Nuclear Energy

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Abstract Nuclear energy can play a role in carbon free production of electrical energy, thus making it interesting for tomorrow's energy mix. However, several issues have to be addressed. In fission technology, the design of so-called fourth generation reactors show great promise, in particular in addressing materials efficiency and safety issues. If successfully developed, such reactors may have an important and sustainable part in future energy production. Working fusion reactors may be even more materials efficient and environmental friendly, but also need more development and research. The roadmap for development of fourth generation fission and fusion reactors, therefore, asks for attention and research in these fields must be strengthened.

Keywords Nuclear energy · Fission energy · Fusion energy · Generation IV reactors · Subcritical thorium reactors

Nuclear energy—the epitome of modernity in the 1950s and 1960s—promised abundant energy for many, but doubts about waste and safety dampened the enthusiasm in the 1970s. The accidents at Three Mile Island and Chernobyl further halted development in almost all countries. Some plants were decommissioned before the end of the intended life span. However, instead of building new reactors, existing ones have had their power upgraded and their licenses extended, thus offering virtual new reactors. The last decade has seen a renewed interest in nuclear energy, with a new generation fission reactors (relying on existing reactor experience and adding more automatic safety systems, e. g.) entering the scene.

Nuclear energy is in many respects an attractive non-fossil alternative. It is excellent for providing reliable base-

load electricity, has a high capacity, and requires very little material for construction and fuel for operation. The effects on the environment during the entire life cycle are also limited. In the opinion of the Academy's Energy Committee, the major problems associated with nuclear fission energy are related to proliferation issues and to some degree with the spent fuel handling.

Fusion energy options are also evolving, but a first fusion power producing reactor will not be operational until the mid-twenty first century. Fusion energy systems will have several advantages over fission-based systems when it comes to material efficiency and sustainability as well as drastically reduced waste quantities.

NUCLEAR ENERGY FROM FISSION

There are six key issues in regard to the use of nuclear energy, according to the Energy Committee. These are:

- Safety
- Nuclear waste
- Non-proliferation
- Fuel availability
- Life-cycle analysis
- Economic competitiveness

Safety is and will continue to be a key issue for nuclear fission. Experience from several decades of operation of the present generation reactors and emerging new results of R&D form the basis for future design, and provide know-how for upgrading the present systems for extended operation. Future reactor generations should put more emphasis on safety in all stages of the fuel cycle. This is also essential if public approval is to be obtained. Another key issue is the spent fuel. This waste will have to be safely

stored for thousands of years, even if the quantities are very small. This problem can be addressed through the design of so-called Generation IV reactors, operating as breeders, which will significantly reduce the amount of fuel needed and the waste produced, as well as the time needed for safe storage. It is extremely important to ensure strict international control of the fuel cycle to counter proliferation. With today's thermal reactors the uranium cycle is not sustainable, especially if the demand for energy from fission increases. Even if very large uranium resources are available, especially uranium diluted in seawater, for long-term sustainability, breeders will still be essential.

It is crucial to use life-cycle analyses of different electricity production systems to be able to compare efficiency. For fission energy, resource use and radioactive emissions from mining to repositories have to be considered. For example, it is important to look carefully into the health issues that are related to the mining of uranium. Nuclear energy from fission rates favorably in such life-cycle analyses. The Generation IV systems will need much less fuel, thus minimizing environmental impact during the life cycle. Part of the downturn of the nuclear energy industry in previous decades was probably due to the more competitively priced coal-produced electricity. Obviously, for the expansion of nuclear energy, new plants will have to be economically competitive, without compromising safety and reliability.

The Royal Swedish Academy of Sciences' Energy Committee has concluded that further and increased research efforts are necessary to allow us to rationally judge the options for future nuclear fission energy.

As has been briefly mentioned above, Generation IV reactors with breeder technology will use nuclear fuel much more efficiently and will also be able to use spent fuel (from existing reactors), thus minimizing the waste and drastically shortening the required storage time for the final waste. Breeder systems will increase the available energy from natural uranium by a factor 60–70.

Among the different plans for the new generation of reactors are the subcritical thorium-based nuclear systems driven by accelerators that could have advantages over uranium-based systems. Thorium-based systems might be able to produce energy for several thousands of years with known thorium resources.

RENEWED INTEREST IN NUCLEAR FISSION ENERGY

The renewed interest in nuclear fission energy is best seen in China where currently 20 new reactors are being built. There are probably several reasons for this renewed interest, one being—as always on energy issues—a secure

energy supply, another the growing concern in regard to CO₂ emissions. One interesting aspect of the current development is that the plans for the Generation IV reactors were not born within national defense programs (where the industry once started), but rather from international peaceful research collaboration.

According to the World Nuclear Association (WNA), 436 nuclear power reactors (2010) in 29 countries provide 15% of the electricity supply worldwide and 30% within the EU. A total of 53 new reactors are currently being built (51 GWe), and according to the World Nuclear Association 142 more reactors are planned (159 GWe). Thus, 195 new reactors are planned or under construction, of which 85 are located in China or India. In addition, 327 reactors (343 GWe) are being proposed in 36 different countries. Reactors being constructed, planned, and proposed (550 GWe) could contribute 3,700 TWh electricity or more than 20% of today's electricity production. At the same time, older reactors will be shut down and not all of the proposed new reactors will be realized (Fig. 1).

Some of the reactors currently being built are of a new generation—Generation III. They rely on the experience gained from existing Generation II reactors, and bring in new improvements, particularly on safety systems. Also, the back end of the fuel cycle will be improved to meet concerns on waste management and proliferation risks. However, only 1% of the energy content of the fuel can be used and, therefore, the Generation III technology will not be truly sustainable.

Further research should be encouraged to develop the next generation of more sustainable nuclear energy systems, Generation IV. The goal is to develop systems for worldwide deployment within 20 years. These future power plants are expected to have advantages that include sustainability, reduced capital costs, enhanced safety,

Fig. 1 Electricity generating capacity from nuclear energy in different countries, as of January 1, 2010. Source: WNA

minimal generation of waste, and further reduction of the risk of weapons material proliferation. In addition to electricity production, they are also planned to be able to produce hydrogen and heat and to desalinate seawater.

THE FUTURE OF NUCLEAR ENERGY

At the Energy Committee's symposium Energy 2050, experts addressed some of the above topics. In his talk about "The Future of Nuclear Energy", Mujid Kazimi from MIT, outlined the reasons for the renewed interest in nuclear energy, and pointed to: economic stability; environmental concerns; energy security; and an excellent operational record during the past 15 years. This operational record consists of high load factors but also less events and shutdowns as well as small dose levels for workers at the US plants. According to Kazimi, to build on these advances and to make the huge investments needed for the new plants feasible, the advanced Generation III+ reactors must enhance safety, standardize design as well as reduce construction costs. The industry is faced with huge challenges since it has not offered any new reactors and plants for many years. Kazimi pointed at four important aspects of this: manufacturing infrastructure; manpower skills; costs and financing; public support. He was also of the opinion that for a quick build-up of nuclear energy, industrial infrastructure must begin to grow again.

Another requisite for an expansion and long-term availability of nuclear energy is the availability of uranium fuel. According to Kazimi, uranium resources have been greatly underestimated. IAEA now estimates 5.5 million tonnes of uranium in assured sources at costs below \$130/kg and another 10.5 million tonnes are considered likely. However, other experts consider that 25 to 50 million tonnes of conventional uranium can become available at reasonable prices. In addition, huge amounts of unconventional resources can be found in sandstone, phosphates, and seawater. In a recent MIT study, it was shown that with a 2.5% rate of growth of nuclear energy, the cumulative uranium demand by 2100 will be 22 million tonnes with the current LWR cycle or 30 million tonnes with a 4% growth.

The nuclear fuel cycle, including all steps from ore extraction, enrichment, fuel manufacture, and disposal of waste, constitutes ca 15% of the cost of nuclear produced electricity. Therefore, even if an increased demand is foreseen this should not impede competitive pricing of nuclear energy. In the long run, however, this issue will need to be addressed. Kazimi was also anxious to point out that, in his opinion, there is no need to rush the development of thorium options or Generation IV breeder reactors, since there are sufficient uranium resources

available for the growing nuclear industry. This fact allows the next generation reactors to be carefully researched and developed. The most important issue right now, as Kazimi saw it, was the cost of producing new plants, where standardized designs and modern IT will help to keep costs down.

Finally, Kazimi concluded, if nuclear energy is to increase its part of the global energy supply it becomes even more important than today that the system of trade in nuclear fuel operates in forms acceptable to all parties and questions regarding storage and enrichment must be adequately resolved.

SUBCRITICAL THORIUM REACTORS

Carlo Rubbia discussed the prospects of thorium-based fission systems in his talk on "Subcritical thorium reactors". Since plutonium is not produced in the thorium cycle it has an advantage over the uranium cycle in that there are no weapons plutonium issues involved. However, the U-233 isotope, which is the fissile element bred from thorium, may still constitute a weapons issue. There are two reasons why it would be very difficult to get access to this U-233 isotope. First, if it were to be chemically separated it would also contain the U-232 isotope, which is very radioactive and makes any further processing virtually impossible. Second, the reactor needs to be refueled only every tenth year, which permits it to be sealed and under international control. Breeder reactors have considerable advantages over current thermal reactors which use either enriched or natural U-235. Enrichment is no longer necessary, since the breeders use the entire bulk natural material, either thorium or uranium. The whole element (uranium-238 or thorium-232) is converted to fissionable, yielding a 100 times greater energy output than that available with U-235 in current thermal reactors. The "waste" consists primarily of intense but short-lived fission fragments, while the much more long-lived actinides can be "recycled".

Subcritical thorium-based systems will have to be driven by an external neutron source in order to provide criticality since one neutron is needed to maintain the chain reaction and another neutron to create the fissile material. Fission of U-233 results in just above two neutrons per fission in the thermal region, which is marginal for maintaining a chain reaction. Rubbia's invention, the Energy Amplifier, includes a reactor and an accelerator providing a proton beam that is brought to a stop in lead where numerous neutrons are produced by the spallation process. In the suggested design, an accelerator with about 2 MW beam power would be needed for a thorium reactor thermal power of 1.5 GW. The long-lived actinides could also be recycled,

further reducing the waste problem. The radioactive “ashes” remaining after 600 years will be similar to the radioactivity of coal ashes if coal power instead had been used to generate the same amount of electricity as thorium.

Rubbia considers that breeder reactors have a considerable advantage, with respect to present thermal reactors, since all the bulk material, thorium or uranium, can be used with less and a more short-lived waste inventory. Thorium has the clear advantage of establishing a proliferation-resistant technology; the basic technological prerequisites exist but extensive development efforts remain.

NUCLEAR ENERGY FROM FUSION

During the past 50 years, a steadily growing collaboration on fusion research has taken place within the world scientific community. Large successful projects are being conducted in many of the industrialized countries such as JET (EU), TFTR and DIII-D (USA), and JT60-U (Japan). These are now followed by an even larger international experiment, ITER, initiated in 2005 and aiming at a burning full-scale reactor-like plasma. This is a joint project of the EU, USA, Japan, Russia, China, South Korea, and India.

A further step after ITER is a demonstration reactor, DEMO, to be decided on around 2020. The international strategy also comprises back-up activities including concept improvements of the stellarator, the spherical tokamak and the reversed field pinch, coordination of national research activities on inertial confinement and possible alternative concepts as well as long-term fusion reactor technology. An important part of the latter is the IFMIF materials irradiation facility that fills the present gap of material tests at the high flux of 14 MeV neutrons in a fusion reactor.

Some key issues in the use of fusion:

- Advantages and disadvantages compared to fission
- Technical and physical issues (initial confinement, magnetic confinement)
- From JET to ITER to DEMO to a power producing reactor
- Non-proliferation and waste
- Economical competitiveness
- Time scale of realization

Due to the inherent physics, fusion has a safety advantage over fission, and no long-lived radioactive waste is produced. However, there is a long road ahead before all the physical and technological issues are solved. The roadmap will address these aspects.

FUSION ENERGY: READY FOR USE BY 2050?

In his talk “Fusion energy—ready for use by 2050?” Friedrich Wagner addressed the state of the development of fusion energy. Fusion energy, being the energy source of the stars, has the advantage of being both sustainable and environmental friendly. He pointed out that the energy within 1 g of fusion fuel corresponds to that of 12 tonnes of coal. The fuel for the first generation of a fusion reactor would be deuterium and tritium, where deuterium can be obtained from seawater and tritium can be bred from lithium, which is contained in the earth’s crust. In order for fusion reactions to take place, the repelling Coulomb forces of the nuclear constituents have to be overcome, which may occur at temperatures of 150 million °C. At such temperatures the fuel is in a plasma state, and needs magnetic confinement. The most popular fusion research facility is of the Tokamak type with magnetic confinement. An alternative way of obtaining fusion energy is by using a Stellarator type device with magnetic confinement in three dimensions.

Already a short pulse of 16 MW of fusion energy has been produced at JET, the Joint European Torus experimental facility at Culham, UK. Plans are already underway to build the first experimental fusion reactor ITER, International Thermonuclear Experimental Reactor, in France as an international collaboration. ITER is a Tokamak type facility for demonstrating the feasibility of a fusion power plant. The goal is to produce fusion power of 500 MW, but most importantly to gain experience in regard to all the inherent physical problems.

The target parameter for fusion research is the triple product of plasma temperature, particle density, and plasma confinement time. The plasma is heated by produced alpha particles and cooled by radiation and transport losses. From the present research, the targets for temperature and density have been achieved, but a factor 4 remains for the plasma confinement time. The solution is to make the containment volume larger and, in ITER with a radius of 6 m, the goal is to reach the sufficient confinement time and required triple product. According to Wagner, it is envisaged to deliver adequate information on physics, technology, and materials so that construction of a demonstration reactor, a DEMO plant can be started in 2030.

In parallel to the ITER research, studies on the Stellarator type facility W7-X will be carried out in Greifswald for studying the plasma physics. When the decision for the final DEMO design is taken, the Tokamak geometry is the main option for the magnetic field layout, but a Stellarator design may be an attractive alternative. Along with the plasma physics studies, material studies are being carried out at the IFMIF 14 MeV neutron source in Japan.

The DEMO will address the technological aspects and test the economy of the design. The main goal is to reach a steady-state operation, to achieve a reliable tritium production, to optimize the ferritic steel material and to demonstrate an economically competitive price. In conclusion, Wagner believed that fusion energy would be available from 2050, at least there is no evidence that there should be any fundamental obstacle in the basic physics. According to Wagner, there is a clear roadmap to commercialize fusion and he concluded that with fusion, we hand over to future generations a clean, safe, sustainable, and—in his expectations—economical power source accessible to all mankind.

IN SUMMARY

Nuclear energy cannot, as once believed, solve all of the world's energy problems, but it can play an important carbon-free role in the production of electrical energy. For this reason, the Royal Swedish Academy of Sciences' Energy Committee sees a need for continued and strengthened research for the development of the third and especially fourth generations of fission reactors. Without functioning fourth generation reactors, nuclear fission energy will not be sustainable, but with such reactor designs in operation it will be a viable option for a long time. Fusion energy has the potential of becoming a long-term environmental friendly and material-efficient energy option. However, concerted scientific research and technology development on an international scale is required for fusion to become a cost-effective energy option in this century.

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