Nuclear fusion: Targeting safety and environmental goals

Analyzing fusion power's potential for safe, reliable, and environmentally friendly operation is integral to ongoing research

by
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For some decades, people have looked to the process powering the sun — nuclear fusion — as an answer to energy problems on Earth. Whether nuclear fusion can meet our expectations remains to be seen: technological problems facing a fusion power plant designer are complex and a fusion power plant has not yet been built. Remarkable progress has been made, however, toward realizing fusion's potential.

Research in fields of nuclear fusion has been pursued in various countries for decades. The efforts include the JT-60, which has provided important results for improving plasma confinement; the D-IIID tokamak experiment, which has achieved record values of plasma pressure relative to the magnetic field pressure; and the Tokamak Fusion Test Reactor (TFTR), which has generated 10 million Watts of thermal power from fusion. The Joint European Torus (JET) is expected to approach breakeven conditions, where the fusion power generated exceeds the input power. Unresolved physics issues, such as plasma purity, disruptions, and sustainment of current, should be resolved by the International Thermonuclear Experimental Reactor (ITER), which is being designed by experts of the European Community, Japan, Russian Federation, and the United States. *(See related article beginning on page 16.)*

There is confidence that the engineering design issues — including those concerning superconducting magnets, vacuum systems, cryogenic systems, plasma heating systems, plasma diagnostic systems, and blanket cooling systems — can eventually be solved. Other important aspects in designing a fusion power plant relate to safety and economics. This article looks at safety aspects of fusion power plant designs, and reviews efforts in safety-related areas that are being made through international co-operative activities.

Safety-related goals and considerations

Reliable predictions of the cost of electricity from fusion power cannot be performed until design details of commercial fusion power plants have been established. Currently, this cost is not projected to be significantly less than the costs of other energy sources.

In areas of safety, however, fusion holds potential advantages over other energy sources. In nearly all studies related to the design of a fusion power plant, safety and environmental considerations are being increasingly emphasized, and safety goals for fusion have been extensively discussed. The safety and environmental goals of a fusion power plant design are to protect workers from radiation, electromagnetic fields, and other hazards; the public from radioactive and toxic materials; the environment from pollutants and waste; and the investor from damage by accidents.

The fusion process. At sufficiently high temperature, nearly all light nuclei undergo fusion reactions and could in principle be used to fuel a fusion power plant. However, technical difficulties increase rapidly with the nuclear charge of the reacting isotopes. For this reason, only deuterium, tritium and isotopes of helium, lithium, and boron have been proposed in practice.

The first generation of fusion power plants will very likely use deuterium-tritium (DT) fuel because it is the easiest to ignite. The main reaction product, helium-4, does not pose a health hazard. The principal energy output from a DT fusion event is a 14 MeV neutron.

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Nearly all materials become activated to some degree by energetic neutron bombardment. Neutron reactions in DT fusion reactors will inevitably create radioisotopes. The principal radioactive materials present in a DT fusion reactor will therefore be tritium and neutron-activated structural materials surrounding the reaction volume.

Safety-related considerations. Specific fusion power plant safety studies, which are complementary to many other safety studies, include those related to tritium safety, the assessment of tritium releases, activation product safety, radioactive waste disposal, and analyses of potential accidents and their consequences.

The release rate of tritium during plant operation has to be kept well within an acceptable safe range. This release of tritium is modeled by computer codes that account for tritium permeation through the materials present in the power plant. Major tritium research laboratories are in Canada, Germany, Italy, Japan, the Russian Federation, and the United States.

The generation of neutron activation products is not a serious problem if they can be contained and if they have short half-lives. They are a byproduct of the fusion reaction, not a direct reaction product. Therefore, their generation in the blanket and structure of the reactor is under the control of the designer and can be minimized by proper design and appropriate choice of materials. The use of a variety of low activation materials is being extensively studied.

There is no potential for a runaway fusion reaction; indeed, the problem is making the fusion reaction proceed adequately at all. Virtually all hardware problems lead to fusion shutdown, and there are inherent limits in any case because of the limited amount of fusion fuel present and the nature of the fusion reaction. However, a particular focus of work in fusion safety is the analysis of various other potential accidents, such as magnet accidents, and "consequence calculations" are performed. For categorization of accidents into event groupings and estimation of the frequency of accidents, specific component reliability data are required.

The approach for conducting a general safety analysis for fusion plants is similar to that used for the design of other large nuclear installations. *(See box, page 25.)* The results of safety analyses indicate that fusion power plants can meet the desired safety goals. For example, the *ESECOM* study compared the safety and economic aspects of many fusion reactor designs.* The general safety issues of ITER were discussed and a draft report has been issued giving preliminary results of the ITER safety analysis.

Fusion power plant safety studies have been evolving for more than 20 years. They are steadily adapting to the evolution of internationally agreed radiation safety concepts and requirements.

In 1994 the IAEA, jointly with five other international organizations issued revised *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources.* The Basic Safety Standards — issued jointly with the Food and Agriculture Organization (FAO), International Labour Office (ILO), Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA), Pan-American Health Organization (PAHO), and World Health Organization (WHO) — take account of new recommendations on radiation protection of the International Commission on Radiological Protection (ICRP). A central part of the dose limitation system is the "optimization of protection" principle. Fusion is a good candidate for the successful application of this principle. Optimization is best achieved when safety assessment is already built into the early design stages of a project.

As pointed out earlier, the first fusion power plants will most likely use the DT fuel cycle. Once a fusion power plant based on the DT reaction has been built, advanced fuels could be further pursued for energy exploitation. This would bring about a lower tritium inventory. Later fusion power plants may evolve to fuels (such as deuterium + ^{3}helium) that generate fewer neutrons, and hence produce less radioactivity in surrounding materials. Thus, during the evolution to advanced fuel cycles, the safety advantages of fusion may increase with time. It may be possible in the future to design power plants with low enough radionuclide inventories so that emergency planning and preparedness are unnecessary.

Practical realization of fusion

It has been estimated that an investment of the order of US $50-100 billion is needed to bring fusion power to fruition. The rate of progress in fusion research is limited by the funding rate, which is estimated to be about US $1.5 billion per year worldwide.

* See "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy", by J.P. Holdren, D.H. Berwald, R.J. Budnitz, et.al., UCRL-53766 (1989).

Currently, expectations are that ITER could begin significant DT operation around 2005-2010, followed by construction of a demonstration power plant. A demonstration fusion power plant could then begin operation about two decades later. If the demonstration reactor is successful, i.e. if sufficient operational experience warrants financing of a commercial power plant, then early commercial fusion power plants could begin operation by about 2050.

This estimated timetable could be delayed or accelerated. It could be delayed by funding shortages or by unforeseen difficulties with plasma phenomena or technology. The schedule could be accelerated by a breakthrough in understanding of plasma behavior (such as, perhaps, the recent success with the "reversed shear mode" of tokamak operation), by a new invention that enhances plasma confinement, and by providing an increased funding rate.

Non-tokamak types of plasma confinement are also being studied, to develop reactors that can produce electricity at a lower cost. For example, large stellarator experiments are under construction in Japan and Europe. It is clear that safety studies will play a major role in earning and keeping public trust, desire, and acceptance of fusion power.

Fusion Safety Philosophy

The fusion safety philosophy now includes the following concepts:

- passive systems and inherent safety features;
- fail-safe design;
- reliability (including redundancy of components (pumps, valves, etc.); diversity (such as two different ways of supplying back-up power); independence (if one component or system fails, it does not cause an adjacent one to fail); simplicity; and surveillance, to detect flawed components before an accident occurs);
- consideration of human factors;
- remote maintenance capability;
- safety culture in worker attitudes;
- quality assurance (including codes and standards; verification and validation; and safety analysis);
- operational controls (fault detection, automatic corrective response);
- safety systems to reduce consequences of failures;
- accident preparedness and management, to preserve confinement integrity;
- emergency planning to mitigate effects of radioactive releases, if needed.

IAEA activities in fusion safety

Guided by the International Fusion Research Council (IFRC), the IAEA is conducting a range of activities that promote international co-operation and help to enhance the safety and environmental advantages of fusion power. They include supporting the ITER project, whose Engineering Design Activity has passed the halfway point. The ITER experiment will have safety built into the design, to ensure that no fatalities can arise during a serious accident by release of radioisotopes. In 1995, the Agency published a discussion of safety in inertial fusion reactors.

Many IAEA activities in the area of radiation safety are relevant to fusion safety. They cover topics such as safety standards for radiation protection, safe transport of radioactive materials and management of radioactive waste, guidelines for safe handling of tritium, and limitation of radioactivity releases into the environment.

Since 1973, fusion safety has been a special item on the Agency's agenda of safety activities. Over the past two decades, the Agency has organized several technical committee meetings on fusion safety which discussed progress, research needs, and future plans. Typically about 50 experts from a dozen Member States have attended these meetings, which were held about every three to four years. The proceedings of the latest meeting in this series, held in 1993 in Toronto, Canada, were published in the *Journal of Fusion Energy* in June 1993. The next meeting is planned in October 1996 in Japan.

Prospects and future directions

Fusion reactors have a significant potential for safe, environmentally benign operation. Safety aspects of fusion power plants, which have been designed on paper, cannot yet readily be compared with safety aspects of fission power reactors or other operating energy sources. In fusion, the bulk of radioactive material is a secondary product resulting from neutron activation, leaving room for optimization of protection through materials development and selection, or by using advanced fuels.

To ensure that the potential safety and environmental advantages of fusion can eventually be utilized, safety engineering must be integrated into fusion reactor designs. This is being done by

Fusion Safety Analysis

As in safety studies of other large nuclear installations, various steps are involved in accident analysis of a fusion power plant.

Each sequence of events may be represented by an "event tree", and each branch of the tree has an associated probability of occurrence. For example, if a valve is ordered to close, it has a finite probability of failing to do so. For loss-of-coolant and loss-of-flow events, the temperature rise in the first wall and blanket must be calculated as functions of time. Then the mobilization of various elements can be estimated, based upon data from laboratory tests.

The amount of a radioisotope that is mobilized during an accident constitutes the "source term". Sometimes the source consists of an oxide aerosol, of which most would plate out inside the building. During a severe accident with damage to the containment, a fraction of the aerosol might leak out of the containment to the atmosphere. Sophisticated computer codes are used to model:

- neutron and gamma ray transport in the first wall, blanket, and shield;
- generation of radioisotopes by neutron absorption;
- temperature rise due to afterheat and chemical reactions during accidents;
- mobilization of radioisotopes during accidents;
- transport of aerosols inside the confinement building (and reaction released);
- transport of released particles and gases to the site boundary;
- radiation dose to the "maximum exposed individual" at the site boundary.

the ITER Project, although ITER is an advanced experimental fusion reactor and should not be viewed as a prototype fusion power reactor.

As fusion safety studies progress, more and more interdisciplinary work will be required. Over the long term one can confidently expect that safety will be strengthened as progress is made in fusion power plant design. A statement made by C.M. Braams, Chairman of the IFRC, 20 years ago in an introductory note to a review elaborated at that time, remains valid today:

"... although the prospects for taking advantage of the environmental merits of fusion are good, it is clear that fusion reactors, if they become a reality, will have an environmental impact - including radiation hazards - whose magnitude will depend on the progress of research, on the availability of materials and on how much society is prepared to spend on minimizing the impact". ❒

Steps of Fusion Power Plant Accident Analysis

I. Consideration of the potential hazards

These include:

- gamma radiation
- routine releases of tritium
- accidental releases of radioactive material from
  - structure
  - coolant
  - corrosion products
  - dust
  - tritium in walls, blanket, coolant, vacuum system, fueling system
- toxic materials, such as berylium, vanadium, lead
- electromagnetic fields
- vacuum
- cryogenic fluids
- asphyxiants (gases such as N_2, He)
- chemical reactions
  - liquid metals with water, air, or concrete
  - hot surfaces with water or air
  - hydrogen generation and explosion
- high voltage
- rotating machinery
- lifting heavy masses
- missiles generated by turbine blades, magnet coil arcs, or high-pressure gases.

II. Analysis of energy sources available to "mobilize" radioactive materials

Examples of estimated values:

● decay heat	[910] GJ in first week
● chemical reactions	[800] GJ
- coolant	
- water/air + hot plasma-facing components.	
● coolant stored energy	300 GJ
● magnet coil stored energy	120 GJ
● fusion reaction full power	1.5 GJ/second
● plasma magnetic energy	1.3 GJ
● plasma thermal energy	1.2 GJ
● vessel thermal energy	small
● vacuum	small

III. Analysis of possible accidents, such as:

- plasma events
  - fusion overpower
  - disruptions
  - delayed shutdown
- loss of coolant event
- loss of flow event
- loss of vacuum event
- magnet events
- loss of cryogen
- tritium plant events
- auxiliary system events