repository to dispose of wastes that decay harmlessly in a few hundred years, instead of creating a legacy issue for eons. Because of the proliferation resistance of electrochemical pyroprocessing fuel cycle technology chosen and because integrated and transparent safeguards will be developed alongside the process technology, the fuel cycle model can become an international norm. The government investment in the fuel cycle would be repaid in following years from very large (and currently unplanned) additional payments into the nuclear waste fund. Whether the constant-dollar costs of the fuel cycle activities (and the prototype reactor) are completely recouped from new nuclear waste fund receipts (and repository savings), the difference will be very small compared to the potential return on investment in the reactor plants.

The 2003 MIT report correctly states that uranium resources will not be a constraint for the next fifty years, but it misses the constraint of finding land where the public will allow disposal of the spent fuel. It is not prudent to assume that a second repository will be any easier to site than the first. Thirty year interim central storage facilities or bore holes recommended by the MIT report may be impossible to site. Nuclear plants operated once-through may not be sustainable. Processing the spent fuel, so that actinides as a group are removed and never separated and are destroyed in fast burner reactors, extends the capacity of the Yucca Mountain repository significantly and should alleviate much of the public concern about the repository.

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