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Abundant thorium as an alternative nuclear fuel Important waste disposal and weapon proliferation advantages

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HIGHLIGHTS

- Thorium is an abundant nuclear fuel that is well suited to three advanced reactor configurations.
- Important thorium reactor configurations include molten salt, CANDU, and TRISO systems.
- Thorium has important nuclear waste disposal advantages relative to pressurized water reactors.
- Thorium as a nuclear fuel has important advantages relative to weapon non-proliferation.

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ABSTRACT

It has long been known that thorium-232 is a fertile radioactive material that can produce energy in nuclear reactors for conversion to electricity. Thorium-232 is well suited to a variety of reactor types including molten fluoride salt designs, heavy water CANDU configurations, and helium-cooled TRISO-fueled systems.

Among contentious commercial nuclear power issues are the questions of what to do with long-lived radioactive waste and how to minimize weapon proliferation dangers. The substitution of thorium for uranium as fuel in nuclear reactors has significant potential for minimizing both problems.

Thorium is three times more abundant in nature than uranium. Whereas uranium has to be imported, there is enough thorium in the United States alone to provide adequate grid power for many centuries. A well-designed thorium reactor could produce electricity less expensively than a next-generation coal-fired plant or a current-generation uranium-fueled nuclear reactor. Importantly, thorium reactors produce substantially less long-lived radioactive waste than uranium reactors.

Thorium-fueled reactors with molten salt configurations and very high temperature thorium-based TRISO-fueled reactors are both recommended for priority Generation IV funding in the 2030 time frame.

1. Introduction

It has long been known that thorium-232 is a fertile radioactive material that after being irradiated with neutrons can produce energy in nuclear reactors for conversion to electricity. Thorium-232 performs this function by transmuting into uranium-233 permitting reactor energy by fission. As do other fertile materials, thorium-232 requires a source of neutrons for the transmutation to take place, from a fissile material (such as uranium-235 or plutonium 239) or from an external source such as spallation neutrons. Thorium-232 appears in nature unmixed with isotopes, does not require enrichment for use as reactor fuel, and only needs relatively inexpensive chemical separation from ore impurities.

The thorium-232/uranium-233 cycle is well suited to a variety of reactor types. They include molten fluoride salt designs, heavy water CANDU configurations, and helium-cooled TRISO-fueled systems. An additional concept in which neutrons are generated by an energy amplifier rather than from a radioactive source element has also been proposed.

Among contentious commercial nuclear power issues are questions of what to do with long-lived radioactive waste and how to minimize weapon proliferation dangers. The substitution of thorium for uranium as fuel in nuclear reactors has significant potential for minimizing (but not eliminating) both problems.

Adding to the advantages of thorium is the fact that it is 3–4 times more abundant in nature than uranium. Whereas uranium has to be imported, there is enough thorium in the United States to provide adequate grid power there for many centuries. Advocates claim moreover that a well-designed thorium reactor could produce electricity less expensively than a next-generation

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coal-fired plant or a current-generation uranium-fueled nuclear reactor. Importantly, thorium reactors produce substantially less long-lived radioactive waste than uranium reactors. In principle, thorium waste can be reduced to the radioactive levels of ordinary coal ash.

Thorium reactors are discussed herein from historical, radiological, and energy production perspectives. The focus is on long-term cost reduction, on substantial radioactive waste reduction, and on the minimization of the inherent dangers from the presence of materials needed for weapons.

Thorium fueled reactors with molten salt cores, and very high temperature thorium-based TRISO-fueled reactors are both recommended for priority Generation IV funding in the 2030 time frame. These reactor configurations have been demonstrated as prototypes and have substantial advantages related to safety, nuclear proliferation and waste disposal. Externally supplied spallation neutron sources for fertilizing thorium-232 is another technology worthy of support but it is not yet ready for prototyping. We recommend an intensive research activity that could lead to affordable spallation neutron sources that are of sufficient energy and power to substitute for fission-generated neutrons.

2. Historical perspective

Thorium was isolated in 1828 by the Swedish chemist Jons Berzelius who named it for the Norse god of thunder. Found by Marie Curie to be radioactive in 1898, Ernest Rutherford subsequently investigated its disintegration products and lifetime. Thorium was determined to be very stable, having existed in nature for more than four billion years.

The nuclear power industry has a long record of experimentation with thorium fuel cycles. That history encompasses several reactor configurations: high-temperature gas reactors (HTGR), pressurized water reactors (PWR), and molten salt reactors (MSR). A fourth configuration using an energy amplifier (EA) to produce spallation neutrons has more recently been proposed.

2.1. High temperature gas reactors

High temperature gas reactor designs using thorium fuel were proposed by the Oak Ridge National Laboratories in 1947. That research led to the Peach Bottom, PA 40-MW reactor that produced electricity from 1966 to 1974. A scaled up 300-MW version was then built and operated at Fort St Vrain, CO from 1976 to 1989. Those reactors, fueled with oxides and di-carbides of thorium-232 and uranium-235, were arrayed in prismatic graphite cores. The coolant was helium.

The German THTR-300 was the first commercial power station to operate almost entirely with thorium. It was a helium-cooled high-temperature pebble-bed reactor that produced electricity from 1983 to 1989. The fuel was TRISO (triple-coated isotropic) containing thorium kernels embedded in a graphite matrix. Intermixed in each kernel was uranium-235 acting as a driver for fertilizing the thorium. The kernels were packaged in baseball-sized spherical pebbles whose outer layer was graphite. The THTR-300 generated 300-MW of power and was scaled from an earlier 15-MW installation.

Japanese and Chinese agencies have both recently implemented domestic thorium-based TRISO-fueled reactors. The Japanese high temperature test reactor went on line in 1999 with a power of 30-MW. It contains a prismatic core configuration and has a high enough outlet temperature to dissociate hydrogen from water. The HTR-10 Chinese version was completed in 2003. It is a pebble bed design, has a power of 10-MW, and is intended as a prototype. The first two full-scale Chinese 250-MW designs are scheduled for 2013 commissioning.

An American-designed gas-cooled reactor, the high temperature teaching and test reactor using ceramic-coated thorium kernels is also under construction. That facility in Odessa, TX will have either a pebble-bed or prismatic-block core. The earliest operational date is 2015.

The United States-led Generation IV International Forum has identified very high temperature reactors (VHTR) among the candidates for hydrogen production, coal gasification, and desalination applications along with electricity production. Intended for commissioning by 2030, the nominal VHTR is a 600-MW gas turbine system with TRISO fuel.

2.2. Liquid water-cooled thorium reactors

A 100-MW pressurized light water reactor operated at Shippingport, PA from 1977 until 1982. The 285-MW Indian Point reactor in Buchanan, NY was commissioned in 1962 and ran until 1980. Both were fueled with thorium-232 oxide pellets and a lesser amount of uranium-235.

India, with about 25% of the world's natural thorium reserves, has begun testing critical components for the Advanced Heavy Water Reactor (AHWR300-LEU). It is a 300 MW, vertical, pressure-tube type, boiling light-water cooled, and heavy-water moderated reactor. The fuel for the reactor is 19.75% enriched uranium oxide and thorium oxide; on the average, 39% of the power is obtained from the thorium. The reactor has a number of passive safety features and a fuel cycle that has reduced environmental impact (Bhabba Atomic Research Centre). India plans to meet 30% of its total power requirements in 2050 by using thorium-fueled reactors.

2.3. Molten salt thorium reactors

The liquid fluoride thorium reactor (LFTR) is a thermal breeder that uses thorium fuel dissolved in molten salt to generate energy. It operates at high temperature and atmospheric pressure. First researched at Oak Ridge National Laboratories in the 1960s (Rosenthal et al., 1971), it has more recently been investigated by nuclear agencies in the United Kingdom, and by private companies in the United States and Australia. The United States-based Flibe Energy Co has recently proposed development of a small modular LFTR using liquid Li/Be fluoride eutectic salt mixtures (Kirk Sorensen, 2011). The Flibe LFTR objective is a 20–50-MW modular design to power military bases. Fielding of such a reactor is estimated to require at least 5–10 years of development.

Development thorium fuel programs using molten-salt technology have also been initiated in Japan and China. The Japanese Fuji molten salt reactor is a 200-MW thermal breeder that has support from the United States and Russia. It is characterized as inherently safe, chemically inert, and operates under low pressure to prevent explosions and toxic releases. The Fuji would require about 20 years at the current rate of development for an operating reactor. The Chinese molten salt project is in a similar time frame. The Chinese thorium-breeding molten-salt reactor is the largest national effort in the world using that technology.

2.4. Accelerator-driven nuclear energy

Neutrons to fertilize thorium need not be provided by a fissile source such as uranium or plutonium. Neutrons can instead be generated by energy amplifiers and impacted on the thorium for fertilization. Professor Carlo Rubbia at the European Council for Nuclear Research (CERN) has proposed such a neutron source both to generate electricity and heat, and to incinerate long-lived

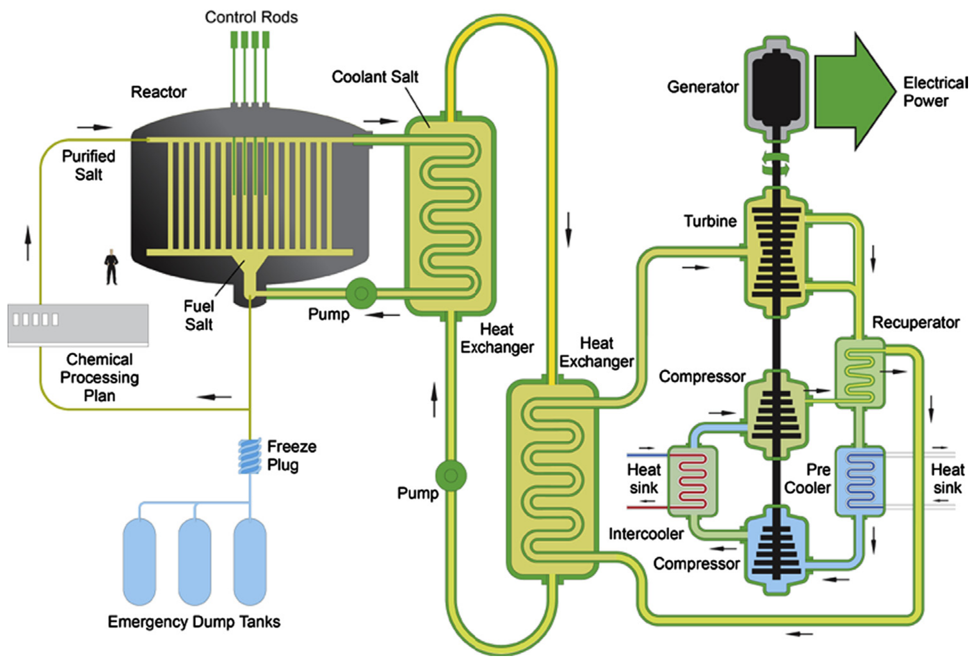

Fig. 1. MSBR molten salt breeder reactor (This diagram is a schematic concept of the reactor system and does not literally represent the Gen IV design.) Oak Ridge National Laboratory—(Rosenthal et al., 1971).

actinides (Carlo Rubbia). If implemented, it would permit operations at the subcritical level and thereby significantly increase safety. It would also greatly reduce the nuclear waste storage task. Although extensive research is required for practicality, the Rubbia approach may lead to more politically acceptable reactor configurations.

2.5. IAEA and other thorium reviews

The International Atomic Energy Agency (IAEA) has independently published a comprehensive study of the thorium fuel cycle in International Atomic Energy Agency (2005). It includes a summary of both experimental and commercial thorium power reactors as of the 2001 time frame; see Michael and Otto (1998) for additional reviews.

3. Reactor design configurations

A variety of thorium cycle design configurations exist. A convenient way to differentiate between them is by core type: molten salt, solid rod bundles, prismatic TRISO, and pebble bed TRISO.

3.1. Molten salt reactors

The Oak Ridge National Laboratory research resulted in a two-fluid design and was called the molten salt breeder reactor (MSBR). It is depicted in Fig. 1. The fuel identified on the left side is liquid

$LiF–BeF_2–ThF_4–UF_4$ (72–16–12–0.4) and the secondary coolant on the right is liquid $NaF–NaBF_4$. Graphite rods serve as a moderator. 2–8 MW designs, suitable for submarine power or aircraft propulsion, were produced. (Historically, those research activities were known as the aircraft reactor experiment and the molten salt experiment). They are the bases of the Generation IV MSR Reactor for the 2030 time frame.

The Gen IV MSR has a number of advantages:

- It uses an abundant nuclear fuel: thorium.
- It possesses inherent safety with passive components and a strong negative temperature coefficient of reactivity; i.e., when the temperature in the reactor increases, the rate of nuclear fission decreases.
- It generates substantially less radioactive residue than pressurized or boiling water reactors. The discharge wastes are predominantly fission products which have relatively short half-lives. This results in practical geologic repository containment periods of a few hundred years compared to tens of thousands of years for light water reactor waste.
- It burns problematic residual actinide wastes.
- It reacts much more quickly to load changes then do traditional solid-fuel reactors.
- It possesses a substantial (although not foolproof) degree of proliferation resistance.

3.2. Solid core thorium reactors

The most straightforward approach for a solid-core thorium reactor is to substitute thorium fuel rod bundles for uranium bundles in an otherwise conventional light water configuration. Thorium fuel-rod bundle concepts were developed by Professors Radkowsky and Galperin (1998).[1]

A number of rod configurations have been found feasible and two are depicted in Fig. 2. Note that these are new fuel assembly designs, not new reactors. They are intended for retrofit into existing pressurized light water reactors with minimum changes to existing hardware. The Radkowsky thorium reactor addresses weapon proliferation concerns by avoiding the isolation of uranium-233. It is under development by the Lightbridge Corporation in conjunction with Russia's Kurchatov Institute.

Another solid-core alternative is the standard CANDU reactor displayed in Fig. 3. It is a pressurized heavy water design using natural uranium or thorium oxide as fuel. Thorium-fueled systems

[1] Radkowsky was the chief scientist of the United States Navy's nuclear propulsion program from 1950–1972 and headed the team that built the Shippingport facility.

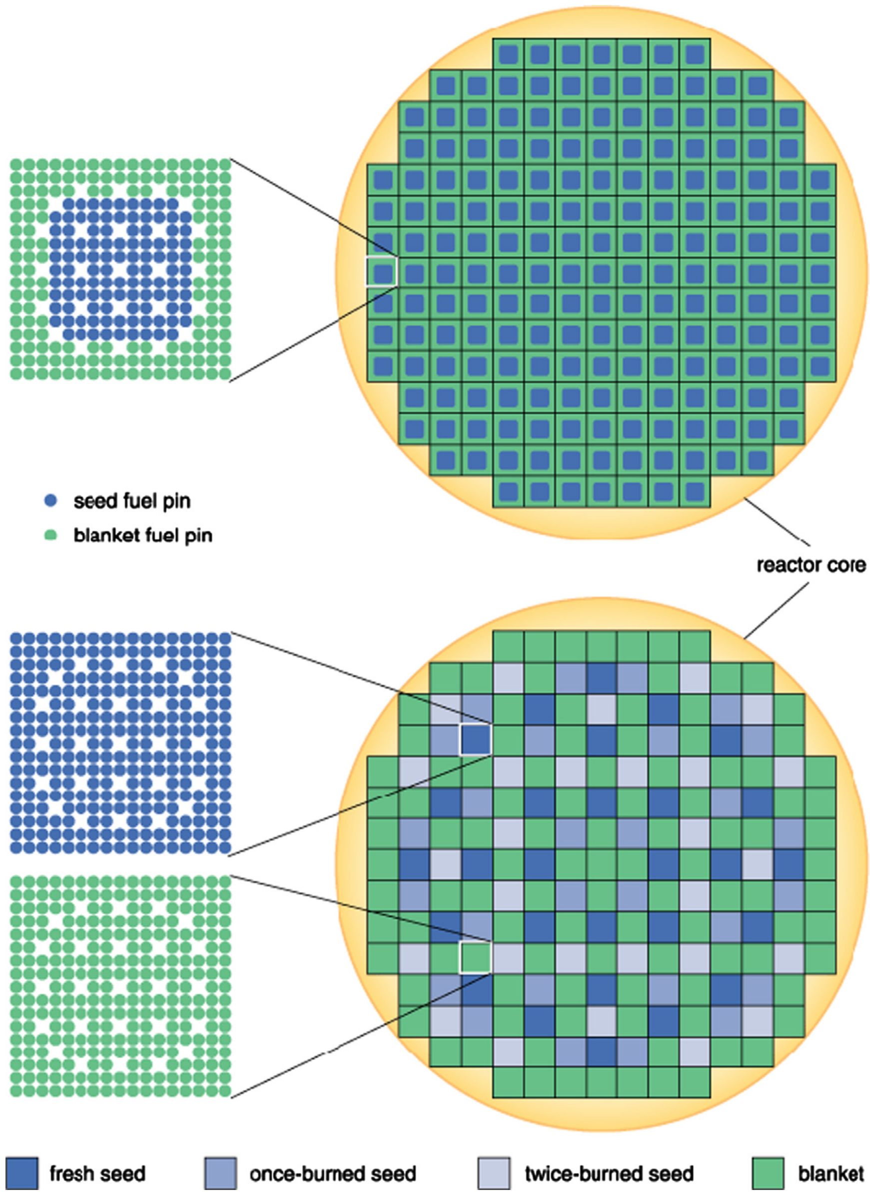

Fig. 2. Alternative seed blanket fuel assembly designs. Radkowsky and Galperin, (1998).

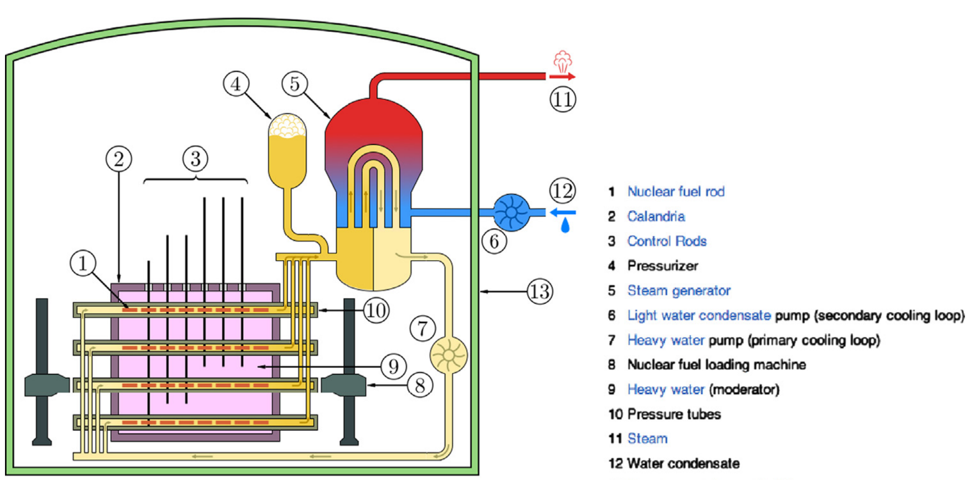

Fig. 3. CANDU configuration with natural uranium or thorium fuel (Roubin, 2005).

of course need a separate source of neutrons to generate fissionable uranium-233.

Some unique features of CANDU reactors are:

- Use of online refueling—CANDU systems use robotic machines to fuel the reactor with natural uranium or thorium oxide while it is in operation. They are therefore continuous in operation and not "batch". As illustrated in Fig. 3, automated machines hook up to the pressure tubes at both ends, push in the new fuel and simultaneously extract the spent fuel.
- Since CANDU uses heavy water both as a coolant and an enhanced moderator, neutrons resulting from fission are used more efficiently and there are fewer losses. This allows the use of natural uranium or thorium as fuel and saves the cost of enrichment. (However, the downside is the very high cost of heavy water. The initial cost of heavy water in a typical CANDU is more than $300 million).
- CANDU uses pressure tubes rather than pressure-vessel type reactors. To allow the neutrons to flow freely between tubes and bundles, they are made of neutron-transparent zircaloy (International Atomic Energy Agency, 1998).
- CANDU reactors normally use natural uranium as fuel. The discharge from such reactors contains 98.7% uranium-238, 0.8% fission products, 0.4% plutonium, and trace amounts of other transuranics. If thorium is used instead of natural uranium, the burn-up is much more complete. Thorium transmutes to fissionable uranium-233 and generates no uranium-238. The volume of fission products is much higher but in principle, these fission products can be removed chemically and stored separately in geologic repositories.

3.3. Accelerator driven systems

In 1996, Professor Carlo Rubbia at CERN proposed the concept of an energy amplifier or "Accelerator Driven System (ADS)" as a way to produce nuclear energy, exploiting existing accelerator technologies. Rubbia's proposal also offers the potential to incinerate high-activity nuclear waste while producing energy from thorium-232 or depleted uranium.

Fig. 4 depicts the energy amplifier proposed by Professor Rubbia. The core is surrounded by liquid lead that serves both as a spallation target and as a medium to transport energy to four 375-MW heat exchangers. The configuration assumes a separate particle accelerator that emits protons with about 12-MW of power and 1-GeV of kinetic energy. The protons impact the liquid lead producing neutrons through spallation. The overall installation cost is estimated at billions of dollars primarily for the high-energy proton beam.

Alternative ADS systems of reduced kinetic energy are also being studied at a number of facilities worldwide (World Nuclear Organization).

- The Kyoto University Reactor Institute has conducted an experiment that projected a 100 MeV proton beam on to a heavy metal target. The neutrons produced by spallation were then used to bombard a sub-critical fuel core.
- The Indian Atomic Energy Commission is conducting design studies for a 200 MW Pressurized Heavy Water Reactor employing an ADS fueled by thorium and natural uranium. The initial fuel charge would contain about 140 t of natural uranium that would be progressively replaced with thorium so that ultimately there would be a full thorium core irradiated by U-233 and the ADS. A 30 MW accelerator would run it.
- The Belgian Nuclear Research Center (SCK-CEN) will begin construction of the MYRRHA research reactor in 2015. Initially it will deliver a 600 MeV, 2.5 mA proton beam to a liquid lead-bismuth spallation target that couples to a subcritical fast nuclear core (MYRRHA).
- A UK-Swiss proposal for a 600 MW accelerator-driven thorium reactor that uses plutonium as a starter is in the feasibility stage. Molten lead is both the spallation target and the coolant. This system requires only a 3–4 MW accelerator.

Clearly the long pole in the ADS tent is the need for a less expensive, more reliable high-energy accelerator. This could come from improved LINAC technology or from development of circular accelerator alternatives; e.g., non-scaling fixed field alternating gradient accelerators or superconducting cyclotrons. Overall, the near-term prospects are not encouraging. A 2008 Norwegian study of the prospects for ADS driven thorium reactors asserts that such a system is not likely to operate within the next 30 years (Thorium Report Committee, 2008).

3.4. Prismatic TRISO reactors

TRISO fuel has been employed in two reactor varieties. The first variant loads fuel in annular prismatic blocks that are removed and replaced after a six-year burn-up. Typical of the design, the joint Russian Federation-General Atomics Gas Turbine—Modular Helium Reactor (GT-MHR) is displayed in Fig. 5 (Kiryushin and Kodochigov, 2002). It couples a helium-cooled reactor with a Brayton cycle gas turbine energy conversion system. The fuel consists of kernels of thorium and uranium oxide packaged and stacked in the annular core. The right-hand side depicts the reactor and the left-hand side the power conversion unit. The reactor delivers 286-MW of electrical power.

GT-MHR TRISO fuel kernels are based on a design dating to the 1970s. They are packaged into cylindrical fuel elements. (Other TRISO fuel designs employ spherical elements called pebbles.) The cylindrical elements are 13 mm in diameter by 51 mm long and there are a total of 1020.

The same fuel is also being studied in the context of a prismatic reactor that uses molten fluoride salt as coolant. The reactor is the advanced high-temperature reactor (AHTR) being developed by Oak Ridge National Laboratories (Ingersoll, 2005). It combines four existing technologies in a new synergism:

- Passively safe pool-type fast reactor
- Brayton power cycle
- High-temperature TRISO fuel
- High-temperature, low-pressure liquid salt coolant

The AHTR is described as having superior economics. Construction costs are about half those of the GT-MHR deriving in part from economies of scale. It has 2650 fuel elements and a projected electrical power of 1,235-MW. However, the AHTR is only in an early phase of development, the expected operational date being 2025.

3.5. Pebble bed TRISO reactors

The second TRISO variant is the pebble bed reactor. It employs a continuous fuel loading/unloading process. Fig. 6 displays the design of both the reactor and the power generation unit.

The pebble bed TRISO fuel contains thorium and enriched uranium kernels each of which is coated successively with layers of porous carbon, pyrolytic carbon, and silicon carbide. As in the prismatic configurations, the layers create a barrier against fission product release while facilitating the transfer of heat energy. In effect, each fuel kernel is a miniature pressure vessel. The fuel

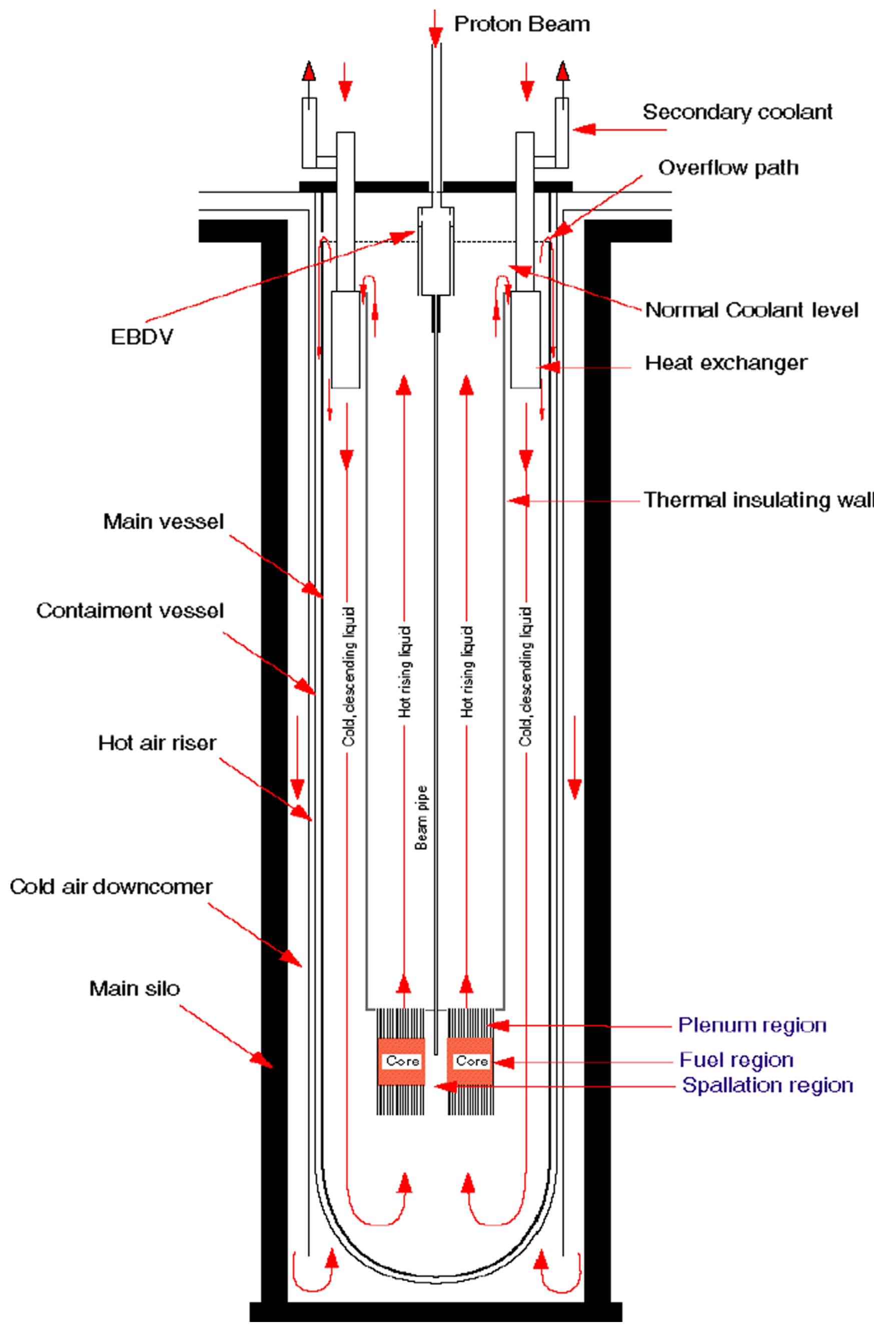

Fig. 4. General layout of the energy amplifier. Carlo Rubbia, CERN.

kernels, each about 1 mm in diameter, are embedded in a 50-mm graphite sphere. Each spherical pebble contains about 15,000 kernels, and a typical reactor contains several hundred thousand spheres (Kadak, 2004).

Fresh pebbles are mechanically fed into the top of the reactor and burned pebbles are removed from the bottom. The coolant is helium. The burn-up is very high, maximizing fuel efficiency and minimizing the waste disposal problem. The waste pebbles are suitable for storage in underground facilities.

If thorium is to be used as the principal TRISO fuel, it can exploit uranium-235 oxide in either of two ways. Thorium kernels can be interspersed with uranium oxide kernels within the fuel spheres, or a mixture of thorium and uranium oxide fuel spheres can be intermingled. The principal function of the uranium is to generate neutrons that will be moderated by both the graphite and the helium to fertilize the thorium, thus producing fissionable uranium-233.

4. Summary of thorium fuel cycles

Table 1 summarizes the various thorium cycles considered. Organized by core type, they include molten salt, solid core bundled rods, prismatic TRISO, and pebble bed TRISO.

5. Thorium wastes

When thorium-232 captures a neutron, it transmutes to thorium-233. It then spontaneously undergoes beta decay to

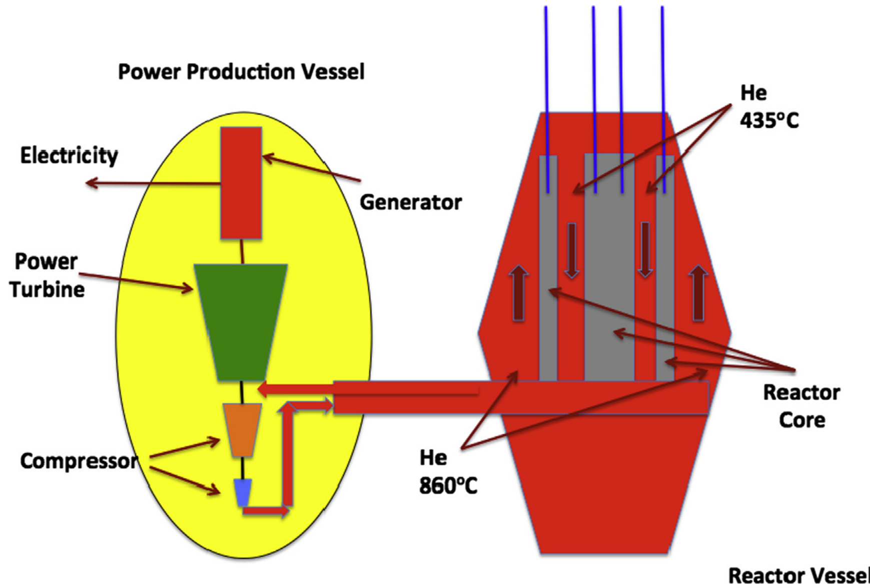

Fig. 5. GT-MHR prismatic TRISO module. General Atomics, April 2002.

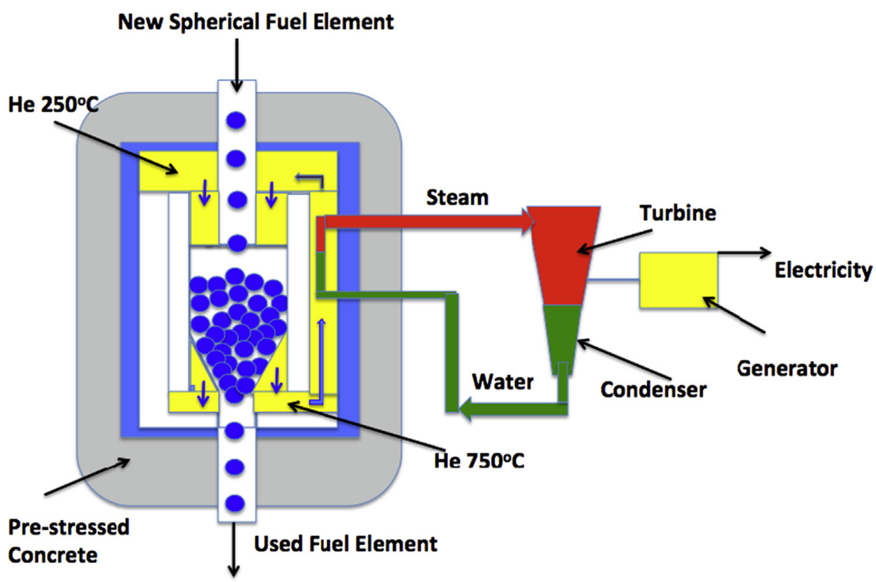

Fig. 6. TRISO fuel pebble bed reactor. Andrew Kadak, MIT (Kadak, 2004).

become protactinium-233 followed by another beta decay to uranium-233. The total transmutation has a half-life of 27 days. Thus, after 9 months, what was originally thorium-232 is now 99.9% uranium-233. This is summarized by

$$n+{}^{232}Th_{90}\rightarrow{}^{233}Th_{90}-\beta^{-}\rightarrow{}^{233}Pa_{91}-\beta^{-}\rightarrow{}^{233}U_{92}$$

Thorium fission cycles produce radioactive wastes consisting of actinides and lower atomic weight elements. According to IAEA, the actinide wastes can be fully recycled. Moreover, the lower atomic waste products decay to negligible radioactive levels after a few hundred years. Thorium fuel wastes are thus suitable for sub-surface storage facilities.

6. Proliferation resistance

Uranium-233 as transmuted in the thorium fuel cycle is typically contaminated with uranium-232 and is not easily separated from it. Uranium-232 has several decay products that emit high-energy gamma radiation, a radiological hazard that necessitates the use of remote handling equipment. As long as that material is in a reactor, it is not a problem and is eventually burned while producing energy. However, if the uranium-233 is removed and used for producing a military bomb, the trace uranium-232 can damage the accompanying electronics. Although it has been used in some early nuclear bomb tests, uranium-233 is therefore largely proliferation-resistant, more so than uranium-235 and plutonium-239. Proliferation resistance of thorium has recently been discussed by S.F. Ashley et. al. (Proliferation Resistance of Thorium-UraniumFuel2.)[2]

[2] S.F. Ashley et al., point out that uranium-233 does not have to be contaminated with uranium-232. There are small-scale chemical techniques permitting extraction of pure protactinium-233 that decays to ultra-pure uranium-233. The upshot is that thorium-232 is proliferation-resistant but not proliferation-foolproof.

Table 1
Candidate thorium cycles. Author.

Core type	Configuration	Coolant	Moderator
Molten salt	Two fluid reactor	Li fluoride	Graphite
		Be fluoride	Graphite
	Single fluid reactor	LBF eutectic	
Solid core rod bundles	CANDU	Deuterium	Deuterium
	Thorium blanket	Molten salt	Graphite
	Energy amplifier	Molten lead	None
TRISO (Prismatic)	VHTR/HTGR	Helium	Graphite
	LS-VHTR	Liquid salt	Graphite
TRISO (Pebble bed)	Thorium/uranium mixed-fill pebbles	Helium	Graphite
	Mixture of thorium and uranium pebbles	Helium	Graphite
	LS-VHTR	Liquid salt	Graphite

To reiterate, thorium-232 can be used to breed uranium-233 useful for producing commercial energy and possibly for making nuclear weapons. However, if a molten salt reactor configuration is used, only a small amount of uranium-233 is made. It is difficult to extract, and is contaminated with highly radioactive uranium-232. The proliferation potential is therefore low. Moreover, by adding uranium-238 to the thorium, the troublesome uranium-233 can be denatured and made non-critical through dilution.

7. Availability, extraction and driving costs

Thorium ore is distributed widely throughout the world. Monazite containing 6–12% thorium phosphate is the primary source. Thorium is extracted from monazite through a complex multi-stage process. Monazite sand is first dissolved in hot concentrated sulfuric acid, and thorium is then extracted in an organic phase containing an amine. Next it is stripped in an aqueous ionic solution and finally thorium oxide is precipitated (Barghusan and Smutz, 1958).

Table 2 summarizes world thorium reserves. India, the United States, Australia and Canada have the largest resources.

Thorium comes out of the ground as a usable isotope that does not require enrichment. In contrast, natural uranium contains only 0.7% fissionable uranium-235 and generally requires expensive enrichment (to 3–5% or more) when used in commercial light water reactors. Separation of the uranium isotopes is done principally by gaseous centrifugation of UF_6 and requires many stages forming a cascade (Fig. 7). New centrifuge plant construction in the United States is very costly, approximately $1–3 billion (World Nuclear Association).

Estimated driving costs for a number of reactor alternatives are summarized in Table 3. Light water reactors are impacted by high uranium costs that are initially three times the cost of thorium and further impacted by the cost of enrichment. Illustratively, a 2007 cost estimate for 5% enriched uranium in a 1300 MW reactor was about 75 million dollars annually (Simnad). Given the expectation that enriched uranium costs will continue to increase over the long term, we estimate an average $100 million per year. Over a 50-year lifetime, uranium costs would then total 5 billion dollars. Another big-ticket item for light water reactors is the reactor vessel itself, the cost of which is small relative to enriched uranium fuel but nevertheless amounting to about one billion dollars.

On the other hand, CANDU-6 reactors achieve big savings in fuel but depend on heavy water whose estimated initial cost is about 0.3 billion dollars per reactor. Although heavy water is not consumed, there is inevitable leakage. Over a 50-year lifetime, heavy water costs might total about 0.4 billion dollars (Jackson).

Table 2
Thorium reserves. United States Geological Survey—2010.

Country	Tonnes
United States	440,000
Australia	300,000
Brazil	16,000
Canada	100,000
India	290,000–650,000
Malaysia	4,500
South Africa	35,000
Other countries	90,000
World total	1,300,000–1,660,000

Fig. 7. Cascade of gas centrifuges. Piketon Ohio 1984.

Accelerator-driven systems or energy amplifiers are conceptually very attractive for transmuting thorium into uranium-233. The big cost driver for energy amplifiers is clearly the huge investment for the required energetic proton-neutron source.[3] If future research and development can bring energetic proton costs down to a more manageable level, energy amplifiers would be a leading contender for thorium reactors.

That leaves very high temperature gas reactors with TRISO fuel, and liquid fluoride thorium reactors as the leading contenders for

[3] One possibility is the proton accelerator in the MYRRHA research reactor being developed at the Belgian Nuclear Research Center (MYRRHA).

Table 3
Driving costs for competing reactors. Author estimates.

Reactor type	Costly component	Cost magnitude ($)
Light water reactors	Enriched uranium	~5 Billion
	Large pressurized reactor	~1Billion
CANDU reactors	Heavy water	~400 Million
Energy amplifiers	Linac or circular equivalent	Billions
VHT gas reactors	Helium	10–20 Million
LFTR reactors	Molten salt plus containment	Millions

future thorium fuel exploitation. The driving cost for high temperature gas reactors is for helium. Although it is a limited resource, helium is 40–500 times less costly than competing reactor alternatives. The cost of molten salt technology together with containment is even less costly.

8. Why thorium

The principal arguments for thorium rather than uranium as fuel for nuclear reactors are the ones stated in the title: thorium is considerably more abundant than uranium; thorium reactors can be configured to minimize the waste storage issue; and thorium reactors are less conducive to proliferation of weapons grade materials. Thorium will be an attractive fuel in 3–4 decades for countries like the United States since it is abundant in both the raw material and the starter materials. The waste disposal issue will be a significant driver, and less so the proliferation issue. However, the United States has a developed nuclear infrastructure and as long as U/Pu costs are low, there is little incentive to change. For countries like India that have a super-abundance of the raw material, thorium will be a near-term driver. It is understandable that India will develop domestic sources of heavy water for the short term and want to develop energy amplifier technology for the long term. For other new nuclear countries, the choice between Th/U/Pu will largely be based on the availability of a secure source for the basic materials. In the short term while energy amplifiers are not available, it is more likely they will opt for U/Pu as the basic fuel. In 3–4 decades, that calculus could change dramatically.

9. Summary

Thorium has a long history of use as a nuclear fuel. Thorium-232 is a fertile material that can be transmuted into uranium-233 for production of fissile energy in reactors. The process requires a source of neutrons either from a fissile starter or from an external source such as an energy activator. The thorium-232/uranium-233 cycle is well suited to a variety of reactor types. They include molten fluoride salt designs, heavy water CANDU configurations and helium-cooled TRISO-fueled systems.

The most promising for near-term applications are the molten salt configurations. They are inherently safe having passive nuclear safety with strong negative temperature of reactivity coefficients, and operate at atmospheric pressure. They substantially diminish the long-term radio-toxicity of the reactor wastes, typically burning transuranic elements and reducing their effect by more than a thousand compared to uranium light water reactors. Remaining radioactive fission products are of relatively low longevity with a typical half-life of 30 years and are suitable for burial in rock or clay. Thorium fueled reactors with molten salt configurations can additionally be made weapon proliferation resistant by denaturing with uranium-238.

Very-high-temperature reactors using thorium-based TRISO fuel and helium coolant-moderators are also promising. In particular, spent TRISO fuel elements are safe for underground storage as waste and are not prone to water table leaching.

These systems contain none of the cost “show-stoppers” associated with other thorium approaches. Thorium is abundant and does not require enrichment. Thorium-fueled reactors with molten salt configurations and very high temperature thorium-based TRISO-fueled reactors are both recommended for priority Generation IV funding in the 2030 time frame. For the longer term, the energy amplifier approach warrants support provided affordable energetic proton accelerators are developed and demonstrated.

References

Andrew C. Kadak, A Future for Nuclear Energy—Pebble Bed Reactors, Massachusetts Institute of Technology, April , 2004.

Barghusan, John, Smutz, Morten, 1958. Processing of monazite sands. Industrial and Engineering Chemistry, 1754–1755.

Bhabba Atomic Research Centre, AHWR300-LEU advanced heavy water reactor with LEU-Th MOX fuel, Department of Atomic Energy, Mumbai, India, 〈http://www.barc.gov.in/reactor/ahwr.pdf〉.

Carlo Rubbia, The Energy Amplifier—A Description for Non-Specialists, CERN/ET Internal Note 96-01, 1/5/1996.

David Jackson, http://〈http://reactorscanada.com/2008/05/21/is-there-enough-heavy-water-for-more-candu-reactors/〉.

Ingersoll, D.T., Status of Physics and Safety Analysis for the Liquid-salt-Cooled Very High Temperature Reactor (LS-VHTR), Oak Ridge National Laboratory ORNL/TM-2005/218, December , 2005.

International Atomic Energy Agency, Assessment and Management of Aging Major Components Important to Safety: CANDU Pressure Tubes, IAEA TECDOC-1037, Vienna, 1998.

International Atomic Energy Agency, Thorium Fuel Cycle—Potential Benefits and Challenges, IAEA-TECDOC-1450, May 2005.

Kiryushin, A., Kodochigov, N. GT-MHR Project, OKB Mechanical Engineering, Russian Federation, 2002.

Kirk Sorensen, Flibe Energy Inc., 2011 Thorium Energy Conference, Huntsville, AL 10/10/2011.

〈http://www.myrrha.sckcen.be〉. MYRRHA: Multi-purpose hybrid research reactor for high-tech applications.

Massoud T. Simnad, Nuclear reactor materials and fuels, University of California, San Diego, pdf. 〈http://cryptocomb.org/〉.

Michael, Lung, Otto, Gremm, 1998. Properties of the thorium fuel cycle. Nuclear Engineering and Design 180, 133–146.

Rosenthal, M., et al., 1971. Molten Salt Reactor Program, ORNL-4728. Oak Ridge National Laboratory 8/31 〈http://www.rusi.org/downloads/assets/〉.

Radkowsky, Alvin, Galperin, Alex, 1998. The non-proliferative light water thorium reactor: a new approach to light water reactor technology. Nuclear Technology 124.

Roubin, B., Basic CANDU Design, 〈http://www.unene.ca/un8023-2005/bin/BasicCANDUDesign.pdf〉, University Network for Excellence in Nuclear Engineering, 2005.

Thorium Report Committee, Norwegian Ministry of Petroleum and Energy, Thorium as an Energy Source—Opportunities for Norway, 2008.

World Nuclear Association, 〈http://www.world-nuclear.org/info/inf28.html〉.

World Nuclear Organization, Accelerator-driven nuclear energy, 〈http://www.world-nuclear.org/info/inf35.html〉.