Utilization Potential of Thorium in Fusion–Fission (Hybrid) Reactors and Accelerator-Driven Systems

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Abstract

World thorium reserves are approximately three times more abundant than natural uranium reserves. Furthermore, nuclear power plants are producing nuclear waste materials in substantial quantities in the form of minor actinides (MA). Large quantities of reactor-grade (RG) plutonium have been accumulated in the course of nuclear electricity generation over the past 50 years in civilian reactors as nuclear waste. Two emerging nuclear energy system for the utilization of thorium and reactor-waste actinides have been investigated. (D, T) fusion reactions produce highly energetic neutrons at 14.1 MeV, which can easily fission thorium. Calculations on a laser-fusion-driven fusion–fission (hybrid) reactor has led to fissile burnups exceeding 400,000 MWd/MT. In addition to fission energy production in situ, such a reactor would produce ~ 160 kg of ^{233}U per year. Highly energetic protons near the GeV range can destroy heavy nuclei so that each proton can initiate creation of multiple highly energetic neutrons, called evaporation neutrons or spallation neutrons. These secondary neutrons will themselves lead to the production of new neutrons in a cascade so that the proton energy will be multiplied through fission processes and, additionally, new fissile fuel will be bred from relatively passive nuclei, such as ^{232}Th and ^{238}U. Calculations have shown that the spallation neutron spectrum in infinite medium by incident 1 GeV protons can range from thermal up to 1 GeV. We note that the high energy tail plays an important role in neutron multiplication. The spallation neutron spectrum peaks at approximately 1 MeV. The maximum number of fission events per proton in ^{232}Th, ^{238}U, and natural uranium will be 2.754, 11.446, and 17.888, respectively. The corresponding combined ^{233}U and ^{239}Pu production will be 48.357, 69.013, and 78.045 atoms per incident proton.

Introduction

World thorium reserves are approximately three times more abundant than natural uranium reserves. Turkey, for example, is rich in thorium resources. Hence, thorium remains a potential energy source for future energy strategies in Turkey. At the same time, nuclear power plants are producing nuclear waste materials in substantial quantities in the form of minor actinides (MA). MA can be regarded as the most hazardous radioactive waste products because of their long-term, high-level radioactivity. A significant fraction of reactor-waste MA consists of diverse plutonium isotopes, which represent a source of serious public and political concern with respect to misuse of this plutonium and also accidental release of highly radiotoxic material into the environment.

The (D, T) fusion reaction produces highly energetic neutrons:

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha(3.5\ \mathrm{MeV}) + \mathrm{n}(14.1\ \mathrm{MeV}) \qquad (1)$$

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Thus, fusion neutron energy is significantly higher than the threshold fission energy of ^{232}Th and ^{238}U. Hence, passive isotopes become fissile fuel through irradiation with 14 MeV fusion neutrons. This would increase the potential exploitation of nuclear fuel resources several hundred-fold. Two emerging nuclear energy systems have shown great potential for the efficient utilization of thorium and reactor-waste actinides, and which are the subject of investigation in this work:

1. Thorium and reactor-waste actinides, either in the form of mixed fuel or separately, in fusion–fission (hybrid) reactors.
2. Thorium and reactor-waste actinides, either in the form of mixed fuel or separately, in accelerator-driven systems (ADS).

Minor Actinide Burning in Fusion–Fission (Hybrid) Reactors

Energy multiplication in a fusion–fission (hybrid) reactor could lead to early market penetration of fusion energy for commercial utilization. Progress at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) brings fusion into focus as a viable energy source in the foreseeable future. A hybrid reactor design concept, the so-called Laser Inertial Confinement Fusion Fission Energy (LIFE) engine, has emerged out of these considerations.

The neutron transport calculations have been performed by solving the Boltzmann transport equation with the SN transport code XSDRNPM in the S8-P3 approximation by using the 238-neutron groups' data library. The resonance self-shielding weighted cross sections have been processed for unresolved resonances and for resolved resonances. Hence, calculations are conducted with high precision.

In the investigated (LIFE) engine design, the first wall is made of oxide dispersion strengthened (ODS) steel (2 cm) and followed by a Li17Pb83 zone (2 cm), which acts as a neutron multiplier, tritium breeding, and front coolant zone. It is separated by an ODS layer (2 cm) from the FLIBE molten salt zone (50 cm), containing MA as fissionable fuel. A third ODS layer (2 cm) separates the molten salt zone on the right side from the graphite reflector (30 cm). For burnup and time calculations, a driver with constant fusion power of 500 MW$_{th}$, by a plant factor of 100 %, has been assumed. This gives a continuous neutron source strength of 1.774×10^{20} (14 MeV-n/s). The main coolant consists of FLIBE, a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF$_2$). MA carbide fuel is placed in the center of TRISO particles, as described in a separate work in these proceedings [1]. The particles are homogeneously dispersed and suspended as microparticles in the FLIBE coolant. The choice of TRISO-type fuel in FLIBE coolant gives three very significant advantages:

1. Very high fuel burnup capability of the TRISO fuel had been successfully demonstrated with Peach Bottom experiments: TRISO fuel pellets charged with plutonium were irradiated in the Peach Bottom Reactor over 30 years ago and reached burnup values in the range of ~740,000 MWd/MT without damage to the coated fuel particles (Fig. 1; adapted from the General Atomics reports [2, 3]).

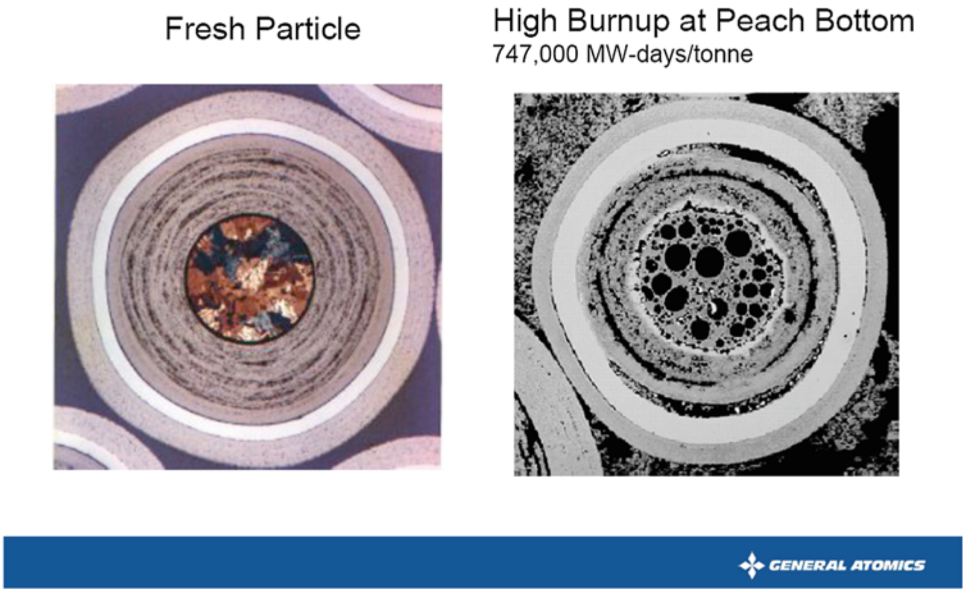
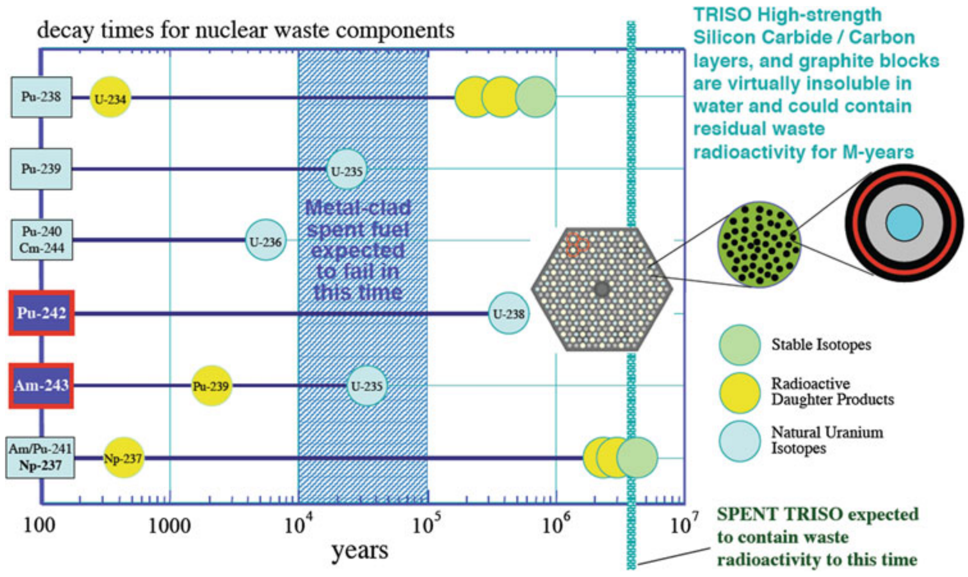


Fig. 1 Very high burnup in a ceramic-coated (TRISO) fuel, as experimentally demonstrated at Peach Bottom-1 Modular Helium Reactor (MHR). Adapted from [2, 3]



TRISO High-strength Silicon Carbide / Carbon layers, and graphite blocks are virtually insoluble in water and could contain residual waste radioactivity for M-years

SPENT TRISO expected to contain waste radioactivity to this time

Fig. 2 TRISO coating provides structure stability and contains fission products

2. Safe accommodation of highly radioactive fission products and fissionable elements over millions of years ($\sim$4 million years) would be possible. TRISO fuel can contain the totality of actinide isotopes produced over long periods without being damaged nor destroyed (Fig. 2; adapted from [2]). Actinides will be transformed in the capsule to either stable isotopes or uranium. Metal clad contains fission products for $\sim 10^4$–10^5 years.
3. The main coolant, FLIBE, remains free of all sorts of fission products provided that the TRISO particles do not fail. As no mechanical force will be applied to the TRISO particles, it can be assumed that TRISO failure is not expected.

The volume fraction of TRISO particles in the FLIBE coolant has been varied as 0, 2, 3, 4, and 5 %. Highly energetic 14 MeV neutrons confer additional neutron production through multiple fast fission processes on all actinide isotopes. This leads to enhanced breeding characteristics and energy multiplication in the blanket. The corresponding tritium breeding ratio (TBR) values have been calculated as TBR = 1.134, 1.286, 1.387, 1.52, and 1.67, respectively. Blanket energy multiplication values become at startup M = 1.36, 3.3, 4.6, 6.15, and 8.1, respectively. Tritium breeding and energy multiplication will be gradually reduced by the continued recycling of the same fuel charge over 10 years. This can be circumvented by seeding fresh fissile fuel periodically.

Under irradiation with 14 MeV fusion neutrons, all actinides become highly fissile materials. For the selected TRISO volume fractions in the FLIBE coolant, fissile burnup exceeds 400,000 MWd/MT. Drastic reduction of final nuclear waste per unit energy production is expected. TRISO particles can withstand such high burnups without being damaged (Fig. 1).

Major damage mechanisms at the first ODS wall, which directly faces the fusion chamber, have been calculated as dpa = 50 (displacements per atom) and He = 176 appm per year. Under these conditions, the first ODS wall will need to be changed approximately every 3 years. Hydrogen production is calculated as 648 appm per year [4]. But, the latter will not reside permanently in metallic lattice as helium atoms. Detailed analysis has been given in [5].

Thorium in Fusion–Fission (Hybrid) Reactors

The use of thorium in connection with fusion–fission (hybrid) reactors has been considered since the 1980s [6–11]. In a recent work, a detailed analysis has been outlined for a laser-fusion reactor for thorium production [12]. Calculations have been conducted with the MCNP6.1/MCNP5/MCNPX code [13] for continuous energy. The main results can be summarized as follow.

The reactor consists of a spherical fusion chamber of 5 m diameter, which is surrounded by a multilayer spherical blanket. The first wall is made of S-304 steel (2 cm) and is followed by the natural lithium coolant zone that is 50 cm thick. A second S-304 steel zone (2 cm) separates the coolant–fission zone on the right-hand side from the graphite reflector (30 cm). ThO_2 is placed in the kernel of TRISO particles, which are homogeneously dispersed and suspended as microparticles in the natural lithium coolant with volume fractions of V_{tr} = 1, 2, 3, 4, 5, and 10 vol%, as described above. Calculations with ΔR_{Li} = 50 by variable V_{tr}, yield TBR = 1.229, 1.222, 1.214, 1.206, 1.1997, and 1.1622, respectively. Parasitic neutron absorption in thorium

Table 1 Integral data for an infinite medium

Fuel	^{235}U(n, f)/p	^{238}U(n, f)/p or ^{232}Th(n, f)/p	Total (n, f)/p	E_f/p[a] (GeV) or M	k_∞	^{238}U(n, γ)/p ^{239}Pu/p or ^{232}Th(n, γ) ^{233}U/p
Nat-U	4.7068	13.181	17.888	3.241	0.764	78.0450
^{238}U	–	11.4455	11.4455	2.075	0.675	69.0129
^{232}Th	–	2.75408	2.75408	0.473	0.321	48.3568

[a] E_f = 190 MeV/fission

leads to a decrease in the TBR values. For $V_{tr} < 5$ vol% of TRISO in the coolant, the increase in the neutron absorption by thorium will be compensated to a great degree by neutron multiplications via ^{232}Th(n, f) and ^{232}Th(n, 2n) reactions, so that the sacrifice of TBR remains acceptable. However, for $V_{tr} > 5$ vol% of TRISO, neutron absorption by thorium increases rapidly. Conversely, blanket energy multiplication, M, increases with more thorium, that is, $M = 1.2206$, 1.2322, 1.2426, 1.2536, 1.2636, and 1.3112, respectively, owing to the contribution of the fission energy. Annual fissile fuel production in the blanket are calculated as 17.23, 33.09, 48.66, 64.21, 79.77, and 159.71 kg/year of ^{233}U, respectively. The reactor remains deeply subcritical with fissile blanket criticality values of $k_{eff} = 0.181$, 0.188, 0.195, 0.202, 0.209, and 0.273, respectively. This gives a high degree of reactor safety.

Thorium in Accelerator-Driven Systems

One of the potential exploitation options of thorium are accelerator-driven systems (ADS). A high-intensity linear accelerator with proton beam energy of 1 GeV, directed on heavy nuclei can cause evaporation of a great number of highly energetic spallation neutrons. These can initiate a cascade of secondary multiple fission neutron multiplication, all of which would result with energy multiplication and fissile fuel breeding. In that respect, a great number of papers have published with the expectation of high grade energy multiplication in a subcritical blanket criticality close to unity. A recent example has been presented at the Thorium Energy Conference (ThEC13) at CERN, where a subcritical value as high as $k_{eff} = 0.997$ and a gain factor of $G = 700$ was cited [14]. The most advanced experimental ADS project, MYRRHA [15], considers $k_{eff} = 0.97$ as the highest permissible blanket criticality limit with respect to reactor safety [16]. It is true that a proton-driven subcritical ADS with $k_{eff} < 1$ would increase the neutron level, and consequently, the fission energy level proportional to the inverse of the times $1/(1 - k_{eff})$. However, one would need either enriched uranium or plutonium to have a subcritical blanket criticality close to unity! Availability of such high-quality nuclear fuel would make such complicated machines like fusion hybrids or an ADS hybrid obsolete, because the same fuel can be used much more simply in conventional nuclear reactors with well-known technologies.

In preceding works, different models in the MCNPX code for ADS calculations have been compared [17–19]. In this work, we investigate the possible upper infinite medium criticality limits, that is, the maximum k_∞ values, for potential breeder materials, namely, metallic thorium, natural uranium, and ^{238}U. Calculations have again been conducted with the MCNP6.1/MCNP5/MCNPX code [13] for continuous energy with the CEM2 k model. Table 1 shows the volume and energy integrated values for fission rate, fission energy release (E_f), k_∞, and infinite fission energy blanket energy multiplication, M, for these breeder materials. One can easily see that the blanket criticality would remain deeply subcritical and energy multiplication via fission remains very modest, even for hypothetical infinite blanket dimensions. On the other hand, fissile material breeding properties are high and needs to be exploited.

Conclusion and Recommendations

A series of calculations has been carried out to assess minor actinides transmutation from LWR spent fuel, as well as the thorium breeding capability of laser-fusion hybrid reactors. The main conclusions can be summarized as follows.

Utilization of a TRISO-type fuel suspended in molten salt coolant or metallic coolant brings new advantages:

- Coolant is not damaged by radiation and, therefore, could be recycled over a long period provided that no particle failure occurs during reactor operation;
- Separation of fission products and highly radioactive actinides from the coolant allows simplified handling of molten salt coolant;
- Very high burnup (>400,000 MWd/MT) becomes achievable with the same nuclear waste charge;
- Thorium in liquid lithium coolant produces high-quality nuclear fuel and multiplies fusion energy;
- Drastic reduction of final nuclear waste per unit energy production will be possible;
- Permanent immobilization of residual radioactivity in TRISO spent fuel after irradiation due to containment of

fission products in the TRISO particles over millions of years;

- Infinite medium criticality calculations for potential breeder materials (metallic thorium, natural uranium, and ^{238}U) have revealed deep subcriticality and modest fission energy multiplication in the blanket; whereas, high-quality nuclear fuel breeding properties are very promising. For blanket criticality close to unity and higher fission energy multiplication values, either enriched uranium or plutonium will be needed. However, high-quality nuclear fuel can be used in a simpler way in conventional nuclear reactors with well-known technology.

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