Mike Follows

Thorium

The perfect nuclear fuel?

Key words
nuclear fission
reactor
thorium
isotope

Thorium is a heavy element, similar to uranium. Some people think that it could be the nuclear fuel of the future. ***Mike Follows*** *explains why.*

The liquid fluoride thorium reactor (LFTR) is a nuclear reactor first developed at the end of the Second World War to keep American strategic bombers and their payload of nuclear weapons airborne for weeks on end. But the Aircraft Reactor Experiment was abandoned in 1956 because intercontinental ballistic missiles (ICBMs) could do a better job of delivering nuclear warheads to the other side of the world. However, the LFTR programme is being revived because it promises safe nuclear power.

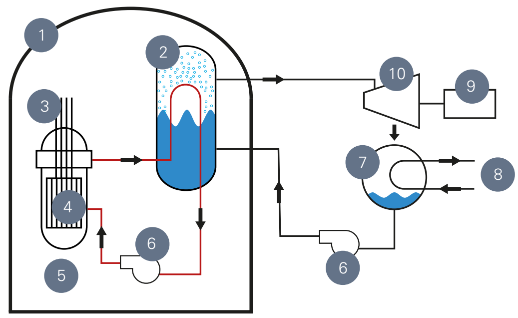
A nuclear test aircraft from the 1950s, carrying a thorium reactor. This is a USAF Convair Peacemaker, with a Boeing Superfortress beyond.

Nuclear fission

Nuclear fission is a nuclear reaction where an unstable 'parent' nucleus splits into smaller 'daughter' nuclei along with free neutrons, which can induce further fission events as part of a self-sustaining chain reaction. The combined mass of the products is less than the combined mass of the original nucleus plus initiating neutron. The difference in mass – the mass defect – manifests itself as energy, according to Einstein's famous equation $E = mc^2$. Paradoxically, in stark contrast to chemical reactions, neutrons need to be slowed down (moderated) to increase the probability of inducing fission. Graphite and water are the most common moderators.

The PWR reviewed

Currently, there are over 400 nuclear reactors worldwide meeting about 5% of the world's demand for energy and 13% of the global electricity supply. The PWR (pressurised water reactor) is the archetypal example so its principle of operation is reviewed here as a standard against which the LFTR can be judged.



1 containment
2 steam generator
3 control rods
4 fuel rods
5 reactor core
6 pump
7 condenser
8 sea water
9 electric generator
10 turbine

The fuel for a PWR is an isotope of uranium, U-235. Water is used as both coolant and moderator. The water coolant in the primary loop (red in the diagram) is pressurised to about 150 atmospheres so that it can be heated to higher temperatures without it turning into steam. This makes a PWR more efficient but it still only achieves 33% efficiency compared to 45% for a LFTR. Heat from the primary loop in the PWR is conducted via heat exchangers to the secondary loop (blue) where steam is generated to spin an electric generator. Conventional nuclear power stations like PWRs use control rods to absorb neutrons to slow down the fission process.

Operation of the LFTR

The liquid fluoride thorium reactor (LFTR, pronounced 'lifter') consists of a 'core' nested inside a 'blanket'. Both contain molten fluoride salts of lithium (LiF) and beryllium (BeF_2). A graphite jacket separates the core from the blanket.

The LFTR uses uranium-233, a different isotope of uranium from that used in a PWR. U-233 is produced from thorium-232 as follows:

U-233 dissolved in the core undergoes fission, producing thermal energy as well as 'daughter' nuclei and neutrons (usually 2, sometimes 3). One neutron induces further fission of a U-233 nucleus in the core so that a chain reaction is set up. The second neutron 'passes outwards through the graphite jacket which moderates it so that it can be absorbed by a thorium-232 nucleus dissolved in the blanket. This produces Th-233, which then undergoes two beta decays to produce a U-233 nucleus.

Th-232 + neutron → Th-233 → U-233 + 2 beta particles

As a consequence, each time a U-233 nucleus is split, a new one is formed in the jacket. U-233 atoms are extracted chemically from the jacket and fed into the core.

Thorium v uranium

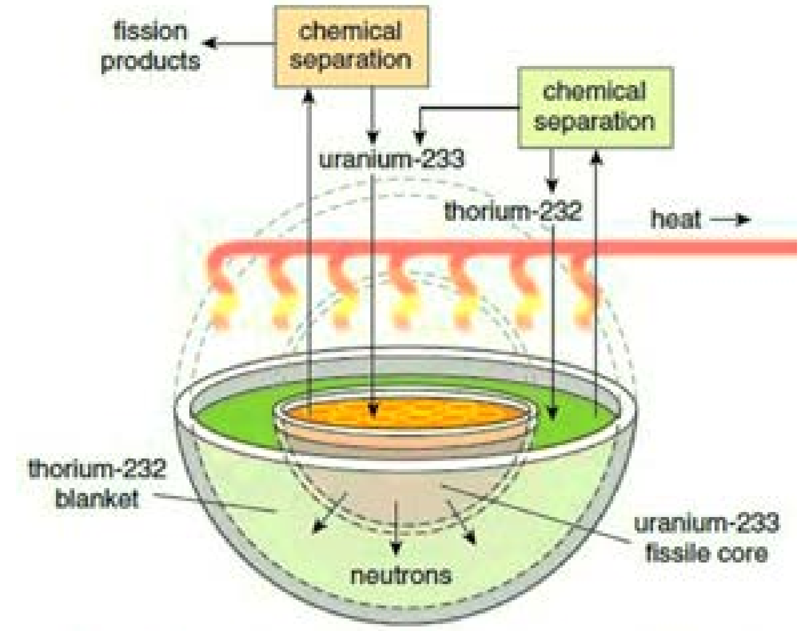
There is about four times as much thorium than uranium in the Earth's crust and it is much easier to extract. Also, U-235 is the only naturally-occurring fissile isotope of uranium but has an abundance of only 0.7%. This means that only seven in every 1000 uranium nuclei dug out of the ground belong to the useful isotope. In order to be usable in a reactor, U-235 needs to make up 2.5% of the total and this requires expensive enrichment.

LFTR v PWR

High pressure in a PWR requires expensive piping and pressure vessels; a leak results in the water flashing to steam. The fact that steam occupies 1000 times the volume of liquid water explains the need for massive containment buildings. Liquid fluoride salt is not under pressure, as it does not boil below 1400 °C. Any breach of the pipework in a LFTR would result in the liquid simply leaking into the catch basin below.

PWRs use solid uranium oxide (UO_2) fuel rods. Because UO_2 is a poor thermal conductor, hot spots create stress within the rods. Fission daughter products also get trapped within the fuel rods, acting as 'poisons' and compromising a sustained chain reaction by absorbing neutrons. This explains why fuel rods need to be replaced when less than 5% of the available energy has been extracted and why the nuclear reactor needs to be shut down every 18 months, when one third of the rods can be removed as 'spent' fuel and the remaining rods shuffled.

The spent fuel from a PWR is intensely radioactive and is waste that needs to be managed. In contrast, all of the U-233 dissolved in the molten salt of the LFTR undergoes fission. This is because the U-233 atoms are circulating freely in solution so that every nucleus is equally available to absorb a neutron. Also, unlike solid fuel, liquid fluoride salts are impervious to radiation damage and not subject to structural stress. Poisons can be chemically removed or can bubble out of solution as xenon does.



A lithium fluoride thorium reactor: a graphite jacket separates the core from the blanket.

What a waste

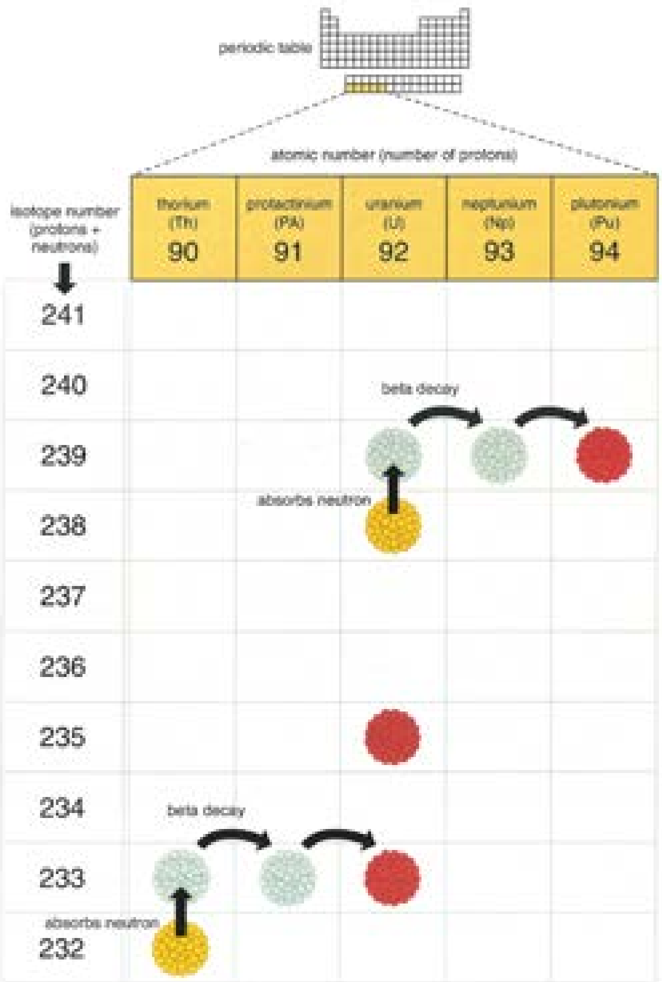
97.5% of the uranium in a PWR is U-238. This can capture a neutron and then decay to become an isotope of plutonium, Pu-239, used in nuclear weapons.

As can be seen from the diagram of fuel paths, a Th-232 nucleus would have to absorb 7 neutrons to become Pu-239, something which is highly unlikely. This means that a LFTR would produce much less Pu-239 and other transuranic nuclides (i.e. elements above uranium in the periodic table). This reduces the headache of waste management and fretting about whether Pu-239 is being diverted into a weapons programme.

After 300 years, the thorium/uranium cycle is about 10 000 times less toxic than the uranium/plutonium cycle. The relatively small amount of waste produced in LFTRs requires a few hundred years of isolated storage versus the few hundred thousand years for the waste generated by the uranium/plutonium fuel cycle.

Meltdown

Control rods in a PWR are designed to absorb neutrons in order to halt the chain reaction. They are usually made of boron or cadmium and suspended from the ceiling by electromagnets. Power failure means these rods fall under gravity



These 'fuel paths' show how Th-232 and U-238 change when they absorb neutrons. The three fissile isotopes (U-233, U-235 and Pu-239) are shown in red.

into their slots in the reactor core below. However, like applying brakes in a car, the reactor has thermal inertia and cannot stop producing thermal energy instantaneously. The uranium oxide is a poor conductor of heat so stays hot even when a power station is shut down and radioactive decay of the daughter nuclei trapped in the fuel rods generates heat for months. This means that meltdown can still occur if the cooling system fails. The Fukushima meltdown in 2011 was caused when the tsunami disabled the cooling system.

Meltdown is impossible in an LFTR partly because the fuel is already molten and partly because it needs power to prevent shutdown of the reactor. It has a 'freeze plug' at the bottom of the core – a plug of salt, cooled by a fan, to keep it below the freezing point of the salt. If the temperature exceeds a critical value, the plug melts and the liquid falls into a catch basin.

The future

The work on LFTRs had been forgotten until Kirk Sorensen revived the idea in 2000. He was working for NASA and was thinking about ways to provide energy for a lunar community. There are no fossil fuels on the Moon. Without an atmosphere, there cannot be any wind power. Solar energy is not an option because the lunar day lasts a month and there is no way to store sufficient energy for the fortnight of night time. Nuclear energy is the only option, but there is no water for coolant on the Moon. Wandering into a colleague's office, Sorensen spotted a book called *Fluid Fuel Reactors*. It was immediately obvious that LFTRs were the answer. But if LFTRs are such a good fit for a lunar community, he reasoned, why not develop them for use here on Earth?

A metro station in Delhi. One billion people in India need a clean and sustainable energy supply.

India plans to produce 30% of its electricity from thorium by 2050, though this may be based on solid fuel, which offers fewer advantages. Meanwhile, China and France have already embarked on research programmes. Perhaps there should be an international collaboration along the lines of the Manhattan Project or CERN to develop LFTRs. The knowledge gained could be made freely available and, in the process, we could simultaneously solve our energy crisis, mitigate the enhanced greenhouse effect, and perhaps make nuclear proliferation a thing of the past.

Mike Follows teaches Physics.

Look here!

See Kirk Sorensen's TED lecture on thorium reactors at *goo.gl/V1BvJ*

More about thorium reactors at *energyfromthorium.com*