Nuclear Recycling: The Logical Next Step

A Policy Recommendation

Benjamin Prewitt

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Abstract: This paper presents a policy recommendation regarding the recycling of nuclear fuels. Currently nuclear plants in the US operate on an open fuel cycle that does not utilize recycling technology. Recycling would enable improved resource utilization of nuclear fuel and reduce the volume of hazardous waste needing storage. Using recycled fuel in commercial reactors will extend the world uranium supply and may be a solution to increased uranium demand in the future as nuclear power expands globally. The next step to determining the viability of a closed fuel cycle in the US is to test the technology on an industrial level. This will evaluate whether or not the technology is ready for commercial application. Potential processes for recycling have been evaluated, as well as options for framework and management structures of possible programs. Economic viability, as well as the reaction of public officials, businesses, and communities will determine the success or failure of a nuclear recycling initiative. For the national policy on the nuclear fuel cycle to change, it must first be proven that any change will be worthwhile. A pilot program demonstrating a new recycling process will evaluate the technology and gauge whether it is ready for commercial implementation.

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Issue Definition

A topic often discussed amongst nuclear engineers, scientists, and members of the energy production community is whether the US will ever adopt a policy of recycling nuclear fuel and if so, when. In the United States today, the commercial nuclear power industry does not engage in recycling. Instead, the currently used model is referred to as an open fuel cycle. It begins with the mining of uranium, which is then enriched and fabricated into a useful fuel form. Then it is used in a power plant until it is no longer useful for efficient power production. This used fuel is then stored at the plant as high level radioactive waste. This used fuel is not recycled; permanent storage is anticipated. New methods and technology continue to be developed to advance the efficiency and profitability of this cycle. Despite any advances in these methods, only about 1% of the available energy in uranium is utilized by the once-through cycle[1]. Utilizing 100% of the available energy is unlikely, but recycling to any degree will improve the resource utilization beyond current levels. Additionally, large amounts of used fuel have accumulated, and will continue to do so as long as nuclear power remains an integral part of the national energy portfolio.

As of 2011, the inventory of used nuclear fuel from commercial power plants was roughly 65 thousand metric tons [1]. The Blue Ribbon Commission on America's Nuclear Future[2] projected that the expected volume of commercial used fuel from power plants will be between 150-200 thousand metric tons by the year 2050. A portion of this spent fuel is being stored at decommissioned nuclear power plants; this is referred to as stranded fuel. Storage and security for this isolated fuel is a significant financial liability for the utilities with that own shut down plants. Under the Nuclear Waste Policy Act of 1982 [2], the Department of Energy has a legal obligation to construct and utilize repositories for used fuel and other nuclear waste. Implementing a closed fuel cycle, which recycles used fuel, will serve to reduce the final volume of high level waste that needs to be stored, decreasing the burden on these repositories or other fuel storage facilities once constructed and utilized. Depending on the price of recycled fuel and incentives for using it, it may become a competitive fuel option. This would reduce the demand for fresh fuel, and as a result reduce the need for uranium mining, which would extend the life of the worldwide uranium supply. If it is set up correctly, a closed nuclear fuel cycle has the potential to be profitable and beneficial for the environment.

[1] This 1% is estimated by the fact that 0.7% of natural uranium is U-235, the isotope used for fission. The other 0.3% is contributed by plutonium produced and fissioned during the current fuel cycle.

[2] This commission was established by the President and the Department of Energy in 2010. A committee of experts from various fields was assigned to investigate the issue of nuclear waste storage in the United States and propose action for the government to take.

One concern with implementing a closed fuel cycle is that switching over to a new cycle will require a massive investment into something that is full of uncertainty. The level of profitability or cost effectiveness is unknown as large scale commercial recycling has never been done in the United States. The only reference for commercial operations would be those of foreign nations, such as France, that have recycled nuclear fuel for several decades. Advanced methods for recycling have only been performed on a laboratory scale. Commercial applications of any of these technologies have not been tested in any country, and doing so would require significant time and investment from businesses and government agencies. There is also a significant lack of infrastructure in the US for commercial nuclear recycling and no pressing need for change as far as the fuel cycle is concerned. There is also the looming concern of proliferation of nuclear materials, which has made this issue a political debate topic for decades. These factors have led to the continuous deferral in addressing this issue in the United States.

Alongside the challenges of making such a cycle cost effective and significantly changing the industry standard, the overriding challenge will be establishing nuclear recycling as national policy, which will be the primary influence and motivator regarding funding, R&D, and public support.

Background

The idea of recycling nuclear fuel in a closed fuel cycle is nearly as old as nuclear power itself. In 1954, the Atomic Energy Commission was charged with the task of enabling commercial use of nuclear reactors for energy production [3]. As a part of the initial plan prototypes were considered for multiple types of reactors, one of which was the breeder reactor which is central to the concept of a closed fuel cycle. In 1963, the EBR-II experimental breeder reactor facility was constructed to test the feasibility of innovative reactor technology and an associated recycling method. This facility reprocessed metallic fuel and used it in an experimental fast reactor [4]. The predecessor to this reactor, the EBR-I, was designed to test the possibility of nuclear power and was the first reactor to produce enough energy for significant electricity generation. Both of these were 'breeder' reactor types, which are designed to produce more fuel than they consume.[3] In 1966 the West Valley Plant in Buffalo, New York began reprocessing fuel from defense programs to be used in commercial plants. At that time, the true abundance of natural uranium was unknown, making the recycle and breeding of nuclear fuel a very attractive notion given the potential scarcity of resources. As a result, a major emphasis

[3]For a more detailed description of nuclear reactor types, see appendix B

was placed on the research and development of fast breeder reactors and implementing a closed fuel cycle. President Nixon advocated for the program himself in an address to Congress, saying "The breeder reactor could extend the life of our natural uranium fuel supply from decades to centuries, with far less impact on the environment than the power plants which are operating today." [4]

In the next few years, GE, Allied Services, and Exxon all began or considered licensing and construction of commercial reprocessing facilities. With the expected growth of the US nuclear capacity in the 1970's (in 1974 two hundred and thirty-three nuclear power units were either ordered, being built, or currently operating) [3], a closed fuel cycle was seen as the most efficient and sustainable way to meet the demand from these new plants.

Many proposed plants were cancelled for various reasons, and uranium was discovered to be much more abundant than previously thought. The resulting low price of natural uranium and the reduced number of plants lowered the urgency to recycle fuel in a closed cycle. The extensive costs of constructing breeder reactors also decreased the economic value of recycling, shifting the mindset of many towards the simpler and more affordable open cycle.

The potential theft or diversion of plutonium, referred to as proliferation, also became a concern during and near the end of the cold war. In all uranium fueled nuclear reactors, some amount of plutonium is produced, or 'bred', as a byproduct of the power production process. As plutonium could be directly extracted using the conventional reprocessing method, the idea of reprocessing fuel was discouraged by the government to prevent the potential loss and misuse of nuclear material. During the Carter administration, national policy officially discouraged commercial reprocessing to protect the US from the dangers of nuclear proliferation, and to encourage other nations not to recycle for the same reasons. That opinion has not changed much over recent years, and is still one of the main political barriers to adopting a closed fuel cycle. In 1972 the West Valley Plant ceased its commercial reprocessing of defense materials and was shut down in 1976. The Three Mile Island accident of 1979 shifted the focus of policy development and research towards improved safety rather than alternative fuel cycles. By 1981 the development of the GE, Allied Services, and Exxon reprocessing facilities were all cancelled because of economics or to focus on other projects of higher priority [4].

New developmental considerations for nuclear plants in the 2000's focused primarily on efficiency, passive safety, and other characteristics of the current generation of reactors. Presidential administrations have alternated in supporting or opposing reprocessing, but the outcome has been to defer the question of closing the fuel cycle to a later date and focus on other objectives. However, the idea of nuclear recycling is not completely out of the question for the future and has continued to be researched by scientists and engineers. Additionally, new environmental regulations call for the expansion of non-carbon energy production. While nuclear energy only contributes to 20% of overall domestic electricity generating capacity, it contributes more than 60% of carbon free electricity in the US [5]. An expansion of the nuclear program may be a key part of the solution to reducing carbon emissions and embracing cleaner sources of energy. If that occurs, and if the use of nuclear energy continues to expand globally, then the value of closing the fuel cycle may again become a consideration as it did in the 1960's and early 1970's.

Key Concerns and Constraints

The significant factors related to implementing any new technology in the United States are a combination of technical and non-technical issues. Funding, research, logistics, regulations, politics, and public opinion must be considered when planning many government programs or business opportunities, especially those dealing with nuclear and energy related technology.

As long as nuclear technology has been around, the public has always been wary with regard to the risk posed by nuclear reactors and radioactive waste for their families and the environment. State governments are also very involved and often vocal when it comes to nuclear facilities within their borders. Support or opposition for nuclear power varies greatly by region in the US, but has generally been positive. In 2012, a Gallup poll determined that 57% of national adults favored nuclear power plants and agreed that they are safe [6] Within that umbrella of policy and opinion lies the matter of recycling nuclear fuel.

As stated earlier, the threat of nuclear proliferation present within conventional reprocessing methods had been central to the debate on closing the fuel cycle. There are practical concerns to supporting a closed cycle as well. The current abundance of natural uranium, as well as the advent of advanced enrichment methods has made acquisition of fresh fuel convenient and favorable. As there is currently no shortage of raw materials or economic difficulties with manufacturing new fuel, there is no urgent demand in the United States to develop an alternative. This lack of urgency may dissuade public or private endorsement of modifying the current fuel cycle. However, whether or not US national policy will endorse a modified or closed fuel cycle in the future has not been permanently decided. As a result, and in consideration of the potential benefits and advantages, discussion and research related to developing a closed fuel cycle has continued as a possibility for the future.

Research in the development of several different processes has been conducted on the laboratory scale, but nothing has been done in the United States on a larger scale or a commercial level since the EBR-II and the West Valley Plant, only research has continued. Internationally, research and improvement of commercial reprocessing technology has been continuous in several European and Asian countries. Most of the developments are still experimental. For a project dealing with experimental technology on an industrial scale, significant government subsidies will be required to construct and license the necessary facilities. None of the required facilities exist today. Current facilities would need to be repurposed or new facilities would need to be built. The type of process used may limit the cost of new facilities, but that cost savings only goes so far. Acquiring discretionary appropriations for such projects is difficult under normal circumstances, and is even more difficult in a period of economic recovery. A common solution to this is to have co-sponsorship from the industry, but that support is dependent on the incentive for companies to make the investment. Any initiative must have potential economic benefits, in either the short term or the long term. That is also a central theme of the discussion of nuclear recycling.

In addition to not having the facilities, the existing regulations written to govern all nuclear facilities have evolved to focus on power plants. There are numerous regulatory gaps in existing regulations that will complicate the licensing of a commercial reprocessing plant [7]. These gaps may result in burdensome or inefficient regulation, but do not necessarily prevent these plants from being licensed. To resolve these concerns a new regulatory framework was developed, known as Part 7x [7][4]. This framework combined existing regulations governing nuclear facilities, handling of radioactive materials, and staffing considerations into one document, designed specifically to oversee licensing, construction, and operation of recycling facilities. However, Part 7x was never made into official regulations as the Nuclear Regulatory Commission (NRC) has not yet conducted the rulemaking process for this framework. This process includes gaining public feedback on proposed rules and numerous other steps which lead to revision and formation of the final rules which if approved are published and adopted.

The economic benefits of using recycled fuel must be able to justify the costs of producing it. These benefits must be seen as an improvement over the current cycle, and a viable option to keep nuclear power competitive among other energy sources. The current cycle includes all costs associated with the once through cycle: fresh fuel production and used fuel storage. Both fresh and recycled fuel production require multi-stage processes with separate costs for each step. Storage and disposal costs for used fuel and waste products produced during fuel creation are added to production costs to estimate the final fuel cost for either fresh or recycled fuel.

[4] This is a working title. If made official this new framework would be added to Title 10 of the Code of Federal Regulations as its own part with a serial number, like the other sections.

In addition to determining the costs of recycled fuel, another challenge for utilities is implementing recycled fuel into their everyday operations. The composition, properties, and behavior of this fuel are different than that of fresh fuel, and there are various technical details that need to be considered. These details may affect plant efficiency, and may alter the safety requirements for normal operations and accident prevention. While there is much completed research and industrial experience in this area, each plant still needs to evaluate these changes individually. To compensate for these details, revisions in the license of a plant are required to ensure adequate levels of safety for the use of different fuel. The Catawba nuclear plant operated by Duke Energy has completed this process as part of a National Nuclear Security Administration (NNSA) program to dispose of weapons plutonium.[5] The mixed oxide (MOX) fuel created from this program will be similar in nature to fuel created from recycled commercial fuel[6].

Another cost aspect is storage of used fuel. Under the current system, used fuel is stored at power plants after it is used, pending storage in temporary or permanent government facilities. The costs of storing all of the used fuel currently in existence and that which will be produced in the future must be compared to the material that would need storage in a closed cycle. There will be a significant reduction in the volume of used fuel that must be stored. A quantifiable value for this reduction is a function of numerous technical variables relating to the scale and procedures of potential operations.

Used fuel is a mixture of several types of material. A fuel assembly removed from a reactor consists of numerous fuel pellets encased in metal cladding. In the United States, used fuel pellets are left in the assemblies during the various phases of storage. Concerning the fuel pellets themselves, a small portion of the fuel, less than 1% is dangerously radioactive and emits large amounts of heat [8]. Significant shielding is required to insure adequate levels of protection for workers and the environment; this protection can be costly. The rest is much safer to handle and requires less shielding. In the current cycle these two parts are not separated; thus they are stored together requiring extensive shielding requirements for the full volume. Recycling would separate these two parts to some degree, enabling separate storage and handling of the two parts. The materials that can be reused and what will require storage may change depending on how the fuel is recycled, but for any case the separation of the hazardous portion

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[5] This program is known as the MOX project, started in 1999. Shaw Areva MOX Services was commissioned by the NNSA to construct a MOX fuel fabrication facility to dispose of weapons plutonium as fuel in commercial reactors. The Catawba plant has also used test assemblies of MOX fuel in preparation for this program. These test assemblies were made in France with US plutonium [23]

[6] While both forms of MOX are made with uranium and plutonium, there is a significant difference in the composition of weapons grade plutonium and reactor grade plutonium. See Appendix A.

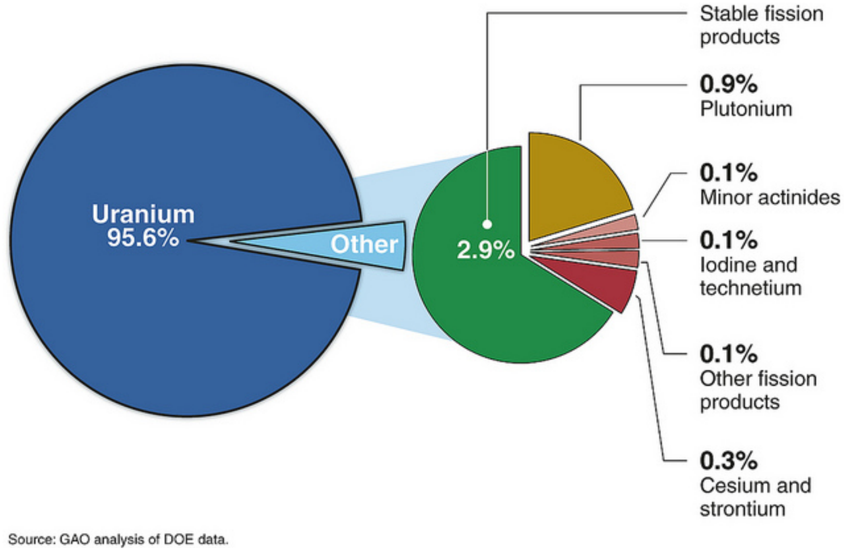
from the rest will reduce the amount of material needing extensive shielding and special handling. These reductions will lower transportation and storage costs during the recycling process. Additionally, depending on the recycling process, there may be a limit to the number of times fuel can be reused before it is no longer practical to recycle. This will contribute to the amount material that is no longer useful and must be stored as high level waste.

The final volume of unsalvageable recycled fuel will be significantly less than the total volume of unprocessed used fuel, or at least an equal volume of recycled waste will have seen more use. This difference in final waste volume, resource utilization being considered, will be another determining factor in the value of investing in a closed fuel cycle. These potential benefits combined with the potential for reduced fuel cost must prove an advantage over the current fuel cycle, as well as being competitive with other forms or energy production. With the current abundance of natural gas and the popularity of renewable, investing billions of dollars into uncertain nuclear technology will be difficult to justify. That is why any change in the nuclear fuel cycle must first be tested on a small scale, with a process that is proven to work well and that will be well accepted.

Process Selection

The primary design consideration of a recycling initiative will be the chemical process used to separate the used fuel into its various components. There are numerous methods that have been used in the past and are currently being used around the world. Many are also being researched or modified to determine the best possible method for processing nuclear material. The costs, space requirements, equipment and material needs, safety considerations, and waste production will change depending on what type of process is used. The proliferation resistance of a process can also vary, based on what steps are performed.

To understand recycling methods, it is important to understand the composition of used nuclear fuel. The following graphic represents the average chemical composition of used fuel elements. This material consists mostly of uranium, which exists naturally in the earth's crust and seawater, and releases very low levels of radiation. This uranium has the potential to be recycled and used for creating additional nuclear fuel. The remaining materials are plutonium and other byproducts created during nuclear reactions. Some of this plutonium is useful for fuel; but the rest is of little value. Part of this portion is highly radioactive, and contributes to the hazardous nature of this material. In addition to the hazards these materials present, they also accumulate and eventually prevent the fuel from being used efficiently to produce power. To retrieve the uranium and plutonium for making recycled fuel, they must be separated from the useless components. Processes have been developed to separate this material as a liquid, a solid, or a gas. Each method has advantages and disadvantages. The two discussed in this paper will be liquid and solid methods.



[7]

Figure 1- Typical Used Nuclear Fuel Composition

Liquid/Aqueous Processes

Liquid processes, also called aqueous processes, were the first to be developed and used for both weapons development and commercial power applications. The most widely used process in the past and the present is the PUREX aqueous process, simply meaning plutonium uranium extraction. This process dissolves the used fuel in acid, and uses aqueous (water based) solutions and organic chemicals to extract uranium and plutonium independently. For fuel purposes, plutonium is combined with either extracted or fresh uranium to create MOX fuel. Separated plutonium isotopes may be concentrated as a result of this process, which can be very convenient for weapons production; this increases the risk associated with the theft or diversion of this material. The various chemicals and solvents used to separate the plutonium and uranium form the organic solutions and are recycled in existing commercial reprocessing plants.

Numerous variants of this process have been developed over the years, as well as additional steps to further separate the waste following the PUREX process. One category of

[7] Taken from United States Government Accountability Office report on nuclear fuel cycles, October 2011

http://www.gao.gov/assets/590/585783.pdf alternative aqueous processes focus on preventing independent plutonium extraction. Some processes solely extract uranium, leaving plutonium mixed in with the rest of the waste. This makes the plutonium useless for making nuclear weapons or being used for fuel. Other processes, including modified PUREX processes, extract the uranium and plutonium together; this mixture is also unsuitable for making weapons but allows for convenient fabrication of recycled fuel. Another category of processes are used in tandem with the modified PUREX process to sort the remainder of the waste that is left behind. As mentioned earlier, only a small portion of this remaining waste is highly radioactive. Methods exist to separate that portion of the waste from the rest, greatly reducing the volume of hazardous waste needing to be stored. These are typically separate processes, requiring additional facilities and equipment to perform them. Waste from these processes is in liquid form but the common practice of the industry is to convert this material into a solid. This makes storage more convenient and eliminates the threat that liquid waste poses to the environment.

Two processes being developed in the United States are the TRUSPEAK and ALSEP processes [10]. These are innovative processes to follow a modified PUREX process. The modified PUREX process will co-extract plutonium, uranium, and possibly neptunium (a minor actinide), making this material useless for weapons purposes. This mixture can easily be made into fuel for commercial reactors. The remaining waste will be processed further using the innovative processes. In both of these processes, the radioactive fission products and the minor actinides are separated from the rest of the waste; after additional chemicals are added, the minor actinides and fission products are then separated from each other. The discrete separation of various waste products allows for more efficient sorting and storage of waste, minimizing the amount of highly radioactive material that needs to be stored. The required facilities for this process would include a plant to perform all of the necessary chemistry, and a facility to fabricate fuel from the retrieved uranium-plutonium mixture, such as the Shaw Areva MOX facility under construction in South Carolina. An additional facility will also be needed to solidify any liquid waste in order to reduce its toxicity and volatility for more convenient storage.

Despite the challenges of aqueous processes, they are the only processes used for civilian reprocessing on a commercial scale today. Military applications of this technology are a completely separate topic. Nations that have implemented PUREX or similar processes on industrial levels include France, Britain, Japan, India, and Russia [9]. There has been much improvement and streamlining of these processes over the years in these countries. Innovative aqueous processes use many of the same steps as conventional industrial processes, but make improvements in the following areas: co-extraction plutonium and uranium to eliminate the proliferation threat; separation of all components of waste for more efficient storage by using multiple processes; and reducing the number of steps to as few as achievable, minimizing the need the for additional facilities.

In addition to these factors, the long term benefits of this process depend on the future of nuclear power plants. If new reactor designs continue to utilize oxide fuels, this process would benefit existing reactors and next generation plants.

Solid/Dry Processes

Solid extraction processes, also called dry processes, were developed in the mid 20th century in conjunction with fast nuclear reactor technology. The absence of water and organic chemical solutions in this process is why it is also referred to as a dry process. In the United States, significant research activity with this method accelerated during the EBR-II project started in 1964. This program was implemented to dispose of defense related waste, while prototyping both the solid extraction fuel separation method and the use of this fuel in an advanced experimental reactor. This process was never commercialized, but has been continued to be researched. There are significant differences associated with this process and conventional methods. Designs for reactors similar to the EBR-II are being developed as options for the next generation of nuclear power plants in the US and other countries. If these reactors are commercialized, the use of this process will certainly need to be commercialized as well.

The fuel form used in this experiment was metallic by design, rather than the ceramic oxide fuel used in current reactors. The solid extraction process is also designed specifically for the repeated use of metal fuel. Solid uranium metal is extracted from used fuel in this process, similar to how sugar crystals collect on a stick or a string when making rock candy allowing for convenient fabrication of metal fuel. When the uranium is extracted, plutonium and other byproducts are left in a single mixture leaving a reduced volume of solid waste. This solid waste is an excellent proliferation deterrent. The plutonium, which presents the most proliferation concern, is embedded within a brick of both thermally hot and highly radioactive materials. In addition to being very difficult to separate out of this mixture, the waste is extremely hazardous to handle without proper shielding. Both of these factors diminish the incentive to divert this material.

There are several benefits to this as compared to aqueous processes. The absence of various chemicals significantly reduces the space required for the operation itself and necessary storage afterwards. Other than the uranium, waste bars, and salts (which can be reused several times), there are few additional waste streams that need to be dealt with as compared to the volume of liquid waste in aqueous processes. Liquid wastes are both toxic and radioactive; used salts waste from solid extraction will eventually need to be disposed of and replaced. These salts will be radioactive, requiring protected storage. While still radioactive, theses salts will not need special chemical processing to be safely stored, removing the need for those additional facilities.

The solid extraction method has unique applications. As stated earlier, uranium is separated exclusively, leaving the other components of used fuel mixed together. Uranium is extracted in a metallic form, and could be made into metal fuel types or converted into a ceramic form to make oxide fuel types. This allows for flexible use of this uranium in multiple types of reactors. The remaining components of the used fuel can be stored as solid waste. However, some fast reactor designs are able to incorporate the remaining components into the fuel. This utilizes the fuel potential of the plutonium contained in the waste and further reduces waste volume. Given these applications, there are several ways that solid extraction processes could be implemented for commercial use.

1. Develop and construct a facility for solid extraction of metallic uranium; design and construct fast reactors to use metallic fuel. Recycle uranium, plutonium, and other useful components of used fuel, store reduced volumes of solid waste.
2. Instead of building and using fast reactors, design and utilize a process to convert extracted metal to oxide for use in reactors requiring ceramic fuel. Storage is required for solid extraction waste and waste from metal-oxide conversion.

While much of this technology is still being developed, there is the potential for flexible use of this process. Whether the next generation of nuclear reactors uses metal or oxide fuels, this method could be adapted for either. Additional benefits include reduced amounts of solid waste, and significantly improved resource utilization of fuel.

Summary

For either of the described processes, the following conditions and goals must be met. The aptitude of each process to meet these goals is shown in the following table.

1. Recyclable fuel material should be extracted from used fuel.
2. The separation process must not isolate plutonium isotopes, as this presents a proliferation threat.
3. To minimize costs and to maximize process efficiency, the number of required steps should be minimized to as few as possible.
4. Volume of hazardous waste must be minimized as much as possible to reduce the burden of storage upon government operated repositories.
5. The selected process must be applicable to the design of current and future reactors; the ideal process will depend on the progression of reactor design.
6. The implementation of the process on a commercial scale must be feasible in the long term.

Criteria	Aqueous	Solid
1	Extracts U and Pu	Extracts U, extracts Pu in a mixture
2	U/Pu extracted together, unsuitable for making weapons	Pu extracted in a high temperature radioactive mixture, lethal to handle and unsuitable for making weapons
3	Variable	Variable
4	Used chemicals and fuel remnant exist as liquid waste, requires solidification and storage	Process waste and fuel remnant
5	Ideal for making oxide fuel Oxide fuel currently used and planned to be used in next gen reactor designs	Ideal for making metal fuel Not compatible with current reactors, planned to be used in next gen reactor designs Method exists to convert metal to oxide, but is not preferred
Facility Requirements	Chemical Plant Fabrication Facility Waste Processing Plant	Chemical Plant Fabrication Facility Fast Reactor

Table 1- Process Comparison

The ideal method will balance cost, resource utilization of fuel, and waste production in the most desirable combination for businesses, governments, and the public. For the continued use and advancement of nuclear reactors that utilize oxide fuels, the combination of a modified PUREX and advanced innovative aqueous processes would be a more effective strategy for implementation in the United States. Metallic fuels are not favorable for use in conventional reactors; conversion to an oxide form would be necessary for the fuel to be suitable. If there is a transition in the nuclear industry towards using metallic fuels in new reactor designs, then the dry solid extraction process would be ideal.

Program Management Options

Regardless of which process is better suited for implementation, the establishment, framework, ownership, sponsorship, and execution of the program are more critical than any technical detail of the processes themselves. The form and management of the program will determine its acceptance in the industry, government, and public spheres, which will result in either the success or failure of seeing the initiative through from start to finish. Key considerations for the structure of a recycling initiative will include mission, scale, leadership, funding, oversight, and evaluation. To conduct a thorough analysis of the options for a recycling project, different possibilities for each of the above listed considerations will be described for different phases of this project from beginning to end. These possibilities will be drawn from a review and evaluation of past and present government programs involving nuclear technology.

Mission and Scale

First and foremost, it is necessary to point out that implementing commercial recycling of nuclear fuel would require a change in national policy. The notion of doing so without sufficient proof of safety, economic viability, and endorsement from the industry and the public would not be well received by any administration or any Congress. For any change in national policy concerning a technical matter, a successful proof of concept will make a strong case for the positive impact of widespread application on the nation as a whole. Before experimental technologies are commercialized, a pilot program is often performed to test the technology on a small, contained scale. This allows concerned parties to observe and participate in a new process without having to commit to the risks and uncertainties of implementing unproven technology on a national level; a pilot program also does not recommend a change in national policy, serving only to test a new technology. A pilot program is the ideal method for testing the potential of recycling commercial nuclear fuel in the United States, as there is a large amount of uncertainty in the application of the technology. Economic projections of commercial operations cannot necessarily be evaluated by a pilot program, but starting on a smaller scale does serve as a favorable starting point for commercial scale up.

A pilot program for recycling of nuclear fuel would consist of a plan to design and construct the necessary facilities to perform the selected process of extracting useful material from used nuclear fuel and then creating useful fuel out of that material. During this process, quality and safety must be ensured continuously. The facilities required for either process are as listed earlier in Table 1. Conventional fuel fabrication facilities cannot be used to create mixed oxide fuel without major modifications and license changes, as there are additional safety concerns that need to be addressed when handling recycled uranium and plutonium. Therefore, specifically designed fabrication facilities may be needed for this program if converting existing facilities is not a favorable option. The possibilities for new construction or repurposing of existing facilities will be addressed later on.

As the facilities are being constructed, the choice must be made as to which used nuclear fuel is to be reprocessed and recycled. As mentioned earlier in this report, there is a large and growing inventory of this material amounting to more than 65000 metric tons. Of this, most is stored onsite at operating nuclear power plants. As of 2012, just less than 3000 metric tons was being stored among 9 plants that have been shutdown [1]. These locations have become unofficial temporary storage sites- something that plant owners, government administrations, and local citizens did not initially intend. The presence of this material is also preventing the land of the decommissioned plants from being repurposed by the host companies, as there are limited options for storage at this time. Until the issue of permanent storage is resolved, using used fuel from decommissioned plants for the purposes of the recycling pilot program may be a convenient way to remove the burden of this material and these facilities from their owners. If this fuel is not selected for use in the pilot program, there are many operating plants from which to acquire material for this project.

Regardless of where it is taken from, ownership of the used fuel must be explicitly defined in the wording of this program's charter. At the end of its use for power production, it will become the responsibility of the Department of Energy via the Nuclear Waste Policy Act [2]. Either the lease or ownership of this material must be defined at all times during the fuel cycle. Ownership and responsibility for any waste materials created must also be defined, and agreed upon by all affected parties.

With a source of material identified and the necessary facilities to create recycled fuel established, the use of this fuel must then be determined. For small scale experiments with either new fuel types or new reactor designs, some programs have built experimental test reactors as with the EBR-II. These are research type reactors and are located at national laboratories. As such, they do not typically produce power for the commercial grid, or use fuel compatible with commercial plants. To adapt this model for a pilot program, building a prototype intentionally designed for power production may be a potential option for either a national lab or a private company. Other initiatives, such as the MOX project, have been set up to allow use of fuel in existing commercial plants. As mentioned earlier, there are slight modifications required for reactors to use MOX fuel, but that decision will depend on cooperation between a utility and the leadership of this program. The number of times this fuel will be recycled is another issue that needs to be addressed by the leadership of the program. That will ultimately become and engineering decision balancing cost, radiation or toxic hazard, and usefulness of recycled fuel to determine the value of additional recycles. This determination will be defined by which process is selected.

Ultimately, all of these considerations will factor into the larger decision of choosing the scale of the program. Geography, plant size, and length of operations will need to be agreed upon and written into the governing legislation of the program. Many programs of this type have a defined goal of converting, using, or disposing of a specified volume of material. This determines the length and cost of the program. For example, the Megatons to Megawatts

Program[8] was established to convert 500 metric tons of weapons grade uranium into commercial fuel over a period of twenty years [11]. The mission of the MOX project is to convert at least 34 metric tons of weapons grade plutonium into commercial fuel [12]. Similarly, a recycling pilot program may have in its establishing legislation a defined mission to convert a specified volume or weight of used nuclear fuel into recycled fuel for either commercial use or use in a test reactor or more general goals of a similar nature. This capacity will define how large the facilities need be, and how large of a source of used fuel will be required. Geographic considerations will limit the number of potential sites for construction, narrowing the range of options for the location. Locating the facilities near the sources of used fuel and reactor facilities using the recycled fuel may be a factor in the placement as these locations if it is practical, as this will affect transportation costs. If new facilities are constructed or commercial facilities are used, cooperation with local governments and communities will be another deciding factor in the success of the program once it begins. In brief, the rhetoric of consent based siting as per the Blue Ribbon Commission on America's Nuclear Future serves as a logical guide to the various factors in placing new facilities. These concerns may not be as relevant if all of the work is restricted to existing federal facilities or national laboratories.

Ownership and Funding

Even with an ideal plan of action and a clear mission and purpose, the success of any endeavor will be determined by its leadership. The governing structure of this program must be set up to protect the progress of the initiative through many years and many potential sources of opposition to ensure that it will be completed. In recent years, government programs related to nuclear processes or technology have suffered from a familiar trend. Initially support is widespread and there is optimism for the completion of the program, which usually is projected to take a decade or two. At some point during that time span, a new administration, Congress, or corporate sponsor may decide that the program is not worth the money, is set up poorly, or is not in line with current national policy. Recommendations to revise or delay construction or operation of these projects have resulted in several half finished projects that have either been canceled altogether or delayed indefinitely. The possible causes for this phenomenon are many, but a possible solution is quite clear: ideally, the source of funding would be immune to changes in leadership of the federal government while still ensuring proper oversight by the appropriate federal agencies and congressional committees. This way, the program will be allowed to endure and reach completion regardless of changes in political climate. A successful program will rely

[8] USEC, the United States Enrichment Corporation, was assigned to convert highly enriched weapons grade uranium into lower enriched reactor grade fuel.

heavily on the initial distribution of ownership, financial responsibility, delegation and assignment of tasks, and liability.

With regard to nuclear technology, startup costs for any new project have always been monumental. Prototypes or small scale experimental projects related to nuclear power are mostly sponsored and managed by the federal government, specifically the Office of Nuclear Energy within the Department of Energy (DOE), formerly known as the Atomic Energy Commission(AEC). The AEC was chartered for the purpose of advancing nuclear technology in the United States, and has the resources of the federal government and the technical expertise of the national laboratories at its disposal[9]. For a research project or the implementation of new policy or technology, a federal agency can execute an approved program out of its budget, or an act of Congress may establish the program, charging a federal agency to accomplish a given task out of its budget and possibly with external sources of funding.

However, as the federal budget is finances a multitude of government agencies and programs, there is a limit to how much money the Department of Energy can spend on one project. Discretionary funding to the department must be approved by Congress, and then the actual budget is established during the appropriations process. With the numerous tasks the DOE seeks to accomplish with its budget request, financing high cost initiatives can be difficult to justify. To compensate for this, costs sharing agreements or contractual arrangements are frequently established between the government and private companies. These arrangements can take multiple forms.

The Megatons to Megawatts program for example was an arrangement between the NNSA; USEC, an American company; and TENEX, a Russian company. Under the contract, USEC financed the operational costs of the program, totaling 8 billion dollars [11]. In return, USEC was allowed to sell reactor grade fuel produced from those operations to offset the costs. In the end, the program paid for itself and required virtually no government funding. For a pilot program to recycle nuclear fuel, this mechanism could be applied but would not cover all program costs. USEC had the convenient position of being able to use existing DOE facilities with little modifications. For a recycling pilot, the sale of MOX to utilities could not nearly offset the costs of construction and operational costs. It is likely that not even operational costs will be covered by fuel sales. Either way, additional financing will be required for a program of this type.

[9] When the DOE was formed out of the AEC, additional energy responsibilities were given to the DOE concerning other energy forms and issues.

Independent of construction costs, the final production cost of MOX fuel may cause it to be more expensive than conventional fuel. If it were to be a competitive fuel option for utilities, the price may need to be discounted to encourage its sale. There are several possibilities for such a discount. If a utility contributes used fuel discharged from a plant it owns, MOX created from that fuel could be sold back at an adjusted rate relative to the volume of used fuel contributed. Additionally, costs of plant license modifications required for using MOX fuel could be subsidized or a general government subsidy could be applied to lower the fuel cost. There may also be contracts set up for a utility to burn a specific volume of MOX fuel for a set price.

A proposed initiative very similar to the pilot described in this report is the Global Nuclear Energy Partnership (GNEP)[10]. This initiative was started by the DOE with the objectives of reducing the volume of nuclear waste and reducing the proliferation risk by experimenting with an alternative fuel cycle. The initial proposal of the DOE was to construct engineering (pilot) scale operations funded solely by the government. The objectives were to reprocess used fuel and convert it into a usable form, as well as construction of a fast reactor to use both the waste and recycled fuel to produce electricity. In the initial proposal, all funding was to be provided by the DOE and all operations to be conducted at national laboratories, including the construction and operation of the experimental reactor. The projected cost for this proposal was between 4.2 – 9.7 billion dollars [13]. The criticisms of the initial proposal are that there was no option for cost sharing or cooperation with industry, which would have saved the government money and allowed for a more efficient transition into commercial operation if the department so chose. The leadership of the GNEP program in the United States then changed direction, and decided to engage in a full scale commercial implementation bypassing the experimental phase. This new proposal established cost sharing with several corporate consortia to accomplish the same goals on a larger scale. While this arrangement may have been a good business model, the goals of the proposal were criticized for imposing too much risk with untested technology. This damaged the credibility of the project and discouraged investment and support. If the cost sharing model were applied in conjunction with the pilot scale demonstration, this program could have been much more successful. This program was ultimately cancelled in 2009, and is a good showcase of the various challenges surrounding government sponsored nuclear projects and innovative energy projects in general.

While the goals of the revised GNEP proposal were too far reaching, the cooperative paradigm for the operations has been used in other initiatives such as the Shaw AREVA MOX Project [12]. This program operates on a government owned, commercially operated basis. In

[10] GNEP: A project to implement a closed nuclear fuel cycle by constructing reprocessing facilities and recycling used nuclear fuel.

1999, the corporate consortium now called Shaw AREVA MOX services entered into a contract with the NNSA to construct and operate a MOX fuel fabrication facility. The program so far has been funded out of the congressional budget alone, including no corporate cost sharing. This setup has made the economic certainty a debated topic over the years. Increased cost projections have caused some to question whether or not to continue this initiative. A cost sharing arrangement may have alleviated some of these concerns, but securing an investor for a project of this scale would have been a challenge. The idea of commercial operation however has several potential benefits that are applicable to both the MOX project and a possible recycling initiative. By delegating responsibility to a corporate entity the engineering and project management expertise of such a company is applied to the project. This will not solve all of the problems of completing a project of this type, but it will provide additional experience and perspective to the process to deal with what challenges are faced. In addition to taking the burden of responsibility off of the sponsoring government agency, it allows the industry to gain experience in construction and operation of the new technology. If MOX fabrication or fuel recycling were ever to become commercialized, the industry experience on this smaller scale would serve as an excellent tool for preparation and observation.

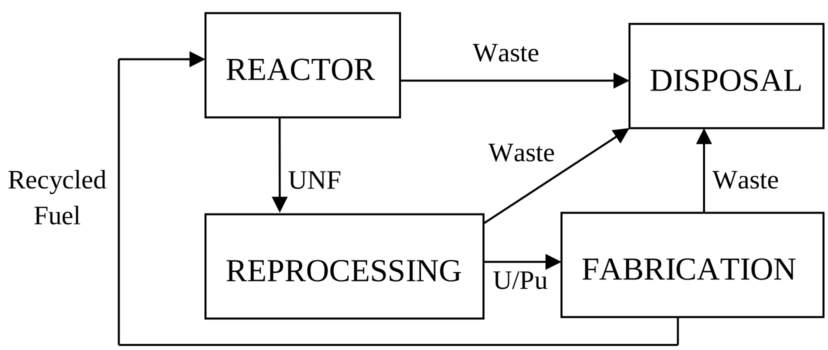
Another facet of the MOX project that relates directly to the idea of a recycling pilot is the fate of the potential fabrication facility upon the successful completion of the contracted program. If everything continues as planned, the facilities will be completed and operations with weapons plutonium will proceed until the specified volume of plutonium prescribed in the project mission is converted to fuel. After the mission is accomplished, it is possible that the operating licenses of the constructed facilities may not have expired, in which case, it is possible that license modifications and, if necessary, plant modifications could be put in place to repurpose these facilities for use in the recycling pilot. The facility of particular interest would be the MOX fabrication facility. This is of course is highly dependent of the future of the MOX project, but must be considered as possible option due to the potential of immense cost savings made by using a preexisting facility. Some costs would be associated with repurposing the facilities, but nothing near the time or financial commitments of new construction.

The final administrative paradigm to consider is that of the Nuclear Waste Policy Act (NWPA). The legislation of this law takes a different approach to management and funding and will relate directly to the operation of a recycling pilot program regardless of how the two are integrated. This act of Congress established a fee to be collected from nuclear waste generators to finance the storage and disposal of used fuel and radioactive waste [2]. This fund was to be used by the DOE to construct and operate storage facilities, to fulfill its obligation to take ownership of this material and dispose of it appropriately as required by the legislation. It was later amended to designate Yucca Mountain as the sole disposal site. This external source of funding was intended to ensure a stable and protected stream of resources, immune to the fluctuations of the budget appropriations process on both congressional and executive levels. Unfortunately various pieces of legislation restricted access to this exclusive fund to budget appropriations, rather than unrestricted access subject to congressional oversight. This funding roadblock and the decision to designate Yucca Mountain as the only site stunted the progress of research and development reducing the enactment of this law to the state of political deadlock that it sits in today.

Regardless, the idea of an assessed fee to corporations has several advantages. To begin with, little to no money would be needed up front, as all expenditures would be financed on loan to the future collection of the assessed fee. This removes the need for co-sponsorship, as funding for future construction and operations would be guaranteed. In this case, a pilot program and any commercial operations decided upon for the future would be funded by this fee. Use of this mechanism would be entirely dependent on the willingness of utilities to use MOX fuel. They should not be forced to use MOX if they do not want to, as there are no environmental or safety concerns compelling them to do so. Nor should utilities and their ratepayers be financially responsible for a fee subsidizing a service that they do not endorse or do not participate in. Only with the cooperation and consensus of utilities and ratepayers can such a measure be justified. If unanimous consent cannot be achieved, exemptions to a portion of the fee or other special conditions may be applied if practical to ensure fair treatment.

These considerations are dependent on first addressing the question of whether a newly assessed fee will suffer the same consequences as the nuclear waste fee established by the NWPA. There has been considerable discussion on this topic, even to the extent of establishing a Blue Ribbon Commission to address the issue. The conclusion of that committee and the general consensus of the current administration and many within Congress is that a new organization must be established and given complete control of managing the waste issue. This entity would take the form of a federal corporation: a commissioned company with leadership appointed by the President and approved by Congress. They would have access to the collected fees (with sufficient oversight) and would have the authority and responsibility to complete the mission of the NWPA. This external body would then be largely insulated from the appropriations process. This is exactly the sort of protection a project of this scope needs to be completed, and would also be an excellent mode of operation for a nuclear recycling initiative. It was discussed during the GNEP whether or not to include the duties of recycling into the use of the Nuclear Waste Fee (NWF) collected by the NWPA legislation. This would most likely result in an increase of the waste fee, and additional responsibilities for the new agency, referred to as a Management and Disposal Organization (MDO). In both the Blue Ribbon Commission's report and statements from the Secretary of Energy, no mention was made of tasking the MDO with the duties of recycling, only those of waste disposal. If such an organization is formed, the establishing legislation could include or be amended to include recycling duties. That will ultimately be a decision made by legislators. For the purposes of this paper it is assumed that such an entity will exist, whether or not they are responsible for recycling. If no such organization exists, than all interaction would be between utilities and whatever leadership structure is assumed for the pilot program.

Some of the uncertainty will be addressed as the independent control of the money will ensure a higher degree of confidence, but the benefit and liability issues concerning those paying the fee will come into question. Combining the responsibilities of recycling and waste management into one administration could potentially result in a more streamlined process. The primary barriers to this would again be justifying the use or possible increase of this fee to perform nuclear recycling, and to use this money for developing technology that is not necessarily endorsed by the entire energy community. If the two groups are not integrated, there will be a triangular relationship between utilities, the recycling organization, and the MDO. The following diagram demonstrates the movement of material from one facility to the other, regardless of ownership. This flowchart will apply to the case of a pilot program or potential commercial operations following a successful pilot and scale up



Discharged fuel from reactors would be transferred to the recycling entity after the fuel is allowed to cool for an adequate time[11]. Transportation logistics for this transfer would also have to be established. Recycled fuel made by this entity would return to the utilities through one or several of the incentive options described earlier for the sale of recycled fuel. Unusable waste and depleted recycled fuel from both utilities and the recycling entity would be given to the MDO for disposal per the MDO's charter. The owner or operator of the recycling facility would most likely finance and operate waste processing facilities, for either liquid wastes produced in

[11] Discharged used fuel is placed in pools of water to allow for thermal cooling and to wait for the radioactivity of the fuel to decrease over time

an aqueous process or solid waste from a dry/electrochemical process. An integrated recycling plant housing both the separation and waste processing cycles will be the most efficient. Final disposal of all waste will be the responsibility of the MDO, and extracted fuel material would be transferred to the fabrication facilities For pilot scale operations, only the host utility will interact in this way; for commercial application, multiple reprocessing facilities would theoretically need to exist to interact with all utilities. Another consideration for the movement of materials is volume and capacity. A reprocessing plant will have a limited capacity, perhaps too limited to deal with the volume of used fuel from utilities. For commercial application, the amounts each plant would have the ability to contribute at one time would be dependent on that capacity. Rationing the amount of used fuel that could be given away by each plant would most likely need to be negotiated, unless each utility had its own exclusive plant. Priority may also be given depending on the age and condition of suitable used fuel at a given location. This would depend on the structure of the commercial network, and would not affect pilot operations.

Oversight

For any management structure, unbiased third party regulation and oversight must be in place to ensure the safe and legal operation of any program. This is why Atomic Energy Commission was split into the Energy Research and Development Agency(ERDA)[12], and the Nuclear Regulatory Commission (NRC) in 1974 [4]. Since then the NRC has continued to enforce and create regulations for commercial facilities and has overseen a few DOE funded projects. The duties of the NRC are to protect the public and the environment from harm due to radiation exposure within the parameters of the *Code of Federal Regulations*, as well as monitoring occupational radiation exposure. This purpose remains the same whether regulating government or commercial projects. To achieve this, designs, proposals, processes, licenses, and other items related to the program must be evaluated and approved to meet the required standards to achieve the above stated mission. As stated earlier in this paper existing regulations are not designed to efficiently govern reprocessing facilities. The necessary regulations for licensing and operating these facilities are strewn across several other regulatory codes regarding different facilities and processes. The proposed regulatory framework to consolidate these regulations, Part 7x, is still subject to the rulemaking proceedings required for proposed regulations to become official NRC regulations. This is a lengthy process of public comment and revisions of the proposed rules culminating in the approval and adoption of the final rules into the *Code of Federal Regulations.* For the duration of a pilot program, the NRC could either conduct the rulemaking proceedings for Part 7x prior to pilot operations or apply existing

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[12] The ERDA was later combined with the Federal Energy Administration to form the Department of Energy in 1977

regulations to the program while conducting the rulemaking. Whichever form this takes depends on the available time and resources of the NRC, and willingness by all affected parties to partake in the rulemaking.

Depending on the administrative structure, Congress and the Executive Branch (via the Secretary of Energy) will also have some degree of oversight of a potential program. If the program is housed within the DOE, the government portion of funding and spending will be subject to federal monitoring and approval. If delegated to an external body (a federal corporation) the President will appoint the leadership with Congressional approval per the charter of that organization. As a result, the elected officials of this nation will always have some influence on the progression of the pilot program. The ultimate decision to scale up the pilot to a commercial scale will most likely be a decision made by Congress, by either writing new legislation establishing a federal corporation, amending the charter of any existing MDO, or at least by agreeing on a change in national policy to reprocess and recycle nuclear fuel commercially. Alternatively, if the DOE or the MDO is responsible for this decision their final say may be subject to approval by either Congress or the President. In any circumstance the federal government will have some degree of decision making power over the fate of this initiative, regardless of what form it takes.

Policy Recommendation

Considering the advantages, disadvantages, challenges, and concerns related to the options for both recycling nuclear fuel and implementing government programs, the following are the recommendations of the author for the content and structure of a nuclear recycling program. These recommendations will achieve the previously mentioned goals of reducing the existing and future volumes of used fuel requiring storage and reducing the need for naturally mined uranium while removing the proliferation threat from nuclear recycling processes.

1. Use dry extraction processes to recycle large portion of used fuel in tandem with an innovative reactor design, allowing for greater resource utilization and greater reduction of waste than achievable with aqueous processes
2. Establish pilot program to perform small scale operations, regulated by the Nuclear Regulatory Commission.
3. Fund construction and operations through cost shared government and industry funding through Congressional budget appropriations
4. Establish contracts with industry for construction and operations of required facilities
5. Utilize isolated fuel from decommissioned power plants for initial operations

6. Establish contractual agreements or adjusted sale prices to incentivize use of recycled fuel in commercial reactors
7. Upon completion of pilot phase, proceed with widespread commercial implementation if technology is proven to be effective
8. Transfer commercial nuclear recycling responsibilities to an already established Management and Disposal Organization to centralize all back end fuel cycle duties into one administration[13].

For any chemical process, the policy structure of the program should take into consideration the successes and failures of past programs, reduce costs by utilizing existing facilities, and also address the needs of the industry and the nation as a whole. Initially a government sponsored pilot program should be established to implement the selected process; augmented by corporate cost sharing and contractual construction and operation. This program should also be regulated by the NRC for its entire duration. The reasoning for a pilot program has been explained, and the recommended level of corporate involvement will ensure a more efficient and interactive process that is insulated to some degree from unexpected cost increases. This will depend on what form the contract takes. For the construction phase, existing facilities that are available and applicable to the selected process should be utilized. Siting of the required construction should be considerate of existing facilities and of the 'consent based siting' rhetoric to ensure the most beneficial and effective setup possible. This will increase local support and reduce project costs, while make good use of past investments.

The recycling operation itself should prioritize the use of stranded used fuel from decommissioned power plants if available. This material is a financial burden and liability to those that possess it, and has been deemed to be the first priority of other initiatives relating to used fuel management. For the use of any recycled fuel, incentives should be established to encourage and promote its sale to utilities, such as those mentioned earlier. If a fast reactor is constructed for this program, the plant should contribute electricity to the commercial grid to serve as an economic benefit to the host region. Waste produced during the pilot phase will be given over to whichever Management and Disposal Organization exists at the time.

Upon the completion of a successful pilot program, the Department of Energy, Congress, and the President will decide if the results of the pilot program justify commercial application of this technology. At the point that it is commercialized, the duties of recycling should be tasked to a federal corporation. This entity would likely own the facilities, but may contract out operational duties. These responsibilities could justifiably be tasked to the same organization

[13] The back end of the fuel cycle refers to all processes following power production in a reactor, including recycling, storage, and waste disposal.

responsible for management and disposal of fuel. All back end fuel cycle operations being consolidated into the operations of a single group would be both efficient and streamlined, funded by a single fee charged to utilities (that being the nuclear waste fee established by the NWPA). This move could not be forced upon the industry, but rather should only be done with industry consent, approval, and cooperation. If the assimilation of recycling duties into the MDO is not approved, then the duties should be tasked to either a separate federal corporation or private industry for selective regional use of a modified fuel cycle. For a separate entity managing the recycling duties regular federal budget appropriations would most likely be required to support the initiative, at least initially. In any of these three cases, the incentives for the sale recycled fuel should be applied.

A multiphase project, or the pilot phase alone, will serve to address the pressing need of nuclear waste management by reducing the future burden on permanent and interim storage facilities. The environmental impact of nuclear energy will be reduced in two ways, both from the reduced need for highly radioactive waste storage and from the decreased use of fresh nuclear fuel as a result of using recycled fuel. The latter decrease will move up the line all the way to the mining of natural uranium ore, reducing the impact of the nuclear fuel cycle on our planet. The impact on waste storage requirements and the greater resource utilization made available to the nuclear power industry by recycling, and the dual purpose achieved by utilizing solid extraction and a fast reactor, will insure the long term viability of this technology as a clean, sustainable power source to meet the energy needs of this country.

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Appendix A: Terms and Acronyms

Actinides
In the periodic table, elements 89-103 are referred to as Actinides. Elements present in nuclear reactions and used nuclear fuel are in this group. The term minor actinides refers to actinides in used fuel that are not uranium or plutonium.

AEC
Atomic Energy Commission: predecessor to ERDA and DOE

ALSEP
Acronym for Actinide Lanthanide Separations Process, a chemical process performed on waste from the PUREX process

DOE
Department of Energy

ERDA
Energy Research and Development Administration

Fuel Assembly
A structured array of nuclear fuel elements; numerous fuel assemblies form the core of a nuclear reactor

Fuel Cladding
A sealed metal tube containing numerous fuel pellets, used to form fuel assemblies

Fuel Cycle
The various steps in the acquisition, creation, use, and disposal of nuclear fuel

1. Open Fuel Cycle: Uranium is mined, processed, and made into fuel, used in a reactor until no longer suitable for power production, and then removed for storage and disposal. Currently used commercially in USA and Canada.
2. Modified Open Fuel Cycle: After use in a reactor a portion of used fuel is recycled for additional use, reactors are fueled by a combination or fresh and recycled fuel. Currently used commercially in France and Britain.
3. Closed Fuel Cycle: All components of fuel will be recycled and reused until all useful fuel material has been consumed, maximizing resource utilization and eliminating large majority of radioactive waste. Not currently used commercially

GNEP
Global Nuclear Energy Partnership: mission to implement closed nuclear fuel cycles and fast reactor technologies

Isotopes
Atoms of the same element having the same number of protons and electrons, but a different number of neutrons

Neutronics
The study of subatomic particle interactions in the atomic nucleus; nuclear fission, neutron absorption, and radioactive decay are areas of this study.

NRC
Nuclear Regulatory Commission

NWPA
Nuclear Waste Policy Act

NWF
Nuclear Waste Fee, established by NWPA

PUREX
Acronym for Plutonium Uranium Extraction, the first chemical separation method used for commercial reprocessing of nuclear fuel

Plutonium Grades[14]

Grades of plutonium are defined by the concentration of different isotopes in a sample of plutonium, specifically the isotopes Pu-239 and Pu-240. Pu-239 is desirable for fuel and weapons; its radiation levels are relatively easy to shield and contain. Pu-240 interferes with weapons production, and emits high levels of heat and hazardous radiation. When uranium is used in a reactor, both isotopes are created, but longer exposure creates additional Pu-240, decreasing the value of the plutonium for weapons. The two defined grades are reactor grade and weapons grade [14].

Plutonium Grade	Composition	Exposure Time	Origin
Weapons Grade	Less than 8% Pu-240	3 months	Military production reactors
Reactor Grade	55-70% Pu-239, greater than 19% Pu-240	12-18 months (typical reactor cycle)	Commercial power reactors

Spent Nuclear Fuel (SNF)

This term can be used interchangeably with the term used nuclear fuel, and is the official terminology in most documentation and legislation for fuel that has been used in a reactor.

TRUSPEAK

Acronym for Transuranic Separation by Phosphorus Reagent Extraction from Aqueous Complexes, similar process to ALSEP (transuranic refers to minor actinides)

Appendix B: Reactor Types and the Proliferation Threat

There are two broad categories of nuclear reactors, referred to as fast and thermal. This is based on the energy of neutrons used to cause fission, and the number of neutrons produced as a result of fission. The nuclear reactions in either of these systems produce plutonium, which can potentially be used to create of nuclear weapons.

Fast Reactor

A fast reactor uses fast neutrons; this essentially means that the neutrons possess high amounts of kinetic energy and are therefore moving very fast. This will change the type and frequency of

[14] Information and table adapted from World Nuclear Association article on Plutonium.

nuclear reactions likely to occur during operations, which is why fast reactors have different capabilities than thermal reactors. Fission caused by high energy neutrons will increase the number of neutrons produced by each fissioned atom. The higher energy neutrons will cause additional chain reactions at a higher energy, resulting in an abundance of neutrons. Often, fast reactor cores are designed to use the excess high energy neutrons for one of two purposes. A breeder type fast reactor would surround the core with a layer of U-238; this uranium would absorb the excess neutrons and Pu-239. In this way, plutonium fuel is ‘bred’ out of natural uranium. If a reactor creates/breeds more fuel than it consumes it is called a breeder reactor. Conversely, burner type fast reactors consume more fuel than they create. In a burner, minor actinides are placed in a layer around the core rather than natural uranium. The excess neutrons will cause fission in the actinides, splitting these atoms into less harmful byproducts. Burners are specifically designed to consume minor actinides and other undesirable isotopes. General examples of fast reactors are the EBR-I and EBR-II experimental breeder reactors.

Thermal Reactor

In thermal reactors, the energy of the neutrons produced in fission is reduced by what is called a moderating material. There are also a decreased number of neutrons produced in lower energy, or ‘thermal’, fission of fuel material. The reduced energy and number of neutrons is designed mainly for causing fission in fuel material. Some plutonium breeding or fission of minor actinides occurs, but is not the primary purpose in most thermal reactor designs. Design of these reactors is convenient from an engineering perspective as ordinary water can be used as both a coolant and a moderator. This contributed to the widespread use of water cooled thermal nuclear reactors. Examples of thermal reactors are commercial boiling water reactors (BWR) and pressurized water reactors (PWR), as well as reactors in submarines and aircraft carriers which are of the PWR type.

The Proliferation Threat

The term proliferation when applied to nuclear reactor material refers to highly enriched uranium or plutonium is lost or stolen, and then used to create nuclear weapons. While reactor grade plutonium is hazardous to handle and far from ideal when making weapons, the argument is that since it can be used to make nuclear weapons it should not be allowed to exist. Regardless of any amount of security tracking and monitoring, the threat is still present and is a criticism of the conventional PUREX process. Whether or not the threat is significant is a matter of opinion, but either way the elimination of this threat entirely is an international effort. Part of this is removing even the slightest possibility of plutonium loss from the commercial nuclear fuel cycle, whether it is open or closed.