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EDA ACTIVITIES RELATED TO SAFETY

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Introduction

This article reviews the accomplishments in ITER safety analysis during the course of the Engineering Design Activities (EDA). The key aspects of ITER safety analysis are:

- effluents and emissions from normal operation, including planned maintenance activities;
- occupational safety for workers at the facility;
- radioactive materials and wastes generated during operation and from decommissioning;
- potential incidents and accidents and the resulting transients.

This work on ITER safety required the integration of detailed analyses by a geographically dispersed safety team consisting of JCT and Home Team experts who initially had different approaches and methods based on conceptual fusion reactor studies and fission power plant practices.

Since an ITER site has not yet been selected, a safety approach was developed for a generic site in such a way that compatibility with the Parties' regulatory frameworks can be expected. The work on safety has contributed to a design providing the basis for regulatory approval with the expectation that only minor changes will be needed to meet the host country's regulations. After siting, safety design and implementation will be finalized in accordance with the host country's regulations and practices.

The implementation of a generic safety approach, the safety aspects of the design, and the assessments of effluents, occupational safety, waste and accidents, are intended to support regulatory submissions by any Party. The assessment is documented in the Generic Site Safety Report (GSSR), whose main purpose, in combination with other ITER documentation, is the provision of this technical information. The GSSR comprises about 1100 pages of text and figures, summarizing the contributions of designers and analysts from the JCT and Home Teams in 11 volumes ordered as follows:

Volume I	Safety Approach
Volume II	Safety Design
Volume III	Radiological and Energy Source Terms
Volume IV	Normal Operation
Volume V	Radioactive Materials, Decommissioning and Waste
Volume VI	Occupational Safety
Volume VII	Analysis of Reference Events
Volume VIII	Ultimate Safety Margins
Volume IX	External Hazards
Volume X	Sequence Analysis
Volume XI	Safety Models and Codes

As a result of the work during the EDA it is concluded that ITER is safe, with little dependence on engineered, dedicated safety systems for public protection because of the fail-safe nature of the fusion energy reaction, limited mobilizable radioactive inventories, multiple layers of confinement, and limited decay heat and passive means for its removal.

Safety Objectives

ITER aims at demonstrating the safety and environmental potential of fusion, thereby providing a good precedent for the safety of future fusion power reactors. Hence, ITER has to address the full range of safety hazards which were taken into account by including extensive safety and environmental assessments in the development work.

The technical safety objectives are broken down into:

General Safety

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

No Evacuation

Demonstrate that, in the light of the favourable safety characteristics of fusion and appropriate safety approaches, it is technically justifiable to assume that the hazard from internal accidents is reduced to a level such that the recommended IAEA criteria for evacuation of the public will not be exceeded.

Waste Reduction

Reduce radioactive waste hazards and volumes.

Safety Principles

The design and the ongoing safety reviews and assessments were guided by the following principles:

As Low As Reasonably Achievable (ALARA)
Exposures to hazards are kept as low as reasonably achievable, economic and social factors taken into account.

Defence-in-Depth
All activities are subject to overlapping levels of safety provisions so that a failure at one level would be compensated by other provisions. Priority is given to preventing accidents. Protection measures are implemented in subsystems as needed to prevent damage to confinement barriers. In addition, measures to mitigate the consequences of postulated accidents are provided, including successive barriers for confinement of hazardous materials.

Passive Safety
Passive safety is given special attention. It is based on natural laws, properties of materials, and internally stored energy. Passive features, in particular minimization of hazardous inventories, help ensure ultimate safety margins.

Consideration of Fusion's Safety Characteristics
The safety approach is driven by a deployment of fusion's favourable safety characteristics to the maximum extent feasible:

- the plasma burn is self-limiting with regard to power excursions, excessive fuelling and excessive additional heating;
- the plasma burn is passively terminated by the ingress of impurities under off-normal conditions;
- the plasma burn is terminated inherently when fuelling is stopped owing to the limited confinement by the plasma of energy and particles;
- the fuel inventory in the plasma is always below 1 g so that the fusion energy content is small;
- the radioactive decay heat density is low;
- the energy inventories are relatively low;
- large heat transfer surfaces are available together with large masses acting as heat sinks;
- confinement barriers exist and must be leak-tight for operational (non-safety) reasons.

The experimental nature of the facility is also addressed. A conservative, fault-tolerant safety envelope is provided to allow flexible experimental usage. In view of the limited operational experience with DT plasmas, experimental components are conservatively designed, taking into account the expected loads from plasma transients so as to reduce the demands on systems which are required for safety. A safety function is not assigned to experimental components, but faults in these are considered as expected events in the safety assessments. The experimental programmes and related machine modifications and operations are developed to take advantage of knowledge gained during preceding operations.

Review and Assessment
Safety assessments are an integral part of the design process and results are used to assist in design improvements and in the preparation of safety documentation for regulatory applications. These analyses comprise normal operation and all categories of off-normal events.

To confirm the acceptance of the generic safety approach, meetings of the Parties' Designated Safety Representatives (i.e. regulators) were convened. A consensus on the safety principles and criteria was reached, based on internationally recognized International Commission on Radiological Protection (ICRP) and IAEA recommendations, in particular on the concept of defence-in-depth and on the ALARA principle. Furthermore, it was agreed that the scope of the implementation and documentation outlined for ITER appears to be a reasonable basis.

Safety and Environmental Criteria

Quantitative safety and environmental criteria have been set against which to judge the success in achieving the safety objectives. These are based on internationally recognized criteria, most notably those recommended by the ICRP and the IAEA.

The quantitative release guidelines are used as a surrogate for regulatory dose limits. They are expressed in physical units (such as grams of tritium oxide released to the environment) rather than doses (expressed in sieverts) since the definitions of doses, the way they are calculated and the related regulatory limits depend on specific sites and vary from Party to Party. The guidelines were derived by considering a range of dispersion parameters, site characteristics and dose definitions so as to be compatible with the more restrictive of the regulatory limits in the Parties. The underlying concept is that events with the greatest likelihood of occurrence should have the least consequences.

An additional category, hypothetical events of such low probability that they can essentially be regarded as an almost impossible combination of failures, is also assessed to demonstrate the ultimate safety margins of the design. The favourable safety characteristics of fusion manifesting themselves in ITER can be further demonstrated if, even for hypothetical events, the calculated doses to the local population are below 50 mSv (early dose). This value is below the generic optimized intervention level for temporary evacuation recommended by the IAEA, which is 50 mSv avertable dose within a period of no more than one week. ICRP and IAEA recommendations were also used to set guidelines for occupational safety.

Safety Approach

The objective in developing the safety approach was to provide confidence to each Party that the design of ITER is safe and licensable, and in so doing to define the facility's safety performance requirements. Early in the EDA, two important issues needed to be addressed, namely, the fact that the safety characteristics of fusion are different from those of nuclear fission and the fact that the safety and regulatory approaches vary from Party to Party. Therefore, the detailed knowledge from conventional nuclear fission power plants can be adopted for ITER only after extensive revision, based on careful review and interpretation. The 'national' approaches are internally consistent, but nevertheless it is not reasonable to apply specific points in isolation to ITER without detailed consideration. The solution was to develop, until a site is selected, an ITER-specific safety approach which is characterized by the following:

- It is comprehensive and internally consistent.•
- It uses agreed basic international safety concepts.
- It is tailored to fusion hazards and safety characteristics.
- It is generally compatible with the Parties' regulatory approaches.

Safety Functions

Protective measures and safety functions were identified by a review of the hazards in ITER and they were assigned to implementing systems and components. This was done by also accounting for beneficial fusion safety features such as inherent plasma burn termination and low nuclear decay heat. The measures and functions are outlined in the following.

- Restriction of inventories, a fundamental preventive measure, is an effective method to control hazards. Of particular importance is its application to tritium and neutron activation products.
- Confinement of hazardous materials is the fundamental safety function. It refers to all types of physical and functional barriers which protect against the unintended mobilization, spread and release of hazardous materials. Since releases can most significantly occur upon failure of barriers, protection of confinement is needed and the following challenges had to be considered:
  - removal of heat to protect against mobilization (by evaporation or melting, for example) of hazardous materials and breach of barriers;
  - control of coolant enthalpy to prevent damage to barriers (from over- or underpressure, for example);
  - control of chemical energy to avoid energy release and pressurization threats to confinement barriers (particularly from potential reactions of plasma-facing materials with steam);
  - control of magnetic energy to avoid damage to confinement barriers in the event of failures (from mechanical impact or electric arcs, for example).

Assessment Tools and Data

At the start of the EDA, the methods for the safety assessments, including the necessary tools and ITER-specific data, needed to be developed. To this end, a safety-related R&D programme with the Home Teams was pursued which up to the end of 1998 was primarily oriented at understanding and investigating ITER-specific safety issues:

- hydrogen isotope behaviour (accumulation, desorption, permeation) in plasma-facing armour materials (beryllium, carbon fibre composites and tungsten);
- formation of erosion products (dust) from plasma-facing materials (characterization, mobilization, transport, removal and monitoring) under conditions simulating ITER modes of operation;
- chemical interaction of plasma-facing materials (especially beryllium) with steam and air;
- activation product volatility;
- corrosion product generation and transport;
- decay heat measurement of plasma-facing component materials;
- transient thermal hydraulic phenomena.

A significant effort was given to the development of analytical tools to undertake the safety analysis. This included the development of new computer codes and the modification of existing ones for fusion applications. By 1998, ITER analysts had a set of tools capable of analysing

- transient behaviours of plasma-wall interactions,
- thermo-hydraulic behaviour of the heat transport system under anomalous conditions including discharge into vacuum and onto cryogenic surfaces,
- temperature and pressure dependent chemical reactions due to ingress of coolant into the vacuum vessel,
- aerosol, dust and tritium mobilization and transport.

Since 1998, the safety-related R&D has had the main objective of verification and validation of data, computer codes and assessment models.

Results of the Safety Assessments

The assessments were conducted by JCT and Home Team analysts. The need to ensure an integrated and consistent assessment of an evolving design led to the introduction of

- a single safety analysis data list to be used by all analysts,
- a single list of detailed analysis specifications (setting the assumptions and conditions to be analysed) to be followed,

- templates for individual analysis documentation to allow ready assimilation into the overall documentation.

Effluents
To estimate effluents, a systematic approach based on ITER's Work Breakdown Structure was developed so that each system could be examined as a possible source of effluents. Conservative estimates of expected end-of-life conditions were used in order not to underestimate potential effluents.

The ITER design incorporates many features to ensure that the environmental impact during normal operation will be low, including confinement barriers to prevent releases, and air and water detritiation and filtration systems to treat releases. The hazards are known and the control technologies are well established at existing facilities. Sources of potential effluents were identified, pathways determined, and design features and release control systems were assessed and, under ALARA, ways to reduce the main contributors were examined. Annual effluents will increase with time from the start of operation but will only gradually approach the estimated levels.

Potential doses to a member of the public from ITER operation will be site dependent. For a 'generic' site, the calculated doses would be less than 1% of the natural background level. The continued application of the process to implement the ALARA principle may further reduce the estimated normal releases.

Occupational Safety
For occupational safety, maintenance procedures and human resources estimates developed by the design engineers were used together with estimates of dose rates from external (including deposits of activated corrosion products) and internal (from tritium in air) radiation to estimate occupational exposure, and most importantly to examine the potential for dose reduction.

ITER has established a programme for personnel protection against hazards anticipated during construction, operation and maintenance activities. The highest exposure and risk areas were identified for potential design improvements (shielding, contamination control, reduced operator exposure times, etc.) aimed at reducing overall exposures and ensuring good contamination control. In addition, there will be several years of operation for further learning and optimization prior to the introduction of tritium. The current assessment of all major systems points to ITER successfully maintaining occupational exposures below the project guidelines,which are in line with guidelines for next generation fission power plants.

Waste and Decommissioning
The issue of radioactive materials, decommissioning and waste is being carefully considered. For waste characterization, activation calculations based on a one-dimensional radial build-up of ITER were used, under a conservative assumption for the total neutron fluence.

In the absence of an actual site for ITER, the ultimate waste amounts were estimated provisionally on the basis of 'clearance'. According to the IAEA concept, materials with activation levels less than the specified clearance level can be released from regulatory control (i.e. control is removed), irrespective of how and where they may be used in the future. The radioactive materials arising during operation and remaining after final shutdown include activated materials (due to fusion neutrons) and contaminated materials (due to activated tokamak dust, activated corrosion products and tritium) and mixtures thereof. Decay and decontamination will reduce the radioactivity with time after final shutdown. Therefore, not all radioactive materials may need to go into waste repositories; rather a significant fraction has the potential to be 'cleared'. Since this fraction increases with time, the project provisionally assumes that radioactive material not suitable for clearance after a decay time of up to 100 years is 'waste' needing disposal in a repository.

The design approach includes provisions for reducing the quantities and hazards of radioactive materials, for example through the use of modular components, appropriate choice of materials, control of impurities, shielding and reuseable components. To ensure that ITER can be safely dismantled at the end of its useful operating life, decommissioning plans have been developed.

The estimated masses are:

- total radioactive material at shutdown — about 30 000 t
- material remaining as waste after a decay time of up to 100 years — about 6000 t.

Accidents

The greatest challenge during the early part of the EDA was to characterize the safety of ITER by analysing in detail the transients resulting from failures. To ensure to the extent possible that all aspects of plant operation have been considered, two fundamentally different approaches have been applied to the identification of initiating events, namely a 'bottom-up' approach (starting upwards from the component level) and a 'top-down' approach (starting downwards from the ultimate consequences of faults). The former systematically catalogues all potential faults in systems and components and considers the conceivable consequences of these faults. The focus is on the failure of individual components and is based on the design in as much detail as is available. In contrast, the top-down approach starts at the plant level and takes a global view of the potential ultimate consequences. By considering the abnormal events which would have to occur to produce these consequences, again a list of event initiators is developed in terms of system or component faults.

The catalogue of events and the event sequences resulting from these studies identified:

- the radioactive inventories at risk,
- the confinement barriers challenged,
- the mitigating systems that must fail for a hazardous plant state to occur,
- the release pathway.

The catalogue has been evaluated to ensure that each event is either clearly insignificant or is covered by a detailed analysis.

A limited set of Reference Events (25 events) was developed consisting of a postulated initiating event and all consequential failures and assumed aggravating failures (additional independent failures in mitigating systems, for example). The Reference Events cover the major systems, the radioactive inventories distributed amongst these systems and the initiator types that have the potential to cause releases. The adequacy of the Reference Events set was confirmed by the detailed event identification described above. It was necessary to proceed in parallel:

- defining and analysing the set of Reference Events (identified by a functional assessment of the facility)
- systematically identifying initiating events on the basis of detailed assessments.

Ultimately it was shown that the consequences of all identified sequences are bounded by the assessed consequences in one or more of the analyses of Reference Events.

In the spirit of conservatism, limiting or bounding conditions were assumed to maximize consequences.

- The plasma behaviour was addressed in a conservative way to show the limited effects of loss of plasma control or exceptional plasma behaviour.
- Loss of power was investigated to determine if there are requirements for the supply of emergency power.
- Many events were grouped around the cooling water systems, which are key features whose safety has to be demonstrated.
- Air and water ingress into the vacuum vessel and cryostat under various off-normal plant conditions was investigated.
- Events during maintenance of the vacuum vessel were considered since maintenance will be a typical state of operation.
- The safety of the tritium plant with its significant inventory was addressed.
- Magnet system structural integrity and the consequences of arcs were examined;
- The consequences of failures of confinement and decay heat removal in the hot cell were investigated.

The analysis of the 1998 ITER design allowed identification of improvements in the further safety design of ITER:

- elimination of the 100 m stack as a requirement for ensuring that off-site dose limits are met;
- changes to confinement design to eliminate failure combinations that lead to bypassing the confinement;
- introduction of a tokamak vent system to help ensure that pressures in the vacuum vessel remain below the pressures in adjacent rooms following accidents;
- improvements to the vacuum vessel pressure suppression system so that pressures following small in-vessel leaks remain below atmospheric pressure.

The results show that radioactive releases for all the Reference Events are well below the project release guidelines, which would lead to doses comparable to the average annual natural background exposure for a generic site. The assessments provide confidence that the operation of ITER will result in no significant risk to the general public from accidents.

In addition, the ultimate safety margins of the facility were examined by analysis of hypothetical events, arbitrarily assuming that more and more failures occur. As a result of the safety characteristics of fusion and engineered design features, it requires an almost inconceivable combination of failures to lead to a significant release of radioactive material. Analysis shows that the design is tolerant to failures, that there is no single component whose failure leads to very large consequences, that there is no single event that can simultaneously damage the multiple confinement barriers, and hence that the design provides a high level of public protection even for these hypothetical events.

Conclusions

Looking back at the activities related to safety carried out during the EDA, a significant step forward for fusion safety has been accomplished. The discipline of an integrated, detailed design and the anticipation of a future regulatory review led to the development and validation of new approaches, tools and data to examine ITER safety. The need to integrate the Home Team and JCT analyses in a single assessment led to the development of means of ensuring a cohesive and internally consistent document. The resulting safety analyses have led to the most comprehensive and well-documented assessment of a fusion design to date.

In summary, the assessments documented in the GSSR show that ITER can be constructed and operated safely and without significant environmental impacts:

- Effluents during normal operation are estimated for a generic site to lead to doses to the public which are less than 1% of natural background radiation levels.
- Occupational exposure of workers is estimated to be within guidelines set for next generation nuclear power plants.
- The majority of the radioactive materials from operation and decommissioning will not remain as waste beyond a human timescale if the present concept of clearance can be applied.
- Doses from accidents are estimated to lead to doses to the population that are at worst comparable to the average annual natural background for a generic site.
- No single component failure leads to very large consequences and no single event can simultaneously damage the multiple confinement barriers provided.

The analyses and assessments completed with the involvement of the Home Teams experts offer a well-developed technical basis for regulatory applications in potential host countries.