Think thorium

Our expert panel answers your questions on thorium-fuelled fission reactors.

Stephen Harris reports

Thorium is increasingly being promoted as an alternative fuel to uranium in civil nuclear fission reactors. Proponents argue it's safer, more abundant and much harder to weaponise. But the most significant development of thorium-fuelled reactors at Oak Ridge National Laboratory in the US was cancelled in the 1970s and the technology would need large amounts of investment to continue readying it for commercial use.

For our latest reader Q&A, we put your questions to a panel of thorium experts:

- **Julian Kelly**, chief technology officer for Thor Energy, a Norwegian firm developing and testing thorium-plutonium (Th-MOX) fuels for use in commercial light water reactors (LWRs);
- **David Martin**, deputy director of research at the Weinberg Foundation, a not-for-profit thorium lobby group;
- **Fiona Rayment**, director of fuel cycle solutions at the UK's National Nuclear Laboratory (NNL);
- **Kirk Sorensen**, founder of US firm Flibe Energy, which aims to build a demonstration liquid-thorium-fuelled reactor (LFTR).

Old idea: **Thorium research dates back to the 1960s.**

What are the advantages and disadvantages of thorium-fuelled reactors over other proposed next-generation nuclear designs?

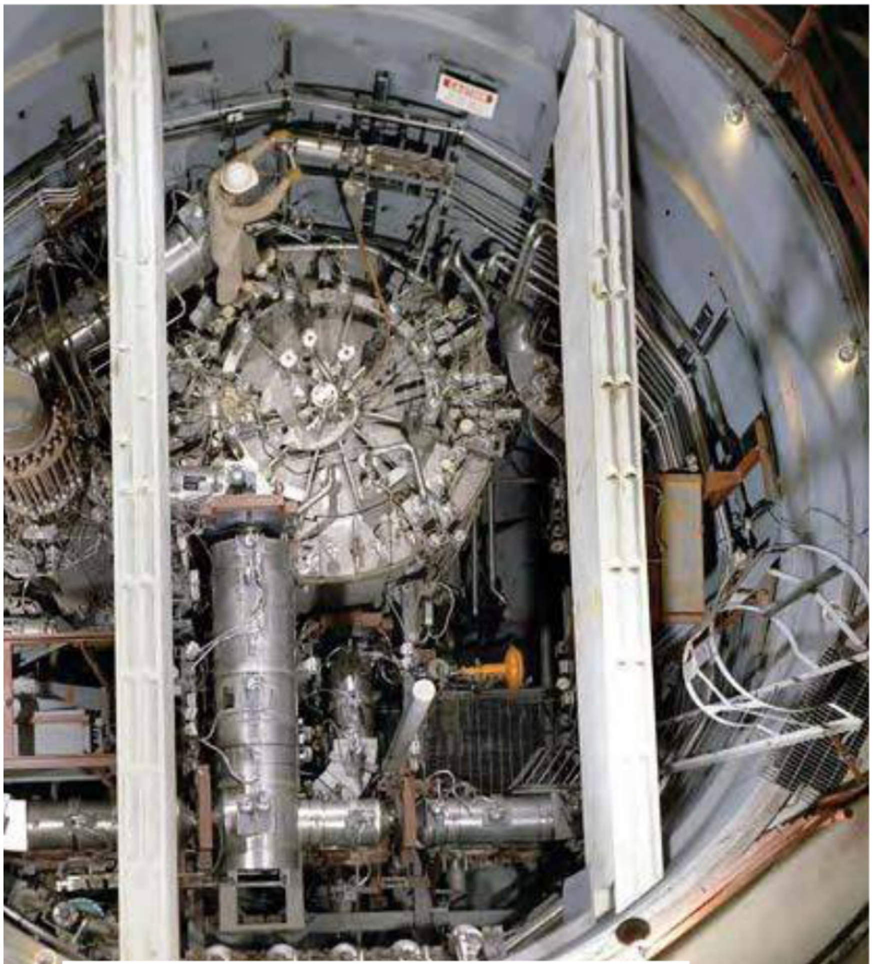
David Martin: First, it is essential to distinguish between thorium fuel and advanced reactors. In practice, most current and future reactors could be fuelled by thorium-based fuel, but only certain reactors are able to fully exploit thorium's potential. The two most promising thorium-fuelled reactors are high-temperature reactors (HTRs) and molten salt reactors (MSRs).

Thorium's high melting point makes it ideally suited to HTRs [but] MSRs offer a step-change in fuel efficiency and inherent safety. Liquid fluoride thorium reactors [a type of MSR] would breed the fissile isotope U233 and would automatically 'burn up' their own wastes, producing minimal long-lived radioactive waste.

Kirk Sorensen: The advantages of LFTRs are the potential for much greater use fraction of fuel, the elimination of the need to fabricate solid-fuel elements, a completely passive approach to decay heat removal and high thermal conversion efficiency achieved at low pressures. That final attribute is unique among reactors in this class. The disadvantages are a small and aged base of scientists and engineers who have actual experience in the technology, regulatory challenges that will be faced to adapt solid-fuel reactor regulations around liquid-fuel technology, the production of tritium in the salt and its containment, and the challenge of developing a materials database to support 30–60 year licensing of this class of reactors.

> **"The use of thorium is a potential strategic alternative to using uranium/plutonium**

Fiona Rayment: The main advantage is that the use of thorium is a potential strategic alternative to using uranium/plutonium, and so could be an additional contributor to secure future energy reserves. The thorium fuel cycle also generates much lower quantities of highly radioactive 'transuranic' materials, which are generally viewed as waste. Under some circumstances, it is predicted that the thorium fuel cycle could give an economic benefit, although this remains to be proven in practice. The main disadvantages are that thorium (in the form of Th-232) is only fertile, not fissile and converting the thorium to fissile uranium-233 involves a neutron capture that is time-consuming and expensive to implement. Another disadvantage is that utilising thorium will involve the development and deployment of new fuel-cycle technology, which has to compete with the established uranium fuel cycle. While it is true that using thorium produces only trace amounts of plutonium, it does produce very high-quality fissile material that is a significant proliferation issue, as is the case with the conventional uranium/plutonium fuel cycle.



Origins: **Oak Ridge National Laboratory (ORNL) in Tennessee built the first molten salt reactor to test thorium-derived fuel.**

Green alternative: **Thorium is relatively abundant and usually found in the crystal mineral thorite.**

Early pioneer: **Alvin Weinberg, namesake of the foundation, led the ORNL in the 1960s and 70s.**

What technical problems stand in the way of making thorium-fuelled reactors a viable working alterative to current nuclear technologies?

Julian Kelly: At the very top of the list is the fact that thorium is not fissile. This is well known, but it is greatly under-appreciated that [converting it] is non-trivial and expensive. It means that you have to provide fresh fissile driver to make thorium 'work'. Surplus plutonium from used nuclear fuel is a viable option and is appealing from a recycling point of view (Th-MOX fuel is being tested in Halden, Norway), but there are headaches and costs associated with handling plutonium. The use of an external neutron source is not currently feasible [as they] require a great deal of energy themselves.

DM: Few technical problems stand in the way of producing thorium fuels for conventional (light- and heavy-water) reactors. The main questions lie in the 'back end' of the fuel cycle, i.e. what happens to the fuel once it's been irradiated. Thorium-fuelled MSRs offer a potential paradigm shift in nuclear fission, but there several technical hurdles. Key concerns are materials corrosion, reactor control and in-line processing of the fuel.

KS: The prime challenge is expanding the materials database. We have the technical information that shows that we could build a reactor of this type and make it last for five years, since that is how long the Molten-Salt Reactor Experiment [at Oak Ridge] lasted. But to show that materials will hold up 10, 20, 30, 50 years or more will require extended testing. There is no magic to this: it is developed through actual construction and operation of these plants, and there really isn't any way to shortcut it.

What are the different technology elements that would comprise a thorium nuclear plant and how much development work do they each require?

KS: There are three main systems in the reactor: the reactor vessel and primary heat transport system, the power conversion system, and the chemical processing system. It is very difficult to say which one will be most challenging or take the longest since each of them, in many cases, can be traded against another. We are accepting a more complicated reactor core design in order to achieve a very simple chemical processing system and enhanced safety.

The difficulty of the power conversion system will also depend in large part on how far we choose to depart from existing combustion-based gas turbine power conversion system technology. We are personally favouring supercritical CO_2 gas turbines that will require substantial development but may save lots of time and complexity in other aspects of the reactor system.

DM: All thorium fuels will require the development of a new supply chain, new fuel fabrication facilities and new reprocessing and storage facilities. Thorium fuels for conventional nuclear plants are the closest to market. HTRs are the next closest and operated successfully during the 'golden age' of nuclear innovation in the 1960s and 1970s, and, as a result, there is a wealth of experimental data already available. China has plans to have a commercial-scale MSR ready by the early 2030s.

JK: 'Thorium nuclear plants' are not a realistic commercial goal. On the other hand, thorium-based fuels are an achievable product for the future nuclear fuel market. The process for commercialising a

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new fuel includes an extensive campaign of physical testing and characterisation in both normal and postulated accident scenarios.

Could thorium-fuelled reactors use nuclear waste in their fuel?

FR: A reactor based on a thorium fuel cycle is, in principle, capable of supplying neutrons to destroy transuranics, in the same way as other reactors, although with the advantage that the 'driver' fuel that provides the spare neutrons would generate negligible amounts of new transuranics.

DM: The prospects are very good indeed. Indeed, it is likely that the first modern-day deployment of thorium will be as a mixed thorium-plutonium fuel in a LWR or HWR. Thorium's physical properties make it an ideal tool for plutonium disposition. In addition, research into thorium fuels based on the troublesome Minor Actinide waste is underway.

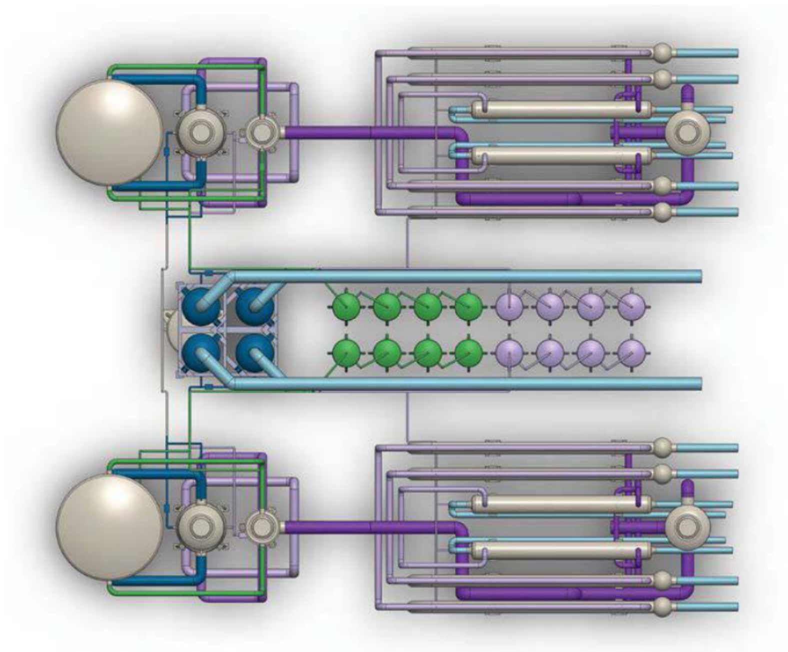
KS: The prospect of consuming long-lived 'nuclear waste', primarily plutonium, are excellent in the LFTR style of reactors. That is because they do not require expensive fuel fabrication and because fuel burn-up is essentially unlimited in the liquid fluoride medium. This is highly advantageous to the goal of plutonium consumption, which is a high priority of both UK and US governments.

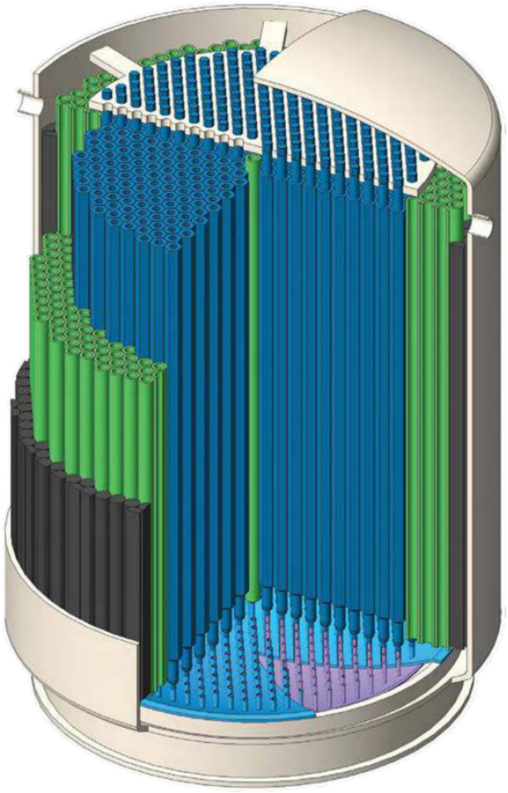
DM: This largely depends on whether an 'open' or 'closed' thorium fuel cycle is pursued, on the type of thorium-fuelled reactor and the choice of initial 'fissile driver', which is needed to kick-start any thorium reactor. Thorium-fuelled reactors would certainly produce much less transuranic waste than uranium- or plutonium-fuelled reactors.

However, surprisingly, thorium fuels actually produce wastes that are harder to handle in the short term, posing new challenges to fabrication of solid-fuel pellets. This is one of the reasons that a growing number of experts support thorium MSRs, whose fuels can be recycled by chemical means with no need for fuel fabrication. If we use solid-fuel reactors, new reprocessing facilities and shielded storage units would be needed.

What would be the ratio of energy generated to waste produced in a thorium-fuelled reactor and how would this compare to conventional uranium reactors?

KS: Roughly a 200-fold improvement in power generated per unit long-lived transuranic waste produced. Roughly 50 per cent improvement in energy generated per unit fission product waste generated.





New thinking: **Kirk Sorensen plans to build a demonstration liquid fluoride thorium reactor (LFTR) that generates electricity from uranium-233 bred from thorium fuel.**

What waste products would a thorium-fuelled reactor produce and what new methods/tools would we need for dealing with this waste?

FR: Using thorium would generate virtually the same fission product wastes as a conventional reactor. Where the use of thorium differs is that it produces only trace amounts of transuranics. This gives the waste a distinct radiotoxicity profile. The difference would only start to come into effect after 500 years of waste storage though — as the fission product wastes are the main factor up to that point.

After 500 years, wastes from a thorium cycle would be less radioactive, although other factors mean that after around 100,000 years the difference flips round and thorium wastes would then be more radioactive than wastes from uranium after that point. Any likely impact on a proposed geological repository would be relatively minor, however.

FR: In terms of the volume of vitrified high level waste or any other form of immobilised high-level waste produced per unit of electrical output, a reactor based on a thorium fuel cycle is essentially the same as a conventional reactor.

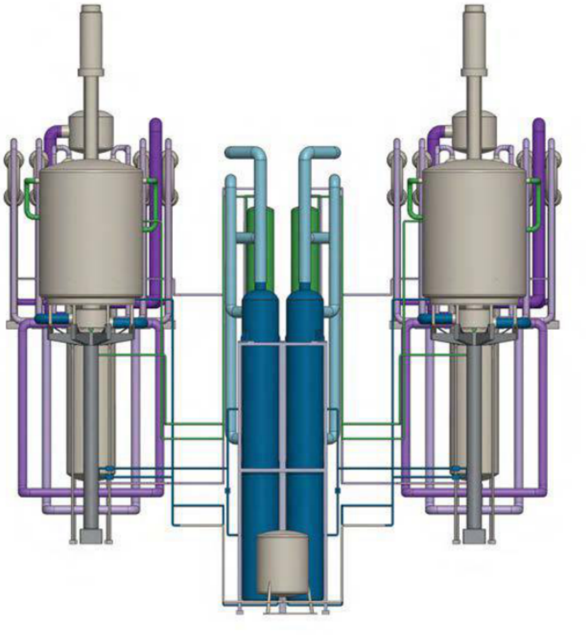
JK: The answer to this question depends entirely on the composition of the fuel and on the reactor system in which the particular thorium fuel is operating. There is no universal rule of thumb giving an energy-waste ratio for thorium fuels. Any future thorium-based fuel will need to have been carefully designed for the fuel-cycle in which it will fit. Broadly speaking… the energy-to-waste ratio is favourable compared to comparable uranium fuels.

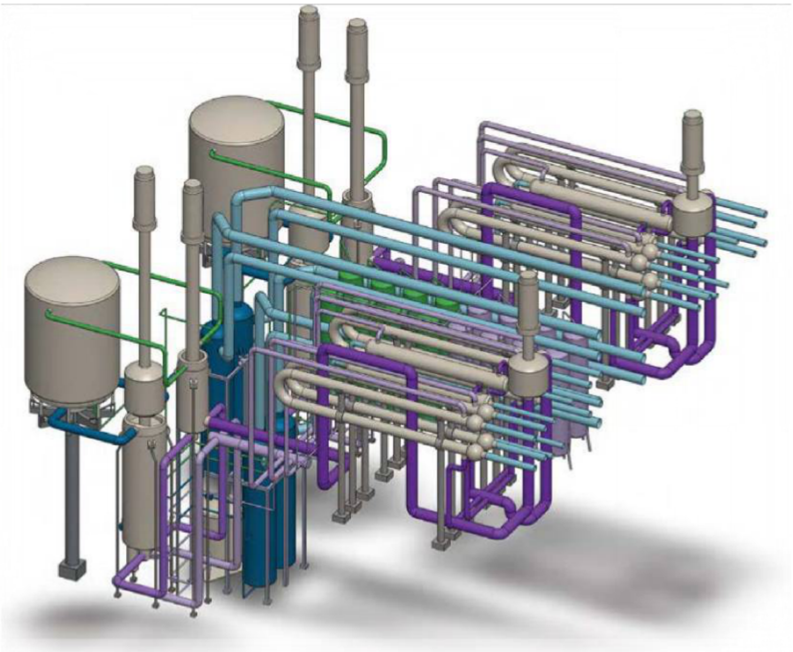
How much of the current reluctance to fund research into thorium is political and how much is related to safety, waste disposal or other technical barriers?

JK: Conspiracy theories about funding denials for thorium work are for the entertainment sector. A greater risk is that there will be a classic R&D bubble [that] divides R&D effort and investment into fragmented camps and feifdoms. 'Thorium' does not deserve funding just for the sake of it — it is well understood, per se. The only 'thorium energy' projects that should attract major funding support are those that are based on: (i) clear business cases, (ii) rigorous technical methods & data collection, (iii) objective fuel cycle assessments.

DM: We must avoid falling into a debilitating cycle, telling ourselves 'it can't be done because it's never been done'. Such an attitude would never have produced antibiotics, safe air travel, the sequencing of the human genome and all the other scientific marvels that we take we granted. All countries, and the UK in particular, must rediscover and support a spirit of technological adventure.

So, it is fundamentally a question of politics. We need a far-sighted nuclear policy, embraced by all political parties, that aims to rapidly accelerate the development of all forms of next-generation nuclear power. That said, however tempting it may be, we cannot just blame the politicians. Society as a whole has to understand that nuclear power offers astonishing benefits but requires long-term national energy policy. History shows that if we give the scientists and the engineers public and political support, they will find a solution.





How quickly could commercial thorium power plants realistically become operational and could they really be rolled out fast enough to help meet emissions reduction targets?

DM: Thorium-fuelled conventional reactors were safely operated in the 1960s, 1970s and 1980s and there are no major technical barriers to their deployment today. Molten Salt Reactors, the 'holy grail' of thorium research, do require R&D. However, China is expecting to have a commercial-scale MSR ready by 2030–35. A significant programme of research in other advanced nuclear nations, such as US or UK, would shorten this time horizon. MSRs readily lend themselves to modular design and it seems likely that MSR could be mass-produced (like airliners), once a viable commercial design is developed.

FR: It is conceivable that thorium could be introduced in current generation reactors within about 15 years, if there was a clear economic benefit to utilities. This would be a once-through fuel cycle that would partly realise the strategic benefits of thorium. To obtain the full strategic benefit of the thorium fuel cycle would require recycle, for which the technological development timescale is longer, probably 25 to 30 years. To develop radical new reactor designs, specifically designed around thorium, would take at least 30 years. It will therefore be some time before the thorium fuel cycle can realistically be expected to make a significant contribution to emissions reductions targets.

Do you see thorium reactors as a long-term solution to our energy needs or as more of a stop-gap until a cleaner/more affordable technology comes along?

FR: The use of thorium is potentially a viable long-term sustainable energy source if the required technologies can be developed to commercial readiness. In particular, it could help uranium reserves to last longer and ultimately perhaps decouple nuclear power production from uranium availability. It is most likely that thorium fuel cycles would be deployed alongside conventional uranium systems, renewables and carbon capture and storage as part of a balanced, low-carbon world energy strategy.

KS: I see thorium reactors as the ultimate solution to our energy needs, capable of sustaining industrial civilisation for hundreds of thousands of years. I don't think we'll ever come up with something better, at least not with the physics that we currently understand.

JK: Neither. Specifically designed thorium-based fuels should be able to serve as valuable niche products in the nuclear fuel market for use in current and new-build water-cooled reactors. It is worth remembering that there is a vast amount of depleted uranium available to mankind as a cheap by-product that will be usable in fast reactors for which there is a reasonable amount of operating experience. So resource arguments in support of thorium energy technologies might never be particularly strong.

DM: It is unlikely that fusion reactors will be deployed in significant numbers before the end of this century. Personally I believe that we are still in the early stages of the fission technology. We have thousands of years of clean fuel available, right now, on 'Planet Earth'. We just have to find the best means of using it.

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