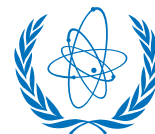


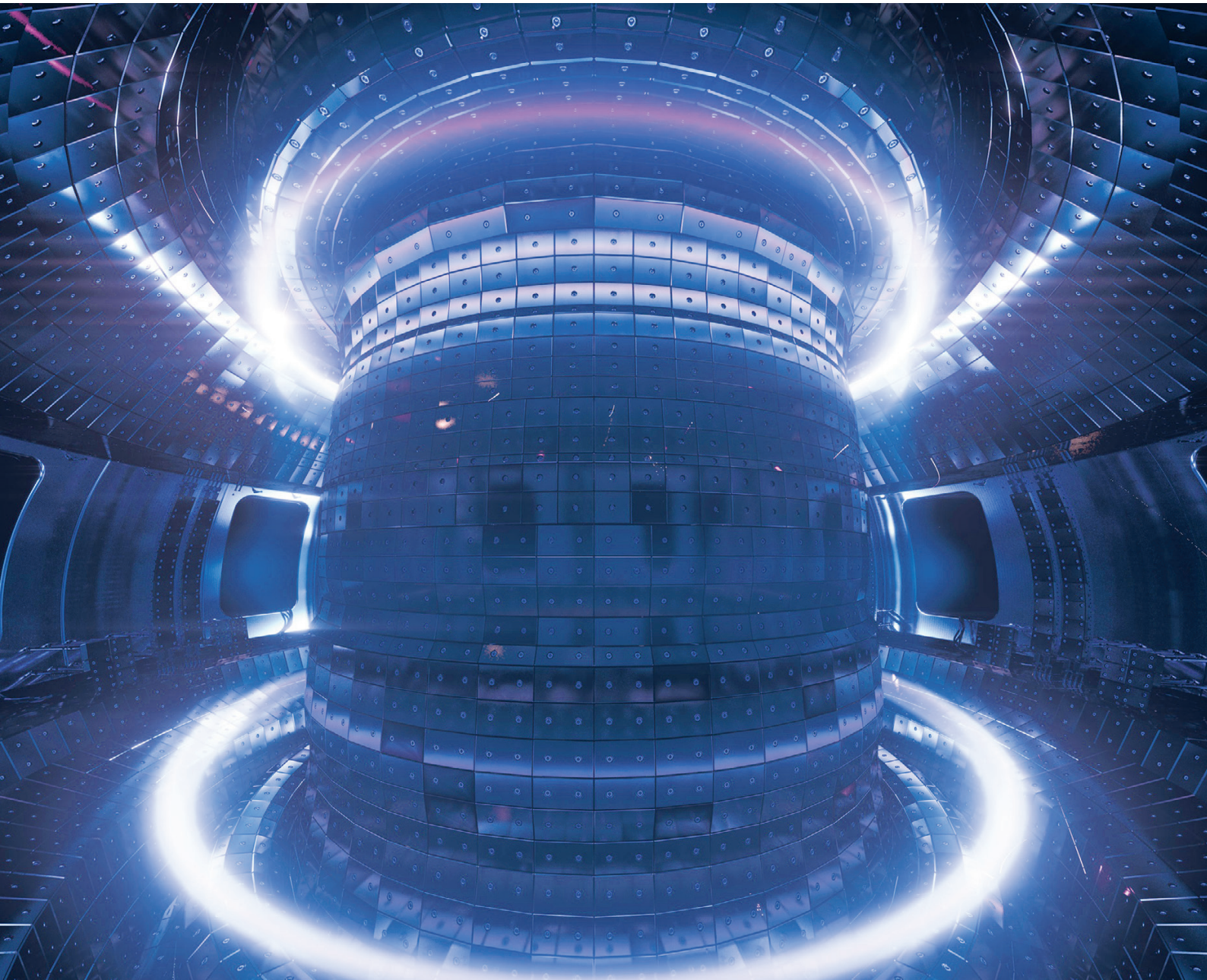
Fusion Energy

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.



Mikhail Chudakov

IAEA Deputy Director General and
Head of the Department of Nuclear Energy



Najat Mokhtar

IAEA Deputy Director General and Head of the
Department of Nuclear Sciences and Applications

Clean Energy through Fusion Technology

Generation of reliable and affordable carbon-free electricity is more important than ever to mitigate global climate change. Fusion energy - the source of energy for stars, including our sun – can potentially throttle carbon dioxide gas emissions from energy generation and thus help mitigate climate change. Scientists and engineers around the globe are achieving significant progress towards making fusion power generation on earth a reality.

Ever since scientists suggested in the 1920s that stars draw their apparent endless energy from the fusion of hydrogen isotopes to form helium, nuclear fusion is of great interest and an area of intensive research. The main drivers are the advantages that fusion power generation offers: a potentially limitless and high yield energy supply without generation of long-lived radioactive nuclear waste. Fusing atoms together in a controlled way releases nearly four million times more energy than burning of coal, oil or gas but does not emit harmful pollutants into the atmosphere as do coal powered plants. Unlike a nuclear power plant, no highly radioactive, long-lived nuclear waste is generated in a fusion power plant and there is no associated risk of any core meltdown accidents.

To generate fusion power, controlled and sustained fusion reactions in high temperature plasmas must be possible and the fuel for these fusion reactions also generated in a closed-cycle, sustainable loop. To accomplish this, challenging technological hurdles must be surmounted and international effort is needed to achieve this difficult task. The International Atomic Energy Agency (IAEA) has fostered and coordinated international fusion research since the second United Nations Conference on Peaceful Uses of Atomic Energy in 1958, when scientists discussed for the first time their recently declassified nuclear fusion research results.

Since 1961, the IAEA organizes the Fusion Energy Conference – a major biannual event, offering a discussion platform of key physics and technology issues as well as innovative concepts relevant to nuclear fusion as a future source of energy. In addition, each year the IAEA coordinates many technical and consultancy meetings and is currently leading 5 coordinated research projects in the field of nuclear fusion. The IAEA also organizes demonstration fusion power plant (DEMO) workshops, which 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. The next DEMO workshop is expected to take place in November 2021 in Japan.

The IAEA continually disseminates information on advances in fusion through numerous scientific and technical publications. In 1960, the Agency established Nuclear Fusion, the leading journal in the field. The IAEA Fusion Portal (<https://nucleus.iaea.org/sites/fusionportal>) provides access to e-materials related to

Melissa Denecke

Director, Division of Physical and Chemical Sciences, IAEA
Department of Nuclear Sciences and Applications



fusion research, including e-learning courses, publications and information materials. The recently released Fusion Device Information System (FusDIS) (<https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx>) offers information on over 100 private and public experimental fusion research devices, which are currently in operation, under construction or being planned.

The IAEA has shaped fusion research and the international cooperation leading up to ITER. ITER is a key experimental fusion research machine paving the way to tomorrow's fusion power plants, located in France. The ITER agreement was signed in 2006 by the seven ITER Members: China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States. The IAEA Director General is the depository of the ITER Agreement.

The year 2020 marked a historic moment for the nuclear fusion community, as the machine assembly at ITER commenced following 10 years construction work. The machine assembly involves the installation of the core machine, the ITER Tokamak – the world's largest tokamak.

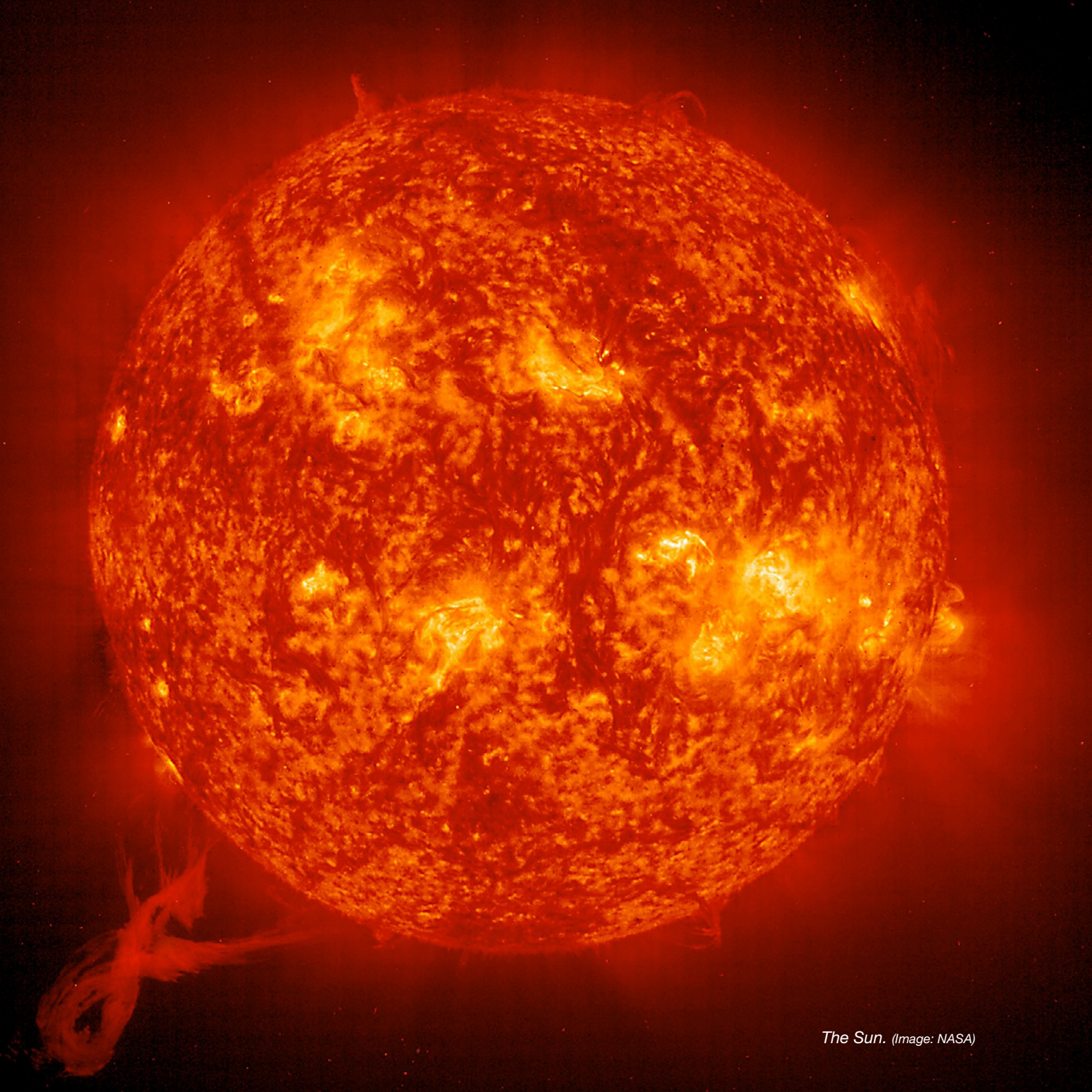
The first stage of assembly will be finished in late 2024, followed by a period of integrated commissioning and testing to prepare for first plasma experiments in December 2025, which are significant steps towards achieving ITER's ultimate goal: demonstration of the feasibility of fusion power.



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

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





The Sun. (Image: NASA)

Nuclear Fusion: The Key to a Sustainable Planet

Shutaro Takeda, IAEA Department of Nuclear Sciences and Applications

Matteo Barbarino, IAEA Department of Nuclear Sciences and Applications

Sehila Gonzalez de Vicente, IAEA Department of Nuclear Sciences and Applications

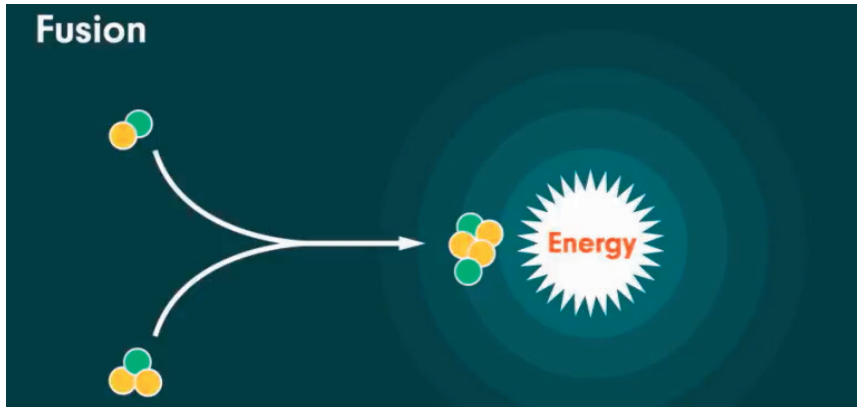
Danas Ridikas, IAEA Department of Nuclear Sciences and Applications



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

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 sun on Earth.

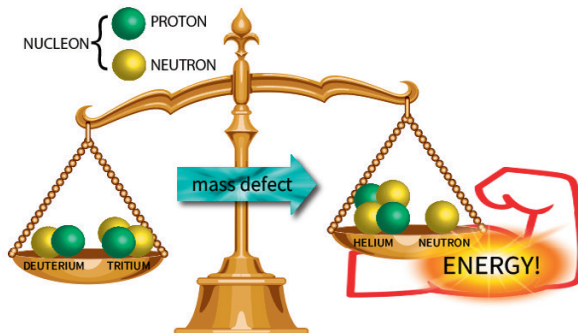
Unlike fission, where the atom is split to produce energy, in fusion two lighter nuclei are joined together to make a heavier nucleus, while energy is released. This is how stars convert tiny amounts of mass into vast amounts of energy (in line with Einstein's famous equation $E=mc^2$). Life on Earth 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.
(Image IAEA).*

Burning Hydrogen

The most convenient process to trigger involves two isotopes of hydrogen: deuterium (heavy hydrogen) and tritium (super heavy hydrogen). This reaction, which is also the most advantageous 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.



*Fusion converts tiny amounts of mass into vast amounts of energy.
(Image Aya Kuretani).*

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.

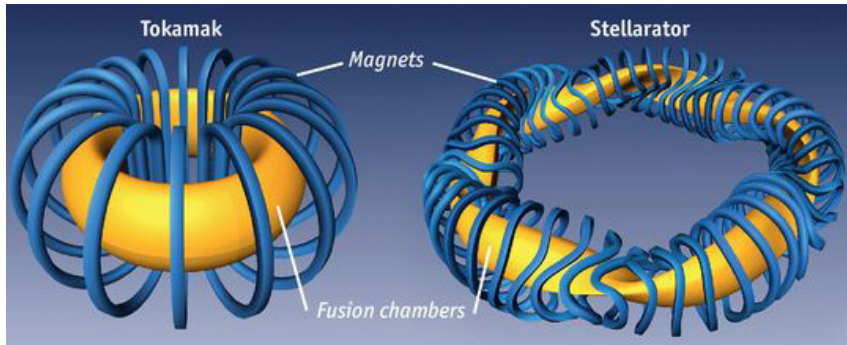
In a controlled nuclear fusion power plant, three conditions must be fulfilled:

- 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 two most studied fusion reactor concepts to date are the tokamak and the stellarator: doughnut shaped configurations that use powerful magnets to confine the plasma. 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. Today these machines can provide the essential conditions for fusion in terms of both plasma density and the high temperatures. With today's technology, fusion energy can already be generated from both systems but not in quantities that exceed the input. The missing piece of the puzzle to producing net power remains better confinement of the plasma, which is a measure of how good the magnetic field is at keeping the plasma energy.



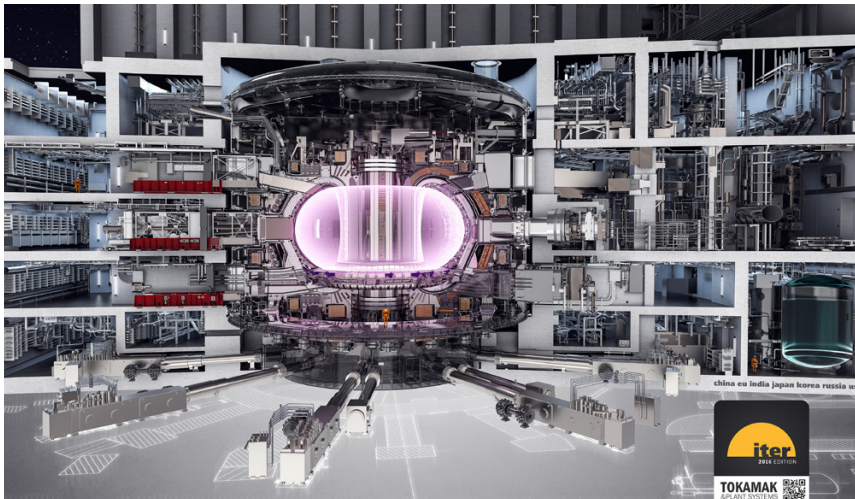
Illustration by Jacob Escobedo.



Tokamak (left) and Stellarator (right). The tokamak has the advantage of keeping the plasma hot, the stellarator has the advantage of operating the plasma in a steady state.

ITER – the Way to New Energy

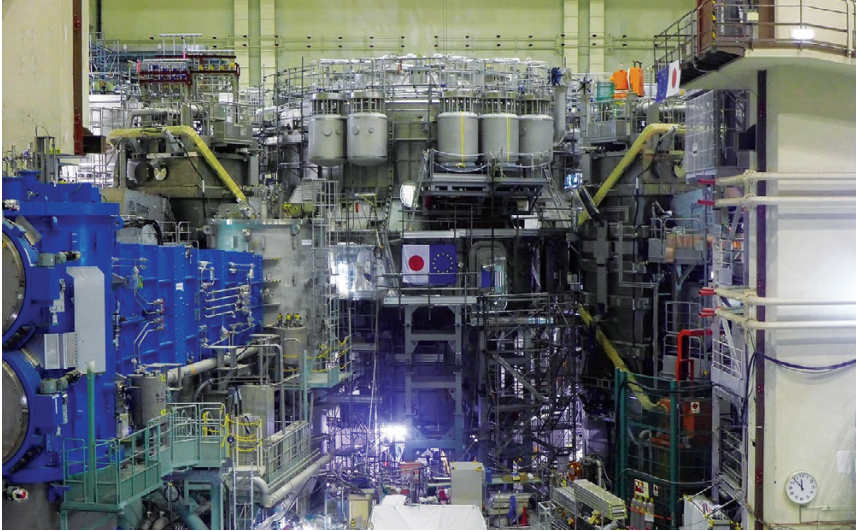
ITER will be bigger than the largest tokamaks operating today and has been designed for demonstrating the feasibility of fusion energy for peaceful purposes. With ITER's construction, the focus of nuclear fusion science is slowly shifting from pure research to material science and fusion engineering. 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.



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

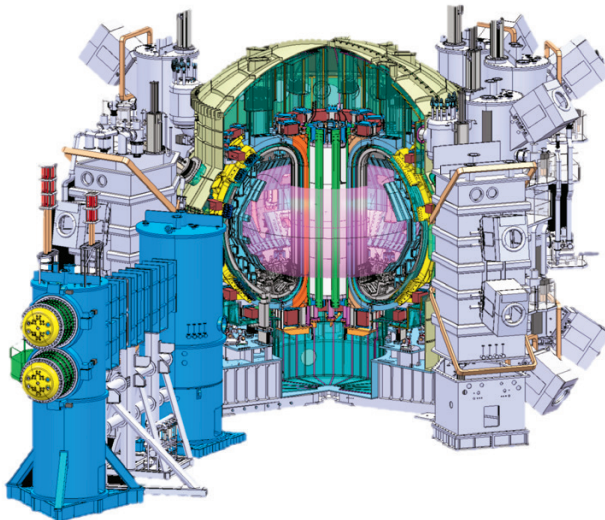
JT-60SA

Japan and the European Union (EU) 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”. The construction of this international joint research tokamak was completed in 2020.



The construction of JT-60SA was completed jointly by Japan and the EU in March 2020.

(Photo QST)

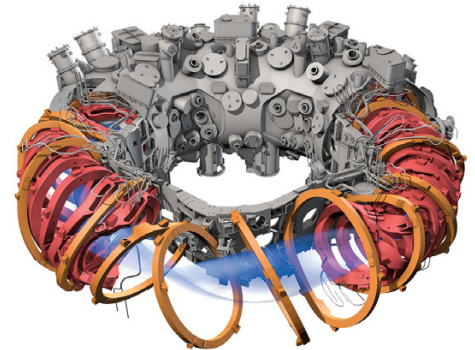


JT-60SA design.

(Image QST)

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 design for a power plant. As a result, a record value for a stellarator's fusion triple product (a plasma's particle density, energy confinement time, and temperature) was achieved in 2018.



Wendelstein 7-X.
(Image IPP).

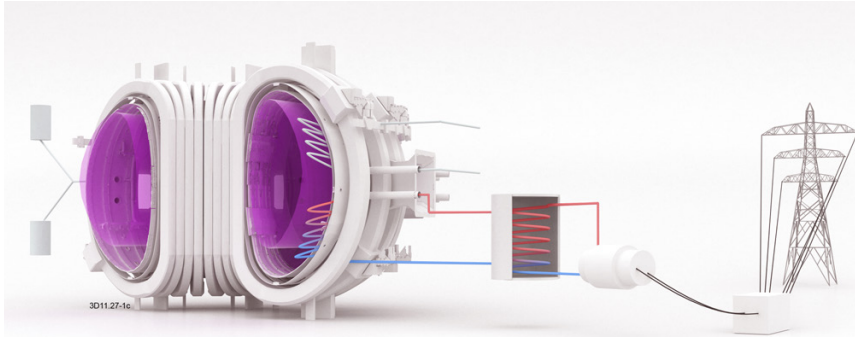
DEMO – Putting the Power into the Grid

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 the China Fusion Engineering Testing Reactor (CFETR) that would bridge the gap between ITER and DEMO. Construction of the CFETR will start in the 2020s and will be followed by construction of a DEMO in the 2030s.

The EU-Japan partnership represents a well-integrated approach to support ITER and to prepare to undertake the engineering design and construction of a subsequent DEMO. In addition to the construction of 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). The Japanese Joint Special Design Team for Fusion DEMO is currently working on the conceptual study of a steady-state DEMO (JA DEMO), the construction of which is planned to start around 2035.

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.



*Depiction of a DEMO.
(Image Eurofusion)*

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.

In addition, in recent years, a number of initiatives have been proposed by private enterprises around the world. As of 2019, such initiatives have attracted over 1 billion USD of investment and these private enterprises are now making strides in the development of fusion power plants that could meet global demands in the near future.

The IAEA DEMO Programme Workshop Series

With the construction of ITER, the global magnetic fusion programme has begun a transition from pure science to proposals aimed at producing fusion energy on an industrial, power plant scale. This is driving an increased emphasis on a fusion technology programme which, along with ITER and accompanying research, will

bring fusion as a power source within our reach. There is no agreement on a single roadmap to fusion but international experts and stakeholders agree on what scientific and technological issues need to be resolved for fusion power to become a reality. Resolving these issues and understanding the options for the next-step towards fusion nuclear facilities are of common interest, even though focus and priorities vary on a national level. To support these efforts, the IAEA has established a series of biennial DEMO Programme Workshops to facilitate international collaboration on defining and coordinating DEMO programme activities.

The main purpose of the DEMO Workshop programme series is to discuss key DEMO scientific and technical issues and define the facilities and programme activities that can lead to solving these issues. Further information can be found at: https://nucleus.iaea.org/sites/fusionportal/Pages/DEMO_landing.aspx

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, reducing environmental and health impacts, and mitigating climate change.

(Image: United Nations)

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

Shutaro Takeda, Matteo Barbarino, Sehila Gonzalez de Vicente, Danas Ridikas

IAEA Department of Nuclear Sciences and Applications

Building and maintaining partnerships with technical experts and researchers in Member States are key IAEA activities. Global cooperation is essential for the ultimate success of fusion energy. Through its Coordinated Research Projects (CRPs), the IAEA brings together scientists and experts from various countries to exchange information and to jointly identify critical issues. CRPs are one of the primary IAEA's mechanisms for transferring knowledge among Member States to help them tackle key development priorities.

With a long history of working together under IAEA coordination, around 50 Member States are involved in plasma physics and fusion technology. The cooperation among laboratories and facilities contributes significantly to fusion research and technology development, 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.

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.

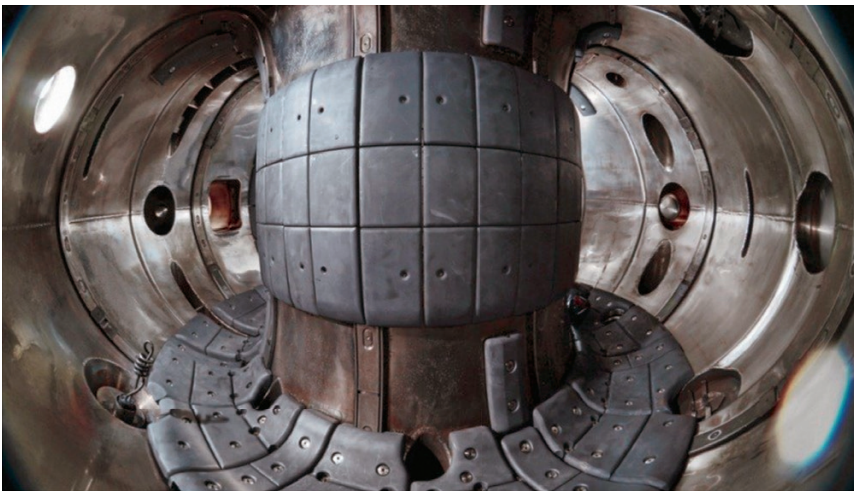
Researchers working with the small and medium-size devices are already making significant contributions toward achieving controlled fusion energy: the potential impact of tighter collaborations between them are even more significant.

With the next generation of large-scale fusion devices — such as ITER, presently under construction in France — preparing for action, the laboratories with small and medium-size devices could help push the research agenda forward. By



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

(Image: United Nations)

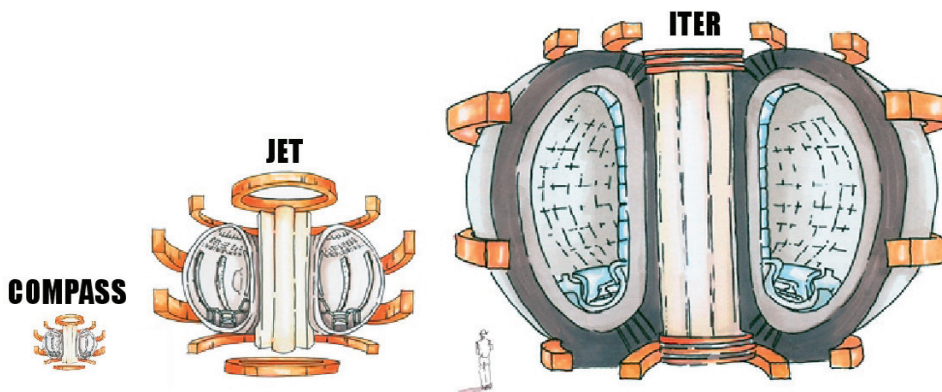


*Picture of the vessel of a toroidal magnetic confinement fusion device – COMPASS tokamak.
(Image IAEA).*

establishing and sustaining a network of laboratories that will perform joint and comparative experiments, train 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:

- develop new computational techniques for modelling plasma processes, in particular for real-time analysis requiring high-data volume processing;
- establish a program on education and training among the participants in the CRP to encourage contribution of developing countries;
- develop and model new advanced diagnostics;
- study the features and the mechanisms of the isotope effect and their relevance to plasma transport;
- investigate Magneto-Hydro-Dynamic (MHD) activity and related fast particle physics;



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

(Image IAEA and Eurofusion).

- optimize start-up phase and plasma breakdown;
- test materials and technologies for liquid metal, high temperature superconductors, functional materials, advanced fueling, modular vacuum-vessel and complex geometries coil manufacture;
- improve the coupling of energy transfer by the auxiliary heating systems;
- investigate edge and core plasma physics, including the coupling between them;
- study turbulence and transport, including the role of electric field and possible mechanisms of turbulence self-regulation.

Development of Steady-State Compact Fusion Neutron Sources

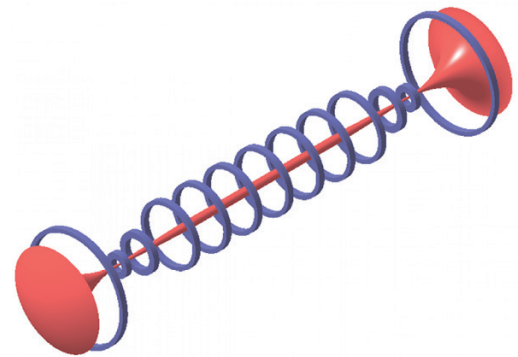
Fusion neutron sources might have many important practical uses, such as assisting fission reactions, producing radioisotopes for medical or industrial applications, testing materials and components for use in future fusion or fission reactors, and ensuring the production of tritium as a fuel for future fusion energy. All these applications could be improved by achieving higher energy levels of Compact Fusion Neutron Sources (CFNS).

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.
(Image IAEA)*

Standardization of Small Specimen Test Techniques

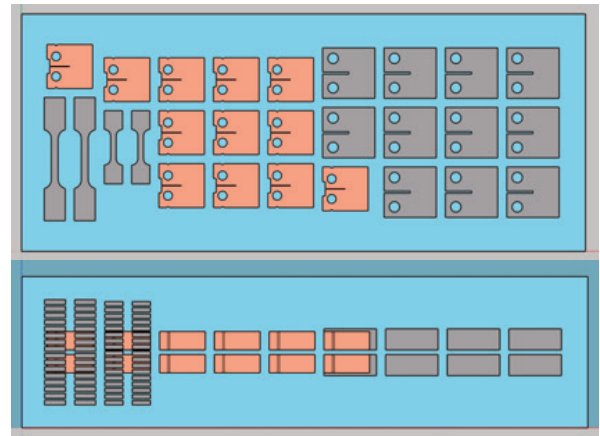
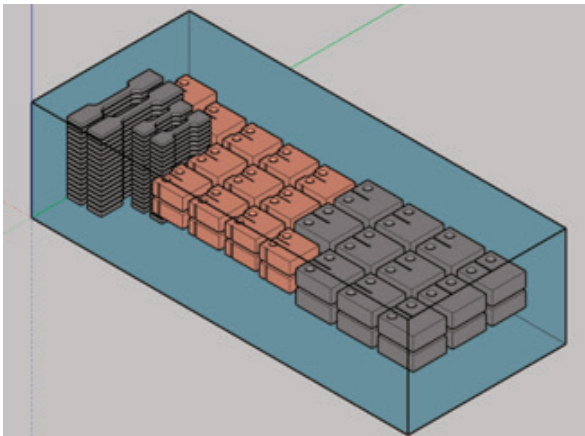
Structural materials research and development for making them suitable for the extreme conditions in a fusion reactor are needed to achieve safety and efficiency of future fusion power plants. Fusion materials development will depend on the progress made in irradiation physics and fusion materials research.

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 and for common practice in the use of SSTT;
- 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 neutron sources.

*Eurofer97-3 machining plan
(Specimens from left to right:
DONES tensile, SSJ3 tensile, mini-
CT, mCT-DONES).*



Pathways to Energy from Inertial Fusion: Materials Research and Technology Development

Developing materials capable of withstanding the extreme conditions that are necessary in operational fusion reactors is among the major challenges to a practical fusion power reactor design, in both Inertial Fusion Energy (IFE) and Magnetic Fusion Energy (MFE) systems.

This new IAEA CRP, the fourth in a series of CRPs in this field of study, is being conducted from 2020 to 2023. It will help to address some of the main challenges related to developing fundamental fusion materials and reactor technologies, in close connection with high-gain target development, needed to construct and operate a future fusion power plant. Such development of materials and technologies would serve the needs of both the IFE and MFE communities.

This CRP will also help establish a network of working groups to facilitate international cooperation and enhance information exchange on IFE research and development and promote the use of IFE technologies in fundamental science and industrial applications.

The overall objective of this CRP is to advance fundamental fusion material research and technologies in close connection with high-gain target development and to enhance information exchange on IFE research and development, establishing an international network of working groups. This will enable more countries to join the research efforts on different levels and contribute to moving forward in developing the peaceful use of fusion energy.

The specific research objectives of this CRP are to:

- advance the underlying science and develop novel materials for fusion energy;
- understand key processes in the target chamber;
- assess tritium inventory and its handling;
- develop next generation targets and diagnostics, that will also help enhance knowledge on high-gain target materials;
- develop driver (including materials research) and target fabrication technologies with an emphasis on repetition systems.

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 fusion community worldwide.



ITER made of Lego.

*(Image Sculpture by Sachiko Akinaga;
photograph by Hironobu Maeda).*

The Challenges of Controlled Nuclear Fusion

Christian Hill and Kalle Heinola, IAEA Department of Nuclear Sciences and Applications

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 wall;
- finding the right material from which to construct the fusion reactor wall and 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.

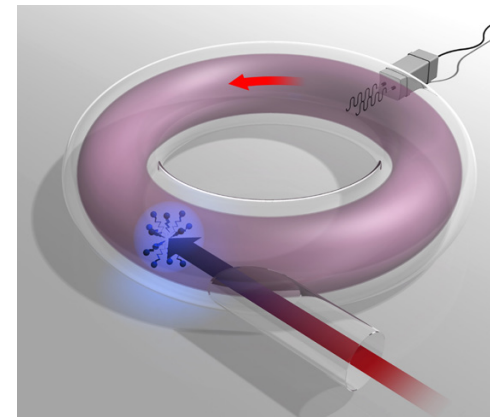
Plasma Confinement

In a fusion process, the high-temperature plasma must be confined for long enough for the hydrogen fuel nuclei to combine. In the Sun, the pressure caused by the hydrogen fusion is balanced by the inward-acting force of gravity which keeps 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 need to be operated at very low temperatures (-270 °C, less than 4°C above absolute zero), but are positioned 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). (Image: 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 neutral particles is fired into the plasma where it is ionized and transfers its energy through collisions.

Alongside the processes which heat the plasma, impurities can lead to 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 ${}^6\text{Li}$, a stable isotope of lithium:



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 ${}^6\text{Li}$ 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 good thermal 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 wall component material for the planned DEMO 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 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 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 knowledge base. This will help researchers to better understand the collisional processes involved and thereby improve the technology and accuracy of data analysis.

Atomic Data for Vapour Shielding in Fusion Devices

When wall material is rapidly evaporated or ablated by an energetic plume of hot plasma, a dense, secondary plasma cloud expands in front of the surface. In this dense plasma the incoming energy may largely be converted from the kinetic energy of fast plasma particles into electromagnetic radiation (light), half of which is directed away from the surface, thereby largely shielding the wall from further damage. This CRP focuses on the provision of fundamental atomic and molecular data, as well as the corresponding plasma-surface interaction data to accurately model the vapour shielding phenomenon, with particular focus on novel liquid metal walls that have been proposed for use in magnetic confinement fusion devices.

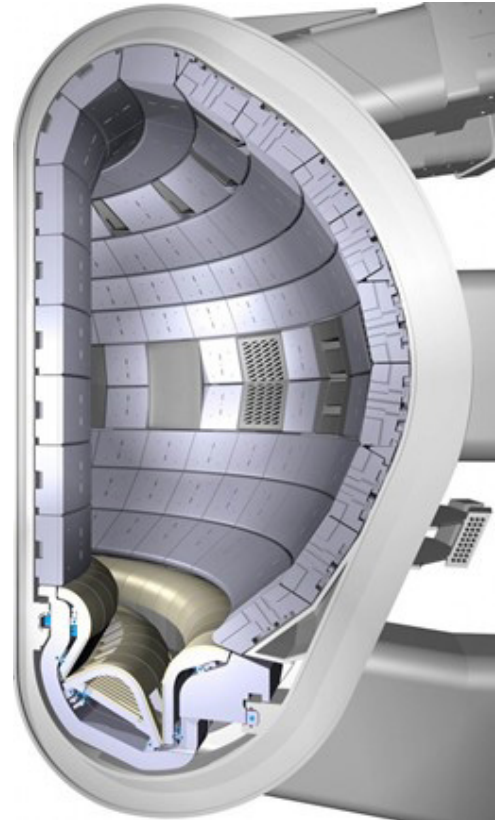
Hydrogen Permeation in Fusion-relevant Materials

This CRP will seek to enhance the knowledge base and reduce uncertainties in data concerning the migration of hydrogen in materials of relevance to nuclear fusion reactors. Materials of particular interest are tungsten, as used in the ITER divertor; various types of reduced-activation ferritic/martensitic steel (RAFM), currently thought of as candidates for the first wall of a future demonstration power reactor and likely used for some components of ITER; and copper and the copper alloy known as CuCr1Zr0.1 (also proposed as a structural material for components such as the cooling system of a nuclear fusion reactor).

It is important to know as much as possible about the behaviour of these materials with respect to permeation, retention and recycling of hydrogen in order to assess their suitability with respect to containing and isolating the radioactive tritium fuel of a fusion reactor from the surrounding components. Of particular concern is the possibility of tritium finding its way into the coolant water where it would pose a potentially serious environmental hazard.

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.



Cross section of the planned ITER tokamak chamber: beryllium will be used as a first wall material in the main chamber (surfaces coloured with light purple); in the bottom of the chamber is the divertor region, which is made of tungsten (beige) and onto which the highest particle flux is directed.

(Image: ITER Organization)

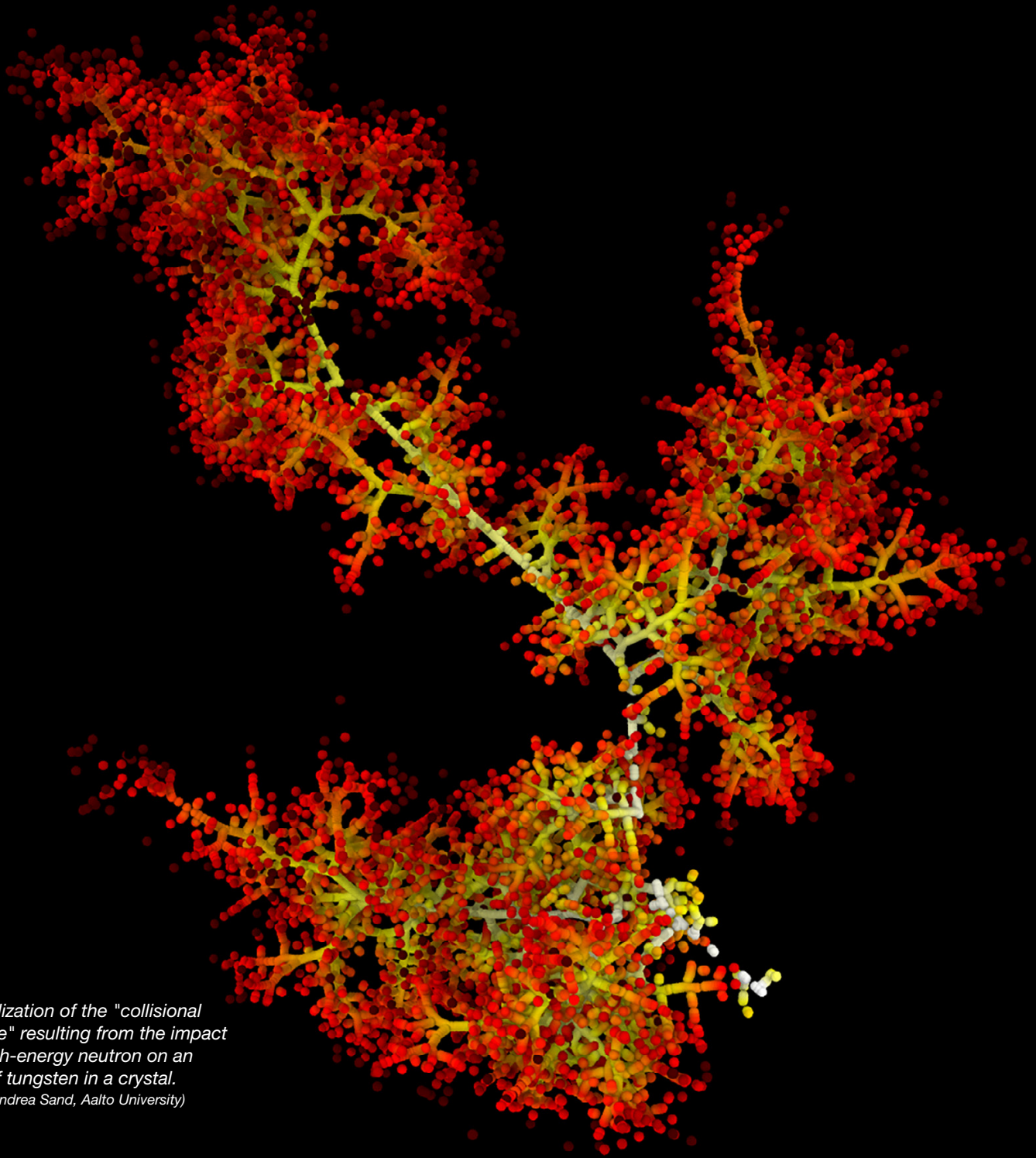
Two recent database resources, CascadesDB and DefectDB provide data on the formation, evolution and properties of radiation-induced defects in reactor materials: a proper understanding, through modelling and computation where experiments are unavailable or unfeasible, is essential for assessing the behaviour of candidate materials for use in fusion devices and for the discovery of new, potentially suitable materials (for example, so-called high-entropy alloys).

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 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. Further, visualization assists in transferring the cascade results to larger scale computational tools, such as multi-scale calculations utilizing Rate Theories and Machine Learning methodologies.



*A visualization of the "collisional cascade" resulting from the impact of a high-energy neutron on an atom of tungsten in a crystal.
(Image: Andrea Sand, Aalto University)*

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

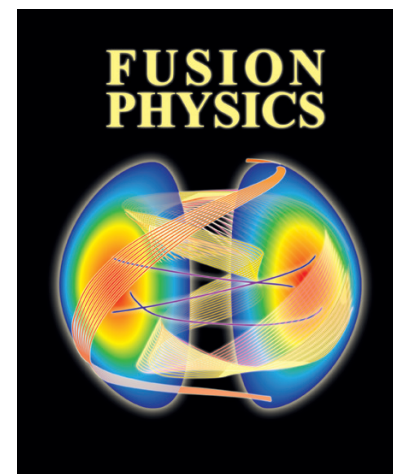
The results of IAEA coordinated research projects and other technical activities are presented in a variety of IAEA publications. These would include the Atomic and Plasma–Material Interaction Data publications and in the IAEA Technical Reports Series and Technical Document (TECDOC) Series.

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. The upcoming book, *Fundamentals of Fusion Technology*, 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 (DEMOs) 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 and technology have therefore resulted in various IAEA publications, such as *Integrated Approach to Safety Classification of Mechanical Components for Fusion Applications*, TECDOC 1851 and *Pathways to Energy from Inertial Fusion: Structural Materials for Inertial Fusion Facilities*, TECDOC 1911.

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. In 2021, there were half a million downloads of *Nuclear Fusion* articles and according to the Journal Citation Reports®, the journal achieved an impact factor of 3.179 in 2021.

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>

Fusion Device Information System (FusDIS)

The Fusion Device Information System (FusDIS), developed and maintained by the IAEA, focuses on experimental fusion research devices worldwide. FusDIS contains information on fusion devices public or private that are currently in operation, under construction, or being planned. All information is collected by the IAEA and undergoes a process of review involving the International Fusion Research Council.

Please visit FusDIS under:

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