Global co-operation in nuclear fusion: Record of steady progress

Working together to pool resources and expertise, countries are moving ahead to design an experimental fusion reactor

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Enough potential energy is locked in the earth's oceans to last millions of years. Their waters contain deuterium, a heavy isotope of hydrogen and the main fuel for a nuclear fusion reactor. Once extracted, the deuterium from just one litre of water could generate as much energy as the combustion of 300 litres of gasoline.

While it will take decades for the potential to become reality, important strides already have been made. Technological and scientific advances today are bringing the technology of nuclear fusion closer to demonstration. To a large extent, the progress in fusion research and development is driven by the world's growing energy needs, environmental concerns, and population trends.

Burning fossil fuels for energy and electricity production has its limits. Four factors in particular limit utilization:

- the human health effects of fossil fuel combustion (emphysema, cancer)
- the environmental effects (acid rain, greenhouse effect, etc.)
- the need to save hydrocarbons for convenient fuels and chemical feedstocks
- the finite reserves of fossil fuels (coal, oil, natural gas).

In estimating global energy supplies, the World Resources Institute (WRI) has placed the world's total proven energy *reserves* at about 3.5×10^{22} joules (J). Of the total, proven coal *reserves* are estimated to be about 2.44×10^{22} J; proven oil reserves about 0.56×10^{22} J; and proven natural gas reserves about 0.50×10^{22} J.

There are additional fossil fuels available called *resources*. They are more difficult to recover, however. Consequently their price will escalate significantly during the transition from the use of *reserves* to the use of *resources*.

In 1994, the world's rate of primary energy consumption was about 11.6 terawatts (TW), about 87% of which was from fossil fuels. At that rate of consumption, the world's fossil fuel reserves would last about 120 year. However, in spite of effective conservation measures, the energy consumption rate is growing, as developing nations improve their standards of living. At a growth rate of 2% in energy consumption per year, these reserves would last only 61 years.

In the coming decades, many new power plants will be required to increase the total capacity for meeting electricity demands, to replace ageing power plants, and to replace fossil fuel plants for reasons related to environmental, health, and cost concerns. Even under the most optimistic scenarios, researchers have projected a shortfall in energy supply by the year 2030 exceeding 5 TW. This is a staggering amount equivalent to 5000 power plants, each capable of generating 1000 megawatts of electricity. Major non-fossil sources of energy must be developed and deployed to provide more than 10% of the world's energy within the next 40 years.*

Most renewable energy sources — although making valuable contributions in specific situations — will be inadequate to produce the large quantities of electric power required. Three sources, however, can potentially meet world needs: solar, fission, and fusion. Each has advantages and disadvantages.

Solar energy is diffuse, intermittent, and not suitable for use in some climates, and it is usually expensive. Fission breeder reactors could extend the world's supply of fissile fuels, but they are not universally welcomed by the public. Fusion

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*See "The need for research and development in fusion: Economical energy for a sustainable future with low environmental impact", by B.G. Logan, L.J. Perkins, R.W. Moir, and D.D. Ryutuv, *Fusion Technology 28*, pgs. 236-239 (1995).

reactors could have many desirable features, but much more work is needed to bring them to fruition. If fusion reactors are successfully developed, as many believe they will be, they could significantly brighten the world's energy picture. *(See box.)*

It is also possible to develop a hybrid fusion-fission reactor by putting uranium in the blanket of a fusion reactor, in order to boost the power output and breed fissile fuel. Such a hybrid reactor could have economic advantages, but it would be more difficult to license because of safety, environmental, and security concerns.

The world needs to pursue nuclear power vigorously, to facilitate both the deployment of advanced fission reactors and then fusion reactors before shortages of fossil fuels cause an escalation of fuel prices. Moreover, the nuclear options will have an essential role in counteracting the threat of global climate change that is increasingly being recognized as a consequence of the use of fossil fuels. Fission power already is partially replacing some carbon-based fuels, and in the future fusion power could be even more attractive. For these reasons, fusion research and development is carried out worldwide in some 40 Member States of the IAEA. The work includes fusion safety studies to ensure that the potential safety and environmental advantages of fusion power will be realized.

For many reasons, global co-operation has characterized the research and development of nuclear fusion. The collaboration has moved from small experiments to the design of a large thermonuclear reactor. This article presents an overview of co-operative efforts and updates the status of current work.

Potential Positive Characteristics of Fusion Power

In terms of many energy and environmental issues, nuclear fusion has a number of attractive characteristics:

Fuel supply: Deuterium extraction from water without harmful by-products; available inexpensively to all countries. Enough deuterium in oceans to last millions of years.
Mining: Limited mining of lithium, used to breed tritium for fusion reactors. (Seawater also contains 0.17 ppm lithium.)
Environmental issues: Fusion is environmentally safe.
Nuclear weapons proliferation: No plutonium or uranium present.
Safety: The amount of fuel in the plasma is so small that even complete burnup would not cause an explosion. Heat removal is not difficult because of low level of decay heat, spread over a large volume. Tritium inventory can be minimized by careful design. Potential off-site radiation dose during accidents may be low enough that no evacuation plans are required.
Radioactive by-products: Generation of long-lived radioactivity in the structure can be minimized by careful choice of materials. The vanadium alloy, lithium coolant, and unburned deuteriuim-tritium fuel could be recycled.

A history of international co-operation

There are several reasons why global co-operation has been particularly valuable in fusion research. They include the need to pool expertise and share the cost of large projects; the desire to speed progress by sharing knowledge of plasma theory, experimental results, computer codes, materials properties, and technology developments; and the desire to help developing countries build up expertise in fusion physics and technology.

In the 1950s, nuclear fusion experiments were small, employed a few people, and cost on the order of a million US dollars. Nowadays, some of the experiments are much larger, they employ hundreds of highly-skilled people (who might not all be available in one country), and they can cost billions of dollars. There are also many small- and medium-scale fusion experiments that provide valuable contributions to the worldwide effort.

Nevertheless, because of the potential importance of fusion power in the future, countries also require strong domestic fusion programmes, so that the science and technology results flowing from international collaboration can be applied at home. While most fusion research is at a pre-competitive stage, there are technical areas where the protection of intellectual property of contributing countries is necessary, and this requirement must be respected in establishing collaborative arrangements. There is also some concern about sharing technology that could have possible military applications, such as inertial confinement fusion.

In the early 1950s nuclear fusion research began independently in several countries, cloaked in military secrecy. Magnetic pinches, mirrors, and toroidal devices were studied, and some neutrons were observed. There was optimism of "fusion power within 20 years." Then the initial optimism was tempered by the realization that the neutrons were not from thermonuclear reactions and that plasma instabilities were spoiling confinement. A better understanding of plasma behaviour would be required, and could be facilitated by sharing results with other countries.

The Soviet Union led the way in 1956 by sharing its fusion research results with Western countries. The first major international co-operation occurred at the Geneva Conference on Peaceful Uses of Atomic Energy in 1958. In that same year, the IAEA began its operations. The first IAEA Conference on Plasma Physics and Controlled Thermonuclear Research was held in Salzburg in 1961, and today this meeting (now renamed the "IAEA Fusion Energy Conference") is held at 2-year intervals. In 1972, the IAEA established the International Fusion Research Council (IFRC), which advises the Agency on its wide scope of fusion research activities.

In parallel with the Agency's activities, many bilateral and multilateral agreements for collaboration in fusion research have developed among countries over the years. Historically, such agreements were often the first steps in bringing new players into international fusion co-operative work. In other cases, they have proved particularly useful when a high level of mutual collaboration is envisaged in specific work areas. Examples of such collaboration are the participation of Japan in the US Tritium Systems Test Assembly and Doublet-III projects, and the participation of Canada in ITER through agreements with the European Union.

The International Energy Agency (IEA), part of the Organization for Economic Co-operation and Development, was formed by the Western industrialized countries in the 1970s as a response to the oil price shocks of 1973. The IEA covers all areas of energy R&D including fusion, while its sister organization, the Nuclear Energy Agency, covers areas of fission.

IEA collaboration is organized by means of implementing agreements with annexes referring to specific work areas. In principle, any IEA member country can participate in any of these agreements by sharing in associated costs as a Contracting Party; other, non-member countries can now also join as Associate Contracting Parties, as Russia has done with a number of the fusion agreements. Currently, there are active implementing agreements covering large tokamaks; TEXTOR; ASDEX-upgrade; stellarators; reversed field pinches; fusion materials; fusion nuclear technology; and the environmental, safety and economic aspects of fusion power.

These activities are overseen by the Fusion Power Co-ordinating Committee, which is the IEA counterpart of the IFRC, and the two committees have several members in common. In recent years increasing efforts have been made through these oversight committees to co-ordinate the fusion activities of the two agencies, in order to avoid overlap and duplication.

Origins of the ITER project

In 1978, the IAEA organized the International Tokamak Reactor (INTOR) workshop to define the next major experimental tokamak, as recommended by the IFRC. This work assembled information on plasma behaviour, cross sections, and materials properties, produced a reference reactor design, and defined the key issues to be resolved. The results were documented in a series of IAEA reports issued from 1982-88.

The success of INTOR in demonstrating the feasibility of sustained technical collaboration was one factor that influenced the subsequent establishment of the International Thermonuclear Experimental Reactor (ITER) project. *(See figure, next page.)* An additional factor was the G-7 ("Western Economic Summit") meetings that had identified fusion as one of the areas with potential for increased economic growth by mutual co-operation. These and other factors provided a fertile background to the immediate political impetus for the ITER project, which was proposed by General Secretary Gorbachev (USSR) to President Mitterand (France), and then to President Reagan (USA) at their 1985 Geneva Summit Meeting.

Ultimately, in 1988, the ITER Conceptual Design Activity (CDA) was launched by four Parties: the European Community, Japan, the Soviet Union, and the USA, which all have major fusion research programmes. After completing the CDA, the four Parties agreed to proceed with the Engineering Design Activity (EDA) from 1992-98.

The Agency played a crucial enabling role in the inception of ITER, and it now provides the auspices for the four-Party collaboaration and certain facilitators, including administration of the ITER joint funds and co-ordination with pertinent technical work conducted by the Agency's Nuclear Data Section.

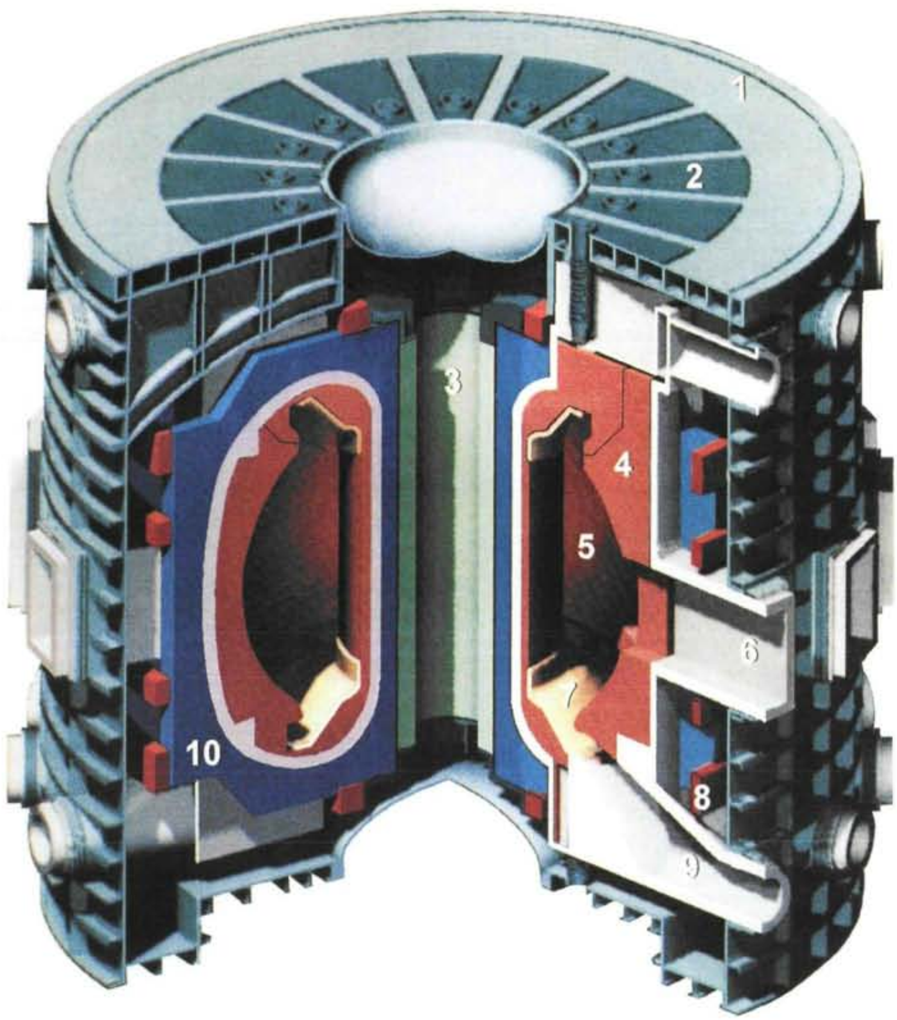
IAEA fusion-related activities

In addition to providing support to ITER, the IAEA has a variety of other activities that promote the development of international collaboration in nuclear fusion research. *(See box page 21.)* In essence, the IAEA is a major focal point for such multinational collaboration in fusion research.

The monthly journal *Nuclear Fusion* has been published since September 1960. The Agency's biennial conference, which covers a broad spectrum of topics in fusion research, typically has about 500 attendees. The IAEA Nuclear Data Section staff update the data libraries, distribute the new information to researchers

Renewed Consensus of ITER Council

Following three decades of steady progress in design and experiments, the four leading participants in world fusion research agreed in 1992 on the objectives and requirements of the optimum next step in the development of fusion as a source of energy. ITER was conceived as the project to achieve these objectives through the equal partnership of the four Parties. The width and depth of fundamental physics, technology, know-how, and research required to support ITER, as well as its cost, speak for this step to be undertaken through international cooperation. In July 1995, about halfway through the ITER Engineering Design Activities, a renewed consensus in the ITER Council reaffirmed that ITER is a necessary step; that its objectives remain attainable and must not be changed; that the design can meet the objectives; that the quadripartite co-operation has shown itself to be an efficient frame; and that the right time for such a step is now. The success of fusion worldwide depends on this step, and ITER should continue to benefit from full international co-operation, so that fusion physics and technological know-how can be focused and consolidated in support of ITER, making the optimum use of large but limited resources.



Computer-generated model of the International Thermonuclear Experimental Reactor (ITER), the fusion device that when built would be about 30 meters high. Shown are 1) the cryostat vacuum vessel; 2) vertical access port; 3) central solenoid; 4) blanket/shield; 5) plasma chamber; 6) port to provide access to plasma chamber; 7) divertor; 8) poloidal field magnet; 9) vacuum pump duct for exhaust; 10) toroidal field magnet.

around the world, and plan research to fill gaps in existing knowledge. The Atomic & Molecular and Plasma-Material Interaction data collected and evaluated by the IAEA are especially useful to the ITER project.

The IFRC provides liaison with member states, contacts with experts in various fusion research specialities, and guidance on planning the IAEA fusion research activities. The IFRC members are appointed by the IAEA Director General.

Some technical committee meetings are held annually, such as the one on research using small tokamaks. Others are held every two or three years, such as those on fusion reactor design and on fusion safety. Held less frequently are some technical committee meetings, as well as advisory group meetings, such as those on alpha particle physics and on H-mode physics.

Co-ordinated Research Programmes (CRP), which may last two to five years, lead to scientific reports summarizing the status of research in a particular field. There are usually several fusion-related CRPs in progress, each with five to 10 participants from both developed and developing Member States. The Agency's technical co-operation program further includes activities such as fellowships for scientists from developing countries to work in major laboratories. More requests are being sought from IAEA Member States to more fully make use of this programme in the fusion research field.

Status of the ITER engineering design

ITER's work and Joint Central Team (JCT) are spread among three electronically-connected Joint Working Sites: Garching, Germany, in the European Union (in-vessel components); Naka, in Ibaraki Prefecture, Japan (ex-vessel components); and San Diego, California, in the USA (design integration, environment, safety, and health). The formal seat of the supervisory ITER Council is in Moscow, Russia.

In addition, each of the four Parties has a Home Team that contributes to the design effort and undertakes the associated R&D tasks. The ITER Council, consisting of two representatives from each of the four Parties, governs the project and appoints the ITER Director, who manages the project. A Technical Advisory Committee, consisting of four leading scientific and technical persons from each party designated by the ITER Council, provides advice to the Council on all technical matters requested by the Council. A Management Advisory Committee, having three representatives designated by each Party, provides advice to the Council on management and administrative matters. This system, although complicated and spread around the globe, is working well.

The six-year ITER Engineering Design Activity involves *design* work with a total professional manpower of 1340 person-years plus basic technology and specific engineering research and development totaling US $750 million (in 1989 US dollars). The *ITER Interim Design Report, Cost Review and Safety Analysis* was prepared by the ITER JCT and accepted in July 1995 by the ITER Council for consideration by the ITER Parties. This report is supported by detailed technical documentation: the *Interim Design Report* and *Design Description Documents* totalling about 4350 pages and 1400 drawings.

In the early Spring of 1996 the IAEA will issue the *Interim Design Report* as a separate technical publication in the ITER Documentation Series. There is good progress towards resolution of most of the technical issues.

The construction phase of ITER is estimated to take about 10 years from the construction decision to the first plasma.

Prospects for future collaboration

In the field of nuclear fusion, there will still be major research projects conducted primarily by one party, but even those projects will employ some experts from other countries. Researchers around the world have learned to respect each other's unique skills and to appreciate the value of exchanging viewpoints. The ITER project has achieved great strides in international collaboration, demonstrating that the problems created by national interests and pride, geographical separation of research teams, and cultural differences can be successfully overcome. Thus, the ITER experience in the management of a large, multinational project could also be helpful to other projects in the future.

Since other potential new fusion devices, such as a 14-MeV neutron source for materials testing and a tokamak Demonstration Reactor, will be very expensive, it is probable those projects will also seek joint funding from several parties. Because of the worldwide political pressures to cut budgets, cost-sharing is encouraged for large fusion research projects.

Another beneficial aspect of international collaboration is the potential for increased participation in major projects by innovative scientists from developing countries. Bringing these scientists together to participate in a laboratory can serve to speed up progress in fusion research, in addition to helping the developing countries.

IAEA Activities Related to International Collaboration in Fusion Research

Publication of the monthly scientific journal *Nuclear Fusion* and its supplements, such as the *World Status of Activities in Controlled Fusion Research* (periodically) and *Atomic and Plasma-Material Interaction Data for Fusion* (annually)

Publication of the *International Bulletin on Atomic and Molecular Data for Fusion* (biannually), distributed to more than 800 institutions and researchers among Agency Member States.

Organization of the Biennial IAEA Fusion Energy Conference and publication of the conference proceedings

Development of libraries of nuclear data (such as FENDL), atomic & molecular data, and plasma-material interaction data that are relevant to fusion research. These data have been internationally recommended for use in fusion research and reactor design work. They are stored in the Agency's Nuclear Data Information System (NDIS) and Atomic and Molecular Data Information System (AMDIS), and are on-line accessible via Internet. The IAEA's International Nuclear Information System (INIS) also includes a fusion specialist.

International Fusion Research Council (IFRC)

Technical Committee Meetings (TCM) on relevant topics, such as:
- Research using small tokamaks
- Advances in computer modelling of fusion plasmas
- Alpha particle physics
- Steady state operation of tokamaks
- H-mode physics
- Fusion safety
- Fusion reactor design

Advisory Group Meetings (AGM)
- Third World Plasma Research
- Inertial Fusion Energy
- Technical Aspects of Atomic and Molecular Data Processing and Exchange

Co-ordinated Research Programmes (CRP), such as:
- Software development for numerical simulation and data processing
- Plasma heating and diagnostics systems in developing countries
- Lifetime prediction for a fusion reactor first wall
- Plasma-interaction induced erosion of fusion reactor materials
- Radiative cooling rates of fusion plasma impurities
- Reference data for thermomechanical properties of fusion reactor plasma facing materials
- Tritium retention and release from fusion reactor plasma facing components
- Atomic and plasma-wall interaction data for fusion reactor divertor modelling

Coordination of the activity of an International Atomic and Molecular Data Centre Network, comprising 15 national data centres.

Book, *Energy from Inertial Fusion (1995)*

Status Report on Controlled Thermonuclear Fusion, Executive Summary prepared by the IFRC on the current state of research around the world, Anniversary Issue of *Nuclear Fusion*, Vol.30, No. 9 (1990).

Technical Co-operation projects with developing countries, such as fellowships

Provision of auspices for the International Thermonuclear Experimental Reactor (ITER) Engineering Design Activity (EDA)

Industrial applications of plasmas are being commercialized around the world. These applications include plasma spray coatings, surface modification, synthesis of new materials, chemical reaction enhancement, and processing of chemical contaminants. The IAEA is starting a CRP to promote collaboration in this area.

The needs of the world fusion research programme include completion of the ITER project; an inertial fusion energy ignition experiment; alternative fusion concept research; development of fusion reactor materials (a powerful neutron source is required for irradiation testing); a strong plasma theory and simulation programme; and support for university research and graduate student education in plasma sciences and fusion technology. International collaboration can help fulfill most of these needs more efficiently than individual countries can on their own.

In summary, the world needs nuclear fusion research to provide a complementary energy source to solar energy and nuclear fission reactors. International collaboration can pool expertise and share the cost of large projects; accelerate progress by sharing knowledge; and help developing countries build their infrastructure in plasma sciences and fusion technology.

The IAEA, the IEA, and various bilateral agreements promote such collaboration. The IAEA is conducting a broad scope of activities, including its monthly journal; the biennial conference; atomic, molecular, and plasma-material-interaction data coordination; technical committee meetings; and Co-ordinated Research Programmes.

Over the past half century, the worldwide nuclear fusion research programme — from the first Soviet initiative through the IAEA activities to the ITER EDA — has become a premier example of scientific co-operation. It should serve to benefit all people, if fusion power plants are deployed to help meet the world's energy and electricity needs. ❒