Fusion Energy

For Peace and Sustainable Development

IAEA
International Atomic Energy Agency

Foreword

The International Atomic Energy Agency (IAEA) is dedicated to helping all countries benefit from the peaceful, safe, secure and sustainable use of nuclear science and technology in many fields, including energy production.

Fusion energy has the potential to become a virtually inexhaustible, safe, environmentally-friendly and universally-available energy source, capable of meeting global energy requirements.

Fusion energy has existed for billions of years shining benevolently upon the earth but mankind still has not managed to capture it in a controlled manner. To make fusion energy production a reality, enormous scientific and technical challenges still need to be overcome. The IAEA is leading international efforts to coordinate research in fusion technology by involving nuclear physicists, material scientists, nuclear data specialists, metallurgists, and plasma experts among others.

Since the early days of its inception, in 1957, the IAEA has supported nuclear fusion research. The IAEA Department of Nuclear Sciences and Applications and the Department of Nuclear Energy implement the IAEA's activities on nuclear fusion, under the guidance of the International Fusion Research Council, an IAEA advisory body with members from all parts of the world.

Big strides in understanding fusion energy science have been made. But more efforts with increased global collaboration, greater investment and coordinated research are required to make nuclear fusion energy production a reality. The IAEA continues to be at the forefront of these international efforts.

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Clean Energy through Fusion Technology: A Sun on Earth

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A ‘sunny day’ or a ‘sunny smile’ is always welcome by all of us! Apart from brightening up our days, many of us recognise that the ‘Sun’ is the basis of life on earth. The incessant emission of energy and light from the Sun with an unending stock of fuel engenders, without exception, curiosity in thinkers and scientists. This is what excites global interest in fusion technology.

Fusion energy is attracting a lot of attention as the world’s energy demands keep multiplying. The excessive dependence on fossil fuels and its impact on climate change due to carbon emissions are leading policy makers to consider fusion as a good option to explore.

Enhancing clean energy production through fusion technology

Through extensive exploration using various tools, logical reasoning and ingenuity, scientists have proven that a seemingly simple combination of the nuclei of two very light atoms (tritium and deuterium — both heavier isotopes of hydrogen) spews out enormous amounts of energy. Such fusion of nuclei — or ‘nuclear fusion’ — has been a topic of great interest and intensive research since the 1920’s.

It is mind-boggling that the deuterium contained in 0.5 litre of ordinary water can provide enough energy for a single family house in Europe for a year, when properly fused with tritium in a fusion reactor.

But despite the apparent simplicity, harnessing commercially-viable fusion power is a very challenging endeavour, although fusion reactions have been successful during experiments and the technologies are continually evolving to address the challenges.

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The difficulties facing fusion technology

Making commercially-viable fusion power a reality is fraught with serious technological challenges such as the ability to create an environment similar to that of the sun. This means reaching temperatures exceeding 100 million degrees Celsius and confining the fusion fuel to the vessel within the reactor. Additionally, finding the right material to construct the fusion reactor, and developing the mechanism that will be used to extract the enormous energy/heat that is emitted, are among the other major challenges in the quest to produce electricity from fusion.

Making progress through international collaboration

To scientists, it was clear from the very beginning that success in using fusion technology would require international cooperation. At the second UN Conference on the “Peaceful Uses of Atomic Energy” in Geneva in 1958, discussion on nuclear fusion led to the newly created International Atomic Energy Agency being entrusted with the responsibility to lead the global collaboration. Five decades later the IAEA remains the natural home for fostering international collaboration in fusion research and development (R&D) through facilitating exchange of scientific and technical information. Supported by the dedicated community of fusion researchers in the Member States, the Nuclear Fusion Journal was set up in 1960 by the IAEA to disseminate knowledge in this niche area of science. Today the journal is considered the main source of information about advances in nuclear fusion.

Since 1961 the IAEA has also been organizing **‘Fusion Energy Conferences’** (initially named Conference on Plasma Physics and Controlled Nuclear Fusion Research) to enable the dedicated fusion research professionals to periodically discuss developments and achievements.

An International Fusion Research Council was also established in 1971 to advise and provide guidelines to the IAEA Secretariat on matters relating to the Fusion R&D programme.

The fusion research community and the IAEA continue interacting closely on the development and evaluation of fusion-relevant basic data for nuclear, atomic and molecular interaction processes in fusion.

The signing of the Agreement that established the ITER Organization.
(Photo: IAEA)

The Sun.
(Photo: NASA)

IAEA’s role in international fusion endeavours

The impetus for the establishment of the international organization for fusion energy, **ITER** (International Thermonuclear Experimental Reactor) in 2006 came from discussions in IAEA fora that covered several initiatives for collaboration on an international fusion facility. The IAEA Director General is the depository of the ITER Agreement.

ITER, under construction in Cadarache, France, is the largest global scientific collaboration aimed at demonstrating the scientific and technological feasibility of fusion energy production.

Currently 35 countries are involved in the ITER project. In addition, individual countries are engaged in research for fusion to become a future source of energy. There is a growing expectation, especially in the fusion community that ‘fusion electricity’ would light the bulbs of their homes soon. While science and technology issues for fusion power are broadly agreed upon, the next steps to upscale the technology to practical use are still some distance away. Here, the IAEA plays a crucial role in bringing together all the Member States interested in fusion energy through the demonstration fusion power plant **(DEMO) Programme Workshops**. This workshop aimed to help experts define the facilities and activities that can lead to the resolution of some of the key scientific and technological challenges to developing a DEMO. Such DEMO would show that controlled nuclear fusion can generate net electrical power and mark the final step before the construction of a commercial fusion power plant.

The scientific community recognises that the realisation of fusion power reactors would be a landmark achievement, taking nuclear science and technology to another level.

Status of the ITER construction site as of 2018.
(Photo ITER Organization)

Nuclear Fusion: The Key to a Sustainable Planet

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Providing energy from nuclear fusion is widely regarded as the grand engineering challenge of the twenty-first century. Many researchers all over the world focus on ways of producing energy by recreating an artificial star on Earth.

Stars burning hydrogen in a fusion way. Life on Earth would not be possible without the nuclear fusion reactions that power our Sun. *(Photo NASA).*

Unlike fission, where the atom is split to produce energy, in fusion two lighter nuclei are joined together to make a heavier nucleus, while energy is released. This is how stars convert tiny amounts of mass into vast amounts of energy (in line with to Einstein’s famous equation $E=mc^2$). Life on Earth would not be possible without the nuclear fusion reactions that power our Sun.

Nuclear fusion. Two lighter nuclei are joined together to make a heavier nucleus, while energy is released.
(Photo IAEA).

Burning Hydrogen

The most convenient fusion process involves two isotopes of hydrogen: deuterium (heavy hydrogen) and tritium (super heavy hydrogen). This reaction, which is also the easiest to perform because it requires the lowest investment in terms of power supplied, yields a helium nucleus and a neutron, whose energies can be harvested for powering the reactor and producing electricity, respectively.

Hydrogen atom and its isotopes. The most convenient fusion process involves two isotopes of hydrogen deuterium (heavy hydrogen) and tritium (super heavy hydrogen).
(Photo IAEA).

Tapping the Energy

At the core of the stars, fusion reactions between hydrogen atoms take place within dense plasma with temperatures exceeding 10 million °C. Plasma is a “fourth state of matter” with unique properties, distinct from solids, liquids and gases. It consists of freely moving charged particles and is formed at high temperatures when electrons are stripped from neutral atoms. More than 99 percent of the universe as we currently understand it exists as plasma, including interstellar matter, stars and the Sun.

In a controlled nuclear fusion power plant, three conditions must be fulfilled:

- very high temperature (more than 10 times hotter than at the centre of the Sun, hence exceeding 100 million °C) to provoke highly energetic collisions at extreme speed;
- sufficient particle density in the plasma – where the reaction takes place – to increase the probability of collisions;
- sufficient confinement to hold the plasma and allow the fusion reactions to take place continuously.

The most performing confinement concept to date has been the tokamak, a doughnut shaped configuration first invented in the 1950s, which uses powerful magnets to confine the plasma. However, in recent years there has been a renewed enthusiasm for stellarators, and the world’s largest one has been operating in Germany since 2015. The tokamak is better at keeping the plasma hot while the stellarator is inherently stable and able to operate the plasma in a steady state. By now, these machines can provide the essential conditions for fusion, in terms of both plasma density and the required temperature, and fusion power can be generated. The missing piece to producing net power remains better confinement, which is a measure of how good the magnetic field is at keeping the plasma energy, for which a bigger reactor is needed.

Wendelstein 7-X

Wendelstein 7-X in Germany is the world’s largest fusion device of the stellarator type. Its objective is to investigate the suitability of this type for a power plant. As a result, a record value for stellarators fusion triple product (a plasma's particle density, energy confinement time, and ion temperature) was achieved in 2018.

Tokamak (left) vs Stellarator (right). The tokamak is better at keeping the plasma hot, while the stellarator is inherently stable and able to operate the plasma in a steady state.

ITER – the Way to New Energy

ITER will be the largest tokamak ever built, two times bigger than the largest tokamaks operating today, and it has been designed for demonstrating the feasibility of fusion energy for peaceful purposes. With ITER construction, the focus of nuclear fusion science is slowly shifting from pure research to technology, material science and engineering. It is expected that ITER will start operating in 2025. However, it is important to note that it is not part of ITER’s mission to convert energy into electricity and transmit it to the electricity grid.

Wendelstein 7-X.
(Photo IPP).

ITER design. This machine has been designed for demonstrating the feasibility of fusion energy for peaceful purposes.
(Photo ITER Organization)

DEMO – Putting the Power into the Grid

Depiction of a DEMO.
(Photo Eurofusion)

The technological challenges of bringing fusion power to the electricity grid will be addressed by a demonstration fusion power plant (DEMO)-type reactor. Individual countries are exploring ways to do this, and the IAEA is providing a platform for information exchange in order to facilitate research and technology development. DEMO is the machine that would explore continuous or near-continuous (steady-state) operation, tritium fuel self-sufficiency, and the large-scale production of energy and its conversion to electricity. This would represent the next stage after ITER.

China has made significant progress in planning for a device called China Fusion Engineering Test Reactor (CFETR) that would bridge the gap between ITER and DEMO. Construction of the CFETR could start in 2020 and be followed by construction of a DEMO in the 2030s.

The **European Union** and **Japan** are jointly building a powerful tokamak called JT-60SA in Naka, Japan, as a complement to ITER in the framework of a partnership called the Broader Approach Activities. In addition to constructing the JT-60SA, the joint programme consists of two other projects, the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA), and the International Fusion Energy Research Centre (IFERC). This partnership represents a well-integrated approach to support ITER and to prepare to undertake the engineering design and construction of a subsequent DEMO.

India has announced plans to begin building a device called SST-2 to develop components for a DEMO around 2027, and then start construction of a DEMO in 2037.

South Korea initiated a conceptual design study for a K-DEMO in 2012 targeting the construction by 2037 with potential for electricity generation starting in 2050. In its first phase (2037-2050), K-DEMO will develop and test components and then utilize these components in the second phase after 2050 to demonstrate net electricity generation.

Russia plans the development of a fusion-fission hybrid facility called DEMO Fusion Neutron Source (FNS), a reactor that would harvest the fusion-produced neutrons to turn uranium into nuclear fuel and destroy radioactive waste. The DEMO-FNS is planned to be built by 2023, and is part of Russia's fast-track strategy to a fusion power plant by 2050.

The United States of America is considering an intermediate step called Fusion Nuclear Science Facility (FNSF) to be used for the development and testing of fusion materials and components for a DEMO-type reactor. Plans call for operation to start after 2030, and construction of a DEMO after 2050.

Fusion as a Sustainable Energy Source

Although much remains to be done to reach commercial electrical power, nuclear fusion is one of a very few sustainable options to replace fossil fuels as the world's primary energy source. Fusion fuel – produced from water and lithium – is in principle so abundant that fusion energy would be inexhaustible and deployable everywhere on the planet. Hence, fusion could guarantee nearly unlimited energy and security of supply at no expense to the environment. In addition, fusion has the potential to be a large baseload source of electricity with a carbon-free footprint, and with no high level radioactive waste. Finally, fusion is an inherently safe process that can be stopped at any moment simply by turning the power off.

Fusion power bears the promise of:

- clean energy production and transmission;
- proliferation-resistant fuel cycle that does not generate high level radioactive waste;
- power plants with inherently safe technology features;
- abundant and inexpensive fuel readily available to all nations.

Big strides in understanding fusion energy science have been made, but more efforts with increased international collaboration, greater investment and coordinated research are necessary to make nuclear fusion energy production a reality.

Sustainable Development Goals 7 and 13. Ensure access to affordable, reliable, sustainable and modern energy for all. Fusion energy can contribute to improving energy security, redcing environmental and health impacts, and mitigating climate change.
(Photo: United Nations)

IAEA’s Coordinated Research Projects: Sharing Knowledge and Training through Global Partnership

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Building and maintaining partnerships with experts in Member States are key IAEA activities. Global cooperation is essential for the ultimate success of fusion energy. Through the framework of its Coordinated Research Projects (CRPs), the IAEA acts as a communication facilitator by bringing scientists and experts from many countries together to exchange information, identify critical issues and transfer specific knowledge for nuclear fusion development projects.

With a long history of working together under IAEA coordination, around 70 Member States are involved in plasma physics and fusion technology. The cooperation among laboratories and facilities contributes significantly to the development of fusion research and technology, and the formulation of the necessary guidelines and related standards. It also provides the groundwork needed for training the new generation of scientists and engineers in fusion, and for developing the diagnostics and technology of next step fusion devices such as ITER and DEMO.

Sustainable Development Goal 17. Global partnership for sustainable development. IAEA Member States share knowledge, technologies and best practices through Coordinated Research Projects.
(Photo: United Nations)

Network of Small and Medium Size Magnetic Confinement Fusion Devices

An excellent example for this long-lasting partnership is the IAEA CRP on ‘Network of Small and Medium Size Magnetic Confinement Fusion Devices for Fusion Research’ — a continuation of former highly successful IAEA activities on small-medium size tokamaks, supported since 2004. Currently, around 40 small-medium size devices (tokamak and stellarators) are operational in 15 Member States.

Researchers working with the small and medium-size devices are already making significant contributions toward achieving controlled fusion energy: the potential impact of tighter collaborations between them are even more significant.

With the next generation of large-scale fusion devices — such as ITER in France — preparing for action, the laboratories with small and medium-size devices could help push the research agenda forward. By establishing and sustaining a network of laboratories that will perform joint and comparative experiments, train

Picture of the vessel of a toroidal magnetic confinement fusion device – COMPASS tokamak.
(Photo IAEA).

personnel across institutions and Member States, and educate a new generation of fusion scientists in cutting-edge technologies, this CRP advances fusion research by building strong ties between research groups and training future fusion experts.

The specific research objectives of this CRP are to:

- publish results from coordinated and joint experiments on turbulence and transport, the role of electric fields, and possible mechanisms of turbulence self-regulation;
- develop new computational techniques for modelling plasma processes, particularly for real time analysis requiring high-data volume processing;
- develop prototypes and models for new advanced diagnostics;
- promote mobility and training of fusion researchers.

Small and medium-size fusion devices can contribute to making significant improvements towards the scaling-up to larger fusion machines.
(Photo IAEA and Eurofusion).

Development of Steady-State Compact Fusion Neutron Sources

Fusion neutron sources have many important practical uses, such as assisting fission reactions, manufacturing medical isotopes, testing materials and components for use in future fusion reactors, and facilitating the production of various isotopes like tritium. All these applications could be improved by achieving higher Compact Fusion Neutron Sources (CFNS) energy levels.

Earlier projects investigated a wide range of power options for CFNS, and confirmed that the potential for significantly higher intensities and fluxes is achievable in the near future.

This CRP aims to demonstrate that even higher ranges of energy for CFNS are feasible, and to support the transition from conceptual to engineering design activities for those compact fusion neutron sources that fit within the scope of the energy levels the project deals with.

The specific research objectives of this CRP are to:

- produce a detailed and substantiated overview of applications of CFNS with currently feasible parameters in the fusion and fission areas as well as in any other potential field;
- define R&D programmes that can support the transition to engineering design;
- perform a comprehensive safety analysis for proposed CFNS;
- obtain results of joint activities on design, simulations, and experiments pertinent to the development of a scientific and technological basis for CFNS;
- create simulation and modelling tools;
- gather input from stakeholders related to design activities for CFNS.

Illustration of a fusion neutron source based on magnetic mirror – Gas Dynamic Trap.
(Photo IAEA)

Standardization of Small Specimen Test Techniques

Structural materials development and research on materials suitable for the extreme conditions in a fusion reactor are needed to achieve safety and efficiency of future fusion power plants. Fusion materials development will depend on the progress made in irradiation physics and fusion materials research.

The CRP *Towards the Standardization of Small Specimen Test Techniques for Fusion Applications* addresses the issues of limited testing volume with needed neutron fluxes in accelerator-driven fusion-relevant neutron sources. This CRP coordinates the production of guidelines based on best practices on main test techniques for reference structural fusion materials (tensile, creep, low cycle fatigue, fracture toughness, fatigue crack growth rate). These guidelines should be the first step towards a full standardization of the standard specimen test techniques.

The specific research objectives of this CRP are to:

- analyse the data available on Small Specimen Test Techniques (SSTT) focusing on fusion structural reference materials (RAFM steels) and produce a comprehensive reference database;
- establish reference guidelines for tensile tests using small specimens for the selected materials;
- establish reference guidelines for creep tests, low cycle fatigue tests, fracture toughness tests and fatigue crack growth rate using small specimens for the selected materials;
- define meaningful round robin tests for establishing best practices in the field;
- define the SSTT to be used for characterization of irradiate materials in dedicated fusion neuron sources;
- establish guidelines for common practice in the use of SSTT.

The Bridge of Knowledge

For the more than 120 IAEA Member States that are not part of the ITER Organization, the IAEA performs an important bridging function, disseminating knowledge from ITER to the wider community and vice-versa, providing a platform for both the scaling up to larger fusion machines and for exchange between ITER and the rest of the world.

ITER made of Lego.

(Photo Sculpture by Sachiko Akinaga; photograph by Hironobu Maeda).

The Challenges of Controlled Nuclear Fusion

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The development of commercially-viable fusion power faces serious technological challenges, the most challenging of which are:

- achieving and sustaining temperatures in excess of 100 million °C, whilst confining the hot fusion plasma to the reactor vessel;
- finding the right material from which to construct the fusion reactor vessel;
- developing the technology to breed the tritium component of the fusion fuel from the neutrons released in an ongoing reaction; and
- designing the mechanism that will be used to extract the enormous amount of energy that is produced and convert it to electricity.

Plasma Confinement

In a fusion process, the high-temperature plasma must be confined for long enough for the fuel nuclei to combine. In the Sun, the pressure caused by the hydrogen fusion is balanced by the inward-acting force of gravity to keep the solar core in equilibrium, but this force is far too weak to provide the necessary confinement on the scale of an Earth-based reactor. Instead, most concepts for fusion reactors are based on magnetic confinement: since the nuclei and electrons are charged, they can be deflected by a magnetic field. In the most common design of magnetic confinement device, the tokamak, magnetic fields are used to drive the plasma around a torus-shaped reaction chamber and keep it from getting too close to the reactor's "first wall" which they would otherwise damage.

However, the plasma confinement is never perfect and periodically instabilities arise, which send plumes of hot plasma into the reactor wall, reducing its lifetime. Research is ongoing to better understand, model and mitigate these instabilities: the reactor components must survive long enough before they need to be replaced for the reactor to produce energy on a commercial basis.

A further concern is the construction and operation of the large, superconducting electromagnets required to create the magnetic fields. These are expensive, heavy and consume a large amount of energy themselves. They operate only at very low temperatures (-270 °C, just 4°C above absolute zero), but in close proximity to the hot plasma (>100 million °C), which creates the largest known temperature gradient in the entire universe.

The ITER Tokamak will rely on three sources of external heating to bring the plasma to the temperature necessary for fusion: neutral beam injection and two sources of high-frequency electromagnetic waves (ion and electron cyclotron heating).

(Photo: ITER Organization)

Heating and Fuelling the Plasma

Before fusion can occur, a stable, high-temperature plasma of deuterium and tritium must be created. The magnetic field driving the plasma particles in a current around a tokamak creates some of this heating through (non-fusion) collisions but to reach the very highest temperatures required additional heating is necessary. This is provided through high-frequency electromagnetic radiation (analogous to the heating brought about in a microwave) and through neutral-beam injection: a high-speed beam of particles (which must be uncharged to penetrate the magnetic field) is fired into the plasma where it transfers its energy through collisions.

Alongside the processes which heat the plasma, impurities can lead to it cooling through unwanted collisions and the emission of light.

The deuterium-tritium fusion process requires tritium as a component of its fuel. Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years and does not occur naturally in any significant quantities. However, it can be formed (“bred”) in a nuclear reaction by neutron activation of ^{6}Li, an isotope of lithium:

$${}^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He}$$

The proposed approach is to surround the reactor with a “blanket” of a lithium-containing material which would slow down and capture some of the neutrons produced by the fusion reaction to breed the tritium fuel. The ^{6}Li reaction also releases energy and so can contribute to the reactor’s power output.

Reactor Materials

The development of suitable materials from which a nuclear fusion reactor can be constructed is the subject of ongoing research. Such materials should have the following properties for a reactor to be viable:

- a high melting point and conductivity, and resilience with respect to damage through exposure to the high-energy plasma particles;
- a low propensity to become activated (become radioactive) through bombardment by the high-energy neutrons produced by the fusion reaction;
- a low tendency to absorb tritium: as well as reducing the amount available as fuel, the retention of tritium creates radioactive waste, which would require special handling when decommissioning the reactor material.

The last property all but rules out the use of carbon-based materials as a plasma-facing component. ITER will use a beryllium and tungsten; it is anticipated that DEMO will employ “reduced-activation steel” and tungsten.

The IAEA’s Atomic and Molecular Data (AMD) Unit: Activities in Support of Fusion

The AMD Unit helps address the challenges of developing controlled nuclear fusion by:

- providing a trusted and permanent repository of fundamental data;
- bringing together experts to evaluate such data and carry out research through the IAEA’s Coordinated Research Project (CRP) programme;
- providing a platform on which non-experts can become involved in research and data analysis through crowdsourcing activities.

Some of the activities in support of fusion over the last 10 years are described below.

The Characterization of Size, Composition and Origins of Dust in Fusion Devices

Depending on the material used in their plasma-facing components, tokamaks can produce a significant amount of dust from erosion of the reactor components. This dust can retain tritium, lead to impurities in the fusion plasma and create a health hazard for workers exposed to it during reactor maintenance. This CRP addressed the data needs relating to such dust and created a database of dust properties for regulatory and other analysis.

Fundamental Data for Modelling Collisional Processes Involving Isotopes of Hydrogen and Helium in Fusion Plasmas

These species are the principal components of a fusion plasma, and, away from the core plasma where the temperature is lower, they exist in many different excited atomic and molecular states which are interchanged through collisions. This CRP provided evaluated data to better model the physics of these collisional processes and provide input for tokamak design and operation.

CRPs on plasma-wall interactions

Beryllium, tungsten and steel are all candidate materials for plasma-facing components in experimental fusion reactors. However, too little is known about their behaviour under the extreme conditions they are exposed to. The following projects coordinated international experimental and theoretical research into the properties of these materials:

Data for Erosion and Tritium Retention in Beryllium Plasma-Facing Materials

Beryllium is an attractive material to use in experimental reactors as it conducts heat well, does not create much dust or cool the plasma much when it acts as an impurity and does not become radioactive through interactions with neutrons. The JET and ITER tokamaks use beryllium as the major component of their first reactor walls. This CRP provided evaluated data on the interactions of beryllium with plasma particles to further assess its suitability and inform the simulation of these and other tokamaks.

Plasma-Wall Interaction with Irradiated Tungsten and Tungsten Alloys in Fusion Devices

Tungsten is another widely-used material in tokamaks, used in the divertor component of JET and ITER, which is exposed to some of the highest heat loads in the reactor. This CRP brought together over 20 research groups from around the world to coordinate research into how the properties of tungsten are altered in the intense radiation environment of a fusion reactor. For example, pure, undamaged tungsten has little tendency to absorb hydrogen (and hence the tritium fuel of the fusion reaction), but bombardment by neutrons and other energetic particles creates cracks, bubbles and voids that increase its propensity to do so. This behaviour must be understood to make confident predictions about the suitability of tungsten in a future commercial reactor.

Plasma-wall Interaction with Reduced-activation Steel Surfaces in Fusion Devices

Steel is considered to be a candidate plasma-facing material for the planned DEMO Demonstration Power Station which, it is proposed, will follow ITER as a prototype commercial fusion power plant. Steel does not cool the fusion plasma as much as tungsten when it acts as an impurity and is less toxic and less prone to erosion than beryllium. However, its composition must be carefully controlled to exclude nuclei which become radioactive under exposure to the fusion neutrons. This ongoing CRP brings together experts to compare different candidate steels under suitably-chosen conditions with respect to their resistance to erosion and hydrogen retention.

Data for Atomic Processes of Neutral Beams in Fusion Plasma

As described above, neutral beam injection is a method for heating and providing diagnostics on fusion plasmas in tokamaks. This ongoing CRP brings together experts in fundamental atomic data with modellers of neutral beam physics to validate their simulation codes and fill gaps in the community's necessary

Carbon composites, beryllium and tungsten are considered as candidate materials for next step fusion devices.
(Photo: ITER Organization)

knowledge base. This will help researchers to better understand the collisional processes involved and thereby improve the technology and accuracy of data analysis.

Databases and Data Evaluation

The AMD Unit is responsible for the long-term management of several databases of fundamental atomic and molecular properties, including ALADDIN (a searchable repository of evaluated collisional data for fusion-relevant processes), and AMBDAS (a bibliographic database); both are widely used in the research community and recognised for their permanence, authority and accessibility.

The Unit’s databases are continuously improved and expanded through Technical Meetings on specific data needs of the fusion community, the quantification and implication of uncertainties in data and on techniques for data validation, curation and dissemination.

Crowdsourcing “Challenges”

The Unit has recently run a successful crowdsourcing “challenge” project inviting non-specialist data scientists to analyse simulations of neutron radiation damage in materials for fusion reactors in order to better understand, classify and predict their behaviour. Since, with rare exceptions, it is prohibitively expensive to conduct actual experiments on the irradiation of materials by high-energy neutrons, researchers have developed virtual, computer-based “molecular dynamics” simulations of the processes that occur following the impact of a neutron on an atom in a solid crystal. The energy of a single fusion neutron is so great that the material locally melts and then resolidifies, leaving many atoms displaced from their original locations. This results in material damage, including dislocations and clusters of vacancies and interstitial atoms in the initially perfect crystal lattice. Such damage needs to be understood, since it weakens the material and increases its propensity to absorb the valuable tritium fuel.

The computer simulations can be run repeatedly for different materials, and impact energies and directions, yielding a large number of virtual crystal configurations. The challenge set to subscribers to this exercise was to produce software that analyses these configurations to identify and visualise their important features. In this way, the algorithms produced will help identify candidate materials with the desired properties for use in an economically-viable nuclear fusion power reactor.

A visualization of the “collisional cascade” resulting from the impact of a high-energy neutron on an atom of tungsten in a crystal.
(Photo: Andrea Sand, University of Helsinki)

Widening Awareness of Fusion Science and Technology: IAEA Publications

Sophia Le Masurier, IAEA Division of Conference and Document Services

The IAEA's publishing activities have played a significant role in the dissemination of information to its Member States. The first technical books were issued in 1958 and, since then, the IAEA has established itself as a leading publisher in the nuclear field. It now publishes over 100 titles annually, ranging from case studies to international safety standards.

In the area of fusion, and in tandem with the IAEA's technical activities, the publishing activities have supported Member States engaged in the field of plasma physics and fusion technology in the following ways: dissemination of research results; assistance and information provision to researchers; facilitation of international collaborative activities such as ITER; documentation arising from technical meetings, workshops and conferences; and the provision of educational resources, including textbooks and training courses. The publications offer an unbiased and authoritative source of information. They are driven by developments in the field and by the changing needs of Member States.

Dissemination of Research

Nuclear Fusion

One of the most important contributions that the IAEA's publishing activities make in support of fusion research is the provision of a high quality, peer reviewed forum. The journal Nuclear Fusion was launched in 1960. It is now the most frequently cited journal in the field. Nuclear Fusion is steered by an international board of eminent scientists, who give direction on content and policy. It facilitates communication between research groups worldwide, disseminating results and concepts and aiding collaboration. The journal now regularly receives submissions from over 30 countries and its geographical balance reflects the significant body of work being done globally in fusion. Every major advance in fusion has been reflected in the journal's published articles.

Conference material

The IAEA has an active programme of conferences the results of which are captured in published proceedings, summary reports or in online collections.

Papers from the flagship biennial IAEA Fusion Energy Conference have been published in various forms, and create an ongoing record of research progress. Currently, the overview papers from this conference are collected in a special issue of the journal, Nuclear Fusion. Many of the contributed papers are also submitted to the journal for publication, and are indexed accordingly.

Coordinated research projects and workshops

The results of IAEA coordinated research projects and other technical activities are presented in a variety of IAEA publications. These would include the Atomic and Plasma–Material Interaction Data publications and in the IAEA Technical Reports Series and Technical Document (TECDOC) Series.

Education

The IAEA has always assisted Member States' efforts in the arena of education, knowledge sharing and training by providing appropriate materials for researchers, students and educators. It has ensured the involvement of leading individuals in fusion and facilitated knowledge transfer. Published in 2012, the 1200 page graduate text, Fusion Physics, with its broad coverage of fusion topics, is an example.

International Collaboration

Arguably, the most strategic contribution of IAEA publications in fusion has been in support of large international projects. The global collaboration in fusion that became ITER was preceded by the experimental power reactor study, International Tokamak Reactor (INTOR), which had been pursued under the auspices of the IAEA. The IAEA published a series of publications arising from the

INTOR workshops. The IAEA has supported the ITER endeavour from its inception and through its founding as an independent international organization; and as part of this support has published a number of ITER-related publications. The importance of publications to the enterprise is indicated by the 2008 cooperation agreement between the two organizations which makes specific reference to, among other things, cooperation on publications.

Looking to the future, the IAEA will facilitate knowledge dissemination in relation to demonstration fusion power plants (DEMO) and beyond.

Responsive to Changing Requirements

The IAEA endeavours to ensure that its information provision is agile and highly responsive to the evolving needs of the user communities. The topicality of the publications in fusion complements on-going activities worldwide. For example, the scope of research papers published in the IAEA journal *Nuclear Fusion* has changed over time. Earlier articles concentrated on plasma physics and the necessary conditions for fusion. Later, discussion on engineering issues, machine concepts and the results from an increasing number of machines were published. Another example would be that throughout the years, IAEA activities, which result in special journal issues, proceedings volumes and technical reports, have always addressed issues of contemporary research interest. Current concerns on fusion materials, safety and technology have therefore resulted in various IAEA publications, such as TECDOC-1829 *Investigations of Materials under High Repetition and Intense Fusion Pulses*, and TECDOC *Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications*.

Impact

Whilst the impact of the IAEA’s contribution to knowledge dissemination through its fusion publications is difficult to quantify, measures such as the number of citations and the traffic to the online publications give an indication of worth and utility. There were nearly half a million downloads of *Nuclear Fusion* articles in 2017, and according to the 2017 Journal Citation Reports®, the journal achieved an impact factor of over 4 (the highest in the field). The book, *Fusion Physics*, remains among the most popular online IAEA books, accessed over 20000 times since its publication.

Through its publications, the IAEA provides continuity and an unbiased, international forum. With its close links with the fusion community, it ensures relevance and topicality of information.

Fusion Portal

For further information regarding the IAEA fusion activities and to access all the news and publications, please visit the IAEA Fusion Portal: https://nucleus.iaea.org/sites/fusionportal.

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