Future nuclear energy systems: Generating electricity, burning wastes

Merging the technology of accelerators with reactors holds the promise of producing energy, and incinerating plutonium and radioactive wastes

by Viktor Arkhipov

One of the greatest challenges in the use of nuclear energy is the highly radioactive waste which is generated during power production. It must be dealt with safely and effectively. While technical solutions exist, including deep geological repositories, progress in the disposal of radioactive waste has been influenced, and in many cases delayed, by public perceptions about the safety of the technology. One of the primary reasons for this is the long life of many of the radioisotopes generated from fission, with half-lives on the order of 100,000 to a million years. Problems of perception could be reduced to an essential degree if there were a way to burn or destroy the most toxic long-lived radioactive wastes during the production of energy.

A new technological option, or rather a viable development of earlier ideas, has been introduced recently. It merges accelerator and fission reactor technologies into a single system that has the potential to efficiently generate electricity from nuclear fission and/or transmute the long-lived radioactive wastes. In its simplest form, this accelerator-driven energy production concept uses neutrons produced by a high-energy proton beam to drive a blanket assembly containing fissionable fuel and radioactive wastes. The blanket assembly is like a reactor in that fission is the source of power. Unlike a conventional reactor, however, it is sub-critical and without the accelerator cannot sustain a chain-reaction. The fuel for this system could be uranium, plutonium, or thorium.

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Even as it destroys highly radioactive wastes, the accelerator-driven system would help to meet rising energy needs by producing electricity, the most convenient and versatile form of energy. Demand for all energy sources is going to increase over the next two decades, if only to meet the needs of the world's growing population, which the United Nations estimates will approach 8.5 billion people by the year 2025.

Transmutation of radioactive wastes

Management of radioactive waste in an environmentally safe manner is an important issue being addressed by all countries developing a nuclear industry. In many countries it has become a serious political issue attracting intense critical attention of the general public.

The concept of a closed nuclear fuel cycle was traditionally considered as transmutation (burning) of only plutonium and recycled uranium, with minor actinides (neptunium, americium, curium) destined for final geological disposal. But as time goes on, a new understanding is emerging: reduction of the quantity of actinides would ease requirements for final repositories and make them relatively less expensive.

Neutron transmutation of long-lived radioactive minor actinides by the fission process — which entails producing energy and simultaneously turning them into shorter-lived nuclides — is being intensely analyzed in the technical community. Also being proposed is the neutron transmutation of selected long-lived fission products.

Several possibilities for the transmutation of long-lived nuclides by nuclear reactions have been suggested. In the beginning, the best choice appeared to be the use of nuclear reactors. However, recently there has been renewed interest in what are called accelerator-driven systems (ADS), a technology that seems to show good promise.

Underpinning the interest is the question of what to do with surplus plutonium accumulated in weapons stockpiles, as well as in the much larger and growing inventory of spent fuel from commercial nuclear operations. There is serious political concern over misuse of plutonium and about the release of this highly toxic material into the environment. Many options are being considered to dispose of this plutonium and one is to burn it using the ADS technology. Such an ADS would produce large amounts of electrical energy while simultaneously destroying the plutonium. This appears to offer a better solution to the plutonium problem than multi-millennium storage.

The capability of the accelerator-driven concept can also be applied to simultaneous burn the long-lived fission products and actinides in the waste from existing commercial nuclear power reactors. The goal of burning these fission products is to destroy those long-lived isotopes that, because of their mobility, would be the greatest contributor to radioactive doses from a repository, namely technetium-99, iodine-129, and caesium-135. These three isotopes constitute about 5% by weight of the total fission products generated during power production and are the principal contributors to possible long-term risks associated with geologic disposition. If these three isotopes are destroyed internally, the remaining short-lived and stable fission product waste can be confined in engineered storage, perhaps even at the power production site.

Maximum burn-up of the fission products requires that they be processed on site. By optimizing the accelerator-driven target/blanket assembly for this burning, the volume and half-life of the waste stream can be reduced considerably, thus simplifying long-term storage and secure disposal requirements. Even in this system, where the primary function is to burn radioactive wastes, it is expected that sufficient electrical energy can be produced to pay for the capital and operational costs of the facility.

The goals are laudable, yet it should be kept in mind that the technology still requires substantial research and development. The technical feasibility, and especially the economic and radiological soundness of transmutation, are still to be proved. Consequently, the arguments both for and against partitioning and transmutation of radioactive wastes will have to be carefully compared and evaluated.

Combining energy production and transmutation

The use of accelerators for nuclear energy applications is not a new idea and was proposed as early as the late 1940s by E. Lawrence, inventor of the cyclotron. In the 1950s he promoted the development of a Materials Test Accelerator at Livermore to produce intense neutron fluxes for plutonium production. The Canadian Chalk River Laboratory began intensive studies of accelerator-based systems to breed nuclear fuel for heavy-water reactors. Scientists at Brookhaven National Laboratory also actively promoted accelerator-based options in the late 1970s and early 1980s. For the last five years, scientists at Los Alamos National Laboratory have been reevaluating the accelerator-based technology in the light of today's advances in technology and the world energy perspective.

Most recently, Nobel laureate and past Director-General of European Nuclear Research Centre (CERN), Carlo Rubbia, has proposed and is actively promoting an accelerator-driven energy generation system based on the thorium-uranium cycle.

There are two types of accelerators that could drive this system at approximately 1 GeV and average currents in the range 10 to 100 mA. The first option is to use a linear accelerator. The second is to use a circular accelerator that has the advantage of being a more compact system. Both can achieve the energy required but both require technology development to achieve the needed beam intensities. The cyclotron is limited to currents of 10 to 15 mA due to the difficulty in adequately confining the beam, whereas the linear accelerator is foreseen to be able to deliver perhaps 100 to 200 mA of beam current. Linear accelerators already produce such currents in pulsed mode but to achieve the near-continuous operation for the highest currents a significant engineering development is still needed. A system delivering 15 mA of protons and 800 MeV can drive a blanket assembly to produce 200 MW of electrical power. A circular accelerator is a possible option at this power level. The high-current linear accelerator might drive an energy producing system of 1200 MW electrical. In either case it is expected that about 15% to 20% of the total electrical power be used to drive the accelerator.

Various technical options for transmutation and power production using ADS are now under investigation in several countries and international organizations. A number of ADS schemes are being studied in the frame of the OMEGA Project in Japan (Options Making Extra Gain from Actinides), in the United States (at the Los Alamos and Brookhaven national laboratories), in France (Commissariat à l'énergie atomique, or CEA), in the Russian Federation, at CERN, at the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development, and at the European Commission (EC).

ADS concepts can be classified according to their physical features and final objectives. The classification is based on the neutron energy spectrum, fuel form (solid, liquid), fuel cycle and coolant/moderator type, and objectives for the system. ADS systems, like reactors, can be designed to work in two different neutron spectrum modes — on fast or on thermal neutrons. There are also attempts at CERN to design a system which will exploit the neutron cross-section resonances in what could be classified as a "resonance neutron" mode. Both fast and thermal systems are considered for solid and liquid fuels. Even quasi-liquid fuel has been proposed based on the particle fuel (pebble bed) concept developed at Brookhaven.

As noted previously, the objective for some ADS is to transmute existing components of spent fuel from nuclear reactors, mainly plutonium and minor actinides, with or without concurrent energy production. Other systems are designed to take advantage of the thorium fuel cycle for energy production. Most concepts are based on linear accelerators. However, the CERN-group and researchers at Brookhaven propose to use a proton cyclotron.

The proposed accelerator-driven energy production system at Los Alamos includes a high-energy proton beam linear accelerator, a heavy-metal target (lead or lead-bismuth), and a liquid fuel system. Liquid fuel is attractive because it avoids the processes of solid fuel fabrication and fuel bundle management while at the same time allows continuous extraction of a significant fraction of fission products during operation. This removal both improves fuel economy and enables destruction of the long-lived component of the fission products. The molten salt option was chosen because it operates at low pressures, has simpler mechanical structures, lower neutron absorption losses, and lower liquid-fuel inventory.

The accelerator-driven subcritical nuclear system proposed by Carlo Rubbia and co-workers at CERN is a fast neutron system. Fuel elements are in solid form, with cladded fuel pins. The nominal fuel is thorium/uranium-233 but it can also run on plutonium (either military or reactor grade) and can fission also the heavier actinides americium and curium. A number of passive safety features of the concept are based on its physical properties.

In Japan during the last two decades, the Japan Atomic Energy Research Institute (JAERI) has been engaged in design studies of transmutation systems. Two types of ADS concepts are being studied: a solid target/core system and a molten-salt target/core system. The concept of an accelerator-boosted molten salt reactor is under study in several universities in Japan. JAERI is about to launch the Neutron Science Project which aims at bringing scientific and technological innovation for the 21st century in the fields of basic science and nuclear technology using neutrons. The study on accelerator-driven transmutation systems and the development of an intense proton accelerator are important parts of this project.

At CEA in France, different laboratories have been working in recent years on several aspects of the technology and on the physics of the ADS. In 1995, it was decided to launch a limited programme, devoted to the experimental validation of the major items related to a generic ADS.

In the Russian Federation, several groups at scientific centres have been working on aspects of the technology and on the physics of ADS systems. Different concepts of ADS with different structures and materials for target and blanket are under consideration. Some studies related to partitioning and transmutation, so-called conversion projects, are financially supported by international institutions, mainly in the framework of the International Science and Technology Center.

The NEA has a comprehensive international work programme related to issues concerning transmutation and separation of fission products and actinides. The NEA Nuclear Development Committee recently set up an expert group to perform system studies on actinide and fission product partitioning and transmutation. The NEA Nuclear Science Committee has a number of co-operative projects covering the scientific and physics aspects of different transmutation concepts.

The EC co-ordinates projects of Member States on a cost-sharing basis and performs studies on minor actinides, fuels, and partitioning at the European Institute of Transuranium Elements. The Institute has been engaged in such research for 30 years. Studies on fuels containing minor actinides have led to a series of irradiation experiments, some of which are already completed. Through another programme, the EC is focusing on the impact of accelerator-based technologies on nuclear fission safety. An objective is to co-ordinate efforts to create the European scientific and technological basis for co-operative projects.

Role of IAEA activities in the field

At the IAEA, activities in this field are being undertaken within the framework of a programme on emerging nuclear energy systems for energy generation and transmutation. The objective is to provide a global forum for the technical review and discussion of programmes, projects, and topics in the development and introduction of nuclear energy, including ADS. The activities focus on the compilation and dissemination of status reports and technical information, and on the support of co-ordinated research. They include the following:

Preparation and publication of a status report on ADS. This work is an outcome of technical discussions at a Special Scientific Programme on "Use of High Energy Accelerators for Transmutation of Actinides and Power Production", held in Vienna, in 1994 in conjunction with the IAEA General Conference. The report is targeted at planners, decision makers, and other parties that have an interest in the development of ADS, and provides an overview of ongoing development activities, different concepts being developed and their project status, as well as typical development trends, and evaluations of the potential of this system for power production, plutonium burning and transmutation of radioactive wastes. It includes contributions by experts from six countries and two international organizations as well as executive summaries of many different areas of ADS technology.

Status report on the thorium-based fuel cycle. This report will update information that has become available over the past six years, and indicate areas which need further investigations. It will include contributions from particular countries and technical groups and feature details of their concepts.

Co-ordinated research programme. This programme focuses on the use of the thorium-based fuel cycle in ADS to incinerate plutonium and to reduce long-term waste toxicities. The first stage covers ADS benchmarks and neutronic calculations, and one objective is to achieve a consensus on the calculational methods and associated nuclear data.

Technical committee meeting on feasibility and motivation for hybrid concepts for nuclear energy generation and transmutation. In September 1997, technical experts will be brought together to review and discuss the advantages and disadvantages of hybrid concepts relative to the current status and potential future direction of nuclear power worldwide, and provide options and recommendations for the IAEA's Member States in this area.

Challenges and opportunities

Many technical and engineering questions remain to be explored and answered before the potential of the ADS concept can be demonstrated. The work ahead will require greater international co-operation to pool expertise and resources.

In many respects, accelerator-driven systems are worth pursuing. By producing electricity, they can contribute to the world's growing energy needs, and by incinerating plutonium and highly radioactive wastes, they can contribute to the goals of environmental protection and safe waste management. Some types of ADS being developed can produce energy from the abundant element thorium in a safe, sub-critical blanket assembly with a minimal nuclear waste stream. Beyond this, there is the promise of systems with the goal to burn weapons plutonium and to incinerate spent nuclear fuel, including its major fission products, from commercial nuclear power plants.

Presently a number of national and regional scientific institutes and laboratories around the world are engaged in research and development of accelerator-driven systems. At the global level, the IAEA's programmes in this field are helping to promote the exchange of information and co-operative research on specific topics. The work is indicative of the heightened interest in ADS technology as a practical tool for contributing to international energy and environmental goals. ❐