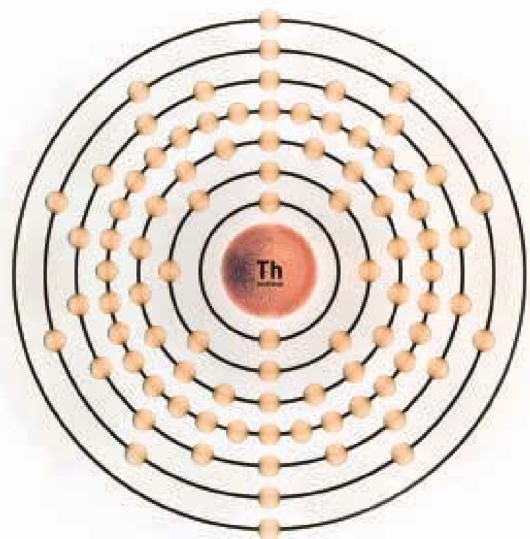
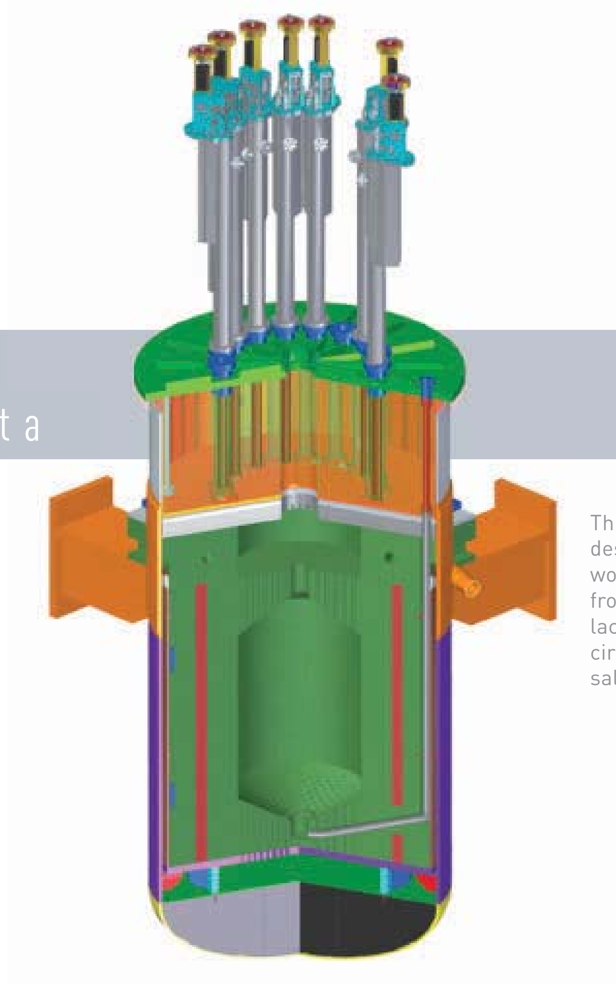
THUNDER ON THE HORIZON



Thorium-based breeder reactors could begin a new era of nuclear power.

By Bridget Mintz Testa



This Chinese-designed reactor would remove heat from its thorium-laced fuel pellets by circulating molten salt.

The Nuclear Renaissance was all the rage 15 or 20 years ago. The idea was that a little boost from the U.S. government would kickstart the industry past its post-Three Mile Island, post-Chernobyl doldrums. Long-planned units would be completed and a new generation of reactors would be built.

It says something about the state of the renaissance, then, that one of the more intriguing plans for advancing nuclear power includes a step where a barge is towed to Indonesia.

"Indonesia has agreed to install these power plants," said physicist Robert Hargraves of ThorCon, a Florida-based nuclear-power startup. "Indonesia is the world's fourth largest country in terms of population, and it wants to have an option not to use coal."

The ThorCon reactor concept has a lot of innovative features—for one, it is borrowing some construction techniques from the world of shipbuilding—but it also has something in common with several reactors that are in various stages of planning: It will be breeding some of its own fuel by irradiating thorium.

The nuclear industry has been built up to now on uranium, the heaviest naturally occurring element. When one of its isotopes, uranium-235, absorbs a neutron, the nucleus breaks apart and releases energy plus a couple of extra neutrons to sustain a chain reaction. Unfortunately, U-235 is relatively rare—it makes up one out of every 139 uranium atoms—so raw uranium requires enrichment to become fuel for nuclear power.

Thorium is about three times more abundant than uranium, and all of it—not just one rare isotope—can be used to create a fuel source for nuclear reactors. And that is why companies and governments from China and India to Norway are developing thorium reactors.

But harnessing thorium will require a new fuel breeding cycle and perfecting some reactor designs that have never left the experimental stage. Though the interest is strong, the stumbling blocks are very real.

A not-so-rare breed

Thorium is not fissile. Unlike atoms of uranium-235, when a thorium atom (almost all thorium is isotope 232, with 90 protons and 142 neutrons in its nucleus) captures a neutron inside a reactor core, it does not spontaneously split apart and produce energy. Indeed, it does not do anything at first except become a new isotope—Th-233. Changing the number of neutrons doesn't change the chemistry of an atom; changing the number of protons does.

But Th-233 isn't stable; its half-life is only 22 minutes. Quickly, one of its neutrons decays spontaneously into a proton to become an atom of protactinium. Pa-233 is also unstable. After an average of four weeks, another neutron decays, and the former

This equipment tested the ability of molten salts to circulate through a reactor to a heat exchanger and back. That work is crucial for optimizing the design of a molten salt reactor.

thorium atom becomes an atom of uranium-233. U-233 isn't as stable as U-235—the isotope isn't found in nature—but it is fissile and can be used to sustain a nuclear chain reaction and produce energy.

When enthusiasts talk about thorium reactors, then, what they are describing is a power plant that breeds its own fuel on the fly within the core of the reactor. Since thorium is more abundant than uranium and can be turned into fuel without the enrichment process needed to concentrate U-235, advocates believe the thorium fuel cycle could be cheaper and more sustainable than the uranium cycle.

Another, ironic, plus is that U-233 is more dangerous to handle, which makes it harder to turn into nuclear bombs. The isotope is radioactive enough to fry the circuitry that controls the bombs, ruling it out as a candidate for nuclear weapons.

Advocates believe the thorium fuel cycle could be more sustainable than the uranium cycle.

For countries such as India, thorium's advantages make it worth the development costs. India already has the world's only operating uranium-233 reactor, and large thorium reserves. According to the Bhabha Atomic Research Center (BARC) in Mumbai, which leads India's nuclear energy program, "The currently known Indian thorium reserves amount to 358,000 GWe-yr of electrical energy and can easily meet energy requirements during the next century and beyond."

"India doesn't possess enough natural uranium to provide the required energy for its masses," said Ganapati Myneni, a physicist at Jefferson Lab in Virginia who has been working closely with physicists at BARC. "Additionally, it is also very short on fossil fuels."

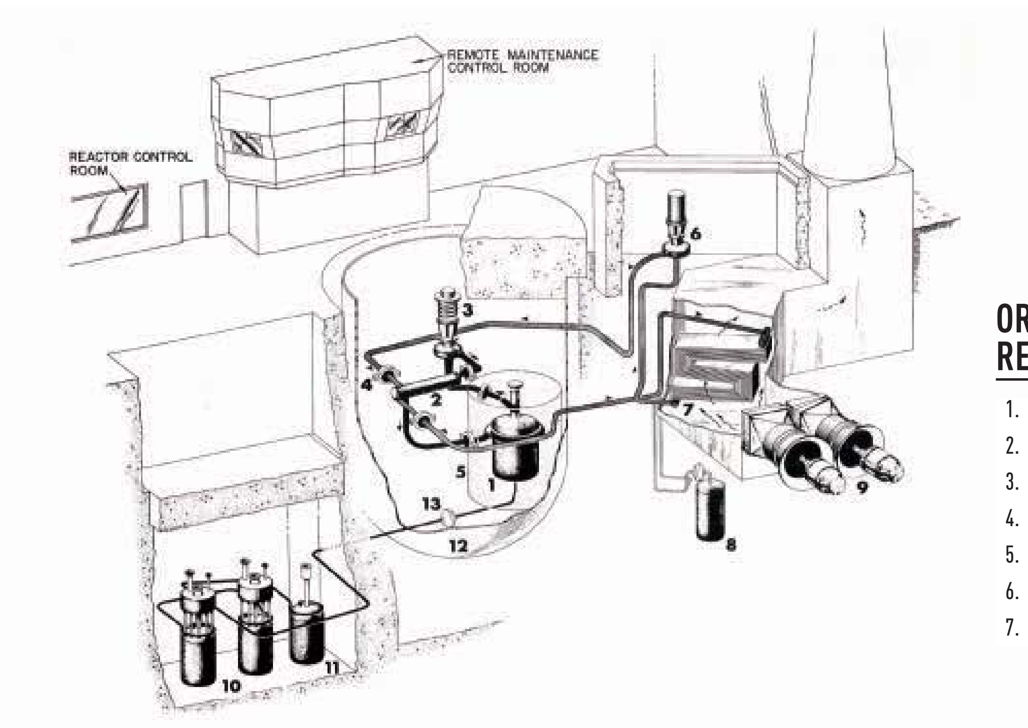
India has a multistage breeder reactor program on the drawing boards, and the country is looking at thorium as part of it.

At the moment, the fuel program is using a more conventional cycle, looking to take plutonium separated from spent nuclear fuel to power a 500 MWe fast breeder reactor; a blanket of non-enriched uranium will capture neutrons and transmute into more plutonium. That 500 MWe reactor is currently under construction and near completion at Kalpakkam. After some delays, the reactor is expected to begin operations by March 2017.

The plan, however, is to swap the uranium blanket with thorium, and use the bred U-233 as the fuel.

"The U-233/Th-232-based breeder reactors are under development in India today and will serve as the mainstay of the final thorium-utilization stage of the Indian nuclear program," according to BARC.

Those reactors will come at the end of a 40-year development program that just started. Other countries can't wait that long.



ORNL'S MOLTEN-SALT REACTOR EXPERIMENT

1. Reactor vessel
2. Heat exchanger
3. Fuel pump
4. Freeze flange
5. Thermal shield
6. Coolant pump
7. Radiator
8. Coolant drain tank
9. Fans
10. Drain tanks
11. Flush tanks
12. Containment vessel
13. Freeze valve

"China needs all the clean energy it can get, and they need it fast," said Andreas Norlin, the Geneva-based publisher of the Thorium Energy Report, which tracks and documents global activities in thorium-based nuclear power.

The Chinese Academy of Science program, run through the Shanghai Institute of Applied Physics, or SINAP, is pursuing a couple of technological options. One is based on the pebble-bed reactor concept tested in Germany, with particles of solid thorium mixed with uranium particles to provide a neutron boost. Unlike previous pebble-bed designs that were cooled with helium gas, this reactor is to be cooled with molten salt which would carry the energy to heat exchangers.

The other option is to build a reactor that dissolves the fuel directly into the circulating salts. The salt would be pumped through the reactor core, where the atoms would fission, and then to a heat exchanger and back to the core.

This sort of fluoride salt-cooled molten salt reactor was demonstrated at Oak Ridge National Laboratory in Tennessee in the 1960s as part of a program to make nuclear-powered bombers, and SINAP is cooperating with ORNL to develop the technology further, said David Holcomb, an Oak Ridge physicist.

ORNL will "work together on fundamental research supporting salt-cooled reactors," Holcomb said, though there won't be any joint work on fuel development.

"An example task that ORNL staff members are performing for SINAP is to develop the capability to calibrate liquid salt flowmeters," Holcomb said. The two labs will also be modifying Oak Ridge's reactor modeling and simulation software to better replicate the physics of a salt-cooled pebble-bed reactor.

In spite of the short track record, dissolving the thorium in the salt provides an advantage in processing the material as it transforms into uranium fuel. (Some concepts call for removing the protactinium from the reactor and setting it aside until it decays, since the element has a tendency to snag neutrons and become non-fissile.) Also, the fission decay products can be chemically removed from the fluid without having to pull out the thorium or uranium. The hope is that virtually all the thorium can be converted to fuel and all the uranium can be "burned." By contrast, in conventional solid-fuel reactors less than 7 percent of the total uranium atoms are burned, either directly or via transformation of U-238 to fissile plutonium.

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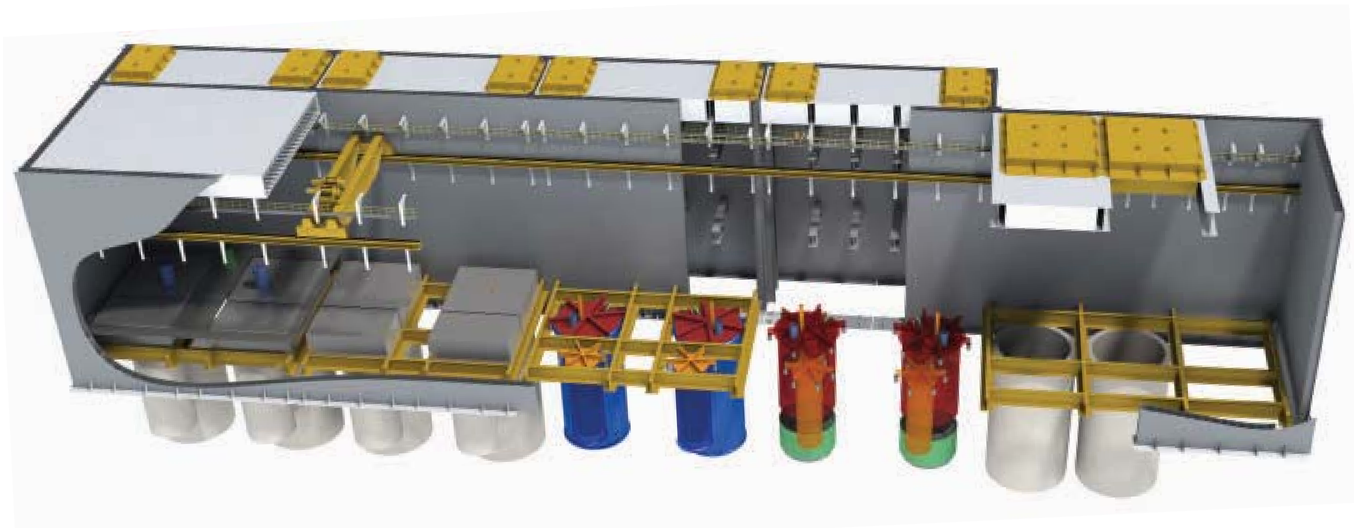


This cutaway shows the nuclear island of a ThorCon power plant. The plant is desiged to be built in a shipyard-like assembly line. *Image: ThorCon.*

By 2020, China plans to have both types of thorium-fueled reactors in operation, according to Norlin. By 2025, those demonstration reactors will be scaled up in size. By 2030, China plans to commercialize both reactor types.

China's top technological challenge in meeting that schedule, Norlin said, is the "need to verify their technology and materials in a realistic environment to prove that everything works before they start building a reactor based on a 'new' technology."

Security blanket

Molten-salt thorium reactors are getting attention in the West, too. Flibe Energy, headquartered in Huntsville, Ala., plans to build a liquid fluoride thorium reactor, or LFTR, based in part on Oak Ridge's original experimental molten salt reactor. The company's name is a nod toward the chemical make-up of the molten salt: fluoride, lithium, and beryllium.

The addition of thorium to the fluid salt helps reduce uranium consumption.

"A huge amount of the design of the LFTR comes from the Oak Ridge work," said Flibe's founder, nuclear engineer Kirk Sorensen, who said he hoped to have a first reactor online in about ten years.

Flibe Energy's LFTR will keep the thorium in its own blanket salt separate from the fuel-laden salt that runs through the reactor core. The bred uranium will be systematically removed from the blanket and injected into the fuel salt.

One improvement over the original Oak Ridge design is in the heat exchanger. The plan is to heat carbon dioxide to run through a gas turbine rather than make steam. Using a gas turbine allows the reactor to run at a higher temperature, Sorensen said, increasing the efficiency of the process to about 45 percent.

"Most reactors use steam turbines. A LFTR uses gas turbines because they have better efficiencies," Sorensen said. "The greater efficiency is due to the higher temperatures—that's the general rule. This reactor operates at 600 °C versus the 300 °C of today's reactors," Sorensen said.

ThorCon's reactor design is also based on the Oak Ridge MSR. But instead of a separate salt blanket for breeding fuel, the ThorCon will have a single, messy fluid cycling through the reactor.

"The fuel salt contains fissile material—U-235, U-233, and Pu-239—that fissions to make heat," ThorCon's Robert Hargraves said. "The fuel salt also contains fertile Th-232 that absorbs neutrons to make U-233, and U-238 that makes Pu-239. The fission process generates enough neutrons to continue the chain reaction and also convert some of the fertile elements to fissile ones, but not enough to continue the process indefinitely."

Since the breeding rate isn't as fast as the burn rate, small amounts of low-enriched uranium will be added as needed.

The reactor could be run solely on uranium, of course. But Hargraves said the addition of thorium to the fluid salt helps reduce uranium consumption. In Hargraves' estimation, half the power will come from burning U-235, while a quarter will come from breeding U-238 into plutonium, and the rest will result from breeding thorium into U-233.

"With improvements," Hargraves said, "future ThorCons will burn less uranium and convert more thorium."

Another unconventional aspect of the ThorCon stems from the background of its principle engineer. Jack Devanney has a degree in naval architecture, and to speed the reactors into production, he wants to bring the experience of building supertankers to the design and construction of nuclear reactors.

"In building supertankers, they complete the design as they complete the specs," Hargraves said. "Once you complete the specs, you present them to likely bidders and get bids inhand. At that point, we will know what these things will cost. ThorCon is a liquid fuel reactor with tanks, pumps, valves—the same components as in a supertanker."

The company will contract with shipbuilders to build a test reactor on a barge, and then begin shaking it down.

"We will use external electric power to raise temperatures," Hargraves said. "We will load salts that melt, and we will check out the performance of heat transfers, pumps, valves, and so on. Lots of tests will get done before we put in fissile fuel. In this phase, we will find all the errors in the design."

Once those design errors are corrected, a steam turbine and an electric generator will be installed. These elements comprise half the cost of a nuclear power plant, according to Hargraves.

Then the plan is to tow the barge to Indonesia.

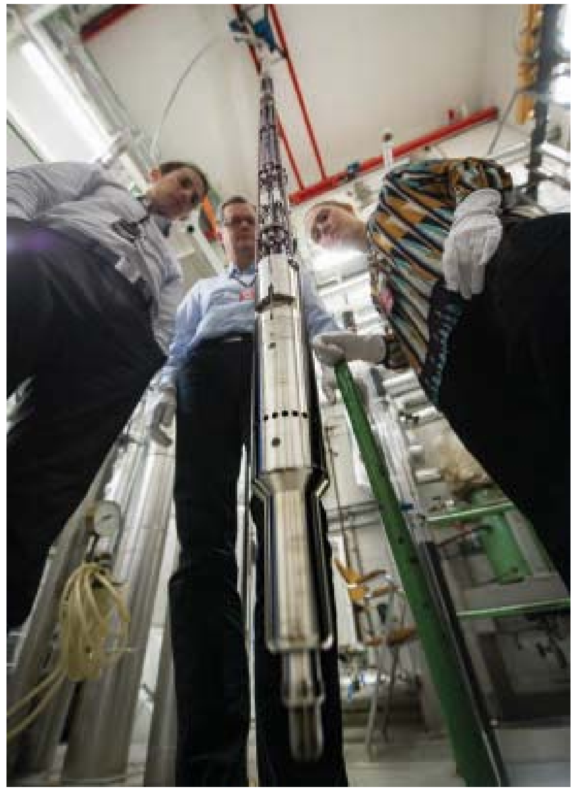
"We will need a year to turn it on, slowly bringing it up to the fission level and test," Hargraves said. "We will work alongside the regulators and incrementally address issues that arise. All the nuclear experience in the world is with light water reactors. So we will work beside the regulators and learn together how to safely operate this kind of power plant."

Thought for fuel

It would be a shame if nuclear power from an element called "thorium" didn't involve a Scandinavian effort. Fortunately, Oslo-based Thor Energy is testing thorium-based fuels in the experimental Halden reactor in Norway, with an eye toward the conventional, light-water reactor market.

"Thor Energy is developing two different families of thorium-based fuels with both U-235 and Pu-239 as the fissile driver material," said Lise Chatwin Olsen, vice president of business development for the company.

The first group of U-235-based fuels will also include thorium, and the company describes this family as a "thorium-additive" fuel. It will either be added to traditional uranium fuel or serve as an alternative to it.



Researchers at Thor Energy in Norway examine a thorium fuel rig prior to inserting it in a reactor for irradiation testing.

Image: Thor Energy.

The second family of fuels is a plutonium-plus-thorium mix (thorium MOX). It will replace traditional uranium fuel or uranium-plutonium mixes known as U-MOX.

All tests of these alternative fuels, conducted since 2013 in the Halden reactor, have the same objective: the "qualification of new thorium-based fuels for use in existing reactors," Olsen said.

"We have seen that the fuel behaves as expected with thorium fuel having lower temperatures, better heat conductivity, better power output, higher conversion ratios, reduced use of neutron poisons (which absorb neutrons) and less long-lived waste," Olsen said. "This would mean higher safety margins or higher power output from the reactor when using thorium fuel compared with traditional uranium-based fuels."

It's impossible to guess which approach to the thorium fuel cycle—if any—will help the nuclear power industry regain its promise from just a few years ago. Does the industry just need a better fuel, or radical new reactor designs?

Whatever the answer is, the interest in thorium suggests that it's going to take an unconventional approach to lead to the much anticipated Nuclear Renaissance. **ME**

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