Preliminary RAMI analysis approach for Chinese Fusion Engineering Testing Reactor (CFETR)

(1th Preliminary version for discussion)

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1 Introduction

There are eight design goals for the first option of Chinese Fusion Engineering Testing Reactor (CFETR), two ambitious purposes are to realize long pulse or steady-state operation with duty cycle time $\geq$ 0.3~0.5, and to explore DEMO blanket and divertor with an easy changeable core by remote handling. Only base on the above purposes, most important system of CFETR require highlighting RAMI analysis. The ITER machine operation will be carried out typically in three 8 hours plasma shifts operation mode with 11 plasma operation days and 3 routine maintenance days every 2 weeks, and typically 16 months operation each 2 years campaign, under the above operation requirement, 33 systems of ITER machine are done RAMI analysis, some have been finished and the others are still going on, of course, the number are still to be updated with the project progressing. Comparisons on ITER, more than 33 CEERT important systems are needed RAMI analysis.

To be able to reach CFETR's scientific and technological objectives, an assessment of the technical risks has to be performed. The RAMI analysis method is one of the main stages of the technical risk control and it focus on the operational functions required by the CFETR operation but not on physical components. And it uses an association of methods and dedicated software tools, allowing defining requirements for the operational functions and providing means to ensure what they met. The RAMI analysis begins during the design 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, definition of the maintenance frequence and the list of spare parts.

Now the first step is to explain the simply conception of RAMI. RAMI is stand for the Reliability, Availability, Maintainability and Inspectability. Reliability: it is possible to write the reliability function as R(t), and the probability $0 \leq \mathrm{R}(\Delta \mathrm{t}) \leq 1$ so that a system perform failure free in a specified time interval Δt under given conditions. Availability: The A(t) of a system must be regarded as a performance, it is the ability that its readiness for correct operation under given condition at a given time t, assuming that all the external resource needed are provided. Availability is an integral measure of the maturity of corresponding technology. Hence, the overall plant availability on CFETR will be an indicator of its technology success. The issue of availability of each system which will contribute to ensure the function "To operation the CFETR machine", therefore, has to be taken seriously right from the beginning of conceptual design of the components. Maintainability: the maintainability of a system is the probability that a given maintenance operation can be accomplished in a given time interval. $0 \leq \mathrm{M}(\Delta \mathrm{T}) \leq 1$, Probability so that the system is repaired in the interval (0, t). And it is simply to say that system has the ability to undergo repair and modifications. Inspectability: it is defined as the characteristic of design and integration that allow in-situ monitoring of equipment performance with regard to the amount of usable lifetime remaining. I(t), probability so that the performance and the usable lifetime of an equipment is monitored at time t. And it is simply to say that system must has the ability to undergo visits and controls.

The RAMI analysis is focused on the functions required to CFETR operation and their failure criticality. It is declined in 5 steps: Functional Analysis (FA); Failure Mode, Effects and Criticality Analysis (FMECA); Reliability Block Diagram (RBD); Risk Mitigation Actions; RAMI Requirements.

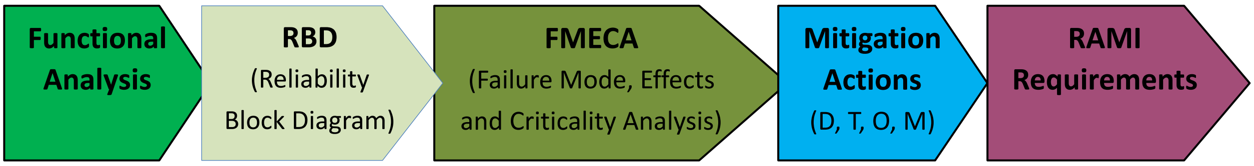

Fig. 1. Simply flow chart of CFETR RAMI analysis approach

Basing on the preliminary ambitious purpose of CFETR project and to reach the targets, there is a preliminary proposal, the RAMI requirements should be the top level requirements documents of the system design review process, which cannot be approved if there is not the approval of CFETR director for the RAMI analysis.

2 Functional Analysis (FA)

Functional analysis (FA) is the first step of the CFETR RAMI process. It allows making an exhaustive understanding of the system from functional point of view. FA starts with the creation of a complete breakdown describing the considered system from its main functions to its basic functions performed by the components, but not a process flow description. And the functional breakdown of the considered system is a top-down description of the system as a hierarchy of functions on multiple levels, using the IDEFØ (Integration Definition Function-languageØ) approach. IDEFØ is not software but a method which is based on the SADT (Structured Analysis and Design Technique) approach to model functions (activities, actions, processes and operations), functional relationships and data for a system. IDEFØ assists the modeler to identify what functions of considered system are performing, what is needed to perform those functions, what the current system does right, and what the current system does wrong. Steps to perform functional breakdown is declined into 4.

a. Think about the top level function of the concerned system. Usually the main function should be come from the system requirements.

b. Consider to keep consistent level of detail for each main function. Put common function across the system in one box under “Supporting” function.

c. Think about the next level after the main function level. Continue breakdown of the system to the basic function level where we associate components. And describe the breakdown chart in a tree structure.

d. Associate the key components to the basic functions.

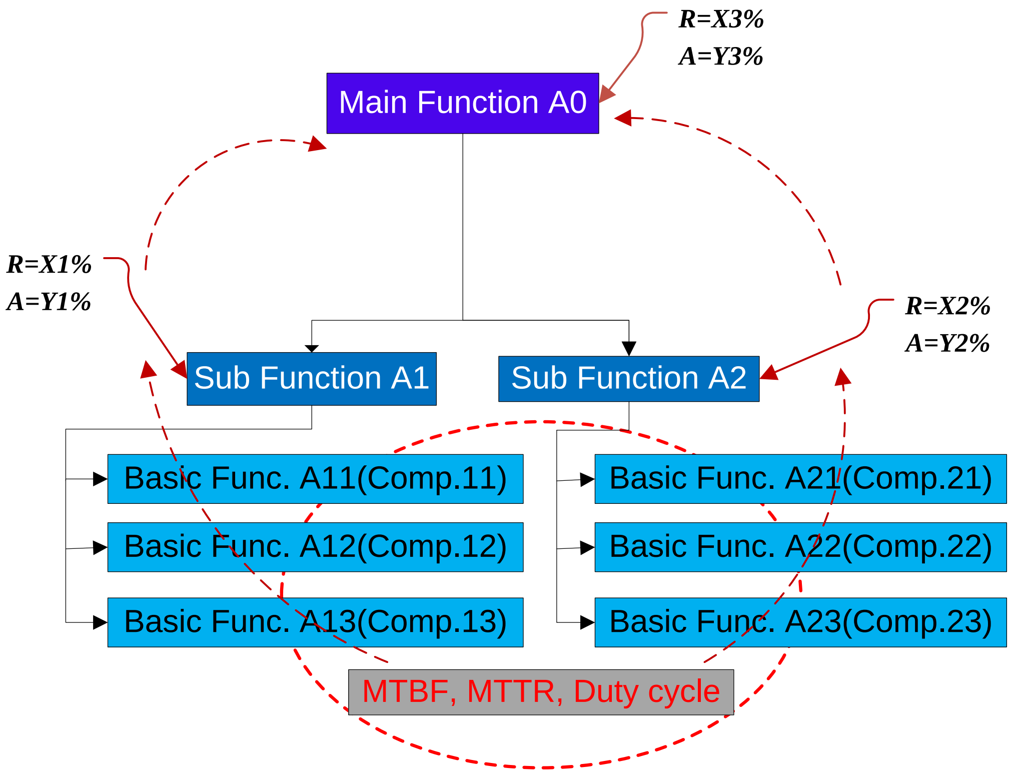

Fig. 2. Simply schematic diagram how to do function breakdown and calculation of reliability and availability for a considered system

3 Reliability Block Diagrams (RBD)

After the considered system functions are breakdown, the next step in RAMI analysis is a bottom-up method basing on RBD to estimate the reliability and availability of its main functions according to the given conditions. The RBD can translate the failure modes, their effects and their causes into reliability and availability parameters, and at last the reliability and the availability of the system can be calculated.

Several diagrams are made to described the multiple levels in a hierarchy consistently with the functional breakdown, the upper level of reliability and availability are calculated by feeding input data to the lowest level blocks (components or basic functions), translating to the main functions of the system or the whole system itself. The input data consists in the Duty Cycle, the Mean Time Between Failure (MTBF) which is the reliability parameters and the Mean Time To Repair (MTTR) which is the maintenance parameters. All the parameters can be obtained from various sources such as manufacturers’ specifications, reliability databases, industry standards, previous experience complied in other scientific devices, the other most important source is that because it is not get the precise data, so assumption data are made following the personal experience of the RAMI analysts and experts available at the time of the analysis. Sometime the available data may not be completely pertinent because the very specific experimental conditions the components will face on CFETR can be not known very precisely, therefore an appropriate estimation has to be carried out. At the same time, the numbers of the components and functions are so large and the system configurations are complex, the calculations have to take into account elements such as series, parallels, redundancy and so on.

The creations of RBDS can be used some commercial software, such as BlockSim and Isogragh and so on. The inputs of the RBDs should be contained: The functional breakdown approved by the CFETR system responsible officer, the list of failure modes, the list of components, reliability parameters: MTBF, Duty Cycle, Failure rate λ, and the maintainability parameters: MTTR, availability of spares. The outputs of the RBDs can be got: the reliability of the system and its functions, the availability of the system and its functions, the optimization proposals and the comparison the technical solutions. The red dotted line in Fig. 2 shows one output of the RBDs for a considered system: bottom-up process reliability and availability calculations.

The overall inherent availability target for CFETR machine operation should be greater than 60% of ITER requirement, because the ITER availability objective is to reach for the machine operation in H phase an inherent availability 60% and 30% in term of operational availability which includes the effects of maintenance delays and other no design factors. In order to reach this target, the CFETR plant systems must satisfy their own availability requirements, which have been defined at the level of the main functions. If the availability results given by RBDs simulations for the main functions did not satisfy the RAMI targets set in the project requirements, then mitigation actions have to be defined and implements. FMECA will give the reference for us to prioritize those risk mitigation actions.

4 Failure Mode, Effects and Criticality Analysis (FMECA)

FMECA is basing on the functional breakdown of the system, according to the importance with respect to the machine operation availability, it is established a list of functional failure modes, their causes and effects. It is going to evaluate the severity of the effect and the occurrence of the cause of main failure modes, use a criticality chart (O, S) to discriminate the major, medium and minor risk. The FMECA uses the functional breakdown, the list of failure modes, rating scales for occurrence and severity and results of RBDs as the input data, and the qualitative description of the technical risks, a prioritization of the actions to reduce risk and the updating of failure modes database are its output.

There are some basic principles of FMECA, as they are applied on every system functional breakdown, are the following:

a. The failure modes, their effects and their causes envisioned are described.

b. These effects and causes are evaluated quantitatively using the severity and occurrence rating scales as in Table 1 and Table 2, S = Mean Down Time induced by the effect of failure (unavailable time for the operation), O = Frequency of the cause of each failure mode. These rating scales are used for all the systems in order to keep consistency between all analyses. What need to emphasize is that the Table 1 and Table 2 are only applicable for ITER which based on the project objects and decided by the ITER organization.

Table 1. ITER rating scale for severity S. (The CFETR rating scale for severity S needed to be

decided by the CFETR technical committee (or the others name who has the top right to decide the rating scale?) basing on CFETR objects in the future)

S **value**	Description	Meaning
1	Weak <1h	Unavailable less than 1h
2	Moderate <1d	Unavailable between 1h and 1day
3	Serious<2w	Unavailable between 1day and 1week
4	Severe <2m	Unavailable between 1week and 2months
5	Critical <1y	Unavailable between 2months and 1year
6	Catastrophic >1y	Unavailable more than 1year

Table 2. ITER rating scale for occurrence O. (The CFETR rating scale for occurrence O needed to be decided by the CFETR technical committee (or the others name who has the top right to decide the rating scale?) basing on CFETR objects in the future)

O **value**	Description	Meaning	
1	Very low	$\lambda_{risk} < 5 \times 10^{-4}$/y	$\lambda_{risk} < 5.7 \times 10^{-8}$/h
		MTRF > 2000years	
2	Low	$5 \times 10^{-4}/y < \lambda_{risk} < 5 \times 10^{-3}$/y	$5.7 \times 10^{-8}/h < \lambda_{risk} < 5.7 \times 10^{-7}$/h
		200years < MTRF < 2000years	
3	Moderate	$5 \times 10^{-3}/y < \lambda_{risk} < 5 \times 10^{-2}$/y	$5.7 \times 10^{-7}/h < \lambda_{risk} < 5.7 \times 10^{-6}$/h
		20years < MTRF < 200years (20years = the ITER lifetime)	
4	High	$5 \times 10^{-2}/y < \lambda_{risk} < 5 \times 10^{-1}$/y	$5.7 \times 10^{-6}/h < \lambda_{risk} < 5.7 \times 10^{-5}$/h
		2years < MTRF < 20years	
5	Very high	$5 \times 10^{-1}/y < \lambda_{risk} < 5$/y	$5.7 \times 10^{-5}/h < \lambda_{risk} < 5.7 \times 10^{-4}$/h
		10weeks < MTRF < 2years	
6	Frequent	$\lambda_{risk} > 5$/y	$\lambda_{risk} > 5.7 \times 10^{-4}$/h
		MTRF < 10weeks	

c. In the RAMI analysis, a Criticality chart is used to distinguish several risk levels, and criticality C is obtained from the product of the severity S and the occurrence O , then the coordinate (S, O) of all (effect, cause) couples are placed on the criticality chart. The chart is to be defined priorities, just as showed in the Fig. 3. Where are 3 zones: Major technical risks (C>13), the mitigation actions addressing them are required (red zone); Medium technical risks (C>7), the mitigation actions addressing them are recommended (yellow zone); Minor technical risks (C<7), the mitigation actions addressing them are optional (green zone). Also the CFETR criticality scale distinction standard is needed to be decided by the CFETR technical committee (or the others name who has the top right to decide the rating scale?).

Of course, the FMECA can be performed in the software Xfmea or the Excel.

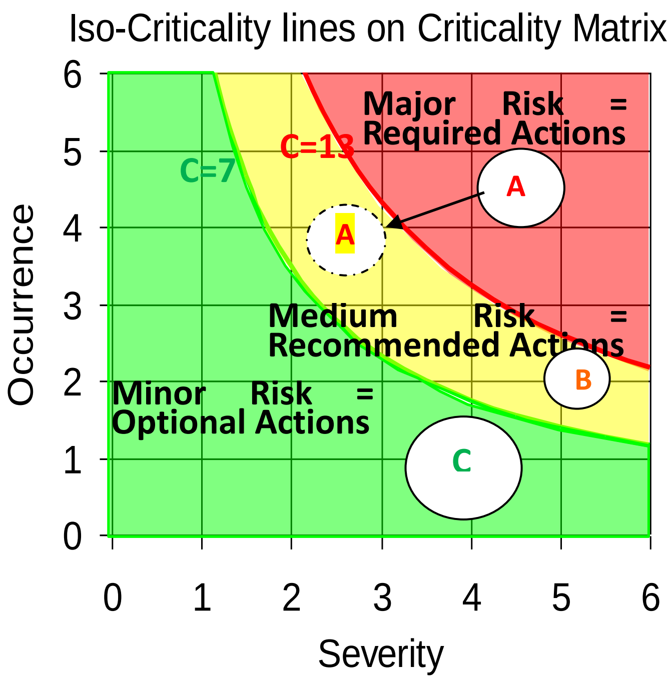

Fig. 3. Criticality chart of RAMI, Risk mitigation actions recommendation and expected criticality

5 Risk mitigation actions

Just as said in the third and the fourth steps, the RBDs have given the different reliability and availability, also the FMECA has highlighted different failure modes with different levels of risk. If the analysis is correct, the RBDs show similar results, highlighting the same failure modes. If the major risks are highlighted in FMECA, the system will not have a sufficient availability to reach the target set in the project requirement. So in order to get a better availability for the main functions of the system, risk-mitigation actions are initiated. The actions are distinguished by the way they reduce either the occurrence or the severity of the failure modes, thus can reduce the criticality. And the risk mitigation actions can be of 4 categories: Design, Test, Operation and Maintenance. Some example actions are shown in Table 3.

Table 3. Examples of risk-mitigation actions.

	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
Test	Apply tests to check reliability of the components	Apply tests to ensure maintainability of components with a long time to repair
Operation	Interlock operation of sensitive components with a safety check to avoid damage	Prepare specific training and procedures allow falling back to safe degraded mode in an emergency
Maintenance	Increase the frequency of inspections and preventive maintenance operations	Keep spares on-site so that to repair is shortened

Once the risk-mitigation actions have been initiated, their expected benefits are assessed in terms of expected severity (Se<Si) and/or expected occurrence (Oe<Oi), so the expected criticality (Ce<Ci) can be obtained and filled the criticality chart. It should be done that there are no major risks remain after the mitigation actions are taken into account. Reduction of severity and/ or occurrence can lead to reduction of the criticality of the failure modes and removes them from the red zone. After the risk-mitigation actions are done, the new expected reliability diagram shows a more reliable and available system. All the other contributions just as maintenances, testing and operation actions are also very important, because it is possible to decrease the criticality and increase the system and machine inherent availability.

Just as showed in Fig. 3, the total numbers of initialed criticality is A major technical risks, B medium technical risks and C minor technical risks. After the risk-mitigation actions are initiated, the major risks are removed to be medium risks, so the total numbers of expected criticality is 0 major technical risks, A+ B medium risks and C minor risks. Unfortunately, there are maybe some major risks are those which criticality remains > 13 without being able to make a reasonable additional mitigation action for many kinds of reasons in the last, but the numbers must to be very few on the whole project.

6 RAMI requirements

The outputs of the CFETR RAMI analysis to be said RAMI requirements, which are integrated into the system requirements documents of the considered system in the CFETR project. The RAMI requirements contain:

a. The availability and reliability targets of the considered system, the main functions according to the project objects.

b. Specific tests introductions which to be performed on the components and the systems.

c. Operation procedures and the specific trainings which to decrease the risks when operating the machine.

d. The design changes which need to be improve the current design.

e. Maintenance requirements in terms of list of spares, intervals of inspection and preventive maintenance, procedures and training.

f. there is one proposal, for common parts used in the project in a great number, suggest to build up standardization. Because the standardization can ensure the inter-changeability of spares in the system, and then allow for shorter maintenance operation and shall reduce the downtime of the systems, increase the availability and reliability of CFETR operation object.

7 Conclusion

Basing on the preliminary ambitious purpose of CFETR, CFETR shall be designed for an inherent availability of the overall machine greater than 60%, more than 20% in term of operational availability which includes the effects of maintenance delays and other no design factors, and the remaining 10% comes from human resource quality and natural factor. To reach the target, an inherent availability requirement of x% is required for the Y system. In order to assess the feasibility of such a requirement, a functional breakdown is performed. Basing on the functional breakdown and using data collected from data base and/or experience on the previous fusion device, RBDs are prepared. A bottom-up approach makes it to evaluate the initial reliability/ availability. Using the rating scales rules defined by the CFETR technical committee (or the others name who has the top right to decide the rating scale?) to put the severity of the effects (Si) and occurrence of the causes (Oi) into the criticality chart, a criticality chart Ci = Si × Oi highlighting the technical risk levels.

The FMECA, listing and rating the potential failure modes of the functions, with their effects and their causes, which results in a list of actions required to reduce the expected severity to be lower than initialed severity (Se<Si), and/or reduce the expected occurrence to be lower than initialed occurrence (Oe<Oi), removing the major risk to lower expected criticality, less threatening for the operation of the system and the CFETR machine (Ce<Ci). To achieve above objects, the risk-mitigation actions needed to be done.

And in the last, the outputs of the CFETR RAMI analysis to be a set of RAMI requirements, which are integrated into the system requirements documents of the considered system in the CFETR project. There is a preliminary proposal, to reach the targets of CFETR project, the RAMI requirements should be the top level documents of the system design review process, the design review cannot be approved if there is not the approval of CFETR director for the RAMI analysis.