RAMI Analysis for PFCs of EAST Divertor

Yang Zhang, Shijun Qin, Lei Cao, Damao Yao, and Jiangang Li

***Abstract*— Experimental advanced superconducting tokamak (EAST) is a D-shaped full superconducting tokamak device. Plasma-facing components (PFCs) of EAST lower divertor are most likely to be damaged during the operation, which become fail easily and have to be replaced and repaired frequently. To evaluate whether the divertor is able to reach the design objective, an assessment of technical risks by means of reliability, availability, maintainability, and inspectability (RAMI) for PFCs of EAST lower divertor has to be performed. A functional analysis is carried out in a bottom–up approach, which is described using the IDEFØ methodology. Based on the functional analysis, a failure mode, effect, and criticality analysis is performed to evaluate potential causes of failures and their effects. Criticality charts highlight the risk levels of different failure modes with regard to the probability of their occurrence and the impact on the operation, and actions are taken to mitigate the major risks. According to reliability block diagrams, the availability and the reliability of functions are calculated under stipulated operating condition. The RAMI analysis results provide the reference for the coming upgrade of EAST lower divertor and will be further optimized as the upgrade of the lower divertor.**

***Index Terms*— Divertor, experimental advanced superconducting tokamak (EAST), plasma-facing components (PFCs), reliability, availability, maintainability, and inspectability (RAMI).**

I. INTRODUCTION

EXPERIMENTAL advanced superconducting tokamak (EAST) is a D-shaped fully superconducting tokamak device with actively water-cooled plasma-facing components (PFCs). With the goal to get 1-MA plasma current, 1000-s plasma charge duration, and above 100 million plasma temperature under high-power heating, EAST will establish technological basis of the fully superconducting tokamak devices.

To achieve better steady-state plasma parameter and higher heat flux performance, new plasma position and shape are calculated and optimized, which consequently bring great challenges to EAST engineering design. Divertor, especially its PFCs, is most likely to be damaged by high heat flux during the operation and becomes fail easily, having to be replaced and repaired frequently. There are various failure modes for PFCs of divertor leading to plasma disruption and even forcing EAST stopping running. Seeking to address this challenge, three generations of divertors have been designed for EAST to extract energy, expel impurity, and improve the boundary of plasma.

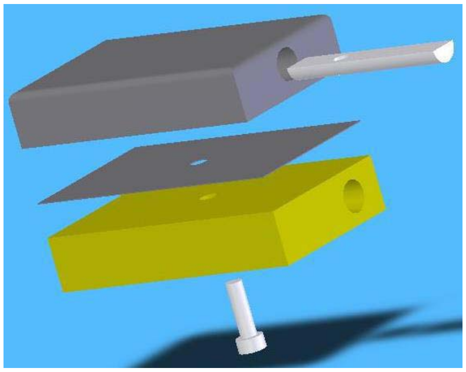

Fig. 1. Bolt structure of PFCs.

EAST divertor geometry is designed as up–down symmetry to accommodate both double-null and single-null plasma configurations. The first-generation divertor is steel divertor, composed of first wall and support, and the first wall is stainless steel plates which are bolted on the support. It has been applied for the first burning of the plasma in EAST since 2006–2007. The layout of the second-generation divertor is the same as the first-generation divertor, while the first wall is full graphite tiles to accommodate the long pulse operation with a higher power injection. It has been applied from 2008 to 2013. In the upgrade of 2013, upper divertor is updated to full tungsten divertor while lower divertor continues to be carbon divertor. The full tungsten divertor is international thermonuclear experimental reactor (ITER)-like design which is based on the cassette structure and monoblock technology.

There are 16 modules of lower divertor, and each module comprises an inner target, a dome, and an outer target. Each target is composed of 27 graphite tiles with thickness of 15 mm, the CuCrZr heat sink with thickness of 20 mm, and the stainless steel support. The water-cooling channels are drilled on the heat sink connecting to outer water-cooling pipes. A piece (0.38 mm) of soft graphite sheet is put between the graphite tile and the heat sink to improve thermal contact. All graphite tiles are bolted to the heat sink as shown in Fig. 1 [1].

Extracted the first letter of each word from reliability, availability, maintainability, and inspectability (RAMI), the RAMI approach, devised by the ITER organization [2], is to perform the technical risk assessment. Focusing on the operational

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functions and their failure criticality, the RAMI approach uses an association of methods, providing means to ensure that the design requirement is met.

The RAMI analysis is a continuously iterative process which begins from the phase of design of a system because corrective actions are still possible at this stage (mainly in terms of design choices, tests before assembly, allowance for accessibility and inspectability in system integration, and input for the operation or the definition of the frequency of maintenance and of the list of spare parts). It has been applied to various systems of the ITER project [3]–[5], aiming at improving inherent availability and the reliability of the operation. RAMI analysis for PFCs of EAST lower divertor during the phase of operation and maintenance is necessary, which evaluates whether the lower divertor is able to reach the design objective and provides the reference for the coming upgrade.

II. RAMI APPROACH

The RAMI approach consists of five major steps.

1) *Functional Analysis:* The first step in the RAMI analysis is the functional breakdown, which is a top–down description of the system as the hierarchy of functions on multiple levels, from the main functions performed by the system to the basic functions performed by the components.
2) *Failure Mode, Effect, and Criticality Analysis (FMECA):* The FMECA analysis is a method using the functional analysis as the input and establishes a list of function failure modes according to the importance with respect to the system operation, evaluation of the occurrence (prevention) of causes, and the severity (protection) of effects of failure modes included.
3) *Reliability Block Diagrams (RBDs):* The next step is a bottom–up approach relying on the RBDs to estimate the availability and the reliability of each function according to the given operating conditions. The RBDs concentrate on the reliability-wise relationships linking the function blocks and compute the resulting availability and reliability for the functions of the system.
4) *Risk Mitigation Actions:* In order to reduce the risk level associated with the failure modes identified in the FMECA, risk mitigation actions are taken. These actions are distinguished by the way they reduce either the occurrence or the severity and also by the phase of development of the system (design, test, operation, and maintenance).
5) *RAMI Requirements:* The output of the RAMI analysis is used to validate the RAMI requirements that are integrated as the final RAMI analysis reports to be reviewed in the system final analysis review.

This paper provides an assessment of technical risks by means of RAMI taken from the analysis performed on PFCs of EAST lower divertor.

III. FUNCTIONAL ANALYSIS

The functional analysis creates a functional breakdown describing PFCs of EAST lower divertor from the main functions to the basic functions. The methodology is inspired by the IDEFØ approach. Based on the structured analysis and design technique, the IDEFØ methodology identifies the interactions between the functions.

TABLE I
FUNCTIONAL BREAKDOWN FOR PFCs OF EAST LOWER DIVERTOR

A0 To maintain the structural integrity for PFCs of EAST lower divertor
A1 To maintain the structural integrity of the inner target
A1.1 To bear thermal loads
A1.2 To bear electromagnetic loads
A1.3 To bear particles loads
A2 To maintain the structural integrity of the outer target
A2.1 To bear thermal loads
A2.2 To bear electromagnetic loads
A2.3 To bear particles loads
A3 To maintain the structural integrity f of the dome
A3.1 To bear thermal loads
A3.2 To bear electromagnetic loads
A3.3 To bear particles loads

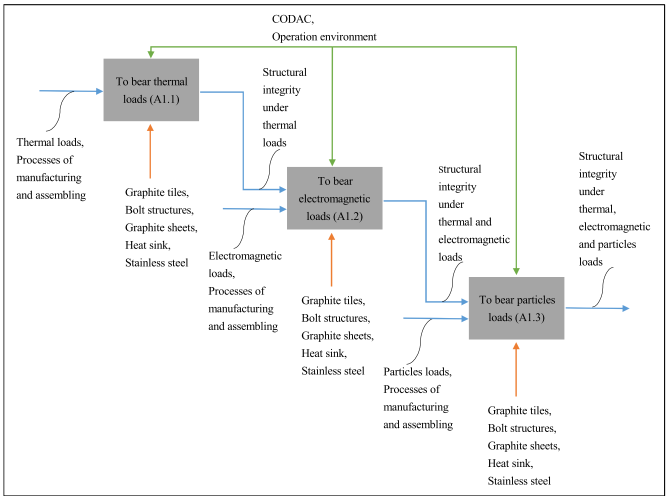


Fig. 2. IDEFØ model of Function A1.

The key function for PFCs of EAST lower divertor is to maintain the structural integrity. There are three main functions which are “to maintain the structural integrity of the inner target” (A1), “to maintain the structural integrity of the outer target” (A2), and “to maintain the structural integrity of the dome” (A3). Taking into account the stipulated operating condition of EAST lower divertor, each main function consists of three similar basic functions: “to bear thermal loads,” “to bear electromagnetic loads,” and “to bear particles loads” (Table I).

As an example, Fig. 2 displays a simplified view of Function A1 “to maintain the structural integrity of the inner target” in the IDEFØ model. Function A1 allows for maintaining the structural integrity of the inner target (outputs) under thermal loads, electromagnetic loads, and particles loads (inputs) only if processes of manufacturing and assembling of the inner target (input) meet the requirements. In order to perform this function, Function A1 also needs both the controls (control, data access, and communication, named CODAC, and

TABLE II

ITER RATING SCALE FOR SEVERITY

S	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 III

ITER RATING SCALE FOR OCCURRENCE

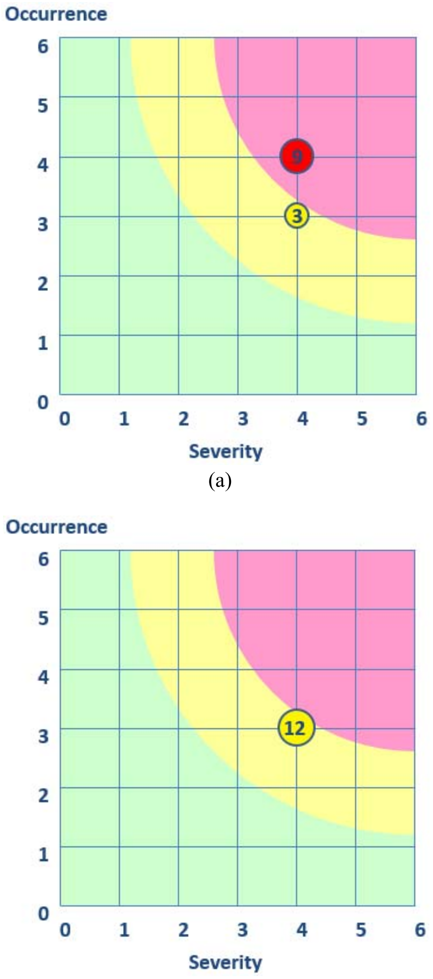
O	Description	Meaning
1	Very Low	λ < 5.7e-8/h (MTBF > 2000 years)
2	Low	5.7e-8/h < λ < 5.7e-7/h (200 years < MTBF <2000 years)
3	Moderate	5.7e-7/h < λ < 5.7e-6/h (20 years < MTBF < 200 years)
4	High	5.7e-6/h < λ < 5.7e-5/h (2 years < MTBF < 20 years)
5	Very High	5.7e-5/h < λ <5 .7e-4/h (10 weeks < MTBF < 2 years)
6	Frequent	λ > 5.7e-4/h (MTBF < 10 weeks)

operation environment) and mechanisms (graphite tiles, bolt structures, and graphite sheets).

IV. FMECA

To translate the results of the functional analysis, the FMECA for PFCs of EAST lower divertor is performed. A critical list of the possible function failure modes and their causes and effects is established, and the evaluation of their risk levels in terms of the basic functions is identified. Considering the same life which is assumed to be 20 years and the similar component performance of EAST and ITER, the ITER rating scales for severity and occurrence are taken as reference standard as shown in Tables II and III [6]. These causes and effects are evaluated quantitatively and are used for all components in order to keep a consistency between all analyses.

In FMECA, criticality C, which is a product of severity S and occurrence O ($C = S \times O$), is used to evaluate the magnitude of each risk. As shown in Fig. 3, the coordinates (S, O) of all couples (causes, effects) are placed on a criticality chart highlighting the major risk (red zone), the medium risk (yellow zone), and the minor risk (green zone). The criticality higher than 13 is categorized as a major risk and risk mitigation actions are mandatory to be implemented, and the criticality between 7 and 13 is considered to be a medium risk and risk mitigation actions are recommended while the criticality less than 7 is a minor risk with optional risk mitigation actions.



(a)

(b)

Fig. 3. (a) Initial criticality chart. (b) Expected criticality chart.

In Fig. 3(a), there are 12 failures in all for PFCs of EAST lower divertor in the initial criticality chart, including nine major risks. Criticality C of major risk is 16, where severity S is 4 and occurrence O is 4, which are mainly because of the failure of graphite tiles covering the fracture of graphite tiles, the ablation of graphite tiles, and the loose of graphite tiles, which have a significant impact on the structural integrity.

According to the calculation, the mean time to repair (MTTR) the components within the primary vacuum of EAST is supposed to be 45 days (15 days for temperature returning, 1 day for removal of port plugs, 3 days for operation, 1 day for installation of vacuum externals, and 25 days for cooling down and pumping down), while severity S is 4. This value has to be the most optimistic assumption which is too difficult to be reduced, so the risk mitigation actions focus on reduction of the initial occurrence as shown in Table IV.

These risk mitigation actions make the failure rate of graphite tiles reduce by an order of magnitude. After the implementation of risk mitigation actions, the maximum criticality C is 12, where severity S is reduced from 4 to 3. There is no major risk in the expected criticality chart in Fig. 3(b).

V. RBDs

After FMECA, the next step in the RAMI analysis is drawing the RBDs. The function breakdown structure preparing for the IDEFØ methodology forms the basis from which the RBDs are derived. All levels of functions of RBDs for PFCs

TABLE IV
RISK MITIGATION ACTION FOR FMECA FOR PFCs OF EAST LOWER DIVERTOR

Component	Failure Mode	Failure Cause	Implemented Mitigation	Further Recommendation
Graphite Tile	Fracture/Ablation of Graphite Tile	Unforeseen Mechanical Stress and Fatigue; Incorrect Manufacturing /Installation/Maintenance	Proper Manufacturing /Installation/Maintenance; On-site Spare Parts	Confirmation of Capability to Tolerate Failure by Further Study and Test about Different Structure and Material; Verification of Possibility to Share Spare Parts among Different Modules; Definition of Optimal Number of Spare Parts
Bolt Structure	Loose of Bolt Structure	Unforeseen Mechanical Stress; Incorrect Manufacturing /Installation/Maintenance	Adjustment for Preload; Proper Manufacturing /Installation/Maintenance; On-site Spare Parts	
Graphite Sheet	Fracture/Ablation of Graphite Sheet	Unforeseen Mechanical Stress and Fatigue; Incorrect Manufacturing /Installation/Maintenance	Proper Manufacturing /Installation/Maintenance; On-site Spare Parts	

TABLE V
INITIAL AND EXPECTED INPUT DATA FOR SIMULATION FOR PFCs OF EAST LOWER DIVERTOR

Component	Initial		Expected	
	λ (1/h)	MTTR (h)	λ (1/h)	MTTR (h)
Graphite Tile of the Outer Target	5.7e-5	1080	5.7e-6	1080
Bolt Structure of the Outer Target	5.7e-5	1080	5.7e-6	1080
Graphite Sheet of the Outer Target	5.7e-5	1080	5.7e-6	1080
Graphite Tile of the Inner Target	5.7e-5	1080	5.7e-6	1080
Bolt Structure of the Inner Target	5.7e-5	1080	5.7e-6	1080
Graphite Sheet of the Inner Target	5.7e-5	1080	5.7e-6	1080
Graphite Tile of the Dome	5.7e-6	1080	5.7e-6	1080
Bolt Structure of the Dome	5.7e-6	1080	5.7e-6	1080
Graphite Sheet of the Dome	5.7e-6	1080	5.7e-6	1080

TABLE VI
AVAILABILITY OF FUNCTIONS FOR PFCs OF EAST LOWER DIVERTOR

Functions	Availability (%)	
	Initial	Expected
A0 To maintain the structural integrity for PFCs of EAST lower divertor	79.20	86.40
A1 To maintain the structural integrity of the inner target	93.20	96.60
A1.1 To bear thermal loads	97.50	98.30
A1.2 To bear electromagnetic loads	97.60	98.40
A1.3 To bear particles loads	97.60	98.40
A2 To maintain the structural integrity of the outer target	91.50	95.70
A2.1 To bear thermal loads	98.10	99.40
A2.2 To bear electromagnetic loads	98.10	99.40
A2.3 To bear particles loads	98.10	99.40
A3 To maintain the structural integrity of the dome	93.60	95.70
A3.1 To bear thermal loads	97.70	98.20
A3.2 To bear electromagnetic loads	97.70	98.20
A3.3 To bear particles loads	97.70	98.20

of EAST lower divertor have been established and calculated using the BlockSim code.

According to the typical operation cycle of EAST, the end-time of simulation in the software is 11 520 h (approximately 16 months), which is as same as ITER. To meet the precision requirement, the number of simulation is set to be 1000. The end-time of simulation for reliability is 264 h (11 days), consistent with the single plasma operation cycle of EAST, which is followed by three days for routine maintenance.

The input data for the simulation consists of the reliability parameters (failure rate, λ) and maintenance parameters (MTTR) that are available for the lowest possible level. These data are obtained from supplier specifications, reliability database and industry standards, and the previous experience compiled on other scientific devices, all of which are collected in [7] and [8]. Regarding the specific experimental conditions, the customized components will face on EAST, the currently available data are not completely pertinent; therefore, an appropriate estimation has to be carried out based on the data source.

Assumptions made following the judgment of experts available at the time of the analysis, consistently with the FMECA, through to the following two steps [9].

1) Assignment of each failure mode of each component to an occurrence rating scale as defined in Table III; the initial failure rate is the upper value of the range of the related frequency of occurrence, used for the evaluation of the initial criticality.
2) Evaluation of risk mitigation actions in the reduction of the initial failure rate of each component; the expected failure rate is the results of reassigning the occurrence rating scale consistently for the assessment of the final criticality.

Overview of the input data used is shown in Table V. It is recommended to confirm the initial and expected failure rate by further studies and tests.

Another critical element of input data is the duty cycle which specifies the proportional time of a component's usage. Because the lower divertor is used during the plasma operation, duty cycle is set to be 20% for all components of PFCs of EAST lower divertor.

After calculated in the software, the inherent availability and reliability for PFCs of EAST lower divertor are shown in Tables VI and VII. The initial availability is 79.2%, and the expected availability is 86.4% after risk mitigation actions.

TABLE VII
RELIABILITY OF FUNCTIONS FOR PFCs OF EAST LOWER DIVERTOR

Functions	Reliability (%)	
	Initial	Expected
A0 To maintain the structural integrity for PFCs of EAST lower divertor	97.50	99.00
A1 To maintain the structural integrity of the inner target	99.70	99.70
A1.1 To bear thermal loads	99.70	99.99
A1.2 To bear electromagnetic loads	99.99	99.99
A1.3 To bear particles loads	99.70	99.99
A2 To maintain the structural integrity of the outer target	98.90	99.80
A2.1 To bear thermal loads	99.60	99.90
A2.2 To bear electromagnetic loads	99.60	99.90
A2.3 To bear particles loads	99.60	99.90
A3 To maintain the structural integrity of the dome	99.40	99.60
A3.1 To bear thermal loads	99.60	99.99
A3.2 To bear electromagnetic loads	99.60	99.99
A3.3 To bear particles loads	99.60	99.99

Likewise, the initial reliability is 97.5% while the expected reliability is 99%.

VI. CONCLUSION

To reach the scientific and the technological objectives, the RAMI approach is applied to PFCs of EAST lower divertor for the assessment of technical risk. Based on the IDEFØ methodology, functional analysis has been established to describe the PFCs from the main functions to the basic functions. FMECA is performed to evaluate the severity and the occurrence of failure modes, listing the possible failure modes and their causes and effects, and their risk levels are sorted according to the importance with respect to the operation and the risk mitigation actions of high initial criticality provided. There are 12 failures initially, including nine major risks. After the implementation of risk mitigation actions, there is no major risk. The initial and expected availabilities are calculated. The initial availability is 79.2%, and after risk mitigation actions, the expected availability is 86.4%, and the initial reliability is 97.5% while the expected reliability is 99%. This RAMI analysis results will be updated as the upgrade of design for PFCs of EAST lower divertor. The RAMI requirements are expected to be integrated in the system requirements' documents and to be implemented during the phase of upgrade, construction, test, operation, and maintenance of EAST lower divertor.

REFERENCES

[1] D. M. Yao *et al.*, "Design, analysis and R&D of the EAST in-vessel components," *Plasma Sci. Technol.*, vol. 10, pp. 367–372, Jun. 2008.

[2] D. van Houtte, K. Okayama, and F. Sagot, "RAMI approach for ITER," *Fusion Eng. Des.*, vol. 85, pp. 1220–1224, Dec. 2010.

[3] S. J. Qin *et al.*, "RAMI analysis for ITER radial X-ray camera system," *Fusion Eng. Des.*, vol. 112, pp. 169–176, Nov. 2016.

[4] K. Okayama, D. van Houtte, F. Sagot, and S. Maruyama, "RAMI analysis for ITER fuel cycle system," *Fusion Eng. Des.*, vol. 86, pp. 598–601, Oct. 2011.

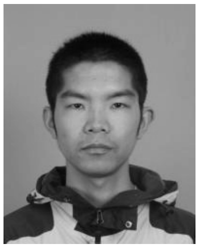
[5] S. Kitazawa *et al.*, "RAMI analysis of ITER CODAC," *Fusion Eng. Des.*, vol. 87, pp. 1510–1513, Aug. 2012.

[6] D. van Houtte, K. Okayama, and F. Sagot, "ITER RAMI analysis program," ITER Org., Saint-Paul-lès-Durance, France, Tech. Rep. ITER_D_28WBXD v4.3, Mar. 2012.

[7] L. C. Cadwallader, "Selected component failure rate values from fusion safety assessment tasks," U.S. Department Energy, Idaho Falls, ID, USA, Tech. Rep. INEEL/EXT-98-00892, Sep. 1998.

[8] International Atomic Energy Agency (IAEA), "Component reliability data for use in probabilistic safety assessment," IAEA, Vienna, Austria, Tech. Rep. IAEA-TECDOC-478, Oct. 1988.

[9] S. La Rovere, "DSM—Diagnostic shield module RAMI analysis report," ITER Org., Saint-Paul-lès-Durance, France, Tech. Rep. ITER_D_U8S79H v1.0, May 2017.



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