India's thorium-based nuclear vision

By **Prachi Patel**
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The Indian peninsula boasts 7,500 kilometers of coastline. Fine white sands that attract towels and umbrellas are scarce. But the country's eastern and southern shores hold the key to its nuclear energy future. Those beach sands are packed with monazite, a mineral that is 6–7% thorium. According to the World Nuclear Association, in fact, India has the world's largest reserves (846,000 tonnes or over 932,000 tons) of thorium, a silvery-white metal that many believe is the magic bullet for a new generation of clean, safe nuclear power.

With climate change unfolding around the world and global energy demand escalating, even environmentalists have accepted nuclear energy as a practical source for carbon-free electricity. But disasters such as the one at Japan's Fukushima plant highlight the nuclear industry's persistent problems.

A growing number of scientists believe that nuclear reactors fueled by thorium are the solution. Thorium-based reactors produce less long-lived radioactive waste than their uranium cousins and are more proliferation-resistant. China, Israel, Norway, and the United States are all stepping up thorium research.

India, in particular, is betting most heavily on the element. Forty percent of its burgeoning population remains unconnected to the grid, something the nation aspires to change. "We have huge energy requirements to meet if we want to supply electricity at a level comparable with developed countries," said Anil Kakodkar, past chair of India's Atomic Energy Commission. "Nuclear is considered important to meet that need." India has a flourishing nuclear power program and aims to get 25% of its electricity from nuclear energy by 2050. However, the country has less than 2% of the world's uranium reserves and relies on imports from countries such as France and Russia. Becoming self-sufficient in nuclear power dictates a pursuit of thorium-fueled reactors.

In February this year, scientists at the Bhabha Atomic Research Centre (BARC) near Mumbai unveiled their latest design for a novel 300 MW thorium-fueled Advanced Heavy Water Reactor (AHWR). They are targeting construction to begin in 2016. If the plans go through, India will be the first country to get power from thorium on a large scale. "India is the only country where reactor design has advanced enough to start building a thorium-based reactor," said L.V. Krishnan, an advisor at India's Center for Study of Science, Technology and Policy. "Other nations are still at basic R&D phase."

All current commercial reactors use uranium as the fuel, typically enriched in the isotope ^{235}U. Most use solid uranium oxide fuel rods and water as a coolant. The pressurized cooling system requires immense, heavily engineered containment structures. The fuel rod bundles swell and distort due to radiation damage and temperature differences, so they have to be replaced even though only 3–5% of the energy in uranium has been utilized. Plutonium-239 in the spent fuel can be used for weapons.

Thorium advocates say that the element, which only exists naturally as ^{232}Th, has many advantages over uranium. It is three to four times more abundant and relatively simple to mine. Thorium's physical properties are also advantageous, said Ram Kumar Singh, head of the reactor safety division at BARC. "Its thermal conductivity is better, so it runs at a lower temperature, resulting in less gas release. Its thermal expansion is less, so it induces less strain on the cladding. Its melting point is higher, so there's a greater degree of safety. And as a matrix, it's much more inert, which is good for long-term storage."

The thorium fuel cycle also has benefits. Thorium isn't fissile, so it cannot start or sustain a nuclear chain reaction. Neutrons from a small amount of driver fuel (plutonium or uranium) are used to bombard thorium and convert it into fissile ^{233}U that can then serve as driver fuel. In an open fuel cycle, the ^{233}U is left in the core to fission and generate heat. In a closed fuel cycle, meanwhile, it is separated from the used thorium fuel and added back to the reactor to replace the driver fuel; the fertile thoria in the spent fuel is also reused. The closed cycle has the key advantage of using fuel more efficiently and lessening the use of plutonium and uranium.

The thorium fuel cycle produces two orders of magnitude less waste than one based on uranium, and the waste is radioactive for a few hundred years as opposed to thousands. What's more, said Kakodkar, "the spent fuel is inherently proliferation-resistant." That's because it contains gamma particle-emitting ^{232}U, which is difficult to handle and separate from the ^{233}U that could potentially be used for weapons.

Of the seven types of reactors that can use thorium, the liquid fluoride thorium reactor (LFTR) is said to be safest. It uses thorium and uranium dissolved in hot lithium fluoride solvents. If the molten salt gets too hot, it expands and loses density, slowing down fission.

The LFTR is an updated version of the molten salt reactor that scientists at the Oak Ridge National Laboratory

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in the United States tested for several years in the 1960s. Soon after, the US government shut down thorium research in favor of uranium reactors. Thorium quickly became a forgotten nuclear fuel source.

Not so in India. The element plays a key role in the country's three-stage nuclear strategy chalked out by physicist Homi Bhabha in the 1950s. Stage one centers on India's indigenous pressurized heavy water reactors (PHWRs), which are based on Canadian CANDU reactors. India currently has 18 operational PHWRs with four more being built. These use ^{235}U as the fuel but have also been using thorium bundles to absorb excess neutrons in the center of the reactor core in order to more uniformly distribute neutrons and hence power generation through the reactor. This has given scientists a chance to handle spent thorium fuel and study its fission products and radioactivity.

In stage two, Fast Breeder Reactors will use thorium and plutonium (reprocessed from the first stage's spent fuel) to further generate plutonium and ^{233}U. The first commercial 500 MW fast breeder is nearly complete at the Indira Gandhi Centre for Atomic Research in the state of Tamil Nadu. It is expected to go critical in September 2014. The Centre already houses a 40 MWt fast breeder test reactor running on a plutonium-uranium mixture and an adjacent 30 kWt research reactor "Kamini," the only ^{233}U-fueled reactor in the world.

Thorium is front and center in the final third stage, on which India's long-term nuclear power supply depends. The goal is to utilize an 80-20 mix of thorium and uranium oxide fuels with plutonium as the trigger fuel to breed yet more ^{233}U. The first two stages will build up enough fissile uranium and plutonium for this.

Around 60% of power in the third stage will come from thorium. And for this key stage, India is blazing a new path. While other countries are more seriously pursuing the molten salt design, Indian scientists and engineers at BARC have developed the unique 300 MW AHWR, the latest design for which they made public in February.

The new reactor design builds on the country's tried and tested PHWRs but uses passive safety systems. The reactor uses solid oxide fuel rods arranged in three concentric rings. It has an eight-year closed fuel cycle, during which ^{232}Th, ^{233}U, and plutonium will be recovered from the spent fuel. The recovered thorium and ^{233}U will be recycled back as fuel in the AHWR, while the reprocessed plutonium will be used in fast breeders.

Scientists at several test facilities have been independently analyzing and validating different systems of the AHWR, Singh said. At BARC, for example, scientists have verified the basic physics of the thorium fuel cycle and studied various fuel rod arrangements on a 100 W research reactor. They have also confirmed natural convection heat-removal on a single coolant channel at a 3 MW test facility.

Because AHWR components differ little from traditional PHWRs, it does not pose any new structural materials challenges, Kakodkar said. The biggest constraint is that its designers want it to last a 100 years, compared to the 40-year design life for current reactors. "That puts significant challenges on the materials of construction like concrete and steel," he said. "We want to stretch their performance to a higher level."

The key challenge with the thorium fuel cycle is the recycling of spent fuel. "It's very difficult because you have to separate three streams: thorium, uranium, and plutonium," said Indian nuclear scientist Baldev Raj. The gamma-emitting ^{232}U in the spent fuel, which makes weapons proliferation harder, also complicates thorium separation. "You need to separate uranium-232 by laser processes, or you can do reprocessing at a suitable time when gamma activity hasn't built up too much. You need shielded facilities that become costly." Indian scientists have only done this separation at a small experimental scale so far.

The lack of thorium fuel reprocessing on a large scale is a chicken-and-egg problem. But India is hopeful and willing to take a stab at it. Officials are currently determining a site for the AHWR pilot unit. Government clearances will be needed before construction can begin. The plan is to have the pilot reactor up and running by 2022, with commercial reactors to be deployed after 2030. "We feel confident that we can build the AHWR," Raj said. "We've completed design and development, and the regulatory process is on. We feel ready to launch." □

The Kudankulam Nuclear Power Plant