Thorium Molten Salt Reactor: A Safe Way Out for Nuclear Energy

By SONG Jianlan (Staff Reporter)

Doubts on the safety of nuclear energy have far from being cleared up since the Fukushima Daiichi nuclear crisis broke out in March 2011, and the elephantine nuclear energy industry remains constrained at the epicenter of a refueled dispute. Some pro-nuclear activists, however, argue that nuclear energy will remain the preferred solution to future energy demand, citing setbacks of other options like fossil fuels, wind and solar energy sources.

Nevertheless, a conscientious scientist would rather take a much more serious, cautious stand on this issue. Don't we have any better choice?

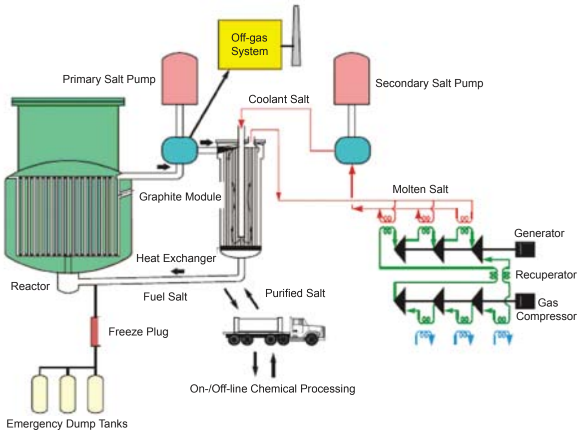
Such a safe solution does exist, actually, and a grand long-term program had been launched to turn it into reality even before the Fukushima crisis occurred by a team of nuclear energy experts led by Prof. XU Hongjie from the Shanghai Institute of Applied Physics under CAS. 'We need better nuclear "furnaces",' XU was reported asserting the pressing need for safer, cheaper and more effective nuclear energy technologies in late February 2011, two weeks before the major tremor attacked Japan.

What XU seeks to develop now is a set of technologies for an innovative but once neglected idea, the thorium molten salt reactor (TMSR) system, with strong support from CAS as a strategic priority research project. Unlike the current mainstream reactors using uranium/plutonium fuels, there will be essentially no possibility of a meltdown in a TMSR, according to materials released by the team.

Lower risks for meltdown

The disastrous meltdown at Fukushima has thrown the public into fears for a potential restart of chain fission reaction in a nuclear reactor in the case of a catastrophe due to the failure of the cooling system. TMSR, however, promises much lower risks for such a meltdown. The special design of the reactor will defuse possible overheat anytime a disaster occurs.

In the case of TMSR, fuels are melted in hot fluorides, which at the same time serve as a coolant that recycles in the inner and outer circles within the reactor. The kind of overheating in Fukushima will not occur here because once the temperature at the core goes beyond a threshold, a "freeze plug" at the bottom of the reactor core will melt down itself to drain the molten salt off an emergency dump tank connected to the core, and thus stop the reaction.



A schematic illustration for the TMSR system.

No spontaneous chain fission reaction

Also this new type of reactor will promise much lower risks of a spontaneous chain fission reaction, based on a thorium/uranium fuel cycle. Natural thorium exists with thorium 232 in abundance, containing only trace amount of self-fissile material like thorium 231, less than necessary to trigger a nuclear chain reaction. Moreover, thorium 232 cannot be used as nuclear fuel until it is transformed into uranium 233 after absorbing neutrons. This absorption will lead to deficiency of neutrons, which are necessary to sustain a chain reaction, and hence further extinguish the possibility to start a spontaneous chain fission reaction in the system.

Therefore a chain fissile reaction cannot be sparkled in natural thorium unless extra neutrons are accelerated to certain energy to bombard it and transform it into some transient elements that will subsequently decay to uranium 233. This distinctive characteristic automatically prevents a spontaneous fissile reaction from occurring in a TMSR and makes it possible to generate electricity in a highly safe way. Moreover, other distinctive characteristics of the TMSR also make it the greenest choice ever, featuring better resistance to nuclear proliferation and substantially reduced production of plutonium and actinides.

Green nuclear energy

Aside from safety, thorium-based reactors also feature other advantages over uranium-based ones, including much higher production rate, much greater abundance of fuel material and lower discharge of nuclear waste.

Without worries about spontaneous fission, TMSRs can be designed in a very simple structure, according to XU. You will not need to stoke them up for a long time once sufficient fuels are sealed in the reactor cores—the fuels will burn mildly and safely for dozens of years inside. The reaction can keep going under normal atmospheric pressure; and theoretically, the wastes produced by these new reactors will be as little as only one thousandth of what the current reactors discharge, because the fuels can be burnt more thoroughly in these furnaces. An added benefit is, according to experts, if properly designed, molten-salt reactors and related enrichment facilities can help burn up the existing radioactive waste through reprocessing of them.

Thorium fuels are much more powerful than uranium, according to experts. One ton of thorium can produce as much energy as 200 tons of uranium, or 3,500,000 tons of coal does. As a sharp contrast to scarce uranium, thorium is widely available and much easier to obtain as a by-product of the extraction process of some rare earth elements. It is estimated that its abundance in nature is four to five times higher than uranium. It is evenly distributed across the earth's crust, and hence many countries have enriched thorium resources. Moreover, the preparation of thorium fuel does not involve some complicated and costly techniques necessary for uranium 235.

In addition, TMSR is a real peace application of nuclear energy, because unlike current mainstream reactors, it produces no plutonium, a well-known material to make nuclear weapons, and its main products, the uranium 233 and uranium 232 are not suitable for nuclear weapon manufacture either. Therefore its widespread application in the world will not result in nuclear proliferation.

Challenges

Before we can enjoy such a perfect energy supply, however, we have to break through a series of fundamental scientific issues. The first one rises from the preparation of thorium-based fuel modules, which are made from high-density thorium oxide ThO_2 and mixed oxide (MOX) fuels based on it. ThO_2 will not melt down until heated to over 3,350°C, much higher than the melting temperature of UO_2 (2,800°C), hence its sintering demands much harsher conditions. The extraordinary stable chemical properties of ThO_2 also make the post-processing of the solid thorium-based fuels a nightmare.

The long time it takes to turn thorium 232 into uranium 233 sets another barrier to the fuel preparing. As mentioned before, thorium 232 itself, the main composition of natural thorium, is not self-fissile; only when transformed into uranium 233 can it serve as a nuclear fuel. Whilst before finally transforming itself to uranium 233, thorium 232 has to experience an intermediate phase in which it becomes protactinium 233, an isotope of long half-life. This transient element slows down the Th-U transformation so greatly that it takes at least half a year to turn 99% protactinium 233 into uranium 233—way too long for industrialized use. More importantly, protactinium 233 will further absorb the existing neutrons in the reactor and transform itself into protactinium 234 rather than uranium 233, running into a “dead-ended” path and leading to reduced production of uranium 233. Therefore the protactinium 233 must be extracted from other transient elements produced during the Th-U transformation, which might involve very complicated processing.

On the other hand the Th-U transformation also produces uranium 232, which releases highly radioactive daughter nucleus of thallium 208 when decaying, hence setting barriers to the storing, shipping, post-processing, safe disposal and reprocessing of the fuels.

In short, so far human understanding of thorium as well as thorium/uranium fuel cycle is still limited and this calls further intensive efforts to address fundamental scientific issues in this field.

Grand plan at CAS

CAS has launched a strategic priority research project to address the fundamental scientific issues concerning thorium/uranium fuel cycle, the design of reactors, and disposal of used fuels, aiming to set up a whole system of TMSR to power the future economic growth of the nation.

At the initial stage, the project will focus on the fundamental scientific issues and build a 2MW experimental molten-salt reactor by 2015. Know-how stemming from the Molten-Salt Reactor Experiment (MSRE) will inspire the R&D activities during the subsequent phases. By 2020, the team will have built a 10MW experimental reactor and reach the critical point of fission reaction. By 2030, a 100 MW demonstrative reactor will have been built and put in operation. After that the TMSR will dash into commercial application, and the team will continue working to deal with the issues popping up from industrial production.

Actually, foresighted efforts had been made in this field before by international nuclear pioneers to deal with fundamental issues. An example was the research by the Oak Ridge National Laboratory (ORNL) of America. The lab even built an experimental reactor to seek possibility to use melted fluoride thorium as a nuclear fuel. Unfortunately, this project was somehow stopped in 1976 due to lack of funding, and the idea of thorium-based nuclear energy was shelved for some time. Nowadays this seed is seeing a second spring to sprout, though still a lot of basic scientific issues remain unsolved.

Now CAS stands out and takes the big challenge to shoulder longtime and stressful R&D tasks to blaze a way in this direction.

CAS’s choice to develop thorium-based nuclear reactors will help to mitigate China’s thirsty for energy in the future. Considering the soaring demand for energy and well-known shortcomings of fossil fuel energy sources, the nation has picked nuclear power as a strategic priority in its mid- to long-term layout of energy sources development. At present, there are a total of 13 nuclear reactors running in this country, with a gross capacity of 10.234 GWe, accounting for about 1.5% of the national total. According to the national layout, by 2020 there will have been over 70 nuclear reactors in operation, accounting for 4~6% of the national gross capacity. It is estimated that by 2030, the share taken by nuclear power will have risen to about 10%.

This ambitious blueprint, however, is challenged by at least two issues, namely the stable supply of nuclear fuels and the safe disposal of radioactive wastes, aside from the building up safety concerns. There seems to be limited margin to win this battle if the nation takes the path toward uranium-based reactors, given that natural uranium contains only 0.7% fissionable U-235 and uranium ore itself is scarce in the nation.

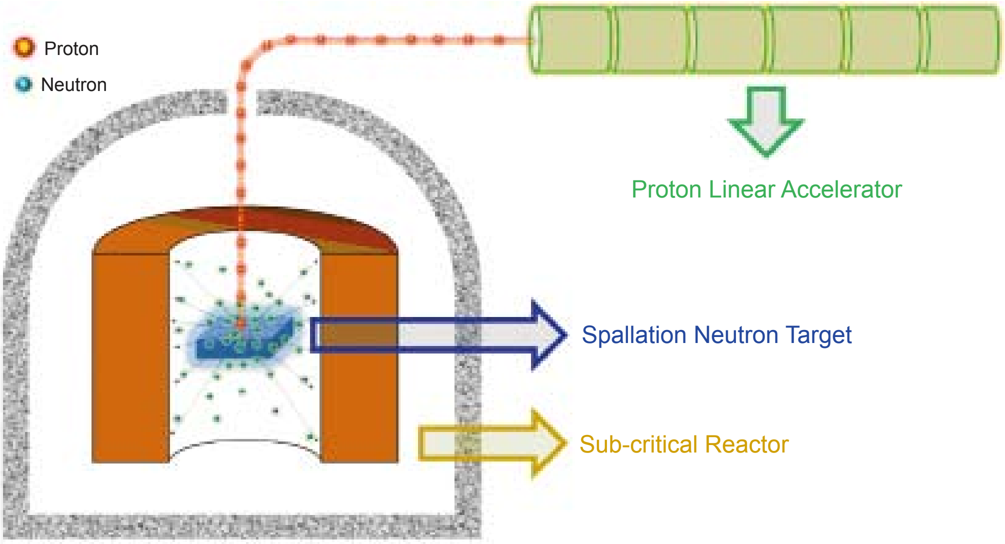
Thankfully natural thorium comes with 100% usable isotopes, thus it needs no enrichment. Plus its abundance it promises a much brighter future in terms of fuel supplies: according to experts, the thorium resources available in China will be enough to power this nation for as long as 1,000 years, if used as a nuclear fuel.

Currently, the relatively large amount of radioactive waste production from traditional uranium-based reactors is an extra curse for nuclear energy. More importantly, so far only one or two countries in the world have commanded necessary technologies to deal with intensive disposal of used fuels. To answer this challenge, the project will deal with this big concern by developing a state-of-the-art technique, the accelerator-driven sub-critical system (ADS).

ADS—a rosier future for nuclear waste disposal

The continuously accumulating used fuels pose a great challenge to the development of nuclear energy in China. It is estimated that by 2020, the stockpile of used fuels will have probably mounted to 10 thousand tons, including about one hundred tons of plutonium, over 10 tons of minor actinides (MA) and over 20 tons of long-lived fission products (LLFP). The half-lives of some long-lived radioactive wastes (including MA and LLFP) could reach dozens of thousands of years; those of some nuclei could even go beyond a million of years. Therefore it is very hard to imagine what kind of impacts their long-term radioactivity will have on the ecosystem, if discharged without being properly disposed.

A new approach to used fuel proposal, the ADS applies an accelerator to drive high-energy protons to bombard heavy nuclei like lead, forcing the latter to produce a large amount of neutrons. The released neutrons will further drive a sub-critical system, where the nuclear wastes will absorb the neutrons and transmute into low-radioactive matters. This technique will greatly reduce the amount and activity of radioactive nuclear wastes. The neutrons from the ADS developed by the CAS team will cover a wide spectrum and be able to turn most of the LLFP into useful fissile resources, according



The ADS represents the most effective approach to nuclear waste disposal.

to the scientists.

The ADS is deemed to be the most promising device to date to safely dispose nuclear wastes. It is revealed that a unit of ADS will be able to process the wastes from as many as 10 light water reactors. Therefore it will effectively solve the issue of waste disposal if succeeds.

The inherent safety and excellent capability of ADS to transmute radioactive nuclear wastes into useful fissile materials have been proven by some developed countries, as a result from their continuous studies and experiments since the early 1990s. Basically, however, scientists devoted to ADS-related research around the world are still addressing the fundamental scientific issues underlying this technique, and so far no construction project has been set up to build an operative ADS, though some projects are making good progress, like the Multi-purpose hybrid research reactor for high-tech applications (MYRRHA) overseen by SCKCEN, namely the Belgian Nuclear Research Centre in Mol, aimed to building an ADS system by 2023 for research on materials and fuel components, isotope production and research on transmutation reaction and biological applications.

Domestic experts began their conceptual studies on ADS about the same time as their overseas counterparts did, according to Prof. XU. Drawing on its buildup over mega-science practice and platforms for ADS-related research, and tapping into its long R&D experiences on related critical technologies including super-conductive accelerator, CAS has also conducted some studies to battle the critical scientific issues for ADS development.

According to XU, the ultimate goal of this project is to build a demonstrative ADS unit suitable for industrial application. The plan involves three phases of R&D. At the initial phase, the project aims to build a series of small experimental systems, tackle related scientific issues and technological hard nuts, and determine the technical path for each sub-system. At this stage the team will also strive to build the accelerator, the spallation target and the reactor integral subsystem. A series of supporting platforms will also be developed, including the platform for superconductive tests, the comprehensive research platform for basic radioactive chemistry and nuclear material research, experiment platform for lead/bismuth reactor core modeling, design and database platform especially for ADS, and a supporting platform for comprehensive testing and debugging. An initial research system will be completed by the end of 2015 integrating the accelerator, the target and the reactor, when all the subsystems have come into smooth operation. Following this, the debugging will last for several years to make sure the whole system meet all the designed goals.

The team might need 20 to 30 years to turn this wonderful dream true, however. According to XU, it took humankind nearly 20 years to move from the first successful experimental reactor to the first real commercial reactor. And we did not obtain what we have nowadays as mature technologies for current mainstream nuclear plants until another 20 years elapsed.

XU's team will cooperate with nuclear experts at home and abroad to meet the goals set for different phases of the project. So far the team has reached initial agreements for cooperation with some domestic nuclear energy giants, including China National Nuclear Corporation (CNNC), China Guangdong Nuclear Power Holding Corporation (CGNPC), State Nuclear Power Technology Corporation Ltd. (SNPTC) and the Institute of Nuclear and New Energy Technology at Tsinghua University. In the meantime the team has also talked with centers of excellence around the world, including SCKCEN in Belgium, *Paul Scherrer Institute* (PSI) of Switzerland, French Alternative Energies and Atomic Energy Commission (CEA) and National Center for Scientific Research (CNRS) of France; related labs like the Jefferson Lab, the Idaho National Laboratory (INL) and ORNL of USA; and Japan Atomic Energy Agency (JAEA) in Japan, reaching agreements for cooperation with part of them.