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Part-2: Small Nuclear Reactors: How Hunger for Power Will Unite Artificial Intelligence and Uranium/Thorium Mining. SMRs with Uranium and Thorium

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"One of the fastest ways to address climate change is by transitioning our society to carbon-free energy sources, and nuclear energy is both carbon-free and able to scale—which is why it's an important area of investment for Amazon. Our agreements will encourage the construction of new nuclear technologies that will generate energy for decades to come.": Matt Garman, CEO of Amazon Web Services (AWS)

"All in all, the total amount of power conceivably available from the uranium and thorium supplies of the earth is about twenty times that available from the coal and oil we have left."

— Isaac Asimov

Abstract

SMRs are compact, reliable, versatile, require minimal land and have the potential for standardized mass-manufactured production that can achieve the scale of deployment required to meet many clean power, heat and clean fuel production use cases for heavy industry, data centres and transport. Recent headlines highlight a strong demand signal for advanced nuclear – major tech giants Microsoft, Amazon, and Google have all publicly made commitments to procuring nuclear energy for their US operations. Due to their size and modular construction, these reactors could be sited within the existing footprint of existing coal plants, or co-located with refineries, steel, chemical and aluminium plants – to directly and competitively–replace fossil fuels by supplying heat, power, steam or hydrogen to enable continued operation of existing assets, including transmission, without emissions. In the US, only the opportunity exists to add up to 174 gigawatt-electric (GWe) of new nuclear capacity at 145 retired or retiring coal plant sites and up to 95 GWe additional capacity at existing nuclear plant sites. The overall prospect of these technologies is discussed in this part.

Keywords: *ANNEL, Safety, Security, Thorium reactors, Uranium*

1.0 Safety and Security

Generally, modern small reactors for power generation, and especially SMRs, are expected to have greater simplicity of design, the economy of series production largely in factories, short construction times, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in malfunctions[1-7]. Figure 11 picturises the issues pertaining to SMR safety and security. Also, many are designed to be emplaced below ground level, giving a high resistance to terrorist threats. A 2010 report by a special committee convened by the American Nuclear Society showed that many safety provisions necessary, or at least prudent, in large reactors are not necessary for the small designs forthcoming. This is largely due to their higher surface area to volume (and core heat) ratio compared with large units. It means that a lot of the engineering for safety, including heat removal in large reactors, is not needed in the small reactors. Since

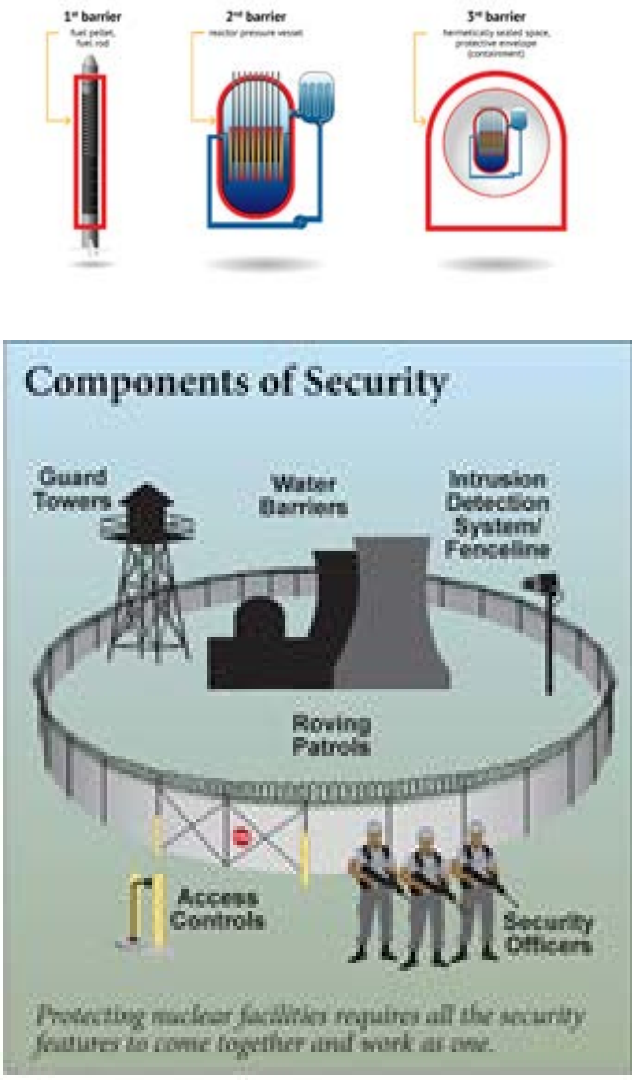


Figure 11. Safety and security preparations of the nuclear plants.

small reactors are envisaged as replacing fossil fuel plants in many situations, the emergency planning zone required is designed to be no more than about 300 m radius. The combined tables from this report are appended along with notes of some early small water-, gas-, and liquid metal-cooled reactors.

Licensing is potentially a challenge for SMRs, as design certification, construction and operation licence costs are not necessarily less than for large reactors. Several developers have engaged with the Canadian Nuclear Safety Commission's (CNSC's) pre-licensing vendor design review process, which identifies fundamental barriers to licensing a new design in Canada and assures that a resolution path exists. The pre-licensing review



Figure 12. The seven pillars of nuclear safety are also applicable to SMR.

is essentially a technical discussion, phase 1 of which involves about 5000 hours of staff time, considering the conceptual design and charged to the developer. Phase 2 is twice that, addressing system-level design. Figure 12 shows the 7 pillars of nuclear safety also applicable to SMR.

> In Washington, our agreement with Energy Northwest, a consortium of state public utilities, will enable the development of four advanced SMRs. The reactors will be constructed, owned and operated by Energy Northwest, and are expected to generate roughly 320 megawatts (MW) of capacity for the first phase of the project, with the option to increase to 960 MW total—enough to power the equivalent of more than 770,000 U.S. homes. These projects will help meet the forecasted energy needs of the Pacific Northwest beginning in the early 2030s.: Amazon release.

The enormous potential of SMRs rests on several factors:

i. Because of their small size and modularity, SMRs could almost be completely built in a controlled factory setting and installed module by module, improving the level of construction quality and efficiency.
ii. Their small size and passive safety features lend them to countries with smaller grids and less experience with nuclear power.

iii. Size, construction efficiency, and passive safety systems (requiring less redundancy) can lead to easier financing compared to that for larger plants.
iv. Moreover, achieving 'economies of series production' for a specific SMR design will reduce costs further.

The World Nuclear Association lists the features of an SMR, including:

i. Small power and compact architecture and usually (at least for nuclear steam supply system and associated safety systems) employment of passive concepts. Therefore, there is less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation.
ii. The compact architecture enables modularity of fabrication (in-factory), which can also facilitate the implementation of higher quality standards.
iii. Lower power leading to reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors).
iv. Potential for the subgrade (underground or underwater) location of the reactor unit, providing more protection from natural (*e.g.* seismic or tsunami according to the location) or man-made (*e.g.* aircraft impact) hazards.
v. The modular design and small size lend themselves to having multiple units on the same site.
vi. Lower requirement for access to cooling water – therefore suitable for remote regions and specific applications such as mining or desalination.
vii. Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

There are a number of small modular reactors coming forward requiring fuel enriched at the top end of what is defined as Low-Enriched Uranium (LEU) – 20% U-235. The US Nuclear Infrastructure Council (NIC) has called for some of the down blending of military HEU to be only to about 19.75% U-235, to provide a small stockpile of fuel which would otherwise be very difficult to obtain (since civil enrichment plants normally cannot go above 5%). A reserve of 20 tonnes of High-Assay Low-Enriched Uranium (HALEU) has been suggested. The NIC said that the only supply of fuel for many advanced reactors under development would otherwise be foreign-enriched uranium. "Without a readily available domestic supply of higher enriched LEU in the USA, it will be extremely difficult to research advanced reactors, potentially driving American innovators overseas." In 2019, the DOE contracted with Centrus Energy to deploy a cascade of large centrifuges to produce HALEU fuel for advanced reactors. Urenco USA has announced its readiness to supply HALEU from a dedicated production line at its New Mexico plant.

2.0 The Global Supply and Demand Situation for Uranium and Thorium

The uranium industry includes production of this heavy metal in about 20 countries, with the largest volumes coming from Kazakhstan. About 60% of the world's uranium reserves are located in four countries: Australia, Kazakhstan, Russia and Canada. At present, thorium consumption is quite small in the global market. The metal is recovered from monazite, which is mined in India, Malaysia, Vietnam, and Brazil. Large thorium resources are located in the USA, Canada, Greenland, Australia and other countries[6,7].

2.1 Uranium

Demand for uranium is expected to increase in the coming decades. The World Nuclear Association's 2023 Nuclear Fuel Report predicts a 28% increase in demand from 2023 to 2030 and a 51% increase from 2031 to 2040. On the supply side, the amount of uranium available is estimated to be between 9 and 22 million tonnes. However, supply is expected to decrease over time, so new assets will be needed to meet demand. Figures 13 and 14 show the production and demand positions of both Uranium and Thorium.

2.2 Thorium

Thorium has potential as a sustainable energy technology, but there are several challenges. Thorium is a by-product, and it's more expensive to extract than uranium. Thorium is fertile but not fissile, so it needs a driver like uranium or plutonium to maintain a chain reaction. Globally, there's a lack of experience with thorium, so research, development, and testing of thorium-powered nuclear installations is expensive. As thorium has recently been getting popularity as a potential nuclear energy source, countries conduct research into the subject. Among those are China, India, and Norway. There are a number of

exploration and development projects related to thorium in the USA, Canada, Brazil, India, and South Africa.

The current Thorium market is focussed on the following sectors:

i. Gas Mantles
ii. Electronic Equipment Coating
iii. Refractory Material Manufacturing
iv. Camera lens/Scientific Instrument
v. Nuclear Reactor
vi. Heat Resistant Ceramics

2.3 Uranium Requirement

Small Modular Reactors (SMRs) and other advanced reactor designs require HALEU, which has a U-235 concentration of 5-20% (Figure 15)[8]. HALEU is not yet widely available commercially, but Russia and China have the infrastructure to produce it at scale. The United States' Centrus Energy began producing HALEU in October 2023. LEU is uranium with a uranium-235 (U-235) concentration of less than 20%. Uranium is considered LEU if it has a U-235 concentration of less than 20%. Most commercial reactors use LEU with a U-235 concentration of 3-5%, which is also known as "reactor-grade uranium". LEU can be safely stored for many years because it doesn't deteriorate. Uranium with a U-235 concentration of more than 20% is considered highly enriched uranium (HEU). HEU is used in: naval propulsion reactors, such as in submarines, nuclear weapons, and some research reactors.HALEU is produced in the Russian Federation and the United States of America, mostly for use in research reactors and for possible use in operating light water reactors. The facility in Russia is currently the only one that manufactures HALEU on a commercial scale.

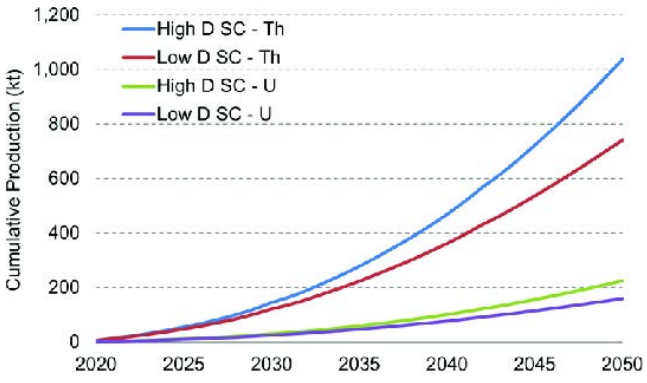


Figure 13. Cumulative global production projection.

The licensing, building, securing and operation of such facilities require significant investment, and the producers say they still need to see the business case for that investment. The US nuclear industry is warning that the deployment of some SMR designs may be delayed by years due to the lack of HALEU. Currently, nine out of ten advanced reactor designs funded by the US Government will need HALEU fuel in the next decade. Projections by the US Department of Energy (DOE) suggest that more than 40,000 kilograms of HALEU will be needed by 2030, with that amount set to grow year after year as the new fleet of advanced reactors is put into operation.

> HALEU-converted research reactors are currently supplied with fuel from Russia and the USA, and the latter says that it can only guarantee this supply until 2035 or 2040, due to the current lack of HALEU production capabilities, which increases the risk of supply shortage for the research reactors to be converted in the future.

Another type of HALEU fuel is beginning to be produced for use by down-blending government stockpiles of highly enriched uranium. Tristructural isotropic (TRISO) particle fuel is made of uranium, carbon and oxygen covered in three layers of carbon- and ceramic-based materials that prevent the release of radioactive fission products. These particles can then be shaped into either billiard-ball-sized spheres called pebbles or cylindrical pellets. TRISO-HALEU fuel is used in high-temperature gas-cooled reactors, and some vendors are planning to use TRISO-HALEU fuel for their SMR and microreactor designs.

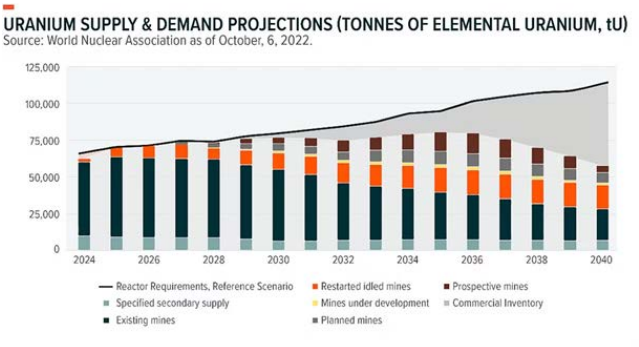


Figure 14. We are heading towards a global Uranium Shortage globally.

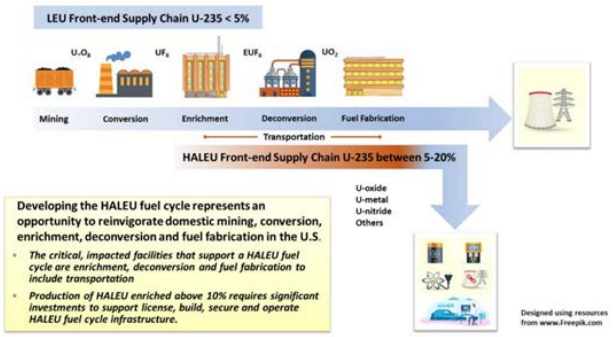


Figure 15. HALEU fuel cycle.

2.4 Four Companies to Boost U.S. HALEU

The U.S. Department of Energy (DOE) has awarded contracts with a total potential value of $8 million to four nuclear fuel companies to further U.S. enrichment capabilities for HALEU, a critical piece of the next-generation nuclear supply chain. The selected companies include Centrus Energy's American Centrifuge Operating, URENCO's Louisiana Energy Services, Orano Federal Services, and General Matter. The DOE on Oct. 17, 2024, said the contracts would allow the selected companies to bid on future work to produce and store HALEU in the form of uranium hexafluoride gas (UF6), which will eventually be made into fuel for advanced reactors." All contracts will last for up to 10 years, and each awardee will receive a minimum contract of $2 million, with up to $2.7 billion available for these services, subject to the availability of appropriations," the agency said. The HALEU that DOE acquires through these contracts "will be used to support reactors like those under development through DOE's Advanced Reactor Demonstration Program—TerraPower's Natrium reactor and X-energy's Xe-100," it noted.

2.5 Thorium in Place of Uranium

Thorium is a promising fuel option for Small Modular Reactors (SMRs) because it can be used as a fertile fuel and a poison[8-10]. It is three to four times more abundant in nature than uranium but historically has found little use in industry or power generation (Figure 16). This is partly because thorium in itself is not a nuclear fuel, but it can be used to create one. Thorium-232, the only naturally occurring isotope of thorium, is a fissionable material but not a fissile one, meaning that it needs high-energy neutrons to undergo fission—the splitting of atomic nuclei which releases energy that is used for electricity generation. However, when irradiated, thorium-232 undergoes a series of nuclear reactions, eventually forming uranium-233, a fissile material that can be burned up as fuel in nuclear reactors (Figure 17). It has several advantages over uranium:

> As we continue on our path to net-zero carbon, we recently announced that we matched all of the electricity consumed by our global operations with 100% renewable energy—seven years ahead of our 2030 goal. As the energy needs of our business and customers continue to grow, we're continuing to invest in renewables while also finding additional sources of carbon-free energy that can both help power our operations and bring new sources of energy to the grid. Nuclear power is one part of that mix—it can be brought online at scale, and has a decades-long record of providing a reliable source of safe carbon-free energy for communities around the world. : Amazon release

2.6 Abundance

Thorium is more abundant than uranium, and there is enough to supply nuclear power for thousands of years.

2.7 Sustainability

Thorium can reduce the demand for uranium, and it can help address concerns about the environmental impact of conventional nuclear energy.

2.8 Safety

Thorium reactors do not emit greenhouse gases and produce less long-lived nuclear waste than other reactors.

2.9 Neutron Characteristics

Thorium has superior neutron characteristics, including a higher conversion ratio and neutron flux.

2.10 Fuel Efficiency

Thorium has the potential for higher fuel efficiency.

Here are some other benefits of using thorium in SMRs:

- *Reduced burnable poison*: Thorium can be used as a poison to reduce the amount of burnable poison needed.

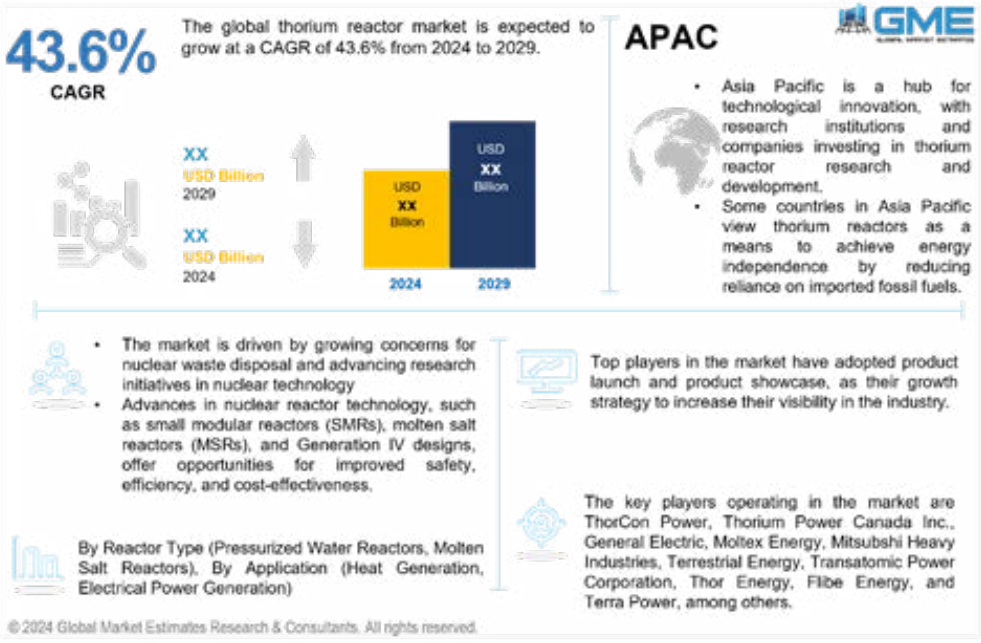


Figure 16. The global thorium reactor market.

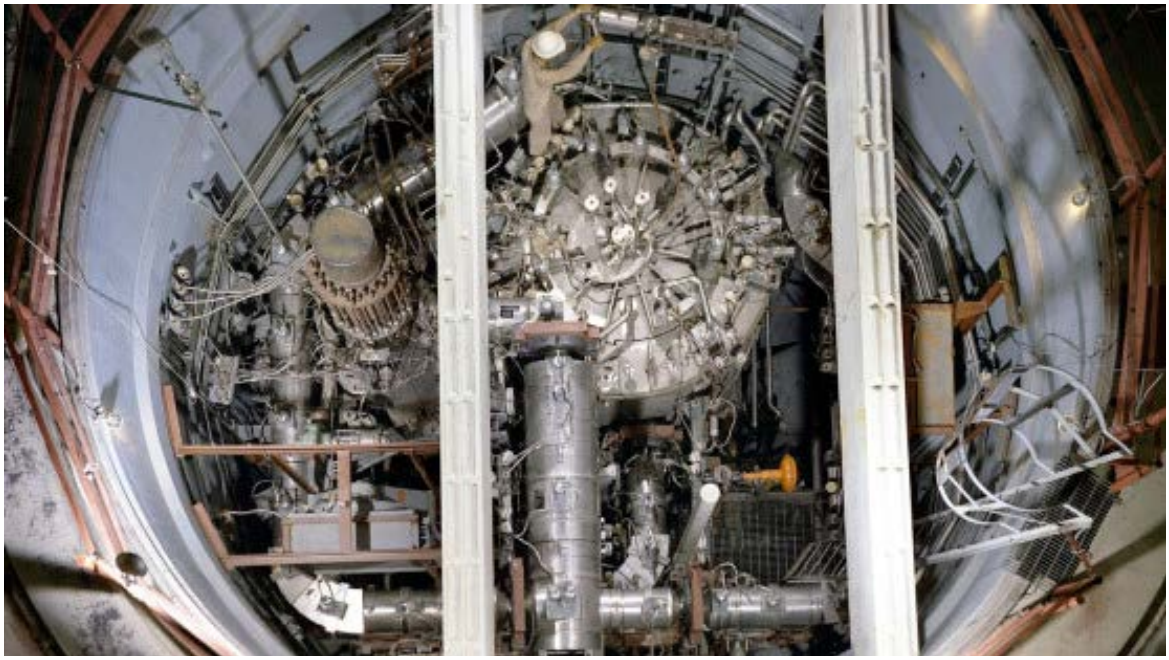


Figure 17. Early experimental thorium-based nuclear reactor at Oak Ridge National Laboratory, USA, 1960s (Photo: Oak Ridge National Laboratory/US DOE).

- *Extended burnup cycle*: Thorium can be used to extend the burnup cycle.
- *Reduced plutonium production*: Thorium fuel cycles produce significantly fewer plutonium isotopes than other fuel cycles.

SMRs are designed to operate for a complete cycle without refueling, and some can operate for up to 30 years without refueling.

In August 2021, China announced the completion of its first experimental thorium-based nuclear reactor.

Built in the middle of the Gobi Desert in the country's north, the reactor will undergo testing over the next few years. If the experiment proves successful, Beijing plans to construct another reactor capable of generating electricity for more than 100,000 homes.

For countries like India, a new development is exciting. Although India has only around 1–2% of the global uranium reserves, thorium reserves are bigger; around 12–33% of global reserves, according to IAEA and US Geological Survey. Several in-depth independent studies put Indian thorium reserves at 30% of the total world thorium reserves. India has a three-stage nuclear power program: Stage 1: Existing nuclear reactors burn uranium to produce power. Stage 2: Reactors breed plutonium as they consume it. Stage 3: Thorium is converted to uranium-233 (233U) in a nuclear reactor and used as fuel. India has been working on thorium since the beginning of its nuclear program. They have developed technology for mining, fuel fabrication, irradiation, and recycling of 233U fuel (Figure 18).

2.11 ANNEL

ANNEL, the nuclear fuel developed by Clean Core Thorium Energy (CCTE), a patented combination of thorium oxide and Halo, has expectations of change. This proprietary mix requires minimal uranium, offering a prolonged burn-up of 60,000 MWhours—nearly eight times more than conventional fuels. The result? A cleaner, safer, and more efficient energy source. ANNEL fuel can fast-track the use of thorium, aligning with India's three-stage program. Commercializing ANNEL fuel as early as 2026, making it market-ready for a sustainable energy transition[11,12].

ANEEL, or Advanced Nuclear Energy for Enriched Life, is a new nuclear fuel that combines thorium and uranium to create a cleaner, safer, and more efficient energy source. The fuel is designed to be used in pressurized heavy water reactors, such as Canada Deuterium Uranium (CANDU) reactors, and is developed by Clean Core Thorium Energy, a Chicago-based company.

ANEEL is said to have several advantages, including:

a) Reduced waste: ANEEL can reduce the volume of nuclear waste produced by over 85%.
b) Reduced operating costs: ANEEL can reduce operating costs.
c) Longer burn-up: ANEEL has a longer burn-up.
d) More efficient burning: ANEEL burns more efficiently.
e) Cannot be used for weapons: ANEEL is proliferation-resistant and cannot be used for weapons.

ANEEL is named after Dr. Anil Kakodkar, a prominent nuclear scientist and former chairman of the Atomic Energy Commission (AEC), India. India has the world's largest reserves of thorium, which could last for over a century. Some say that if India uses its thorium, it could produce enough green energy to meet its net-zero target by 2070.

Engineering major Larsen & Toubro (L&T) and US-based nuclear fuel company Clean Core Thorium Energy (CCTE) have signed a Memorandum of Understanding (MoU) to provide efficient solutions in clean energy globally. Through the partnership, L&T and CCTE aim to accelerate nuclear power deployment globally, particularly in developing countries that require large amounts of carbon-free electricity for their growth, the company said in a regulatory filing. This would be provided through CCTE's patented fuel advanced nuclear energy for enriched life (ANEEL).

3.0 Opportunities and Challenges

3.1 Opportunities

Thorium boasts several advantages over the conventional nuclear fuel, uranium-235. Thorium can generate more fissile material (uranium-233) than it consumes while fuelling a water-cooled or molten-salt reactor. According to estimates, the Earth's upper crust contains an average of 10.5 parts per million (ppm) of thorium, compared with about 3 ppm of uranium.

Another advantage is that thorium-fuelled reactors could be much more environmentally friendly than their uranium counterparts. In addition to the fact that these reactors—and nuclear power in general—do not emit greenhouse gases in operation, they also produce less long-lived nuclear waste than present-day uranium-fuelled reactors.

3.2 Not Without Challenges

However, there are several economic and technical obstacles to the deployment of thorium. Despite its abundance, the metal is currently expensive to extract[13].

Thorium (Th-232) is not itself fissile and so is not directly usable in a thermal neutron reactor. However, it

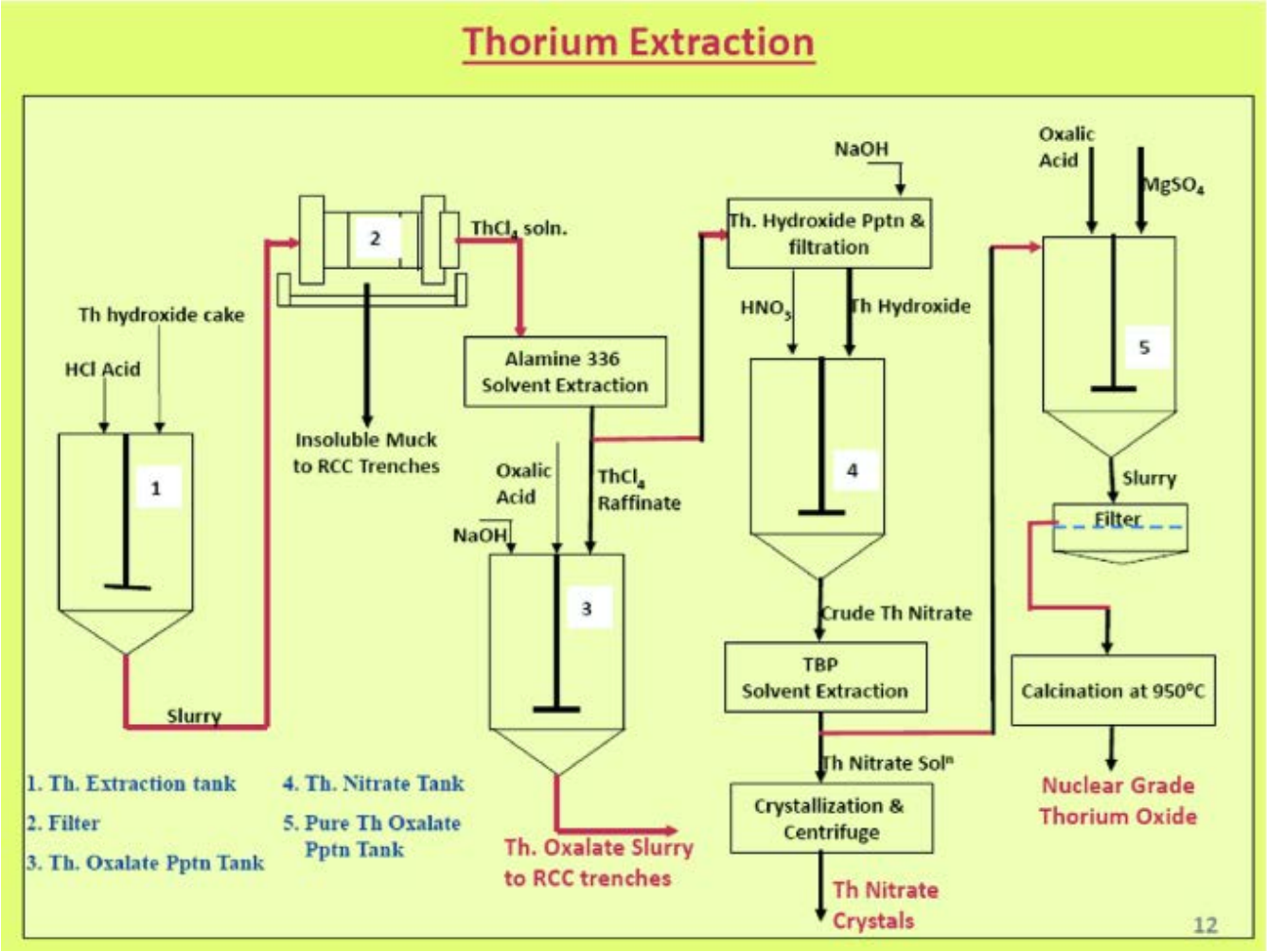


Figure 18. Thorium extraction.

is 'fertile' and, upon absorbing a neutron, will transmute to uranium-233 (U-233)[a], which is an excellent fissile fuel material[b]. In this regard, it is similar to uranium-238 (which transmutes to plutonium-239). All thorium fuel concepts, therefore, require that Th-232 is first irradiated in a reactor to provide the necessary neutron dosing to produce protactinium-233. The Pa-233 that is produced can either be chemically separated from the parent thorium fuel and the decay product U-233 and then recycled into new fuel, or the U-233 may be usable 'in-situ' in the same fuel form, especially in Molten Salt Reactors (MSRs) (Figure 19).

> "Because of its abundance and its fissile material breeding capability, thorium could potentially offer a long-term solution to humanity's energy needs," Kailash Agarwal, a Nuclear Fuel Cycle Facilities Specialist at the IAEA.

Thorium fuels, therefore, need a fissile material as a 'driver' so that a chain reaction (and thus a supply of surplus neutrons) can be maintained. The only fissile driver options are U-233, U-235 or Pu-239. (None of these is easy to supply)[13,14].

An important principle in the design of thorium fuel systems is that of heterogeneous fuel arrangement in which a high fissile (and therefore higher power) fuel zone called the seed region is physically separated from the fertile (low or zero power) thorium part of the fuel – often called the blanket. Such an arrangement is far better for supplying surplus neutrons to thorium nuclei so they can convert to fissile U-233; all thermal breeding fuel designs are heterogeneous. This principle applies to all the thorium-capable reactor systems (Figure 20).

In Norway, Thor Energy is developing and testing a thorium-bearing fuel for use in existing nuclear power plants. Fuel rods containing thorium additive (Th-Add)

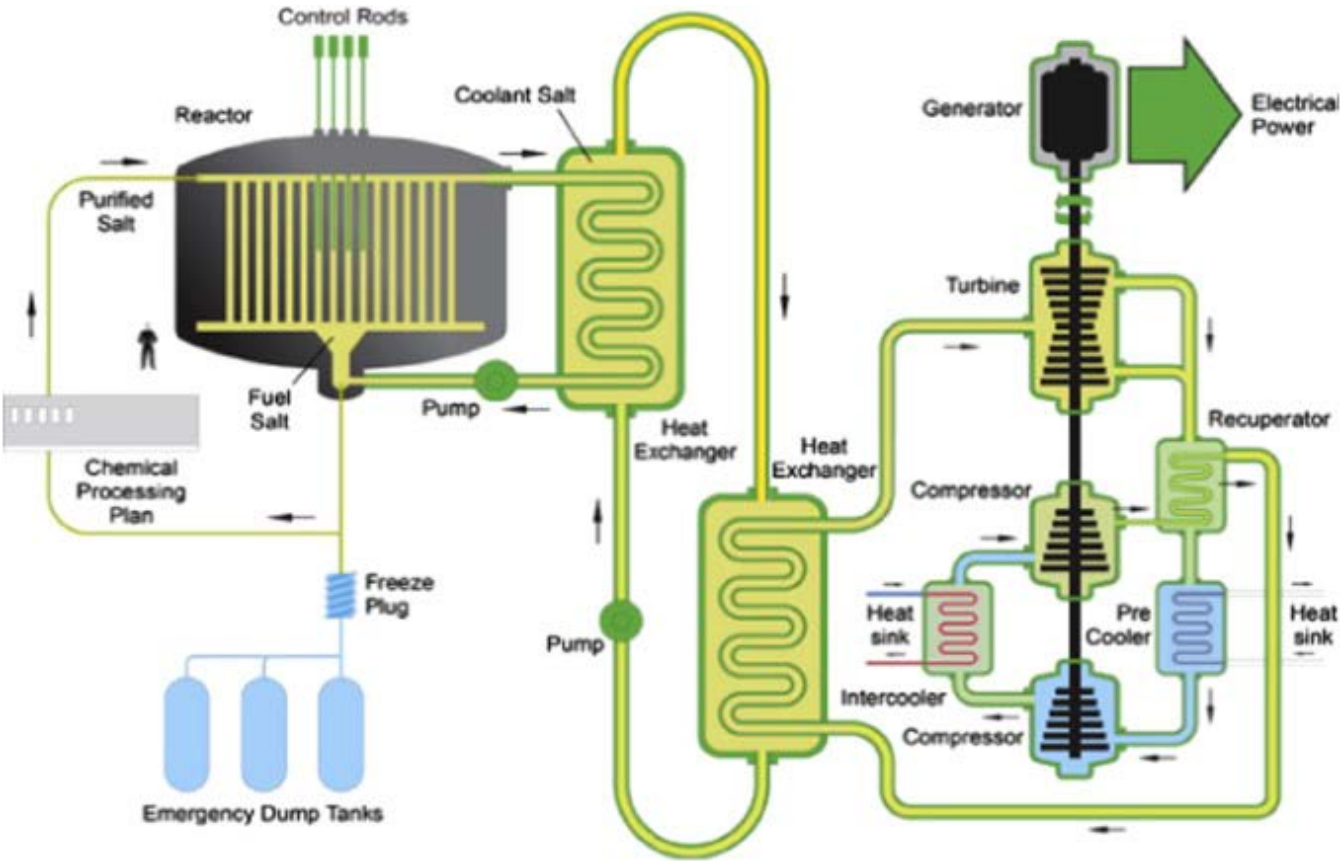


Figure 19. Thorium reactor schematic.

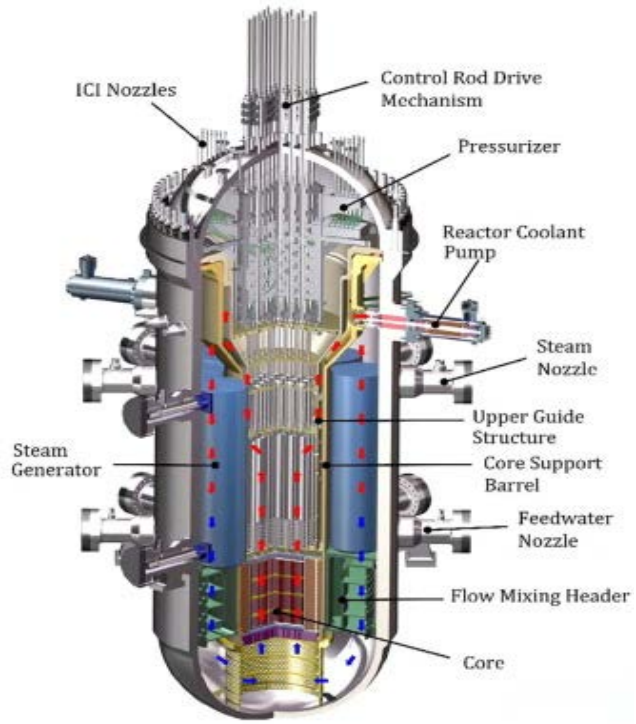


Figure 20. A schematic of a small thorium reactor.

and also thorium MOX (with Pu) fuel rods were tested in a five-year irradiation trial that started in April 2013 at the Halden test reactor. The company is working towards obtaining regulatory approval for the commercial production and use of Th-Add fuel. In February 2018, a third batch of Th-MOX fuel pellets commenced testing. This fuel is promoted as a means to improve power profiles within commercial reactors.

"The mineral monazite, which is a major source of rare earth elements, is also a primary source of thorium," said Mark Mihalasky, a Uranium Resources Specialist at the IAEA. "Without the current demand for rare earth elements, monazite would not be mined for its thorium content alone. Thorium is a by-product, and the extraction of thorium requires methods that are costlier than those for uranium. So, as it stands, the amount of thorium that can be pulled out of the ground cost-effectively is not as great as for uranium. This, however, could change if there was a higher demand for thorium and its application in nuclear power."

Equally expensive are the research, development, and testing of thorium-powered nuclear installations due to a lack of significant experience with thorium and uranium's historical pre-eminence in nuclear power. "Another hurdle for thorium is that it can be difficult to handle," said Anzhelika Khaperskaia, Technical Lead on Fuel Engineering and Fuel Cycle Facilities at the IAEA. Being a fertile and not fissile material, it needs a driver, such as uranium or plutonium, to trigger and maintain a chain reaction.

"To meet growing energy demand and achieve global climate objectives, the world is looking for alternative sustainable and reliable energy technologies. Thorium may become one of those," concluded Clément Hill, Section Head at the IAEA. "We will continue our research to deliver credible and science-based results for those interested in working with thorium."

Approaches to a thorium reactor include[14]**:**

a. Molten thorium salt fuel, such as ThF_4 or $ThCl_4$;
b. A driven subcritical molten salt system using fusion or accelerator-generated neutrons;
c. Use of a graphite moderated, He cooled pebble bed reactor;
d. The use of a seed and blanket solid fuel with an LWR cycle.

The *Th^{232}–U^{233} breeder* fuel cycle has the following advantages over the *U^{238}–Pu^{239} breeder* fuel cycle:

(i) Th^{232} is about four times as abundant as U^{238} in the earth's crust.

> *Thorium will create the Second Nuclear Era.… The molten-salt technology is entirely different from the technology of any other reactor. To the inexperienced, [fluoride] technology is daunting… Perhaps the moral to be drawn is that a technology that differs too much from an existing technology has not one hurdle to overcome—to demonstrate its feasibility… :Alvin Weinberg's 1994 autobiography "The First Nuclear Era, the Life and Times of a Technological Fixer"*

(ii) Almost all the thorium can be converted to fissile U-233, but it is more difficult to convert U-238 to Pu-239 with high efficiency.
(iii) Breeding is possible in thorium with both slow and fast neutrons (Figure 21).

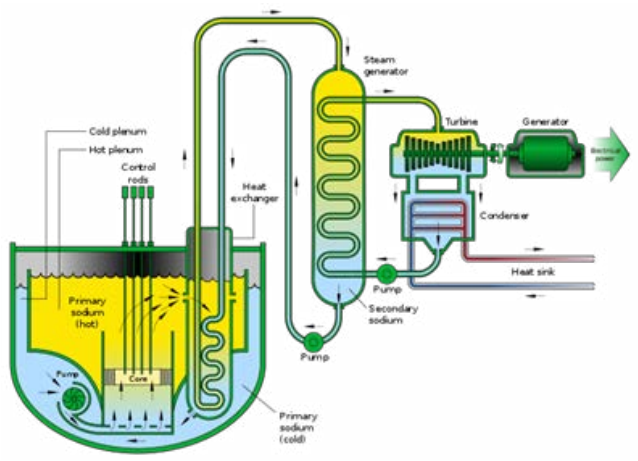


Figure 21. Thorium (Th) based Small Medium Reactor (SMR)-molten salt reactors.

3.3 The Way Ahead

The Indian government is also developing up to 62 reactors, mostly thorium-based, which it expects to be operational by 2025. India is the "only country in the world with a detailed, funded, government-approved plan" to focus on thorium-based nuclear power. The country currently gets under 2% of its electricity from nuclear power, with the rest coming from coal (60%), hydroelectricity (16%), other renewable sources (12%) and natural gas (9%). It expects to produce around 25% of its electricity from nuclear power. In 2009, the chairman of the Indian Atomic Energy Commission said that India has a "long-term objective goal of becoming energy-independent based on its vast thorium resources to meet India's economic ambitions."[15]

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