HELIUM-COOLED REACTOR TECHNOLOGIES FOR ACCELERATOR TRANSMUTATION OF NUCLEAR WASTE

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Abstract

Helium-cooled reactor technologies offer significant advantages in waste transmutation. They are ideally suited for use with fast, thermal or epithermal neutron energy spectra. They can provide a relatively hard thermal neutron spectrum for transmutation of fissionable materials such as ^{239}Pu using ceramic-coated particles, a graphite moderator, and a non-fertile burnable poison. These features (1) allow deep levels of transmutation with minimal or no intermediate reprocessing, (2) facilitate passive decay heat removal via heat conduction and radiation, (3) allow operation at relatively high temperatures for a highly efficient generation of electricity, and (4) discharge the transmuted waste in a form that is highly resistant to corrosion for long times.

They also provide the hardest possible fast neutron environment since the helium coolant is essentially transparent to neutrons and does not degrade neutron energies. This facilitates transmutation of actinides that have low fission-to-capture ratios in the thermal neutron energy range. In this paper, we report work on the development of two concepts using helium-cooled reactor technologies for transmutation. Both concepts make use of thermal and fast energy spectra. One concept (thermal-fast) may be more attractive for transmutation of nuclear waste in a once-through mode, without reprocessing after initial removal of fertile uranium and fission products from the waste. It uses a single type of transmuter to eliminate essentially all weapons-useful material in the waste and achieve a significant reduction in total toxicity. It also has the potential to be economically attractive by generating substantial amounts of electricity.

The other concept (two strata) may be more flexible and attractive to achieve deeper levels of transmutation. In this system, the thermally fissile isotopes are destroyed in a critical reactor operation in the passively safe Gas-Turbine Modular Helium Reactor, or GT-MHR, followed by a deep burn-up phase in an accelerator-driven GT-MHR. Then the discharge material is processed into fast reactor fuel, and irradiated in an accelerator driven Gas-Cooled Fast Assembly. The processing of the thermally irradiated fuel would not require burning off the graphite. Instead, fuel compacts would be mechanically extracted from the graphite fuel blocks, and the coated particles would be mechanically separated from the compact binder material. The particles would then be chemically processed to separate the remaining transuranics and produce fast reactor fuel. This is a similar process to that being considered for the multiple-pass liquid metal transmutation process.

The gas-cooled fast assembly provides the hardest neutron spectrum for minor actinide transmutation, and hence, maximum transmutation per pass. This minimises the number of reprocessing steps required to reach a given degree of transmutation.

1. Introduction

Nuclear waste can be stored in geologically stable repositories and allowed to decay for long times. However, technologies are becoming available that have the potential to add significant value to the disposal process. They provide for transmutation of nuclear waste into more stable materials that decay relatively fast and are not attractive for use in nuclear weapons, thus reducing long term toxicity and proliferation risks in the repositories.

Transmutation of nuclear waste could have profound benefits for world political stability and the environment. It could drastically reduce the availability of weapons materials in the world, and reduce waste disposal requirements in terms of space and safeguarding time.

2. The problem

Nuclear fuel production begins with uranium ore, which is not without hazard as it contains some natural fission products and daughter elements that are created as uranium naturally decays to lighter elements. However, this naturally occurring material provides a useful benchmark for evaluating the nuclear waste that is ultimately produced. Uranium ore goes through several processing steps, including an enrichment step in which the fraction of the lighter ^{235}uranium is boosted from 0.7% to higher values (typically 3% for LWR reactor fuel) relative to the more naturally abundant ^{238}U. As a fuel, the uranium is usually converted into oxide form (uranium oxide) and encased in a metal rod for use in LWRs.

In addition to the production of fission products, neutron capture in both ^{235}U and ^{238}U leads to the creation of plutonium, as well as minor actinides, (i.e. isotopes of elements with atomic number greater than 92), including neptunium, americium, and curium. The fuel is used until the ^{235}U content becomes too low to sustain the chain reaction, around 0.8%. It is then moved to a spent-fuel water pool, where the hundreds of radioactive isotopes generated by the fission process begin to naturally decay to stable, and generally harmless forms. After ten years of decay, spent nuclear reactor fuel is composed of the materials listed in Table 1.

Table 1. **Spent nuclear reactor fuel after 10 years decay**

Actinides		**Fission products**	
Uranium	95.6%	Stable or short-lived	3%
Plutonium	0.9%	Caesium & strontium	0.3%
Minor actinides	0.1%	Iodine & technetium	0.1%

The table shows that about 98.6% of the spent-fuel inventory is not a concern for long-term disposal. The uranium can be separated from the other materials and disposed of as class C waste, or can be recycled. The stable and short-lived fission products are also of little concern, except for very small quantities that may be classified as hazardous or mixed waste. The remaining 1% that is composed of plutonium and minor actinides, as well as the 0.4% that is composed of caesium, strontium, iodine, and technetium, need to be dealt with.

Plutonium is the unique waste component. It is fissionable, and capable of releasing significant amounts of energy. It is also a hazardous material, particularly if inhaled in particulate form. Because

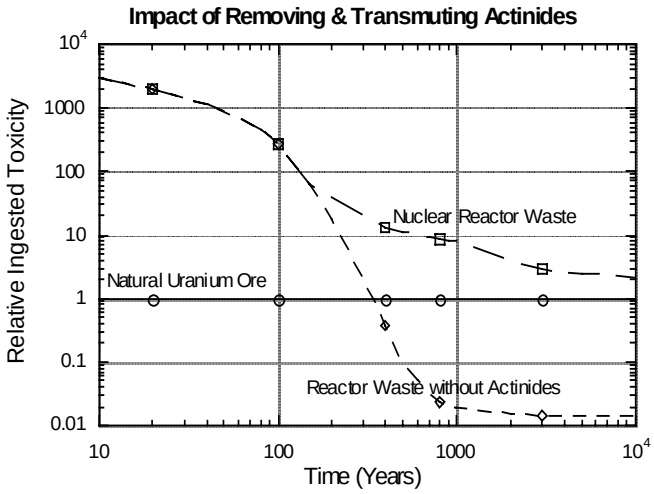
of its potential use in nuclear weapons, there is great sensitivity about isolating plutonium from other components of the nuclear waste stream. Minor actinides contain potential energy proportionate to plutonium, although their generally small thermal cross-sections make them much more difficult to fission.

If the 1% of the reactor discharge that consists of plutonium and minor actinides is transmuted, the resultant waste stream would contain nearly 90% stable or short-lived fission products, and about 10% caesium, strontium, iodine, and technetium. This is a favourable trade-off, as a significant amount of energy would be produced, equal to about 18% of the energy that was produced in the reactor. Therefore, in transmuting the plutonium and minor actinides (i.e. Np, Am, and Cm) from the 100 nuclear power plants in operation in the US, one would be generating the equivalent to another 18 power plants worth of electric power.

But what of the 0.4% of problem fission products? The caesium and strontium problem is caused by a couple of isotopes having half-lives of about 30 years, which are hard to transmute. However, with 30-year half-lives, the inventory drops by a factor of nearly 10 every century, so four centuries of decay would drop the inventory by a factor of nearly 10 000. We can trust containers to provide isolation for that long, and the need for isolation thereafter is greatly diminished. In contrast, the technetium and iodine isotopes of concern are very long-lived and are primarily of concern well after the containers have ceased to be effective. Fortunately, the iodine and technetium isotopes of concern can be converted to stable isotopes if one has enough neutrons available. In that respect, we are fortunate that the transmutation of the plutonium and the minor actinides can provide many available neutrons.

The potential impact of removing and transmuting the plutonium and actinide wastes is illustrated in Figure 1. The data for this figure are taken from the 1989 CURE report. Since that time, however, the DOE ingestion toxicity hazard indices have been increased significantly. The net result is that the toxicity levels illustrated in the figure have increased by about two orders of magnitude. Taking this into account, even after a million years, untreated nuclear reactor waste is still significantly more hazardous than natural uranium ore, and continued isolation from the environment is still important. Furthermore, significant amounts of plutonium still remain in the untreated waste. In contrast, the step of transmuting the actinides offers the potential to make the waste stream less hazardous than uranium ore within three to four centuries, and reduce the need for isolation and safeguarding. However, although this looks very attractive, it should be recognised that the real impact may be somewhat less dramatic than the figure shows since even some minor residual amounts of plutonium and minor actinides will tend to make the treated waste toxicity curve cross the natural uranium ore line farther to the right.

Figure 1. **Impact of removing & transmuting actinides**



3. Gas-cooled systems for transmutation of nuclear waste

As stated above, if the 1% of the waste stream that is plutonium and minor actinides is transmuted, and the iodine and technetium isotopes of concern are also converted to stable isotopes, one has the basic elements of a solution to the nuclear waste problem.

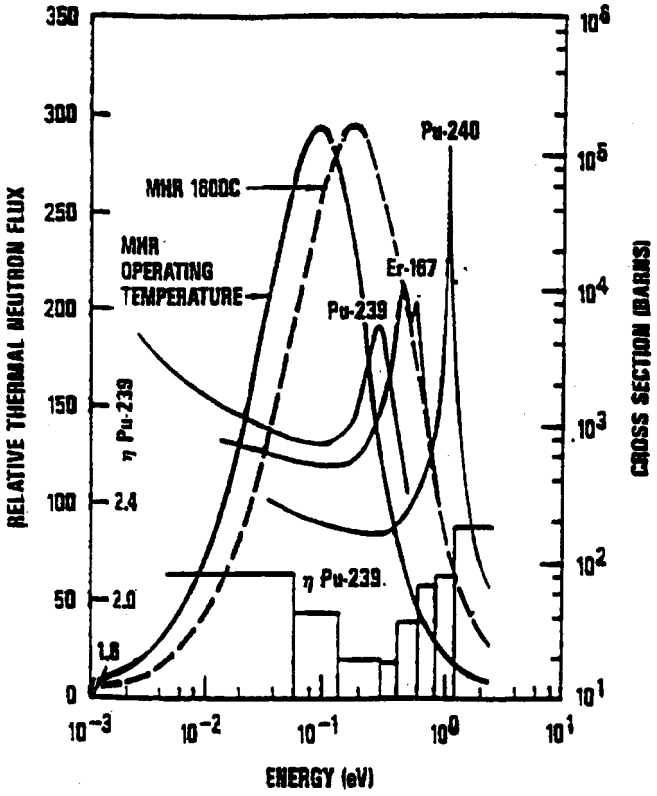
Let us consider some of these elements. In the transmutation process, the materials to be transmuted are irradiated in a neutron flux. Neutrons (1) can fission the atoms of the irradiated materials creating atoms of lower atomic weight that are generally more stable, or (2) are absorbed by the irradiated atoms. In the latter case, new heavier atoms are formed, which may in turn fission when hit by other neutrons. For the long-lived fission products, neutron absorption transmutes them to stable or short lived species.

Gas-cooled reactor technologies offer significant advantages in accomplishing this transmutation process. They are ideally suited for use with thermal neutron spectra since they allow operation at high temperatures and neutron energies that produce plutonium fission without the need for fertile material as a burnable control poison. In addition, they also are ideally suited for use with fast neutron spectra since they provide the hardest possible fast neutron environment for transmutation of higher actinides, which are more inclined to fission in the fast neutron energy spectra. This is due to the fact that the gas coolant is essentially transparent to neutrons and does not degrade the energy spectrum as is the case with other coolants.

3.1 Thermal neutron systems

Generally both capture and fission cross-sections for thermal neutrons are an order of magnitude larger than in a fast neutron spectrum. Thus, a suitably designed thermal system is a most effective tool to destroy essentially all the proliferation-offensive Plutonium isotopes (^{239}Pu and ^{241}Pu). A helium-cooled, graphite moderated, thermal neutron energy spectrum assembly using ceramic-coated fuel, and operating as a critical system or as an accelerator-assisted sub-critical system, is an attractive choice for this fission function for several reasons.

Figure 2. **Neutron flux distribution and flux sections of plutonium and erbium in gas-cooled assembly**



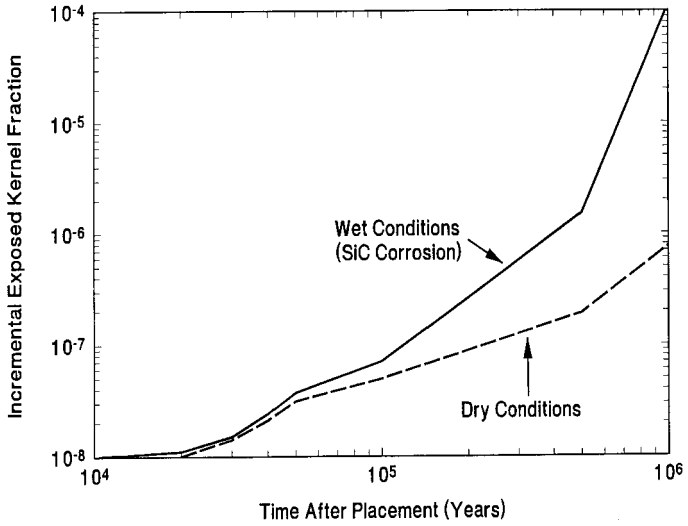
As shown in Figure 2, a Modular Helium Reactor (MHR) type assembly produces a relatively large flux in the thermal regime where fission cross-sections are quite high. This promotes fission. In addition, the assembly operates in a temperature range (shown in Figure 2) in which the capture cross-section of erbium has a resonance at a neutron energy such that it can be used as a burnable poison to produce a strong negative temperature coefficient of reactivity. The lack of interaction of the helium with neutrons means that temperature feedback is the only significant contributor to the power coefficient. This provides for a stable operation of the reactor or sub-critical assembly. In addition, it does not require ^{238}U as a burnable poison so no additional plutonium is produced in the process.

Another feature of great importance in the thermal gas-cooled reactor or sub-critical assembly is the use of ceramic-coated “TRISO” fuel particles. The ceramic materials are stable at high temperatures, and have very high melting points. This provides large thermal margins to ensure fuel integrity during loss of coolant events. Moreover, the coated particles are nearly spherical, and include large gas expansion volumes within the coated particles. The expansion volumes are able to accommodate the production of fission gas products within the coated particles with lower resultant internal pressures. In addition, the spherical shape is better able to withstand the mechanical stresses due to these pressures. The composite effect is that the particles can tolerate high levels of irradiation, and allow deeper levels of transmutation (burn-up) without reprocessing. This capability has been demonstrated in multiple reactor irradiations.

An important advantage of the ceramic coatings is that they are much more durable than metallic coatings. Extrapolated corrosion test results indicate that the incremental waste exposure in the

repository due to corrosion of the ceramic coatings is expected to be negligible for hundreds of thousands of years (Figure 3). We believe these particles offer the only practical chance to achieve the toxicity reductions illustrated in Figure 1.

Figure 3. **Particle integrity**



Given these important features, the use of gas-cooled, graphite-moderated ceramic-coated-fuel thermal reactors, or accelerator-driven sub-critical assemblies of the same type for destroying weapons grade plutonium has been studied in detail [1]. The studies have led to the conclusion that an assembly operating as a critical system can transmute about 90% of ^{239}Pu, and 65% of a total load of Pu in a three-year pass. Then, if the 3-year irradiated load is further irradiated in an accelerator driven sub-critical assembly for one more year, the destruction of ^{239}Pu and total Pu increases to 99.9% and 87% respectively, with no intermediate reprocessing.

3.2 Fast neutron systems

Fast reactor systems are typically much smaller than thermal reactors since they need a high neutron flux and no moderator, and typically have higher fuel densities. This leads to higher power densities, more demanding cooling requirements, and more complex cooling and cooling control systems. The smaller delayed neutron fractions and complex reactivity feedback effects in fast neutron systems can potentially produce severe reactivity and heating effects.

The fission cross-sections in the fast-neutron region are smaller than in the thermal region; however, fission-to-absorption ratios are higher in the fast-neutron region than they are in the thermal region. So, even though many minor actinides are hard to fission at any energy level because of their small cross-sections, their relative destruction rates can be better than in thermal reactors if a high neutron flux is provided.

Calculations show that a fast sub-critical assembly cooled with helium gas allows a destruction rate of actinides of approximately 26% (in weight) per year. This is somewhat better than has been reported in other studies for liquid metal cooled systems, possibly because the gas coolant allows the production of a harder neutron energy spectrum, and consequently, a higher fission to absorption

ratio. Given this rate of destruction, one could irradiate the actinides for several years and then store the discharge in a geological repository where further natural decay would take place. So, if one desires to destroy certain minor actinides, there is merit in using fast neutrons after plutonium is transmuted in a thermal spectrum. And if one wishes to do so, it helps that the amount of actinides is a very small portion of the initial waste (0.1%) since the fast transmutation assemblies end up being smaller than they would have to be to transmute plutonium as well. These findings form the basis for a transmutation scheme utilising both fast and thermal neutron spectra as discussed in the next section.

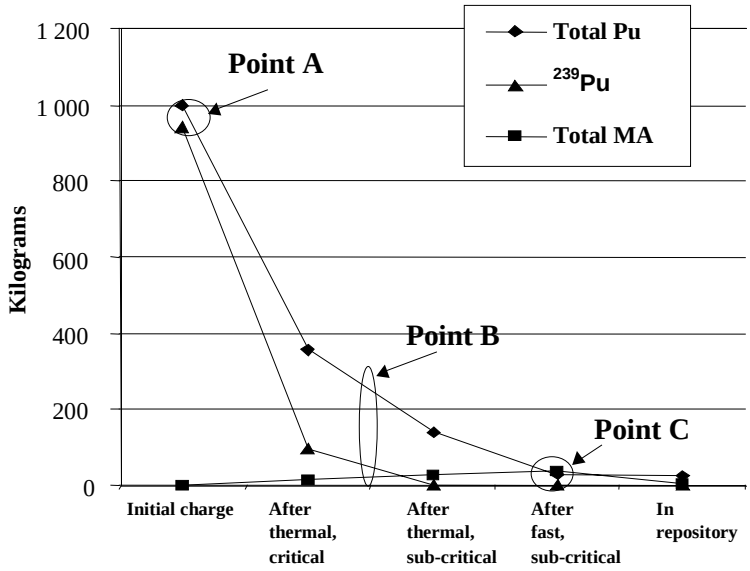
4. Burn-up possibilities

Based on the above considerations, we have explored the process of using (1) thermal neutrons (near the cross-section resonance peak) to do what they do best, i.e. fission plutonium, and (2) fast neutrons to fission minor actinides. One advantage of using this process is that most of the transmutation of plutonium is done in the thermal regime where technologies are more mature and development risks are lower. Since the amounts of minor actinides found in the waste material are significantly lower than the amounts of plutonium, the fast assemblies needed can be significantly smaller or fewer than the thermal assemblies.

The fuel cycle that we have studied for this scheme is as described in the previous section: three years of transmutation of plutonium and minor actinides in a thermal neutron spectrum assembly operating in the critical mode, followed, without reprocessing, by one year of transmutation in the same thermal neutron spectrum assembly operating as an accelerator-assisted sub-critical system. At this point, essentially all fissionable materials are burned up. What remains is mainly non-fissionable minor actinides, which are moved to a fast neutron spectrum assembly operating as a sub-critical system.

Burn-up calculation results for this fuel cycle are shown in Figure 4 for an initial 1 000 kg charge of weapons-grade plutonium. As the figure indicates, most of the Pu transmutation is accomplished in a thermal critical regime. When this is followed by a one-year irradiation step in a thermal sub-critical regime (accelerator driven), essentially all ^{239}Pu is gone. At this time, a three-year step of transmutation in a fast subcritical regime leads to Point C in the chart, when most of the initial charge is gone. If this remaining material is placed in a repository for 200 years, only 60 out of 1 000 kg of the initial charge are left.

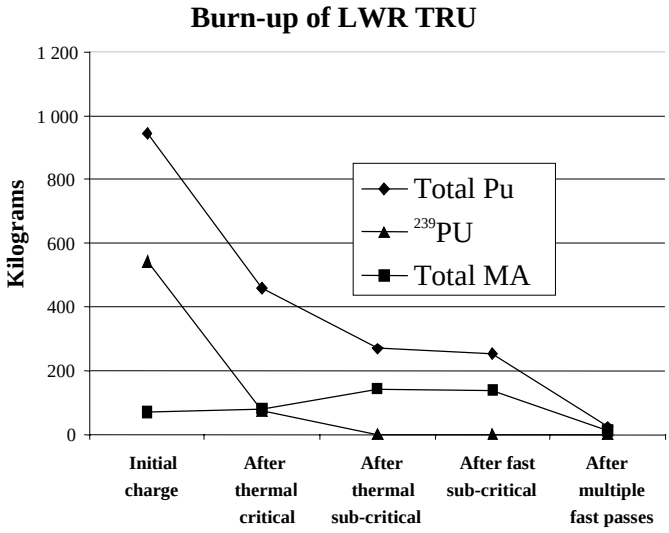
Figure 4. **Burn-up of plutonium using thermal and fast neutron spectra**



Residence times
Thermal, critical: 3 years
Thermal, critical: 1 year
Fast, sub-critical: 3 years
Repository: 200 years

The significance of Point B in the above figure is that it is equivalent to the level of transmutation demonstrated in the Peach Bottom 1 reactor. In that test, Plutonium fuel particles coated in Silicon Carbide were irradiated to levels exceeding 700 000 MW-days per Metric ton of Pu fuel, which transmuted over 95% of ^{239}Pu, and corresponds to the Point A-to-Point B trajectory in Figure 4. Two irradiated "TRISO" particles from this test are shown in Figure 5. The second (lighter) layer (from the outside in) is the silicon carbide coating. The two gray layers on each side of the silicon carbide layers are pyrocarbon layers that provide mechanical protection and pre-compression for very high structural strength margins in the silicon carbide. The central part of the particle contains the transmuted material. The dark areas within the silicon carbide layer are empty spaces occupied by fission gasses.

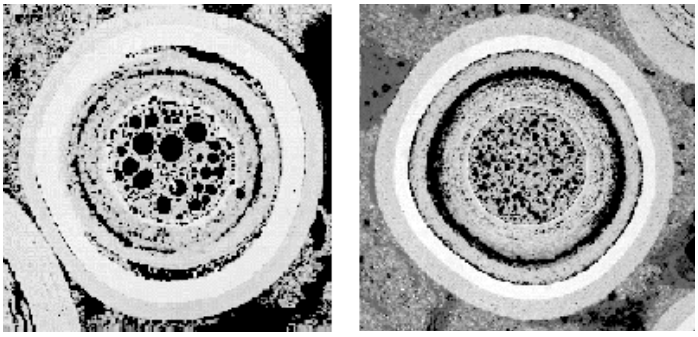
Figure 5. **Irradiated TRISO particles**



The conclusions from the burn-up levels shown in Figure 4 and the durability of the silicon carbide "TRISO" particles illustrated in Figure 3 are that (1) transmutation can reduce plutonium and minor actinides waste by about two orders of magnitude, and (2) the transmuted material will remain isolated from the repository environment for hundreds of thousands of years.

Similar preliminary calculations have been performed for LWR transuranic waste. In this case, the isotopic composition of the plutonium material to be transmuted is somewhat different than weapons-grade plutonium. In addition, there are other minor actinides present in the mix. Nevertheless, the results are equally encouraging, as shown in Figure 6.

Figure 6. **Burn-up of LWR TRU waste using thermal and fast neutron spectra**



Pu Oxide
747,000 MW-days/tonne
>95% ^{239}Pu, and
>65% all Pu transmuted

Th-Pu Oxide
183,000 MW-days/tonne
>95% ^{239}Pu transmuted

Consider now the manner in which the thermal and fast neutron energy spectra could be packaged together. There are two concepts that seem attractive for different reasons. One is based on the use of a single type of transmuter, running part time in the critical mode, and part time in the

accelerator-driven sub-critical mode. We call it the thermal-fast concept. The other uses two separate types of transmuters, one thermal and the other fast. We call this the two-strata concept.

5. The thermal-fast concept

The single transmuter-type, thermal-fast concept is illustrated in Figures 7 and 8. Referring to these figures, the transmutation assembly consists of a steel vessel housing, inside of which there is an annular nuclear transmutation region that operates in the thermal neutron energy regime. In this annular region, plutonium and minor actinides from LWR waste are fissioned together in TRISO particles. Most of the mixture, about 90%, is plutonium. The remaining 10% is minor actinides. Fission neutrons in this annular region are thermalized in graphite blocks in which the TRISO particles are contained as shown in Figure 9. Surrounding the annular thermal region there is an inner and an outer graphite neutron reflector. This thermal region operates in the critical mode for 75% of its cycle time, followed by operation in an accelerator-assisted sub-critical mode for the remaining 25%.

Still referring to Figures 7 and 8, in the centre of the inner reflector there is a cylindrical region, approximately 15% of the size of the active thermal region, that operates in the fast energy neutron energy regime. This region consists of tungsten tubes that house TRISO particles already transmuted in the thermal region. Therefore, they contain mainly minor actinides. The main motivation for including this fast assembly inside of the thermal assembly is to take advantage in the fast fission process of the large heat storage and conduction heat removal capabilities of the thermal assembly.

Figure 7. **Thermal-fast transmuter elevation**

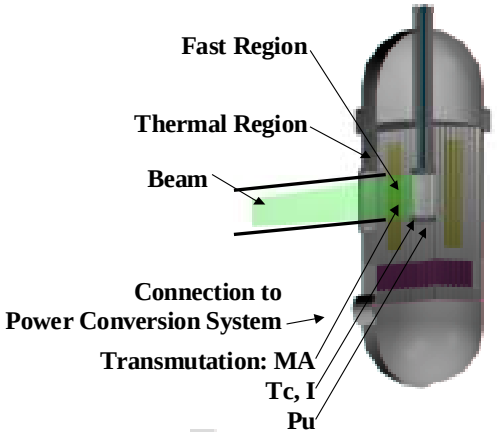
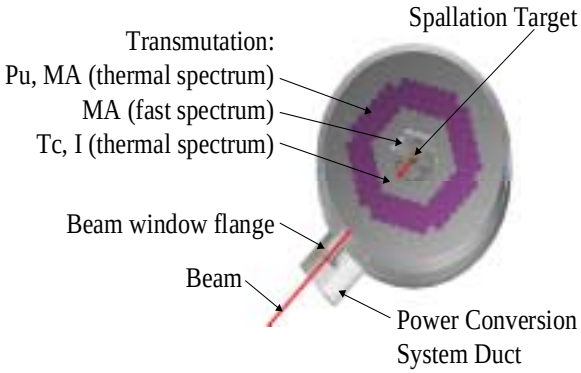


Figure 8. **Thermal-fast transmuter cross-section**



The fast cylindrical region is designed so that, by itself, it is sub-critical. However, neutrons reaching it by travelling from the thermal region through the reflector can cause fission and get amplified, thus creating sub-critical transmutation.

As discussed above, the transmuter operates in the critical mode for approximately three years, which corresponds to 75% of its cycle time. In this mode, the fission process is driven by the critical reaction in the thermal region. After that, the thermal region becomes sub-critical, and is then driven for a fourth year to cause deep levels of transmutation by neutrons generated in a spallation target located in the centre of the fast region. The target is driven by the proton beam illustrated in Figures 7 and 8. Deep levels of transmutation can be achieved with no reprocessing thanks to the encapsulation

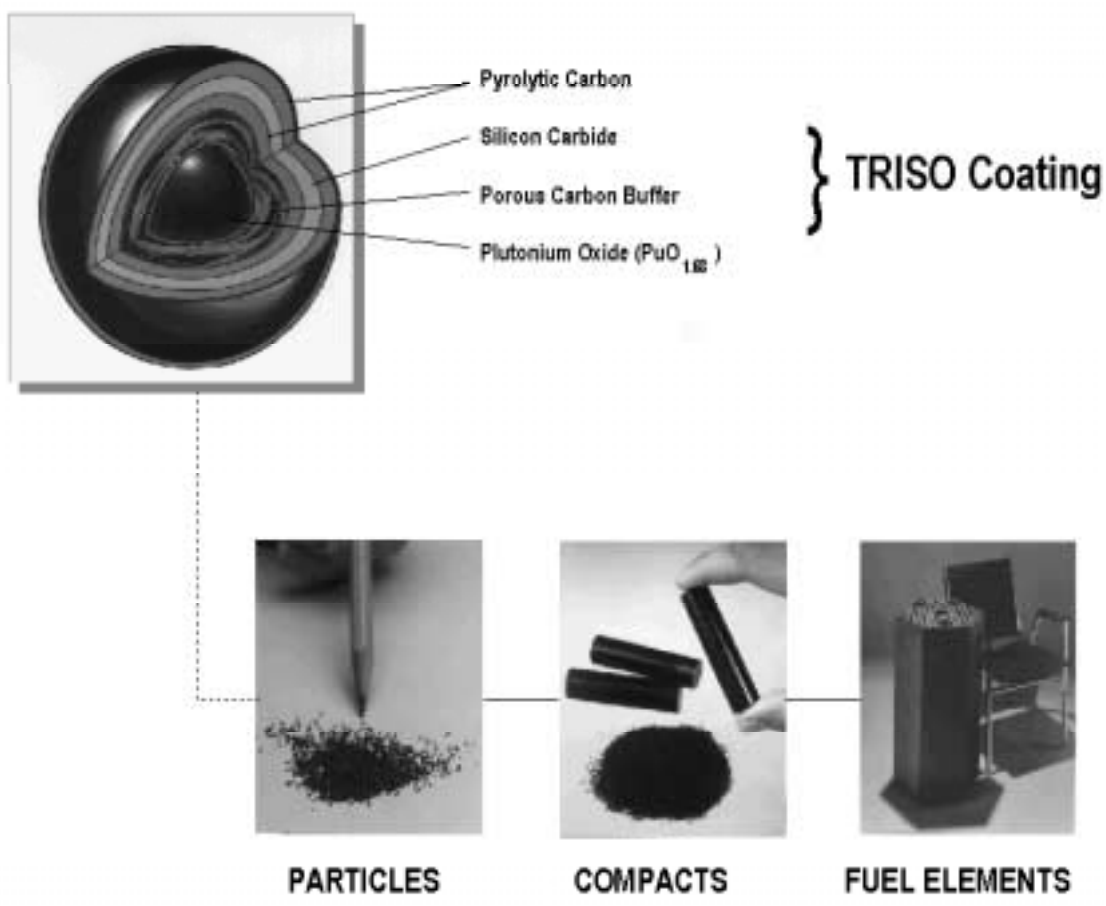
in ceramic-coated microspheres of the materials to be transmuted, which accommodate the production of fission gas products within internal expansion volumes.

A beneficial anti-proliferation effect of including the fast assembly within the thermal assembly is that the neutron economy in the integrated assembly cannot support breeding.

Going back to the operating sequence, the fact that the transmuter needs the proton beam for only a part of its operating time makes the entire process more economical because the accelerator can be time-shared by several transmuters in the plant configuration such as that illustrated in Figure 10.

Referring again to Figures 7 and 8, there is shown a coaxial duct in the lower part of the transmuter. The outer part of the duct brings in cold cooling helium to remove fission heat from the transmuter. The helium then flows upward in an annular space between the inside of the vessel and the outside of a steel barrel that contains the thermal-fast assembly.

Figure 9. **TRISO coatings and graphite are excellent engineering barriers for normal operation, severe accidents, and permanent disposal**



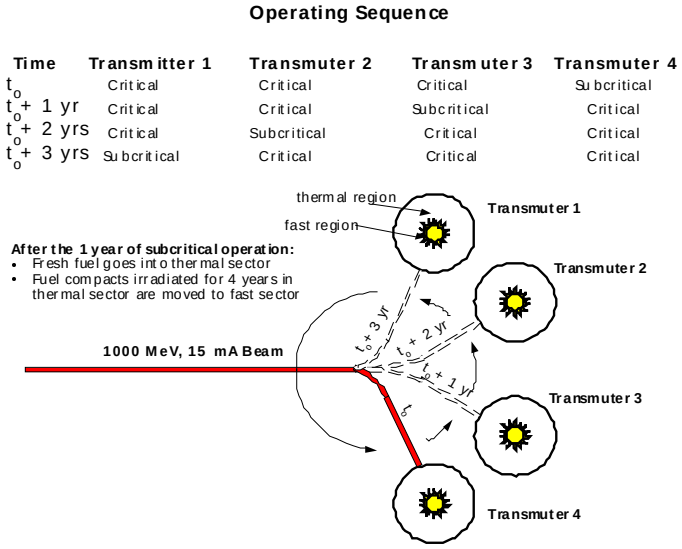
Helium then flows downward through cooling channels in the fission regions of the transmuter, and carries the heat at a temperature of 850°C through the central part of the coaxial duct to a direct-cycle gas-turbine-generator system that generates electricity. The high operating temperatures and the

characteristics of this direct (Brayton) power conversion system allow electric generation with a high net thermal efficiency of approximately 47%.

This high power conversion efficiency, the fact that 75% of the transmutation is done in a critical operating mode, and the fact that the proton accelerator is time-shared by four transmuters, leads to a favourable revenue-cost balance and the potential to attract investment for the deployment of these units.

Roughly, the cost of the plant configured as shown in Figure 10 (four 600 MW_{th} transmuters, and one 15 MW beam accelerator) would be expected to be in the \$1.5B to 2.0B range. This would translate into an annual cost of \$190M assuming interest on and return of capital of 8.8%, plus typical nuclear plant operations and maintenance (O&M) costs increased by 50% to account for accelerator O&M. It also includes an allowance for decommissioning the plant, but assumes, however, that the fuel (to be transmuted) is government-supplied.

Figure 10. **Thermal-fast plant representative configuration**



The revenues, assuming 4 cents per kWe-hr, 75% plant availability, 47% transmuter thermal efficiency, and an accelerator efficiency (beam to electric power ratio) of 32% would be approximately \$270M per year.

These estimates suggest that transmutation plants of this type have the potential to be economically viable and possibly attract investment.

From the safety standpoint, there are two important considerations. Criticality and cooling. Criticality safety in this respect is ensured by the use of erbium in the thermal assembly. Erbium has a neutron capture cross-section that increases with temperature, and peaks a higher temperature than the fission cross-section of ^{239}Pu. Erbium and plutonium quantities can be selected that provide a strong negative temperature coefficient of reactivity during the entire fuel cycle.

The other important safety consideration is cooling. In this respect, the geometry of the assembly (tall and thin, and annular thermal configuration) has been shown to provide for passively safe conduction cool-down of a 600 MW_{th} thermal spectrum-only assembly, even in a loss of coolant

(LOCA) event. The effect on this feature by the inclusion of a fast fission region is currently being studied. However, preliminary conservative calculations suggest that including a fast region may still allow passive conduction cooling in a LOCA event if thermal region power is lowered so that total power of the transmuter is kept below 600 MWt.

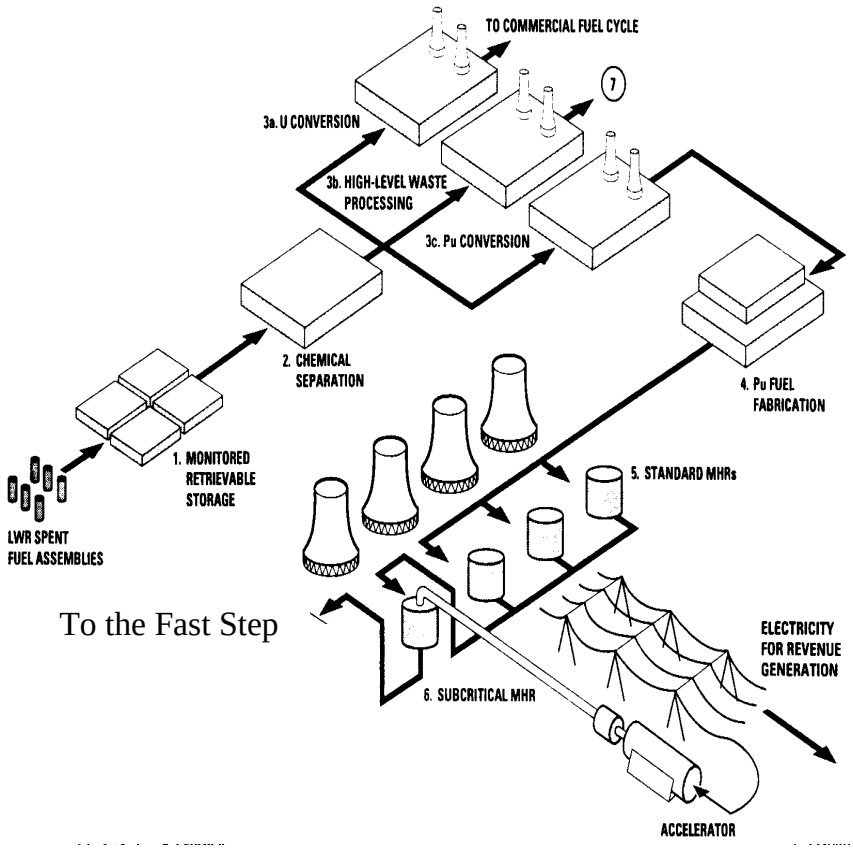
Thus, it appears that levels of safety comparable to those that are encountered in gas-cooled reactors may also be achievable in a thermal-fast gas-cooled transmuter.

Important work is still needed, however, to further advance the design of the thermal-fast transmuter. Preliminary analyses seem to indicate, for example, that the fast flux generated in the central region during critical operation of the thermal region can be relatively low. This would mean that transmutation of minor actinides during this time would also be low, and that more reliance on the accelerator to generate a fast flux would be needed. However, there are potentially more attractive ways to obtain a higher fast flux during these conditions that need to be evaluated. These include reducing the density of the graphite immediately surrounding the fast region.

6. The two-strata concept

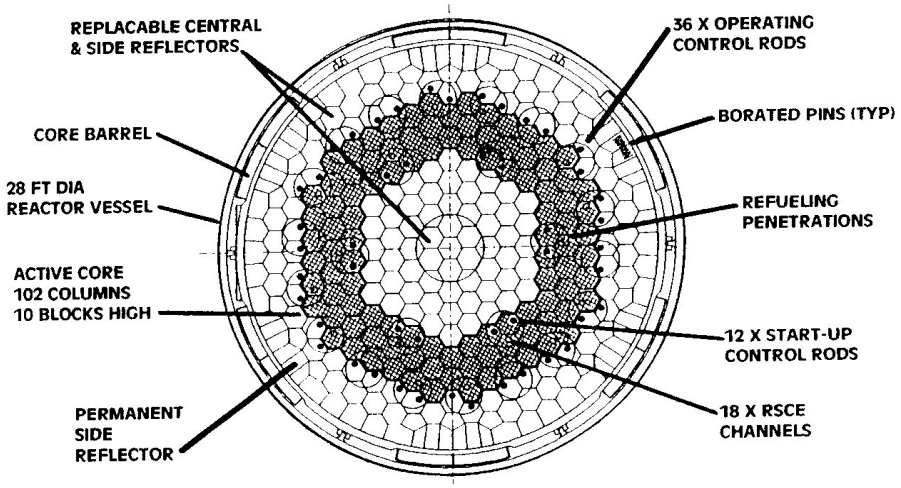
In the two-strata concept, the thermal and the fast neutron spectra are separated. The system is illustrated in Figure 11. As shown in this figure, the system includes the front-end separation step in which uranium in the waste stream is separated and recycled to the commercial fuel cycle, or disposed of as low-level (Class C) waste.

Figure 11. **The two strata process**



The plutonium and minor actinides are then converted to silicon carbide-coated fuel particles and assembled in the three graphite-moderated thermal spectrum critical reactors shown in the figure. The fuel fabrication stage is shown as step 4 in the figure, and the thermal reactors are shown as step 5. The GT-MHR operates at a sufficiently high coolant temperature that it can be coupled to a direct cycle gas turbine for electricity generation at approximately 47% efficiency [2]. A cross-section of the MHR core is shown in Figure 12.

Figure 12. **GT-MHR cross-section**



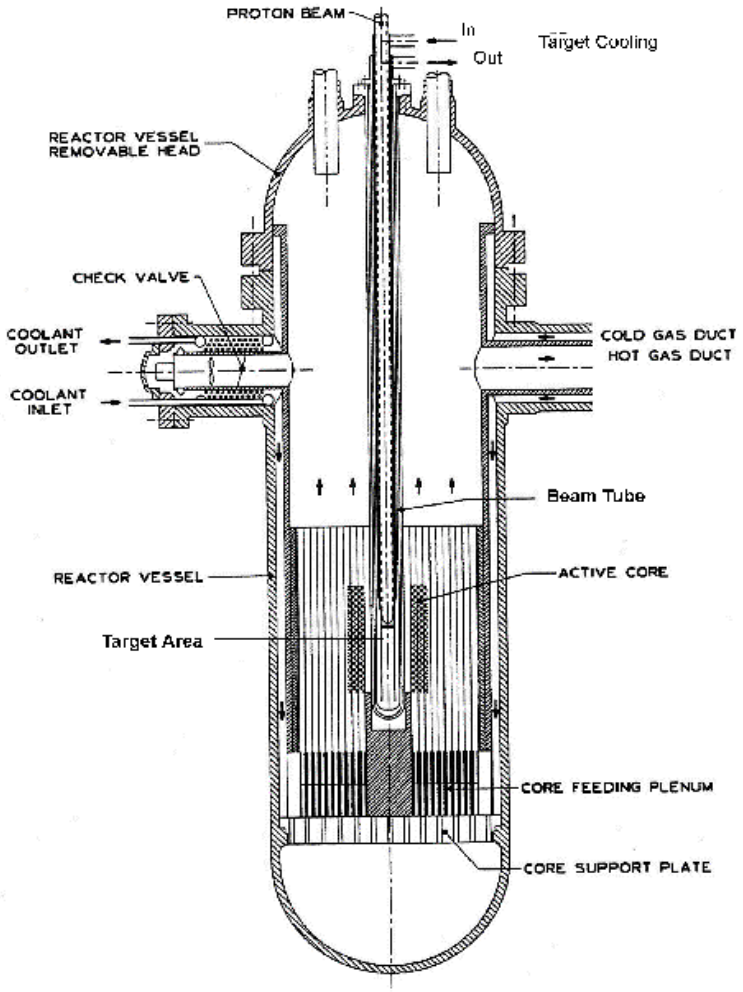
The discharge from the reactors is further burned-up in an accelerator driven MHR, or AD-MHR. This is step 6 in Figure 11. The AD-MHR core is very similar to the GT-MHR core, the primary difference being the provision for an accelerator target for neutron production by spallation, and a surrounding pressure vessel, both located in the central graphite reflector. This graphite reflector serves to moderate the spallation neutrons and produce a thermal flux spectrum in the fuel annulus.

The beam enters at the top of the vessel, and is directed onto the target in the middle of the core assembly to produce high-energy neutrons. However, methods are being evaluated to allow a straight side beam entry into the core assembly. This would eliminate the need for a 90-degree beam turn from its normal horizontal orientation to the vertical entry.

Following the GT-MHR and AD-MHR there would be a sub-critical fast neutron energy assembly used mainly to finish the job of burning minor actinides.

An elevation section of this modular, fast helium-cooled assembly (AD-FMHR) is shown in Figure 13. A similar design has been proposed by Framatome [3] also to burn Minor Actinides. In this concept, the proton beam enters at the top of the vessel and is directed onto the target in the middle of the core assembly to produce high-energy neutrons. However, as for the AD-MHR, methods are being evaluated to allow a straight side beam entry into the core assembly.

Figure 13. **Elevation AD-FMHR**



The fast helium-cooled assembly (AD-FMHR) shown in Figure 13 is based on the gas-cooled fast reactor (GCFR) developed by General Atomics in the 1970s with US DOE support. In the GCFR design, the elements in the core and blanket assembly are externally similar, and each element is hexagonally shaped. The overall length of the elements is 118.25 inches The structural material for the GCFR element was 20% cold worked type 316 stainless steel. Other structural materials, such as Inconel 718 and tungsten, are being considered for the AD-FMHR application, to ensure that a loss of flow or pressure accident does not result in fuel damage or release of fission products. The fuel and blanket elements are clamped rigidly and pre-loaded at their upper end into the grid plate. This preload force reacts on the upper face of the grid plate through a compression tube.

In the AD-FMHR, the fuel section of the elements would be 150 cm high, with 100-cm top and bottom blankets. The helium coolant would flow in the upward direction. The inlet temperature would be 300° C and the outlet temperature would be at least 530°C or higher, based on the use of high-temperature fuel coatings.

The assembly would use the same fuel form as envisioned for the liquid metal options that are also being considered. Obviously, no moderator material would be used. However, the use of ceramic-type high-temperature fuel coatings that would result in wider safety margins is being

investigated. Most of the fuel in this assembly would consist of minor actinides, which would allow the assembly to be fairly small. Sizes in the order of 60 to 100 MWt would be attractive. Fission products, such as ^{99}Tc and ^{129}I, could be placed in the outer blanket for transmutation.

The energy in the hot helium exiting the fuel would be available to either generate steam or directly drive a gas turbine and generate electricity.

The use of helium coolant in this accelerator-driven fast-spectrum sub-critical assembly offers important potential advantages, such as the following:

- Potential use of coated fuel with its capability to 1) withstand higher temperatures than other fuels, 2) retain radionuclides in the event of accidents, and 3) provide an extra long-life barrier for the retention of radioactivity in the repository.
- No metal-air or metal-water chemical reactions.
- No generation of mixed waste coolant.
- No leakage of highly toxic metal.
- Potential elimination of high pressure steam generators by using a direct-cycle gas turbine.
- Potentially harder neutron energy spectrum for more effective burning of actinides.
- Much more viable in-service inspection. In the gas-cooled assembly, the integrity of the fuel, fuel supports, etc. is easily observable, which provides for greater safety assurance.

Earlier analyses performed for the development of the GCFR showed that the natural circulation of helium would provide adequate passive cooling following a loss of forced circulation for reactor ratings up to 840 MWt. This capability needs to be explored beyond design basis events.

7. Conclusions

Gas-cooled nuclear reactor technologies offer the potential to eliminate essentially all weapons-useful material in nuclear waste, and achieve more than two orders of magnitude reduction in the amount of high-level waste. Repository heat loads and the toxicity of the waste are also significantly reduced. The process provides a durable transmuted waste form that is highly resistant to corrosion, without generating mixed waste.

The process uses thermal and fast neutron energy spectra. ^{239}Pu and other fissionable materials have large fission cross-sections in the thermal spectrum. Thus, they are fissioned in a thermal fission region of the transmuter. Minor actinides are more inclined to fission in a fast neutron energy spectrum. Thus, they are fissioned in a fast fission region of the transmuter.

The process has the potential to transmute about 75% of the waste in a nuclear critical mode. Then, use is made of a proton accelerator to generate spallation neutrons and drive the fission process in a sub-critical mode to deep levels of burn-up. Most importantly, these deep burn-up levels are achieved with no plutonium reprocessing. This is made possible by encapsulating the waste to be transmuted in ceramic-coated microspheres that accommodate large amounts of fission products in spherical expansion volumes.

Deep burn-up of ^{239}Pu and fissionable materials with no plutonium reprocessing, and the possible use of a fast neutron region within the thermal region in the transmuter, which precludes breeding, are important proliferation-resistance features of the proposed process.

Preliminary calculations suggest that the unique reactivity and cooling safety features offered by gas-cooled nuclear reactors can also be implemented in the proposed transmuter.

The use of a direct-cycle gas turbine-generator power conversion system with the proposed transmuter would lead to conversion efficiencies of approximately 47% when the transmuter is operating in the critical mode. This, along with the fact that the accelerator may only be needed for the 25% deep burn-up phase of the cycle, leads to a relatively high overall efficiency and low cost. Preliminary economic analyses suggest that the proposed transmutation process has the potential to be economically viable and attract investment for deployment.

REFERENCES

[1] D. Alberstein, A. Baxter, and W. Simon, *The Plutonium Consumption Modular Helium Reactor*, IAEA Technical Committee on Unconventional Options for Plutonium Disposition, November 1994, Obninsk, Russia.

[2] *Gas Turbine-Modular Helium Reactor (GT-MHR) Conceptual Design Description Report*, General Atomics report 910720, Rev. 1, July 1966.

[3] B. Carluec and P. Anzieu, *Proposal for a Gas-cooled ADS Demonstrator*, 3rd International Conference on Accelerator Driven Transmutation Technologies and Applications, Praha, Czech Republic, June 7-11, 1999.