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Engineering Analysis

ITER RAMI Analysis Programme

This document defines a RAMI (Reliability, Availability, Maintainability, Inspectability) Analysis Programme for ITER, together with a description of the engineering processes and essential tools to be used.
In addition, a phasing of the RAMI Programme is briefly given.
The objective is to implement RAMI engineering standards for the ITER Project's construction, testing, and operation and initiate a RAMI Analysis in a technical risk control framework to support the overall ITER Project Management.

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	Name	*Action*	*Affiliation*
Author	**Antonov Y.**	**07 Jan 2025:signed**	**IO/DG/ESD/ACSD**
Co-Authors	**Serpi A.**	**07 Jan 2025:signed**	**Leonardo S.P.A (EU)**
Reviewers	**Colin P.** **Reichle R.**	**09 Feb 2025:recommended (Short Cycle)** **08 Jan 2025:recommended (Short Cycle)**	**IO/DG/ESD/ACSD** **IO/DG/CP/DIAG**
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Approver	**Kamada Y.**	**11 Feb 2025:approved**	**IO/DG/ST**
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Change Log			
ITER RAMI Analysis Programme (28WBXD)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v1.0	In Work	17 Oct 2007	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 to support the overall ITER Project Management.
v2.0	Signed	18 Dec 2007	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 to support the overall ITER Project Management.
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v3.0	Signed	30 Jun 2009	The ITER RAMI Analysis programme has been updated taking into account new rules for Occurence and Severity of the failure modes and integrating the RAMI process as validated by the Quality Management and the roles of RAMI Process actors.
v3.1	Signed	02 Jul 2009	The chapter on Roles & responsibilities has been updated together with some minor changes in the text.
v3.2	Signed	03 Jul 2009	New list of reviewers and some minor changes
v3.3	Approved	23 Jul 2009	All the comments made by the reviewers have been taken into account in this new version.
v4.0	In Work	03 Aug 2011	Update of the document regarding the roles and responsibilities to take into account the new IO organization an to introduce milestones related to the mandatory requirements during the design review process.
v4.1	In Work	10 Aug 2011	New version which integrats the Design Review milestones, administrative steps, an update of the process, roles and responsibilities in the new ITER Organization and some additional sections.
v4.2	Signed	11 Aug 2011	In this version 4.2 "RAMI analyst" has been replaced by RAMI RO.
v4.3	Approved	20 Mar 2012	Minor changes in the Definition section
v4.4	Approved	24 Feb 2021	No changes to existing version 3.3, for DA review to be included in the MPA #3.
v4.5	Approved	22 Nov 2024	The new version of the RAMI Programme contains minor updates to reflect the changes in Project Requirements (27ZRW8), the RAMI report template (2N3SS9), and the new WI for RAMI Analysis (C8U8V8). The RAMI Programme is no longer an MQP document (since WI for RAMI analysis is available) and will contain only technical details related to the IO RAMI methodology.
v4.6	Approved	07 Jan 2025	Minor updates as per reviewers' comments: Chapter 10.2.4 was added per Tim's comment, Some statements were rephrased per Pierre's and Roger's comments (see

			details in the documents attached

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1 Purpose

The purpose of this document is to define a RAMI (Reliability, Availability, Maintainability, and Inspectability) Programme for ITER, along with a description of the engineering processes, phasing, and essential tools to be used. This document aims to implement RAMI engineering standards for designing, manufacturing, testing, commissioning, operating, and maintaining the ITER machine and initiate RAMI analyses in the framework of technical risk control to support the overall ITER Project.

The detailed explanation of roles, responsibilities, and quality management of the process is detailed in the Working Instruction for Reliability, Availability, Maintainability, and Inspectability (RAMI) Analysis [2].

2 Scope

The RAMI analysis aims to handle technical risks that may impact ITER machine operation, physics programme, and maintenance-related function availability.

It covers RAMI analysis activities during the design development phases of all permanent systems and system updates driven by project evaluation and nonconformances found (PCR, NCR, DR).

Project management risks, such as schedule and cost risks, will not be considered in the RAMI analysis. Risks from safety or regulation will not be discussed in the RAMI analysis except for the investigation following a safety event triggered by a technical failure that stops the machine's operation.

3 Definitions and acronyms

All abbreviations used in the document are listed below. For a complete abbreviation list, please refer to the ITER Abbreviation list available at ITER_D_2MU6W5.

Acronym	Term	Definition
A	Availability	Ratio of operating time to the sum of operating time and downtime during experimental campaigns, assuming that required external resources are provided
Ae	Availability (Expected)	Calculated availability after implementation of risk-mitigating actions
Ai	Availability (Initial)	Calculated availability before implementation of risk-mitigating actions
ALARA	As Low As Reasonably Achievable	As per [13]
	Basic Function	Bottom-level system function identified as per the IDEFØ methodology
C	Criticality	Product of Occurrence and Severity, used to rate the risk level of a component failure (C = S x O)
Ce	Expected Criticality	Expected Criticality, after implementation of risk-mitigating actions (Ce = Se x Oe)
Ci	Initial Criticality	Initial Criticality, before implementation of risk-mitigating actions (Ci = Si x Oi)
CDR	Conceptual Design Review	
CIS	Central Interlock System	
CMMS	Computerized Maintenance Management System	
CODAC	Control, Data Access and Communication	

CSS	Central Safety System	
CWS	Cooling Water System	
DA	Domestic Agency	
DIRO	Design Integration Responsible Officer	
	Duty Cycle	Percentage of time a single component is expected to be in operation
DR	Deviation request	As per [30]
FDR	Final Design Review	
FMECA	Failure Modes, Effects & Criticality Analysis	Method using both the functional breakdown and RBD as input
FM	Failure modes	Means by which a component or equipment may fail
FA	Functional Analysis	In the context of this document, schematic representation of all the functions that a system is intended to perform
IDEFØ	Integration Definition Function Modelling language Ø	Format used to describe the top-down functional breakdown of a system using blocks for functions, with their input, output, controls, and mechanisms
IAEA	International Atomic Energy Agency	
I	Inspectability	Capacity of a system or its component to be monitored, accessed, and diagnosed (in the RAMI process, it is assessed in terms of access constraints, condition monitoring etc., but not calculated as a probability)
IDM	ITER Document Management (system)	
IO	ITER Organization	
	Lambda λ	Failure rate, i.e. the number of failures averaged per unit of time (λ = 1/MTBF)
LTM	Long Term Maintenance	
M	Maintainability	Capacity of a system or its component to be repairable (in the ITER RAMI process, it is quantified in terms of access constraints and availability of spares but not calculated as a probability)
MDT	Mean Downtime	Highlights the average time during which the system is not in a condition to perform its intended function, and it includes the MTTR and MLD (MDT=MTTR +MLD)
MIIP	Maintenance & In-Service Inspection Plan	As per [14]
MLD	Mean Logistics Delay	Consists of the time required to place a procurement contract, the time to manufacture the spare part, and the time to deliver the part. If no spare is provided on-site, its procurement depends on whether the units are procurable in the market (COTS components) or not (CUSTOM components)
MRR	Manufacturing Readiness Review	
MTBF	Mean Time Between Failures for repairable components, Mean Time Before Failure for non-repairable components	For a repairable component, the expected time between two component failures. For a non-repairable component, the expected time is before failure. MTBF = 1/λ
MTTR	Mean Time To Repair	Considers the time to access the component, extract/reinstall it, execute the repair/replacement required, and test the component before switching it in.
MUT	Mean Uptime	Average time during which the system is in a condition to perform its intended function without any downtime
NCR	Nonconformity Report	As per [31]
O	Failure Occurrence	Frequency of a failure mode that makes the related function unavailable
Oe	Expected Failure Occurrence	Failure occurrence after the implementation of risk-mitigating actions
Oi	Initial Failure Occurrence	Failure occurrence before implementation of risk-mitigating actions
OEM	Original Equipment Manufacturer	
O&M	Operations &	

	Maintenance	
PA	Procurement Arrangement	
PBS	Plant Breakdown System	
PCR	Project Change Request	As per [29]
PDR	Preliminary Design Review	
R	Reliability	Probability that a device will perform its function without failure over a specified length of time and under given conditions
RAMI	Reliability Availability Maintainability Inspectability	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.
RAMI RO		Person ensuring the ITER RAMI transverse function
RBD	Reliability Block Diagram	Diagrammatic method for modeling a complex system to calculate its reliability and availability based on the properties and configuration of its components' reliability and maintainability.
RH	Remote Handling	
RoX	Return of Experience	
RO	Responsible Officer	
S	Failure Severity	Term used to rate the downtime resulting from a component failure to the related basic function
Se	Expected Failure Severity	Failure severity after implementation of risk-mitigating actions
Si	Initial Failure Severity	Failure severity before implementation of risk-mitigating actions
SMART	Specific, Measurable, Achievable, Relevant, Trackable	
SOA	Sign off Authority	Sign off Authority for project documents as per [3]
SRD	System Requirements Document	
SSRD	Sub-System Requirements Document	
SSC	Structures, Systems, and Components	
SSEN	Steady State Electrical Network	
STM	Short Term Maintenance	
SysRO	System Responsible Officer	System RO oversees the system's full life cycle. It is, by default, the Project Leader of the delivered system. Project Leader (System RO) may nominate qualified staff(s) for System RO duties with associated responsibilities and authority to one or more employees of the ITER Organization who have the competence to accomplish the tasks under her/his Organization Breakdown Structure (OBS).
WI	Working Instruction	

4 Reference Documents

[1] Design Development Procedure (U34DDZ)

[2] Working Instruction for Reliability, Availability, Maintainability, and Inspectability (RAMI) Analysis (C8U8V8)

[3] Sign-Off Authority for Project Documents (2EXFXU)

[4] Project Requirements (27ZRW8)

[5] RAMI Analysis Report Checklist (Y2LYQA)

[6] Fusion Component Failure Rate Database (EFPDV9)

[7] Template for RAMI Analysis Summary Reports (2N3SS9)

[8] GIN 033 - Duties and Responsibilities of the ITER Organization Transverse Functions Officers and Coordinator (5CQWZU)

[9] T. Pinna, et. Al, Operating experiences from existing fusion facilities in view of ITER safety and reliability, Fusion Engineering and Design, Volume 85, Issues 7–9, 2010, Pages 1410-1415, ISSN 0920-3796

[10] FAILURE RATE DATA SOURCE (34P8A8)
[11] Fusion component Failure rate database (E9AE43)
[12] Practical Guidance for Reliability Prediction of the ITER components (Y2LZDY)
[13] Guidelines for ALARA Implementation (W6655F)
[14] Working Instruction for the Preparation of System Maintenance & In-Service Inspection Plans (YH3TFW)
[15] Template for Criticality Bubble Charts (44TMJP)
[16] MIL-HDBK-217F, Military Handbook-Reliability Prediction of Electronic Equipment. Washington D.C.: United States Department of Defense, 1991 (external link)
[17] IEEE 493 Design of Reliable Industrial and Commercial Power Systems
[18] IEC 61709 Ed. 3.0 b:2017 Electric Components - Reliability - Reference Conditions For Failure Rates And Stress Models For Conversion
[19] Telcordia SR-332, Reliability Prediction Procedure for Electronic Equipment. Red Bank: Telcordia Technologies, Inc., 2001.
[20] ITER RAMI Reports Overview (B9TVWP)
[21] IO Risks and Opportunities Register
[22] Design Development Procedure (U34DDZ)
[23] Design Verification & Validation Procedure (R3KD8C)
[24] Maintenance and Maintainability Design Plan (7WSRDW)
[25] Remote Handling Compatibility Procedure (2NRTWR)
[26] Procedure for Inspection and Testing (TVL3Y5)
[27] WI - Management of operational documentation (5EYHR7)
[28] Template for RAMI & Operations Requirements in SRDs (section 4)(2NCA24)
[29] Project Change Procedure (22F4E5)
[30] Procedure for the management of Deviation Request (2LZJHB)
[31] Procedure for Management of Nonconformities (22F53X)
[32] How to guide for computing the required number of spare parts (27N358)
[33] RAMI Kick-Off Meeting Check List (BBMRN9)
[34] EN 1990-2002: Eurocode - Basis of structural design [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]
[35] M. Sykora, M. Holicky. Target reliability levels for the assessment of existing structures
[36] ITER Structural Design Code for Buildings (I-SDCB) - Part1: Design Criteria (283B24)
[37] Availability of Present Fusion Devices | IEEE Conference Publication | IEEE Xplore

5 Introduction

The ITER project shall be a highly reliable, efficient, and safe device to produce quantitatively and qualitatively predefined scientific data output. It shall be available for experiments with low operation and maintenance costs. To achieve this, a RAMI analysis aims to provide designers and engineers with 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, 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).

This document describes the ITER RAMI analysis programme that is adopted and implemented to evaluate and control the RAMI aspects throughout the project for the design, test, operation, and maintenance of ITER and to initiate the RAMI analyses in the framework of technical risk control to support the overall ITER Project.

6 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. ITER represents an intermediate device which is both:

- A nuclear machine with objectives in terms of availability and neutron fluence,
- An experimental device with an ambitious scientific and technological programme.

For these reasons, it is essential to respect the following guidelines in the approach:

1. To integrate the ITER RAMI Programme requirements into procurement specifications for suppliers, operation instructions, and maintenance plans.
2. To reach the target values defined for each system in order to obtain the whole plant availability objective.
3. To analyze operational functions, draw up the list of the most critical function failure modes and implement the most efficient ways of improving the availability of the functions required to operate the machine.
4. To reduce the criticality of major risks by initiating corrective or preventive actions. A mitigating action shall be required, recommended, or optional depending on risk criticality.
5. To consider the risk mitigation actions as an input for design development, predictive maintenance established regarding operational rhythm, efficient spare parts management, equipment testing at commissioning and operation phases, human performance, and operational and maintenance procedures.
6. To extend the ITER RAMI 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.
7. To accumulate reliability data, particularly concerning the fusion technology, which ITER successors can then use.
8. To assess the system updates driven by project evaluation and nonconformances found.

7 RAMI Concepts

7.1 Functional Breakdown

Reliability and availability are characteristics primarily assigned to the system's functions.

Knowledge of the system’s hardware architecture is usually not enough. Functional analysis methods are used to determine availability.

The main functions identified for RAMI requirements are regrouped into three functional groups:

- **Machine Operation** regroups the Safety and Investment Protection functions, the functions related to structures, the utilities function necessary to sustain the plant's activity, and the main functions (components) of the tokamak.
- **Physics Programme** gathers the functions required for physics experiments that are not explicitly required for machine operation but important as an output of the ITER as a research project.
- **Maintenance** relates to the functions that are not necessary for performing a plasma pulse but are nevertheless essential to keep ITER in working order.

To allocate separate RAMI objectives to each function, the systems (PBS) have been broken down as a hierarchy of functions on multiple levels, from the system's main operational functions to the components' basic functions.

The systems that contribute to the abovementioned main functions are the core interest of the RAMI Programme.

7.2 Reliability

Reliability is defined as the probability that an item will perform failure-free its intended function in a specified time interval Δt.
When the failures identified for this item cannot be predicted and are assumed to occur at any time, the failure rate is constant. In such case, the reliability law is defined as exponential and is calculated as follows:

$$R = e^{-\lambda \Delta t},$$

Where λ is the failure rate (λ = 1/MTBF), and Δt is the time of the experimental campaign or the time from the component start.

From the practical point of view, the reliability of a single component is the opposite of the cumulated probability of this component failure. It's equal to 100% when the component is put into operation and reaches a minimum acceptable value at which further operation of the element is dangerous or economically unfeasible.

When the component is restored to " as new " condition after each maintenance intervention, reliability can be restored to 100%. If the periodic control does not imply the subsequent component replacement, an estimation of the test coverage must be conducted and justified.

Though the Project Requirements [4] do not provide the reliability target values, the low value of Reliability shall be understood as a potential risk that may impact the system functionality.

7.3 Availability

Availability is the probability that the device can perform the required function for which it was designed under given conditions at a given time *t* if the required external resources are provided. Its time characteristics differ from those of reliability since the concept of interest is an instant in time t instead of a given length of time. Functioning at time t does not necessarily imply functioning between [0, t] for a repairable system.

From the practical point of view, Availability is the ratio of operating time to the sum of operating time and downtime during experimental campaigns, assuming that the required external resources are provided.

Project Requirements [4] maintain a distinction between two types of availability: Inherent A_I and operational A_O.

Inherent Availability reflects the percentage of time a system would be available if there were no delays due to the planned maintenance, supply, etc., and it is calculated with the formula mentioned below where only corrective maintenance is considered:

$$A_i = \frac{MTBF}{MTBF + MTTR},$$

MTBF (Mean Time Between Failures) is the average time between two failures, and MTTR (Mean Time To Repair) is the average time to diagnose the failure mode, access to the failed component, repair/replacement, and post-maintenance tests.

Operational Availability includes the effects of planned preventive maintenance, corrective maintenance, logistic time, waiting, and other non-design factors:

$$A_o = \frac{MUT}{MUT + MDT},$$

Where MUT (Mean Uptime) is the average time during which the system is in a condition to perform its intended function, and MDT (Mean Downtime) is the average time during which the system is not in a condition to perform its intended function (MDT includes MTTR).

Thus, A_O reflects the totality of the product's inherent design, the availability of maintenance personnel and spares, maintenance policy and concepts, and other non-design factors, whereas A_I reflects only the inherent design.

7.4 Maintainability

Maintainability is the capacity of a system or its components to be repairable.

Maintainability engineering is regarded as implementing basic principles for future equipment repair while equipment is being designed, developed, and/or fabricated. 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 the accuracy and adequacy of maintenance actions.
2. Least quantities of:
    - required facilities,
    - maintenance personnel,
    - training to enable the performance of maintenance requests,
    - tools, tests, and support requirements.

7.5 Inspectability

Inspectability is the capacity of a system or its components to be monitored, accessed, and diagnosed.

It is defined as the characteristic of design and integration that allows in situ monitoring of equipment performance regarding the amount of remaining lifetime.

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

Both Maintainability and Inspectability are qualitative characteristics of the components introduced via MTTR, which measures the time a single component can be repaired and returned to operation.

8 ITER & Systems RAMI Objectives

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

- Operating mode in terms of working days,
- Needs for scheduled maintenance and upgrades with the needs for the scientific and technological program of ITER,
- Time required for scheduled routine maintenance,
- Number of shifts,
- Operational machine availability translated to the system's inherent availability targets that reflect the percentage of time that each system would be available if no expected delays were planned.

8.1.1 Operational rhythm

ITER shall be designed to continuously conduct plasma operations for up to 16 months in three 8-hour work-shift daily operating modes to perform the following actions: plasma operations, test, conditioning, and routine maintenance.

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 (STM)), corresponding to a cycle, with a significant shutdown of a few months for maintenance/upgrades (8 months are currently envisaged (LTM)) and further installation after a long plasma operation period (16 months are currently envisaged). Three 8-hour shifts are presently envisaged as a basis for planning during the operation. The third shift will be used for plasma operations, tests, conditioning, or routine maintenance. The operating scenario will use four global operation states: Plasma Operation State (POS), Test and Conditioning State (TCS), Short Term Maintenance (STM), and Long-Term Maintenance (LTM) (**Figure 1**).

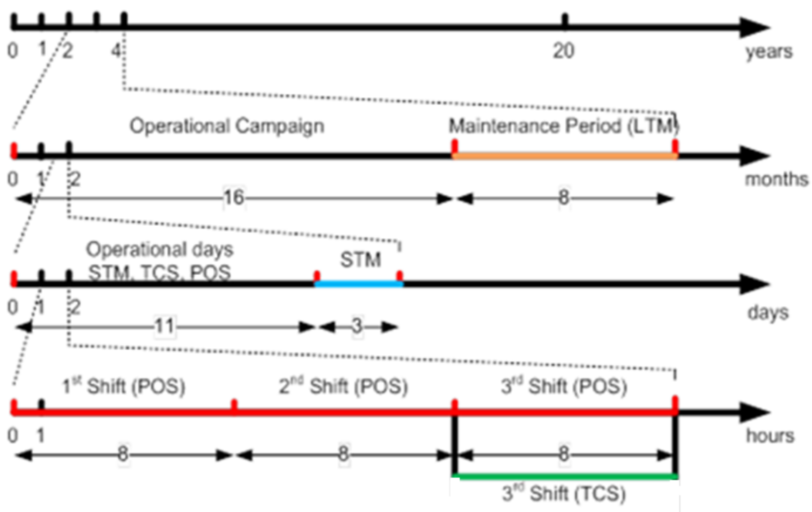

Figure 1. ITER operating scenario

8.1.2 Operational and Inherent Availability Targets

Taking into account 365 working days per year and 24 working hours per day, ITER shall be designed for an operational machine availability of at least 32% on average in a three-shift operating mode with a Mean Scheduled Down Time (MDT) not greater than 11.3 months over every two-year experimental campaign. When considering the scheduled downtime for planned inspection, maintenance, and upgrades of ITER systems, the machine shall meet an inherent machine availability of 60% for "basic" plasma operation [PR974-R] [4].

Those targets are comparable with the availability of present water-cooled fusion devices [37].

The operational availability target is used to assess the machine's overall availability for plasma operation and the execution of the scientific program. It considers management decisions such as the operation rhythm and the planned maintenance programme. The machine's overall availability target is translated to the main functions, and systems (PBS) contribute to those functions. The Project Requirements [4] define the inherent availability targets that represent the systems' engineering maturity and are not concerned with the ITER operational rhythm.

Unless the system under assessment is a Level 1 (basically, ITER systems), the availability requirement may need to be refined to the subsystems (Level 2 or 3). The product of all subsystems' availability should equal the parent element's availability requirement to ensure consistency with the overall project availability target. Thus, additional study can be required.

8.1.3 Systems lifecycle

The RAMI Programme provides inputs for the systems design evaluation, which aims to reach availability targets within the project and every system lifecycle.

ITER shall be designed for an operating lifetime of no less than 20 years [4].

The design life of systems (including buildings) that shall be operational during commissioning or deactivation periods shall be specified accordingly.

The Tokamak Complex and Hot Cell Building shall be designed for a 70-year life [4].

This time interval used for the availability simulation should confirm that the proposed system design can meet availability requirements, provide inputs for the efficient concept of operations, rationalize the system's maintenance and testing throughout its lifecycle, and allow to formulate risks in the risk register (including suitable mitigation actions), should the availability prediction for a given subsystem fall short of its availability target.

9 RAMI Process

The RAMI analysis is an iterative process that begins with a Conceptual Design Review (CDR) to ensure that the design does not contain features that could cause unreliable equipment operation and insufficient system availability for executing the scientific programme and aims at each step of the design development review to confirm the system design meets Project Requirements and assess the function failure modes criticality and integrate the criticality mitigation proposals.

While subordinate to the Project Requirements, the output of the RAMI analysis shall be considered an input in the design, operation, and maintenance, as important as other decision drivers trading off cost, delay, and performance.

It's also important to ensure that certain structures, systems, and components (SSC) still meet the availability requirements if the SSC is subject to change.

In case of any system modification driven by project change [29], a temporary modification that may impact system reliability [30] or nonconformance, which shall be resolved [31], it is also required to investigate whether the system can perform its function(s) and reach target availability translated from the ITER target availability given in [4].

All details related to the RAMI Analysis Summary Report production shall be clarified during the dedicated kick-off meeting as per [2] and stated in the standard kick-off meeting checklist form [33].

9.1 Functional Analysis

This section presents the first part of the functional analysis of the analyzed PBS as an overall view aiming at showing in one figure all functions, from the main functions through the intermediate functions down to the basic functions, along with the components they are associated to. This is expected to be presented during a CDR, along with a list of envisioned failure modes. Both elements are the basis on which the rest of the RAMI analysis will later be built, so they should be agreed on early in the process by both the design teams and the RAMI practitioners.

The methodology selected by IO is inspired by the IDEFØ (**I**ntegration **DE**finition **F**unction Modelling– 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 shall be expressed as a verb (e.g., to provide confinement, to dissipate the heat in the environment etc),
- Each function shall be represented by an activity block with its Inputs, Controls, Outputs, and Mechanisms,
- Blocks shall be linked following their functional relationships.

IDEFØ uses several "layers" to represent a complex system, from the top-level system to the intermediate functions and the basic functions. This allows complex diagrams to be decomposed and activities refined into greater detail as required for understanding and making decisions.

The failures of components highlighted at the level of the basic functions lead to failure of the main function they are related to, and this main function failure can impact a specific part of the system's and machine's whole operation.

It is an essential input for designing Control Systems (as CODAC, CIS and CSS) it analyses the connections of the various functions through those systems.

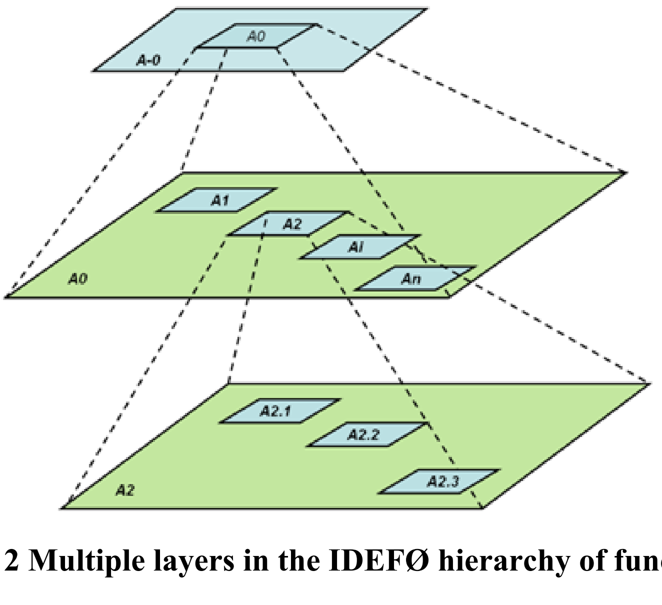

Figure 2 Multiple layers in the IDEFØ hierarchy of functions

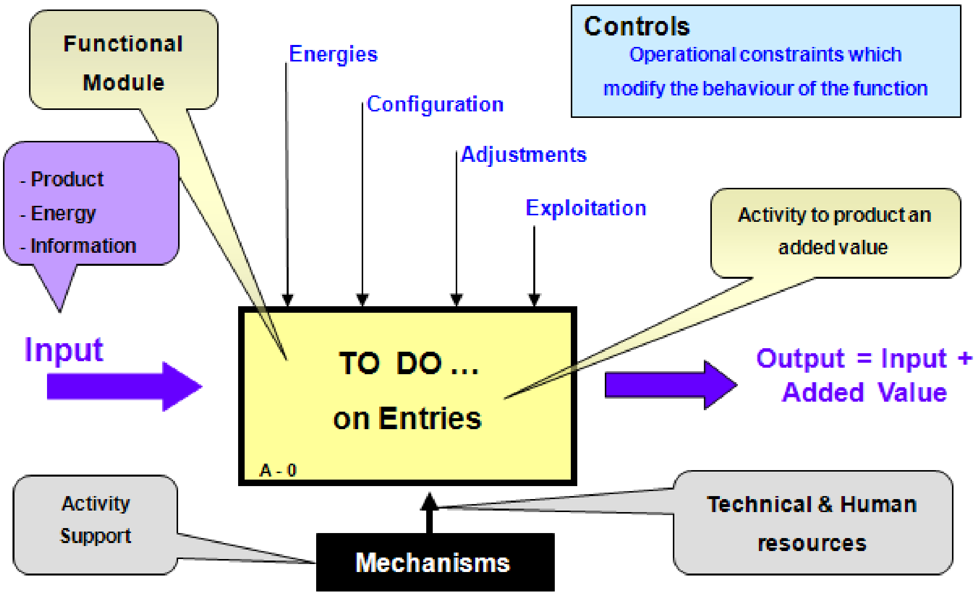

Figure 3 IDEFØ basics

The breakdown's highest (A0) level diagram **(Figure 2)** typically shows main function(s), represented by blocks labelled A1 to A6. The next level of the functional breakdown is a set of diagrams named A1 to A6, each describing one of the main functions as a set of intermediate functions labelled A1.1, A1.2…, A2.1, A.2.2… and so on. At the next level, each intermediate function is described in its diagram as a set of basic functions labelled A1.1.1, A1.1.2…, A1.2.1, A1.2.2… and so on. In the cases of very complex systems, there could be several levels of intermediate functions between the high-level main functions and the low-level basic functions.

In each of those diagrams, each of those function blocks **(Figure 3)** has four arrows linking it either to other functions at the same level or to different systems:

- Coming from the left, going into the function block is the **Input** to the function, it is the initial situation, the fluid, beam or signal and their properties of conditions that will be transformed by the function. It can also be the output from another function block in the same diagram, as explained below.
- The right side of the block has the function's **Output**, which is the resulting situation, the fluid, beam, or signal, and their properties or conditions after the function has transformed them. As explained above, this output can be an input to another function block in the same diagram.
- Coming from the top, going into the function block, are the **Controls**, which govern how the function will be performed when it starts and stops… Those are usually the central control systems but also the experimental program, operating conditions, and the other plant systems that are required to perform the function, but on which the analyzed PBS has no authority like the utilities (those shall be excluded from the RAMI analysis, but still shown in the IDEFØ diagrams to highlight the dependencies between plant systems).
- Coming from the bottom, going into the function block, are the **Mechanisms**, which are the means used to perform the function. Those are the components that are part of the analyzed PBS.

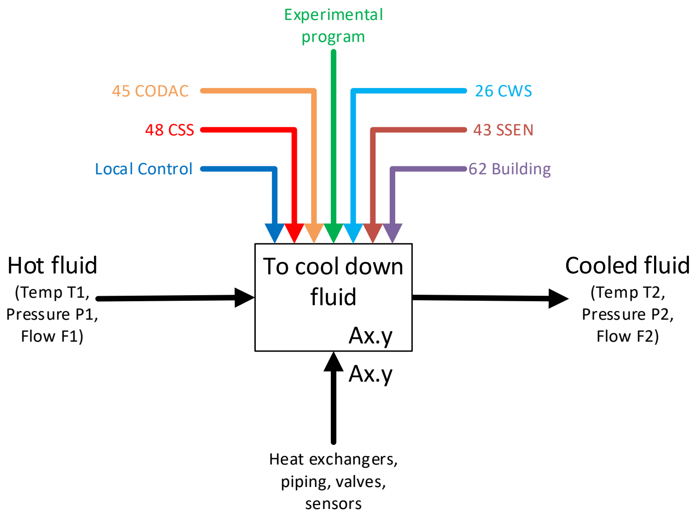

Figure 4 IDEFØ Methodology example

For example, one could consider a function to cool down a fluid **(Figure 4).** The Input (arrow from the left) would be the hot fluid with its initial temperature, flow, and pressure; the Output (arrow to the right) would be the cooled-down fluid with its resulting temperature, flow, and pressure; the Controls (arrow from the top) would be the analyzed PBS' local control system, CSS, CODAC, the experimental program from Operations, CWS for the secondary loop, SSEN for power supply and the building housing the analyzed PBS itself, and the Mechanisms (arrow from the bottom) would be the analyzed PBS' piping, heat exchanger, valves, instrumentation…

Color-coding the different Controls makes the diagrams easier to follow when the same Controls link multiple functional blocks, and many arrows intersect on the same page.

9.2 Failure Modes, Effects & Criticality Analysis

By the CDR, a draft list of failure modes is envisioned for the analyzed PBS to highlight the most severe system issues that may be designed driving. This should, however, be developed further by the PDR into a full FMECA and an overview of the failure modes and effectiveness of risk mitigation actions presented in the initial and expected criticality bubble charts. The most severe risks and the associated risk-mitigating actions should be discussed in detail. Finally, the spare recommendations and standardization proposals should also be completed.

The Failure Modes, Effects, and Criticality Analysis (FMECA) uses the Functional breakdown and reliability data applicable to the components identified through the Functional breakdown itself as input and envisages criticality as a risk of a single function failure (unavailability) which impacts the entire system functionality.

It does not consider the possible transfer of part of the functionality between systems in the event of the considered system's failure since the availability of the second system can be impacted by its failure occurring simultaneously. This approach could result in failure accumulation and jeopardize machine availability.

The reliability data needed are as follows:

1. MTBF, MDT, MTTR, MLD.
   Component failure rate data may be taken by order of importance from the RoX, Original Equipment Manufacturer (OEM) failure rate data, industrial or military standards [16], [17], [18], [19], and available research databases [6], [10], [11]. For

some components where MTBF and MTTR are unavailable (e.g., first-of-a-kind), the part count and part stress analysis can be used per [12].
The component environmental conditions shall be considered when defining MTBF and MTTR when applicable (recommended at PDR, required at FDR stage). Refer [12] for details.

2. Duty Cycle as a percentage of time a single component is expected to be in operation. It's essential to distinguish between the duty cycle and the component's environment, such as radiation or ambient temperature, which impacts MTBF and (in some cases) MTTR (e.g., operational radiation exposure following the ALARA principles).
The duty cycle application differs for active and passive components.
The IAEA defines a passive component as one whose function does not depend on an external input such as actuation, mechanical movement, or power supply.
For example, the active component's duty cycle can be 30% depending on the operational demand, while its cover or support experiences the workload 100% of the time.
As a rule, the following example can be used: the duty cycle of a component (e.g., the centrifugal pump) that operates 2 out of 3 8-hour shifts 11 out of 14 days (not in use while STM) 16 out of 24 months (not in use while LTM) can be calculated as $\left({}^{2}/_{3}\right) \times \left({}^{11}/_{14}\right) \times \left({}^{16}/_{24}\right) = 0{,}35$ or 35%.

The FMECA can be divided into four main phases:

- Identification of all the Failure Modes (FM) for the basic functions,
- Qualitative assessment of the causes of these failure modes and their effects on the main functions of the system as well as their effects on the system itself;
- Quantitative assessment of the Occurrence of the causes O (based on MTBF) and Severity (based on MDT) 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).

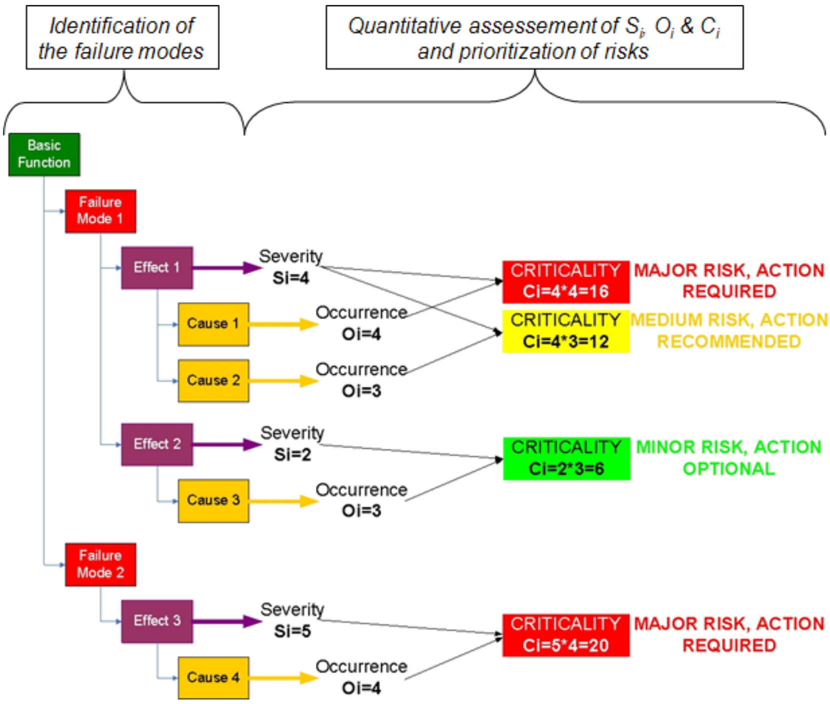

Figure 5 Basic principles of the FMECA

Figure 5 describes the basic principles of the FMECA as they are applied to 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 to maintain consistency in 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.
- Bubble charts highlight the distribution of the failure modes throughout the diagram and its three risk level zones.

Value	Description	Meaning
1	Weak ≤1h	Unavailable for 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 for more than 1 year

Table 1 Severity rating scale

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

Table 2 Occurrence rating scale

Once the failure modes of a system have been integrated into the Criticality Chart [15], it is possible to set priorities in the measures envisioned to reduce the risk levels (**Figure 6**):

- The "red" zone represents the Major Risks calling for required actions for those the Criticality is higher than 13,

- The "yellow" zone represents the Medium Risks for which actions are only recommended for those the Criticality is between 7 and 13
- The "green" zone represents Minor Risks; the corresponding actions are optional for those with a Criticality of less than 13.

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

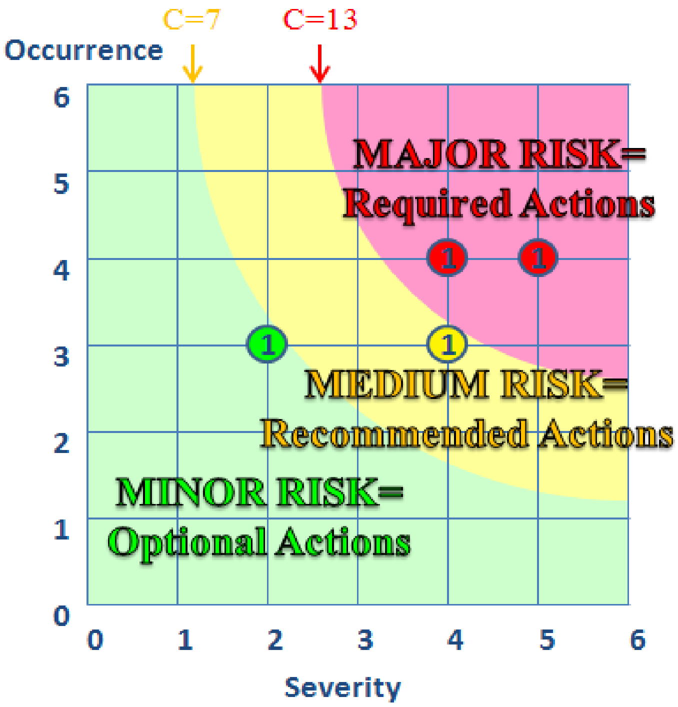

Figure 6 Example of Initial Criticality Matrix

9.3 Risk Mitigation Proposals

Risk-mitigation proposals are made to reduce the risk level associated with the failure modes identified in the FMECA. These proposals can be distinguished by lowering 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:

Effect / Category	Prevention (decreases Occurrence)	Protection (decreases Severity)
Design	Use higher quality components with improved reliability or implement redundancy to reduce the risk of losing the function. See also [23], [24]	Implement risk-containment provisions to avoid cascading failures. Make remote-handling maintenance possible for critical parts of the system. See also [25]. Optimize the accessibility of the component.
Test	Define specific component qualification tests in simulated operating conditions to check the reliability of a component.	Apply specific tests to ensure the maintainability of components that require a long time to repair. See also

		[26]
Operation	Interlock operation of sensitive components with a functional safety check to avoid damage. Swap redundant components to extend their effective lifetime.	Prepare specific training and procedures to allow reaching a safe mode in an emergency. See also [27]
Maintenance	Establish inspections and preventive maintenance operations. See also [24], [14]	Keep spares on site so that the MDT is shortened. See also [14]

Table 3 Examples of risk-mitigation proposals

In the previous example (**Figure 6**), two failure modes are in the red zone, with an Initial Criticality higher than 13. They are thus considered a Major Risk to the system's operation and require risk-mitigation actions.

The most critical failure mode is failure mode 2, with an initial effect Severity Si of 5 and an initial cause Occurrence Oi of 4, resulting in an Initial Criticality C_i of 20. This means such a failure could happen more than once in the ITER's lifetime, resulting in function unavailability between 2 months and one year.

It is possible to assess the benefits of an alternate design using two components instead of one so that the failure of one would not result in the total loss of function during the repair (**Figure 7**). Moreover, if a spare is kept available on-site or by the supplier, it is possible to avoid waiting for a replacement part to be manufactured and delivered (MLD=0); the resulting downtime could be reduced to less than two months (**Figure 8**).

If implemented, those two actions would push the risk out of the red zone by reducing 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.

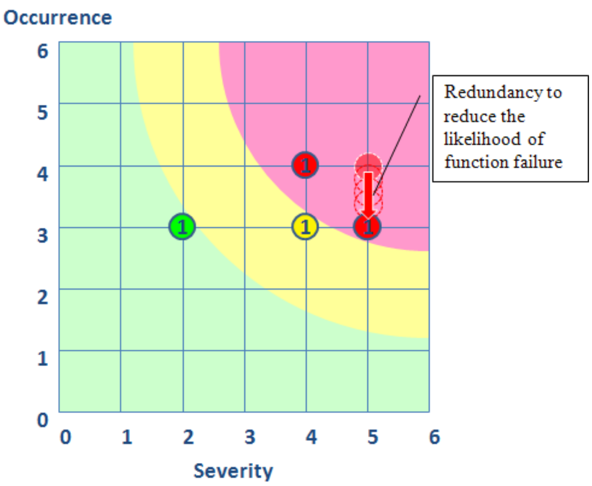

Figure 7 Action Example 1 (Redundancy)

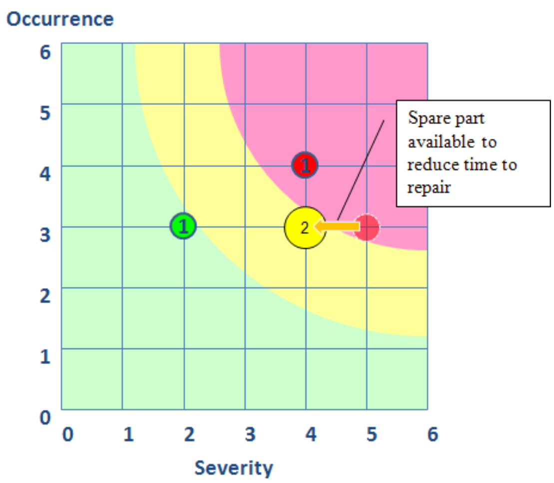

Figure 8 Action Example 2 (Spare parts)

The actions given above are generic examples. However, by the FDR, the risk mitigation actions proposed by the RAMI practitioners should be SMART, that is:

1. Specific: They cannot be generic statements such as "use more reliable components" or "perform more maintenance," the RAMI practitioners need to define precisely which components are considered and what minimum MTBF they should stand for, or what maintenance interval is required in comparison to what would be the industry standard;

2. Measurable: The action's intended effect meaningfully reduces either the likelihood of failure or the resulting downtime (or both) in a way that can be reflected in the RBD model calculations, showing improved expected availability and/or reliability.
3. Achievable: There are physical constraints that may make some actions impossible, such as limited space preventing the installation of a redundant component; those have to be taken into account by the RAMI practitioners to avoid pushing for unrealistic actions;
4. Relevant: If a component needs multiple months to be repaired because of accessibility concerns or because it needs to be treated in the Hot Cell Complex, then pushing for spares on-site might not reduce the MDT significantly if they can be procured from the manufacturer in an as-needed basis;
5. Trackable: Actions shall be implemented to have any effect. If spares are required, they should be added to the Procurement Arrangement and budgeted; if redundancy is necessary, then the 3D models, plans, pipe and instrumentation diagrams, and bill of materials should include the redundant components.

9.4 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. Then, an Expected Criticality Ce must be assessed, and an Expected Criticality Chart must be prepared.

In the example above, additional actions could be proposed to reduce the Severity or Occurrence of the remaining Major, Medium, and Minor Risks **(Figure 9).**

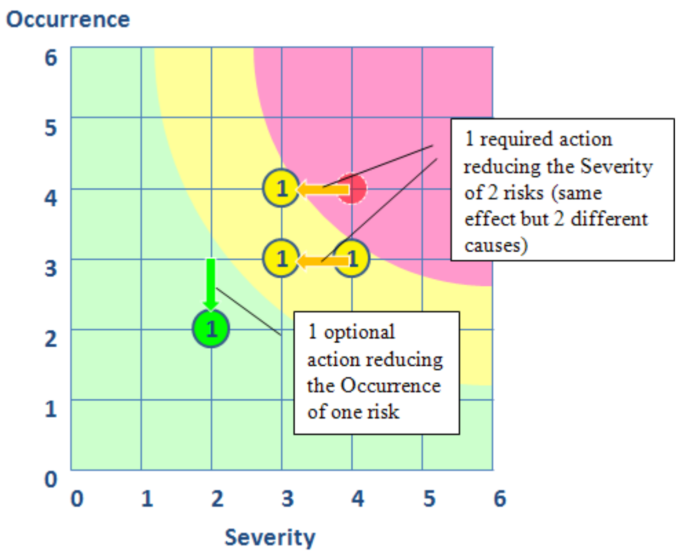

Figure 9 Expected Criticality Chart Example

The completed list of mitigation actions can be used as input for Operations, Maintenance, Testing, or system design evaluation. See [2] for details.

Risk mitigation actions should be analyzed from several points of view and demonstrate a balance of ways to mitigate criticality, such as preventing or protecting (where applicable), changing the design, or adapting the maintenance policy.

The Major risks for which criticality wasn’t mitigated shall be recorded in [21].

SysRO shall be assigned to these records. Unresolved criticality shall be considered an exception due to the imperfections of modern technologies or the cost of mitigating risks that significantly exceed the effect of a single SSC failure. Thus, it shall be considered a Project risk.

9.5 Reliability Block Diagrams

This section, which will be completed for the Preliminary Design Review and updated (at least) for the Final Design Review, should present the quantitative results obtained by running availability simulations using the ReliaSoft BlockSim software (version 10 or later). Any alternative tools shall be agreed upon by the RAMI RO during the dedicated RAMI kick-off meeting [33].

The RBD (Reliability Block Diagrams) approach uses the functional breakdown as a basis but focuses on the reliability-wise relationships linking the function blocks. Several diagrams allow for a consistent description of the multiple levels in a hierarchy with the functional breakdown. At the same time, 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 system's main functions or the whole system itself.

This input data consists of the reliability parameters (MTBF), maintenance parameters (MTTR), and system operational rhythm (duty cycles, time the corrective or preventative maintenance task can be executed (LTM, STM, night shift, right after the failure mode was identified if the component is redundant, etc.)). These data were previously identified when completing the FMECA.

As the number of components and functions increases and the system configuration becomes more complex, the calculations shall consider elements such as series, parallels, k-out-of-n, and redundancy to provide reliability and availability ratings.

The environmental conditions and the system's operational rhythm must be considered. Where the components experience severe environmental conditions (radiation, high temperature, vibration, etc.), can be repaired/replaced immediately or only during the next STM or LTM, spare parts available or to be shipped, as well specific preventative maintenance or tests aimed to extend the component's failure-free functioning planned – all those factors directly impact the system's availability and thus shall be considered at least for the Final Design Review.

For **Availability** simulation, the RAMI practitioners shall choose a specific time (called "simulation end time" in the ReliaSoft BlockSim software).

Since the simulation shall demonstrate that the system design satisfies the target availability values derived from [4] within the system's lifecycle, the simulation end time shall be set to 20 years (175,200 hours) for subsystems not included in a maintenance plan with earlier scheduled repair or replacement. In other cases (e.g., for systems required for decommissioning), the time can be extended accordingly.

The minimal number of simulations shall be selected from the criteria that resulting convergence will not exceed 0,1% for target $A \geq 99\%$, 0,2% for $95\% \leq A < 99\%$, and 0,5% for $A < 95\%$ [4]. It is mandatory to perform at least four simulations of a model.

It should be noted that Reliasoft BlockSim software calculates both operating A_O and inherent A_I availability, while system target availability refers to inherent availability.

Reliability expresses the failure risk evaluation within the operation time.

For Reliability calculation, the mission end time is to be chosen time interval between two maintenance interventions where the system is planned to be refurbished to "as new" condition, such as the 11 days (264 hours) of scheduled operating time between two Short-Term Maintenance phases (for systems and components that can be accessed and repaired during STM), or the 16 months (11,520 hours) between Long-Term Maintenance phases (for the systems and components that can only be repaired during the LTM).

Availability and Reliability results should be provided for the main and basic functions to identify the biggest contributors to the analyzed system's unreliability and unavailability. They should also be given for both an **initial** and an **expected** assessment.

The **initial** availability and reliability are those obtained in the first analysis of the analyzed PBS, using the design "as-is" and referring to FMECA's initial state. It allows a first overview of the system, reliability- and availability-wise. It should be noted, especially for plant systems for which relevant input data relies heavily on assumptions based on non-ITER-like conditions, that the absolute numbers obtained for the analyzed PBS are less important than the results of the different main functions compared to one another. They should nonetheless be compared to the requirements set in the [4] and the target values propagated to the System Requirements Documents (SRDs) and SRDs and sub-System Requirements Documents (sSRDs).

The **expected** availability and reliability are those obtained in a second run of the calculations and simulations after risk-mitigating actions have been defined in FMECA and their expected benefits implemented in the RBD model, in the form of a reduced failure rate, i.e., increased Mean Time Between Failures (reducing the Occurrence of a failure mode cause) and/or a shortened Mean Down Time (reducing the Severity of the failure mode effects).

If the target Availability value is not met, the risk mitigation actions should be reassessed, and a new simulation performed.

It must be noted that the RAMI analysis is ultimately reviewed with the help of the checklist [5] to ensure the methodology used is compliant with the present document.

9.6 Spare Parts Recommendations

This section, which is to be completed for the PDR and updated (at least) for the FDR, presents the list of spare parts advocated for the analyzed system (including but not limited to the spare requirements issued from required risk-mitigation maintenance actions). The information provided should cover the components considered, the number of spares, and the location where they are expected to be stored (on the Iter site, at the supplier…), as this may impact the MDT.

Using [32] based on the Poisson distribution as a guide for the spare quantity definition is recommended.

9.7 Standardisation proposals

This section, which is to be completed for the PDR and updated (at least) for the FDR, presents a list of the analyzed system's components for which the possibility of standardization with other plant systems using similar items has been identified. The objective is to improve its maintainability and reduce the overall cost of the whole Iter project.

A table should list those components, the number in which they are required in the analyzed system, and the other Iter systems that are expected to require similar components so that specs can be compared between each plant system and made identical as much as possible, and orders of initial components, spare parts, or tools can be regrouped and shared among plant systems.

10 RAMI requirements

The RAMI process outputs validate the RAMI requirements integrated into the System Requirements Documents (SRDs) and sub-System Requirements Documents (sSRDs) of the considered systems by referring to the Project Requirements document.

10.1 Project Requirements

As a result of the RAMI Analysis, the RAMI requirements are integrated into each System Requirements Document by propagating the PR requirements to SRDs and sSRDs, and by this document being applicable. Those requirements shall be considered when designing the system and preparing its commissioning, operation, and maintenance.

The Operational Availability and Inherent Availability set as requirements for the ITER machine 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 [4].

These targets have been defined by considering the machine's operational constraints and the expected RAMI performance of the systems or their main functions. The PRs provide tables that define the requirements regarding availability for each of these systems or main functions 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 an RBD approach as described in the current document.

10.2 Requirements and Entry Criteria at Design Review Milestones

In the Design Review process framework, the RAMI requirements allocated to plant system functions are reviewed to ensure that they have been properly considered and transcribed in the SRDs, adequately addressed in design through systematic evaluation of design options, and plausibly achieved.

RAMI analyses must begin with a system design because corrective actions are still possible at this stage (mainly in design changes, tests before assembly, and sub-system integration for accessibility, operation, and maintenance frequency…). This evaluation ensures the design does not contain features that could cause unreliable equipment operation before production starts.

10.2.1 Conceptual Design Review (CDR)

Requirements	Supporting activities
• Acknowledgment of the Reliability & Availability objectives set in [4]. • Functional analysis shall be performed according to [2], reviewed by the RAMI RO, and approved by the SysRO line manager • The first list of potential failure modes is to be considered in the design.	• SRD chapter 4 consistent with the approved template [28] referring to Reliability & Availability objectives set in [4] • The first drafted version of the system design with the major components defined • Report is registered in [20] and [21]

10.2.2 Preliminary Design Review (PDR)

Requirements	Supporting activities
• RAMI analysis is completed according to the current document and includes Reliability Block Diagrams (RBDs) and Failure Modes, Effects & Criticality Analysis (FMECA).	• Analysis reports and deliverables were posted in IDM, reviewed, and approved. • SRD chapter 4 updated with requirements

• Requirements for Design, Test, Operation, & Maintenance risk-mitigation actions are included in the SRD. • ITER operational rhythm was considered while adding the corrective maintenance as failure mitigation where possible • The first version of the spare parts list is drafted • MLD is calculated if essential spare parts are not considered in stock	and/or recommendations for risk-mitigation actions. • Updated version of the report is registered in [20] and [21]

10.2.3 Final Design Review (FDR)

Requirements	Supporting activities
• Report contains significant details of the components used with reliability-related characteristics • MTBF, MTTR are corrected with available environmental conditions • Corrective actions with ITER operational rhythm • A list of essential spares is available, and possible standardization options are considered • MLD is calculated if essential spare parts are not considered in stock • Required Design risk-mitigation actions implemented in the system's design description document. • Required Test, Operations, and Maintenance risk-mitigation actions are acknowledged for further development of MIP and operational procedures	• The design description document was uploaded to IDM, and implementing RAMI required design actions. • System Testing Procedures uploaded in IDM • Operating Instructions & Conditions of the system, uploaded in IDM • MIP uploaded in IDM

10.2.4 Manufacturing Readiness Review (MRR)

Though the RAMI Analysis Summary Report is not required at MRR, manufacturers shall confirm that the selected components satisfy the technical specifications derived from the Report produced at FDR.

10.3 RAMI Updates Driven by Further System Development

The RAMI reassessment shall confirm that any change (such as PCR, NCR, DR) is consistent with the initial target availability and associated considerations for design, predictive maintenance, operations, and testing.

As general guidance, the RAMI reassessment shall be launched in the following cases:

a. System changes its designation (functionality),
b. Deterioration of environmental conditions (humidity, ambient temperature, dust, radiation, etc), which may lead to a reduction in the service life of equipment or an increase in the time required for its repair (e.g., accessibility),
c. Changing the approach to forming a pool of spare parts for the main system's components, which may lead to unexpected logistics delays,
d. Increasing the duty cycle of the system's components,

e. Changing the service life of components, changing the time required to repair components, using components that have these values different from the original, and changing the number of identical components,
f. Changing operating instructions, the concept of operations, or the testing of system parts may lead to the above changes.

These changes can lead to updates to the corresponding RAMI Analysis Summary Reports.

10.4 Recommended Reliability Targets for Buildings and Other Permanent Structures

While the target Availability is available in [4] for most systems, the recommended Reliability value is not given as such. In most cases, proper risk management through criticality mitigation actions and system Availability that satisfies the target values are enough to ensure the acceptable risk within the system or single component operation and provide optimum system design and appropriate operation, testing, and maintenance programs.

For permanent structures, such as concrete buildings, the minimal risk of failure is paramount since those structures provide specific functions (e.g., to host plant equipment, to provide confinement in case of hosted system failures) and are available for the entire lifecycle until decommissioning.

The Eurocode EN 1990-2002 [34] provides recommendations on Reliability values depending on the possible failure consequences as follows :

Consequence Class	**Description**	**Examples of buildings and civil engineering works**
CC3	**High** consequence for loss of human life *or* economic, social, or environmental consequences **very great**	Grandstands, public buildings where the consequences of failure are high (e.g., a concert hall)
CC2	**Medium** consequence for loss of human life, economic, social, or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g., an office building)
CC1	**Low** consequence for loss of human life, *and* economic, social, or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter storage buildings), greenhouses

Table 4 Definition of consequence classes

The target failure probability $p_f$can be calculated depending on the Consequence Class:

CC1: $p_f \leq t_{ref} \times 10^{-3}$

CC2: $p_f \leq t_{ref} \times 10^{-4}$

CC3: $p_f \leq t_{ref} \times 2 \times 10^{-5}$,

Where t_{ref} – reference lifetime in years (refer to Chapter 8 and [4]) [35]

$R = p_S = (1 - p_f) \times 100\%$,

Where p_S – system survival probability equal to the Reliability.

Exhaustive design criteria for buildings are specified in [36].

11 RAMI Activity Planning

Four main stages concerning 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

The Design & Development stage corresponds to searching for and establishing alternative concepts for systems that fulfill RAMI performance requirements. The RAMI engineering activity is the most efficient during this project phase.

The IO System Responsible Officer is requested to promptly plan the first iteration of the concerned system RAMI analysis together with the RAMI RO. Since design reviews are carried out during this phase, analysis results will be part of the input package for each design review.

The final deliverable describing a summary of analysis results shall be prepared using [7].

11.2 Manufacturing & Procurement stage

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

11.3 Testing, Individual Commissioning and Installation stage

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

11.4 Integrated Commissioning, Operation & Maintenance Stage

The RAMI report output shall be used when writing Operational and Test Procedures, Maintenance and In-Service Inspection Plans [14].

When the system is subject to a change, the RAMI shall be reassessed to confirm that the changes won't impact the system availability, as discussed in 10.3.

The RAMI database update to consider the modifications, the experimental results, and the preparation of the major shutdowns for Availability 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. A Computerized Maintenance Management System (CMMS) will be the main system to register all the testing results, spare parts, maintenance information, technical notes from manufacturers, etc.

12 Conclusion

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

- Monitor the RAMI engineering process regularly in RAMI progress meetings by producing 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 regarding availability objectives for all main ITER systems to maximize 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.
- Continuously update the database and compare the theoretical forecast regarding RAMI requirements with the experimental RAMI results during the machine operation and maintenance phases.
- Ensure the possible system or project changes won't impact an overall machine availability.