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Statements on Energy from Nuclear Fusion

by the Energy Committee of the Royal Swedish Academy of Sciences*

Introduction

The Royal Swedish Academy of Sciences (Kungl. Vetenskapsakademien, KVA) is an independent organization, with knowledge in science as well as in economical, social and humanistic fields. The KVA has set up an Energy Committee that will summarize scientific knowledge on the supply and use of energy as well as predicted impacts on society over the coming fifty years. Easily accessible, 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 energy from the nuclear fusion of light elements. Results are summarized usually as statements and are part of a portfolio from which a synthesis and final recommendations will be made when all the studies have been completed.

The committee arranged a Hearing on January 17, 2007, at the KVA, concerning the current status of energy from nuclear fusion. Among the invited participants were representatives of the Academy, and ten scientists from the Swedish Fusion Research Unit associated with the fusion research programme of Euratom in Brussels. Lectures were given by Bo Lehnert, Jan Scheffel, Mikael Tendler, Torbjörn Hellsten, James Drake, Marek Rubel, Sture Nordlinder and Per Brunsell. These scientists altogether with Elisabeth Rachlew and Einar Tennfors took part in the Hearing.

These statements are based on the presentations and the discussions in the 17 January Hearing. They have been elaborated by a working group consisting of Sven Kullander, Rickard Lundin, Bo Lehnert and Elisabeth Rachlew. The conclusions and recommendations have been approved in meetings with the Energy Committee on March 14 and May 9. Furthermore the factual statements presented below have been discussed and endorsed by the Academy's Physics Class in its meeting on June 12.

Background

In the *World Energy Assessment: Overview 2004 Update,* produced by the United Nations Department of Economics 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; therefore more sustainable energy sources will be required. It is suggested that, in order to meet the challenges of sustainable development, policies have to shift to favour non-conventional fuels. All options leading to such a development have thus to be forcefully and broadly executed, by 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, as well as fission and fusion technologies where current problems connected with their use and development must be resolved.

For many reasons there is a worldwide interest in energy from nuclear fusion. Some points often brought up which favour its use are:

- availability of very large fuel reserves,
- inherent safety of the fusion reactor in which there is only a small amount of fuel in the reaction zone, no critical "meltdown" accidents are possible, and there is a low power density of afterheat,
- no long-lived radioactive waste and a low biological hazard of the inventory also including the activated wall material,
- and no contribution to the greenhouse effect.

The most promising way of producing fusion energy is by "hot fusion" where the fuel is heated to extremely high temperatures of about 100 million degrees, thereby ionizing the fuel to a plasma

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of electrons and ions. The high temperatures are needed for a sufficiently high reaction rate. For the fusion reactions to provide energy to be extracted and allowing for radiation losses, the temperature has to exceed an ignition value T_c. In addition, the product of the particle density n and the plasma cooling time τ_E (energy confinement time) has to exceed a critical value $(n\,\tau_E)_c$ (the Lawson criterion) for covering all other losses than those by radiation from a pure plasma, such as losses of particles and heat transport due to diffusion, conduction, instabilities and turbulence. This leads to two hot-fusion alternatives; magnetic fusion at low n and long τ_E where the hot plasma is confined by a magnetic field and inertial fusion at high n and short τ_E where small pellets of the fuel are heated intermittently by laser or particle beams focused to a "point". The magnetic fusion is a continuously burning nuclear furnace whereas the laser fusion is more like an internal combustion engine where the energy is delivered in bursts.

There have also been attempts to realize controlled reactions by "cold fusion" at room temperature. In muon-catalyzed fusion, the reaction rate is enhanced through a replacement of atomic electrons by muons bringing the two fusing nuclei closer to each other, but this scheme has difficulties with the short lifetime, 2 microseconds, of the muons. Another attempt is the "metal catalysis" by the implanting of deuterium in a metal. A noticeable production of particles due to fusion reactions and an associated energy generation (1989 cold fusion in Utah) has not been confirmed despite numerous experiments, nor is it supported by theory.

There are finally some other schemes such as sono fusion where the implosion of bubbles in combination with spherically focussed sound waves are used to create enhanced temperatures at their focal point. These schemes are, however, far from the goal of energy production.

The most promising road towards the fusion reactor is at present believed to be provided by the magnetic confinement of a plasma at about 200 million degrees temperature in a magnetic field ("magnetic bottle ") but where the plasma current itself provides part of the magnetic field. A nearly steady plasma confinement has been successfully realized in a tokamak field geometry. Some other magnetic field systems such as the stellarator, where the entire magnetic field is generated by external sources, could also become candidates for a future reactor.

The present state of fusion research and its prospect to realize a power-producing reactor are encouraging. The development of the basic physics of controlled fusion as well as the progress in fusion technology have been substantial, and experiments and theory have been brought close together. The fuel, in the form of a fully ionized hot plasma, has now in experiments been heated to more than 300 million degrees, thus exceeding the range of the required ignition temperature of a reactor. Simultaneously, values of particle density and energy confinement time have been reached for which the produced fusion power is close to the total power loss ("breakeven"). Thus there is now a solid base for scaling present experiments up to the size of burning fusion reactor plasma, in the GWe power range. A remaining, not fully clarified question, concerns the plasma-wall interaction i.e. high-energy plasma particles striking the walls of the vacuum vessel. These interactions release impurities that poison the plasma and increase its radiation losses. The possible ways of reducing such interactions depend on an increased understanding of the plasma-boundary region, to be gained from the next step of large experiments.

During the last fifty years, a steadily growing collaboration on fusion research has taken place within the world scientific community. Large successful projects are 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, decided in 2005 and aiming at a burning full-scale reactor-like plasma. This project is jointly performed by 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.

Progress has also been made on pulsed inertial confinement, where the fuel consists of small pellets irradiated by laser or particle beams. Examples of facilities are the laser-driven ones in Osaka (Japan), Livermore (USA), Limeil (France) and the beam-driven ones in Osaka, Albuquerque (USA), Livermore (USA) and Darmstadt (Germany). A large-scale laser system designed to demonstrate significant energy production from inertial fusion, HiPER, is planned in Europe (included in the ESFRI Roadmap 2006) and expected to start in 2015.

The energy committee's key points concerning nuclear fusion energy

1. Fuel availability

A mixture of the heavy hydrogen isotopes deuterium (D) and tritium (T) provides the highest reaction rates and will be used in the first generation of fusion reactors. High-energy neutrons carry the main portion of the released energy. The fuels, including the lithium for the breeding of tritium, are so abundant that fusion becomes a very sustainable source, being at least comparable to that of the fission breeder (about 10^{26} J = 3×10^{10} TWh).

In a second generation of reactors, deuterium may be burnt directly. The reaction rate of the DD fusion is lower than that of the DT fusion. Hence, a more efficient confinement of the fuel is required. The neutron flux is smaller and more of the released energy is carried by electrically charged particles. At the present rate of the world's energy consumption, the reserves of deuterium would last for a period being comparable to the age of the solar system.

In a remote future, advanced fuel reactions such as DHe^3 and proton-boron reactions may be used in a third generation of reactors. The reaction rates are even smaller than that of the DD reaction and the requirement on the confinement of the fuel is stricter. There is, however, no neutrons released at all. The fuel reserves are large.

It should be pointed out that the requirements on the ignition temperature and energy confinement of the DD reaction and the other advanced ones are much stronger than those of the DT reaction which is the only one that will be attempted in the early stages of energy production from fusion.

2. Advantages and disadvantages compared to fission

The fusion fuel is abundant and available everywhere in the earth crust and in the sea.

The fusion reactor has an inherent safety and its reaction zone contains fuel only for some ten seconds of burning. The reactor has an inherent safety in the form of a self-limiting reaction rate so that critical "meltdown" accidents are impossible, and the afterheat power is small. For the DT reaction, fires in a breeding mantle of metallic lithium would become a problem, but this can be avoided by e.g. the choice of lithium ceramics. In the case of an accident with mechanical damage, the possible spreading of the solid radioactive inventory will be limited to a zone in the neighbourhood of the reactor which will not contain long-lived radioactivity. Tritium gas is certainly spread far away into larger columns of the atmosphere, but it has a short half-life (12.3 years) and would not become a major concern.

The fuel and the direct-end products ("ashes") of the considered fusion reactions are neither toxic nor radioactive. No long-lived radioactive waste is produced. In the case of the DT reaction, there is a radioactive inventory due to the breeded tritium fuel, and to the secondary radioactivity arising from neutron interactions with the reactor structure. Even so, the biological hazards are much lower than those of a comparable fission reactor. This situation with DT can be substantially improved by using low-activation wall materials. For a suitable choice of the latter, the residual radioactivity after 100 years of storage thus becomes lower than that of coal ashes. The DD fusion and the other advanced fuel reactions make a further reduction of the radioactivity possible, in some cases practically down to zero.

As compared to fission, fusion has greater difficulties to reach criticality by self-sustained reactions. Even if fusion research has been successful, there is still a long road to the goal of a power-producing reactor, both with respect to physics and to technology. The strong flux of 14 MeV neutrons in the fusion reactor has no counterpart in fission, and corresponding material tests are not yet available in full scale but planned through the large irradiation facility IFMIF.

3. Inertial confinement

Inertial fusion is one of the two "hot fusion" research schemes. It is based on small fuel pellets of deuterium and tritium that are dropped into a reaction chamber and become subject to intense and focused radiation by high-power lasers or ion beams. The pellet surface then strongly evaporates, and a radially ingoing shock wave arises as a reaction force that heats the pellet centre to high temperature. The shock must be spherically symmetric to avoid instabilities that weaken its compressive effect. This scheme is successful, in reaching near "breakeven" condition of the parameter values for which a produced fusion power becomes comparable to the total power losses. The spherical symmetry is somewhat easier to realize by laser beams than by ion beams, whereas the latter provide more power than the former.

For military reasons, laser fusion has not so far been part of the official fusion program of Euratom. However, extensive research has since a long time been conducted on laser fusion in Limeil (France), Garching (Germany) and Rijnhuizen (Holland), and on ion beam fusion in Darmstadt (Germany).

The technical problems with the fast igniter are still large. The lasers need to be much larger and more efficient than those existing today, the repetition rates need to be increased by orders of magnitude, the manufacturing of the fuel pellets will require an entire industry using technologies not even demonstrated today, and the biggest challenge is to figure out how to integrate the system into a reactor.

4. Magnetic confinement

At this stage, magnetic confinement appears to be the most obvious path towards energy production from nuclear fusion, and already today plans exist for an integrated reactor design. It is based on the concept of a "magnetic bottle" where the hot fuel in the form of a fully ionized plasma is confined by electromagnetic forces. Equilibrium between the plasma pressure and these forces has to be established and become stable against disturbances that destroy the confinement. An efficient energy balance also requires a sufficient reduction of anomalous transport processes such as those caused by turbulence. Furthermore, plasma-wall interactions and radiation losses from released impurities become crucial for the energy balance. To reach the required high plasma temperature, auxiliary heating by high frequency and by particle beams has to be added to the ohmic heating by the plasma currents. When having passed the ignition temperature, the burning fusion plasma should sustain its temperature by the energetic helium ions (alpha particles) created by the DT reaction.

Especially in the tokamak scheme, with devices such as JET, TFTR, DIII-D and JT60-U, substantial progress has been made. Here the confining magnetic field partly consists of a strong component generated by external current sources, partly by a weaker component generated internally by plasma currents. Temperatures up to 300 million degrees have been reported, as well as a "breakeven" state where the experimental fusion power is of the order of the total power loss, and an extended knowledge has been gained with a closer contact between theory and experiments, also with improved methods of plasma heating and diagnostics. In JET for example, a fusion power up to 16 MW has been produced during about a second by introducing small amounts of tritium into a deuterium plasma. It should be noted that the experiments are for most of the time carried out with deuterium to avoid contamination.

Research on magnetic confinement has further been conducted on a number of other configurations, such as the stellarator, where the magnetic field is almost entirely generated by external current sources, and the reversed field pinch where a larger portion of the magnetic field is due to the plasma currents than that in a tokamak.

5. From JET to ITER

The successful results with JET and some other large tokamaks, and the corresponding confirmed scaling laws, form a solid base for the extrapolation of the parameters to an even larger scale. Thus, there are several reasons for the now thoroughly investigated plasma in JET to be followed by experiments in a larger device, ITER. An important experimental parameter is the efficiency Q defined as the ratio between the generated fusion power and the externally supplied heating power required to sustain the hot plasma. Since the experiments are normally done using ordinary deuterium, the produced fusion power is calculated from the plasma parameters. In JET, a value of $Q \approx 1$ has been obtained. In ITER, studies will be done of a burning fusion plasma with $Q=10$ at reactor-like conditions: of discharge pulses with a duration of minutes at a fusion power of 0.5 GW, and of the plasma-wall interactions and of the behaviour of the wall-near boundary region of the plasma.

6. The demonstration reactor DEMO

The demonstration reactor DEMO is the next step after ITER. As compared to ITER, it is a power-producing device which is fully equipped with reactor components, has an improved confinement system, is run in a steady state at a power of 2.5 GWth with an efficiency of $Q=25$, and has a mantle for generation of tritium.

7. A power-producing reactor

A commercial power-producing reactor will be built after the performance of the DEMO has been shown to be satisfactory. However, a power-producing reactor cannot be fully designed until a reliable operation of the DEMO reactor has been proven. In any case, it will most likely be based on the DT reaction, and may have the form of a concept-improved tokamak, or possibly some other magnetic confinement system.

8. Non-proliferation and waste

The problem of non-proliferation does not appear to be serious for fusion. No weapon-grade material is handled since the tritium fusion fuel is generated internally from lithium in the mantle. The nuclear fuel cycle can be restricted to the area of the power station, and there are no long-lived radioactive components involved. Low-activation wall materials would give rise to only a limited amount of radioactive waste. The latter can be reprocessed and recycled.

9. The economic competitiveness

No power producing fusion reactor is at this stage available, and the economic competitiveness of fusion energy can therefore only be based on preliminary estimates. The larger part of the cost for electricity from fusion is expected to be due to the investments in a power station, and a smaller part will be external costs (externalities).

The investment costs of ITER are estimated to about 5 billion euros, and the costs of the DEMO are likely to be even larger. The investment cost for a power plant in series production has recently been estimated to about 3.5 $ cents/kWh, being twice that of fission power.

The external costs of generated electricity are expected to be as for fission. These have in 1999 been further estimated to about 0.3 $ cents per kWh, which would become quite competitive (fission 0.3, coal 4.5, oil 6.5 and natural gas 1.9 $ cents/kWh; according to UK Energy Sectors Indicators, 1999).

10. The time scale for the realization of fusion power

One of the most important issues of fusion energy is the time scale for its ultimate realization. Fusion researchers have often been confronted with the question why it takes so long time to reach the goal. The general answer to this is that fusion research does not concern a single problem but a whole complex of questions from basic R&D to the environmental, practical and economical issues. The large number of complicated problems to be tackled, the threshold of a self-sustained reactor which has to be surpassed, and shortages of resources and political intentions, contribute to this situation.

On the other hand, it should also be noticed that there are time scales comparable to those of fusion research also for the development of some other technologically advanced systems such as of transistors and solar cells.

In a European perspective, the present strategy began with JET which started its operation in 1983, and where a large amount of knowledge has been assembled up to the limits of what can be obtained from a device of its size. JET will be followed by ITER, which was decided on in 2005 and is expected to come into operation in 2016. According to current plans, the decision on the DEMO will be taken in 2020. Technology and concept improvement programmes for the DEMO will go on in parallel with the ITER experiment. Backup activities in national laboratories, including continued basic research and work on concept improvement as well as on long-term technology, will thereby have a decisive importance for the final outcome of this strategy. The time scales given by the fusion physicists in their planning appear optimistic and are very much dependent on priorities given to the development of fusion power, an option that may be essential for the World's future energy supply.

11. Conclusions and recommendations

Fusion is a truly sustainable energy source. The "fuel" is widely distributed on the Earth and sufficient to last for billions of years. But fusion energy will, according to present knowledge, not be available for many decades. More concerted scientific research and technology development on an international scale is required for fusion to become a cost-effective energy source in this century.

Research on fusion energy is, after the approval of the international ITER project, focusing on magnetic confinement. The profound experience gained up till now on tokamak research makes it possible to predict fairly well the performance of the ITER experiment. The R&D efforts on tokamak fusion are well defined and a road map with clearly given milestones is available. The next step after ITER will be a DEMO reactor, designed and built on the basis of experiences gained from the ITER experiment. The fusion physicists plan that a decision on a DEMO can be made already in 2020, only after a few years of experiments at ITER. This planning appears optimistic. After a satisfactory operation of a DEMO reactor, a first power-producing reactor can be designed and built. Such a power-producing reactor is expected to be ready for use around 2050. These estimates are however uncertain and made on the assumption that no major difficulties will be encountered.

Fusion reactors will have a power production capacity of 0.5-1 GWe i.e. similar as today's fission reactors.

Even if the track currently leads to tokamak reactors, it should not be excluded that other solutions, non-tokamak magnetic confinement, inertial fusion or tabletop fusion, may emerge in the quite long period during which magnetic confinement fusion is being developed.

Fusion has a potential of becoming a long-term environmental friendly and material efficient energy option. In view of its importance it is necessary that, besides the huge investments spent on the large international facilities, basic and applied research connected with fusion is supported at universities and national laboratories in order to exploit the emerging new knowledge.

Glossary (in order of appearance)

DT reaction	Fusion of deuterium and tritium results in helium-4 ions (alpha particles) and neutrons.
DD reaction	Fusion of deuterium and deuterium first results in two reactions of nearly equal probability. One yields tritons and protons, the other helium-3 ions and neutrons. The tritons then burn with the deuterium into helium-4 ions and neutrons, whereas the helium-3 ions burn with the deuterium to helium-4 ions and protons.
D-He^3 reaction	Fusion of deuterium and helium-3 results in helium-4 ions and protons.
H-B reaction	Fusion of hydrogen and boron results in helium-4 and beryllium ions.
Li-n reaction	Bombardment of a mantle of lithium with neutrons results in helium-4 ions and tritons.
Q	Efficiency of a fusion experiment is defined as the ratio between the equivalent (calculated) fusion power and the externally imposed auxiliary heating power being required to sustain the hot plasma.
Breakeven	The marginal case Q=1, the fusion power equals the supplied power.
Ignition	The marginal state in which the heating by produced alpha particles in DT fusion sustains the hot plasma.
GWe and GWth	Giga watt, electric and thermal, respectively.
JET	Joint European Torus, EURATOM's facility in Culham, UK.
TFTR	Tokamak Fusion Test Reactor experiment (Princeton, USA).
DIII-D	Doublet 3D (San Diego, USA).
JT60-U	Japan Tokamak Upgrade.
ITER	International Thermonuclear Experimental Reactor.
ESFRI	European Strategy Forum on Research Infrastructures.
HiPER	High Power Experimental Research facility.

DEMO	Demonstration reactor, power producing prototype to be built after results of ITER experiments have been acquired and analysed.
IFMIF	International Fusion Materials Irradiation Facility.
Tokamak	In Russian: Toroidalnaya Kamera Magnitnaya Katushka (toroidal chamber and magnetic coil); the plasma is confined in a magnetic field which is partly generated by a toroidal coil, partly by the circulating electric plasma current.
Stellarator	A facility in which the magnetic field is generated exclusively by magnetic coils.
RFP	Reversed Field Pinch; similar to a tokamak, but with larger part of the magnetic field generated by plasma currents.
External costs	Costs inflicted to third parties caused by the activities of producers
Externalities	and consumers of energy. Can be effects on health and environment due to mining, material production, facility operation, emissions, and leakage of waste from storage sites.

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