COSMOS - New age nuclear

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by Tim Dean

Nuclear energy produces no greenhouse gases, but it has many drawbacks. Now a radical new technology based on thorium promises what uranium never delivered: abundant, safe and clean energy - and a way to burn up old radioactive waste.

Credit: Justin Randall

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What if we could build a nuclear reactor that offered no possibility of a meltdown, generated its power inexpensively, created no weapons-grade by-products, and burnt up existing high-level waste as well as old nuclear weapon stockpiles? And what if the waste produced by such a reactor was radioactive for a mere few hundred years rather than tens of thousands? It may sound too good to be true, but such a reactor is indeed possible, and a number of teams around the world are now working to make it a reality. What makes this incredible reactor so different is its fuel source: **thorium.**

Named after Thor, the warlike Norse god of thunder, thorium could ironically prove a potent instrument of peace as well as a tool to soothe the world's changing climate. With the demand for energy on the increase around the world, and the implications of climate change beginning to strike home, governments are increasingly considering nuclear power as a possible alternative to burning fossil fuels.

But nuclear power comes with its own challenges. Public concerns over the risk of meltdown, disposal of long-lived and highly toxic radioactive waste, the generation of weapons grade by-products, and their corresponding proliferation risks, all can make nuclear power a big vote-loser.

A thorium reactor is different. And, on paper at least, this radical new technology could be the key to unlocking a new generation of clean and safe nuclear power. It could prove the circuit-breaker to the two most intractable problems of the 21st century: our insatiable thirst for energy, and the warming of the world's climate.

BY THE END OF this century, the average surface temperature across the globe will have risen by at least 1.4°C, and perhaps as much as 5.8°C, according to the United Nations Intergovernmental Panel on Climate Change.

That may not sound like much, but small changes in the global average can mask more dramatic localised disruptions in climate.

Some changes will be global: we can expect sea levels to rise by as much as 0.9 metres, effectively rendering a huge proportion of what is now fertile coastal land uninhabitable, flooding low-lying cities and wiping out a swathe of shallow islands worldwide.

The principal culprit is carbon dioxide, a gas that even in quite small quantities can have a dramatic impact on climate, and has historically been present in the Earth's atmosphere at relatively low concentrations.

That was until human activity, including burning fossil fuels, began raising background levels substantially.

Yet while we're bracing ourselves to deal with climate change, we also face soaring demand for more energy - which means burning more fossil fuels and generating more greenhouse gases.

That demand is forecast to boom this century. Energy consumption worldwide is rising fast, partly because we're using much more of it - for air conditioning and computers, for example. In Australia alone, energy consumption jumped by 46 per cent between the mid-1970s and the mid- 1990s where our population grew by just 30 per cent. And energy use is expected to increase another 14 per cent by the end of this decade, according to the Australian Bureau of Statistics. Then there's China, which, along with other fast-growing nations, is developing a rapacious appetite for power to feed its booming economy.

And fossil fuels won't last forever. Current predictions are that we may reach the point of peak production for oil and natural gas within the next decade - after which production levels will continually decline worldwide.

That's if we haven't hit the 'peak oil' mark already. That means prices will rise, as they have already started to do: cheap oil has become as much a part of history as bell-bottomed trousers and the Concorde.

Even coal, currently the world's favourite source of electricity generation, is in limited supply. **The U.S. Department of Energy suggests that at current levels of consumption, the world's coal reserves could last around 285 years.** That sounds like breathing room: but it doesn't take into account increased usage resulting from the lack of other fossil fuels, or from an increase in population and energy consumption worldwide.

According to the U.S. Energy Information Administration, as of 2003, coal provided about 40 per cent of the world's electricity - compared to about 20 per cent for natural gas, nuclear power and renewable sources respectively. In Australia, coal contributes even more: around 83 per cent of electricity.

This is because coal is abundant and cheap, especially in Australia. And although a coal-fired power plant can cost as much as A$1 billion (US$744 million) to build, coal has a long history of use in Australia. Coal is also readily portable, much more so than natural gas, for example - which makes it an excellent export product for countries rich in coal, and an economical import for coal-barren lands.

But the official figures on the cost of coal don't tell the whole story. **Coal is a killer: a more profligate one than you would expect. And it maintains a lethal efficacy across its entire lifecycle.**

One of the main objections held against nuclear power is its potential to take lives in the event of a reactor meltdown, such as occurred at Chernobyl in 1986. While such threats are real for conventional reactors, the fact remains that nuclear power - **over the 55 years since it first generated electricity in 1951 - has caused only a fraction of the deaths coal causes every week.**

Take coal mining, which kills more than 10,000 people a year. Admittedly, a startling proportion of these deaths occur in mines in China and the developing world, where safety conditions are reminiscent of the pre-unionised days of the early 20th century in the United States. But it still kills in wealthy countries; witness the death of 18 miners in West Virginia, USA, earlier this year.

But coal deaths don't just come from mining; they come from burning it. The Earth Policy Institute in Washington DC - a nonprofit research group founded by influential environmental analyst Lester R. Brown - **estimates that air pollution from coal-fired power plants causes 23,600 U.S. deaths per year. It's also responsible for 554,000 asthma attacks, 16,200 cases of chronic bronchitis, and 38,200 non-fatal heart attacks annually.**

The U.S. health bill from coal use could be up to US$160 billion annually, says the institute.

Coal is also radioactive: most coal is laced with traces of a wide range of other elements, including radioactive isotopes such as uranium and thorium, and their decay products, radium and radon. Some of the lighter radioactive particles, such as radon gas, are shed into the atmosphere during combustion, but the majority remain in the waste product - coal ash.

People can be exposed to its radiation when coal ash is stored or transported from the power plant or used in manufacture of concrete. And there are far less precautions taken to prevent radiation escaping from coal ash than from even low-level nuclear waste. In fact, the **Oak Ridge National Laboratory in the U.S. estimates the amount of exposure to radiation from living near a coal-fired power plant could be several times higher than living a comparable distance from a nuclear reactor.**

Then there are the deaths that are likely to occur from falling crop yields, more intense flooding and the displacement of coastal communities which are all predicted to ensue from global warming and rising oceans.

There's so much heat already trapped in the atmosphere from a century of greenhouse gases that some of these effects are likely to occur even if all coal-fired power plants were closed tomorrow. Whichever way you look at it, coal is not the smartest form of energy.

THERE ARE MANY REASONS to move away from coal as our primary source of electricity generation, but it's not an easy task. The list of required attributes for an ideal power generation technology looks intimidating.

First of all, it should offer abundant power.

It also needs to be clean, safe and renewable as well as consistent. And ultimately, it needs to be economical.

Solar power contains much promise as a clean and practically infinite renewable power source. But photovoltaics, the most common form of solar electricity generation, are still a very expensive form of electricity, and lack the consistency to be suitable as a primary source of power - to provide the 'baseload' that is, the kind of power you can rely on to be there to keep everyone's refrigerators humming all day and night.

Wind has seen application in specialised wind farms, both onshore and offshore, especially in Europe where solar power is less efficient than in sunnier climes such as Australia's. Germany alone accounts for around 40 per cent of the total wind power generated worldwide.

Wind is an effective and clean form of power, but it too has its drawbacks. First, it is uncommon for a wind generator to be operating at more than 35 per cent of capacity, and 25 per cent is more common. This means it's idle and not generating power for 65 to 75 per cent of the time. Wind power is relatively cheap, with a cost per kilowatt-hour similar to that of coal in some places, although the volume of wind power is limited and often the best locations for wind turbines are far from the populous areas where electricity is needed. Environmentally, wind power poses a minor threat to birdlife, as well as being considered an eyesore in some communities.

While solar power is relatively expensive, and wind is limited in its implementation, both have a highly important role in renewable electricity generation. Unfortunately, even granting considerable advances in technology and efficiency of both technologies, neither has the potential to become a primary source of electricity ***because of their intermittent nature***: neither could ever be relied upon to meet baseload supply.

IN THE 1950S, nuclear power generation, or the so-called 'peaceful atom', promised to unshackle us from fossil fuels and provide our society with limitless clean power that was going to be "too cheap to meter". Like many utopian visions, the truth was considerably less appealing. While nuclear power has for the most part provided bountiful energy without significant environmental impact, what everyone remembers are the accidents: the Windscale fire at Sellafield in 1957, the meltdowns at Three Mile Island in 1979 and Chernobyl in 1986. At a time when the public psyche was reeling from the fear of global nuclear war, the threats from nuclear power plants were suddenly seen in a similar light.

Another issue that caused growing public concern was the disposal of high-level nuclear waste. Some of the by-products of nuclear power include spent fuel rods: mostly byproducts of nuclear fission, including some highly radioactive actinides with half-lives of many thousands of years - which means they remain lethally toxic for millennia. They have to be housed in waste dumps isolated from all possible contact with the environment for up to 10,000 years. This means building a structure that will survive for twice as long as the Great Pyramid of Egypt has to date.

Needless to say, the engineering difficulties involved in building facilities that can safely contain such waste for 100 centuries, are immense - as are the costs.

Then there are nuclear weapons. Some waste can be reprocessed into weapons-grade plutonium. In particular, the processing of plutonium for re-use as fuel for reactors is difficult and, as such, much of the waste is left to build in weapons-grade stockpiles that could pose a serious security threat were some to fall into the wrong hands.

All three of these issues result from the nuclear fuel cycle in conventional reactors.

The typical nuclear fuel cycle kicks off with a quantity of refined uranium ore. This ore is primarily composed of uranium-238 (U-238), the most common, weakly radioactive isotope that has a very long half-life and is not fissile.

This means U-238 doesn't easily undergo fission, the process in which the nucleus of the atom splits, releasing tremendous quantities of energy.

Usually, a very small percentage of the ore will be U-235. Unlike U-238, U-235 is fissile, and makes up the primary fuel for most nuclear reactors. It is also, incidentally, the uranium isotope that can be used to make nuclear weapons.

This is because when a U-235 atom splits, it releases a spread of high-energy neutrons.

If one of these neutrons then collides with another U-235 atom, it can cause the atom to split, releasing more neutrons in the process.

This runaway chain reaction is responsible for the fantastic explosive power of an atom bomb - and for the meltdowns at Chernobyl and Three Mile Island.

However, there is too little U-235 in mined uranium ore to maintain enough fission for a nuclear reactor or a bomb. The ore needs to be 'enriched', boosting the proportion of U-235 in the ore. Nuclear reactors require around 3 per cent to 5 per cent of U-235, while nuclear weapons often require 85 per cent or more. One of the most popular methods of enriching uranium is a gas centrifuge, where the uranium in the ore is converted into uranium hexafluoride gas and rapidly spun, forcing the heavier U-238 gas to the extremities for separation.

Once a sufficient proportion of U-235 is achieved, the ore can be made into fuel suitable for a reactor. Also, while U-235 is busily destroying itself in the reactor, the U-238 in the fuel is not sitting idly by. This is because U-238 is 'fertile', which means it can transmute into other, fissile elements in a process called 'breeding'. In this process, if an atom of U-238 absorbs a neutron, such as one thrown out by a nearby splitting U-235 atom, it can transmute into the short-lived U-239. This then rapidly decays into neptunium-239, which itself quickly decays into plutonium-239 (Pu-239). Pu-239 is another possible fuel for nuclear reactors because, like U-235, it is actively fissile and can maintain a chain reaction. The problem is that many reactors are not optimised for burning plutonium, and as a consequence large quantities of Pu-239 remain as a waste by-product in spent fuel rods.

Pu-239 can be reprocessed from spent fuel rods and turned into a compound called MOX (Mixed Oxide) fuel. This can then be reused in some nuclear reactors in the place of conventional enriched uranium. However, it is Pu-239 that also represents the greatest weapons proliferation threat. So reprocessing plutonium becomes a very costly and a politically sensitive business. This means it is less likely to be used as a nuclear fuel for a civilian power plant and is less likely to be reprocessed.

Nuclear physics is a complex and messy business, especially when dealing with large unstable elements such as uranium. When the U-235 in nuclear fuel burns down to around 0.3 per cent concentration, it's no longer of use in a reactor. At this point, the proportion of U-238, along with other fission by-products, including some very radioactive isotopes of americium, technetium and iodine, is too high. Many of these elements are called 'neutron poisons' because they absorb neutrons that would otherwise be happily colliding with other U-235 nuclei to spark off more fission.

This spent fuel can be reprocessed - but this is a much more difficult job than basic enrichment because of the high number of fission by-products in the spent fuel. This means that a great deal of spent fuel - highly radioactive as it is - becomes waste that needs to be stored. For a very long time.

THIS IS WHERE THORIUM steps in. Thorium itself is a metal in the actinide series, which is a run of 15 heavy radioactive elements that occupy their own period in the periodic table between actinium and lawrencium. Thorium sits on the periodic table two spots to the left (making it lighter) of the only other naturally occurring actinide, uranium (which is two spots to the left of synthetic plutonium). This means thorium and uranium share several characteristics.

According to Reza Hashemi-Nezhad, a nuclear physicist at the University of Sydney who has been studying the thorium fuel cycle, the most important point is that they both can absorb neutrons and transmute into fissile elements. "From the neutron-absorption point of view, U-238 is very similar to Th-232", he said.

It's these similarities that make thorium a potential alternative fuel for nuclear reactors. But it's the unique differences between thorium and uranium that make it a potentially superior fuel. First of all, unlike U-235 and Pu-239, thorium is not fissile, so no matter how much thorium you pack together, it will not start splitting atoms and blow up. This is because it cannot undergo nuclear fission by itself and it cannot sustain a nuclear chain reaction once one starts. It's a wannabe atom splitter incapable of taking the grand title.

What makes thorium suitable as a nuclear fuel is that it is fertile, much like U-238.

Natural thorium (Th-232) absorbs a neutron and quickly transmutes into unstable Th-233 and then into protactinium Pa-233, before quickly decaying into U-233, says Hashemi- Nezhad. The beauty of this complicated process is that the U-233 that's produced at the end of this breeding process is similar to U-235 and is fissile, making it suitable as a nuclear fuel. In this way, it talks like uranium and walks like uranium, but it ain't your common-or-garden variety uranium.

And this is where it gets interesting: thorium has a very different fuel cycle to uranium. The most significant benefit of thorium's journey comes from the fact that it is a lighter element than uranium. While it's fertile, it doesn't produce as many heavy and as many highly radioactive by-products. The absence of U-238 in the process also means that no plutonium is bred in the reactor.

As a result, the waste produced from burning thorium in a reactor is dramatically less radioactive than conventional nuclear waste. Where a uranium-fuelled reactor like many of those operating today might generate a tonne of high-level waste that stays toxic for tens of thousands of years, a reactor fuelled only by thorium will generate a fraction of this amount. And it would stay radioactive for only 500 years - after which it would be as manageable as coal ash.

So not only would there be less waste, the waste generated would need to be locked up for only five per cent of the time compared to most nuclear waste. Not surprisingly, the technical challenges in storing a smaller amount for 500 years are much lower than engineering something to be solid, secure and discreet for 10,000 years.

But wait, there's more: thorium has another remarkable property. Add plutonium to the mix - or any other radioactive actinide - and the thorium fuel process will actually incinerate these elements. That's right: it will chew up old nuclear waste as part of the power-generation process. It could not only generate power, but also act as a waste disposal plant for some of humanity's most heinous toxic waste.

This is especially significant when it comes to plutonium, which has proven very hard to dispose of using conventional means.

Current programs used for the disposal of plutonium reactor by-products and weapons-grade material using the MOX process are both expensive and complex. Furthermore, thorium proponents say that in conventional reactors, MOX fuel doesn't use plutonium as efficiently nor in the same volumes as thorium fuel would at lower cost.

So thorium might just be able to kill two birds with one stone. Not only does a thorium-fuelled reactor produce significantly less high-level waste, but it can also dispose of the decommissioned nuclear weapons and highly radioactive waste from nuclear reactors using more conventional fuels. Oh yes, it can also generate electricity.

SO WHY ISN'T EVERYONE using thorium reactors? The main drawback to thorium is that it's not vigorously fissile, and it needs a source of neutrons to kick off the reaction.

Unlike enriched uranium, which can be left to its own devices to start producing power, thorium needs a bit of coaxing.

Thorium also cannot maintain criticality on its own; that is, it can't sustain a nuclear reaction once it has been started. This means the U-233 produced at the end of the thorium fuel cycle doesn't pump out enough neutrons when it splits to keep the reaction self-sustaining: eventually the reaction fizzles out. It's why a reactor using thorium fuel is often called a 'sub-critical' reactor.

The main stumbling block until now has been how to provide thorium fuel with enough neutrons to keep the reaction going, and do so in an efficient and economical way.

In recent years two new technologies have been developed to do just this.

One company that has already begun developing thorium-fuelled nuclear power is the aptly named Thorium Power, based just outside Washington DC. The way Thorium Power gets around the sub-criticality of thorium is to create mixed fuels using a combination of enriched uranium, plutonium and thorium.

At the centre of the fuel rod is the 'seed' for the reaction, which contains plutonium.

Wrapped around the core is the 'blanket', which is made from a mixture of uranium and thorium. The seed then provides the necessary neutrons to the blanket to kick-start the thorium fuel cycle. Meanwhile, the plutonium and uranium are also undergoing fission.

The primary benefit of Thorium Power's system is that it can be used in existing nuclear plants with slight modification, such as Russian VVER-1000 reactors. Seth Grae, president and chief executive of Thorium Power, and his team are actively working with the Russians to develop a commercial product by the end of this decade. They already have thorium fuel running in the IR-8 research reactor at the Kurchatov Institute in Moscow.

"In the first quarter of 2008, we expect to have lead test assemblies in a full-size commercial nuclear power plant in Russia," said Grae.

He believes mixed thorium fuels can not only dispose of weapons-grade plutonium, but also be developed into a fuel for many conventional reactors to prevent production of any further plutonium as a by-product.

Thorium Power believes there is a market for about four thorium-powered reactors each in Russia and United States just for plutonium disposal. It's also aiming for reactors dealing with commercial plutonium by-products in Europe, Japan, Russia and the USA.

Grae is also enthusiastic about the benefits thorium fuels offer the environment. "All nuclear compares well to coal, in terms of no emissions into the atmosphere, including no carbon dioxide," he said. The environmental credentials of his company are also boosted by the presence of environmental lawyer and former member of the Centre for International Environmental Law, David MacGraw, he added. Grae muses that Thorium Power may be the "only nuclear company in the world with an environmentalist on the board".

AN ALTERNATIVE DESIGN does away with the requirements for uranium or plutonium altogether, and relies on thorium as its primary fuel source. This design, which was originally dubbed an Energy Amplifier but has more recently been named an Accelerator Driven System (ADS), was proposed by Italian Nobel physics laureate Carlos Rubbia, a former director of one of the world's leading nuclear physics labs, CERN, the European Organisation for Nuclear Research.

An ADS reactor is sub-critical, which means it needs help to get the thorium to react. **To do this, a particle accelerator fires protons at a lead target. When struck by high-energy protons the lead, called a spallation target, releases neutrons that collide with nuclei in the thorium fuel, which begins the fuel cycle that ends in the fission of U-233.**

A nuclear reactor that requires a particle beam to keep it running might seem a bit strange. But on the contrary, this is one of the ADS design's most attractive features**. If the particle beam is switched off, it is impossible for the fuel to enter a chain reaction and cause a meltdown. Instead, the rate of fission will immediately begin to slow and the fuel will eventually cool down and die out. According to Sydney's Hashemi-Nezhad, a sub-critical reactor such as this has clear safety benefits over uranium reactors. "It has zero chance of a Chernobyl-type accident," he said.**

Another major advantage of this design is that it only requires thorium as fuel.

Hashemi-Nezhad also says thorium is a highly abundant resource "550 times more abundant in nature than uranium-235".

It's also an element in which Australia is well blessed - we have the largest known thorium reserves in the world. Thorium mining is also less complex than uranium mining; and the ore doesn't even require enrichment before use in an ADS reactor.

In a non-proliferation sense, there are also good reasons to prefer a sub-critical thorium reactor, as it **is impossible to make weapons-grade materials from thorium.**

Even traces of unburnt U-233 in thorium reactor waste products are more difficult to convert into a usable nuclear weapon than U-235 or Pu-239. Imagine the West offering thorium-fuelled ADS reactors to countries such as Iran or North Korea: this would satisfy their demands for cheap nuclear power, but entirely avert the risk of the civil nuclear program leading to the development of nuclear weapons.

The other key advantage of the ADS design is that it can be used to dispose of dangerous weapons-grade material and commercial reactor by-products in a similar way to mixed thorium fuel.

While the ADS design has promise, it presents challenges. First, there's the design itself: while lab tests have proven the concept of using a particle beam to start the thorium fuel cycle, the physics of scaling it up to the size of a commercial reactor are unproven and could be more complex. Then there's the way the particle beam interacts with the spallation target and the fuel in order to operate efficiently. Also, while there are plenty of existing conventional nuclear reactors that can be fairly inexpensively converted to mixed thorium fuel, an ADS reactor would have to be designed, built and paid for from scratch.

Retrofitting old reactors is not an option.

Does this make a large-scale ADS reactor viable? **CERN thinks so. It recently released a detailed report covering the financial viability of the ADS design for power generation, and found it to be at least three times cheaper than coal and 4.8 times cheaper than natural gas.** Any nuclear reactor will have a high establishment cost, but CERN stresses that a long-life reactor will be highly competitive compared to fossil and renewable energy fuels.

Hashemi-Nezhad has been working on the ADS reactor concept with colleagues in Germany, Russia, India and Eastern Europe, and is enthusiastic about it. "The future of nuclear reactors is in ADS because it operates in a sub-critical condition. Only under this condition it is possible to transmute waste isotopes while gaining energy and producing fuel at low cost. And it's safe," he said.

He also thinks Australia could play a leading role in the development and promotion of thorium-fuelled reactors. "It is up to the Australian government to make an investment in this research. Huge thorium resources in Australia can provide green energy at low cost for several centuries." An enticing prospect, to say the least.

CAN ATOMIC POWER be green? Physics suggests it can. And our consumption of energy is accelerating at the same time the climate is being affected by power generation.

Unless we start seriously exploring energy alternatives to burning fossil fuels, erratic and destructive weather conditions could be with us for generations to come. Renewable energy such as wind and solar have bright futures, and will play a large role in any future energy program - but they can never hope to satisfy baseload requirements of a city.

Hydroelectric power is an option - but most of the economical sites have been exploited, and biodiversity suffers when valleys are flooded to create dams. So, unless some groundbreaking discovery in nuclear fusion is made, making it not only possible but efficient and economical - then nuclear fission will remain on the agenda for promising baseload energy alternatives.

Despite its drawbacks, conventional uranium-fuelled nuclear power is a realistic option that is likely to be continued worldwide.

But it is thorium reactors that present a real quantum leap forward. Humble thorium could potentially alleviate three of the most pressing issues facing modern civilisation in the 21st century: the hunger for energy, the spectre of climate change and the need to eliminate nuclear weapons.

Tim Dean is a science and technology journalist in Sydney, editor of the Technophile section of COSMOS, and a former editor of the computer magazine, *PC Authority*

http://www.cosmosmagazine.com/features/print/348/new-age-nuclear?page=0%2C3

http://www.speclab.com/elements/thorium.htm