

Statements on Energy from Nuclear Fission

by the Energy Committee at the Royal Swedish Academy of Sciences

Introduction

The Royal Swedish Academy of Sciences (RSAS) is an independent non-governmental organization, with expertise in most of the sciences as well as in the economical, social and humanistic fields. The RSAS has appointed an Energy Committee that will summarize scientific knowledge on the supply and use of energy as well as the predicted impacts on society over the coming fifty years. Readily available, inexpensive and environmentally friendly energy provides the foundation for economic growth and prosperity.

The Energy Committee has selected a number of subjects to be studied in some depth, one of these being nuclear energy from the fission process. Therefore, the Committee arranged a Hearing on February 28, 2006, concerning the current status of nuclear energy and subsequently, on 15 May 2006, an open seminar on the Future of Nuclear Energy. The latter was organized together with the Committee for Energy and Environment of the Royal Academy of Engineering Sciences, and included presentations by leading scientists from Finland, USA, France and Japan.*

Summarized below is the information presented at these two meetings and our conclusions.

Background

In the *World Energy Assessment: Overview 2004 Update*, produced by the United Nations Department of Economic and Social Affairs and the World Energy Council, the question was posed as to whether or not global energy supplies are sustainable. Oil and gas will become scarce and probably increase substantially in price, during the present century; thereafter more durable and preferably truly sustainable energy sources will be required. It is suggested in this report that in order to meet the challenges of sustainable development, policies have to change to favour non-conventional fuels. Options that support sustainable development include more efficient use of energy, increased reliance on renewable energy sources and accelerated deployment of new technologies. The latter will include fossil-fuel technologies, with near-zero harmful emissions and nuclear technologies if the issues surrounding their use can be resolved.

For different reasons there is a renewed interest in nuclear energy around the world. An obvious concern is that ageing reactors need to be replaced. Some points often brought up favouring the use of nuclear energy are:

- environmental concerns with fossil-fuel power stations,
- ambitions to reduce the import-dependence on oil, gas and coal,
- improved operational standards of existing nuclear power reactors, and
- needs for relatively cheap base-load availability of electricity.

Other advantages of nuclear energy are that the uranium producers are considered to be more reliable as suppliers than some of the oil and gas producing countries and the uranium fuel price is only a small share of the kWh production price.

What then is the present status of nuclear energy in the world? According to IAEA figures, there are at present 441 reactors (369 GW_e), in operation, so-called Generation II reactors, in 30 countries and another 27 (21 GW_e) are being constructed in 11 of these (May 2006). According to the World Nuclear Association there are 38 more reactors (40 GW_e), planned. Thus 66 new nuclear power plants are planned or under construction, of which 19 are in China and India.



Additionally, 113 more reactors (82 GWe) are being proposed in 17 different countries (March 2006). Totally reactors under construction, planning and proposed (144 GWe) could contribute to around 1000 TWh electricity or 6 % of today's electricity production.

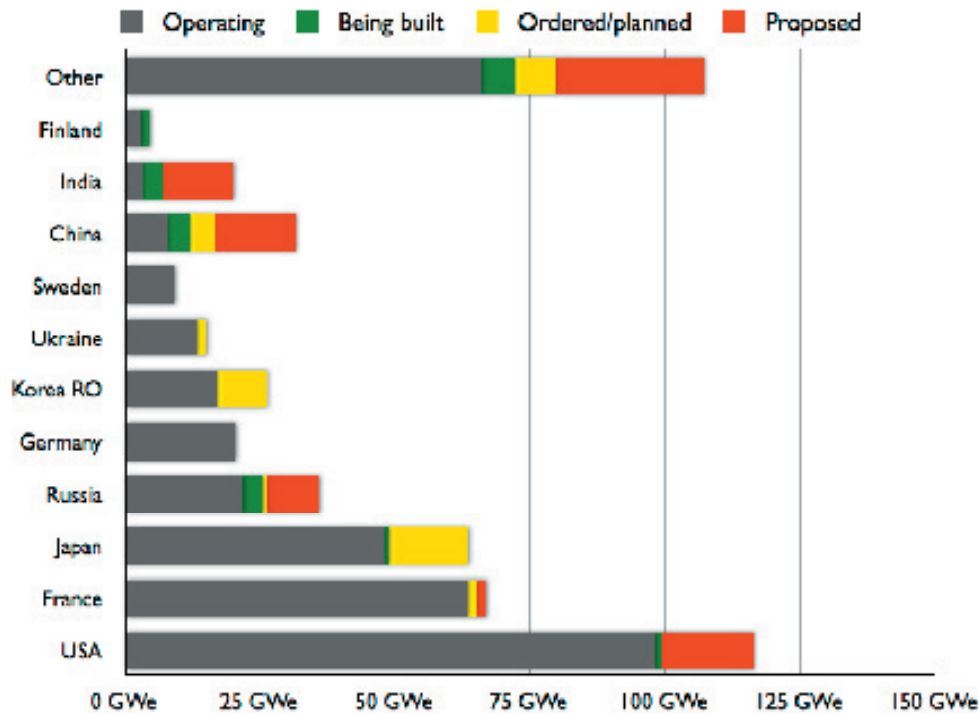


Diagram: Electricity generating capacity from nuclear reactors in different countries. Sources: IAEA & World Nuclear.

Generation III reactors

Facing the challenge of a strong increase of the worldwide demand for nuclear energy, there is now a rather large industrial offer of Gen III reactors (Gen abbreviates Generation) on the market. This new generation of reactors relies on the experience gained from existing light water reactors (Gen II), and brings in new improvements particularly on safety systems which will have more automatic controls and be less dependent on the operators. Also the back end of the fuel cycle will be improved to meet concerns on waste management and proliferation risks. The first of these Generation III generation of reactors, the EPR is being built in Olkiluoto Finland by Framatome ANP and Siemens now the AREVA consortium. Its reactor containment is reinforced and has double walls.

Also US nuclear industry has elaborated new designs for emerging markets. Various passive safety features are considered for example by Westinghouse and General Electric. The designs aim at reduced number of pumps and tubes. The Westinghouse AP1000 has baffles for natural circulation of air close to the steel containment vessel.

Many of the new reactors to be built worldwide during the coming two decades will have Gen III features. The Finnish Olkiluoto reactor will come into operation around 2010 when according to the current plans, the building of reactors in the US will start.

Generation IV reactors

The USA has initiated an international forum of governments, industry and research communities in developing the next generation of nuclear energy systems to follow the Gen III systems, the so-called Gen IV. The goal is to develop systems that would be available for worldwide deployment in about 25 years from now. These future power plants are expected to have advantages that include sustainability, reduced capital costs, enhanced safety, minimal generation of waste, and further reduction of the risk of weapons materials proliferation. In

addition to electricity, they should also be able, to produce hydrogen, heat and desalination of seawater. The Gen IV International Forum (GIF) has established an international research and development program for Generation IV nuclear energy systems. The members of GIF are Argentina, Brazil, Canada, EU, France, Japan, South Africa, South Korea, Switzerland, United Kingdom and USA; they have divided the R&D efforts of the different reactor types between themselves.

Gen IV candidates		R&D country (examples)	Breed	High temp.
GFR	Gas-Cooled Fast Reactor System	Fr, UK, CH, USA	×	
LFR	Lead-Cooled Fast Reactor System		×	
MSR	Molten Salt Reactor System	USA	×	
SFR	Sodium-Cooled Fast Reactor System	Jp, Fr, KRO	×	
SCWR	Supercritical-Water-Cooled Reactor System	Can, CH		
VHTR	Very-High-Temperature Reactor System	Jp, USA, EU, Fr, KRO, UK		×

Four of these are breeder reactors with a closed fuel cycle and the prospects of achieving a 100 times better utilisation of the uranium fuel than in present reactors. Two reactors, the SFR and the VHTR, have already been developed in several countries and have operated as prototypes, demonstrating their basic feasibility together with the need for further improvements; the latter, in particular concerning operational reliability and plant costs.

The future of nuclear energy is thus anticipated through the industrial development and commissioning of Gen III reactors and, in parallel, the development of Gen IV systems. Most of the countries working with the future of nuclear energy are gathered in GIF and other main contributors to the R&D should join soon. There are many R&D challenges and it will take time to develop the new technologies even with efficient international cooperation. Various demonstrations, for both new reactor designs and fuel cycle improvements, will be needed and some of them are likely to be tested during the R&D phase. There are also other initiatives like IAEA's INPRO, dealing with the principles of future regulations of sustainable nuclear energy. A first phase deals with methods to compare the performance of different systems.

The Energy Committee's key issues concerning nuclear energy

We have identified six key issues. Each of them requires very careful analysis during the coming years. It is probable that broadly based research is necessary for each of these issues.

1. Safety

Safety remains a key issue. It is one of the major activities of OECD's Nuclear Energy Agency (NEA). 40 years of multilateral cooperation has led to improvements in the analysis and management of accidents and in the assessment of safety margins in the fuel cycle. In particular, attention is focused on ageing and structural integrity of reactor components as the lifetime of reactors is extended to up to 60 years. The new Gen III reactors have improved safety features such as double containment, better separation of critical safety systems and improved possibilities to handle steam explosions and core meltdown. The new EPR being built in Finland has reinforced containment to withstand a direct hit by an airplane. Several other Gen III reactor models have safety systems relying mainly on passive techniques for their functioning. The risk for a major accident should thus be further diminished. The Gen IV reactors will be designed with a goal to further improve safety features.

2. Handling of the nuclear waste

Today, in most light water reactors, the fuel is used once only ("once through") and then sent directly to repositories. After some cooling time, the waste will be buried in underground repositories. In Sweden and Finland, the rock is well suited for storage of high-level waste and the schemes that are planned there have been well studied from a technical viewpoint. Another important aspect is that a final decision for waste disposal is of great importance to the public's acceptance of any new nuclear ventures. A decision is expected this year in France for their final repository, but also a decision about how to improve the handling of the waste.

In France (and UK) the closed fuel cycle has already been demonstrated in industrial scale by removing the long-lived waste, the plutonium isotopes and other minor actinides thus shortening the time of radioactivity of the waste from several 100 000 years to a few hundred years. Plutonium and other minor actinides are in this way partitioned from the rest of the waste and then recycled in the reactors with fast neutron spectra, where they are destroyed by the fission process and produce energy. This mixture of actinides is not suitable for bomb manufacture and in this way safer burning and production of energy may be accomplished. Alternatively the actinides or a portion of them could be brought into an accelerator driven transmutation plant. Evidently the waste handling in future reactors is an important item for future research and its solution will also influence how the waste from current reactors is managed.

3. Non-proliferation

The nuclear fuel cycle is a challenging problem area. Cooperation, transparency and safety are key issues. With increased use of nuclear energy, more countries may build up facilities for the whole fuel cycle, thus also, at least theoretically, being able to extract plutonium for weapons use. These points to the difficult question of non-proliferation. Can this scenario be compatible with a strict international regime of inspections and reciprocity?

Nuclear fission bombs can be manufactured either from uranium-235 or from plutonium-239. Uranium-235 is produced by enriching natural uranium either by diffusion or by centrifuge methods. Ordinary light-water reactors need an enrichment of uranium-235 up to 3-5% for the fuel to be useable. The problem is to prevent that the enrichment process, used for the reactor fuel, being continued up to about 90%, which is needed for bomb manufacture. The spent fuel reprocessing and recycling may also lead to diversion of fissionable material. Thus it is obviously necessary to have strict international control of the fuel cycle under the auspices of the IAEA in order to prevent any future transfer of fissile material to the weapons sector.

Two initiatives are currently being discussed for a stricter control of the fuel cycle. One is the Global Nuclear Energy Partnership (GNEP) initiative proposed by the United States. Nations with secure nuclear capabilities (fuel cycle states) would both provide fresh fuel to, and recover used fuel from, those nations that agree to use nuclear energy for peaceful purposes only. Another initiative is the Advanced Fuel Cycle Initiative (AFCI), which aims at sustainability, economics and non-proliferation. It should be mentioned that if fast breeder reactors, with a closed fuel cycle are developed and with uranium as a fuel, many of the problems with present light-water reactors can be avoided as far as proliferation is concerned, due to elimination of uranium enrichment and recycled actinide (not pure plutonium-239) fuel, which precludes unauthorized handling.

4. Fuel availability

According to NEA the world's present demand for natural uranium is 67 000 tons per year (July 2004). 36 000 tons are provided from mining and the rest from so-called secondary sources, weapons material etc. Known resources that are accessible for mining in the Earth's crust are 4.6 million tons and in addition 10 million tons of so-called speculative resources could be retrieved. At present 47% of the uranium comes from Australia and Canada. There are huge additional resources in the Earth's crust, many of which can be economically exploited at a higher price. However, the production from the lower grade U-ores may be limited by environmental considerations.

A huge additional resource is the uranium naturally contained in seawater and estimated to be 4.5 billion tons i.e. 300 times more than so far known resources. A group at the Japan Atomic Energy Agency has pioneered a method to collect uranium from seawater. They have managed to separate about 1 kg of uranium from seawater and estimated that the price for large-scale

uranium production should be ten times the present market price of USD90/kg. Research in the coming years will aim at reducing this price and making the method more efficient.

Besides using uranium, there is increasing interest in using another isotope – thorium-232 as a fertile material to produce fissile fuel. Thorium is 3.5 times more common in the Earth's crust than uranium. [Th 8.1g/ton, U 2.3g/ton].

In view of all these potential resources, nuclear fission energy may for practical purposes be characterized as being a durable energy source in particular with the development of fast breeders reactors where the fuel for the fission process, even with a significantly larger nuclear power production than today, would last for many thousands of years.

5. Life Cycle Analyses

Effects on health and environment of different kinds of energy are normally quantified by means of Life Cycle Analyses (LCA), which include resource use and emissions from mining to repositories. Construction, operation, decommissioning of the power plant and dealing with the fuel and waste are considered in such analyses of the effects of the use of nuclear energy. In a European Union project ExternE, the estimated costs of all effects on health and environment by electricity production have been quantified by means of Life Cycle Analyses. The estimates show that electricity generation by Hydro, Nuclear and Wind have very small external costs, 5–10 % of the kWh production cost, compared to generation by fossil and bio fuels. Since part of the environmental and health impact is caused by the mining of uranium, future Gen IV breeder reactors, using 100 times less natural uranium are expected to be less harmful to health and environment than present-day reactors provided the reprocessing facilities can be properly designed.

6. The economical competitiveness

Electricity generated in nuclear plants is characterized by a very high capital cost and a comparatively small cost for the operation, the maintenance and the fuel. The cost distribution for nuclear plants thus differs from fossil-fired plants. Since a nuclear facility is very large it is often risky for individual companies to invest in nuclear energy. Therefore states as well as companies have to be involved. In Finland major industry consumers of electricity have joined to build the 5th Finnish reactor. The decision to choose a nuclear solution was based on cost estimates of different alternatives. The estimated power generation cost for this reactor is 23 euro/MWh and significantly lower than the costs for any of the other kinds of production sources considered: gas, coal, peat, wood, wind. In the United States new power plant orders are now anticipated in the next two to three years. The government has stepped up support for licensing of new reactors, offering to share the permitting costs as well as to provide financial incentives for the first 6 000 MW_e of new plants. These will include light water reactors with passive means for safety, such as the AP1000, and the ESBWR, and evolutionary reactors such as the EPR.

It should be noted that the cost for the uranium fuel is presently only a few per cent of the kWh production cost for electricity, and increasing uranium prices will only have a small effect on the electricity price.

Conclusions

For making a rational decision about the future global energy supply, it is essential that the plans for the development of nuclear energy worldwide get our full attention. The funds for nuclear R&D have already been increased in several countries, in particular those that take part in the Generation IV International Forum. To contribute to the ambitious goals set up for the proposed Gen IV reactors in a reasonably short time, significantly increased resources for research are needed. The answers will guide us in deciding the role of nuclear fission energy in the future global energy mix. The Gen IV initiative is an open international and collaborative effort with no military intention, which makes it quite different from the development of previous generations of nuclear systems. It is our opinion that it will be important also for other countries with nuclear energy such as Sweden, to increase their public funding in order to be able to collaborate internationally and have access to the new technologies emerging from nuclear R&D.

Members of the Energy Committee at the Royal Swedish Academy of Science

Sven Kullander, Professor em., Uppsala University, chairman
Gia Destouni, Professor, Stockholm University
Harry Frank, Professor, Mälardalens University
Karl Fredga, Professor em., Uppsala University
Bertil Fredholm, Professor, Karolinska Institutet
Karl Grandin, Ph.D., Center for History of Science
Peter Jagers, Professor, Chalmers Institute of Technology
Bengt Kasemo, Professor, Chalmers Institute of Technology
Rickard Lundin, Professor, Swedish Institute of Space Physics
Karl-Göran Mäler, Professor em., The Beijer International Institute of Ecological Economics
Kerstin Nilblaus, Director General, Council of the European Union
Bengt Nordén, Professor, Chalmers Institute of Technology

Contact persons

Malin Lindgren, Information Officer, +46 8 673 95 22, +46 709 88 60 04, malin@kva.se
Sven Kullander, Professor, +46 8 673 97 05, sven.kullander@kva.se

Abbreviations

AFCI	Advanced Fuel Cycle Initiative (US)
AP1000	Advanced Passive PWR (Westinghouse design of Gen III reactor)
BWR	Boiling Water Reactor
EIA	Energy Information Administration of DOE
EPR	European Pressurized Water Reactor (Gen III)
ESBWR	Advanced Passive BWR (General Electric design of Gen III reactor)
Gen	Generation
GFR	Gas-Cooled Fast Reactor System (Gen IV)
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
IAEA	International Atomic Energy Agency
IEO2005	International Energy Outlook 2005 by EIA
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles of IAEA
LCA	Life Cycle Analyses
LFR	Lead-Cooled Fast Reactor System (Gen IV)
MSR	Molten Salt Reactor System (Gen IV)
NEA	Nuclear Energy Agency of OECD
OECD	Organisation for Economic Co-Operation and Development
PWR	Pressurized Water Reactor
SFR	Sodium-Cooled Fast Reactor System (Gen IV)
SCWR	Supercritical-Water-Cooled Reactor System (Gen IV)
VHTR	Very-High-Temperature Reactor System (Gen IV)

Sources

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* The invited speakers were: Mikko Kara – VTT Technical Research Centre of Finland, Mujid S. Kazimi – Massachusetts Institute of Technology, Jacques Bouchard – Commissariat à l'Énergie Atomique and Masakazu Ichimiya – Japan Atomic Energy Agency. Hans Blix, the former IAEA Director General, introduced a panel focusing on how future civil nuclear energy may be developed without the risk of proliferation of weapons material. In connection with the Seminar, the Energy Committee conducted a Hearing with lecturers. More information about the seminar can be found on the Academy's web page www.kva.se. The Energy Committee also arranged a Hearing on February 28th, 2006 about the state of the current nuclear energy situation especially from a Swedish perspective. Panel members were Tomas Lefvert, Head of Swedish Centre for Nuclear Technology, Royal Institute of Technology (KTH), Sten Bjurström, previous Head of Swedish Nuclear Fuel and Waste Management Co. (SKB), Lars Högberg, previous Head of Swedish Nuclear Power Inspectorate (SKI) and Lena Oliver, Weapons group at Swedish Defence Research Agency (FOI). A report (in Swedish) with title "The global status and future development of nuclear energy" – issued by Elforsk was discussed at depth. The results of the Hearings and the Seminar have been evaluated in the Energy Committee and discussed in its Reference group.