CLOSING THE NUCLEAR FUEL CYCLE

POLICY RECOMMENDATIONS TO PREPARE FOR NUCLEAR FUEL RECYCLING

By Abbey Hageman

Summary

The United States is one of the most wasteful countries in the world. In the case nuclear energy, this is depicted by how little fuel is used before packaged for disposal. Most of the potential energy contained in a nuclear fuel pellet for commercial energy purposes is left untapped. This not only wastes resources but also creates a higher volume of high level waste, a difficult material to store. Once inserted and used in a power reactor, the fuel pellet must undergo chemical separation before it is in a form that can be refabricated into a new fuel pellet and reused in a reactor. These technologies exist, and some have been used on a commercial scale. Politics and lack of sufficient existing regulations hold the US back in this area, as do public perceptions of nuclear power in general.

In the past, several commercial chemical separations facilities have made their way into existence. While some failed earlier, none of them were able to survive past the 1977 policy change made by President Carter. Since the removal of President Carter's ban, no new facilities have been constructed because of the lack of positive economic conditions. Primarily, it is less expensive to mine, mill, and enrich uranium for fuel fabrication than to pay for chemical separation and recycle used nuclear fuel.

As we progress toward the deployment of advanced nuclear power reactors, the possibility of nuclear recycling making a breakthrough to the commercial nuclear market is once again presented. If an attempt were made today, it would fail because of several factors, including public perception, policy, and lack of regulation.

The views, fears, and ideals of the average citizen are powerful when used to form an actionable basis. Yucca Mountain is a prime example of this, where the public disagreed with the decision to create a deep geologic repository. This policy was originally implemented in 1982, amended in 1987, and stalled shortly after. Public pushback led to the defunding of the Yucca Mountain project and will lead to the failure of nuclear recycling facilities if nothing is done to sway their views.

The policy limiting the characterization, construction, and operation of repository, interim, and disposal sites must be amended to allow the advancement of nuclear waste storage and disposal options. Progress must be made in the area of radioactive waste management regardless of a change to regularly use recycled fuel materials or continuation of the open fuel cycle.

While basic regulations exist and can be used to license a chemical separations facility and recycling process, there are important gaps so far unaddressed that indicate existing regulations are not enough. Until these gaps are filled in or new regulations written specifically for this case, most of the nuclear industry is not willing to expend the extra time to "write around" the gaps in regulation. The risk of constructing a facility or pilot plant before regulations are fully written is not risks members of the nuclear industry are willing to take.

To solve these issues, I recommend the design and implementation of education programs for the general public, amendment or repeal of the policy limiting movement forward in waste disposal, and completion of regulations for chemical separations and recycling facilities.

Foreword

About the Author

Abbey Hageman is a rising senior at the University of Nevada in Reno pursuing a bachelor's degree in Materials Science and Engineering with an emphasis on Nuclear Materials. She works as an undergraduate researcher and will begin the UNR accelerated master's program in Fall 2023. Abbey has been an active member of her ANS student chapter's leadership group and is currently on the national organization's Student Sections Committee. She is also an active member of the Phi Sigma Rho Sorority and several other clubs on campus.

About the WISE Program

The Washington Internship for Students of Engineering (WISE) program began in 1980 through a collaboration of several professional engineering societies. It has become one of the premier Washington internship programs, and prepares engineering students for their future as leaders by exposing them to legislative and regulatory policymaking. Four professional organizations: the American Nuclear Society, the American Institute of Chemical Engineers, the Institute of Electrical and Electronics Engineers, and the American Society for Testing and Materials each sponsor two students. The eight students spend nine weeks researching federal laws and regulations to determine a public policy solution to a topic of their choice. Each solution is presented in a paper written by and presentation given by each student at the end of the nine-week period. For more information about the WISE program, visit www.wise-intern.org.

About ANS

The American Nuclear Society is an organization for those who embrace nuclear sciences and technologies for their contributions to improving the lives of people and preserving our planet. The mission of ANS is to advance, foster, and spur the development and application of nuclear science, engineering, and technology to benefit society. The organization's vision is to see nuclear technology embraced by the public of the United States of America for its vital contributions to improving life and preserving the planet.

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Introduction

In 2022, nuclear energy generated 18% of the electricity in the United States. Twenty-two percent came from renewable energy sources, and the other 60% was generated by fossil fuels. Despite the country being home to 93 nuclear power reactors, most citizens of the country have no understanding of the technology they live nearby. Media depictions of violence, fatal accidents, and proliferation make up the basis of their knowledge. Much of the population does not recognize nuclear energy as a clean, carbon-free source, and as arguments progress for turning to solar and wind power to phase out fossil fuels, nuclear is getting left behind.

Media representation of nuclear operations is usually misleading and negative. It is also the major source of information for the American public in regard to nuclear processes. There have been several major commercial nuclear power plant accidents since the beginning of nuclear power technology, all widely publicized. These incidents have influenced media to show nuclear in a negative light, typically as an unstable and terrifying process that only the smartest minds of our time have a chance at understanding.

With trepidation from these portrayals of nuclear, it is understandable that most citizens want nothing to do with nuclear operations of any kind. Fear is not the only contribution to some communities' avoidance of nuclear power, past actions of the United States government have also negatively impacted willingness to host nuclear sites. In the past, the United States government has used the "decide, inform, defend" strategy. Instead of keeping local governments informed about ongoing operations, the government simply makes decisions and acts. When it becomes necessary, they inform the local governments and residents of what they are doing, then defend their actions.

A 10-gram nuclear fuel pellet generates around 2500 kilowatt-hours electric energy after going through a nuclear power reactor, after which used fuel assemblies are stored in wet storage for around 5 years. The assemblies are then moved from the pool to on-site dry cask storage. This means used nuclear fuel (UNF) has been accumulating around the country at temporary storage sites. It is estimated that (in the US) one in three people live within 50 miles of a nuclear waste storage site. A geologic repository is the intended home for UNF but has not been approved or constructed. This means the casks of used fuel sit above ground at nuclear power sites, left to be taken care of by the private party or utility that owns the reactor in which the fuel was used[1].

Long-term storage is not the only option for UNF. A once through cycle – where fuel is used only once in a reactor before being placed in long-term storage - uses only a small piece of the power contained in a Uranium fuel pellet. Recycling, while more complicated in some ways and currently economically unfavorable, is another option. In the field of nuclear power, recycling is the operation of recovering uranium and plutonium isotopes from the used fuel for reuse in a nuclear power reactor. The rest of the fission products, transuranics, and other materials

[1]While this is typically the case, title of the UNF can be transferred. One such example would be a company assuming ownership of the site after reactors are permanently shut down for decommissioning.

(cladding, contaminated material, etc) become high and low level wastes that are to be disposed of as directed by existing policy (Nuclear Waste Policy Act at this point in time). In some cases, the fission products and transuranics may be reintroduced into a reactor environment to be bombarded with neutrons and further decay until they become more stable isotopes and shorter half-lives, decreasing the required end-of-life storage by many years. There are two main categories of reprocessing: Single-pass reprocessing, where the spent fuel is reprocessed only once to extract materials, and multirecycling, where the products are reprocessed multiple times and reused for as long as possible, then stored as waste.

The failure of the United States to operate a nuclear waste plan is seen by its nuclear community as a policy issue. The lack of movement towards a long term waste storage facility is not because of a deliberate strategy or response to current events, but lack thereof. The technology is developed and understood but lack of actionable policy holds siting and construction back. This issue is not limited to storage but encompasses all nuclear fuel end-of-life pathways. Present day recycling technology is directly descended from that used in 1940s. It has come close to entering the civil nuclear market on more than one occasion but was stalled by changes to federal policy before the market was able to stabilize. As the world looks toward the upcoming construction and rollout of the next generation of reactors, recycling fuel may have another opportunity to break through to the commercial market in the Unites States. If it is to succeed, policy must support it.

Background

Can Recycling Win Out?

Based on a country's bond with, trust, and say in their government their view on the back end of the nuclear cycle can vary widely. In France, the policy changes to fit the people. This means in any given situation, if the general population wants something to happen then the policy makers will change the law to make it so. In the case of nuclear waste, the public recognized a possible future necessity. France is one of few countries to have sustained reprocessing capabilities, largely because of how their government appeals to its people. The reprocessing structure in France blossomed out of the oil embargo of 1973. With oil becoming too expensive to sustain, the French government turned to nuclear power. The country substantially shifted its energy strategy to use a robust nuclear program and recognized their reliance on imported uranium. To avoid this becoming a future issue, they also began research to close the fuel cycle. By allowing French citizens to stay openly informed on the situation and decide on a course to take, the country was able to avoid issues of citizen's will vs government decision. Other notable countries with positive public-to-nuclear relationships are Finland, Sweden, Canada, and the Netherlands. While not all of these countries engage in reprocessing their fuel, they all agree that the spent nuclear fuel must be stored in a deep geologic repository after permanent removal from reactor.

United States Structure

There are several government organizations that share the responsibilities of governing and regulating research and commercial nuclear operation in the United States. The nuclear agencies have changed and developed several times since the inception of nuclear technologies. In 1946 the Atomic Energy Commission was established to oversee both the weapons and energy factions of nuclear. The AEC has since been abolished and its duties taken over by the newly formed Nuclear Regulatory Commission (NRC) (1975) and the Department of Energy (DOE) (1977). The NRC is responsible for regulating and licensing civilian use of nuclear materials, including the construction and operation of nuclear facilities, production, handling, and use of nuclear materials including medical radioisotopes, fuel waste, and irradiated gems (until they are no longer radioactive). The DOE is in charge of nuclear weapons and energy research and development, some of which may impact commercial nuclear energy development. The Nuclear Waste Technical Review Board was created to evaluate the technical and scientific validity of DOE actions relating to the implementation of the Nuclear Waste Policy Act. The NWTRB allows US citizens to comprehend not only what actions the DOE is taking in this area, but also the recommendations and thoughts of specialists on those actions. The National Nuclear Security Administration, established in 2000, is in charge of managing and securing the United States nuclear weapon stockpile, safeguarding nuclear materials, and supporting nonproliferation efforts.

The Making of Nuclear Waste Policy

When the topic of what to do with the waste products left after nuclear power generation was explored, the Nuclear Waste Policy Act was created and enacted. In 1982, the act stated that a deep geologic repository (DGR) should be used to dispose of radioactive waste. It established evaluation and selection procedures for repositories in the USA and interaction guidelines for the state and federal governments on the topic. The act also constructed the requirement that utilities using nuclear reactors pay (per MWe) into a "Nuclear Waste Fund" (NWF), which is to be used for the creation and operation of the repository, and in return the DOE agreed to take title of and responsibility for the utilities' UNF. The article also designated that the DOE would be responsible for the siting, building, and operation of the repository and stated the Nuclear Regulatory Commission would be the licensing body for the DOE and would only administer the license if the Environmental Protection Agency standards and all other relevant requirements were met. The NWPA was amended in 1987, and designated Yucca Mountain in Nevada as the DGR site. It also prohibited the DOE from conducting any activity or characterization at a second site unless authorized by Congress. The NWTRB was also established at this time with a mission to review the technical and scientific validity of activities relating to nuclear waste site characterization activities and those relating to packaging and transportation of high-level waste and UNF. The amendment of 1987's designation of Yucca Mountain unfortunately raised many concerns and a large pushback from the state of Nevada, eventually resulting in the defunding and license withdrawal of the Yucca Mountain development. Because of this around 88,000 metric tons (Waste piling up) of used nuclear fuel sits in spent fuel pools and dry cask storage across the country at 77 reactor and interim storage facilities operating in 35 states.

The Useful Portions of UNF

The reactions of a nuclear power reactor are possible due to more than one isotope and element. Both fissile – capable of undergoing a fission reaction, and fertile – must first be irradiated before becoming fissile- isotopes are contained in nuclear power fuel. ^{235}U is the isotope most often used to kick off the fission reactions as it is a fissile isotope, but transmutation of fertile isotopes such as ^{238}U are also important in the process. The incorporation of ^{238}U specifically with ^{235}U leads to the production of ^{239}Pu, which is fissile. Since ^{238}U is abundant in nature, it plays a significant role in nuclear power production in this way.

Types of Chemical Separation Processes

The two main types of chemical separations processes for nuclear waste recycling under research and in use today are aqueous-based and electrochemical refining. Aqueous based chemical separations processes include the PUREX process and its derivatives. In these processes, the used fuel assemblies are chopped and separated using aqueous solutions as the name implies. This technology is well understood but has the negative of the end waste being in liquid form. It is possible to separate specific elements out using this process without much difficulty, so proliferation is a concern with some of these processes. Non-aqueous processes are under development but have not yet been implemented on a commercial scale. In these processes, electrochemical technology is employed. It does not create large amounts of liquid waste and minor actinides are recovered along with uranium and plutonium (so proliferation is not as large of a concern) but has not been tested on a commercial scale.

Chemical Separation Facilities

Hanford Site

The Hanford reactor and chemical separation site was created in 1942 as part of the Manhattan Project. The original mission of the facility was to construct several nuclear reactors, fuel management facilities, and chemical separation facilities to produce sufficient amounts of plutonium for US defense weapons. The Plutonium-Uranium Reduction Extraction (PUREX) process was used at this facility.

West Valley Demonstration Project

The AEC granted the first commercial reprocessing permit to Nuclear Fuel Services in 1966, and the West Valley reprocessing plant was opened. The PUREX process was implemented at West Valley to reprocess 330 t of fuel from defense weapons and civilian energy programs per year. The West Valley plant only operated until 1972, when stricter regulations were implemented and led to the necessity for modifications to the plant. The modifications were extensive enough to deem the plant uneconomic and Nuclear Fuel Services made the decision to shut the plant down.

EBR II

The "Experimental Breeder Reactor II" (EBR II) was an AEC sponsored project at Argonne National Laboratory West[2]. The facility recycled irradiated fuel by "melt-refining". The next year, the AEC was given the authorization to issue licenses for commercial reprocessing. In 1969, the reactor moved on from chemical separations and recycling to test integral fast reactor concepts.

Morris Facility

General Electric Company was the next entity to gain the AEC's authorization and construct a reprocessing facility. Construction on the Morris facility began in 1967. The plant was to use a UF_6 volatility process that was proven to work well at a pilot plant but failed to succeed on a commercial level. Due to this, construction on the facility was halted and GE did not pursue a reprocessing operating license, instead applying for and receiving one to store spent fuel in 1972.

Barnwell Facility

Construction of a new reprocessing facility in Barnwell, South Carolina began in. The plant, planned to process 1500 tons of used fuel/ year, was paused in 1976 due to President Ford's halt on reprocessing of plutonium and aborted in 1977.

Timeline of Events Relating to Policy of UNR recycling

1954 the Atomic Energy Act relaxed restrictions on private companies, allowing them the use of fissionable material after being licensed by the AEC. Shortly after (1956) the AEC launched a program to encourage private industry to invest in and begin recycling spent nuclear fuel.

1969 AEC began work on creating policy for the siting process to build a recycling plant.

1976-1980 The last license application for a recycling facility in the US before this policy change was Exxon, whose application received no final action. President Carter implemented a ban on reprocessing in 1977, after which the NRC terminated any proceedings and licenses for Mixed Oxide Fuel[3] and other plutonium reuse processes with a statement that the decision would be reexamined after two studies of alternative fuel cycles were completed.

Nuclear Nonproliferation Act amended Atomic Energy Act to establish export licensing to govern peaceful nuclear exports by the US. This included the requirement of prior US approval and consent must be given for any re-transfer and chemical separations. President Carter also signed the US to cooperate with the European Atomic Energy Community (EURATOM), though the agreement was not consistent with the requirement of prior approval from the US for recycling. This agreement was extended through 1995 and has since been replaced by a new agreement.

1981-82 President Reagan took office and lifted the ban on commercial nuclear recycling. Allied deemed recycling as commercially impractical and stuck with their earlier cancellation of the

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[2] Now part of Idaho National Lab.
[3] Mixed Oxide, or MOX, fuel is reactor fuel composed of both fissile elements ^{235}U and ^{239}Pu.

Barnwell facility. President Reagan approved a directive pertaining to nonproliferation and statutory conditions for safeguards and security for continued commitment by Japan to stand with nonproliferation efforts.

1992 The Long Island Power Authority attempts to enter into a contract with Cogema[4], a French recycling company, to recycle the core from the Shoreham reactor (decommissioned). Contract was voided due to proliferation and national security concerns. President Bush halts weapons reprocessing in a policy statement that also defines principles to follow with the intent of guiding nonproliferation efforts. The Hanford site permanently closes.

1993 President Clinton states that the USA will maintain commitments to Western Europe and Japan to use plutonium in civil nuclear programs but does not encourage civil plutonium use and will not engage in plutonium separation and use itself for either weapons or power purposes.

1995 The updated EURATOM cooperation agreement is submitted to Congress, and entered into effect without a vote despite some disagreements on if all requirements of 123a if the Atomic Energy Act were met.

2001 President Bush's Energy Policy recommends that the US should consider development of recycling and fuel treatment technologies, in collaboration with international partners, to create cleaner, more efficient, proliferation-resistant, and less waste intensive energy processes.

2006 The DOE creates the Advanced Fuel Cycle Initiative (AFCI), which is given the responsibility of carrying out the DOE's long-term direction of recycling spent nuclear fuel. Through this initiative, the DOE announced work initiation toward a Uranium Reduction Extraction (UREX+) demonstration and development of a laboratory facility to research advanced separation and fuel manufacture technologies. Extra focus was to be given to the development of proliferation resistant nuclear technologies. Proliferation resistant projects were to be developed in association with the Global Nuclear Energy Partnership. Domestic and international expression of interest in construction of a SNF recycle and transmutation facility was requested for project continuation.

2007 AREVA, EnergySolutions, GE-Hitachi Nuclear Americas, and General Atomics were selected to receive $16 million for technical and support studies to reach the AFCI's goal. In August, the US offers $20 million in return for detailed siting studies for public or commercial organizations interested in hosting GNEP facilities. GNEP grows from China, France, Japan, Russia, and USA to include Australia, Bulgaria, Canada, Ghana, Hungary, Italy, Jordan, Kazakhstan, Lithuania, Poland, Romania, Senegal, Slovenia, South Korea, and Ukraine.

[4] Later incorporated into AREVA, which is presently part of ORANO.

U.S. national Research Council releases their finding that there is no economic justification for developing nuclear recycling facilities prior to finalization of the technology. They report that pursuing the program will require more DOE investments.

2009 Environmental review (groundwork for developing commercial recycling facilities) ended by President Obama. Yucca Mountain site closed and defunded by DOE until NRC decision is made public. GNEP program is cancelled, citing proliferation concerns. DOE continues research in reprocessing, with industry remaining "generally interested" in domestic recycling. 10 CFR part 70 gap analysis conducted by the NRC. 14 high priority gaps were identified (5 medium priority).

2010 The Blue Ribbon Commission released its report, which details recommendations for implementing policy changes that will lead to the opening of a spent fuel facility and progression in advanced fuel cycle technologies (including recycling).

2011 Gaps identified in 2009 analysis of 10 CFR Part 70 are addressed, with new parts for reprocessing and technology neutral rule addressing large facilities (1000+ MT SNF annual throughput). See 2013 and 2016 for outcome of this effort.

2013 Gap 5 (Safety and Risk assessment Methodologies and Considerations for a Reprocessing Facility) chosen for first recycling specific rule development. Regulatory basis completed for Gap 5. DOE announces they will follow a new strategy focusing on the development of a storage facility and research into advanced fuel cycle technologies (Versatile Test Reactor program).

2016 Lack of industry interest in recycling along with budget constraints lead to suspension of work on reprocessing regulations in the NRC.

2017 NRC licenses the first centralized interim storage facility for SNF in the US, proposed by Holtec International.

2018 DOE releases the Nuclear Energy Innovation Capabilities Act (NEICA) report, which outlines a long-term strategy for nuclear energy research and development emphasizing the need for advanced fuel cycles and innovative waste management approaches.

2020 NRC holds public meeting to receive input from stakeholders on their interests in construction, operation, and licensing of recycling facilities in the foreseeable future. Some organizations (including NEI and ANS) indicated support of continuing to lay regulatory groundwork but did not indicate plans to submit a facility application for licensing within two decades. Other stakeholders expressed concern for proliferation and expressed their desire to discontinue regulations for recycling. U.S. Congress passes NEIMA, streamlining the regulatory process for advanced nuclear technologies.

Commented [ah1]: Was NEI in favor of or against? Dr.Bader made it sound like they were opposed

2021 NRC announces its intention to discontinue rulemaking based on limited interest and the expectation of no potential applications in the foreseeable future. They declared the rule to not currently be a justifiable cost. President Biden implements the Advanced Nuclear Energy Working Group, which aims to improve nuclear power innovations including fuel cycle and waste management areas.

2023 Several companies (including Oklo and Curio) discuss executing commercial recycling processes for advanced reactor designs and fuel production. The National Academies of Science, Engineering, and Medicine release an article containing their findings and recommendations for moving forward in the field of nuclear waste and reactor technologies.

Key Findings

Reprocessing Intro

Many other nuclear capable countries have researched how to close the nuclear fuel cycle. While several reprocessing techniques have been discovered, the only existing commercial reprocessing company is France's Orano. Reprocessing is possible because the once-through cycle, where the fuel is used in one reactor term before being placed in storage, uses very little of the energy stored in a uranium fuel pellet. This not only allows potential energy to sit in storage, but also takes up a higher volume than reprocessed waste, as around 96% is reclaimable uranium (World Nuclear). Like UNF, the waste from the chemical separations process must also undergo a post-use process before storage. Instead of simply encasing this waste in canisters of stainless steel and cement (as we currently do when we place used fuel rods in storage casks), it must first be converted into solid waste. Most countries do this by immobilizing it in glass, a process called vitrification. By the end of reprocessing, the volume of high level waste is an estimated 20% of that created by a once-through cycle. This amount of volume reduction is a good estimate for all reprocessing but varies depending on what process is used.

Recycling Pros

With many reactor sites filling up their dry cask storage spaces, one of the most important pros of reprocessing is the decrease in waste volume. Since there is no progress on beginning surveys for a new repository site and Yucca Mountain Repository is not likely to exit the policy lock it is in anytime soon, storage space for dry cask storage space will continue to grow as a concern. If no interim or long-term storage facilities are constructed, utility companies will be forced to expand their land holdings, increasing the cost of storing UNF. Likewise, if a recycling facility is created the processed fuel must be stored until fabrication. The NRC must approve this storage facility. A decrease in volume will buy time for the government to follow through on their responsibility to create a long-term waste site. One other aspect of a geologic repository that is difficult to fulfill but would be negated by the use of recycling is that of retrievability. While a site for deep geologic disposal may fit all environmental and political criteria, if it is a collapsing or shifting formation there may be issues with storing the used fuel in a location from which it is irretrievable. If UNF is stored within a salt formation for example, the plastic nature of the salt formation will creep in and close the mined openings relatively quickly. While the site is stable and may work politically, choosing a repository site with these characteristics to store once-through fuel will remove the decision to recycle any part of the stored fuel in the future. It will effectively take options away from future generations, where technology may be vastly improved. If the nuclear fuel cycle is closed, this is not such a dilemma. Making this waste irretrievable will not impact future generations as the elements will be spent and the desire to retrieve casks in the future is unlikely. Furthermore, the vitrified waste form is extremely difficult to extract anything from.

Reprocessing opens more opportunities than recycling uranium and plutonium to reuse in fuel, it also opens the door to transmuting the minor actinides and long-lived fission products present in used fuel. By removing the long-lived isotopes, long-term radiation emitters are removed from the end waste stream. This can greatly simplify the requirements for a long term storage facility's design and operation by changing considerations for decay heat and radiation dose. In addition to simplifying design and site requirements, the transmutation of separated minor actinides would also decrease safety concerns for the storage and disposal processes.

For many green advocates, the most appealing part of reprocessing is the utilization of resources. Since the main nuclear fission fuel elements (uranium and plutonium) are extracted and can be reused, reprocessing allows a path that maximizes the utilization of already mined uranium. For advocates against mining natural resources, this possibility gives them a pro-nuclear platform to stand behind. It also gives the nuclear industry the option to move away from mining and milling, which can help to reduce the overall environmental impact of nuclear energy. The waste from the enrichment process is also a possible source of material for recycling, as much of it is ^{238}U. The ^{238}U can be irradiated to create ^{239}Pu, which can then be used as fissile fuel in a reactor.

National fuel security and diversity could also be improved with the implementation of recycling. While it has some domestic uranium supply, most of the uranium used commercially in the Unites States is imported from Kazakhstan, Canada, Australia, and Russia. By recycling reprocessed uranium and plutonium, the US can reduce its reliance on foreign uranium supplies. This give the US more control over the fuel supply and reduces energy vulnerability to disruptions in the international market.

Recycling Cons

The 1977 ban on nuclear reprocessing was implemented by President Carter with a statement calling for "research into alternative nuclear fuel cycles which do not involve direct access to materials usable in nuclear weapons (Presidential Documents). The concerns for proliferation attempts are a major political block. Chemical separation can potentially contribute to proliferation risks as plutonium can be extracted through some processes and as chemical separations are not perfectly efficient, the amount of each material reclaimed is not equal to that calculated as existing. Without more advanced monitoring and tracking technology, this concern of plutonium being separated and diverted will remain. For these processes strict safeguards, security, and international cooperation may be implemented but the concern for diversion will remain.

The main non-policy factor dissuading the industry from partaking in nuclear reprocessing is the high economic cost. Regardless of the chemical process chosen for separating the elements, reprocessing is a complex process. Construction, operation, and maintenance are only a few of the costs associated with opening a reprocessing facility. Additional infrastructure may be necessary for transport of used nuclear fuels from power plants to disposal facilities and for storage of recovered and vitrified materials. Moreover, while there has been a good deal of research on reprocessing methods, few methods have been tested on a commercial or pilot scale. This makes it a big risk for any company to jump into reprocessing as it limits their options of reprocessing with a process pre-tested at a commercial scale to one reprocessing method: the PUREX process or one of its modified versions. The high economic cost alludes to another con of reprocessing: its technical limitations. Since few countries have used reprocessing, the technologies are still undergoing a lot of research and development and have not been in use (in general or commercially) long enough to become a refined process.

Other cons for reprocessing are cons for nuclear power technologies in general. They are the beasts of public perception and environmental, health, and safety concerns. Like other parts of the nuclear fuel cycle, reprocessing generates waste streams that contain radioactive and hazardous materials. While recycling may reduce volume of high-level waste at the end of the fuel life, more low level waste (LLW) is created. While LLW storage and disposal facilities are easier to find good sites for, they must still be constructed to handle the high volume created by the recycling process. If the opportunity of transmutation is taken, this handling is complicated only until the long-lived isotopes arrive at their transmutation destination after which the waste is not as difficult to manage and transport. Concerns and common perceptions by the public are not as easy to solve. While consent based siting is the preferred approach to creating a waste location, it is not timely or simple but acceptance, engagement, and communication from and with the community in which the plant is located are crucial for the successful implementation of any nuclear-related project.

Recycling Economics

Outside of policy, economics is the major challenge of recycling spent fuel. The production of nuclear power begins as an expensive process requiring high capital, land for facility construction, high licensing, fuel production, and plant security costs before any fuel is even used to create power. To close the fuel cycle requires these costs and more to be taken care of. Costs to be considered are those of construction, operations, transport, and storage.

Capital Costs

In a once-through fuel cycle, capital cost is very simple. It is the cost to construct long-term storage facilities. In the United States, policy dictates that Yucca Mountain should be used as this repository. If Yucca Mountain had gone to plan the licensing, construction, and regulation of the site and transportation routes to it would have constituted the only capital costs of the once-through plan. As that did not go to plan, capital costs have expanded to include the cost of interim storage on reactor properties and any other storage facilities that will be constructed prior to the repository. At this point in time, capital costs must expand to include more than one storage facility, and likely multiple types of storage facilities. Since UNF has been created and stored for a long period of time, it is unlikely one DGR will be able to store all the waste, especially if the open fuel cycle is continued. Furthermore, if recycling is pursued on a large commercial scale, more facilities for LLW storage must be created.

The capital cost of recycling includes those of a once-through cycle and include capital for the recycling facility itself. The facility cost may be at least two to three times more expensive than that of a conventional light water nuclear power plant. This is because of the complexity, isolation, and complex equipment design. The other major capital cost of recycling is the licensing, construction, and regulation of the separation site and the specialized equipment.

Storage(cooling) Costs

If the cost of storage is measured by volume of end-of-process HLW, recycling has less expensive storage costs than the once-through cycle. When storage of the recycled material is considered, it gets a bit more complicated. Some key conclusions can be drawn about factors that affect cooling and storage.

1) Cooling time is dependent on the refabrication process used.
2) Physical storage costs are appreciable.
3) As radiological hazard of a material increases, the elements stored per unit volume decreases because of safety considerations and extra security investments must also be pursued. NRC radioactive waste classifications define radioactive materials as class A, B, C, or GC and regulate storage and security requirements for each class.
4) The storage area will be proportional to plant through put (should be pretty stable for constant enrichment).
5) Cooling time for discharged fuel depends on mode of irradiation (continuous vs batch) and number of cycles as well as reactor and fuel types.

Because of these dependencies, it is very difficult to determine the cost difference of cooling the used fuel. Furthermore, since there is no way to determine exactly what amounts of each fission product (or even which fission products) will be produced from each used fuel assembly, it is impossible to determine a consistent cooling time to use for all used fuel assemblies.

Transportation Costs

Transportation is necessary in all cases of nuclear waste disposal. For the open fuel cycle, waste must be transported from the reactor site to the storage or disposal site. If no long-term disposal site is operational and the reactor site is at capacity the waste may have to be stored at an interim storage facility, incurring extra transportation costs.

In the closed fuel cycle, transportation costs will be incurred in transport of UNF from reactor to separation facility, of useful separated materials from the separation facility to fabrication facility and separation waste from the separation facility to disposal site, and fabricated fuel to the reactor plant.

Reprocessing Operational Costs

The cost of separating UNF is difficult to characterize. For an open fuel cycle, there is no cost of separation. The used nuclear fuel leaves the reactor and is placed in spent fuel pools to cool before moving to temporary and eventually long-term storage or permanent disposal. The separation costs of a closed fuel cycle are largely dependent on the separation process used. There are many factors to consider when determining cost. According to the analyses of the Idaho Chemical Processing Plant, Hot Semi-Works at Hanford, and Metal Recovery and Thorex Pilot plants at Oak Ridge National Laboratory (ORNL), a few general conclusions can be drawn about the operational costs of a separation site. The requirement of the plant to have specific and specialized equipment to operate portions of the site and lengthy training of facility workers will drive costs up. The incremental cost of adding capacity and new fuel is quite low but will still impact the economics of the site.

Discussion

Storing HLW

WIPP

The history of the WIPP site indicates that if the community is interested in hosting a nuclear facility the construction and use of that facility will receive more community and local government support, making it more likely to succeed and reach completion on schedule. To influence communities to consider hosting a nuclear facility, they must be educated and kept informed. The WIPP was not created under the same "decide, inform, defend" routine that has caused so many issues between federal and local governments. Instead of hiding characterization research, the citizens of Carlsbad, NM were kept informed of licensing and construction progress. The construction of a federal nuclear storage facility was not seen as an infringement on their lands, but as a positive influx of job opportunities and saving grace both for their community and nation. The community is a perfect example of a group showcasing "yes in my backyard" (YIMBY) and is what should be replicated for nuclear storage and disposal facilities. WIPP is far from an ideal situation though. While citizens of Carlsbad may have cheered when waste shipments travelled through their community, those in Santa Fe protested on roadsides. This is still the case, with Carlsbad citizens fighting New Mexico regulators who want to halt waste shipments. This shows that it is not only the hosting community but also surrounding communities that may be impacted. Being informed should not be limited to education and operations of the site, but also of any expected or arising issues at the site.

Moving Forward

Any movement forward in recycling will require the collaboration of the federal government for waste management, cooperation with native tribes near land holding that may be used, and communication with any other local governments and peoples. While policy in the United States has halted the use of used nuclear fuel technology in the past, the future seems promising. But in order to make room for the future, some decisions from the past must first be altered. While recycling the UNF decreases the amount of high-level waste overall, there will still be too much waste to store on-site as many nuclear power plants do. Experts around the world agree that a deep geologic repository is the best solution, but in the United States that is many years – likely decades – away. The use of interim storage sites is a short term solution to take care of UNF and recycling waste until the completion of a DGR. While this is an option overall, it is not one the DOE can make happen without the help of the nuclear private sector. Because of restrictive language used in the NWPA amendment, the DOE is not able to store UNF or radioactive waste until a repository is in operation. Since the amendment also designates Yucca Mountain to be aforementioned repository, the DOE's hands are tied in this matter until the policy is repealed, invalidated, or changed. With the help of the private sector, however, interim storage sites could be implemented.

Though it is known and agreed upon that a DGR should be constructed for use, the United States has not been successful in using such a site in part because of pushback from the state of Nevada, where the proposed site is located. Complexities of using the NWF, created specifically to be used for storage or disposal of UNF, also contributed. A report by the Blue Ribbon Commission details a plausible solution to both these issues and a way to pre-emptively avoid local and state government pushback. They suggest the establishment of a new organization, henceforth referred to as NWO in charge of civil nuclear waste handling and storage. NWO should be government - chartered and have assured funding through the NWF. Their immediate goal should be to characterize and construct a DGR for the nation's high-level waste working with entities contracted with the federal government and paying into the NWF using a consent-based siting process.

It is my opinion that the best way to achieve a consent-based site is to educate citizens on nuclear power and waste. Public forums should also be held to allow people to ask questions. By educating and making members of the nuclear community available to members of the general public, a trust may grow between the local citizens, government, and nuclear community. While implementing trust on a social side is necessary, it does not negate the need for a technical and scientific overseer. A separate organization (henceforth NWOR), also government based, should exist to do parallel research, and evaluate the actions of this new organization with findings open to public view. By creating not only an open view to the impacting actions of NWO, but also unbiased technical recommendations, the public will be able to coexist with nuclear facilities free of concern for negative health or safety impacts.

Options

In general, there are three options for the end life of used nuclear fuel. It can be stored or disposed of immediately after removal from a reactor, recycled once and then stored or disposed, or recycled until the uranium is spent or contains too high of a U^{236} percentage to be an efficient fuel before disposal. There is always room for technological improvement and the future may hold separation technologies unimaginable in present day. Over time, UNF contents continue to decay. If stored too long, the contents may decay to leave materials undesirable for some nuclear applications. This significance of this may change in the future, either because of the development of new technologies, improvements to current ones, or shift in what materials are considered useful. With the possibility of use by future generations, the decision of repository type becomes more important. If the open fuel cycle is used and UNF is placed in permanent disposal, or in other words is made irretrievable, the future choice to and possibility of using the materials contained in UNF is taken away. Long-term storage is more difficult to achieve because retrievability must be considered. By taking retrievability into consideration, long term storage/disposal site characteristics change to be more restrictive and difficult to meet. There are several routes that can be taken to allow irretrievability:

1) Removal of useful materials from UNF. If this is done, retrievability will not need to be a consideration, simplifying the characteristics of the searched for DGR site. Separating useful isotopes may also help parts of the nuclear industry with supply chain issues but will not improve the economic feasibility of the separations process as it adds extra steps and requires extra equipment.
2) Separate long-lived fission products and place them back into a nuclear reactor to be irradiated. By converting the long-lived isotopes to be shorter lived, the radioisotopes can decay into stable elements more quickly, decreasing the amount of time UNF must be stored in a DGR.

Limits of the Recycling Process

UNF from a light water reactor (a common nuclear power reactor) is composed of approximately 96% uranium, 3% stable fission products, 1% plutonium, and the rest minor actinides and unstable fission products. Most of the reclaimable uranium is U^{238}, not the fissile U^{235} that generates the nuclear reaction. In addition to these two uranium isotopes, UNF usually also contains U^{236} which is not fissionable and generally considered a nuisance. While theoretically all 96% is reclaimable, it is unlikely that will happen in reality as current chemical separation technologies are not 100% efficient. Furthermore, in the separation processes UNF is separated by element, not isotope, so the U^{236} will accumulate in the fuel throughout the multi-recycle process until the batch is considered fully used up and disposed of. It is also important to consider the type of fuel used in a reactor. Some fuels have different compositions of UNF materials, and others may not be eligible for recycling with present-day technology.

Realistic Constraints

In addition to limits of reprocessing technologies are limits and constraints of recycling UNF, especially with new fuel designs. Proliferation will always be a constraint where plutonium is involved. In some separation processes, plutonium is left mixed in with minor actinides and fission products to address this concern. This means that it will not be used in common nuclear fuels but may be used in some advanced fuels that contain actinides in fuel. Other processes, like the PUREX process, are unlikely to have a place in United States commercial reprocessing because of proliferation concerns and the resulting pushback from the NNSA. This being said, there are easier, more efficient, and less expensive ways to acquire materials for a nuclear weapon than infiltrating a high security-level fuel reprocessing facility. Part of this is because the plutonium separated from spent fuel is a lower quality than weapons grade plutonium (^{239}Pu enrichment is too low for weapons composition), so any diverted plutonium would still have to undergo enrichment (and likely purification) before it could be used to create a nuclear weapon.

New fuel designs also bring challenges and constraints to the backend of the fuel cycle. One is the realistic ability to reprocess and recycle some used fuel forms. One example of a fuel that is extremely difficult to separate and reuse is the TRISO fuel. If these advanced fuel types are to be commonly used in the future, the current separation and recycling processes must continue to evolve. Public acceptability may also become a constraint on recycling. While the public opinion of nuclear technologies is following a positive trend, there is still a nationwide case of the "not in my backyard" (NIMBY) with most state and local governments as well as many citizens claiming they support the technology but would not want it to operate near them. The French have shown that by educating and listening to the concerns of nearby communities, the areas of this trend may shrink. In some communities it may even quickly turn into positive "YIMBY" if the community is both educated and incentivized in some way or sees the opportunity for job and income opportunities and community growth. If this model is followed, perhaps a new standard for the construction and operation of government facilities in the United States will evolve. These limitations are not what holds reprocessing back in the United States. They contribute to the challenge of opening and operating such facilities, but the main constraint is economics. The French industry and government show us that the implementation of recycling is feasible but must be started at the right time. For France that was the Oil Embargo of 1973. For the US, maybe it can be with the construction of the next generation of nuclear reactors. No matter when the economic timing comes around, many issues and preparation must be taken care of before it has any chance of succeeding.

The Complication of Transportation

One such issue, affected by both policy and technology, is transportation. This limitation is a possible issue not only for recycling implementation, but also for the use of a DGR. The protective packaging for UNF is too large to ship using they typical commercial methods of trucks and airplanes. The most efficient and economically possible way to transport these packages is by rail. This brings up several issues, the largest being the limited infrastructure already available in the United States. For transportation of the packages, it is likely that new railways hubs would have to be constructed, oftentimes across state borders. This causes a possible policy issue as each state must agree to the construction of the railway and transportation of radioactive materials through it. It also brings up the concern of how this new infrastructure will be paid for. In the case of the DGR it is logical that the NWF be used, as (according to the NWPA) transportation of UNF is supposed to be handled by the federal government. If the infrastructure is built for transport from regional sites to the DGR, commercial separation facilities should strategically locate (near the nuclear power plants, a regional transport facility, or waste location) based on the characteristics of the plant.

Recommendations

There is no simple solution to this situation, and the recommendation reflects this. Ideally, I would recommend that the US begin implementing multi-recycling of UNF, with an extra step of separating minor actinides and long-lived fission products and reintroducing them to a reactor to be converted into materials with shorter half-lives. Any useful radioisotopes could also be available to be introduced to the domestic or international supply chain, making the recycling process more economic. This would not only allow the mined uranium to be utilized as much as possible, but also decrease the restrictions of a DGR as converting the radioactive materials with long half-lives to materials with short half-lives shortens the amount of time a DGR must contain the radiation from them. It also avoids the necessity for a repository that allows for retrievability, as the usable elements of the UNF will have already been separated out and utilized. Unfortunately, the current situation of the US is not ideal. Many changes must first be implemented if the country is to be ready to help recycling succeed when its chance to break into the market rolls around.

The first part of my recommendation is one that has been reiterated by many members of the nuclear community and was detailed by the Blue Ribbon Commission in their 2010 report. It is that there should be a creation of a new government-chartered organization with assured funding through the NWF. It should have jurisdiction over UNF and its derivatives, including how UNF and recycling waste are handled and where they are stored. The immediate goal of the organization should be to characterize and construct a DGR for the nation's high-level waste from entities contracted with the federal government and paying into the NWF using a consent-based siting process. The NWTRB mission should be amended to include review and evaluation of all decisions regarding UNF, including recycling, by the DOE and new organization. The NWTRB should also not evaluate technical and scientific impacts as well as social impacts of the plans and actions of the DOE and new organization.

With regard to beginning nuclear recycling in the United States, I have found that the issue of recycling is no longer held back by federal policy, but by economics. Because of this, I must pull back my initial inclination and instead recommend that the US continue with the open fuel cycle but begin preparing for the market entry of nuclear recycling. The reuse of UNF has many possible positive impacts. Not only does it have the ability to decrease the overall amount of high level waste and better utilize the mined uranium, but also positively impact national fuel security and open the possibility of converting of minor actinides and long lived fission products to be less difficult to dispose of.

Moving Forward

Before recycling is a large-scale commercial operation, the primary DGR for the US should be at least under construction, but ideally operation ready. The first step in making way toward this goal is to organize the creation of the nuclear waste management organization suggested by the BRC. Once the organization is in the works, amendments, or invalidation of the NWPA to expand the possible operations of the NWTRB to also evaluate the actions new organization regarding anything related to UNF, including recycling. Such an amendment should also include a retraction of the requirement to use and develop the Yucca Mountain site as a repository before moving forward on any characterization of new repository sites or interim storage sites. Transportation infrastructure to move packages from the place in which they are filled to the repository should be created, and any conflict between states resolved in regard to building of transportation lines and the goods transported on them by the federal government. If the transportation infrastructure is to be used only for the transport of UNF, then the NWF should be used to finance these operations.

With regard to choosing possible locations for the DGR, the consent-based siting approach should be used. Both the federal government and private sectors interested in building nuclear facilities should take part in educating citizens on nuclear power and waste. Public forums should also be held to allow people to ask questions. Educating members of the general public and making members of the nuclear community available to them will stimulate trust between the local citizens, government, and nuclear community. Pursuing the issue in this way will ideally spur communities to request site characterization in their areas. If it is not a promising location for a repository, it may still have the characteristics necessary for industry operations (new power plants, recycling facilities, or interim storage facilities). It is important to recognize that if the education and communication stops after receiving permissions for operations the community may later change its mind. In present day more than ever, children may learn from their parents, but this does not guarantee they will have the same views and education. If one generation makes a choice to support a facility but education of the community does not continue, the community may later attempt to displace the contracts and responsibilities taken on by their predecessors.

While the process for storage and disposal is underway, the preparation for recycling to enter the market should also begin. Research into more efficient and economic nuclear recycling programs should continue to be funded, with the goal of a pilot plant being constructed in the near future to prove the possibility for commercial functionality. This is especially important as the only present day process commercially used is the PUREX process at La Hague under ORANO. If the federal government decides to construct a commercial nuclear reprocessing service, they should organize a panel of experts in the field and solicit advice. One piece of advice may be to strive for the separation and fabrication facilities to be located near each other (on the same site if possible), thus eliminating a major cost contributor in the form of employing security during long transportation routes.

While some of the nuclear industry is making strides to begin using nuclear recycling, most is at least a decade away from such moves. This is largely because recycling spent fuel in the fleet of reactors currently operating is more expensive than simply buying fuel made from fresh uranium. Research on chemical separations processes and advanced reactors may improve this, so should continue to be funded. Within this funded research should be the goal of constructing a pilot plant for other methods of chemical separation than the PUREX process. By doing this, members of the nuclear industry will be able to see that the process is commercially viable, alleviating the uncertainty of constructing a new type of recycling facility with the possibility of failure (avoiding a repetition of General Electric's failure at the Morris Facility).

Research into options for the undesirable minor actinides and fission products contained in UNF and safe packaging of them should also be funded. The mission of this research should range from research for use of these materials in advanced fuel to use in medicine to transmutation to allow the disposal facilities to be differently characterized and rated for such waste. That is, if the unwanted by-products are transmuted to at least become elements and isotopes that are radioactive for a shorter time period, there should be disposal sites specifically for them. The goal of this is to have less strict characterization requirements, allowing more locations to fall within the requirements for a waste disposal facility.

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