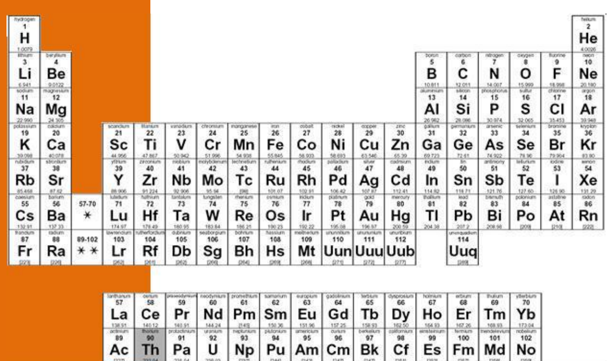
Fuel for Thought:

The Importance of Thorium to China

by Cindy Hurst



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Introduction

Over the past few years China has launched efforts to develop the world's first commercial thorium-fueled reactor based on the use of liquid salt. At one point thorium was widely used in gas mantles. It has also been used in night flares from the Milan weapon system and in magnesium alloy aircraft components, optical lenses, refractory ceramics, and some laboratory compounds. As a magnesium alloy, a small quantity of thorium can be used for its hardening and lightweight properties, making it ideal for the aerospace industry.[1] One problem with thorium is its mildly radioactive nature, producing concerns over its safety and potential harmful effects. Therefore, today there is little use for thorium.

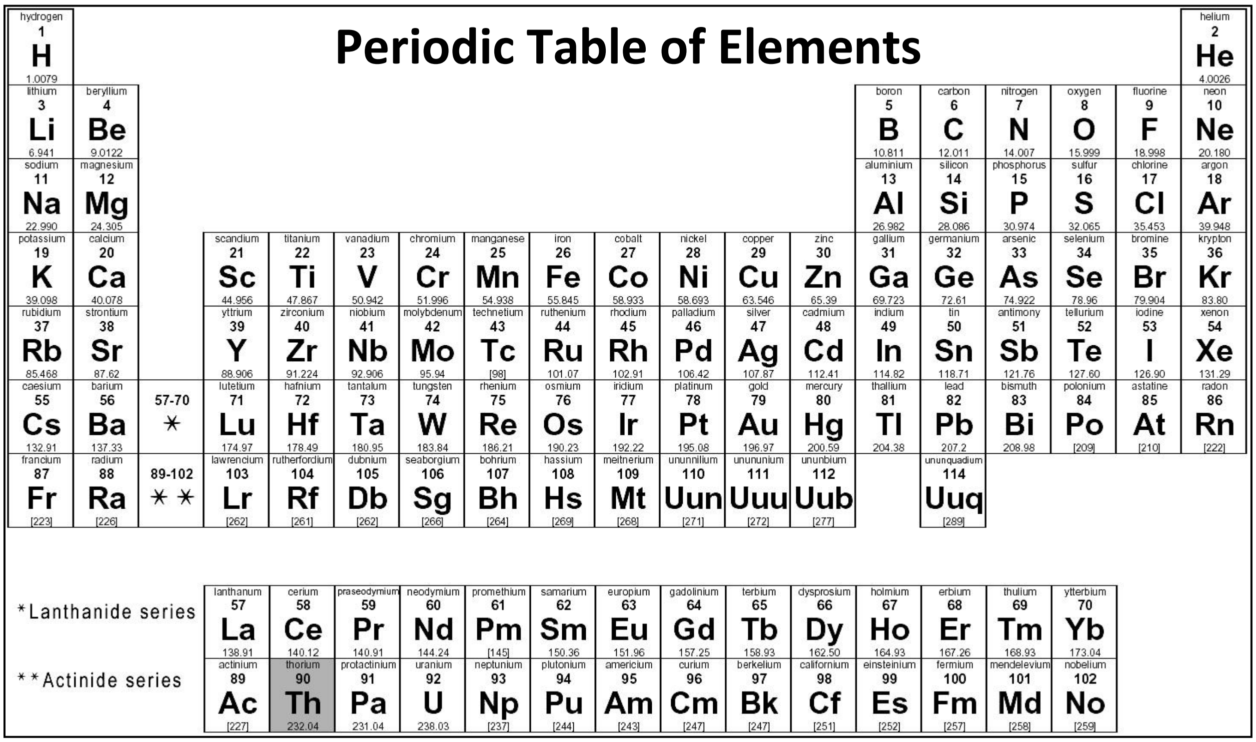
There are a number of reasons thorium-fueled reactors, in particular the thorium molten salt reactor (TMSR), would work for China. First, nuclear fission does not produce air pollution. Second, thorium, being a by-product of rare-earth mining, is believed to be far more abundant in China than uranium. Third, it could turn thorium, currently considered a waste-by-product in the processing of rare earth elements, into something of value.

China's effort of developing a TMSR is part of a bigger program to develop both solid fueled and liquid fueled reactors. Originally, the Chinese government had set a deadline for the project to be developed within 25 years. Shortly after that development target was set, in early 2014, according to the *South China Morning Post*, the government seems to have stepped up the TMSR pace by urging scientists to develop the new design by 2024,[2] leading some observers to question the country's possible motives.

Developing the TMSR would have a number of positive impacts on China, including giving the country an economic advantage, to include China's economic threat to U.S. competitiveness.[3] This article will give an overview of China's thinking in regard to thorium and the actions it is taking to develop the first thorium molten salt reactor. Some possible implications for both the country and the rest of the world are included.

Background: China Looks to the TMSR as Part of a Broader National Strategy

Thorium is a naturally occurring metal (atomic #90) found on the periodic table of elements. It is at the bottom of the table and is included in the series of elements known as the actinides. Like other actinides, which include uranium, plutonium, and 13 less familiar elements, thorium contains unstable isotopes (the single natural-occurring isotope being Th-232) that produce a chain of radioactive decay products.



Thorium is a "fertile material," which means that by itself, it cannot be used to start a nuclear reactor. It first has to be converted into a fissile material, which allows it to sustain a chain reaction with neutrons of any energy. Simply put, fission is a process of breaking apart. When breaking apart, the fissioning nuclei create a large amount of energy, radioactive fission products, and more neutrons. Thorium is converted into fissile material (uranium-233) through neutron irradiation through the following reactions:

- Th-232 + neutron → Th-233
- Th-233 (beta-decay) → Pa-233 (22 min)
- Pa-233 (beta-decay) → U-233 (27 days)[4]

Today, it is widely believed that most nuclear reactors have the potential to use thorium to fuel them. However, only certain reactors are able to fully exploit thorium's potential. David Martin, deputy director of research at the Weinberg Foundation, a not-for-profit nuclear energy lobby group supporting thorium reactor development, said that the two most promising thorium-fueled reactors are high-temperature reactors (HTR) and molten salt reactors (MSR).[5]

The idea of using thorium in advanced energy technologies was conceptualized in the United States in the 1940s by Drs. Alvin Weinberg and Eugene Wigner. Weinberg would go on to become Director of the Oak Ridge National Laboratory (ORNL). The first experimental MSR was the Aircraft Reactor Experiment in 1954 and the second was the more familiar Molten Salt Reactor Experiment (MSRE) conducted by ORNL (1965-1969). Despite great strides being made, the MSRE program was halted in 1972 after the Nixon Administration decided to focus all development efforts and funding on the uranium-based solid fuel liquid-metal fast breeder reactor. The U.S. molten salt reactor program continued at reduced scale until the late 1970s with an emphasis on proliferation resistant fuel cycles.

While China has been developing and/or utilizing a variety of uranium and thorium-fueled reactors, the country seems to be keenly interested in the TMSR. For one thing, the groundwork for the MSR has already been laid. This makes it ideally suited for China because the country, which continues to lag behind its competitors in overall technological research and development, would not have to start from scratch.

In February 2011, a Chinese article claimed that TMSRs could become a pillar of China's energy supply in 30 to 40 years when sources of fossil fuel become depleted and other sources of energy are insufficient to maintain the country's needs.[6] Since then, Chinese experts have been touting the possibilities of these types of reactors.

Today, Jiang Mianheng, eldest son of former Chinese leader Jiang Zemin and head of the newly established Shanghai Tech University, is directing a team of scientists to try to develop the first TMSR. The project is a pioneer initiative of the Chinese Academy of Sciences and, according to Jiang, is 100 percent funded by the Chinese government.

In 2010, Jiang and other members of the Chinese Academy of Sciences visited the Oak Ridge National Laboratory. In 2011, the Chinese government signed a memorandum of understanding with the United States Department of Energy. According to an investigation conducted by Reuters in late 2013, China budgeted $350 million for the project.[7] By 2015, Jiang is expected to have 700 scientists and other staff members working full-time on advanced nuclear reactors including thorium-fueled reactors at the institute.[8]

During a speech at the University, Jiang said, “In order to accomplish the Chinese Dream, China needs to adopt a new national strategy that relies on innovation to propel developments.”[9] In another speech, Jiang explained his reasoning behind China’s need to develop the thorium technology using economic terms. He pointed out that China has the second largest economy in the world and that over the next two decades, the country was expected to increase its gross domestic product in the world economy. However, the difficulty lies in that China is still in the process of urbanizing. Jiang compared China’s urbanization to other countries, explaining that the urbanization level in China is under 50 percent. In contrast, the United States has reached nearly 99 percent and Korea 90 percent. “We are the second largest economy in the world, but we are still in the stage of the urbanization evolution processes,” he said.[10]

As China’s economy continues to evolve, more energy is needed to support it. With the drawbacks in other sources of energy, such as depleting and polluting fossil fuels and the anticipated decrease in availability of uranium, more viable sources of energy are necessary to continue to propel the country forward in its urbanization process.

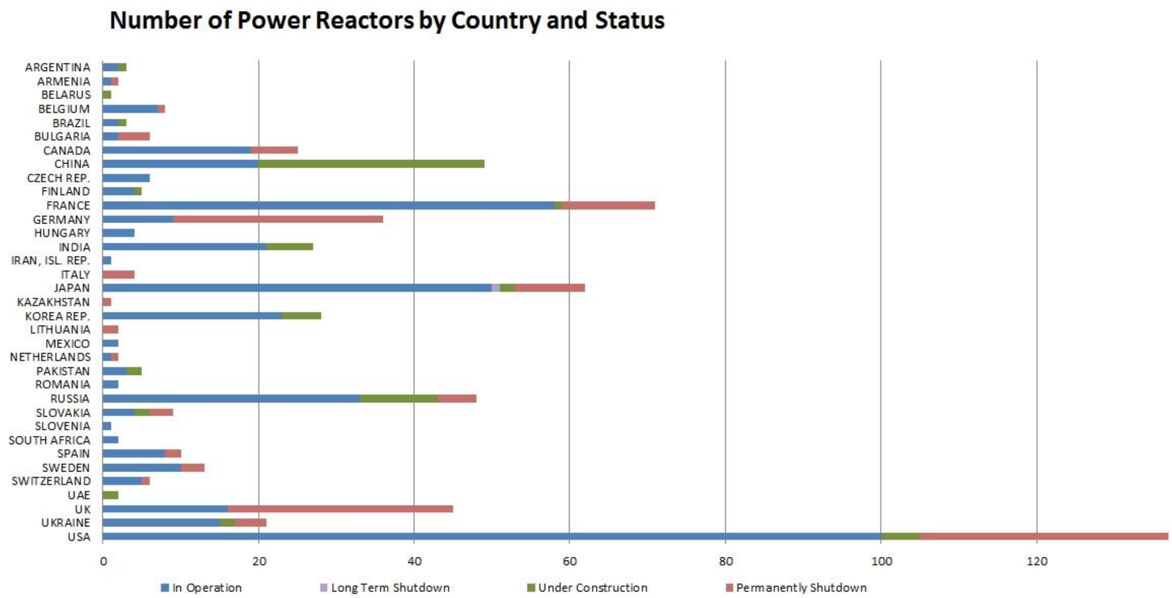
Thorium-fueled Reactors to Curb Pollution

Initially, China’s interest in developing a thorium-fueled reactor was spawned out of a growing concern over energy shortages. In the early 1990s, experts within the country felt there was an abundance of domestic energy resources, including coal, oil, natural gas, uranium, and geothermal energy. During that time, China was viewed as a “resources-abundant country.”[11] Over the next decade, however, this viewpoint began changing as the reality of China’s economic growth, which drove the expansion of transportation and industry in the country, set in. As a result, not only was China becoming a net importer of most energy resources, but the pollution rate soared. Today the Chinese leadership and media realize they have a huge problem with smog and pollution.

On March 5, 2014 Premier Li Keqiang told the national legislature in Beijing that the government had declared “war on pollution.”[12] The problems associated with smog have been growing, causing increased safety and health hazards in the country. In January 2014, for example, a 40-car pile-up on a Chinese motorway was at least partially attributed to poor visibility due to smog. A 2007 World Bank study associated 750,000 premature deaths per year with pollution in China. Today, other sources are saying that more than two-million premature deaths are due to pollution, and that the incidents of lung cancer have soared by 60 percent over the past decade.[13] In 2013, a small particles air index, which is maintained by the U.S. Embassy in Beijing, is said to have reached 517. According to the World Health Organization, the recommended daily level should not exceed 20.[14]

The two top polluters in China are automobiles and industry. In 2013 there were reportedly some 20 million vehicles in Beijing alone. That number is growing by about 250,000 every year. China produces and consumes almost as much coal as the rest of the world combined.[15] Industry powered mostly by coal in China is the second biggest polluter. According to the Energy Information Administration, China accounts for nearly half of the world's coal consumption

In August 2013, the State Council said that China should reduce its carbon emission by 40-45 percent by 2020 from its 2005 levels. Due to rapid economic growth and urbanization, the country’s consumption of electricity continues to increase steadily each year. Uranium based nuclear power stations offer a clean alternative to fossil fuels. However, they currently generate only about one percent of the country’s power.[16] The first indigenously-designed and constructed nuclear power plant began in China in 1985. In December 1991, it became the first to be connected to the country’s power grid.[17] In contrast, the former Soviet Union began operating a 5 megawatt nuclear power plant in 1954 and the United States began operating its first large-scale nuclear power plant in 1957. Due to the more than 30-year jump in the technology and research and development of nuclear power in China, today there is a global shift in the use of nuclear power. China has 21 nuclear power reactors in operation, 28 under



construction, and more in the planning phases.[18] In 2011, the International Atomic Energy Agency reported that 27 out of 65 nuclear reactors being built worldwide were in China.[19]

Despite this seemingly positive upward trend, concerns related to China's increase in nuclear power are growing. He Zuoxiu, a member of the Chinese Academy of Sciences who is often considered the country's leading nuclear physicist, has openly expressed concerns over the rapid expansion of China's nuclear energy program. Among his fears were those surrounding a potential lack of uranium resources. According to He's calculations, which he based on data from the International Atomic Energy Agency, there are less than 300,000 tons of uranium reserves in China.[20] He, who participated in the development of China's first nuclear bomb, expressed further fears that it might become increasingly difficult to acquire uranium abroad. According to the scientist, "I am afraid it will be much more difficult (to acquire uranium) than importing oil and natural gas."[21]

China appeared to have a plan to meet this expected decline in the availability of uranium. Less than one year after He expressed concern, according to the *Westpac-BREE China Resources Quarterly*, between December 2012 and December 2013, there was a huge spike in imports of uranium into China.[22] According to an article published in the *Australian*, China had pre-purchased uranium at low prices prior to the commissioning of new nuclear plants, investing some $2.39 billion. Like He, the article also expressed concern over a severe world shortage of uranium expected to arise later this decade.[23] The problem is not that there is a shortage of uranium in the earth's crust, but rather that prices have been falling, resulting in a decrease in mining and processing efforts. While the cost of uranium had spiked sharply in 2007, and then again just prior to the Fukushima nuclear accident in 2011, it has since dropped dramatically and has yet to recover.

With a potential transient shortage of uranium looming over the horizon coupled with the ill-effects of fossil fuels, some observers view thorium as an ideal solution due to both its abundance and its clean energy producing properties. By one estimate, the use of 100 tons of thorium fuel each year might substitute for 250 million tons of coal.[24]

A Possible Transition from Waste to Strategic Importance?

For China, a country desperately trying to resolve its severe pollution problem while ensuring its energy security, it makes sense to consider thorium to fuel nuclear reactors because of a potential abundance of supply. Thorium is reportedly about three to four times more abundant in the earth's crust than uranium. It is said to be as abundant as lead while uranium is as abundant as tin or zinc. Some experts believe that thorium reserves could provide more energy than both uranium and fossil fuels combined.[25] While China possesses only an estimated three percent of the world's uranium, the country boasts having the second largest reserves of thorium.[26,27]

There is no firm resource data available on this claim and the data differs from source to source. According to the U.S. Geological Survey (USGS), there are some 1,400,000 tons of known thorium reserves in the world. The World Nuclear Organization puts that amount at 5,385,000 tons. According to the USGS, the United States has the highest reserves of thorium, with Australia and India trailing behind it. However, there is no mention of China. The World Nuclear Organization ranks India as number one in reserves, trailed by Turkey, Brazil, Australia, and the United States respectively. Meanwhile, the organization ranks China as number 12. Therefore, at this point it is impossible to determine who really has the largest reserves since each organization has a different definition for the concept of "reserves." Also, as the World

Nuclear Organization points out in its disclaimer, “thorium is not a primary exploration target and resources are estimated in relation to uranium and rare earth resources.”

Throughout the last few decades, thorium has been viewed and treated as a waste by-product of the country’s rare earth industry. China, which possesses an estimated 42 percent of global reserves of rare earth elements, has carefully positioned itself so that today it produces approximately 86 percent of the world’s supplies.[28] Rare earth elements are vital to hundreds of high-tech applications, many of them critical to national security.[29] Rare earth elements are found predominately in baestnesite and monazite mineral deposits. Thorium, meanwhile, is found predominately in monazite deposits. The largest rare earth mine in China is located in Baotou, in the Northern Province of Inner Mongolia. According to one Chinese report, the Baotou Steel’s tailing (residue/waste) reservoir contains enough thorium reserve in it “to light the whole country (China) for 200 years if that reserve is all used for power generation.”[30]

Not only would creating a market for thorium help to reduce the country’s dependence on foreign imports of natural resources, it would also resolve the problem of what to do with a potentially hazardous waste-by-product. For years, China’s rare earth industry has suffered from lax regulations, which has resulted in extensive damage to the environment. Throughout the process of separating rare earth elements, thorium has regularly been discarded into tailings ponds, often ending up as runoff, and finding its way into rivers and the country’s water sources and fields.

In 2011 Xu Guangxian, considered to be China’s father of rare earth chemistry, suggested that the national government should store up reserves of thorium resources “in consideration of cost and price.” Xu also urged the national government to invest in the research and development, recovery, and collection of thorium due to its potential application for nuclear power. This, he pointed out, would prevent the secondary pollution of thorium in rare earth operations and protect the environment in Baotou and areas downstream along the Yellow River.[31]

In summary, if China were to successfully develop a thorium-fueled reactor, it would accomplish several goals. First, it would help to reduce some of the pollution caused by fossil fuels. Second, it would resolve the issue of what to do with a radioactive waste-by-product. Third, it would reduce China's dependence on imported natural resources. Finally, it could also give China an economic leg up.

Thorium: One Tiny Step Toward Building a Nation through Research and Development

As part of a bigger picture, China's TMSR project is becoming an integral part of the country's national effort in research and development. These efforts tie into the economy and therefore serve to strengthen the country in many ways, including militarily.

In 2012, China spent more than an estimated $168 billion on research and development, which is about 1.97 percent of gross domestic product (GDP). By 2013, that amount rose to 2.05 percent.[32] China intends to become an innovative country by 2020, when, according to one document, scientific progress is expected to contribute 60 percent of the country's economic development, and investment in research and development is predicted to jump to 2.5 percent of GDP.[33]

The advantage of using thorium and the molten salt reactor technology is that it has promising attributes, and research and development should help commercialize the technology. China is already making headway into other nuclear reactor technologies. Should China develop the first TMSR, it would help to fill the country's growing research and development portfolio with a diversity of reactor types.

Other Possible Motives behind China's Push

Dr. Cecil Parks, Director, Reactor and Nuclear Systems Division at the Oak Ridge National Laboratory pointed out that high temperature reactors, such as the TMSR, could be designed to operate with low water usage. This could provide another reason for China to pursue the TMSR since the country has been suffering from diminishing sources of water and much of in-land China is arid. According to an article in the *Economist*, "China is dangerously short of water… China has 20 percent of the world's population but only 7 percent of its fresh water…"[34] On January 14, 2014, the Chinese media reported on the country's fears of diminishing water supplies. According to a report in *China Daily*, wetlands across 131,274 square miles, an area larger than the Netherlands, have disappeared. The Forestry Administration attributed this to infrastructure projects and climate change. According to Zhang Yongli, deputy director of the State Forestry Administration, "The factors threatening wetlands have expanded." Ten years ago the threats consisted of pollution, land reclamation, and illegal hunting. Today, the threats consist of "pollution, excessive fishing and gathering, land reclamation, invasion of alien species, and occupation by infrastructure."[35]

Also, while successfully developing a TMSR will likely have positive environmental, social, and economic implications for China, it also could help to quell some of the disputes that arise over natural resources, including regional conflicts centered around territorial disputes. History is filled with conflicts arising over natural resources. Jin Bosong, a research fellow with China's Academy of International Trade and Economic Cooperation under the Ministry of Commerce of the PRC, highlighted the importance of securing natural resources by writing, "historically, when the developed countries went through a similar developmental stage (as what China is going through now), they started two world wars over natural resources." Even following the two world wars, there were two rounds of oil crises. At the time that Jin had written the article, the developed countries had a total population of 800 million, while China's population topped 1.3 billion (when the article was published).[36]

Challenges Confronting China

While there seem to be many reasons that China should pursue developing the TMSR, the country appears to be facing a number of issues. Researchers working on the project have pointed out that, despite the recent pressure to succeed, there are some technological challenges that make the endeavor difficult, if not impossible to accomplish in such a short period of time. Actual knowledge on how to use thorium is limited. Professor Li Zhong, a scientist working on the CAS project, voiced his concern of rushing the technology. According to Li, "We are still in the dark about the physical and chemical nature of thorium in many ways. There are so many problems to deal with but so little time."[37]

Other scientists also are not optimistic about the potential transition to thorium-fueled reactors. Professor Gu Zhongmao, an official at the China Institute of Atomic Energy, believes that thorium-fueled reactors will need years, or even decades, to overcome corrosion issues.[38] Gu noted that, “These projects are beautiful to scientists, but nightmarish to engineers.”[39]

There remain many unknown variables and contradictory information. For example, while some sources claim that extracting thorium is cheaper than extracting uranium, other sources claim that thorium’s extraction and conversion can be costly. Another fear is that the molten salt reactors use highly corrosive chemicals, such as fluorine, that, if not carefully controlled, could damage the reactor materials.[40,41]

There is also an element of uncertainty surrounding nuclear energy in general. The 2011 nuclear accident at Fukushima Japan caused concern among Chinese citizens. Some observers question whether any nuclear power worth the risks. Meanwhile, however, others believe that there is a “glowing future” on the horizon for nuclear power plants in China.[42]

Fuel for Thought: Possible Military and Economic Implications?

From China’s viewpoint, the push to come up with the world’s first TMSR is based on a necessity for cleaner, more readily available sources of energy, while also having a positive impact on the environment. However, one concern is in the possibility of nuclear proliferation. Some proponents of thorium claim that it is “nearly impossible to produce nuclear weapons” using thorium.[43] Other researchers, however, believe this is not necessarily true. Dr. Fiona Rayment, Director of Fuel Cycle Solutions at the UK’s National Nuclear Laboratory, explains that "while it is true that using thorium produces only trace amounts of plutonium, it does produce very high-quality fissile materials, which is a significant proliferation issue, as is the case with the conventional uranium/plutonium fuel cycle." Rayment goes on to clarify her statement by explaining that “thorium on its own can't produce a nuclear reaction. In order for a sustained nuclear reaction, small quantities of fissionable plutonium (Pu) or uranium (U) are required to start the reaction and create power. These fissionable materials are present in both U/Pu and Th/U fuel cycles and as such the proliferation issue should be considered in both cases.” Therefore, it would be imprudent to create a false sense of security by believing thorium-fueled reactors would prevent nuclear proliferation. With China being a nuclear reactor exporting nation, it is essential to understand the possibilities.

Conclusions

There are several reasons China would benefit from commercializing TMSR technology and most of these reasons are seemingly benign. First, one of China's primary goals appears to be to provide energy to its growing economy. Currently all of the country's nuclear power generators use uranium to fuel them. Developing the TMSR would reduce China's external dependence on imported oil, natural gas, and even uranium. These are resources with highly unstable prices. Second, fossil fuels create huge carbon dioxide emissions, while nuclear energy does not. At the same time, the ability to use up thorium rather than treat it like a waste-byproduct of mining operations will alleviate some of the environmental damage that arises as a result of careless disposal techniques. Third, the TMSR offers the added benefit to a country suffering from a shortage of water because it does not require much water to operate. Current uranium- fueled light water reactors, on the other hand, require vast amounts of water to operate. Fourth, China's development of the TMSR would mark another achievement in a growing list of impressive endeavors in China's research and development portfolio. Finally, the TMSR groundwork was laid at the Oak Ridge National Laboratory decades ago, which will save time and effort.

Dr. Jess Gehin, Reactor Technology R&D Integration Lead at ORNL, refers to China's goal of completing the first MSR as "an ambitious time frame," saying, "I think it's very challenging, but they've got a lot of motivation and resources to try to do this." There are ample hurdles to overcome and steps to take in a short period of time to accomplish it. For example, the salt chemistry must first be mastered. There are also material compatibility issues in a radiation environment. There are technology components for the pump heat exchanger. In other words, there is a lot of technological development that must take place before a reactor can become operational. Gehin does not foresee a fully functioning commercial power reactor coming to fruition over the next ten years, but rather "something that would be used for testing."[44]

With so many unknown variables, the verdict is not yet out. Developing a commercial TMSR is difficult and will take a long time. By developing the first TMSR, China will have achieved another great milestone, and taken another step in its effort to become an innovative country. It is anyone's guess what the final outcome will be and how and even whether the technology might be used in a way that industry and policy nexus could negatively impact the rest of the world.

NOTES

[1] "Leaflet 29, Items and Components Containing Thorium," MOD Radiation Safety Handbook, JSP 392, Vol 2, October 2013.

[2] Stephen Chen, "Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024," South China Morning Post, March 18, 2014, http://www.scmp.com/news/china/article/1452011/chinese-scientists-urged-develop-new-thorium-nuclear-reactors-2024?page=all

[3] Justin Dove, "The Future of Nuclear: Is Thorium a True Threat to Uranium?" Investmentu, September 23, 2011.

[4] These reactions are analogous to those in the production of plutonium from uranium. Thus, in order to produce fissile uranium-233 a source of neutrons is required. This can be provided through the addition of fissile materials such as uranium-235, plutonium-239, or self-generated uranium-233 to create a neutron-generating chain reaction. Alternatively, it is also possible to provide neutrons from an external source, such as an accelerator or fusion reaction.

[5] MSRs are a class of nuclear fission reactors in which the primary coolant, or even the fuel itself, is a molten salt mixture. They have two primary subclasses. In the first subclass, fissile material is dissolved in the molten salt. In the second subclass the molten salt serves as the low pressure coolant to a coated particle fueled core similar to that employed in High-Temperature Reactors (HTRs). Stephen Harris, "Your Questions Answered: Thorium-Powered Nuclear," The Engineer, January 9, 2014.

[6] Xu Qimin, 钍基熔盐堆：喝液态燃料"杂食性"未来核反应堆 (Thorium Molten Salt Reactor: Liquid-Fuel Drinking "Omnivorous" Future Nuclear Reactor)," State Nuclear Power Technology Corporation, February 23, 2011, http://www.snptc.com.cn/index.php?optionid=705&auto_id=5991

[7] Yao Jin, "China's Green Development Plans," About Oil, January 17, 2014, http://www.abo.net/oilportal/topic/view.do?contentId=2188644

[8] Ambrose Evans-Pritchard, "China Blazes Trail for 'Clean' Nuclear Power from Thorium," Telegraph.co.uk, January 6, 2012.

[9] Chris Luo, "Former President Jiang Zemin's Son Endorses Chinese Dream," South China Morning Post, September 4, 2013.

[10] Jiang Mianheng, "Why Nuclear Power in China? Thorium & the Energy Outlook of china," Thorium Energy Conference, Shanghai, 2012, https://www.youtube.com/watch?v=iLX8jCKL9I4

[11] Lu Yazhou, "Status of Natural Resources Utilization," Ziranziyuan (Chinese), November 1 1994.

[12] Stephen Chen, "Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024."

[13] "China on Red Alert Over Pollution," January 31, 2013.

[14] Ibid.

[15] "China Produces and Consumes Almost as Much Coal as the Rest of the World Combined," U.S. Energy Information Administration, May 14, 2014.

[16] Stephen Chen, "Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024."

[17] "Nuclear Power in China," World Nuclear.org, May 15, 2014.

[18] "Nuclear Power in China," World Nuclear Association, April 2014, http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power/

[19] Wang Kan, "Glowing Future on Horizon for Nuclear Power Plants in China," Global Times, March 25, 2011.

[20] The International Atomic Agency puts that figure at just below 200,000 tons, http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Supply-of-Uranium/

[21] Stephen Chen, "Nuclear Safety Under Threat, Physicist Warns," South China Morning Post, May 30, 2011.

[22] See, for example, the Southern autumn – Northern spring 2014 issue.

[23] Robin Bromby, "China Stockpiles Cheap Uranium as Severe Shortage is Anticipated," The Australian, February 17, 2014.

[24] Qiao Hui, Li Bo, and Guo Ting, "China Regulates Orderly Exploitation of Rare Earth Resources," Ta Kung Pao (Chinese), October 23, 2010.

[25] "Thorium," Royal Society of Chemistry website, accessed May 22, 2014, http://www.rsc.org/periodic-table/element/90/thorium

[26] Qiao Hui, Li Bo, and Guo Ting, "China Regulates Orderly Exploitation of Rare Earth Resources," Ta Kung Pao (Chinese), October 23, 2010.

[27] Organizations, such as the United States Geological Survey, which monitor global reserves, make no mention of reserves in China. This is likely due to varied interpretations of the term "reserves." According to the USGS, reserves are defined as the "part of the reserve base which could be economically extracted or produced at the time of determination." They "include only recoverable materials."

[28] Figures are estimates taken from the U.S. Geological Survey Mineral Commodity Summaries, January 2015.

[29] For more information on rare earth elements, please refer to Cindy Hurst, "China's Rare Earth Elements Industry: What Can the West Learn?" Institute for the Analysis of Global Security, March 2009.

[30] Qiao Hui, Li Bo, and Guo Ting, "China Regulates Orderly Exploitation of Rare Earth Resources," Ta Kung Pao (Chinese), October 23, 2010.

[31] Li Shaofei et al, “An Exclusive Internview with Academician Xu Guangxian, China’s Father of Rare Earths – Resolving China’s Rare Earth Appllied R&D Stalemate,” Liaowang (Chinese), July 11-31, 2011.

[32] “Xinhua Insight: China Eyes to Become High Tech Exporter,” Xinhua, June 19, 2014.

[33] Ibid.

[34] “Water in China: Desperate measures,” The Economist, October 12, 2013.

[35] Yang Yao, “Shrinking of Wetlands Spurs Call for Regulation,” China Daily, January 14, 2014.

[36] Jin Bosong, “The World in Contention for Resources and China’s Strategic Direction,” Zhongguo Jingji Shibao, September 24, 2009.

[37] Stephen Chen, “Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024.”

[38] Other scientists have cited experience, such as ORNL’s MSR Experiment, which did not appear to experience significant corrosion issues.

[39] Stephen Chen, “Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024.”

[40] Ibid.

[41] Scientists at ORNL expressed doubt about the corrosive nature of MSR projects saying that if done carefully in a controlled environment, corrosion should not be an issue.

[42] Stephen Chen, “Chinese Scientists Urged to Develop New Thorium Nuclear Reactors by 2024.”

[44] Cecil Parks and Jess Gehin, Telephone Interview, May 12, 2014.