Fusion Reactor Safety

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The assessment of the safety and environmental (S&E) characteristics of future commercial fusion power plants (those using magnetically confined plasmas) is an ongoing effort in the European fusion programme. This article highlights the goals and results of these European assessments.

Leading S&E topics are: radiation exposure of operating staff and the public from normal operation, exposure due to accidents, and activated materials. Most discussions centre on doses due to the inherent use of tritium by the DT process and on the activation of reactor materials by fusion neutrons. Assessment emphasis is put on these aspects to clarify whether the more extreme impacts, *ie* evacuation and disposal of large waste masses in 'geological' repositories 500 to 1000 meters deep, are a matter for real concern.

The European studies in reference are Safety and Environmental Assessment of Fusion Power (SEAFP) which reported in 1995; Safety and Environmental Assessment of Fusion Power – Long Term Programme (SEAL), which aims at broadening the scope, initiated in 1995 and still ongoing; and SEAFP-2, initiated in 1996 and still ongoing. The studies are based on three different power plant 'models', each with 3000 MW of fusion power. These model designs use the database of the planned large fusion experiment, ITER, and reasonable extrapolations thereof. Overall, these models use low activation materials and cover the range of structural materials, coolants and tritium-generating materials presently conceivable for power reactors.

Model 1 assumes a vanadium alloy for the in-plasma-vessel structures, lithium oxide to generate tritium, and helium cooling for all components.

Model 2 uses low-activation martensitic stainless steel, the lithium-lead eutectic for tritium generation, and water cooling throughout.

Model 3 is based on low-activation martensitic stainless steel, all helium cooling, a ceramic breeder pebble bed and beryllium as neutron multiplier.

Models 1 and 3 emphasize the importance of avoiding chemical reactions between coolants and reactor materials, as well as improved energy conversion. All models put particular emphasis on passive safety. Tritium inventories in the reactor components are carefully minimised and are about 2 kg maximum. The normal operation dose target for the most exposed member of the public is 50 μSv/a (micro Sieverts per year). For the most severe design-basis (*ie* design-based) accidents the dose target is 50 mSv. Similar values have been proposed for future commercial fission power plants in Europe. Fusion plants are expected to achieve these without reliance on active systems or operator actions. In the context of fusion's ultimate safety potential, the International Atomic Energy Authority's (IAEA) recommendation of 50 to 100 mSv was used to make judgements on the evacuation issue.

Effluents and doses to the public

Radioactive effluents, tritium and activation products, have been assessed for normal operation. In terms of activity released to the environment, airborne tritium and tritiated effluents dominate. The estimated public doses from both tritium and activated materials, airborne and waterborne, are significantly below the target (by more than one order of magnitude).

Doses to operating staff

Doses to operating staff, both from tritium and activation products have been estimated. The potential of a reactor using helium cooling is indicated by the 0.2 man-Sv/a of collective dose for the vanadium-alloy reactor, similar to the best performance of modern pressurized water fission reactors. First conservative estimates for fusion reactors using water cooling and steel have demonstrated the necessity to reduce the mobilisation of activated steel by water corrosion. More detailed studies show that the doses can be significantly reduced by optimized water chemistry, and by taking careful account of the ex-plasma-vessel cooling loop details and neutron streaming. At present the estimated dose is about 5 man-Sv/a. An additional factor-four reduction would be expected from internal coating of cooling pipes.

Accident analyses

No uncontrolled power runaway can occur in a fusion power reactor, since reactivity excursions of the plasma are limited by inherent processes. The total fuel inventory within the plasma is so small that it will burn up typically within one minute once the supply is shut off.

Event sequences

Systematic studies were made to identify hazards and to rank event sequences in order of importance so as to guide the accident analysis effort. Representative accidents are the following: loss of reactor cooling, tritium release in the fuel system, air ingress into the plasma vessel (although it is surrounded by two barriers with a vacuum in between or an inert gas shroud), and hydrogen generation from chemical reactions between steam and hot plasma-facing materials if water is used as a coolant. Overall it has been concluded that major in-vessel loss-of-coolant-accidents are bounding design-basis accidents (*ie* the accidents with the most serious consequences) from in-plant events. The plasma will extinguish due to coolant ingress and all analyses show that any temperature increase due to heat from nuclear decay is moderate. This feature also limits the mobilization of activated materials even from the hottest surfaces. Eventually a fraction of the mobilized radioactivity will have leaked into the building, assumed to be the ultimate radioactivity confinement. Representative beyond design-basis accidents were defined by further assuming a failure to adequately operate this ultimate confinement.

Doses due to accidents

Doses to the most exposed member of the public at 1 km distance were calculated for the design-basis and beyond design-basis accidents. The prime feature is that all doses are much lower than the related dose target. The low doses arise from the combination of low mobilization (structure temperatures are always very much below the melting temperature of steel) and substantial in-plant retention. To judge on fusion's ultimate safety potential estimates of the consequences were made for the upper-bound vulnerable tritium inventory which is around 1 kg. The consequence was expressed by the dose from ground level release to the most exposed members of the public at 1 km distance from the release point. Only for the worstcase meteorological assumptions do the calculations show that the dose would exceed 100 mSv in a small sector (an area less than 1 square kilometre).

Amounts of activated material

During its life a fusion power plant would generate, from component replacement and decommissioning, radioactive material similar in volume to that from a fission plant, but of considerably lower radiotoxicity. After 10 to 100 years, integral fusion radiotoxicity indices are comparable (*ie* 4 to 5 orders of magnitude below fission plants) to those for ashes (containing small quantities of uranium, thorium and their derivatives) from coal-fired plants, having delivered the same electrical energy over their lifetimes. The total activated masses are around 65 000 tonnes. The assessments take into account 'commercial impurities' and confirm that the dominant portion of the radioactivity stems from the plasma facing components.

Waste management and disposal

The IAEA has recommended activity limits by nuclide for the release of activated materials from regulatory control by a process called 'clearance'. On this basis the most recent studies for the three models yield the following overall picture: 35 to 45% of the reactor mass could be cleared, 50 to 65% could be recycled (either by hand or with remote handing) and only a few per cent may need repository disposal.

In conclusion, fusion has a significant potential for safety. There is no uncontrolled power runaway. In the case of a total loss of active cooling the low decay heat strongly limits the mobilisation of radioactivity and excludes gross melting of reactor structures. The present view is that there would be no rupture of the radioactivity confinement due to internal events or external events with occurrence rates larger than 10^{-7} per annum and that these events can be covered by the design. Evacuation is not considered to be a matter of real concern.

Over their lifetimes fusion power plants would generate activated material similar in volume to that of fission reactors but different in that the long-term radiotoxicity would be very much lower. An important issue is the use of advanced low activation materials, and of clearance and recycling which would further ease the management of radioactive waste. Only a small fraction of the activated material may need repository disposal.

The assessments confirm that safety and environmental advantages of fusion are not entirely inherent to the fusion process but rest also on the choice of materials and on design decisions.

Overall, the studies place on a firmer footing the judgement that fusion provides ultimate safety margins thanks to the self-limiting nature of the basic reaction, modest radiotoxicity of the inventories, passive means of decay heat removal and moderate confinement requirements.

Fusion Reactor Materials

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The selection of appropriate materials for fusion reactors relies on a trade-off between multiple requirements which are mainly driven by economic, safety and environmental factors. The selection is particularly important for the most highly exposed parts of the machine such as the blanket structure. The following issues must be considered in this respect:

- **The components need to be suitable for operating under severe thermomechanical loadings and intense irradiation by energetic neutrons up to high dose rate: fluence of up to 200 displacements per atom (dpa) are expected for these plasma-facing materials.**
- **Public acceptance of fusion is tied to its pledge of cleaner energy. Therefore low activation materials allowing firstly a significant reduction in the risk of exposure of personnel to radiation damage in case of an accident and secondly solving the problem of long life wastes, are an attractive solution for these components in a commercial reactor.**
- **Making fusion economically viable requires high energy conversion efficiency and low maintenance. Materials able to work at elevated temperature with high reliability will thus need to be developed.**
- **In addition, highly advanced manufacturing processes will be developed to cope with other constraints such as complex shapes and low leak level requirements.**

A number of classes of materials able to fulfill these requirements have been identified from a reasonable extrapolation of current knowledge. The choice of a blanket structural material has also to be combined with those of the coolant, of other blanket materials and to be discussed on the basis of a global definition of the machine, taking into account their technological limits, considering their specific function and the necessity to reduce their maintenance.

Martensitic steels

Due to their excellent resistance to irradiation induced swelling, low thermal expansion and high thermal conductivity allied to industrial maturity, ferritic/martensitic (F/M) steels have been selected in the EU and Japan as the reference blanket structural material for the DEMO reactor. Recent irradiation testing in a fast breeder reactor up to 160 dpa has shown promising results and one can contemplate using these alloys for the internal structure of a fusion reactor.

The embrittlement induced by low temperature irradiation has been considered as a key issue for using the F/M steels in a fusion reactor. Indeed F/M steels are ductile at high temperature but brittle at low temperature. The transition from ductile to brittle mode of failure occurs at a temperature called DBTT. The DBTT increases with irradiation level and the steel can become brittle at reactor working temperatures. Therefore efforts are being made to shift down this critical temperature by improving the steel chemical composition but without introducing elements that would form long-lived isotopes or unacceptable corrosion behaviour. The present information on steel irradiation testing indicates that 9CrWTaV steel exhibits the best compromise between low irradiation hardening, low activation and resistance to corrosion. Control of the impurities that have the strongest impact on the long term radioactive activity is a major goal in demonstrating the feasibility of producing a low activation material on an industrial scale. This work is now in progress.

At high temperature, up to 550°C, irradiation hardening is lower or does not occur. In contrast, ductility can be lower compared to the unirradiated state. This is usually due to segregation of He at the grain boundaries. Swelling could appear.