Advanced Fuel Cycles in CANDU Reactors

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An Undergraduate Level Submission

Summary

Despite recent estimates indicating that we will have enough uranium to fuel our reactors at the current rate of consumption somewhere in the 50 to 200 year range, different methods of fueling nuclear reactors are worth looking into. Advanced fuel cycles such as recycled uranium (RU), plutonium, the DUPIC (Direct use of PWR (Pressurized Water Reactor) fuel in CANDU) and thorium will be imperative as conventional methods of fueling become more expensive. These advanced fuel cycles stretch the amount of energy that can be drawn out of every kilogram of fuel and to reduce the final volume of nuclear waste that must be disposed of. CANDU reactors are a perfect fit for these fuels because their high neutron flux leads to flexibility. This paper will investigate advantages of these different fuel cycles in CANDU reactors.

1. Introduction

The integral reason that CANDU reactors are the “chosen ones” for the exploitation of advanced fuel cycles is because of their amazing neutron economy. A high neutron economy enables them to burn natural uranium and virtually any other fuel; they attain this by using heavy water and zirconium alloys which have small nuclear cross sections making it so that they absorb neutrons less often. More neutrons are allowed to make contact with more fuel making a reaction sustainable with far less enrichment than that of a LWR (light water reactor), so little in fact that natural uranium is the standard fuel for the CANDU reactor. This amazing attribute means that CANDU reactors are capable of utilizing nearly any fuel.[2]

2. Recycled Uranium/Plutonium and DUPIC

Currently once a fuel bundle has been passed through a reactor it sits in storage awaiting disposal. Inside of these dispensed bundles lie large amounts of unused energy that could be tapped by reprocessing and removing unwanted actinides. There are still significant amounts of both uranium (238 and 235) and plutonium left in spent fuel bundles from all kinds of reactors. A chemical method called the PUREX (Plutonium URaniumEXtraction) process can be used in order to isolate out these fuels for reuse.

The PUREX process was invented in the early stages of the Manhattan Project at a metallurgical laboratory in the University of Chicago as a way of separating out the plutonium needed to make bombs.[3] This same process can now be used in order to extract fissionable material for use in MOX fuels. Currently the PUREX process is not frequently applied as it is cheaper to mine and enrich new uranium. Not only would this increase the quantity of fuel that can be used to make more energy but it would also decrease the volume of nuclear waste material that in the future will have to somehow be disposed of. The fuel that would have to be disposed of would be shorter lived because of the lower quantity of heavy elements like plutonium and uranium.[4]

DUPIC (Direct use of spent PWR fuel in CANDU) is another method of both stretching the fuel supply and limiting the volume of nuclear waste. Spent fuel from PWRs still retains a higher ratio of U-235 to U-238 than natural uranium so in most cases it could actually produce more power than the natural uranium conventionally used in CANDUs. The real benefit to this method is that it can be utilized in the short term as a way of immediately improving fuel burn-up. In order to apply this process, spent PWR fuel must be cut up and reformed into a shape suitable for CANDU fuel bundles. The only country in the world to attempt this so far has been South Korea, but only as a test of implementation and not as a regular fuel supply.[5] Currently this method is not in use as there are some problems with reforming the fuel into a CANDU fuel bundle. When the fuel comes out of the PWR it is highly radioactive and cannot be handled; machines must be developed that can complete the task of refabricating the fuel into the proper shape remotely. Also current methods of fueling in CANDU reactors only allow for very lightly radioactive natural uranium to be loaded, this must be changed to a more automated system if the DUPIC bundles are to be used. [6] In order for DUPIC to be fully utilized changes in policy associated to international shipping of spent fuel specifically in North America must be made. This would allow for spent PWR fuel from the United States to be shipped to the large number of CANDU reactors in Canada, this is however outside of the scope of this paper.

Recycled uranium and DUPIC are the most promising short term solutions to future fuel shortages as they could be easily implemented and require little research in order to begin use. The problem of high radiation levels with DUPIC could be easily avoided by a slight change to the CANDU fueling system. Currently CANDU reactors are equipped with the ability to move and store spent fuel using an automated system; by installing a similar system on the fueling side the use of previously irradiated fuels could be allowed. These methods of stretching our current fuel supply can be implemented immediately and would pave the way for the long term answers to our fuel sources such as thorium.

3. Thorium

Thorium is 3 to 4 times more abundant in the earth’s crust than uranium. Just like U-238 thorium is a fertile material, meaning it can be easily made into fissile U-233 by the absorption of a neutron. Countries such as India and China have a particular interest in this fuel due to its high abundance in their countries. India is perhaps the furthest along in thorium research because of a realization that they do not have a significant amount of uranium but they do have large abundances of thorium. Thorium must be ‘burned’ very similarly to how U-238 currently is, it needs a high flux of neutrons in order to get started but once enough Th-232 absorb neutrons and turn into U-233 the reaction will be self-sufficient. Many different sources have been proposed for the initial neutrons to get the reaction going but really any fissionable material will work once the proper quantity can be entered into the fuel bundle. The two current sources for this would be either U-235 or Pu-239 both of which exist in large enough quantities to start the thorium fuel cycle. The ideal fuel for this process would without a doubt be plutonium 239 (weapons grade plutonium) due to the larger number of neutrons produced in each reaction, which would allow the Th-232 to begin to contribute to the reaction far sooner than other fuels.[7] By blending a small amount of high grade fuel like Pu-239 or HEU (highly enriched uranium) with Th-232 for use in CANDU reactors we could tap into a source of power that would extend our supplies for hundreds or perhaps thousands of years.

With the construction of more and more uranium fueled reactors around the world, the levels of uranium in the earth's crust are being depleted; there will come a time when it will be more economical to use thorium in CANDU reactors. This is the first step to the thorium fuel cycle as we currently do not have enough U-233 to seed new reactors. A longer term option for large production of fissionable fuels would be to seed breeder reactors using U-233 that has been extracted from spent thorium fuel. The process of plutonium breeder reactors has already been widely researched in the context of making U-238 into Pu-239, similarly a thorium breeder would use Th-232 to make U-233. This unfortunately is met with the same problem as plutonium, in that U-233 is an easily separated fissionable fuel and could be used for nuclear weapons. Something that can be viewed as both a positive and negative side effect of exploiting the thorium cycle is the production of U-232. This isotope of uranium emits large amounts of gamma radiation upon radioactive decay, but with proper orientation and quantity of fuels in the reactor the production of U-232 can be limited.[8] The issue with gamma radiation is its ability to penetrate through some shielding, making it so that any reforming of the spent fuel would require significant shielding and remote controlled fabrication. The silver lining here is that the same issue that makes U-233 difficult to reform into new fuel also makes it non-proliferation friendly because of the increased measures needed to make fission bombs.

4. Mixed Oxide Fuels

Mixed oxide (MOX) fuels are the most promising way of ensuring proper burn up of fertile materials. MOXs are fuels that are a homogeneous mixture of usually plutonium and U-238 but can also be any other combination of oxide fuels. Similarly we could combine HEU or Pu-239 with thorium in a homogeneous mixture to ensure a high neutron flow to breed enough U-233 to continue the reaction. The entire purpose of MOX fuels in relation to advanced fuel cycles is to provide a high enough breeding ratio of fissile materials to continue the reaction and obtain most of its energy from the originally fertile material.

Plutonium and HEU are powerful sources of energy that could be used to provide the neutron economy needed to burn thorium in CANDU reactors. Plutonium's high neutron count per reaction makes it perfect for down blending with fertile materials. Normally using pure plutonium in a reactor would be disastrous but if properly mixed with other materials such as U-238 or Th-232 in small portions it can actually unlock more energy from these sources than if it just were to be utilized by itself. [7]

The benefit of Pu-239 and HEU is that there are already large stockpiles inside of nuclear weapons in countries like Russia and the USA that more treaties similar to the ‘Megatons to Megawatts’ could free up. ‘Megatons to Megawatts’ is an American-Russian program that allowed the purchase of weapons grade uranium from Russia. Russian HEU was extracted from warheads then down blended with natural uranium to create LEU that would be sold to the USA for use in their LWRs. By the time this program is completed it will have supplied the USA with 500 metric tons of HEU.[9] The mixing of weapons grade plutonium and thorium would be able to provide CANDU reactors with a substantial quantity of MOX fuel for years to come.

5. Reduced Volume of Waste Fuel

Another primary benefit to reusing and recycling spent fuels is the drastic decrease in volume of radioactive waste. In an ideal system natural uranium would be enriched to LEU then sent to a LWR, once used to its full ability it would be transferred into short term containment. The spent LWR fuel would be left to sit in containment for a period of time to allow some of the shorter lived isotopes and burnable poisons to decay. Next the fuel would be sent to be refabricated for use in a CANDU reactor (DUPIC). After the CANDU cycles the bundle out the spent fuel is put through the PUREX cycle where its remaining usable fuel would be extracted for reuse either in a LWR or CANDU reactor and begin the fuel cycle again. Different countries would go about waste disposal and reuse differently depending on what kind of reserves of fuel, processing facilities and types of reactors they possess.

6. Conclusion

Currently the cost of natural uranium is far too low to give the incentive to switch to other fuel sources, as long as we can continue to mine and enrich uranium at a lower cost than changing our fuel source that is exactly what we will do. As mentioned earlier some fuel sources such as thorium and DUPIC could be very cost effective but the research must first be done in order to make this feasible. The industry currently has no motive to switch because it would cost them an added expense to change fueling methods from something that they know works and is reliable, to something new that the industry has yet to have experience with. Large scale adoption of new fuel cycles would lower costs but someone must first step forward and take the initiative. The same problem is currently seen in fossil fuels, there are alternatives but currently switching does not, from an industry point of view, make sense at this time. Economically the best choice currently for future fuel supplies lies in the large stockpile of weapons that currently serve no purpose. These sources of fuel could be easily combined with thorium, depleted uranium or natural uranium at a very low processing cost providing enough fuel for decades of reactor use. In the end it will be the profit motive that drives a change in policy towards new methods of reusing, recycling and utilizing different fuel types. We will likely continue using our current methods until it is profitable to change.

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