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MQP Specific Plan

ITER RAMI ANALYSIS PROGRAM

The purpose of this document is the definition of a RAMI (Reliability, Availability, Maintainability, Inspectability) Analysis Program for ITER together with the description of the engineering processes and basic tools to be used. In addition, a phasing of the RAMI Program is briefly given. The objective is to implement RAMI engineering standards for the construction, test, commissioning and operation of the ITER Project and initiate a RAMI Analysis in the framework of a technical risk control ...

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1 Purpose

The purpose of this document is the definition of a **RAMI** (**R**eliability, **A**vailability, **M**aintainability, and **I**nspectability) Program for ITER along with the description of the engineering processes, phasing and basic tools to be used. In addition the roles and responsibilities of the actors of RAMI Program are briefly described. The objective of this programme is to implement RAMI engineering standards for the design, manufacturing, test, commissioning, operation and maintenance of the ITER machine and initiate RAMI analyses in the framework of a technical risk control to support the overall ITER Project.

2 Scope

The RAMI analysis aims to handle technical risks that have an impact on the availability of the ITER machine operation. Project management risks such as schedule and cost risks will not be considered in the RAMI analysis. Risks that come from safety or regulation will not be discussed in the RAMI analysis as well, unless the investigation following a safety event triggered by a technical failure results in a stop of the machine operation.

3 Definitions

This chapter provides abbreviations used in this document.

A: **A**vailability is the probability that a device is in a state to perform the required function.

C: Criticality is the product of the failure frequency (Occurrence) and unavailability due to the failure.

CDR: **C**onceptual **D**esign **R**eview

C_e: **e**xpected **C**riticality is the failure criticality after applying risk mitigating actions

C_i: **i**nitial **C**riticality is the failure criticality before applying risk mitigating actions

CMMS: **C**omputerised **M**aintenance **M**anagement **S**ystem

DA: **D**omestic **A**gency

FA: **F**unctional **A**nalysis

FBS: **F**unction **B**reakdown **S**tructure

FDR: **F**inal **D**esign **R**eview

FMECA: **F**ailure **M**odes, **E**ffects and **C**riticality **A**nalysis

I: **I**nspectability characterizes the ability to access and monitor a device

IDEFØ: **I**ntegration **DE**finition **F**unction – language **Ø** is a method for making a Function Breakdown Structure

M: **M**aintainability is the probability that a given maintenance activity can be done in a given time

MDT: Mean Down Time is the average duration of unavailability

MTBF: Mean Time Between Failures (or Before Failure in the case of non-repairable items) is the average duration between 2 consecutive failures

MTBM: Mean Time Between Maintenance is the average time between 2 maintenance activities

MTTR: Mean Time To Repair is the average duration of repair

MTTF: Mean Time To Failure is the duration of correct operation before the failure

MUT: Mean Up Time is the average duration of correct operation

O: Occurrence is the frequency of a failure mode (O_e: Expected Occurrence; O_i: Initial Occurrence)

PA: Procurement Arrangement

PBS: Plant Breakdown Structure
PDR: Preliminary Design Review
R: Reliability is the probability that an item (device) will perform failure free its intended function in a specified time and under given conditions
RAMI: **R**eliability, **A**vailability, **M**aintainability and **I**nspectability is a technical risk control approach based on a functional analysis of devices for identifying and classifying the possible failure modes and then reducing their effects thanks to corrective or preventive actions.
RBD: **R**eliability **B**lock **D**iagram is a method to perform analyses of Reliability and Availability of large and complex devices using block diagrams to show network relationships
RO: **R**esponsible **O**fficer
S: **S**everity (S_e: Expected Severity; S_i: Initial Severity) corresponds to the unavailability of a device due to the effects of a failure mode

4 Introduction

The ITER project has to be a highly reliable, efficient and safe device built to produce a quantitatively and qualitatively predefined output of scientific data. It has to be available for experiments whenever needed with low operation and maintenance costs. In order to achieve this, a RAMI analysis aims to provide designers and engineers the optimum system design and appropriate operation, testing and maintenance programmes.

The RAMI analysis process is an association of methods and integrative concepts based on the results obtained for the control of technical risks and which makes it possible to have a better guarantee that a device meets the project requirements in terms of Reliability (continuity of correct operation), Availability (readiness for correct operation), Maintainability (ability to undergo repairs and modifications) and Inspectability (ability to undergo visits and controls).

In this document are described the various phases, procedures and standards of the ITER RAMI analysis programme that are adopted and implemented to be able to evaluate and control the RAMI aspects throughout the project for the construction, test, commissioning, operation and maintenance of ITER and to initiate the RAMI analyses in the framework of a technical risk control to support the overall ITER Project.

5 Guidelines for the ITER RAMI Analysis Programme

ITER is the first fusion device for which a RAMI approach is formally implemented before its construction and operation. The project represents an intermediate device which is both:

- A nuclear machine with objectives in terms of availability and neutron fluence as a power plant,
- An experimental device with an ambitious scientific and technological programme which needs many diagnostics, numerous maintenances, upgrades and tests of components.

For these reasons, for cost and schedule concerns, it is important to respect the following guidelines in our approach:

1. To define together, IO and DAs, the ITER RAMI analysis programme of which the requirements will be integrated in procurement specifications for suppliers and operation instructions and maintenance plan for operators;
2. To maintain a clear distinction between safety issues which are addressed very formally due to specific requirements and operation issues even if we have to take the safety into account where there is an overlap;

3. To be realistic for the scope of the ITER RAMI analysis programme. Output from the RAMI analysis will mainly provide RAMI allocations for fabrication, testing, maintenance and operation;
4. To be able to reach the whole plant availability objective required by the project;
5. To make an analysis of operational functions and not of the components, to draw up the list of the most critical function failure modes and implement the most cost-efficient ways of improving availability of the functions required to operate the machine;
6. Not to fight for improving by 1% the reliability by correcting the design whereas we can gain 10 % in availability with preventive and corrective maintenance;
7. To reduce the criticality of major risks by initiating corrective or preventive actions, the level of risk from which a mitigating action have to be required, recommended or optional has to be decided by the project management as a function of its objectives and resources;
8. To extend the ITER RAMI analysis programme beyond machine availability to pulse availability (power, measurements, data, fluence) to produce the predefined output quantity and quality of scientific data required by the project;
9. To train operation team and prepare clear & validated documentation for increasing the human reliability which is a critical factor in terms of performing the correct action in a particular operation, failure and maintenance situation;
10. To provide the ITER RAMI analysis programme results as an input to logistic support functions (staffing and training requirements, spare parts provision, Reliability-Centred Maintenance and RAMI improvement programme) before the start of ITER operations.

6 RAMI Concepts

6.1 Reliability

The Reliability (R) is a characteristic assigned to the system function. Knowledge of its hardware architecture and components is usually not sufficient to determine its reliability so it is necessary to rely on a functional analysis, and to take into account the environment and operating conditions.

What differentiates the reliability of its neighbours (maintainability, availability…) is that it is calculated "for a given length of time". Indeed, reliability is the concept which characterizes continuity, the absence of interruption of the awaited service. Reliability emphasizes the scarcity of failures over an interval of time $\Delta t = t_2 - t_1$ as opposed to a specific instant t. Initially, the system is supposed to work. The problem is to determine for how long. In general $t_1=0$ and it is possible to write the Reliability function $R(\Delta t)$ as the probability, $0 \le R(\Delta t) \le 1$, that an item will perform failure-free its intended function in a specified time interval Δt under given conditions.

Reliability refers to an expression of needs. One cannot speak about reliability without having expressed what is expected of the considered system. It is an essential point which can result in the existence of several reliabilities for the same system corresponding to the same required functions, but in different conditions of use. Each time one will speak about the reliability of the system, it is important to make sure that the necessary functions are well identified. Reliability has significance only under limit conditions of operation of the system (electromagnetic waves, vibrations, variations in temperatures, variations of characteristics of power supply…). It is important to specify them. Usually, the RAMI approach will consider that either a function is fulfilled up to its nominal performance, or it is not fulfilled. As a result, degraded modes, with less-than-optimal performance are considered as function failures by RAMI.

An essential part of any reliability program is the testing which is directed at improving, demonstrating, or assuring the achievement of reliability levels. Unfortunately, as the test of a complete system is not economical and greedy in time, the reliability demonstration is often not decided. Attention must be given to this kind of decision because it is often an error in terms of operation. It is very important to be able to describe the ability of a system to meet a specified performance or operational requirements.

The aim of such demonstration programmes is also to ensure that manufacturing possible faults are eliminated. In addition, these demonstration tests include functional testing under typical operational conditions and they make it possible to train the teams which will be in charge of operating the system.

6.2 Availability

The Availability A(t) of a device must be regarded as a performance. It is the probability (ability) that the device is in a state to perform the required function for which it was designed under given conditions at a given time t, assuming that the required external resources needed are provided. Its time characteristics are different from those of reliability since the concept of interest is an instant in time t instead of a given length of time. For a repairable system, functioning at time t does not necessarily imply functioning between [0, t].

Fusion power plants will have to achieve overall plant availabilities in the same range as today's power plants, i.e. they must be available for full power operation for around 75% of the calendar time. To accomplish a meaningful test programme, ITER will require full power operation for about 10% of the calendar time. It is an average expected over a total calendar time of about 20 years, including not only unscheduled outage times but also scheduled downtime which may be required in the program to replace components of different designs that are to be tested. Hence the availability required during certain campaigns will be higher:

- For campaigns of 2 years, an operational availability of up to 25% may be requested,
- For campaigns of about 2 weeks, an operational availability of up to 50% may be requested,
- Operating at 100% availability, i.e. without any interruption, may be required for periods of between 500 s and 3000 s (the envisioned length of one plasma discharge).

Referring to full power operation, availability is an integral measure of the maturity of corresponding technology. Hence, the overall plant availability achieved on ITER will be an indicator of its technological success. The issue of availability, therefore, has to be taken seriously right from the beginning of conceptual design of the components.

Operation is characterized by the following parameters:

- MTTF (Mean Time To Failure): duration of correct operation before the failure,
- MUT (Mean Up Time): average duration of correct operation,
- MDT (Mean Down Time): average duration of unavailability,
- MTTR (Mean Time To Repair): average duration of repair (may include the time to diagnose the failure, have access to the failed,
- MTBF (Mean Time Between Failure): average length of time between 2 consecutive failures of a repairable component,

or

- (Mean Time Before Failure): average length of time before the failure of an non-repairable component,
- MTBM (Mean Time Between Maintenance).

With respect to unscheduled outage, the availability A of a power plant, averaged over a certain time span, can be approximated under the simplifying assumption of series system outage logic by:

$$A = 1 / (1 + \Sigma_{i=1 \text{ to } n} G(i\square)) \qquad (1)$$

where n is the number of plant components, the failure of which causes an outage of the plant and $G(i\square)$ represents the outage risk of the ith component such as:

$$G_i = \lambda_i.MDT_i \qquad (2)$$

where λ_i is the rate of occurrence of unscheduled failures of the i component which cause a Mean plant Down Time of MDT_i.

The Inherent Availability reflects the percentage of time a system would be available if no delay due to maintenance, supply, etc… (i.e., not design-related) was encountered:

$$A_i = MTTF / (MTTF + MTTR)$$

The Operational Availability includes moreover the effects of maintenance delays and other non-design factors:

$$A_o = MTBM / (MTBM + MDT)$$

where MTBM addresses all maintenance, corrective and preventive, whereas MTBF only accounts for failures. MDT includes MTTR and all other time involved with downtime, such as delays. Thus A_O reflects the totality of the inherent design of the product, the availability of maintenance personnel and spares, maintenance policy and concepts, and other non-design factors, whereas A_i reflects only the inherent design.

The information gained from probabilistic analyses of the actual fusion plant is of paramount importance. A key procedure is the Failure Modes, Effects and Criticality Analysis (FMECA) in which the Criticality of a function (component) failure mode is characterized by the outage risk, Eq. (2), of the plant.

Two systems can have poor availability: the first one has frequent failures and the other one does not fail often but instead requires a long time for maintenance or repairs. Thus, although the reliability is an important component of the availability, the aptitude to being promptly repaired is also of paramount importance: this is measured by the Maintainability.

6.3 Maintainability

Many designers seek top performance for their products, sometimes neglecting to consider the possibility of failure. However, even when no effort has been spared to have a functioning system, it is of the utmost importance to consider what would happen in case of failure.

If a system is to have high availability, it should very rarely fail but it should also be able to be quickly repaired. In this context, the repair activity must encompass all the actions leading to system restoration, including logistics. The aptitude of a system to be repaired is therefore measured by its Maintainability.

The Maintainability of an item is the probability that a given active maintenance operation can be accomplished in a given time interval $[t_1,t_2]$. It is written as $M(t_1,t_2)$. It shows that the maintainability is related to repairs in a manner similar to that of reliability and failures. The maintainability M(t) is thus also defined using the same assumptions as reliability R(t). The repair rate m(t) is introduced in a way analogous to the failure rate λ. When it can be considered constant, the implication is an exponential distribution for: $M(t) = \exp(-m.t)$.

Maintainability engineering is regarded as implementing basic principles to future equipment repair while equipment is being designed, developed and/or fabricated. It must be planned as part of design. Maintainability characteristics must be specified and incorporated during system design and concurrent with development. The objective of Maintainability is to develop equipment and systems which can be maintained in the least time, at the least cost, with a minimum expenditure of support resources, without adversely affecting their performance and/or their safety characteristics.

Maintainability is directly concerned with the ease and economy of maintenance, expressed as:

1. Minimum time to:

- recognize, isolate and correct a malfunction,
- understand and apply technical data for the maintenance technician,
- gain access to faulty items,
- repair or replace faulty items,
- test and verify accuracy and adequacy of maintenance actions.

2. Least quantities of:

- required facilities,
- maintenance personnel,
- training to enable performance of maintenance requests,
- tools, tests and support requirements.

6.4 Inspectability

The last basic tools used in RAMI engineering is the “Inspectability”. It is a term recently added to “RAM” because that characteristic appears essential when the component reliability cannot be improved enough. It is one of the characteristics of maintainability with a preventive objective. It is in fact defined as that characteristic of design and integration that allows in situ monitoring of equipment performance in regard to the amount of usable lifetime remaining.

This includes the accessibility to equipment, removable samples to evaluate the material degradation and diagnostics to determine incipient failure. The inspectability concerns also the monitoring aspect during the various stages of production and testing period for the inspection processes. Test engineering as a provision and access of test points, should be involved at an early stage to define test requirements and design the test approach.

7 ITER & Systems RAMI Objectives

It is necessary to define an availability target of the ITER machine which must enable achieving the scientific and technological missions. This overall machine availability requirement depends on:

- Operating mode in terms of working days,
- Needs for scheduled maintenance and upgrades in relation to the needs for the scientific and technological program of ITER,
- Time required for scheduled routine maintenance,
- Number of shifts,
- Inherent machine availability which reflects the percentage of time that a system would be available if no expected delay (such as preventive maintenance or inspections) was planned.

7.1.1 Operation rhythm

ITER is designed and will be constructed and operated to fully optimize the available time, 24hours/day, 365 days per year. It is anticipated that machine operation will be carried out in long periods separated by maintenance periods (such as 11 day continuous operation and 3 day break for routine maintenance), corresponding to a cycle, with a major shutdown of a few months for maintenance/upgrades (8 months are currently envisaged) and/or further installation after a long plasma operation period (16 month are currently envisaged). Three 8-hour shifts are currently envisaged as a basis for planning during the operation. The third shift will be used either for plasma operations, test, conditioning or routine maintenance. The operating scenario will use 4 global operation states: Plasma Operation State (POS), Test and Conditioning State (TCS), Short Term Maintenance (STM) and Long Term Maintenance (LTM) (**Figure 2**).

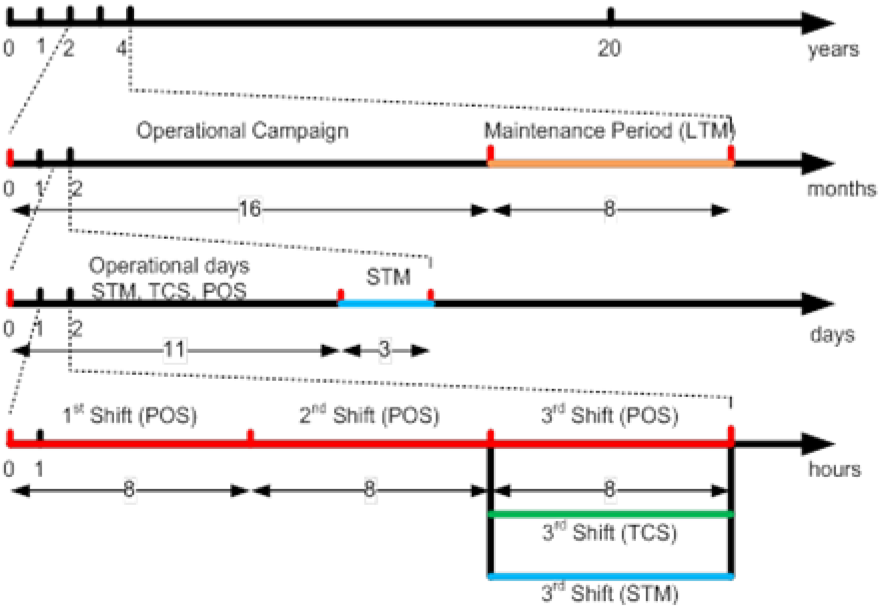

Figure 2. ITER operating scenario

7.1.2 Inherent Availability target

Taking into account this envisioned operational rhythm, an average Machine **Inherent Availability target of 60%** on a 20-year reference period appears a challenging but reasonable objective as compared to the inherent availabilities obtained in the current magnetic fusion devices. Assuming there is no scheduled downtime, the ratio between the operation time and the not-scheduled downtime can be written as $MUT / MDT_{NS} = (A_i / 1 - A_i)$. The inherent availability A_i of a plant, averaged over a certain time span, is totally dependent on the inherent availability A_{iSS} of the Sub-systems.

7.1.3 Operational Availability target

As compared to the Inherent Availability, the Operational Availability includes moreover the effects of maintenance delays and other non-design factors. A_O reflects the totality of the inherent design of the product, the availability of maintenance personnel and spares, maintenance policy and concepts, and other non-design factors. The Operational Availability is strongly dependent on the Mean Time Scheduled Down-time, i.e. maintenance time (major shutdown, routine maintenance, “quiet shift”). Taking into account an inherent availability A_i

of 60%, a scheduled Down-Time of 3 days of Short-Term Maintenance every 14 days and 8 months of Long-Term Maintenance every 2 years, 365 working days per year and 3 operational 8-hour shifts in POS per day, a Machine Operational Availability A_O up to 32% of the total Calendar Time is achievable.

To be able to reach such availability targets, ITER systems and/or main functions shall be designed to have their own specific Inherent Availability objectives. These targets are allocated on the basis of a Functional Breakdown Structure and are given in the Project Requirements.

8 RAMI Process

The RAMI analysis is a continuously iterative process which begins during the design & development phase of a system because corrective actions are still possible at this stage (mainly in terms of design changes or choices, tests before assembly, allowance for accessibility and inspectability in the system integration, input for the operation, definition of the frequency of maintenance…) (**Figure 1**).

From the start of the project, it is thus essential to examine and evaluate the RAMI parameters to consider them as design parameters. This evaluation aims to ensure, before the production starts, that the design does not contain features which could cause unreliable operation of the equipment and insufficient availability of the system for an execution of the scientific programme.

While subordinate to the Project Requirements, the output of the RAMI analysis must nevertheless be considered as an input in the design, operation and maintenance as important as the constraints issued from safety or regulations.

The studies must, on the one hand, make it possible to achieve the foreseen goals of RAMI and, on the other hand, identify all the function failure modes and technical risks being able to compromise them compared to the functional needs. They make it possible to decide to treat the concerned technical risks or to accept them. This last point is at the base of the process of reduction of risks but the analyses of risks are always complex exercises and it is important to adapt them to the studied systems and the conditions of their operation.

As system complexity increases in the ITER tokamak device, RAMI engineering is very difficult to define and achieve as a design parameter and to assure as an operational characteristic. Thus problems may never be completely removed but they can be minimized by a deliberate and positive RAMI analysis. It is not enough to qualify a product to test its aptitude for a given characteristic. It is necessary also to define the tests and to have on-site spare parts which make it possible to have the insurance that this product will have and maintain its characteristics for the operation life of the system under the specified conditions. The General Rules for ITER Operations as well as the software of command-control must take the dependability into account.

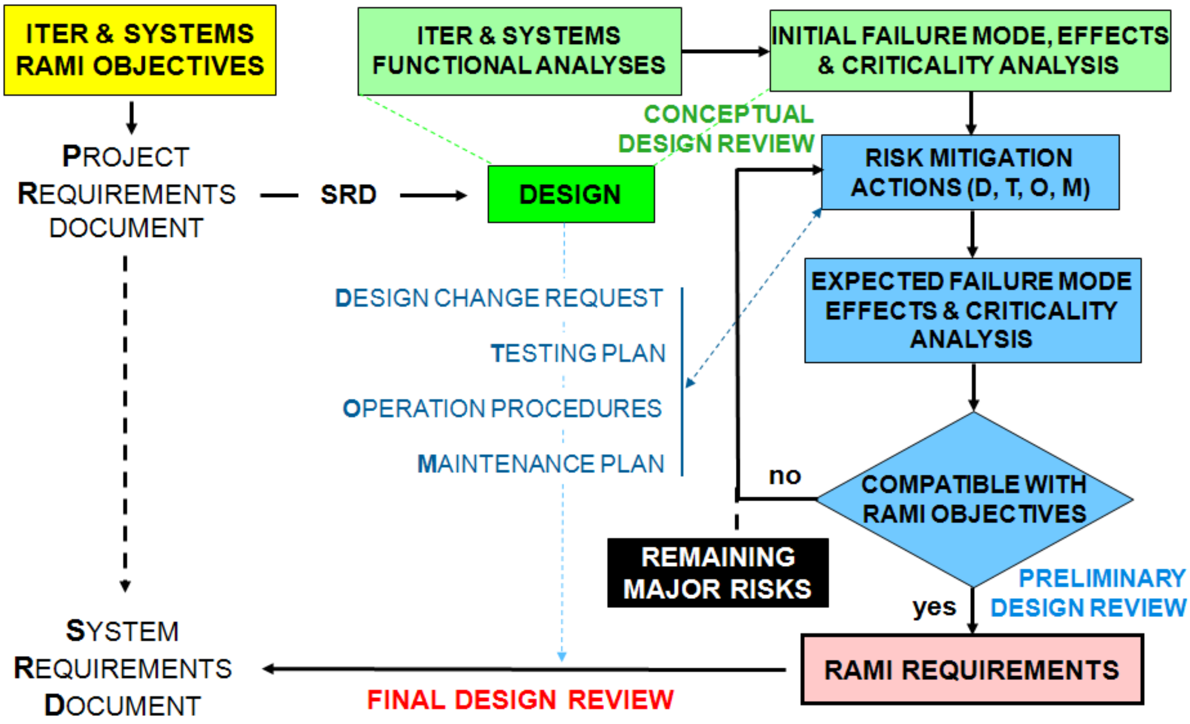

Figure 1. ITER RAMI Process

The analysis of the risks must also make it possible to evaluate the safeguard measures necessary in the event of abnormal situations, in the studied component as well as in the surrounding components. Lastly, in any operational system, the human factor (the operator) is the least "robust" element. This factor is not quantified in the RAMI approach but the operational methods must thus aim at minimizing the failures due to the human errors.

8.1 ITER & Systems Functional Analysis

The first step of the RAMI analysis of a system is the functional breakdown of this system, which is a top-down description of the system as a hierarchy of functions on multiple levels, from the main functions fulfilled by the system to the basic functions performed by the components.

The methodology selected by IO is inspired by the IDEFØ (**I**ntegration **DE**finition **F**unction Modeling– language **Ø**) approach (developed by D. Ross for Softech Organization in 1977) and is used with the Microsoft Visio software. Based on the SADT (**S**tructured **A**nalysis and **D**esign **T**echnique) methodology, IDEFØ represents the interactions between the functions of the considered system:

- Each function is represented by an activity block with its Inputs, Controls, Outputs and Mechanisms (3)
- Blocks are linked following their functional relationships.

IDEFØ uses several “layers” to represent complex system, from the top level system itself to its main functions, then to the intermediate functions, down to the basic functions, so that complex diagrams can be decomposed and activities can be refined into greater and greater detail as required for understanding and making decisions (**Figure 3 & 4**).

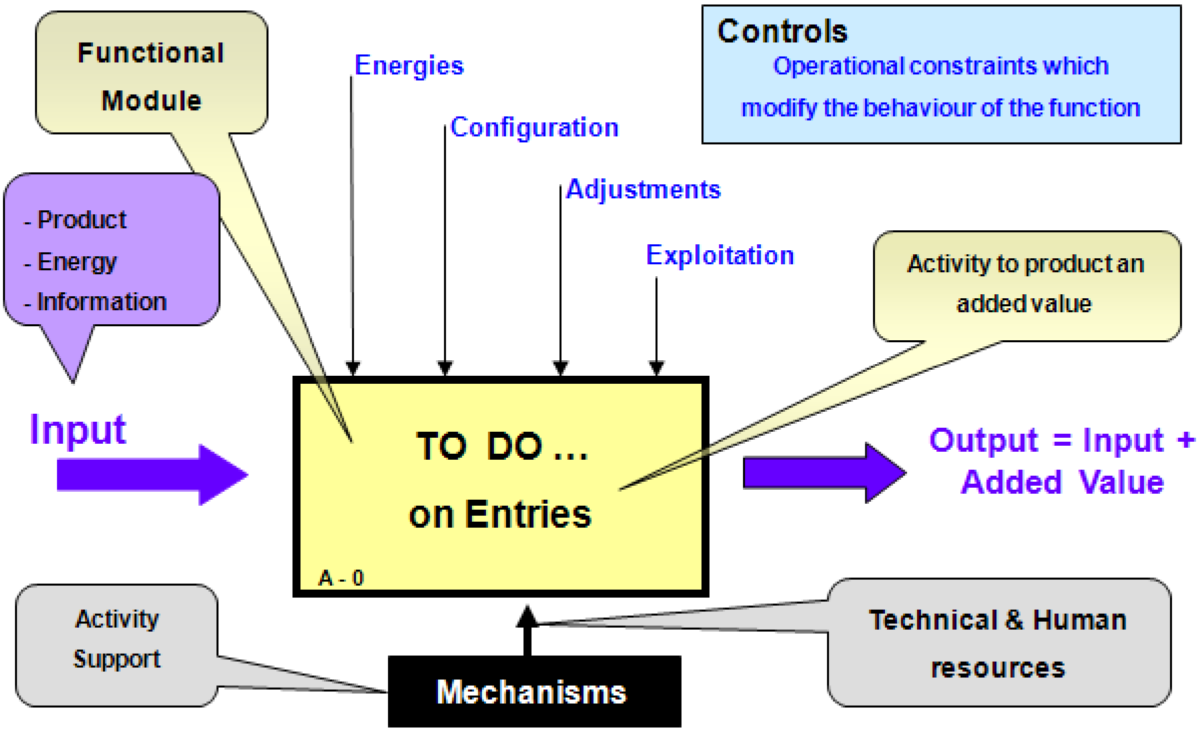

Figure 3. IDEFØ basics

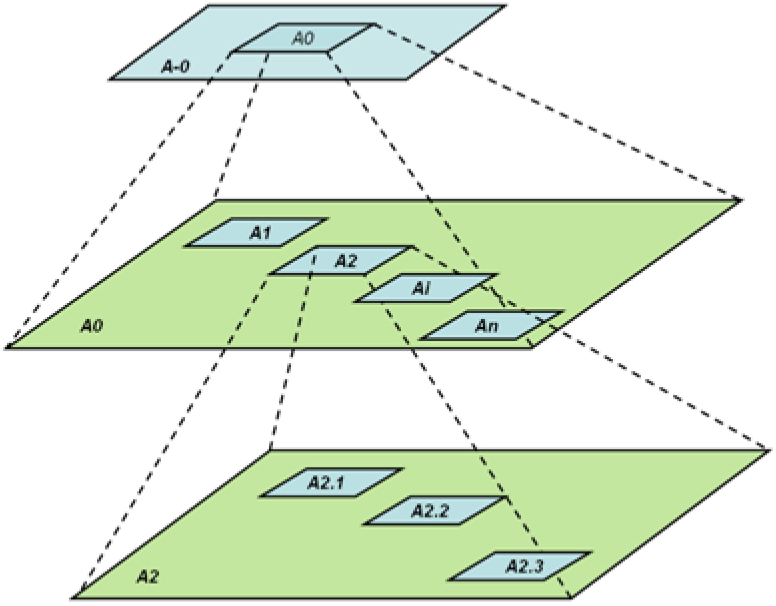

Figure 4. Multiple layers in the IDEFØ hierarchy of functions

The failures of components highlighted at the level of the basic functions lead to failure of the main function they are related to, and through this main function failure it is a specific part of the whole operation of the system and of the machine that can be impacted.

It is of the utmost importance that this functional breakdown is reviewed and approved by both the IO RAMI RO and the IO system RO so that the following steps of the RAMI analysis are performed on a solid and correct basis. Failure to identify errors or misunderstandings in this early stage would lead to whole parts of the analysis being performed on wrong input data and might lead to inappropriate RAMI results and requirements.

8.2 Reliability Block Diagrams

The next step in the RAMI analysis of a system is a bottom-up approach relying on Reliability Block Diagrams (RBD) to estimate the reliability and availability of each of its main functions according to given operating conditions.

The RBD approach uses the functional breakdown as a basis, but concentrates on the reliability-wise relationships linking the function-blocks. Several diagrams allow describing the multiple levels in a hierarchy consistently with the functional breakdown, while the input data is fed to the lowest level block so that the BlockSim software can compute the resulting reliability and availability for the upper levels up to the main functions of the system or the whole system itself.

This input data consists of the reliability parameters (MTBF) and maintenance parameters (MTTR) that are available for the lowest possible level. These data can be obtained from supplier specifications, reliability database and industry standards, previous experience compiled on other scientific devices, or assumptions made following the personal experience of experts available at the time of the analysis. In some cases, the available data may not be completely pertinent regarding the very specific experimental conditions the components will face on ITER, therefore an appropriate interpretation or estimation has to be carried out.

Another critical element of input data is the duty cycle which specifies the proportional time of a component’s usage in the concerned system. Depending on its roles and characteristics to the ITER operation, some of those components such as utilities, structural components, etc. are continuously used, whereas the others which are used depending on a scientific programme are used intermittently during the ITER life. This parameter makes it possible to obtain the same final results in terms of function Reliability whatever the functional decomposition (number of branches and levels) used for the analysis.

As the number of components and functions increases and the systems configuration is more complex, the calculations have to take into account elements such as series, parallels, k-out-of-n, redundancy… to provide reliability and availability ratings.

8.3 Initial Failure Modes, Effects & Criticality Analysis

The Failure Modes, Effects and Criticality Analysis (FMECA) is a method using both the Functional breakdown and the RBDs as input. Its four main phases are:

- Identification of all the Failure Modes (FM) for the basic functions,
- Qualitative assessment of causes and effects on the main functions of the system, the overall system itself and the operation of the whole ITER machine,
- Quantitative assessment of the Occurrence of the causes O and Severity of the effects S,
- Prioritization in Minor, Medium and Major Risks as a function of the Initial Criticality, C_i , of all failure modes in a Criticality Matrix (Chart).

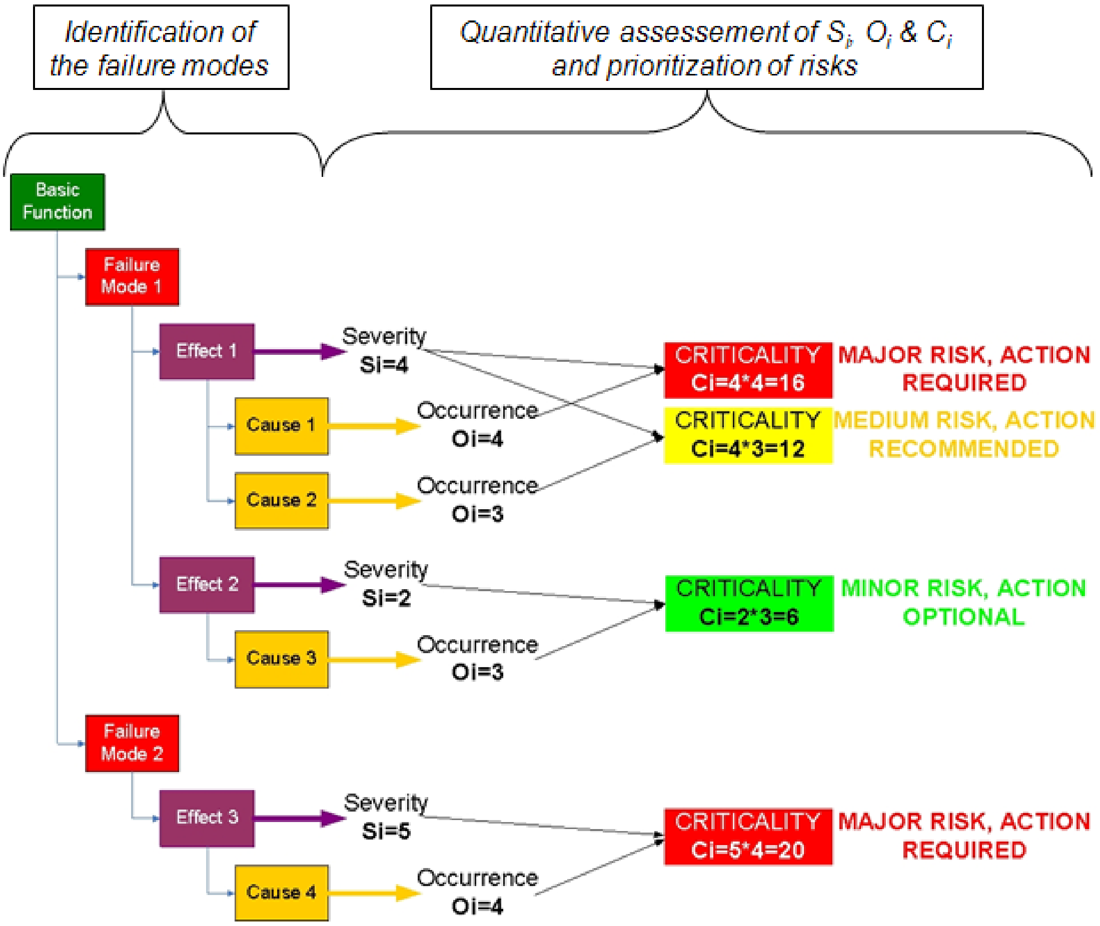

Figure 5. Basic principles of the FMECA

Figure 5 describes the basic principles of the FMECA, as they are applied on every basic function identified in the system functional breakdown:

- The failure modes, their effects and their causes envisioned are described.
- These effects and causes are evaluated quantitatively using the Severity, and Occurrence rating scales as in **Table 1** and **Table 2**. These rating scales are used for all systems in order to keep a consistency between all analyses.
- The Criticality C is obtained as the product of Severity S and occurrence O, and the coordinates (S, O) of all (Effect, Cause) couples are placed on a Criticality Chart highlighting the Major, Medium and Minor Risks depending on the Criticality thresholds defined by IO.
- In addition to mere points, bubble plots are used to highlight the distribution of the failure modes throughout the diagram and its 3 risk level zones.
-

Table 1 IO-defined Severity rating scale

Value	Description	Meaning
1	Weak <1h	Unavailable less than 1 hour
2	Moderate <1d	Unavailable between 1 hour and 1 day
3	Serious <1w	Unavailable between 1 day and 1 week
4	Severe <2m	Unavailable between 1 week and 2 months

5	Critical <1y	Unavailable between 2 months and 1 year
6	Catastrophic >1y	Unavailable more than 1 year

Table 2 IO-defined Occurrence rating scale

Value	Description	Meaning	
1	Very Low	$\lambda_{risk} < 5e-4/y$	$\lambda_{risk} < 5.7e-8/h$
		MTBF > 2000 years	
2	Low	$5e-4/y < \lambda_{risk} < 5e-3/y$	$5.7e-8/h < \lambda_{risk} < 5.7e-7/h$
		200 years < MTBF < 2000 years	
3	Moderate	$5^{e}-3/y < \lambda_{risk} < 5^{e}-2/y$	$5.7e-7/h < \lambda_{risk} < 5.7e-6/h$
		20 years < MTBF < 200 years	
4	High	$5e-2/y < \lambda_{risk} < 5e-1/y$	$5.7e-6/h < \lambda_{risk} < 5.7e-5/h$
		2 years < MTBF < 20 years	
5	Very High	$5e-1/y < \lambda_{risk} < 5/y$	$5.7e-5/h < \lambda_{risk} < 5.7e-4/h$
		10 weeks < MTBF < 2 years	
6	Frequent	$\lambda_{risk} > 5/y$	$\lambda_{risk} > 5.7e-4/h$
		MTBF < 10 weeks	

Once the failure modes of a system have been integrated in the Criticality Chart, it is possible to set priorities in the measures envisioned to reduce the risk levels (**Figure 6**):

- "red" zone represents the Major Risks calling for "required" actions, for those that the Criticality is higher than 13,
- "yellow" zone represents the Medium Risks for which actions are only "recommended", for those that the Criticality is between 7 and 13
- "green" zone represents Minor Risks and the corresponding actions are considered "optional", for those that the Criticality is l than 13.

Whatever their priority, all actions aim to reduce the risk level either by decreasing the Occurrence of the cause of failure or the Severity of the effects, thus reducing the resulting Criticality.

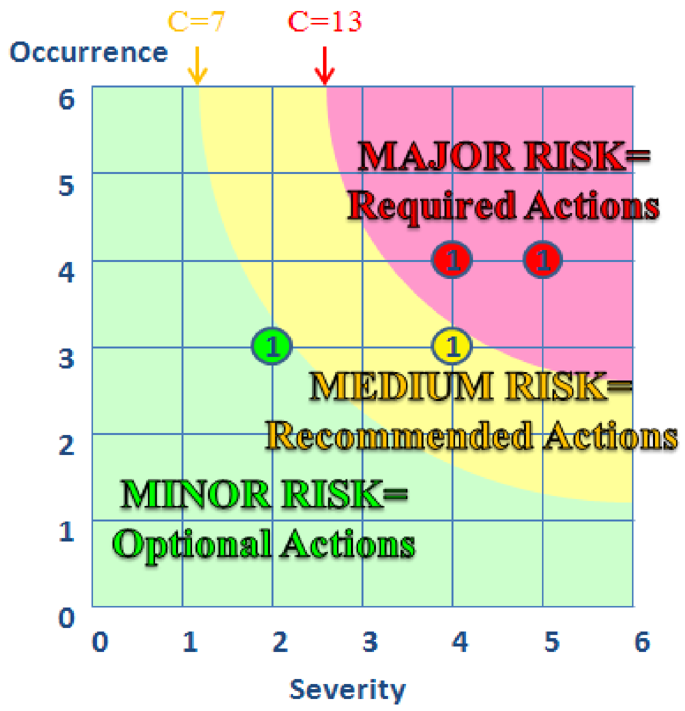

Figure 6. Example of Initial Criticality Matrix

8.4 Risk Mitigation Proposals

In order to reduce the risk level associated to the failure modes identified in the FMECA, risk-mitigation proposals are made. These proposals can be distinguished by the way they reduce either the Occurrence (Prevention) or the Severity (Protection) of the failure modes, and also by the phase of the development of the system they relate to (Design, Test, Operation or Maintenance). **Table 3** below provides examples of risk-mitigation proposals:

Table 3 Examples of risk-mitigation proposals

Effect Category	Prevention (decreases Occurrence)	Protection (decreases Severity)
Design	Implement redundancy to reduce the risk of losing the function	Implement risk-containment provisions to avoid cascading failures as a recovery system of a BM assembled by RH and which could fall on the Divertor
Test	Apply specific tests in simulated operating conditions to check reliability of a component	Apply specific tests to ensure maintainability of components that require a long time to repair
Operation	Interlock operation of sensitive components with a safety check to avoid damage	Prepare specific training and procedures to allow falling back to a safe degraded mode in an emergency
Maintenance	Increase the frequency of inspections and preventive maintenance operations	Keep spares on-site so that time to repair is shortened

In the previous example, 2 failure modes are in the red zone, with an Initial Criticality higher than 13. They are thus considered as Major Risk for the operation of the machine and require risk-mitigation actions.

The most critical failure mode is failure mode 2 with an initial effect Severity S_i of 5 and an initial cause Occurrence O_i of 4 resulting in an Initial Criticality C_i of 20. This means that such a failure could happen more than once in the ITER lifetime, with a resulting downtime between 2 months and 1 year.

It is possible to assess the benefits of an alternate design using 2 smaller components instead of on single big one, so that the failure of one would not result in the total loss of the function during the repair. Moreover, if as a result of a spare being kept available on site or by the supplier, it is possible to avoid waiting for a replacement part to be manufactured, the resulting downtime could perhaps be reduced to less than 2 months.

Those 2 actions, if implemented, would result in pushing the risk out of the red zone by reducing first its Occurrence from 4 to 3 and then its Severity from 5 to 4, with a resulting Expected Criticality C_e of 12 instead of the Initial Criticality C_i of 20. It would thus become a Medium Risk rather than a Major Risk.

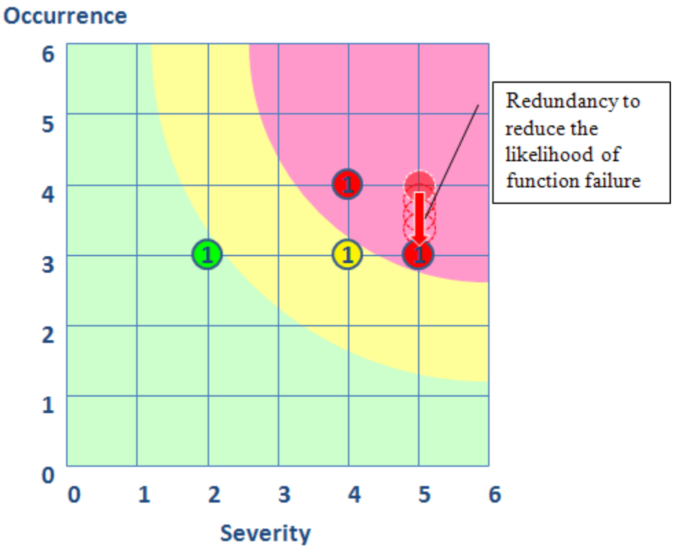

Figure 7. Action Example 1 (Redundancy)

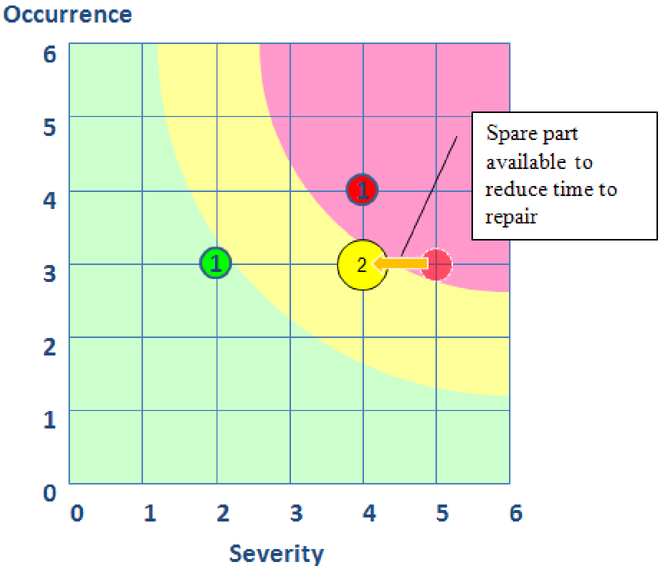

Figure 8. Action Example 2 (Spare parts)

8.5 Expected Failure Modes, Effects & Criticality Analysis

Once the risk mitigation actions have been proposed, their expected benefits are assessed in terms of Expected Severity S_e or Expected Occurrence O_e. It is then possible to obtain an Expected Criticality C_e and to prepare an Expected Criticality Chart.

In the example used above, additional actions could be proposed to reduce the Severity or Occurrence of the remaining Major, Medium and Minor Risks.

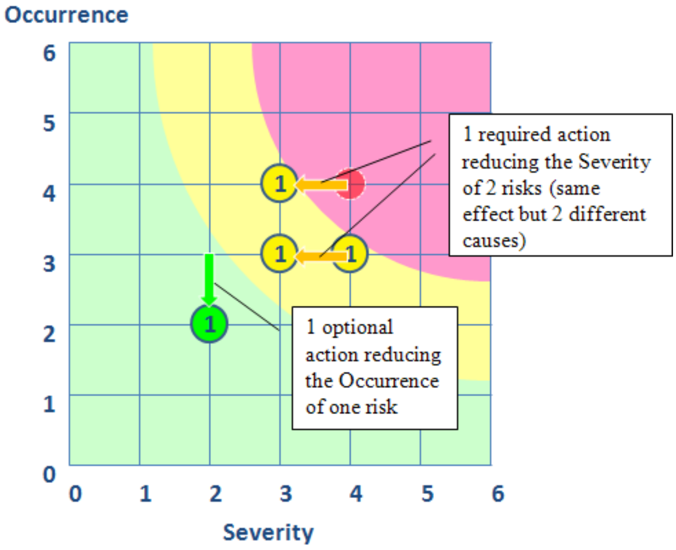

Figure 9. Expected Criticality Chart Example

In a same way, after proposing risk-mitigating actions, new Reliability Block Diagrams shall also prepare to ensure that the expected benefits shown in terms of criticality level are indeed sufficient to allow reaching the defined availability objectives.

8.6 Definitions

This section provides additional explanations for terminologies used in the RAMI Analysis process.

8.6.1 "Quantitative" assessment for level of risk

Three criteria are used to assess quantitatively the potential risk associated to various failure modes and thus allow prioritization of the appropriate risk-mitigating measures. The two main criteria, rated on 6-points scales, are Severity and Occurrence.

The evaluation of the risk level of any given failure mode is given through the product of the Severity of its effect (S) and the Occurrence of its cause (O), giving thus a quantified assessment on a scale from 1 (non-existent risk) to 36 (maximum risk). This product is called Criticality (C=S x O).

8.6.2 "Initial" and "Expected" ratings

The RAMI program relies first on an analysis of the current state of the design of the considered system. This first step of the technical risk control provides a list of the potential failure modes, with their Severity, Occurrence and Criticality as "Initial", i.e, calculated before the implementation of any risk mitigation measures.

Those ratings are thus designated Initial Severity S_i, Initial Occurrence O_i and Initial Criticality C_i.

In order to reduce the risk level of the identified failure modes, risk mitigation actions are proposed to either reduce their Severity or Occurrence. It is thus necessary to reassess those criteria after implementation of the actions to quantify their expected benefits.

Those ratings are thus designated Expected Severity S_e, Expected Occurrence O_e and Expected Criticality C_e.

8.6.3 Criticality of the "System" and criticality of the "ITER Machine"

Definition for the "system" is given by the PBS (Plant Breakdown Structure). In the PBS, there are more than 40 systems just below the ITER Machine level.

When rating the severity of particular failure modes on a system, it is necessary to distinguish between the consequences for the system itself and for the operation of the whole ITER machine.

If the failure of the system induces a longer downtime for the machine than for the system itself, then the severity rating will be higher for the machine than for the system.

However, if a failure on a system that is not absolutely necessary for the machine to operate renders it unavailable for a long time (typically more than a week), then, when this is possible, the experimental programme could be modified so that the machine can be operated in another way to do other experiments. The rating is thus not so high for the machine than it is for the system itself.

8.6.4 Design, Test, Operation and Maintenance

Risk mitigation measures can be categorized according to the phase to which they relate to.

A measure requiring a change in the design of the system, such as the implementation of redundancy, a change in the technology used or the implementation of margins in the specifications is a "Design Action".

A measure that does not relate to the design of the system is a Compensating Provision in any of the following category:

- Test: specific tests to be performed from the manufacturing of the components up to the commissioning of the machine (Test Compensating Provisions do not include Quality Control as this is considered a basic requirement for all components).
- Operation: specific procedures and training, interlock
- Maintenance: list of required specific spares, increased maintenance frequency

9 Administrative work plan

9.1 Kick-off meeting

The RAMI analysis begins with a Kick-Off Meeting where the RAMI team is introduced to the Plant System RO. Other members of the Plant System team can also attend if required. During the meeting, the Plant System RO briefly describes his/her system and the current state of his/her design, and the RAMI RO describes the RAMI process and the proposed schedule for the analysis.

9.2 Progress meetings

Following the Kick-Off Meeting and the beginning of the work, regular progress meetings are held regularly between the RAMI RO or his representative and the PS RO in order to ensure that potential difficulties are overcome and that the analysis progresses according to the schedule.

- The first important milestone is the review by the RAMI team of the functional breakdown prepared by the RAMI RO. When both parties agree that the functional breakdown is satisfactory from the RAMI point of view, it is presented to the PS RO for his approval.
- Following this is the RBD and FMECA review, where the Operations section leader or his representative is the approver of the availability calculations and failure mode analysis performed by the RAMI RO in collaboration with the PS RO.

9.3 Final Review meeting

The last important milestone is the review of the complete RAMI analysis that is attended by the RAMI RO and the PS RO. A presentation is made by the RAMI RO or member of the RAMI team to summarize the complete results, in terms of functional breakdown, RBD calculations and FMECA. Following agreement over the results during this meeting, the content of the presentation can then be used as a basis for presentations in Design Reviews of the considered plant system and a RAMI Analysis Summary Report is produced by the RAMI RO according to ITER_D_2N3SS9 - Template for RAMI Analysis Summary Reports, reviewed by the PS RO and approved by the Operations section leader, thus completing the RAMI analysis of the system.

10 RAMI requirements

The outputs of the RAMI process are used to validate the RAMI requirements that are integrated in the System Requirements Documents (SRDs) of the considered systems by referring to the Project Requirements document. In addition, the RAMI RO has to highlight the possibilities for standardisation.

10.1 Project Requirements

As a result of the RAMI Analysis, the RAMI requirements are integrated in each System Requirements Document by introducing a reference to the PR. Those requirements shall be taken into account when designing the system and preparing its commissioning, operation and maintenance.

The Operational Availability and Inherent Availability set as requirements for the ITER machine in order to ensure that it will be able to perform the experimental programme and provide the expected output of scientific and technical data are described in the Project Requirements document (ITER_D_27ZRW8).

These targets have been defined by taking into account the operational constraints for the machine and the expected RAMI performance of the systems or their main functions. Tables are provided in the PRs that define for each of these system or main functions the requirements in terms of reliability and availability that will allow the whole machine to meet its objectives. Values given in these tables have been obtained using a functional breakdown of the whole ITER machine into its constituting systems or main functions and a RBD approach as described in sections 7.2 and 7.3 of the present document. Such Project Requirements are an input.

10.2 Requirements and Entry Criteria at Design Review Milestones

In the framework of the Design Review process, the RAMI requirements which have been allocated to functions of plant systems, are reviewed to control that they have been properly taken into account and transcribed in the SRDs, adequately addressed in design through systematic evaluation of design options and that they can be plausibly achieved.

It is essential that RAMI analyses begin from the design of a system because corrective actions are still possible at this stage (mainly in terms of design changes-choices, tests before assembly, sub-system integration for accessibility, operation, maintenance frequency…). This evaluation is to ensure, before the production starts, that the design does not contain features which could cause unreliable equipment operation.

10.2.1 Conceptual Design Review (CDR)

Requirements	Entry Criteria
- Acknowledgment of the Reliability & Availability objectives set in the PR. - Functional analysis performed according to the RAMI Analysis Programme (ITER_D_28WBXD - ITER RAMI ANALYSIS PROGRAM) reviewed by the RAMI RO and approved by System RO. - First list of potential failure modes to be taken into account in the design.	- SRD chapter 4 consistent with approved template (ITER_D_2NCA24 - Template for RAMI & Operations Requirements in SRDs (section 4)), referring to Reliability & Availability objectives set in the PR (ITER_D_27ZRW8 - Project Requirements (PR)). - Functional analysis approved by the System RO and uploaded in the RAMI ANALYSIS RESULTS folder on IDM (https://user.iter.org/?uid=2M588T).

10.2.2 Preliminary Design Review (PDR)

Requirements	Entry Criteria
- RAMI analysis completed according to the ITER RAMI Analysis Programme (ITER_D_28WBXD - ITER RAMI ANALYSIS PROGRAM), including Reliability Block Diagrams (RBDs) and Failure Modes, Effects & Criticality Analysis (FMECA), reviewed by the System RO and approved by the RAMI RO. - Requirements in terms of Design, Test, Operation & Maintenance risk-mitigation actions included in the SRD.	- Analysis reports and deliverables posted in IDM, reviewed by the System RO and approved by the RAMI RO. - SRD chapter 4 updated with requirements and/or recommendations for risk-mitigation actions.

10.2.3 Final Design Review (FDR)

Requirements	Entry Criteria
- Required Design risk-mitigation actions implemented in the Design Description Document of the system. - Required Test risk-mitigation actions implemented in the System Testing Procedures approved by the RAMI RO. - Required Operation risk-mitigation actions implemented in the Operating Instructions & Conditions of the system, uploaded in IDM and approved by the Operations RO.	- Design Description Document uploaded in IDM and implementing RAMI required Design Actions. - System Testing Procedures uploaded in IDM and approved by the RAMI RO. - Operating Instructions & Conditions of the system, uploaded in IDM and approved by the Operations RO.

10.2.4 Standardisation Process

The RAMI analysis shall provide input for the Standardisation process undergone by the ITER project. In the framework of their study of the considered systems, RAMI RO is required to provide as part of their deliverables a list of potential components to be considered for standardisation not only inside the boundaries of the system but also relatively to other systems that might require similar components.

Implementing Standardisation (inter-changeability of spares) in the design of the systems shall then allow for shorter maintenance operation (replacement of consumables, repairs of failed components) and shall reduce the downtime of the systems and the Severity ratings in the FMECA, reducing the risk level and allowing for more availability of ITER for the experimental programme.

11 RAMI Activity Planning

Four main stages in relation to the project phasing have been considered for the activities and necessary resources:

- Design and Development,
- Manufacturing and Procurement,

- Testing, Individual Commissioning and Installation,
- Integrated Commissioning, Operation & Maintenance.

11.1 Design & Development stage

Design & Development stage corresponds to the period of searching for and establishing of alternative concepts for the systems with respect to the fulfilment of RAMI performance requirements. The RAMI engineering activity is maximum during this project phase during which a fist complete RAMI approach must be considered for all the main systems.

The IO System Responsible Officer is requested to plan the first iteration of concerned system RAMI analysis together with the IO RAMI Officer in a timely manner. Since design reviews are carried out during this phase, analysis result will be a part of input package for each design reviews described in chapter 7.

The final deliverable describing summary of key analysis result should be prepared using an IO official template [ITER_D_2N3SS9].

11.2 Manufacturing & Procurement stage

During Manufacturing & Procurement stage, more focus should be on tracking of the RAMI requirements which were required in the ITER baseline, whereas in the previous phase theoretical analyses were the main tool. The design actions initiated by the RAMI analysis to optimize the system availability, have to be now tracked (controls, inspections…) and a testing plan for installation acceptance has to be prepared to verify if the corrective actions are taken into account.

11.3 Testing, Individual Commissioning and Installation stage

The systems will be tested and installed at their operation site during Testing, Individual Commissioning and Installation phase. Proper individual testing at the end of the manufacturing process before the Machine Integrated Commissioning is an effective means to eliminate material and workmanship defects. Verifications of the RAMI characteristics and additional controls during tests for installation acceptance have to be made when it is possible. In addition a system support organisation for machine and system operation (procedures, limits, human training…), and for maintenance (preventive & corrective maintenance activities) has to be established according to the risk mitigating provisions recommended in conclusion of the initial RAMI analyses.

11.4 Integrated Commissioning, Operation & Maintenance stage

The RAMI database update to take into account the modifications, the experimental results and the preparation of the major shutdowns for an Availability Centred Maintenance and management of the available spare parts will be the main activities of the Maintenance RO in collaboration with the RAMI RO during the Integrated Commissioning, Operation & Maintenance. Computerized Maintenance Management System (CMMS) will be the main system to register all the testing result, spare parts and maintenance information, technical notes from manufacturers, etc.

12 Roles and Responsibilities

12.1 The Director General

The Director General oversees the entire RAMI activities performed by the RAMI Responsible Officer and other stakeholders. Of particular interest are the Major technical Risks which are identified as a result of RAMI analyses that could negatively impact the overall project scope during the operation phase if they are not mitigated.

12.2 The Head of Department for ITER Project

The Head of Department for ITER Project is responsible for overall project technical risk based on the RAMI analysis to ensure that the ITER Machine will be highly reliable and available to perform expected experiments during the operation period. Therefore the Head of Department for ITER Project is responsible for approving overall RAMI program and plan, implementing RAMI organization and various RAMI related activities within the IO, and ensuring that the compensational provisions as a result of RAMI analysis are implemented in designing, operation, testing and maintenance of ITER program. An appropriate direction and decision must be provided.

12.3 The Head of the CIE Directorate

The Head of the CIE Directorate is responsible for all the RAMI activities performed within his directorate. His role includes:

(1) Ensure appropriate resources required for RAMI activities,
(2) Solve any issues arising between the stakeholders,
(3) Solve any management issue occurring during the conduct of RAMI analyses,
(4) Provide advice and give approval to required RAMI actions.

12.4 The Heads of the DAs

The Head of the Domestic Agencies (DAs) are responsible for assisting and supporting the IO RAMI RO to define the RAMI programme and RAMI working plan, and to conduct necessary RAMI analysis for the systems. In order to achieve this, DAs are required to provide information about the system and resources to perform the analysis, as needed to be able to match the RAMI analysis plan with the Procurement Arrangement plan. Since failure rate of particular component could be obtained from suppliers, the DAs are required to collect that information on the basis of actual system design and to feedback on the RAMI analysis.

12.5 The Operations Section Leader

The Operations Section leader is responsible for defining the ITER RAMI analysis programme and managing the activities related to the RAMI work plan in the framework of the WBS related to Operations oversight which under his responsibility. He has to define the RAMI requirements for the ITER Systems and to report to senior management regarding the RAMI analysis results and any issues within the scope

12.6 IO RAMI Responsible Officer

The IO RAMI Responsible Officer (IO RAMI RO) is responsible for delivery of the RAMI analysis requested by ITER project. The roles of the RAMI RO are to:

(1) Develop RAMI analysis action plan

(2) Collect all supporting information from systems RO and other sources and coordinate daily RAMI analyses
(3) Communicate with stakeholders and prepare / deliver RAMI analysis report
(4) Ensure that the RAMI requirements are incorporated in the design baseline such as SRD
(5) Input RAMI analysis results into the database

12.7 IO Plant System Responsible Officers

The IO Plant System Responsible Officers are responsible for collaborating with the IO RAMI RO to provide any information and suggestion regarding the ITER system of interest when required, and to coordinate and approve the system Functional Breakdown, to establish the list of Failure Modes and contribute and validate FMECA with the objective to deliver comprehensive RAMI analysis reports.

After the completion of the RAMI analysis of the system, the Plant System ROs are in charge of integrating the RAMI results and requirements in the System Requirements Document, and later ensuring that these requirements are taken into account in the design of the system as well as in the testing plan and preparation of its operation and maintenance.

13 Conclusion

It is obvious that the ITER RAMI Analysis Programme with its associated procedures is constraining and, at the beginning, expensive in time and money. It can be applied only if the human and financial resources are sufficient and if all the stakeholders are convinced of the interest of the RAMI approach for the future machine operation and feel responsible for optimizing the whole ITER Life Cycle cost.

The planning of the analyses is regularly updated to match as much as possible the design review process and the Procurement Arrangements planning. To be able to advance quickly and efficiently in the ITER RAMI Analyses and to implement the RAMI requirements in System Requirement Documents, it is necessary to:

- Monitor the RAMI engineering process at regular intervals in RAMI progress meetings with the production of a status/progress report intended as a direct input to ITER Progress meetings.
- Have regularly (every 6 months) IO-DA RAMI & Standardisation Board Meetings with the RAMI & Standardisation Board members (ITER Organization + Domestic Agencies).
- Make decisions in terms of availability objectives for all main ITER systems in order to maximize the overall ITER machine availability beyond a minimum target as required in the Project Requirement document.
- Check the implementation of risk-mitigation actions in the various phases of the project.
- Update continuously the database and compare the theoretical forecast in terms of RAMI requirements with the experimental RAMI results during the machine operation and maintenance phases.