Nuclear Safety and Nuclear Safety Culture in Fusion Reactors

The international nuclear community gives priority to Nuclear Safety in order to protect the population, workers and the environment from the harmful effects of ionizing radiation. It also recognizes the importance of establishing, developing and maintaining a positive Nuclear Safety Culture. Nuclear Safety basic concepts and principles are implemented in each country member legislations and are applicable also to Fusion Reactors.

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Introduction

Nuclear Safety (NS) refers to all the technical dispositions and the organizational measures taken to prevent accidents or to limit the effects during the manufacturing, functioning, cessation and disassembly of nuclear installations with ionizing radiations sources as well as during the transport of radioactive substances. Nuclear organizations consider that NS is the top priority over other competing goals like time and budget when dealing with nuclear projects. All the possible measures should be considered to protect the population, workers and the environment from the harmful effects of ionizing radiation [1-7].
Nuclear Safety Culture (NSC) refers to the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety to ensure protection of people and the environment [5]. NSC applies to every stage in the nuclear plant life cycle including design, construction, operation, shutdown and decommissioning. The purpose of NSC is to limit the impact of a failure in a nuclear installation on people health and the environment on the long run; hence the necessity of a particular attention in Nuclear Safety for all installations.
Ensuring NS and a strong NSC is a fundamental expectation of each Nuclear organization involved in nuclear activities including those that deals with the fission and fusion fields [1-10].

Nuclear Safety concerns in fusion and fission reactors

There are specific differences between the implementations of Nuclear Safety (NS) concepts in fusion and fission reactors due to the physical and technological characteristics of each. However, nuclear safety concepts that are adopted in fusion reactors are based on those of other types of installations with radioactive materials, especially from nuclear fission power plants. Defense in Depth (DiD) is a safety philosophy that guides the design, construction, inspection, operation, and regulation of all nuclear facilities to protect public, workers and the environment.
A common risk framework for the safety of fusion devices is under development with the active support of all the main actors involved on this new technology.
In fusion facilities the NS concerns are somehow different from fission power plants. Fusion reactors, unlike fission reactors, produce no High activity Level and long life radioactive Waste (HLW). The burnt fuel in a fusion reactor is helium, an inert gas. Activation produced in the material surfaces by the fast neutrons will produce waste that is classified as Very Low activity Level Waste (VLLW), Low Level Waste (LLW), or Medium Level Waste (MLW). All waste materials - such as components removed by remote handling during operation - will be treated, packaged, and stored on site. Because the half-life of most radioisotopes contained in this waste is lower than ten years, within 100 years the radioactivity of the materials will have diminished in such a significant way that the materials can be recycled for use in other fusion plants. Through the continued analysis and development of low activation materials, LLW and MLW could possibly be reduced in future devices.
In fusion reactors, there are also energetic (14.1 MeV) neutrons and small amounts of tritium, a radioactive form of hydrogen with a half-life of 12.3 years, that will be used as fusion fuel together with deuterium.

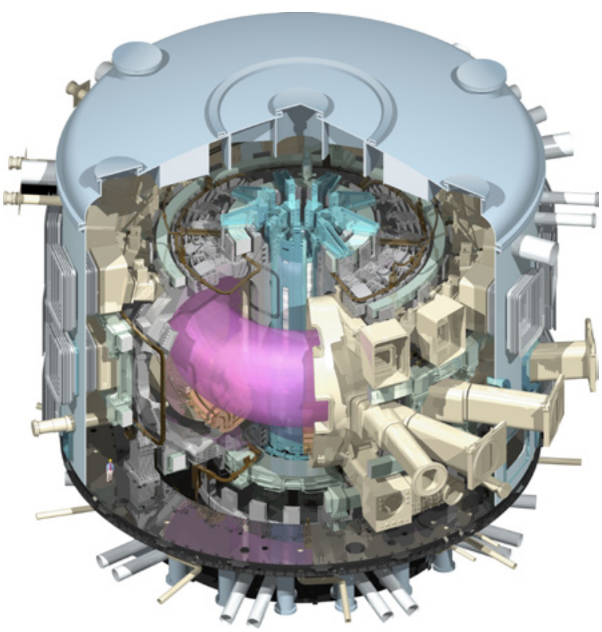


Fig. 1

ITER (International Thermonuclear Experimental Reactor).

ITER Fusion Reactor

International Thermonuclear Experimental Reactor (ITER) is the world's largest fusion experiment that is being built next to the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) Cadarache facility in Saint-Paul-lès-Durance, in Provence, southern France. ITER is a major international collaboration to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. The project is funded and run by seven member entities: People's Republic of China, the European Atomic Energy Community (Euratom), the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. Overall, 35 countries are participating in the project directly or indirectly.
The purpose of the ITER Organization (IO) is to provide for and promote cooperation among its Members for the benefit of the ITER Project. It acts as the overall integrator of the project and nuclear operator of the ITER facility.
Upon completion, ITER will be the largest of more than 100 fusion reactors built since the 1950s. Its planned successor, DEMO will be the first fusion reactor to produce electricity in an experimental environment leading to full-scale electricity-producing fusion power stations and future commercial reactors [9, 10].

Nuclear Safety in ITER

ITER is classified as a basic nuclear installation—an Installation Nucléaire de Base (INB) in accordance with French nuclear safety regulations, which ITER Organization (IO) observes. ITER is identified in France by the number "INB no. 174". Like any nuclear installation in France, ITER submits to the stringent controls and inspections of the country's regulatory body Autorité de Sûreté Nucléaire (ASN).

The ASN Nuclear Safety Autority demanded the same approach as for any nuclear installation in France, where it is the responsibility of the nuclear operator - IO for the ITER project - to define safety objectives and functions, identify risks, and describe means to mitigate and minimize them. ITER is the first fusion device fully categorized as a nuclear installation that had successfully gone through the process of nuclear licensing. Throughout construction, commissioning and operation, ITER's safety processes will always comply with French regulations, as verified regularly through audit and inspection by the French nuclear authorities. "Generic" safety studies for ITER began in the mid-1990s, at a time when a site had yet to be chosen to host the installation. These studies where later adapted to the present location in Cadarache (France) [9, 10].

The main French regulations applicable to ITER are briefly summarized in Figure 2.

The main INB regulation, carefully observed by IO, is the order dated 7 February 2012 relating to the general technical regulations applicable to basic nuclear installations or "Arrêté du 7 février 2012 fixant les règles générales relatives aux Installations Nucléaires de Base" [11].

With Decree No. 2012-1248 dated 9 November 2012, IO was authorized to create a basic nuclear facility called "ITER".

With ASN Decision 2013-DC-0379 dated 12 November 2013, the prescriptions applicable to IO for the design and construction of the licensed nuclear facility INB No. 174 called ITER were established.

With ASN Decision 2015-DC-0529 dated 22 October 2015, ITER requirements were amended.

With ASN Decision 2017-DC-0601 dated 24 August 2017, ITER prescriptions were amended.

ITER is inherently safe

The fundamental differences in the physics and technology used in fusion reactors make a fission-type nuclear meltdown or a runaway reaction impossible. The fusion process is inherently safe.

In a fusion reactor, there will only be a limited amount of fuel (less than four grams) at any given moment. The reaction relies on a continuous input of fuel; if there is any perturbation in this process and the reaction ceases immediately. Even in the event of the total loss of the cooling function, ITER's confinement barriers would not be affected. The temperatures of the vacuum vessel that provides the first confinement barrier would under no circumstances reach the melting temperatures of the materials.

The confinement of the tritium radioelement within the fuel cycle is one of the most important safety objectives at ITER although the amount of tritium used during plasma pulses is very small and of the order of only a few grams at any one time.

Defense in Depth for fusion reactors like ITER

The central purpose of the Defense in Depth (DiD) concept is to protect the health and safety of the public, workers and environment. Successful DiD requires creating, main-

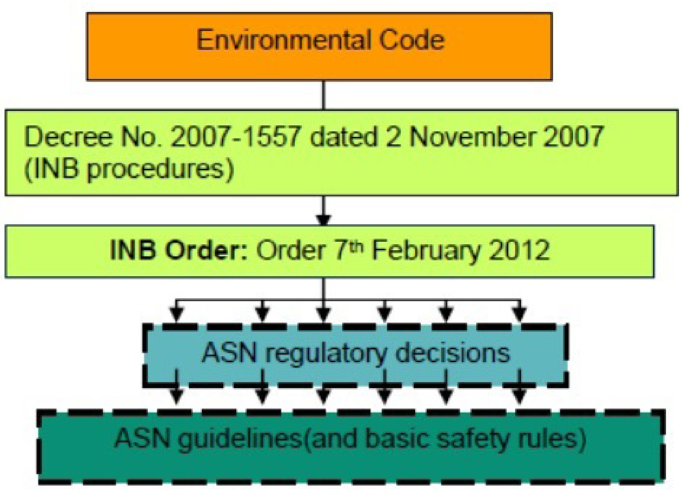
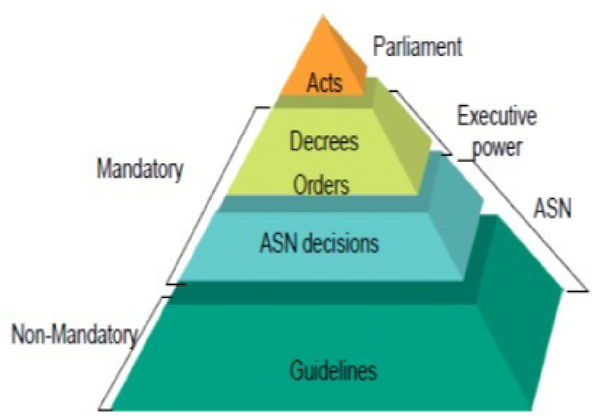


Fig. 2

Main French regulations applicable to ITER.



taining, and updating multiple independent and redundant layers of protection to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon.
A multiple-layer barrier system has been designed to protect against radioactive releases from fusion reactors into the environment.
The first level of the safety confinement barrier is the fusion reactor's Vacuum Vessel (VV). Beyond the VV there is a second level of security comprising the buildings and advanced detritiation systems for the recovery of tritium from gas and liquids. Where tritium is handled, an efficient static confinement barrier with air pressure cascading in the buildings will inhibit the outward diffusion of tritium.
Even in the event of a cataclysmic breach in the tokamak, the levels of radioactivity outside the ITER enclosure would remain very low. The ITER Preliminary Safety Report presents an analysis of risks that demonstrates that during normal operation, ITER's radiological impact on the most exposed populations will be one thousand times less than natural background radiation. For postulated "worst-case scenarios," such as fire in the Tritium Plant, the evacuation of neighboring populations would not be necessary.

Beryllium management in ITER

IO dedicated much efforts for the safe handling of beryllium, which has been chosen as armor material for the plasma-facing components of the ITER Vacuum Vessel (VV). Beryllium is classified as a potential carcinogenic. The inhalation of beryllium dust can cause severe respiratory problems, although in block form the material does not present much risk. Dust can result when microscopic residue surface particles on the beryllium are released into the air due to transport, handling and/or assembly activities.
From a licensing point of view, the French regulator ASN requested that special attention be paid to this toxic material since it provides the highest risks for the workers, the public and the environment. There is an airborne concentration limit above which specific control measures are necessary; thus, all industries manufacturing or employing beryllium components must set up procedures in order to satisfy safety requirements. The blanket is the component that will make the most use of beryllium due to the compatibility of this element with the plasma as well as its good thermal and mechanical properties. Other ITER components will also employ beryllium, albeit on a much lower scale.

Nuclear Safety Culture for nuclear fusion organizations

There are specific differences between the implementations of safety concepts in fusion and fission reactors due to the physical and technological characteristics of each. However, NSC main concepts that are adopted in fusion reactors are also based on those of other types of installations with radioactive materials, especially from nuclear fission power plants.
The highest level affecting nuclear plant safety is the legislative level, at which the national basis for Nuclear Safety is set. Safety policies and their implementation, promoted at all levels within nuclear organizations, create the working environment and conditions for individual behaviors.
All organizations involved in nuclear activities makes its responsibilities well known and understood to all staff with the public commitment of management to NSC.
NSC relies on:
- The management commitment to give priority to the safety principles in the decisions;
- The individual responsibility to report in full transparency;
- A questioning attitude (understanding the purposes, knowing the limits of procedures);
- A rigorous and cautious approach for each person - duty of alert exercised;
- The know-how and competences proved by training, accreditation, qualification;
- The persons motivation for setting goals, recognitions, penalties.

Figure 3 presents the NSC cycle: the top of the NSC structure is the policy level, secondly managers and finally employees. The structure is presented as a cycle in which there is a continuous feedback between all the level because all levels and their interaction must be considered: top-down from the managers and bottom-up from the employers.
An open communication is one of the fundamental aspects of NSC and is assuring the interaction inside and between all levels.

Fig. 3

Nuclear Safety Culture (NSC) cycle.

Principles of a healthy NSC

The knowledge of the principles related to NSC is important not just to meet the precise legislative requirements, but also for users themselves. A worker that is conscious and appropriately informed about critical issues and possible matters related to safety aspect of his activities, knows how to put into effect all the procedures; this demonstrate a strong NSC.
The essential traits and attributes of a healthy NSC has the goal of creating a framework for open discussion and continuing evolution acting such that NSC is emphasized over competing priorities. Several main fundamental principles guarantee a good NSC and are generally valid for leaders and employees.
The top ten principles of a positive NSC [1-6] are divided into the following three main categories (A,B,C):

A. Management Commitment to Safety
1. Leadership Accountability
2. Decision-Making
3. Respectful Work Environment

B. NSC Management System
4. Continuous Learning
5. Problem Identification and Resolution
6. Environment for Raising Concerns
7. Work Processes

C. Individual Commitment to Safety
8. Personal Accountability
9. Questioning Attitude
10. Safety Communication

Management Commitment to Safety

The Top Management Commitment to Safety can be considered in three main traits:

1. Leadership Accountability
Leadership need a capable organization and information to make good decisions. Executives and senior managers are the principal supporters of NSC and prove their commitment in their decisions, in words and actions. The NSC message is communicated frequently and consistently, occasionally as a standalone theme and/or by NSC dedicated meetings. Leaders throughout the nuclear organization set an example for safety. Corporate policies emphasize the overriding importance of NSC.

2. Decision-Making
Decisions that support or affect NSC are systematic, rigorous and complete. Top Management shall establish a well-defined decision-making process. Information feed forward and feed-back through the management system. Senior leaders must support and reinforce conservative decisions.

3. Respectful Work Environment
Trust and respect permeate the organization. A high level of trust is established in the organization, promoted, in part, through timely and accurate communication. Differing professional opinions are encouraged, discussed, and resolved in a timely manner. Employees are informed of steps taken in response to their concerns.

NSC Management System

The key to an effective NSC in individuals is found in the practices involved in the environment and adopting attitudes contributing to NSC. It is the responsibility of Management to institute such practices in accordance with the NSC principles and purposes inside the organization.

4. Continuous Learning
Opportunities to learn about ways to ensure NSC are pursued and implemented. Operating experience is highly valued, and the capacity to learn from experience is well developed. Training, self-assessments, and benchmarking are used to stimulate learning and improve performance.

5. Problem Identification and Resolution
Problems potentially impacting NSC are promptly identified, fully evaluated, quickly addressed and corrected commensurate with their significance. Identification and resolution of a general spectrum of problems, including organizational matters, are used to reinforce NSC and improve performance. Leaders are responsible for identifying and diagnosing organizational or technical deficiencies, taking corrective action, and anticipating emerging complications. All members support problem identification and resolution by promptly raising and reporting concerns (for example, by working through a corrective action program).

6. Environment for Raising Concerns
Promoting an environment for raising concerns is an important attribute of a Positive NSC. It must be ensured a work environment in which all employees are encouraged to raise NSC concerns and to give their feed-back and share their ideas and opinions.

7. Work Processes
The process of designing and controlling work to ensure NSC is an important feature of a good NSC. For example, effective work processes in a positive NSC have a well-designed workflow that includes the assignment of responsibilities to leaders, work

groups and individuals. Work activities are prioritized, coordinated across workgroups and communicated effectively. Policies and procedures incorporate the appropriate risk insights and be effectively planned, executed, verified, and documented. The rigorous development, management and observance to work processes reflects a positive NSC. Particular attention is placed on Documentation (created and maintain complete, accurate, and updated) and Procedure Adherence (processes, procedures and work instructions), Audit, review and comparison.

Individual commitment to Safety

NSC is characterized by everyone acting in a way which is safety oriented and with consciousness of their own responsibility according to their own abilities, existing tools and competencies, as well as by the formation of an environment which is constructive to high level of NSC. The response of all those who seeking to achieve excellence in matters affecting nuclear is characterized by:

8. Personal Accountability

All individuals take personal responsibility for NSC. Responsibility and authority for NSC are well defined and clearly understood. Reporting relationships, positional authority, and team responsibilities emphasize the overriding importance of NSC.

9. Questioning Attitude

Questions used as a basis for discussion and as 'prompts' which might be made available to encourage everyone to review critically their actions and to consider how they personally can contribute to enhancing NSC. Individuals demonstrate a questioning attitude by challenging assumptions, investigating anomalies and considering potential adverse consequences of planned actions.

10. Safety Communication

Effective safety communication is vital to maintaining a NSC. When employees regularly communicate with each other in an open, respectful manner, they are also more disposed to give and receive feedback. Active communication also supports teamwork and coordination between groups. Top-down communication is most efficient when senior managers communicate directly with immediate supervisors and immediate supervisors communicate with their staff. This ensures that supervisors are informed about organizational issues, and then allowing them to communicate these issues to their staff, helps create and reinforce the supervisor's rule. Effective safety communication includes plant-level communication, job-related communication, worker-level communication, equipment labelling, operating experience and documentation. In the same way also the bottom-up communication is necessary between the staff and their immediate supervisor so that he's immediately informed about any problem or doubt raised from the staff.

ASN	Autorité de Sûreté Nucléaire (in French) or Nuclear Safety Autority
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
DiD	Defense in Depth
EU	European Union
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
ICF	Inertial Confinement Fusion
INB	Installation Nucléaire de Base (in French) or basic nuclear installation
IO	ITER Organization
ITER	International Thermonuclear Experimental Reactor
LLW	Low-Level Waste
MCF	Magnetic Confinement Fusion
MLW	Medium Level Waste
NPPs	Nuclear Power Plants
NS	Nuclear Safety
NSC	Nuclear Safety Culture
UN	United Nations
US	United States
VLLW	Very Low Level Waste
VV	Vacuum Vessel

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