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Accelerator-driven Nuclear Energy

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- **Powerful accelerators can produce neutrons by spallation**.
- **This process may be linked to conventional nuclear reactor technology in an accelerator-driven system (ADS) to transmute long-lived radioisotopes in used nuclear fuel into shorter-lived fission products.**
- **There is also increasing interest in the application of ADSs to running subcritical nuclear reactors powered by thorium.**

Used fuel from a conventional nuclear power reactor contains a number of radionuclides, most of which (notably fission products) decay rapidly, so that their collective radioactivity is reduced to less than 0.1% of the original level 50 years after being removed from the reactor. However, a significant proportion of the wastes contained in used nuclear fuel is long-lived actinides (particularly neptunium, americium and curium). In recent years, interest has grown in the possibility of separating (or partitioning) the long-lived radioactive waste from the used fuel and transmuting it into shorter-lived radionuclides so that the management and eventual disposal of this waste is easier and less expensive.

The transmutation of long-lived radioactive waste can be carried out in an accelerator-driven system (ADS), where neutrons produced by an accelerator are directed at a blanket assembly containing the waste along with fissionable fuel. Following neutron capture, the heavy isotopes in the blanket assembly subsequently fission, producing energy in doing so. ADSs could also be used to generate power from the abundant element thorium.

Accelerator-driven systems

High-current, high-energy accelerators or cyclotrons are able produce neutrons from heavy elements by spallation[a]. A number of research facilities exist which explore this phenomenon, and there are plans for much larger ones. In this process, a beam of high-energy protons (usually >500 MeV) is directed at a high-atomic number target (*e.g.* tungsten, tantalum, depleted uranium, thorium, zirconium, lead, lead-bismuth, mercury) and up to one neutron can be produced per 25 MeV of the incident proton beam. (These numbers compare with 200-210 MeV released by the fission of one uranium-235 or plutonium-239 atom[b].) A 1000 MeV beam will create 20-30 spallation neutrons per proton.

The spallation neutrons have only a very small probability of causing additional fission events in the target. However, the target still needs to be cooled due to heating caused by the accelerator beam.

If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or thorium-232 which can breed to U-233), there is a possibility of sustaining a fission reaction. This is an ADS[c]. In such a system, the neutrons produced by spallation would cause fission in the fuel, assisted by further neutrons arising from that fission. Up to 10% of the neutrons could come from the spallation, though it would normally be less, with the rest of the neutrons arising from fission events in the blanket assembly. An ADS can only run when neutrons are supplied to it because it burns material which does not have a high enough fission-to-capture ratio for neutrons to maintain a fission chain reaction. An ADS can therefore be turned off simply by stopping the proton beam, removing the need to insert control rods to absorb neutrons and make the fuel assembly subcritical. Because they stop when the input current is switched off, ADSs are seen as safer than normal fission reactors.

Thorium utilisation

For many years there has been interest in utilising thorium-232 as a nuclear fuel since it is three to five times as abundant in the Earth's crust as uranium. A thorium reactor would work by having Th-232 capture a neutron to become Th-233 which decays to uranium-233, which fissions. (The process of converting fertile isotopes such as Th-232 to fissile ones is known as 'breeding'.) The problem is that insufficient neutrons are generated to keep the reaction going, and so driver fuel is needed – either plutonium or enriched uranium. Just as with uranium, if all of it and not a mere 0.7% of uranium is to be used as fuel, fast neutron reactors are required in the system. (A fast neutron spectrum enables maximum fission with minimum build-up of new actinides due to neutron capture.)

An alternative is provided by the use of ADSs. The concept of using an ADS based on the thorium-U-233 fuel cycle was first proposed by Professor Carlo Rubbia, but at a national level, India is the country with most to gain, due to its very large thorium resources. India is actively researching ADSs as an alternative to its main fission program focused on thorium.

The core of such an ADS is mainly thorium, located near the bottom of a 25 metre high tank. It is filled with some 8000 tonnes of molten lead or lead-bismuth at high temperature – the primary coolant, which circulates by convection around the core. Outside the main tank is an air gap to remove heat if needed. The accelerator supplies a beam of high-energy protons down a beam pipe to the spallation target inside the core, and the neutrons produced enter the fuel and transmute the thorium into protactinium, which soon decays to U-233 which is fissile. The neutrons also cause fission in uranium, plutonium and possibly transuranics present, releasing energy. A 10 MW proton beam might thus produce 1500 MW of heat (and thus 600 MWe of electricity, some 30 MWe of which drives the accelerator). With a different, more subcritical, core a 25 MW proton beam would be required for the same result. Today's accelerators are capable of only 1 MW beams.

There have been several proposals to develop a prototype reactor of this kind, sometimes popularly called an energy amplifier. India is already running a very small research reactor – Kamini – on U-233 fuel bred and extracted from thorium which has been irradiated in another reactor. When this started in 1996 it was hailed as a first step towards the thorium cycle there, utilizing 'near breeder' reactors. The Power Reactor Thoria Reprocessing Facility (PRTRF) was under construction at the Bhabha Atomic Research Centre (BARC) at Trombay in 2013, and is designed to cope with high gamma levels from U-232.

A UK-Swiss proposal for an accelerator-driven thorium reactor (ADTR) has gone to feasibility study stage, for a 600 MWe lead-cooled fast reactor. This envisages a ten-year self-sustained thorium fuel cycle, using plutonium as a fission starter. Molten lead is both the spallation target and the coolant. In contrast to other designs with neutron multiplication coefficients of 0.95 - 0.98 and requiring more powerful accelerators, this ADTR has a coefficient of 0.995 and requires only a 3-4 MW accelerator, with fast-acting shutdown rods, control rods, and precise measurement of neutron flux.

A 2008 Norwegian study summarised the advantages and disadvantages of an ADS fuelled by thorium, relative to a conventional nuclear power reactor, as follows, and said that such a system was not likely to operate in the next 30 years:[1]

Advantages	Disadvantages
Much smaller production of long-lived actinides	More complex (with accelerator)
Minimal probability of runaway reaction	Less reliable power production due to accelerator downtime
Efficient burning of minor actinides	Large production of volatile radioactive isotopes in the spallation target
Low pressure system	The beam tube may break containment barriers

Waste incinerator

An ADS can be used to destroy heavy isotopes contained in the used fuel from a conventional nuclear reactor – particularly actinides[d]. Here the blanket assembly is actinide fuel and/or used nuclear fuel. One approach is to start with fresh used fuel from conventional reactors in the outer blanket region and progressively move it inwards. It is then removed and reprocessed, with the uranium recycled and most fission products separated as waste. The actinides are then placed back in the system for further 'incineration'[e].

ADSs could also be used to destroy longer-lived fission products contained in used nuclear fuel, such as Tc-99 and I-129 (213,000 and 16 million years half-lives, respectively). These isotopes can acquire a neutron to become Tc-100 and I-130 respectively, which are very short-lived, and beta decay to Ru-100 and Xe-130, which are stable.

Commercial application of partitioning and transmutation (P&T), which is attractive particularly for actinides, is still a long way off, since reliable separation is needed to ensure that stable isotopes are not transmuted into radioactive ones. New reprocessing methods would be required, including electrometallurgical ones (pyroprocessing). The cost and technology of the partitioning together with the need to develop the necessary high-intensity accelerators seems to rule out early use. An NEA study showed that multiple recycling of the fuel would be necessary to achieve major (*e.g.* 100-fold) reductions in radiotoxicity, and also that the full potential of a transmutation system can be exploited only with commitment to it for 100 years or more[2].

The French Atomic Energy Commission is funding research on the application of this process to nuclear wastes from conventional reactors, as is the US Department of Energy. The Japanese Omega (Options Making Extra Gain from Actinides) project envisages an accelerator transmutation plant for nuclear wastes operated in conjunction with ten or so large conventional reactors. The French concept similarly links a transmutation – energy amplifying system with about eight large reactors. Other research has been proceeding in USA, Russia and Europe.

The Chinese Academy of Sciences has the Venus II ADS, which passed field tests early in 2017. The zero-power ADS transmutation system – developed by the China Atomic Energy Research Institute and the Chinese Academy of Sciences' Institute of Modern Physics – will be used for research into transforming long-lived radioactive waste into short-lived waste.

Another area of current interest in the use of ADSs is in their potential to dispose of weapons-grade plutonium, as an alternative to burning it as mixed oxide (MOX) fuel in conventional reactors. Two alternative strategies are envisaged: the plutonium and minor actinides being managed separately, with the latter burned in ADSs while plutonium is burned in fast reactors; and the plutonium and minor actinides being burned together in ADSs, providing better proliferation resistance but posing some technical challenges. Both can achieve major reduction in waste radiotoxicity, and the first would add only 10-20% to electricity costs (compared with the once-through fuel cycle).

ADS research and development

What was claimed to be the world’s first ADS experiment was begun in March 2009 at the Kyoto University Research Reactor Institute (KURRI), utilizing the Kyoto University Critical Assembly (KUCA). The research project was commissioned by Japan’s Ministry of Education, Culture, Sports, Science and Technology (MEXT) six years earlier. The experiment irradiates a high-energy proton beam (100 MeV) from the accelerator on to a heavy metal target set within the critical assembly, after which the neutrons produced by spallation are bombarded into a subcritical fuel core.

The Indian Atomic Energy Commission is proceeding with design studies for a 200 MWe PHWR accelerator-driven system (ADS) fuelled by natural uranium and thorium[f]. Uranium fuel bundles would be changed after about 7 GWd/t burn-up, but thorium bundles would stay longer, with the U-233 formed adding reactivity. This would be compensated for by progressively replacing some uranium with thorium, so that ultimately there is a fully-thorium core with in situ breeding and burning of thorium. This is expected to mean that the reactor needs only 140 tU through its life and achieves a high burnup of thorium – about 100 GWd/t. A 30 MW accelerator would be required to run it.

The Belgian Nuclear Research Centre (SCK.CEN) is planning to begin construction on the MYRRHA (Multipurpose Hybrid Research Reactor for High-tech Applications) research reactor at Mol in 2015. Initially it will be a 57 MWt ADS, consisting of a proton accelerator delivering a 600 MeV, 2.5 mA (or 350 MeV, 5 mA) proton beam to a liquid lead-bismuth (Pb-Bi) spallation target that in turn couples to a Pb-Bi cooled, subcritical fast nuclear core (see *Research and development* section in the information page on Nuclear Power in Belgium).

In mid-2014 the Swedish nuclear regulator SSM issued a conditional licence for construction of the European Spallation Source (ESS) facility in Lund. The research facility will feature the world's most powerful neutron source. The ESS will be used for material research and life sciences. It is designed around a linear accelerator which produces intense pulses of neutrons from a heavy metal target. They are led through beamlines to experimental stations, as in a research reactor set-up. The ESS was designed to reach 5 MW, but cost constraints will see the facility commissioned initally at 2 MW. In the project plan laid out in 2014, completion was scheduled by 2019, with the facility set to be fully operational by 2025. Funding for the project involves 13 European countries through a combination of cash and in-kind contributions. Sweden and Denmark are the host nations. Construction costs of the ESS facility are estimated at about €1.8 billion ($2.4 billion), with annual operating costs of some €140 million ($188 million).

In March 2016 a strategic cooperation agreement to develop accelerator-driven advanced nuclear energy systems was signed between China General Nuclear (CGN) and the Chinese Academy of Sciences (CAS). The CAS has a major R&D program on thorium molten salt reactors, including a 2 MWe accelerator-driven sub-critical liquid fuel prototype designed to demonstrate the thorium cycle as well as its Venus II ADS for transforming long-lived radioactive waste into short-lived waste.

Notes & references

a. Spallation is the process where nucleons are ejected from a heavy nucleus being hit by a high energy particle. In this case, a high-energy proton beam directed at a heavy target expels a number of spallation particles, including neutrons. [Back]

b. An average fission event of U-235 releases 200 MeV of energy and is accompanied by the release of an average of 2.43 neutrons. [Back]

c. Accelerator-driven systems are also referred to as energy amplifiers since more energy is released from the fission reactions in the blanket assembly than is needed to power the particle accelerator. Professor Carlo Rubbia, a former director of the international CERN laboratory, is credited with proposing the concept of the energy amplifier, using natural thorium fuel. [Back]

d. In the case of atoms of odd-numbered isotopes heavier than thorium-232, they have a high probability of absorbing a neutron and subsequently undergoing nuclear fission, thereby producing some energy and contributing to the multiplication process. Even-numbered isotopes can capture a neutron, perhaps undergo beta decay, and then fission. Therefore in principle, the subcritical nuclear reactor may be able to convert all transuranic elements into (generally) short-lived fission products and yield some energy in the process. [Back]

e. As well as fission products, the process generates spallation products from the target material, in direct proportion to the energy of the proton beam. Some of these are volatile and will find their way into the cover gas system above the coolant, posing a major maintenance challenge. Their radiotoxicity is likely to exceed that of the fission products in the short term, which is relevant to operation and storage rather than final disposal. Ultimately the burning of actinides means that overall radiotoxicity of them is reduced greatly by the time 1000 years has elapsed, and is then less than that of the equivalent uranium ore. [Back]

f. India is already running a very small research reactor on U-233 fuel extracted from thorium which has been irradiated and bred in another reactor. When this started in 1996 it was hailed as a first step towards the thorium cycle there, utilizing 'near breeder' reactors. [Back]

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