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Thorium for Use in Plutonium Disposition, Proliferation-Resistant Fuels for Developing Countries, and Future Reactor Designs

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Executive Summary

Thorium has been examined as an alternate nuclear fuel source to uranium since the 1960s. Early experiments were aimed at generating electricity as economically as possible. These early thorium fuels provided poorer than expected performance in contemporary reactors and resulted in significantly higher costs than typical uranium fuel. While thorium-based fuels may not be economically competitive to uranium in current reactor designs, there are some policy goals to which thorium is well suited:

- Plutonium disposition—destroying and degrading of weapons-grade plutonium.
- Proliferation-resistant fuels for developing nations—ensuring global security.
- Next generation fuel cycles—extracting maximum energy while minimizing waste.

The first two goals can be achieved using a modern thorium-based fuel design in current reactors that has better economic performance. The last goal would be best achieved using thorium in a molten salt reactor. In addition to being suitable for use in the molten salt reactor, thorium will be researched as a possible fuel for the Next Generation Nuclear Plant.

As it stands, the joint plutonium disposition plans of the United State and Russia have stalled. This is because MOX, the technology chosen to undertake disposition, has taken more time and money than expected. In addition to this, Russia refuses to bear any of the cost of plutonium disposition through the use of MOX. This has opened the door to other options including thorium based fuels. A program in Russia examining thorium-based fuels has made a lot of progress and promises to be an excellent way to dispose of plutonium. The United States cannot directly benefit from this research and should start a program equal in size to the Russian program so that if thorium-based fuels turn out to be a better option for disposition there will be less delay in implementation.

The United States outlines a desire in the Global Nuclear Energy Partnership (GNEP) to establish reactors in developing nations to provide potable water, heat for industrial processes, and electricity to growing populations. There are currently no designs that have all of the characteristics desired for reactors to be deployed in developing countries. Thorium-based, proliferation-resistant fuels can provide an evolutionary step until better technologies are developed. The design of this fuel shares a lot of the same technology as thorium-based fuel for plutonium disposition. Because of this, the same program could cover both research objectives with marginal added cost.

Molten salt reactors meet all of the goals of next generation fuel cycles. However, the United States is not currently funding research into the technology. Recent research done in France has shown that some of the issues that prohibited development can be resolved. The United States is the only country with operating experience with molten salt reactors. Considering these facts, it makes sense for the United States to fund some research into this promising technology.

Thorium could be used to reach several goals in the United States. The technology is not ready for implementation. The United States should fund research into thorium to reach these goals. In doing so, the United States could become a leader in thorium-based technology.

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Introduction

There are two important political and technical issues that may affect the possible "nuclear renaissance" in the United States: proliferation[1] and waste. In the short-term the United States and Russia have agreed to dispose of thousands of metric tons of weapons-grade plutonium resulting from disarmament of nuclear arsenals built during the Cold War. There is also an increasing stockpile of reactor grade plutonium in civilian spent fuel. In Europe and Japan, where there is commercial reprocessing, the plutonium supply outstrips the demand. This means that without a major change in civilian plutonium usage and production, plutonium contained in spent fuel will be an ever greater proliferation concern. With this in mind, it makes sense for the United States and the world community to pursue technologies that can reduce the quantity and quality of fissile[2] material in nuclear waste.

In the long-term, the Global Nuclear Energy Partnership (GNEP) not only outlines the desire for the United States to increase the proliferation-resistance of the fuel cycle, but also addresses waste management and delivering power to developing nations. As part of GNEP, the Advanced Fuel Cycle Initiative (AFCI) examines different technologies that could be used to achieve long-term fuel cycle goals. Thorium-based fuels can achieve some of these goals, and are particularly suited to the following goals of the United States:

- Plutonium disposition—destroying and degrading of weapons-grade plutonium.
- Proliferation-resistant fuels for developing nations—ensuring global security.
- Next generation fuel cycles—extracting maximum energy while minimizing waste.

[1] Proliferation is the spread of nuclear weapons to states or groups that do not already have them.
[2] Fissile materials are any materials that can sustain a chain reaction either in a reactor or in a nuclear weapon such as uranium-233, uranium-235, and plutonium-239.

The first two goals can be reached using thorium-based fuels in current reactor designs. To reach the long-term goals, new reactor designs are needed. The Generation IV International Forum has selected six reactor technologies that will help achieve these long term goals. Of these technologies, thorium is best suited for use in molten salt reactors. However, the most funded design in the United States is the very high temperature reactor through funding of the Next Generation Nuclear Plant (NGNP). Thorium-based fuels are likely to be highly compatible with the NGNP. The other four designs are neither as suited to thorium fuels as the molten salt reactor nor as well funded as NGNP and will not be addressed[3].

Background

Thorium as a fuel

Thorium is about three times as abundant as uranium in nature. In addition to being more common than uranium, thorium has higher chemical stability and has better thermal conductivity than uranium. In addition to these properties thorium produces virtually no transuranics (TRU), the primary contributors to long-term waste toxicity and heat load on geologic repositories. Because of these advantages, thorium has been researched as a possible nuclear fuel by the United States, United Kingdom, Germany, and other countries.

During the 1960s thorium-based fuels were tested in the United States at “BORAX” in Idaho, Elk River in Minnesota, and Indian Point in New York. Thorium was not accepted early on because of poorer performance than expected in these early experiments and high fuel manufacturing costs [1,2]. From 1977 to 1982 a thorium-based fuel intended to create more fissile material than loaded was successfully tested at the Shipping Port reactor in Pennsylvania.

[3] Gas cooled fast reactor, supercritical water cooled reactor, sodium cooled fast reactor, and lead cooled fast reactor.

However, the fuel design produced 30% less power, and cost more to manufacture and reprocess than typical uranium fuel [3].

In these experiments the goal was to create inexpensive power. It was concluded that while thorium fuels could be used with minimum modification in light water reactors, it does not make sense economically [3]. Modern designs are different than these older fuels and are meant primarily for plutonium disposition and proliferation-resistance. Additionally, modern designs have longer burn than older designs. This makes modern designs more economically competitive than older designs and more suited to plutonium disposition [2].

What makes thorium suited to plutonium disposition? While thorium is not fissile, it is fertile. This means it can absorb a neutron to become fissile.

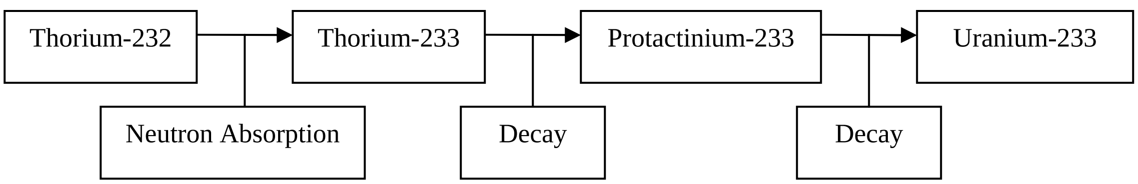

Fig. 1 - Thorium-232 changing into Uranium-233
Thorium changes it into thorium-233 through neutron capture. This decays into protactinium-233 and further into uranium-233, which is fissile.

Since thorium is only fertile that means that it must be “primed” with some initial fissile material. This can be either enriched uranium or plutonium. As the plutonium or uranium burns out of the fuel, some of the thorium is converted into uranium-233. The uranium-233 created burns in place and remains at a fairly constant level for about 10 years [4]. This makes thorium well suited to plutonium disposition because it requires a driving fuel, and does not discharge much fissile material or TRU.

Unfortunately if one assumes a closed fuel cycle[4], thorium has a disadvantage in that there are some highly penetrating radioactive materials, thallium-208 and bismuth-212, that are unavoidably created in the spent fuel. They occur as part of the decay of uranium-232 which cannot be separated chemically from the uranium-233 in the spent fuel. This means more of the process would need to be remotely operated compared current plutonium reprocessing which has a lower concentration of highly penetration radioactive materials resulting in a 30% greater cost to reprocess than uranium based fuels [3].

On the other hand, the same radioactive isotope makes uranium created in this process difficult and unfavorable to use in weapons. In fact, thorium-based waste is considered to be inherently more resistant to proliferation than typical uranium waste because of this radiation [5]. This inherent resistance can be increased by blending natural uranium into the thorium fuel. This limits the fissile percentage of uranium in the waste. While there are ways to enhance the protection of plutonium, it cannot simply be blended with non-fissile plutonium because non-fissile plutonium is not naturally occurring.

General

Nuclear power plants need fuel to run. Currently almost all reactors use uranium and/or plutonium derived from natural uranium as their fuel, though uranium-233 derived from thorium can also be used. To use uranium in a reactor[5] it must be enriched, because only 0.7% of naturally occurring uranium is uranium-235 a type of uranium that is fissile. Reactors need a greater percentage (around 3~5%) of the uranium to be fissile to operate. The rest of the

[4] See background section on fuel cycles.
[5] Except for heavy water moderated reactors which can run on natural uranium.

uranium is uranium-238 which is fertile. This means it can become fissile through the following process (similar to how thorium becomes fissile).

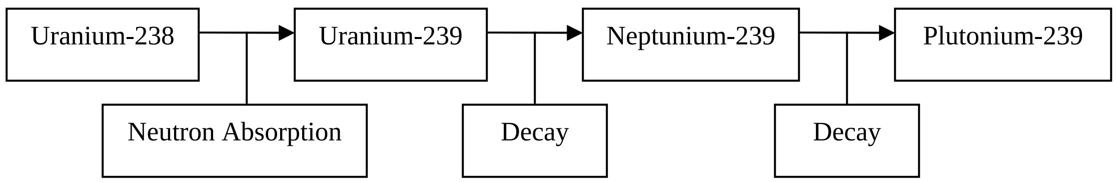

Fig. 2 - Uranium-238 changing to Plutonium 239
First uranium-238 absorbs a neutron which changes it into uranium-239. This decays into neptunium-239 and finally into plutonium-239. Plutonium-239 is fissile.

According to IAEA standard any uranium that is greater than 20% fissile is considered "highly enriched uranium" and is the point at which making a nuclear device becomes possible, although it is much easier at higher enrichments [6]. When using thorium, enough uranium is mixed in such that the uranium in the spent fuel is no more than 20% fissile. This process is called denaturing.

There is no natural plutonium so the same standard cannot be applied. There are other types of plutonium created with plutonium-239, most of which are not fissile. There are two mixtures of plutonium of particular interest. One is "reactor grade" plutonium which is contained in the spent fuel of a typical reactor after a full burn cycle. Reactor grade plutonium as a standard is about 70% fissile. The other type is "weapons-grade" plutonium which is greater than 90% fissile, and has been made intentionally for use in weapons. While it is easier to build a weapon out of weapons-grade plutonium, weapons can be built out of reactor grade plutonium [7].

Fuel Cycles

While there are different materials and processes that may be used for the nuclear fuel cycle, all cycles can be designated either "closed" or "open.". In an open fuel cycle, the fuel is burned in the reactor once. The spent fuel is the high-level waste form. In a closed fuel cycle, the waste is processed to separate unwanted materials from materials that can still be used in a reactor. What constitutes wanted and unwanted materials may vary depending on the fuel cycle but there are three basic constituents of spent fuel [8]:

- Uranium and plutonium, which can be relatively easily be made into fuel again (about 95% of the waste is uranium and 1% is plutonium)
- Fission products, which are unusable but become safe after about 300 years (about 3.4% of waste is fission products)
- Minor actinides, which may or may not be extracted for further processing and take much longer to decay to safe levels than fission products (about 0.6% of waste)

The separation of these elements of the spent fuel is called reprocessing or recycling. The United States currently uses an open fuel cycle (Fig. 3). Some other countries such as France and Japan reprocess their fuel once to extract plutonium and uranium from spent fuel while fission products and minor actinides as disposed of as high-level waste (Fig. 4). The recovered plutonium and uranium are made into mixed oxide (MOX) fuel which is a mixture of plutonium and uranium oxide. After the MOX fuel has been burned in a reactor, it is disposed of as high-level waste. This means using the current fuel cycle, there is still a great deal of un-harvested energy in spent fuel. This can be improved upon with next generation reactors using multiple recycles. Two of these possible full recycle options are outlined below. One is the closed fuel cycle as proposed by GNEP.

The other full recycle shown is the molten salt reactor which would use thorium as the main part of its fuel. The molten salt reactor runs using liquid, or molten, salt as the fuel and coolant. Thorium, natural uranium, and TRU would be manufactured into a solid salt form. The salt would then be melted at the reactor and added at the front of the fuel stream. Thorium in the salt would change into uranium-233, which in turn is the fissile material driving the reactor. The natural uranium in the fuel is incapable of sustaining the reaction on its own. It does not need to be enriched and is added to denature the uranium-233, not as a primary fuel source. Finally, the TRU would be added to drive the reactor, with the goal being to destroy TRU that would otherwise be disposed of as high-level waste.

The liquid fuel would be constantly reprocessed on-site to remove fission products. Along with the fission products, trace amounts of thorium, uranium, and TRU would unavoidably extracted. Overall, the molten salt reactor would create far less waste than current reactors, and could even be used to burn some of the waste from current reactors.

It should be noted that the "repository" step has not been reached. Even in other countries, waste is being put into interim storage pending final processing. This step is taking a long time to be studied and achieved. However, issues regarding the repository step are beyond the scope of this paper.

Fig. 3 Open Fuel Cycle
The current cycle the United States uses, uranium is simply mined, enriched, burned once in a reactor, and then disposed of as high-level waste.

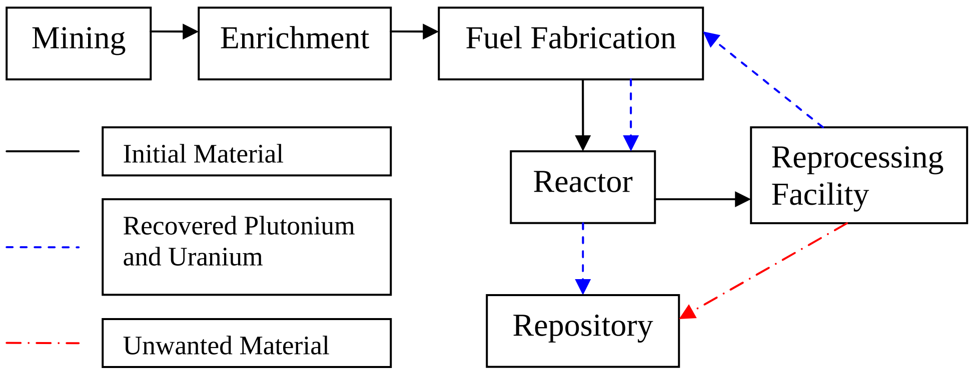

Fig. 4 Current Reprocessing Cycle
At the reprocessing facility the initial material is separated into uranium and plutonium, which can be used again, while fission products and minor actinides are sealed in glass and sent to final disposal. Fuel that comes from the reprocessing facility is also high-level waste after being burned once.

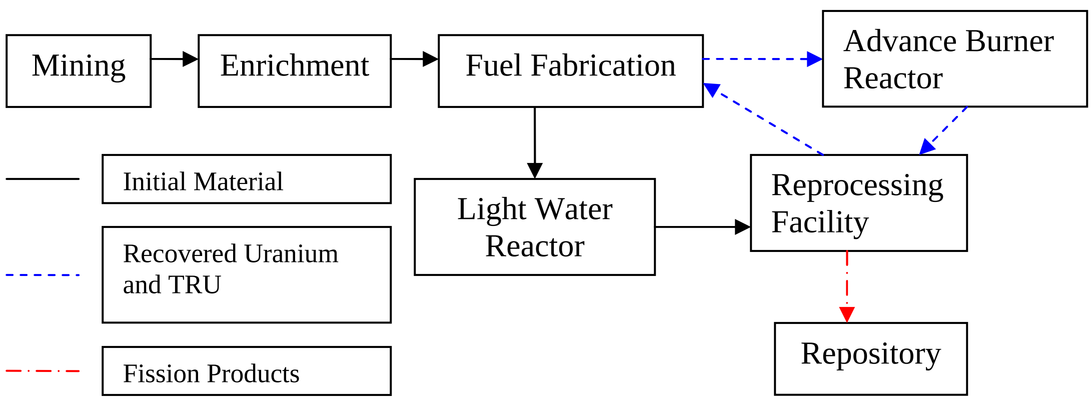

Fig. 5 Full Recycle (As proposed by GNEP)
In this cycle, fuel is reprocessed over and over again out of the advanced burner reactors which are designed to destroy TRU. The goal is to maximize TRU destruction so the vast majority of high-level waste is fission products.

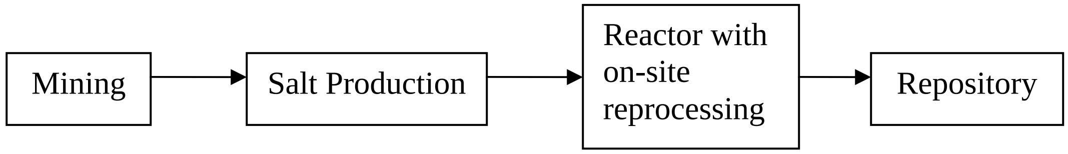

Fig. 6 – Molten Salt Reactor Cycle
While this looks similar to an open cycle, the on-site reprocessing means that only fission products are sent to the repository.

All fuel cycles have a proliferation risk involved and it must be controlled through both policy and inherent technical safeguards. The reference for minimum proliferation-resistance is the “spent-fuel standard.” This means fissile material must be roughly as difficult to extract and make a weapon from as plutonium in current spent-fuel [9]. Moving beyond this, it would be preferable if it were more difficult to build weapons through material diversion from any part of the fuel cycle than it is to build weapons through uranium enrichment.

Issue Specific Background and Analysis

Plutonium Disposition

Since the Cold War has ended, both the United States and the former Soviet Union have dismantled thousands of nuclear weapons and plan on continuing to dismantle more. This has resulted in a large stockpile of weapons-grade plutonium in both countries. In 1994 the National Academy of Science’s Committee on International Security and Arms Control deemed the stockpiles a "clear and present danger to national and international security." The National Academy of Science recommended that the weapons-grade plutonium be disposed of to meet the spent-fuel standard [10].

In 1995, the United States declared 50 metric tons of weapons-grade plutonium in surplus to defense needs. In 1997, Russia declared it also had 50 metric tons of surplus weapons-grade plutonium. In 2000 both countries agreed to dispose of 34 metric tons of plutonium each. A dual track approach was decided on in the United States where 8.5 metric tons would be immobilized in glass and 25.5 metric tons would be burned in reactors using MOX fuel. In 2002, the United States announced that it was canceling the immobilization of materials and would focus solely on the MOX option. Russia planned on using the MOX option to dispose of all 34 metric tons of plutonium from the outset [11].

The original plan was to have MOX burning in operating reactors by 2007, with 2 metric tons being disposed of every year in each country, done in parallel. This start up goal will not be reached due to the MOX program running behind schedule, over budget, and because Russia is demanding that the international community funds their MOX program.

The House of Representatives has shown its disapproval by authorizing a limited 50 million dollars to the MOX fuel fabrication plant for FY 2007, until the Secretary of Defense certifies that given the sunk costs to date for the United States MOX project and an evaluation of other alternatives for plutonium disposition, proceeding with the MOX project is the most effective means, from both a cost and technical perspective, for managing and disposing of United States weapons-grade plutonium. Additionally the Secretary must certify that the Department of Energy has developed a corrective action plan for addressing the issues raised by the Inspector General concerning the management of the United States MOX project [12].

Meanwhile, the Senate has stated that none of the amount authorized for defense nuclear nonproliferation will go to the construction of a MOX fuel fabrication facility until 30 days after the Secretary of Energy provides and independent cost estimate of the MOX project, and a certification that the Department of Energy intends to use MOX regardless of what Russia decides to do [13]. Both of these actions show little tolerance for any more delays in plutonium disposition.

This has opened the door to other options for plutonium disposition including thorium-based fuels and fast reactors designed to burn plutonium. Pursuing fast burners likely take longer than getting MOX or thorium-based fuel into current reactors. With fast reactors, the new fuel type and reactor must be constructed, where as MOX and thorium are just new fuels for current reactors.

Russia is currently pursuing thorium-based fuels for plutonium disposition. Through a joint operation between the Kurchatov Institute and Thorium Power, Inc. funded by the United States, a plutonium incinerating thorium-based fuel design for current reactors is about two or three years from implementation in a reactor, according to Thorium Power [14,15]. Westinghouse Corporation, which has been assigned by the Department of Energy to review the progress of the program, agrees with the timeline. However, the National Nuclear Security Administration[6] believes that these plans are risky and not likely to be as successful as MOX [14]. Therefore, one must consider the possibility that thorium-based plutonium incineration might meet the similar cost overruns and political pitfalls that MOX has run into.

How do different methods compare for plutonium disposition? When disposing of plutonium in a reactor there are two things that occur. The first is that some fissile plutonium is actually burned. The second is that the remainder of the plutonium is degraded and discharged, presumably at the spent-fuel standard. Plutonium disposed of consists of both the plutonium burned and the plutonium that has been degraded. While political emphasis has historically treated both the burning and the degrading equally, burning as much fissile plutonium as possible is preferable to degrading the composition.

An international study shows that a typical reactor loaded with thorium could burn plutonium at a rate of about 700-850 kg per GW(e)-year[7] in a typical reactor [16]. The study concludes, "Generally, there is a remarkable potential to effectively constrain the production of plutonium and to reduce existing plutonium stockpiles by implementing the thorium fuel cycle in a large number of current reactors." Another study at MIT suggests that slightly less than 1000 kg per GW(e)-year of plutonium could be burned in a plutonium and thorium fueled reactor

[6] A semi-autonomous agency within the U.S. Department of Energy
[7] A GW(e)-year is an amount of energy. 1 gigawatt of electricity produced for a year.

depending on particular composition. However, when the thorium is denatured the destruction rate is reduced to about 800 kg per GW(e)-year [17]. Finally, one of the two optimizations proposed by Galperin, Radkowsky, and Todosow is for plutonium incineration with denatured thorium. They conclude that 634 kg of plutonium can be burned per year in a reference Westinghouse reactor with 1183 kg of weapons-grade plutonium being disposed of per year. [4] Assuming the desired plutonium disposition rate is two metric tons per year as agreed upon by the United States and Russia, only two reactors[8] would need to be loaded with thorium.

By comparison, MOX fuel in the same reference Westinghouse reactor can only dispose of 462 kg, about 2/5 as much as using thorium-based fuel, of plutonium annually assuming a maximum loading of 45% MOX. [18] Only 30% of the 462 kg of the fissile plutonium is actually burned [19].

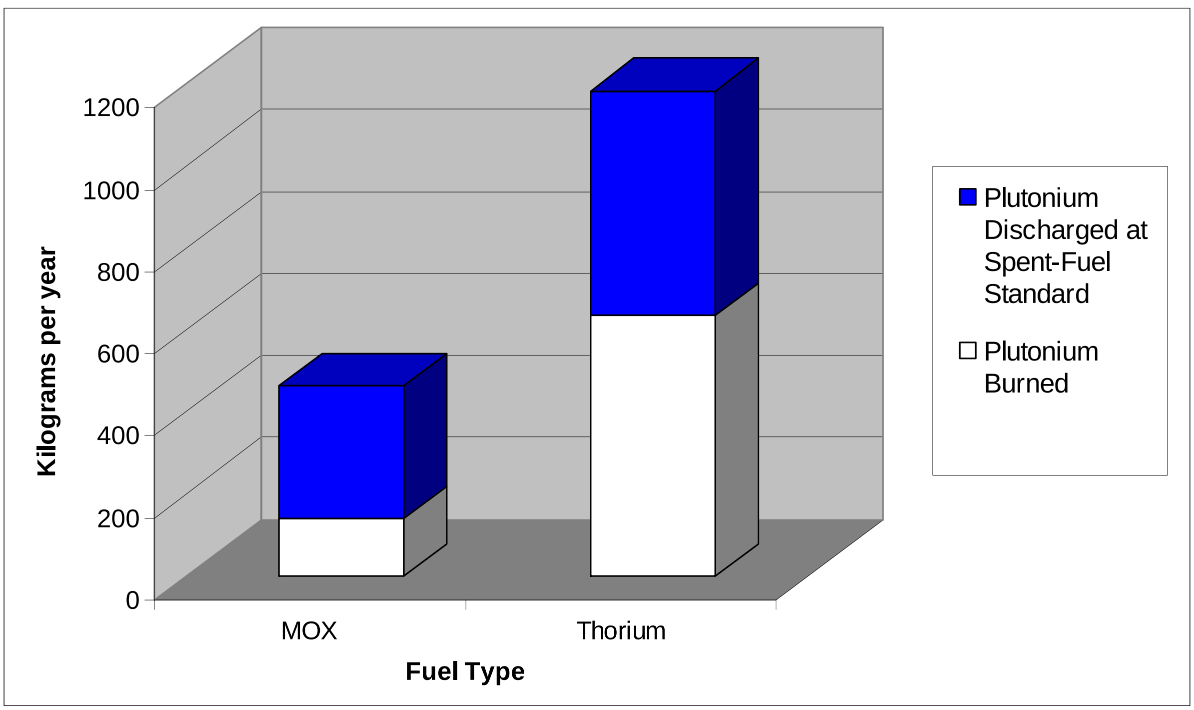

Fig. 7 – Thorium fuel vs. MOX fuel
This graph shows that thorium can dispose of plutonium twice as fast with a greater burn percentage than MOX fuel in equivalent reactors.

[8] Assuming a typical reactor of 1 gigawatt electric.

Thorium-based fuels could reach the disposition goal more than twice as fast as MOX in the same reactor. Alternatively, the job could be done at the same pace with fewer reactors. This means fewer reactors would need to go through licensing procedures to use a different fuel.

While MOX and thorium-based fuels have a great deal of data, it is difficult to get any hard data on how much plutonium can be disposed of per year using fast reactors. The AFCI estimates they are capable of burning 720 kg per GW(e)-year which is about the same rate estimated for thorium based fuels[9]. This lack of data is primarily due to the fact the United States does not currently have any fast reactors in operation, and those operated were not designed and tested with plutonium disposition in mind. Russia has a fast reactor, the BN-600, but it is not typically configured as a burning reactor. However, research is being done to figure out the plutonium throughput this reactor would be capable of.

If fast reactors are pursued to burn weapons-grade and reactor-grade plutonium in the long-term as planned by the AFCI, investing in thorium-based fuels for current reactors would still be beneficial. One study currently underway shows that if TRU is first burned in a current reactor using thorium-based fuel before being put in a fast reactor, the ease of control and safety characteristics of the fast reactor are improved [20]. In this way, researching thorium-based fuels immediately could provide plutonium disposition now and a possible future safety advantage for advanced reactors. MOX fuel does not have the same advantage due to the additional TRU produced during the burning of MOX fuel.

[9] As AFCI is more concerned with waste reduction the amount burned is given, but the amount degraded to the spent-fuel standard, or whether discharged plutonium meets the spent-fuel standard is not addressed.

Proliferation-resistant Fuels for Developing Countries

Under GNEP, the United States wants to help provide nuclear power plants for electricity, desalination of water, and heat for industrial processes, available to developing countries. Since many of the nations that may build these reactors are likely to have less security than the United States or other developed countries with nuclear technology, it is important to supply them with inherently proliferation-resistant reactors and fuels as well as political safeguards against weapons production.

According to the TOPS[10] report by NERAC,[11] reactors for developing countries should be smaller and produce less plutonium. The reactors should also be designed to reduce the frequency of refueling or the production of materials attractive for use in weapons [21]. Currently there are no designs that meet these criteria. If the United States and world community are committed to providing civilian nuclear power to developing countries, reactors that meet at least some of the goals must be considered in the near-term and mid-term.

If developing countries are left to choose and build their own reactors for civilian use, they might start with heavy water reactors. Both Canada's early choice and later India's choice to pursue this reactor type serve as reminders. This is because heavy water reactors require fewer specialized facilities to be constructed. There is no need for an enrichment facility because heavy water reactors can run on natural uranium. There is also no need to build pressure vessels which require specialized heavy manufacturing facilities since they operate at a lower pressure.

Not only does this simpler design make heavy water reactors more attractive, but its spent fuel contains high quality plutonium that is between standard reactor-grade and weapons-grade. With this design a country can more easily develop a covert weapons program under the guise of

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[10] Technological Opportunities To Increase The Proliferation-resistance of Global Civilian Nuclear Power Systems
[11] Nuclear Energy Research Advisory Committee

a civilian power program than with other civilian reactors. For example, India used plutonium from their first heavy water reactor, that Canada helped them build, to construct their first weapon

To avoid having situations where civilian nuclear power is used as a vehicle for proliferation the United States is examining reactors that are more proliferation-resistant. While no reactor has been deemed perfectly suitable, using proliferation-resistant fuels already developed would be preferable to doing nothing.

For example, a proliferation-resistant thorium fuel for light water reactors was looked at as one of two optimizations by Radkowsky, Galperin, and Todosow with the other optimization being plutonium incineration, discussed above [5]. They concluded that an open fuel cycle using thorium and enriched uranium results in spent fuel that is more proliferation-resistant than typical spent fuel:

- Annual plutonium output is reduced by a factor of 6-7
- The fissile percentage in the discharged plutonium is reduced to 62% in the seed and 55% in the blanket, this means more material is needed to make a weapon
- The heat generated from an increase in a type of plutonium presents a significant barrier to designing a weapon that uses the discharged plutonium
- The spontaneous fission rate of the discharged plutonium is higher, making the chance of a “fizzle” more likely

Uranium from the spent fuel could be extracted chemically, but enrichment would be needed to make it weapons useable. Enriching and manufacturing a bomb from uranium in the spent fuel would be difficult due to the highly penetrating radiation. This makes the spent fuel less attractive for weapons use than natural uranium, and thus a very low risk to proliferation.

A similar thorium-based fuel design was studied by Bae and Kim [22]. Their design is intended to increase the proliferation-resistance of spent fuel while also being economically competitive with the typical open uranium cycle. Their results show that approximately the same energy performance as a typical cycle can be achieved using thorium-based fuels with a 4.6% savings in overall fuel cycle cost, when capital costs for fuel fabrication are not included. They also found that the spent fuel was more proliferation-resistant than standard spent fuel. Their results are similar to the results of Galperin et. al.

These results are only applicable to an open cycle. A closed fuel cycle involves additional issues. The spent fuel from these thorium-based above would be more difficult and expensive to reprocess than standard fuel. However, this added difficulty is part of the proliferation-resistance characteristic. If it is hard to get fissile material out to use in a reactor, it is also hard to get the material out for use in weapons. If a closed fuel cycle is pursued, the extra cost of reprocessing would have to be measured against the added proliferation-resistance.

Next Generation Reactors, Closed Fuel Cycle, and the Long-term

Looking further into the future of nuclear energy, it is important to develop fuel cycles that are inherently more resistant to proliferation. The optimal cycle would maximize fuel utilization, minimize TRU in high-level waste, and be highly proliferation-resistance. One of the primary features desired by the United States in an advanced closed fuel cycle is that the material suitable for use in weapons is never extracted in a pure form. For example in a uranium/plutonium cycle, there should be no phase where plutonium is separated by itself. In a thorium/uranium cycle, there should be no phase where the uranium (U-233) is separated by itself.

Technologies that can be both proliferation-resistant and minimize waste volume are being considered as the next advancements into solving these problems. The July 2006 report by the Advanced Fuel Cycle Initiative (AFCI) articulates four objectives [23]:

- Reduce the long-term environmental burden of nuclear energy through more efficient use of disposal of waste materials.
- Enhance overall nuclear fuel cycle proliferation-resistance via improved technologies for spent fuel management.
- Enhance energy security by extracting energy from spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.
- Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

Reactors technologies that are meant to help meet these goals among other are outlined in the Generation IV (Gen-IV) roadmap. These reactors must meet or exceed the following goals to be considered for further research [24]:

- Sustainability-1 – provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.
- Sustainability-2 – minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
- Economics-1 – have a clear life-cycle cost advantage over other energy sources.
- Economics-2 – have a level of financial risk comparable to other energy projects.
- Safety and Reliability-1 – excel in safety and reliability.

- Safety and Reliability-2 – have very low likelihood and degree of reactor core damage.
- Safety and Reliability-3 – eliminate the need for offsite emergency response.
- Proliferation-resistance and Physical Protection – increase the assurance that nuclear energy systems are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Gen-IV and AFCI together outline the United States' long-term goals for domestic nuclear energy. Thorium as used in a molten salt reactor can meet all of the goals of Gen-IV and of the AFCI. The Generation IV roadmap scores the molten salt reactor as meeting or exceeding all criteria [24]. Molten salt reactors are also able to meet all of the goals for the AFCI [23]. Currently, the United States is not researching this technology despite the fact that it meets all goals set forth.

However, the United States has built and operated the only molten salt reactors. In 1954 molten salt reactors were developed as the propulsion system for the nuclear powered airplane. The molten salt reactor experiment was completed successfully at Oak Ridge National Laboratory in the 1960's. The program resulted in a detailed conceptual design for a commercial scale molten salt breeder that was a backup design for liquid metal breeders. The program was downsized considerable when the focus was shifted to a single breeder. This is because a molten salt reactor cannot breed as well a liquid metal reactor. The view then was that a reactor that could breed as much extra fissile material as possible could make the best use of natural uranium supply which was thought of as quite limited.

The political climate towards breeding reactors and view on uranium availability has shifted. A reactor capable of making more fissile material than it consumes is not currently considered necessary or even valuable. Additionally, other capabilities such as the ability to burn TRU have become more important because repository space was not considered an issue when the molten salt breeder reactor was being considered. Both fast reactors and molten salt reactors have the capability to burn TRU. Molten salt reactors do not require fuel fabrication which is a major issue when burning TRU in a fast reactor through multiple recycles. While the fabrication step is avoided, the TRU must be extracted from spent fuel of other reactors and converted to a salt that can but mixed in to the fuel of the molten salt reactor.

French work on the AMSTER (Actinides Molten Salt Transmuter) shows that molten salt reactors could be used to incinerate TRU from current reactors. Additionally, in a long-term cycle, the AMSTER project suggests that a molten salt reactor would produce about 1/1500th as much TRU as current commercial reactors. [25] Given this high capability to reduce waste and maximize fuel usage, the molten salt reactor the top-rated technology for sustainability of any system outlined in the Gen-IV roadmap [24].

There are some questions surrounding molten salt reactors. For example, it is difficult to know the final cost of operation. Only one economic study of a molten salt reactor was done by Oak Ridge National Laboratory which concluded that it would cost 3.8 cents per kilowatt hour for the molten salt reactor compared to 4.1 cents per kilowatt hour for a pressurized water reactor [26]. The analysis was done with pre-1980 vintage plants and is most likely no longer valid, especially since the reactor was not intended primarily for TRU destruction.

There may also be some regulatory issues, since virtually all of the rules for the NRC assume solid, uranium oxide fuel, in a light water reactor. New rules would have to be drawn up for liquid fueled reactors. While this might be problematic, the NRC is currently working on a “risk-informed, technology-neutral framework” for licensing advanced reactors. Presumably, the new regulatory framework will be finished well before any new, significantly different reactor designs are ready to be deployed.

The final question is that it is difficult to know the proliferation-resistance of a molten salt reactor because it is so different from solid fueled designs. To address proliferation concerns, it would make the most sense to pursue a design that breeds exactly as much fissile material as it burns. The fuel shipped to the plant would be of the same content as natural uranium, thorium and TRU from other reactors, which would be highly unattractive for use in weapons. The high-level waste would be primarily fission products with only trace amounts of fissile material and TRU. This would make diversion from transported fuel or waste a non-issue.

The main proliferation concern with the most molten salt reactor designs is that the Pa-233, which is the precursor to U-233 (see Fig. 1), is sequestered during the reprocessing to avoid loses cause in the core. If the Pa-233 was somehow taken out of sequestration, it would provide a source of pure weapons-grade U-233, but would also cause the reactor to shut down. This particular problem goes against the desire to keep fissile material below weapons quality in all phases of the fuel cycle. AMSTER aims to leave Pa-233 with the rest of the fuel, and combat losses by increasing the breeding ability of the core [27]. Additionally, the TRU feed could be increased to add fissile material as needed.

Although thorium is best suited for use in molten salt reactors, thorium based fuels are also highly compatible with very high temperature gas reactors such as the designs being considered for NGNP. Long burn times relative to current reactors allow for a great deal of the thorium to be converted to uranium-233 and burned in place. Presently there is a plan to build a high temperature test reactor at University of Texas of the Permian Basin called the HT3R (High Temperature Teaching and Test Reactor). The pre-conceptual design of the reactor is being undertaken by General Atomic, while Thorium Power, Inc. is involved in a thorium fuel design that will be tested in the reactor. This program could be complementary to the NGNP and will show the feasibility of using thorium in high temperature gas reactors. Additionally this test reactor will allow for the proliferation-resistance of the fuel to be examined. In the future, the NGNP may also provide a way to dispose of reactor and weapons-grade plutonium. The IAEA found that the higher burn-ups provided by gas cooled reactors result in a superior percentage of fissile plutonium burned in thorium-based fuels.

Recommendations

Plutonium Disposition

There is a large body of evidence showing that thorium-based fuels are economically competitive with MOX and more effective at burning weapons useable material. Additionally, thorium may be used in the same configuration to burn reactor grade plutonium which may be desirable in the future. Lastly, burning TRU once in the same thorium-based fuel design used for plutonium disposition may increase the safety of advanced fast reactors.

Most of the research has been done through simulations on computers. Only the project in Russia by the Kurchatov Institute and Thorium Power, Inc. is currently testing a physical assembly. This work may end up helping Russia, if real life holds true to what computer codes have predicted, but because reactors built in the United States use a different fuel assembly shape, several years would be spent testing assemblies that fit into United States reactors. This means that any economic or performance advantage that might be gained using thorium over MOX will not be gained in the United States until several years after Russia is able to implement the technology. In a time sensitive issue like plutonium disposition, a delay in gaining a possibly better technology would be undesirable.

As such, it makes sense research physical assemblies in the United States as soon as possible. The project in Russia has not been very expensive; having been appropriated 4 million dollars in 2003 compared to a total requested budget of 600 million dollars for plutonium disposition for FY 2007, and has made significant progress. The United States should start its own thorium-based fuel project equal in size, $4 million, to the one in Russia with the goal of creating and testing a physical assembly designed for plutonium disposition. This would prevent or decrease the delay in implementation should thorium-based fuels turn out to have the benefits preliminary research suggests.

Proliferation-resistant Technology for Developing Countries

Thorium mixed with uranium provides a more proliferation-resistant spent fuel than does a standard enriched uranium fuel. Economic analysis shows modern, once through thorium-based fuels to be competitive economically, and perhaps even cheaper than the standard enriched uranium cycle. However, GNEP foresees a closed fuel cycle with advanced burners. In this sort of fuel cycle, thorium is likely more expensive to reprocess than is spent uranium.

As it stands there are still no designs that meet all the desired capabilities of reactors for small countries. However, if nuclear reactors are going to be built in developing countries, the benefit to global security of providing a more proliferation-resistant fuel for countries would likely be worth the initial investment. Since the proliferation-resistant, thorium-based fuel design is based on a great deal of the same technology as the thorium-based fuel for plutonium disposition the, the United States should use the same research program proposed for plutonium disposition to research a proliferation-resistant, thorium-based fuel design.

Next Generation Reactors, Closed Fuel Cycle, and the Long-term

Reprocessing thorium-based fuels using the same processes as reprocessing uranium fuels is likely to be more difficult and more expensive. However, if a thorium/uranium/TRU mix is used in a molten salt reactor instead of the proposed fast burners the picture becomes much different. Early research in France on the AMSTER project shows progress in addressing some of the questions around using molten salt reactors. The on-site continuous reprocessing is so different from the proposed fast reactor method that it is difficult to compare the two economically, from a proliferation standpoint, and in waste reduction.

Therefore, a whole-system economic analysis of molten salt reactors and their proliferation-resistance should be done. If molten salt reactors are found to be competitive with advanced burner reactors in these categories, the United States should fund work on the molten salt reactor through the AFCI, Gen-IV, or both. The United States is the only country with operating experience for molten salt reactors, and is therefore the most suited to help with new designs.

It is also important to find out the economic and proliferation characteristics of thorium in gas cooled reactors because, as it stands, the NGNP is the most funded Gen-IV design in the US. Planning and funding are already underway to do modern testing on thorium in the HT3R at the University of Texas. If it turns out that thorium makes economic and proliferation-resistant sense, it may be used in advanced gas cooled designs.

Conclusion

While thorium has long been considered a possible component to nuclear fuel, the motivation early on was simply cheap energy. Poorer-than-expected performance in early reactors led to thorium's falling out of favor as a possible fuel. New fuel designs and motivations such as weapons-grade plutonium disposition and minimization of waste bring more value to some of properties of thorium. As such, recent research into thorium has been directed at the possibilities of exploiting these characteristics.

The initial results show that using thorium should work well for plutonium disposition, proliferation-resistant fuels, use in gas cooled reactors, and may be an economically competitive way to close the fuel cycle and minimize waste using molten salt reactors. The United States should start a program to test physical assemblies of thorium-based fuels designed for plutonium disposition and proliferation-resistance. Additionally, as the only country with operating experience the United States should put funding into the molten salt reactor through GNEP and Gen-IV. These programs would make the United States a world leader in thorium technologies.

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