Thermonuclear fusion: Progress in a multinational project under IAEA auspices

Scientific collaboration to demonstrate the technical feasibility of fusion energy moves ahead

by David Banner and Paul Haubenreich

"We have only three options for a long-term energy supply: sun, breeder, fusion." With this succinct statement, the German Federal Minister for Research and Technology, Dr Heinz Riesenhuber, pointed out in 1989 the incentive for current worldwide co-operation in fusion energy development.

The status and prospects for success in the development of controlled thermonuclear fusion were reassessed in 1990 by the International Fusion Research Council, an advisory body to the IAEA with members from all parts of the world. The Council's report included the following statement: "Against the background of recent experience, the need for the development of diverse and widely accessible, long-term sources of energy is perceived more and more acutely. These energy sources should not only be technologically feasible but also acceptable from the economic, safety, and environmental points of view. Fusion has the potential of becoming one of these sources.

"Developing a new source of energy such as fusion is a formidable scientific and technological challenge which spans several human generations. Yet the continuity in, and the magnitude of, the progress achieved so far on the way to the reactor are impressive and augur well. The primary fuels for deuterium-tritium fusion reactors (deuterium and lithium) are so abundant in nature that, practically speaking, deuterium-tritium fusion is an inexhaustible source of energy for global energy requirements."

Two basically different approaches to peaceful application of fusion energy are being pursued. They are usually called "magnetic confinement" and "inertial confinement". *(See boxes.)*

Although the feasibility of international exchange of information on inertial fusion is the subject of recent interest, this line of development has been supported mainly by the United States. In contrast, research on magnetically confined fusion has long been carried out in many countries, at a total annual expenditure approaching two billion dollars. The bulk of the effort is in four large programmes in the European Community (EC), Japan, Soviet Union, and United States. Several other countries support smaller but significant research programmes.

For more than 30 years, magnetic fusion research has enjoyed an extraordinary degree of international co-operation. From its inception, the IAEA has actively promoted the worldwide exchange of scientific information on fusion. Since 1987, it has been actively involved in more concrete, larger-scale multinational co-operation in the International Thermonuclear Experimental Reactor (ITER) project.

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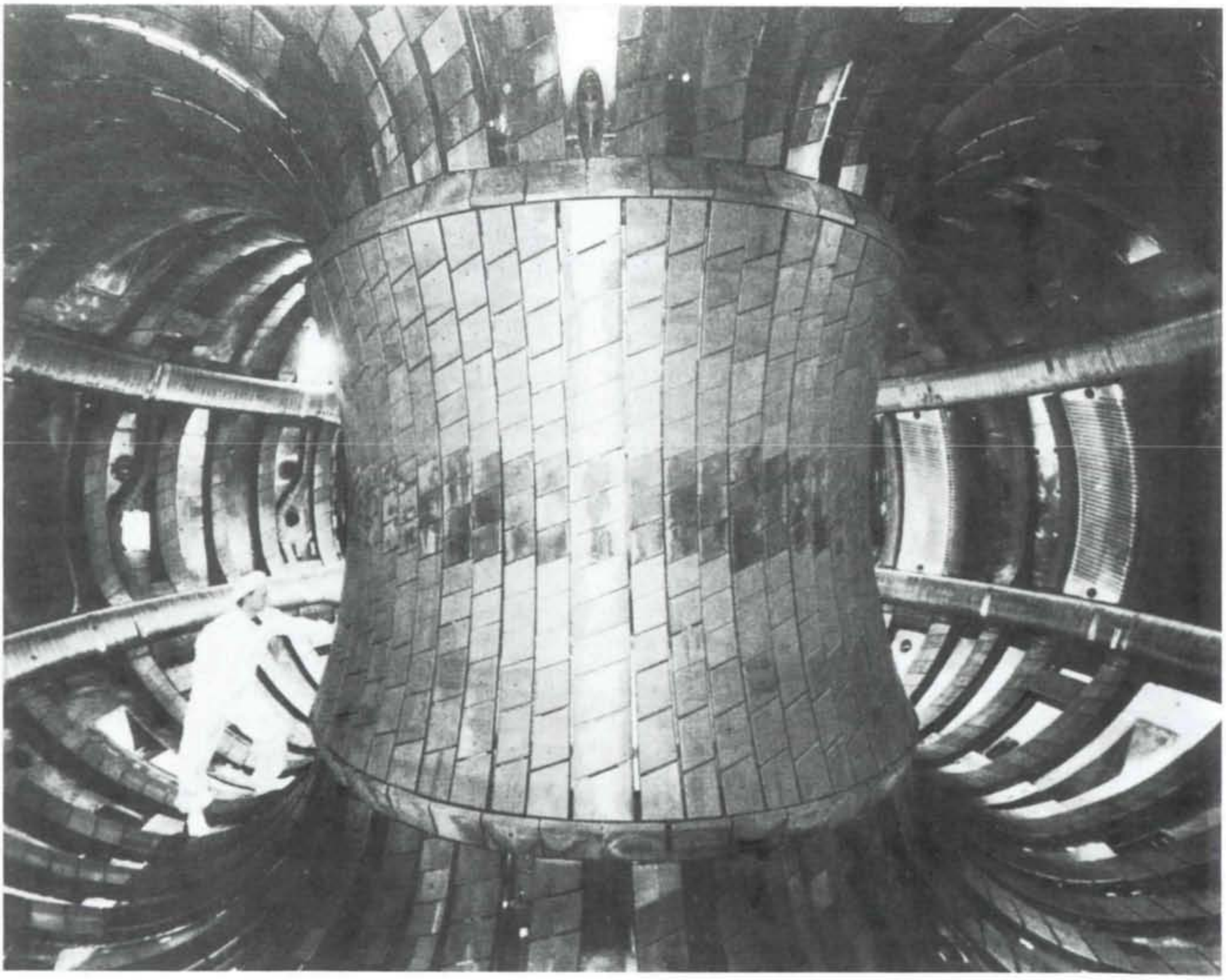
ITER project: International thermonuclear experimental reactor

A view inside the Joint European Torus (JET) tokamak, the world's largest magnetic confinement experiment. In this chamber, during experiments, hydrogen plasma is created and magnetically confined at conditions required for thermonuclear fusion, including temperatures approaching 100 000 000° Celsius.

By about 1986, progress in each of the four major fusion programmes had reached the point that the next logical step was to build a device incorporating fusion reactor technologies that would be large enough and powerful enough to achieve "ignition" and "controlled burning" of fusion fuel. It was apparent to all involved that this next step would require great resources, both of technical personnel and of funds for construction and operation. In view of the tremendous incentive for further progress and the scale of the next step, leaders of the governments supporting fusion development began calling for expansion of existing co-operation in fusion research.

In response to these calls, the IAEA Director General invited representatives of the four major fusion programmes to a series of meetings in Vienna during 1987, at which they developed a detailed description of a 3-year joint effort called International Thermonuclear Experimental Reactor Conceptual Design Activities (CDA). The purpose was to take a first concrete step toward construction of a machine that would meet the needs of all four programmes. The unanimously chosen technical concept was the so-called "tokamak" concept of magnetic confinement of plasma, which had been developed originally in the USSR and subsequently, in increasing scale and sophistication, in many countries. The Director General then invited each interested Party to co-operate in the CDA, under the auspices of the IAEA, in accordance with the Terms of Reference that had been worked out. The four Parties accepted and committed themselves to the efforts necessary to produce a conceptual design, cost estimate, and siting requirements by the end of 1990.



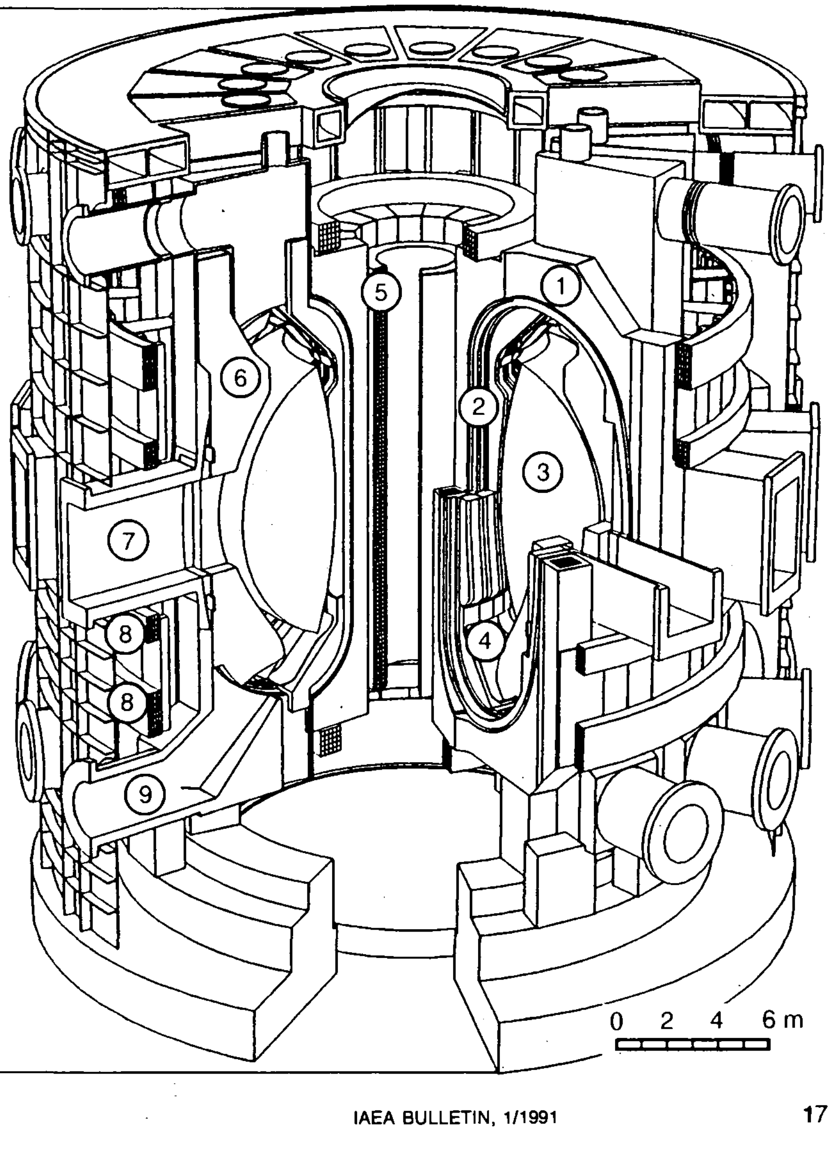
Joint design activities began in April 1988 and were successfully completed in December 1990. Part of the effort was in the home countries, part at a joint work site provided by the European Community at Garching near Munich. During joint work sessions, which lasted about 6 months each year, more than 50 scientists and engineers were in residence at the joint site while an even greater number continued to work at home. An integrated organization for the joint work encouraged close collaboration of scientists and engineers from the four Parties. Overall direction of the ITER activities was provided by the ITER Council, with two members from each Party.

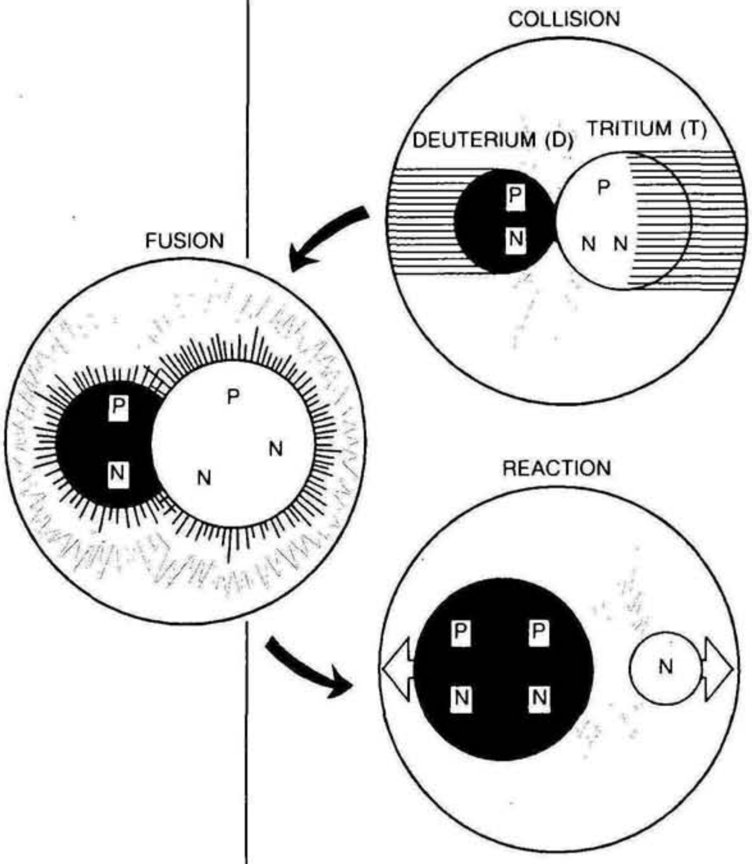
Although the four fusion programmes had similar objectives for an experimental reactor and were in agreement on the general technical approach at the beginning of the ITER activities, there were differences among the specific design concepts that each had developed. Thus, it was no small accomplishment of the joint work that understanding and resolution of these differences were soon achieved. By the end of 1988, the ITER Parties had agreed on choices of machine parameters and design concepts for magnets, materials, and maintenance arrangements.

The design process was supported by extensive research and development (R&D) by the Parties. Each spent about US $10 million per year on technology R&D, besides ongoing confinement physics experiments that included many tasks specifically undertaken for ITER. ITER's results were analysed and adopted as part of the basis for confident design.

By the end of 1990 the four-party teamwork had produced a conceptual design of an entire plant and a clear picture of how ITER might be built and operated. This included a description of construction site requirements and a suggested project plan. The plan includes descrip-

The principal elements of the ITER tokamak:
1) toroidal field coil;
2) vacuum vessel;
3) plasma;
4) divertor;
5) central solenoid;
6) blanket and shield;
7) horizontal access port;
8) poloidal field coils;
9) vacuum pumping duct.





Thermonuclear fusion

Thermonuclear fusion and its effects are ubiquitous. It is the process that powers the stars. It is the source of the solar energy that warms the Earth. Nuclear fusion results from very high-speed collisions of certain light atomic nuclei. A single new nucleus is produced and copious energy is released. Fusion of deuterium (D) and tritium (T), both isotopes of hydrogen, is the least difficult to make occur and is most likely to be the basic process in at least the first fusion power reactors. The D and T nuclei must collide with velocities corresponding to thermal motion at temperatures on the order of 100 million degrees. The compound nucleus immediately emits a neutron, leaving a stable helium nucleus identical to those occurring naturally. The energy released in the process appears initially as kinetic energy of the neutron and the helium nucleus (called an alpha particle), which fly apart at high velocities.

Fusion of one gram of D-T mixture releases as much energy as combustion of 10 000 litres of gasoline, but produces no noxious gas.

tion of physics and technology R&D tasks, shared among national programmes, which would be needed to support detailed design. The ITER parties also developed a possible schedule and a preliminary cost estimate for construction and operation.

At the conclusion of the CDA, the results were thoroughly reviewed, both jointly and by panels within each of the four Parties. All reviews reached the same conclusion: that the results provided a good technical basis for proceeding with the next logical phase of the ITER project.

The ITER team during the CDA made a preliminary estimate that construction of ITER would require 7 years and a capital investment of about US $4.9 billion, shared among the participants. Before ITER construction could begin, about 6 years would be required for Engineering Design Activities (EDA), including detailed engineering, further development of components, and evaluation of proposed construction sites.

The prospective EDA Parties developed a logical organization of the work that could allow equal sharing. They estimated that about US $250 million would be spent on design work and US $750 million on direct support of technology and engineering R&D. About half of the design work would take place at a joint work site, carried out year-round by a Central Team of up to 180 scientists and engineers, drawn from all Parties, plus local support. Specified design tasks would be done in laboratories and industrial firms located in the home countries of the four Parties. Programmes of physics research by ITER Parties and others would continue to provide information to confirm the ITER design and to plan its experimental programme.

All of the ITER-specific technology R&D tasks would be carried out by one or more Parties at sites within the home countries. Project management would be by a Director and his staff, supported by a common fund. Since ITER is viewed by the four Parties not

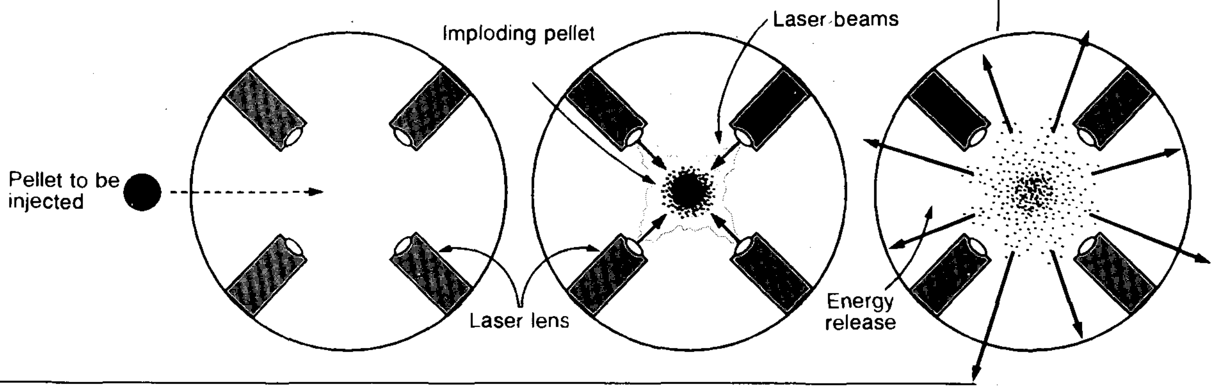
Fusion initiation and confinement

In magnetic confinement concepts, fuel that is initially in the form of rarefied, cool gas is heated by any of several means until it becomes a plasma. This "fourth state of matter" is reached when the thermal motion of the atomic particles is so vigorous that nuclei and electrons become separated.

Since every particle in a plasma has an electric charge, they are subject to forces when traversing a magnetic field. The trick in magnetic confinement is to configure the magnetic fields so that most of the charged particles are forced to travel in curved paths that do not intersect the walls of the chamber in which the plasma is formed. Heating must then continue until the thermal motion of the particles reaches the velocity range at which collisions produce fusion.

Scientific understanding has been highly developed, to the point that heating methods and confinement efficiencies required for practical fusion power can be defined. The latter is effected primarily by making the plasma chamber large and the magnetic fields strong.

The basic principle of inertial fusion is extremely rapid heating of fusion fuel, resulting in abundant, energy-producing fusion reactions before the forces on the atomic and subatomic particles cause the reacting mass to fly apart. In the approach being considered for power-station applications, a tiny pellet of frozen hydrogen is dropped into a chamber where it is abruptly hit by a pulse of laser energy, focused on the pellet from several directions. *(See figure.)* The rapid surface heating creates an implosive shock wave that heats and densifies the center of the pellet to thermonuclear fusion conditions. In the tiny fraction of a second before the pellet explodes, the fusion energy is produced. Utilization as a power source requires a continuing series of such events at close intervals.



only as a demonstration of the technical feasibility of fusion power, but also as a demonstration of the safety and environmental advantages, ITER's safety and environmental concerns would continue to be guiding principles in the engineering design.

The results of the CDA produced not only confidence among the technical communities; governments also were convinced of the desirability of continuing with ITER in view of the tremendous potential pay-off of successful fusion energy. Although international collaboration would be complicated, the Parties recognized that such a joint effort would offer the beneficial prospect of sharing scarce scientific and technological resources, as well as costs in a priority energy development area.

After preliminary discussions among the ITER Parties revealed a high degree of commonality on possible arrangements for co-operation in EDA, governments of each Party authorized formal negotiations. The Director General of the IAEA invited the Parties to meet in Vienna for these negotiations and assured them of the Agency's readiness to provide its services in establishing and supporting the envisioned EDA Central Team. The first negotiating meeting was held at the Vienna International Centre on 11–12 February 1991.

Typical of the Parties' views were those of the US Secretary of Energy, who said with regard to the negotiations of an agreement for ITER's EDA: "It is fitting that, as international research partners, we continue our co-operation by jointly designing the reactor that could demonstrate the feasibility of fusion energy as an energy source. Science and the taxpayers have already benefited from this shared research that has gone on literally around the world and around the clock."

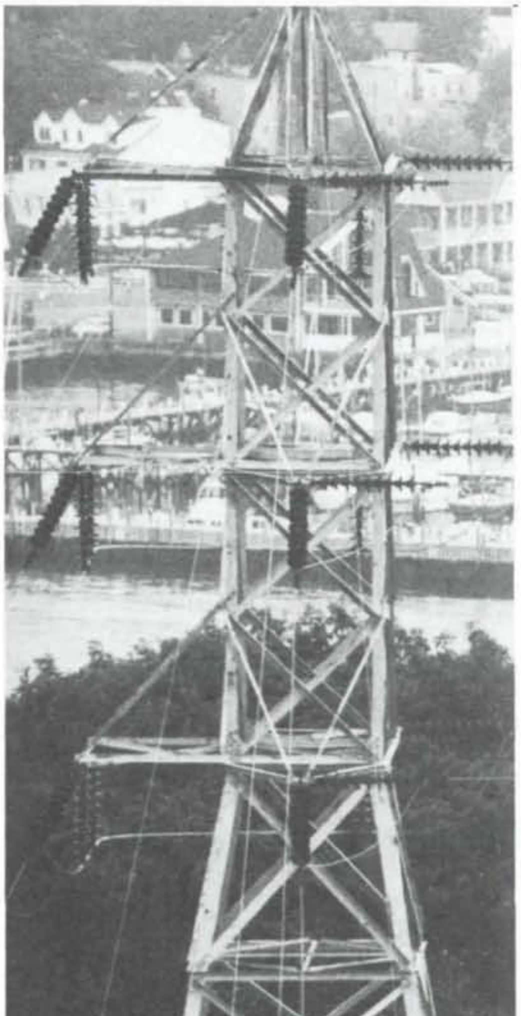
Three of the Parties offered to host the EDA: the EC at the site of the CDA in Garching, Germany; Japan at the research center in Naka; and the United States at a university and fusion center at San Diego. Each offered buildings that would accommodate up to 180 scientists and engineers and 120 support personnel, together with computer facilities that would be used in the design. Communications systems would enable effective collaboration among the Central Team and ITER workers in the home countries.

Decisions on the EDA site as well as a choice of key personnel will be made during the negotiations. Based on early progress, the Parties expect that, barring unforeseen difficulties, an agreement could be concluded by mid-1991.

Potential of fusion energy

Fuels for thermonuclear fusion energy production are widely distributed in practically inexhaustible amounts. The physical requirements for the production and control of thermonuclear fusion have been progressively determined by decades of research carried out in laboratories around the world. The process that produces the energy is the same as that which produces all of the heat in the sun and stars. Thus, the ultimate objective in fusion development can be described as the production and sustaining of a "miniature sun", whose energy is harnessed to produce electricity.

Furthermore, environmental and safety aspects of a fusion power industry promise to be quite acceptable by society. If, as ITER participants deem likely, the required equipment proves to be practical to build, operate, and maintain, fusion could play a large role in supplying the world's energy needs after this century.



Safety and environmental aspects of fusion power

A fusion reactor is somewhat analogous to a gas heater: turn off the gas and the "flame" (fusion reaction) immediately goes out. There is no chance of a "runaway" reaction or widespread damage due to uncontrolled fusion reaction.

The primary particles from fusion reactions are not radioactive. The inevitable absorption of fusion neutrons in structure or other material produces radioactive nuclides, but these are not mobile nor are they extremely long-lived, which makes containment and disposal less difficult. "Afterheat" due to radioactivity after shutdown of the reaction is relatively mild and easily manageable by simple, reliable systems.

One component of the fusion fuel, tritium, is radioactive, so care must be taken in the design and operation of the facility to ensure its containment. Suitable measures are well defined and have been proven to be quite effective and practical.

ITER conceptual design analyses indicate that this fusion reactor could meet all requirements of existing regulations pertaining to safety and environment.