Safety Methodology Implementation in the Conceptual Design Phase of a Fusion Reactor

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Abstracts

The licensing of ITER in France represents the first process for licensing a fusion facility in the framework of an experimental device with a total Tritium inventory of 3 kg. The main ITER parameters are far from those expected in the future demonstration reactors where the fusion power will be at least 5 times higher and the additional heating power could also reach up to 5 times the one foreseen in ITER. Main safety requirements for these reactors are based, among other conditions, on their inherent features as low amount of fuel, very low impurity content of structural materials, minimum waste repository, no active systems for safe shut-down, and no need for evacuation of population after the most severe accident. The design of such reactors is at the stage of conceptual studies and is mainly dealing with plasma performances, tritium breeding, blanket/divertor designs and solution of engineering issues, as well as bounding accidents or classification of waste [1].

The methodological approach for integrating safety analysis as a tool for optimizing the design of the overall fusion installation for future reactors in the conceptual design phase is sketched, including the machine itself and the different auxiliary nuclear buildings.

1. Introduction

Since last Technical Meeting on Fusion Reactor Safety [2] few facts have changed the bounding conditions of the future of fusion energy: ITER site has been chosen, the establishment of a new organisation of ITER in undergoing, ITER is entering in the phase of detailed design.

This allows following up the licensing and construction of ITER for getting feedback experience and planning the next step for DEMO and future reactors in a concrete and realistic way, although the approach will still stay generic because of the unknown parameters related with results of the forthcoming research.

In the following a feedback of safety knowledge in fusion is summarised, then the feedback of fission installations is recalled and the application of the Defence In Depth (DID) to fusion reactor is presented together with an illustrating example and few forthcoming new issues which are underlined. The conclusion focuses in the way to integrate the present knowledge in sound safety attitude for future fusion reactors design.

2. Safety culture in the fusion community.

The relationship of the Fusion Community with safety issues has been evolving in the last years. In Magnetic Confined Experiments (MCE), although tokamak fusion research has concentrated upon resolving the issues for power production, most experiments have not used tritium, due to the requirements of handling the radioactive gas and of dealing with the 14...
MeV neutron activation [3]. Only two fusion machines in the world have been prepared for tritium handling and have been involved in safety and licensing procedures: TFTR and JET.

In 1991 JET performance had reached the level which warranted the use of tritium for the first time in a laboratory plasma experiment. A peak fusion power of 1.7 MW was produced, averaging 1 MW over a 2 second period. This was the world first controlled production of significant fusion power. In 1993, TFTR became the first tokamak experiment to use a 50:50 deuterium-tritium mixture resulting in 11.5 MW of fusion power [4]. In 1997, 16 MW of fusion power was obtained in JET, and alpha particle heating clearly observed [5]. Since then T-traces have been used in JET for tritium transport plasma studies [6]. Tritium laboratories for fusion research also play an important role in the safety understanding in the fusion community.

Inertial fusion research, which is now in the design or construction phase of new experimental reactors, is also enlarging the safety culture of the fusion community. In the last years a significant progress has been made in several areas related to the safety and environmental aspects of inertial fusion energy (IFE). See [7, 8] and presentations at this meeting.

2.1-DT TFTR experiment


During the DT campaign in TFTR, the tritium fuelled the plasma either by gas puffing or by tritium neutral beam injection. For than 3 years, about 1MCi (37 PBq) of tritium (100 g) had been processed while maintaining a 50 kCi site limit. During the last 3 months of TFTR operation, the tritium was processed on site, with a tritium purification system. During this time and also during the post operation shutdown, the radiation doses to PPPL workers were maintained at pre-tritium levels [9,10]. The key factors, which allowed this safety record, were thorough documentation of the installed hardware and careful planning of all activities. The TFTR Decontamination and Decommissioning (D&D) Project started at the beginning of October 1999. The last commitment of the TFTR Project was the removal and safe disposal of the TFTR device. The TFTR D&D Project was completed in three years in time and cost [11].

2.2-DT JET experiments

A safety case for JET D-T operation was required before starting DT experiments. UK requirements and standards were followed. This corresponded to a formal approval for tritium operation for the Active Gas Handling System (AGHS) and for the torus systems. [12] Safety principles were identified. Accident sequences were analysed both with deterministic and probabilistic methods. Results in terms of source terms, on-site and off-site doses were carried out. Although an extension for JET has been recently approved in the scope of the Broad Approach and JET ITER-relevant experiments the dismantling of JET in part of the UKAEA decommissioning safety [13]. As neutron production has been much lower than the original programme, activation is significantly lower and tritium is the dominant decommissioning strategy.
2.3-Other safety related activities.

In the last years a big effort has been done mainly in the preparation of ITER and other projects in source term hazard characterization, energy source evaluation, safety assessment tool development [8] and fusion safety methodology [14,15,16]. For example, a big effort of experience gathering data is held through the failure mode and effect analysis data collection in fusion machine and from tritium laboratories: the Tritium Systems Test Assembly at Los Alamos (TSTA), the Tritium Process Laboratory at Naka, the Active Gas Handling System at JET, the Tritium Laboratory Karlsruhe [17,18]. In spite of this, only specialised articles mention the related safety R&D activities when summarising fusion activities. This could be due to the fact that fusion has been generally considered as being out of the classical nuclear framework or because safety has been a second priority in fusion, maybe for preserving a favourable public perception. The IFRC reported in 2005 on fusion research in the world: about 7% of the article is safety related information [19]. It should be checked if this is the appropriate weight to be put for safety in fusion reactor design in agreement with the risks.

3. The fission background in the design phase

Nevertheless is obvious that thanks to the nuclear fission, the development of safety related activities in fusion has been eased and that the existing background should continue to be extrapolated to fusion. Fission approach was presented to a large fusion community during the 21st Symposium on Fusion Technology in an Invited talk [20] where it was quoted that the three basic fission safety functions can also be applied to fusion power plants: control of the nuclear fission process in the reactor core, removal of heat from the core, confinement of the radioactive materials. It was also pointed out that the first two are of lower significance because of the limited potential of a fusion power increase and the lower power density of activated material, concluding that the most important basic safety function is the third one, asking for a very reliable confinement system which has to stay intact during accidents, including those originating from magnetic systems, and after internal (e.g. fire) and external hazards.

IAEA public information sheets summarises how to promote safety in the nuclear installations [21], 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.

IAEA Safety Series No. 110 on nuclear installations Safety, specifies the following design principles:

- The design shall ensure that the nuclear installation is suited for reliable, stable and easily manageable operation. The prime goal shall be the prevention of accidents.
- The design shall include the appropriate application of the Defence-In-Depth (DID) principle so that there are several levels of protection and multiple barriers to prevent releases of radioactive materials, and to ensure that failures or combinations of failures that might lead to significant radiological consequences are of very low probability.
- Technologies incorporated in a design shall be proven or qualified by experience or testing or both.
• The systematic consideration of the man–machine interface and human factors shall be included in all stages of design and in the associated development of operational requirements.
• The exposure to radiation of site personnel and releases of radioactive materials to the environment shall be made by design As Low As Reasonably Achievable (ALARA).
• A comprehensive safety assessment and independent verification shall be carried out to confirm that the design will fulfil the safety objectives and requirements before the operating organization completes its submission to the regulatory body.

Recently implementation of the safety in the design phase has been underlined in an “Overview of the European Union fusion nuclear technologies development and essential elements on the way to DEMO”: It has been recognised that a safe reactor will not depend solely on factors inherent to the fusion process itself but also on appropriate plant design [22].

4. Safety approach in future fusion reactor

Fission methodology approach has been extrapolated to fusion, considering the fusion specificities, mainly the lack of criticality and no need of fuel cooling. Future reactors will follow today internationally accepted basic principles and safety criteria for fusion energy. 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.

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 [23]. Confinement of radioactive material and removal of fusion product decay heat are the two other functions that have been considered, although the last one will benefit of quicker decay of lower activated materials under research for future reactors. In addition ITER is far from fusion reactor conditions where damage per atom would be of the order of 80 dpa instead of 3 dpa and far from the Tritium consumption of about 55 kg for 1GW.year fusion power reactor. In this conditions 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.

Then, the generic methodology of fission applies to fusion reactor design as already pointed out in [20] and first applied in [14]. Avoidance of unacceptable risks is the main goal of the safety and this is implemented since the design phase by mitigation of the damage and reducing the occurrence of the damage. Consequently, the first step is to define the source term and the energy sources and the associated risk and check that the foreseen safety functions are implemented through an appropriated design, which will respect the safety limits. The second step is to study internal accidental situations and internal and external hazards that will lead to design safety protection means satisfying the safety functions. Internal hazards like fire or explosion can have an impact in the design. The calculation of the radiological consequences should be focused in checking that they will be inside the safety limits and that the foreseen prevention systems and protection means are good enough for
harnessing the effluents and releases in respect of the function of confinement and limitation of the exposure for workers and environment. The five levels of DID principle are the basis for the implementation of the safety in the conceptual design. The fifth level will not apply in fusion reactors for which no evacuation of population is a requirement. The safety approach should demonstrate that the foreseen means for implementing the DID level allow keeping the facility below the safety limits during normal operation (including maintenance) and in incidental and accidental conditions. In particular ALARA principle must be implemented in the design phase avoiding later modifications of buildings or systems for implementation of an optimisation that was not initially foreseen. 

Up to now, the methodological approach to the design have been mainly deterministic for accident analyses although it can be expected that for the future fusion reactors probabilistic risk assessment could be required following regulators recommendations (for example [24]) and supported by a data basis that may be improved by future fusion experiment inputs [18]. Forthcoming tools would also need to be progressively introduced.

5. Steps forward integration of safety in the design of future reactor

Safety improvement will always been practised. It is a continuous process especially due to two principles: the continuous integration of the most recent state-of-the-art in science and technology and the use of the feedback from operating experience. ITER being an example of licensing a fusion installation [25], it is expected that all the results will be a valuable database for future reactors. Apart from the safety features already indicated above, future fusion reactors will share nowadays unknown systems: A core with plasma at Q>10 in a still to be define configuration, T-breeding systems, DT fuel cycle, Low activity materials, Remote handling and very high automatism, …

Besides, depending on the type of fusion machine and the type confinement, based on magnetic or inertial confinement, auxiliary systems will be developed: Superconducting coils, Heating systems, Laser drivers, Target fabrication and injection, Reduced number of diagnostics, …

For all the possible version of future reactors it should be considered since an early phase 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 scheme in figure 1 illustrates this enlarged approach to safety. Although Tritium laboratories and hot cells are classical nuclear installations, fusion will have specific features related to the large size that the systems and components could have, from the today’s extrapolations. As an example tritium plants operate now with off-the-shelf components, but large isotopic separation systems will be new brand ones and will need to be qualified and withstand internal and external hazards. The iterative process of assessment of the safety design illustrated in figure 2 applies to all the parts of the future fusion reactor.

6. References

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[17] CADWALLADER L. C., Comparison of Tritium Component Failure Rate Data. Fusion Science and Technology, 47(4), (2005), 983-988
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Auxiliary systems
Control system
Auxiliary systems

Power supply
Control system
Auxiliary systems

Ventilation
detritiation
System

Hot cells-Radwaste

Figure 1: schematic of a fusion power plant

Accidental Scenarios
• Transients
• Accidents

Analysis of the events
Models, codes, experiments,
(Damage, frequency)

Safety functions
Safety Objectives

Design
Systems
Equipments
Buildings

Modification

Optimisation

Cost/Benefit

Implementation in the Design

Figure 2: Safety analysis scheme