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Safety and Environment aspects of Tokamak- type Fusion Power Reactor- An Overview

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Abstract. Naturally occurring thermonuclear fusion reaction (of light atoms to form a heavier nucleus) in the sun and every star in the universe, releases incredible amounts of energy. Demonstrating the controlled and sustained reaction of deuterium-tritium plasma should enable the development of fusion as an energy source here on Earth. The promising fusion power reactors could be operated on the deuterium-tritium fuel cycle with fuel self-sufficiency. The potential impact of fusion power on the environment and the possible risks associated with operating large-scale fusion power plants is being studied by different countries. The results show that fusion can be a very safe and sustainable energy source. A fusion power plant possesses not only intrinsic advantages with respect to safety compared to other sources of energy, but also a negligible long term impact on the environment provided certain precautions are taken in its design. One of the important considerations is in the selection of low activation structural materials for reactor vessel. Selection of the materials for first wall and breeding blanket components is also important from safety issues. It is possible to fully benefit from the advantages of fusion energy if safety and environmental concerns are taken into account when considering the conceptual studies of a reactor design. The significant safety hazards are due to the tritium inventory and energetic neutron fluence induced activity in the reactor vessel, first wall components, blanket system etc. The potential of release of radioactivity under operational and accident conditions needs attention while designing the fusion reactor. Appropriate safety analysis for the quantification of the risk shall be done following different methods such as FFMEA (Functional Failure Modes and Effects Analysis) and HAZOP (Hazards and operability). Level of safety and safety classification such as nuclear safety and non-nuclear safety is very important for the FPR (Fusion Power Reactor). This paper describes an overview of safety and environmental merits of fusion power reactor, issues and design considerations and need for R&D on safety and environmental aspects of Tokamak type fusion reactor.

1. Introduction

Achieving controlled fusion could provide civilisation with a safe, sustainable, emission free and low cost energy source. Our ability to transition from fossil fuels to renewable sources of energy will likely determine the fate of the planet. Many countries are progressing towards the goal of using solar, wind, hydro (and possible future nuclear fusion) power. For example, China decided that solar and wind power would account for 20 % of China's total energy production by 2030. Denmark, which aims to completely eliminate its use of fossil fuels by 2050 and will rely on its cutting-edge wind power industry. Germany has focused on solar and wind power in its push to remake its electricity system, Brazil now derives more than 75 % of its electricity from hydro-power sources, Similarly India is also focusing on solar energy and energy from Thorium for securing India's sustainable energy future.

India is targeting to ensure that a significant fraction (say 50 %) of electricity supply coming from non-fossil sources like renewable (hydro included) and nuclear energy by the year 2035. To ensure long term energy resource security, our effort to develop fusion energy is also very crucial. An attractive fusion power plant will need to have major safety and environmental advantages, and prove to be economically viable compared with other sources of electrical energy, to meet the needs of the second half of this century and future. A swift transition from fission to fusion not only would allow us to escape the worst medium- to long-term environmental and social ramifications of climate change, it also would enable the creation of a more stable and credible equilibrium in a world with no nuclear weapons. A world without nuclear weapons but with fissile material will always be in fragile equilibrium; a world without both would be far more sustainable. First-generation tokamak type fusion reactors generating electricity for the grid will use the heavy hydrogen isotopes of deuterium and tritium as fuels; deuterium is abundant in nature and stable, while tritium is extremely rare and radioactive, with a half-life of 12.6 years.

2. Safety and Environment merits of Fusion Power Reactor

Fusion power will not create greenhouse gases, produce other harmful pollutants or result in long-lasting radioactive waste. A reactor using nuclear fusion to generate electricity is intrinsically safe: First, a runaway nuclear chain reaction cannot take place, under any circumstances. Second, no long-lived, highly radioactive products are created. Third, of those magnetic confinement fusion reactors that will require radioactive fuels such as tritium, both the radioactive fuel requirements and fuel half-life are orders of magnitude lower than their fission counterparts. Its fuel consumption will be extremely low. A 1000 megawatt electric fusion power station would consume ~100 kg of deuterium and three tonnes of lithium a year to generate 7 billion kilowatt-hours of power. The neutrons generated by DT fusion reaction will interact with the materials close to the reactor, but careful choice of these materials will ensure that no long-term legacy of radioactive waste is produced by fusion power. It is difficult to get the fusion reaction going in the first place, however it can be quickly stopped by eliminating the injection of fuel. After engineers learn how to control the first generation of fusion plasmas, from deuterium and tritium fuels, advanced second- or third-generation fuels could reduce radioactivity by orders of magnitude as shown in table 1. Radioactivity Levels in Fusion Power Plants are very low and decay rapidly after Shutdown. The fusion energy may have advantages of competitive cost of electricity (5 c/kWh); Steady-state operation; Low level waste; Public & worker safety and High availability [1].

The volume of gas in a fusion reactor will always be low. Any problem will always cool the plasma and stop reactions - so a runaway situation is impossible. Also the raw fuels for the reactor (deuterium and lithium) are not radioactive. Tritium is mildly radioactive having a short half-life of 12.6 years, but will be produced and used within the reactor. Consequently, no transport of radioactive fuels will be needed for a fusion power plant - and even the worst possible case accidents would not require evacuation of neighbouring populations. The inherent safety characteristics of a fusion reactor are due to the very low fuel inventory in the reactor during operation and to the rapid cooling that extinguishes the fusion reactions should a malfunction occur.

The main benefits of fusion are; there is an abundance of fuel in nature: deuterium is extracted from seawater and reserves are estimated at several millions of years; tritium is produced from lithium, which is highly abundant in the Earth's crust and in the oceans.

The safety of Tokamak type fusion reactor operations includes intrinsic termination of the fusion reaction (hence no runaway reactions) in case of power transient, excessive fuel supply ,loss of fuel supply, excessive heating, uncontrolled perturbation of the plasma (e.g. by ingress of impurities), low quantity of fuel in the plasma and hence the energy of the fusion reaction, low energy density and large surfaces allowing heat transfer and use of significant heat sink masses, vacuum-tight chambers providing sealed material confinement systems, absence of high-level waste or high residual energy; the deuterium-tritium reaction produces 14.1 MeV neutrons whose interaction with the materials surrounding the plasma causes the progressive activation of these materials. However, after the plasma reaction is terminated, the residual power decreases rapidly.

Fusion is believed to have favourable safety and environmental characteristics:

- Reactors will be designed for complying with a maximise use of inherent fusion safety characteristics as intrinsic passive shutdown and fail safe termination of plasma.
- The worst accident initiated in a fusion plant could not result in the need for public evacuation from around the site.
- Waste from a fusion power plant would not become a burden on future generations.

3. Issues and Design requirements for S&E aspects of Fusion Power Reactor

Fusion's success as an energy source will depend on how the challenges to build and operate it safely and reliably can be met in a way that makes the cost of fusion electricity economically competitive. The deuterium-tritium reaction produces 14.1 MeV neutrons whose interaction with the materials surrounding the plasma causes the progressive activation of these materials. The large flux of energetic neutrons through the first wall and blanket is an issue. In the fusion reactor the damage per atom would be of the order of 80 dpa instead of 3 dpa (In case of ITER) and the Tritium consumption of about 55 kg for 1GW.year fusion power reactor. The need for developing radiation-resistant, low-activation material such as Ferritic steels, Vanadium alloys, SiC composites are essential. Tritium breeding and feasibility of the DT fusion fuel cycle are one of the main technical problems to be solved for the future fusion reactors. Dose rate in operating accessible zones of a fusion power reactor is a crucial point in calculating the Occupational Radiation Exposure for maintenance staff. It also plays a significant role in radiation shielding design.

Risk of Radioactive Tritium release:

The use of tritium induces a risk of atmospheric release of tritium in gaseous or in oxidised forms due to leaks (desorption or diffusion from the intact equipment under normal operation conditions or from the failed equipment under accidental conditions) into building rooms and then through leaks and through ventilation systems into the environment. Gaseous tritium can be oxidised and there is a risk of suspension of tritiated water aerosols in the building rooms or atmospheric release of tritiated water vapour in the rooms. Tritium contamination of water in the primary cooling systems of Tokamak in-vessel components is caused by the diffusion of tritium accumulating in the in-vessel components during plasma operation. The production of tritium by water activation is negligible in comparison with the diffusion phenomenon. Tritium is a radioelement emitting low-energy β radiation (less than 20 keV). Its specific activity is approximately 3.7×10^{14} Bq/g. The various form of tritium is gaseous tritium HT, DT or T_2. The oxidised form is tritiated water, HTO, DTO or T_2O.

The key safety requirements could be; the avoidance of sheltering or evacuation in the event of an accident; all waste generated in the fusion plant must be able to be disposed of as low level waste.

Specifically, concerning safety and environment, the following points needs to be addressed as a design requirement:

(1) It must be clearly shown that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.
(2) Radioactive wastes from the operation of a fusion plant should not require isolation from the environment for a geological time span and therefore should not constitute a burden for future generations.
(3) The worst possible accident would not be able to breach the confinement barriers. Even when a hypothesis is done that confinement barriers shall be breached, any accidental radioactive release from a fusion power station in this case cannot reach the level that would require the evacuation of the local community.

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4. ITER an experimental Fusion Reactor-Example of S&E design

The main objective of ITER is to demonstrate the scientific and technical feasibility of a controlled fusion reaction capable of the production of approximately 500 MW of fusion power for durations of several hundred seconds. ITER is an experimental facility as shown in figure 1, whose purpose is to demonstrate the control of plasma and the fusion reaction using deuterium (D) and tritium (T) as fuel. It will allow the exploration of plasma scenarios and technological testing essential for the preparation of a future fusion reactor. Hence the goal of ITER during its nominal 20 years operating period is to:

- Achieve fusion plasmas with a ratio Q of fusion power produced to external power supplied (Q-factor ratio) ≥ 10 between 300 to 500 s duration.
- Test the feasibility of controlled ignition.
- Demonstrate the availability and integration of technologies required for a fusion power reactor (e.g. in-vessel components, superconducting magnets, remote maintenance systems, tritium production and fuel cycle).

ITER is an indispensable step for the pursuit of the program of development of fusion energy, with the final objective being to achieve a fusion power reactor. The main goal of ITER is to demonstrate the safety and environmental potential of fusion and thereby provide a good precedent for the safety of future fusion power reactors. Key aspects of the safety of ITER are effluents and emissions during normal operation, occupational safety of workers at the site, proper storage and treatment of radioactive materials generated during operation and decommissioning, and potential accidents and incidents. To ensure the safety of ITER, top-level safety objectives have been defined;

- General safety: to protect individuals, society and the environment; to ensure in normal operation that exposure to hazards within the premises and due to release of hazardous material from the premises is controlled, kept below prescribed limits and minimised; to prevent accidents with high confidence, to ensure that the consequences of more frequent events, if any, are minor; to ensure that the consequences of accidents are bounded and the likelihood is small.

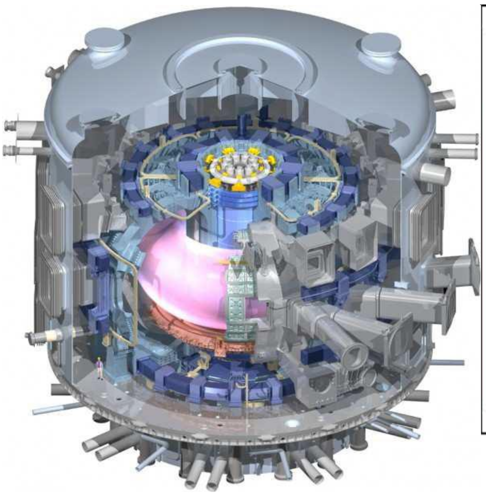

Figure 1. 3D view of ITER

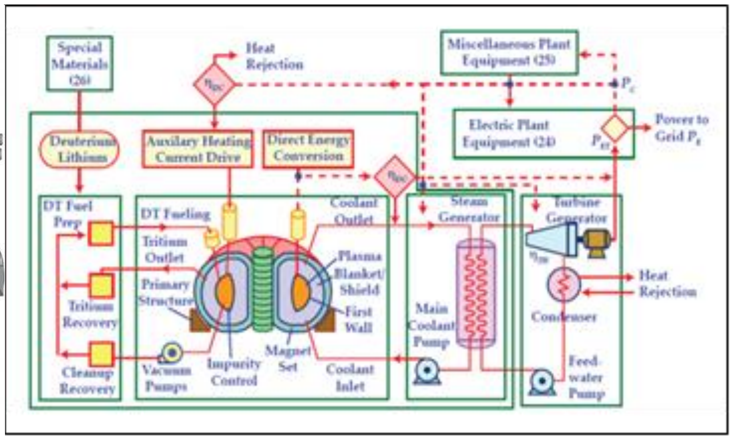

Figure 2. Schematic of a typical Fusion power Reactor

- No evacuation: to demonstrate that the favourable safety characteristics of fusion and appropriate safety approaches limit the hazards from internal accidents such that there is technical justification for not needing evacuation of the public.
- Waste reduction: to reduce radioactive waste hazards and volumes.

These objectives have been defined based on internationally recognized safety criteria and radiological limits following ICRP and IAEA recommendations, and in particular on the concept of defence in depth and the As Low As Reasonably Achievable (ALARA) principle.

Comprehensive safety and environmental assessments of the ITER design and operation have been performed under site specific assessments required for the licensing process in France. The result of the study has been reported in the Preliminary Safety Analysis Report.
ITER will be a precedent for future fusion licensing. Safety functions that have been defined for ITER differ slightly from fission approach since "limitation of exposure for workers and environment" is also considered as a safety function in the scope of Cadarache site licensing [2].
The potential nuclear risks induced by the DT fusion reaction in the ITER facility are following [3]:

- Risk of radioactive materials release (risk potentially impacting personnel, the public and the environment).
- Risk of external exposure (mainly concerning personnel).

The following radioactive materials are identified in the ITER facility:

- Tritium, inherent to deuterium-tritium fusion reactions and also produced by nuclear reactions in beryllium and in the lithium contained in materials used in TBM.
- Activated products that are mostly produced and located in the in-vessel components. Smaller quantities are also produced and located in the components outside the vacuum vessel or in the cooling systems of the in-vessel components.

With respect to the radiological risks identified, the following two safety functions have been adopted for the ITER installation:

- Confinement of radioactive material.
- Limitation of external exposure to ionizing radiation.

The risk of exposure to ionizing radiation potentially affects installation personnel. This risk is associated with neutrons, produced during fusion reaction and emitted from the plasma, the γ radiation emitted by activated products, X-rays emitted by some heating and current drive generators and the β radiation emitted by tritium.
Safety considerations for the ITER:

- Analysis of normal operation illustrating the measures to optimize the design, based on the ALARA principle.
- Preliminary safety studies relating to design basis accidents and beyond design basis situations.
- Preliminary safety studies relating to internal and external hazards and structural design justification with regard to the hazards considered.
- Preliminary assessment of radiological impact on workers and the environment in normal, incident and accident situations.
- Internal emergency plan design for ITER facility.

5. S&E approach in design of future Fusion Power Reactor

A fusion power plant possesses not only intrinsic advantages with respect to safety compared to other sources of energy, but also a negligible long term impact on the environment provided certain precautions are taken in its design and in the selection of structural materials [4]. Safety consists of taking measures to avert any hazards that could jeopardise a facility. In particular, this means preventing accidents and if they occur minimising their consequences. In the genesis of the idea of fusion reactors, the notion of safety appeared very early on in the literature. Thus, at the IAEA conference in 1971, the first TOKAMAK-type fusion power plant as well as a first safety assessment was presented [5]. The 1989 ESECOM Report, for example, drew up a first comparison of various possible reactor options with regard to safety [6]. A few years later, the Colombo Report stressed that fusion potentially possesses 'inherent environmental and safety advantages over all current alternatives for base load electricity generation' [7]. Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity. Low-activation material will generate low Rad-waste. Rad-waste generated in DT fusion is similar to advanced fuels (D-^{3}He). For liquid coolant/breeders (e.g. Li, LiPb), most of fusion energy (carried by neutrons) is directly deposited in

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the coolant simplifying energy recovery. The safety relevance characteristics of D-T and advanced fusion fuels is shown in table 1.
The safety approach shall respect two major important points:

(1) The worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.
(2) Radioactive waste from the operation of a fusion plant should not constitute a burden for future generations.

The licensing process for Fusion Power Reactor (FPRs) may well be regulated with common administrative procedures and supportive licensing documentation as being done for Fission Reactors. From the owner's point of view, a FPR could be contracted as turnkey plant and the FPR supplier would be responsible for obtaining Design Approval once compliance with the country's legislation had been substantiated, and the owner would be responsible for the operating permit once the site had been selected.

Table 1. Comparison of characteristics of D-T and advanced fusion fuels with relevance to safety [8, 9].

Characteristic	D-T	D-D	D-^{3}He	D-^{6}Li	p-^{11}B
Main reaction products and energy yield (MeV)	n + ^{4}He + 17.6	p + T + 4.0 n + ^{3}He + 3.3	p + ^{4}He +18.3	2 ^{4}He + 22.4 p + ^{7}Li + 6.0 n + ^{7}Be + 3.4 p + T + ^{4}He + 2.6 n + ^{3}He + ^{4}He + 1.8	3 ^{4}He+8.7
Energy yield per reaction pair (MeV)	17.6	>3.65[a]	<18.3[b]	Not quantified	8.7
Fraction of energy carried by neutrons (%)	80	35	Small	Not quantified	None
Neutron energy (MeV)	14.0	2.45(14.1)[a]	2.45(14.1)[b]	2(14.1)	-
Ratio of activation in structure (%)	100	20 to 60	25	20 to 60	-
Radioactive fuel or ash	T	T	T	T, ^{7}Be	-
Total inventory of Tritium (kg)	10	0.1	0.01	0.001	-
Special fuel cycle requirements	Li blanket	None	Production fusion reactors for ^{3}He	None	Feasibility for ignition is doubtful

[a] The energy limit is due to contributions from D-T side reactions.
[b] contributions from D-D and D-T side reactions.

The radioactive material in a fusion reactor includes tritium gas, burned as a fuel, and activation products produced by high energy neutrons from the fusion reactions. Ensuring that these materials will not affect the environment and public, requires a strategy to minimize inventories, develop adequate containment and control, and eliminate potential release mechanisms. The accident with the greatest potential for a large radioactive release is a lithium fire. Less active forms of lithium, under consideration for use in fusion reactors, would eliminate this concern. Potential energy releases from large magnet systems, and the health effects of long-term exposure to magnetic fields are also concerns.

The Safety and Environment (S&E) objectives set by various study of conceptual designs of Fusion Power Reactors by EU, US and Japan are as follows[10]:

European Safety and Environmental Assessment of Fusion Power (SEAFP) looked at conceptual designs of fusion power stations and their safety and environmental assessments and set the S&E objectives:

- It must be clearly shown that the worst possible fusion accident will constitute no major hazard to populations outside the plant perimeter that might result in evacuation.
- Radioactive wastes from the operation of a fusion plant should not require isolation from the environment for a geological time span and therefore should not constitute a burden for future generations.

The US fusion S&E objectives:

- The avoidance of sheltering or evacuation in the event of an accident; all waste generated in the fusion plant must be able to be disposed of as low level waste (e.g. Class C by US rules).
- The facility must demonstrate that day to day activity in the local community is not disturbed and that workers must not be exposed to risks greater than from other power plants.

The Japanese fusion S&E objectives:

There is no official recommendation for the safety and environmental objectives for future fusion power plants. However, it is believed that for a fusion power plant to obtain social acceptability it is important to significantly improve environmental and safety aspects over those of fission power plants. IAEA public information sheets summarises how to promote safety in the nuclear installations [11], which perfectly applies to the future fusion reactors: safety analysis is conducted on the whole range of plant situations: normal operation, anticipated operational occurrences and possible accidents. By examining all these situations in detail, the robustness of the plant design and the effectiveness of the safety systems have to be demonstrated. A safely designed nuclear power plant is one that ensures basic functions at all times, even in an accident situation. All possible accident scenarios have to be taken into account at a very early stage in the design process. Appropriate safety analysis for the quantification of the risk shall be done following different methods such as FFMEA (Functional Failure Modes and Effects Analysis) and HAZOP (Hazards and operability). Safety analysis shall include systematic identification and ranking of the potential accident sequences within design basis and beyond design basis.

6. Safety classifications and its level

The safety classification for SSCs of FPR based on their functional boundary, like nuclear safety function and non-nuclear safety functions etc. is very important. Safety level shall be defined based on the radiation releases and shall be classified as class II, III or N2 and N3 as per ASN and ESPN respectively. Seismic categorization of SSCs of FPR is crucial for radiation releases. In case of FPR tritium release is more crucial. A set of top level system requirements and goals for system economics, safety and waste disposal, and reliability and availability needs to be established for demonstration and commercial fusion power plants. For all the possible version of future reactors it should be considered that a fusion plant is not only a fusion-machine reactor and the same importance should be paid to all the nuclear buildings and to their integration and interfaces. The schematic of typical tokamak type fusion reactor is shown in figure 2.

7. Conclusion

Fusion power possesses numerous advantages with which to meet the challenge of safety and protection of the environment in the future. It appears possible to ensure negligible radioactive releases whatever type of accident is postulated, as well as a very small volume of wastes requiring permanent disposal. At the end of a fusion power station's working life the radio toxicity in the reactor chamber and other structural and waste materials will decay rapidly. In less than 100 years the residual activity of these materials would be less than the radio toxicity found in the waste from a conventional coal-fired power station. Fusion power will not burden society with a long-term toxic waste issue. However, to meet these objectives, this concern has to be taken into account in the early design stage of the reactor: the choice of material and appropriate safety systems. In addition, specific R&D needs to be performed in order to confirm the safety assessment and to develop efficient and reliable safety systems.

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