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Why should you be interested in Thorium Power? (Part 2)

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A subcritical system driven by an accelerator

An accelerator-driven system (ADS) is a subcritical approach to energy production and nuclear waste destruction, where a high-energy particle accelerator provides an external neutron source through a spallation reaction, coupled with a core in which both spallation neutrons and fission neutrons are at work, with a moderator allowing for a fast neutron spectrum. Figure 1 represents a sketch of this approach.

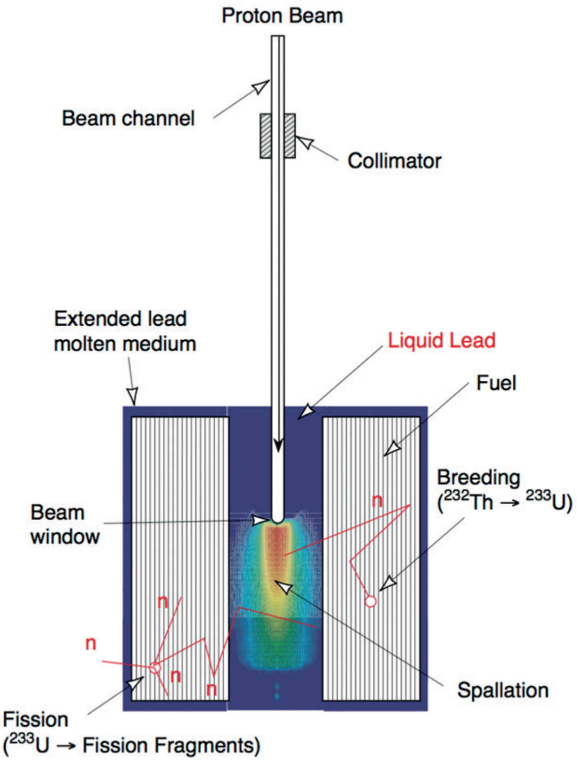

Figure 1. Sketch of an accelerator-driven system [1]

Some basic ADS concepts were developed in Switzerland:

- the FEAT experiment at the CERN PS was the first “Energy Amplifier” test, whose purpose was to verify the simulation studies for an accelerator-driven thermal subcritical system (with an effective multiplication factor k of about 0.9), at very low power level, coupled to a spallation source [1];
- the TARC experiment at the CERN PS, whose purpose was to demonstrate the possibility of using adiabatic resonance crossing for nuclear transmutation by spallation neutrons slowing down in lead [2];
- the MEGAPIE project at the Paul Scherrer Institute (PSI), the goal of which was to produce neutrons from a liquid metal lead-bismuth target when hit by a 1 MW proton beam [3].

The ADS development is pursued in several research institutes worldwide [4]. Three major projects, all driven by proton linear accelerators (linac’s), are presently at the forefront of the field:

- MYRRHA [5], at SCK•CEN, in Mol, Belgium, which should be the flagship of accelerator-driven systems, with a proton linac (600 MeV, 2.5 mA) driving a subcritical core cooled with a eutectic lead–bismuth mixture, designed to produce a thermal power of 50 to 100 MW;
- ADANES [6] developed by the Chinese Academy of Sciences, both at the Institute of High Energy Physics in Beijing and at the Institute of Modern Physics in Lanzhou. The project includes notable innovations in target design and the goal is to reach 1000 MW of electrical power by 2032. A site for the first prototype was recently chosen by the Chinese Government at the city of Huizhou, in the Guangdong Province;
- HISPA [7] at the Bhabha Atomic Research Centre in India, concentrating on the development of a high-power proton linac, with as first stage a 30 mA, 20 MeV injector, and the goal of reaching 30 MW of beam power with 1 GeV protons. This project is carried out in cooperation with the USA.

In the United States, the Argonne National Laboratory (ANL) has designed and constructed an ADS facility using a 100 kW, 100 MeV electron accelerator [8] for the Kharkov Institute of Physics & Technology (KIPT) in Ukraine. The facility is in the start-up phase. This activity is supported by the Russian Research Reactor Fuel Return (RRRFR) program of the United States Department of Energy. The facility is planned to produce medical isotopes, train young nuclear professionals, support the Ukraine nuclear industry, and provide capability for performing reactor physics, material research, and basic science experiments. It is suitable for studying accelerator-driven systems and performing basic neutron research, including a cold neutron source. Other USA R&D activities are being carried out to study and investigate various aspects of ADS including monitoring and controlling the system subcriticality. The development of ADS for disposing of US spent nuclear fuel inventory is being carried out by different institutes and private corporations. Among the other countries involved in ADS-related activities, are Japan at J-PARK, the Japan Accelerator Research Complex, where ADS research was restarted as a consequence of the Fukushima accident, Russia, at INR Troitsk (see below), and South Korea with the HYPER project, (Hybrid Power Extraction Reactor: a system for clean nuclear energy), to name only the most significant activities. Europe, including Switzerland, is building the most powerful spallation neutron source, the European Spallation Source (ESS), at Lund, in Sweden, also based on a linac [9]. The ESS proton beam power will reach 5 MW. This project will provide Europe with the most advanced expertise on target technology for ADS. The overarching goal of those projects is to demonstrate the feasibility of energy generation, radioactive waste incineration and medical isotope production with ADS.

A technological breakthrough: the thorium-fueled accelerator-driven system

An ADS will have safety features which rely on physical properties of the system as opposed to active control in critical reactors. It eliminates the possibility of criticality accidents by keeping the system subcritical. Indeed, stopping the proton beam from the accelerator instantly stops the fission reaction and the low-pressure liquid metal, which remains well below the boiling point, allows natural circulation to provide the decay heat removal. Unlike water, the chemically inert liquid metal coolant carries no danger of formation of hydrogen as in Fukushima Daiichi's reactors. Natural circulation is independent of pumps and does not require a power supply. Furthermore, the combination of fast neutrons from the spallation source, and recycling of long-lived transuranic elements reduces long-lived waste. With an ADS fueled with natural thorium instead of uranium (see part I in the *SPG Mitteilungen* Nr 54), plutonium and high-level wastes such as minor actinides, namely neptunium, americium and curium, are produced in much lower quantities. In the envisaged system, the waste mainly consists of fission fragments. Their radioactivity is intense, but limited to a few hundred years compared with the one-million-year lifetime of the long-term waste in the present uranium fuel cycle.

It is even possible to eliminate much of the waste resulting from the operation of existing conventional plants, thus reducing the size and complexity of long-term nuclear waste storage sites. The key to this unique characteristic is the ability of the ADS to accept fuels incorporating minor actinides and excess plutonium without compromising safety, as the ADS does not depend on the so-called beta factor, the proportion of delayed neutrons, for control of reactivity. In addition the destruction of minor actinides and plutonium by fission releases energy that can be used to produce electricity, thereby minimizing the cost of the operation. The resulting fission energy can be collected in a classical manner by a liquid heat carrier such as gaseous helium or molten metal (lead for example) via an exchanger and turbine.

The creation of a new, appropriate end-of-cycle fuel reprocessing is still a necessity for the practical realization of any closed thorium cycle. However, for the spent nuclear fuel in a fast neutron ADS, it is not necessary to separate out plutonium as is done in PUREX. Therefore, the pyro-electrolysis method can be used to extract the entire transuranic actinide mixture to manufacture fresh thorium-based fuel.

What are the main requirements for an ADS accelerator? In practice, for industrial applications, there are many requirements which make the accelerator challenging. The proton beam energy should ideally be above 900 MeV, but a lower energy can be compensated by a higher current. The beam power should reach a value between a few MW to about 10 MW, depending on the required application. A large operational range is desirable to adapt the beam power to the operation of the reactor and the fluctuating electric power demand associated with the network, when renewable sources are used on a large scale. The size of the beam spot at the target entrance window has a large impact. Beam losses have to be tightly controlled to minimize irradiation of the accelerator and of the environment: a figure of merit for linac's is less than 1 W/m, while for cyclotrons losses are mainly localized at injection and extraction.

The issue of reliability requiring minimizing beam trips is a significant challenge: the limitation mainly comes from thermal stresses inducing fatigue in the beam window, fuel claddings and vessel structures. Solutions include making the accelerator more reliable, adding redundancy (several sources, several accelerators, etc.), improvements in materials, maintenance and operation, relaxing the demands from reactors with the fuel in a liquid molten salt mixture, etc. At the ThEC13 conference, an innovative concept for a high power superconducting cyclotron, in principle adoptable as a driver for an accelerator-driven system, was presented. A design study is in progress, including partners at PSI, INFN, CERN, ENEA, and in private companies [10].

Resistance to military diversion

The resistance to proliferation of thorium-fueled ADS requires a careful analysis, but one can already conclude on a high degree of resistance by the following arguments.

Thorium-based fuels breed significantly less plutonium than current uranium fuel cycles, which we recall is one of the reasons why, between 1950 and 1980, the uranium-plutonium fuel cycle necessarily was established first (in order to start breeding reactions) and once the infrastructure was in place the thorium fuel cycle was disadvantaged.

The production of protactinium-233 in the thorium portion of the reactor could constitute a proliferation objection to thorium fuel. If it could be extracted chemically, it would decay quickly into pure U-233, a weapons-grade isotope. The solution would be to denature any bred U-233 by mixing it with U-238. But some discount altogether this risk, because the U-233 in the reactor would be mixed with U-232, whose decay products produce high energy gamma radiation that renders it lethal to handle. And furthermore the long presence of the fuel in the reactor (five to ten years) minimizes access to extract protactinium-233.

The proliferation concerns which are presently raised by the IAEA about ADS can be answered in a straightforward way. Diverting an ADS for producing macroscopic quantities of tritium to manufacture a fission-fusion bomb can be avoided by control, as tritium is unstable and production has to continue on a regular basis. Thus, tritium production would be relatively easy to spot, as it requires very high power accelerators running continuously for long time periods without producing energy.

An ADS experiment at the Institute for Nuclear Research (INR) in Troitsk

An experimental facility of significant power would today be needed in order to validate technological solutions for thorium-fueled ADS. At the ThEC13 conference, a proposal was presented for an ADS experiment at INR Troitsk in Rus-

Proliferation resistance of thorium-fueled ADS

- Negligible production of plutonium
- Hard gamma radiation from U-232 rendering fuel completely unsuitable for weapons material
- Simple controls avoiding diverting production of macroscopic quantities of tritium
- Long burnup cycles reducing access to nuclear fuel

sia using the Moscow Meson Factory [11]. At this facility it would be possible to couple the proton beam to a subcritical core for the first time at significant power (≥ 1 MW thermal) to characterize the properties of ADS, demonstrate safety and learn how to operate such a system. This would provide invaluable input for designing and constructing an industrial prototype, as well as for developing a future thorium fuel cycle.

Thanks to the availability of the facility, the experiment would be faster and cheaper than other current projects. The pit to be used for the target and the core already exists, with the reflector already in place (Fig. 2). The main features of the core concept are: a fast neutron flux similar to a fast reactor flux (10^{14} n/cm^2/s), a minimum inventory of fuel, a fast driver zone, a simplified cooling system and control of reactivity, which should result in a significant cost reduction.

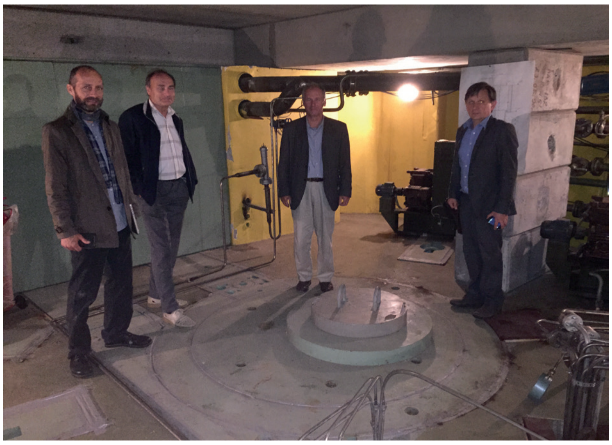

Figure 2. The INR core facility at Troitsk, Moscow.

The technical specifications include a beam power of 30 kW to 90 kW for 300 MeV protons on a water-cooled tungsten target. The maximum thermal power reached, 1 to 2 MW, will depend on the investment in the accelerator refurbishment, while the effective multiplication factor k must not exceed 0.98, in order to ease the licensing requirements. During the experiment, k can be varied up to this maximum value to characterize the core-to-accelerator coupling over the largest k range.

Other expected benefits of ADS

When the feasibility studies have proven the ADS concept at a significant power, business will have to adapt it to the market and plants will be constructed. I believe that capital will also be invested to capture incremental value through diversified applications. For example, nuclear reactors generate heat. That heat can be converted partially into electric energy or used as process heat. Future nuclear reactors will provide much higher temperatures, thereby enabling technologies with high efficiencies that can also produce hydrogen through water-splitting. And perhaps even the path for carbon dioxide sequestration is to use CO_2 as a carbon source for making liquid fuels, such as methanol, using nuclear energy at high temperatures, a prospect that could recycle CO_2 emissions.

Radiopharmaceutical production and material irradiation testing offer other significant potentials of incremental profits. Those additional sources of revenue would drive down direct costs, while securing margins and balancing global risks, using similar or even identical plants.

Conclusions

It is difficult to imagine how the “decarbonization challenge” discussed at the UN Climate Change Conferences would work globally without energy from nuclear power. Large-scale growth in much of the developing world will have to be powered by nuclear energy. Innovative thorium-fueled ADS can ensure the long-term societal acceptance of this energy source, and thus contribute to protecting climate and reducing pollution from fossil fuels. Most importantly, they have the potential of reducing the inventory of long-lived nuclear wastes produced in reactors.

In parallel with the technical feasibility studies of this application of particle accelerators, its socio-economic value should be demonstrated, so that industry can prepare the entry of such technologies into the market. We should be interested in thorium.

Acknowledgments

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