Fault Modes and Criticality Analysis of the EAST cryogenic system based on operating experience over 10 years

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Abstract. The cryogenic system of EAST (Experimental Advanced Superconducting Tokamak) facility has been put into operation for fourteen experimental campaigns since the first commissioning in 2005, which provides the adequate cooling power to keep the cold components of EAST Tokamak in the superconducting status. Its reliability directly influences the long time safe and steady operation of the Tokamak device. Through these years’ operation, the process control flow and operational modes have been determined eventually. According to the ITER RAMI analysis approach, the fault modes of the EAST cryogenic system as well as the corresponding effects and criticality have been analyzed and assessed for its safety. The risk mitigation actions were also presented and implemented for future operation and maintenance to archive the goal of enhancing the reliability of the EAST cryogenic system.

1. Introduction
The Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting steady-state plasma experimental device. The cryogenic system provides a maximum equivalent refrigeration capacity of 14 kW at 80 K for the thermal shields and 2.5 kW at 4.5 K in the plasma operation for the magnets, built-in cryopumps and pellet injection system [1]. Till now, it has been put into operation for fourteen experimental campaigns since 2005. In recent years, the EAST cryogenic system were required operating continuously for 3 to 6 months in each cool-down experiment. As one of the critical sub-systems of the EAST Tokamak device, the cryogenic system must have high reliability to ensure the normal and safe physical experiment operation. A major failure within the helium refrigerator or the cryogenic distribution system could cause a fast energy discharge of the toroidal field (TF) coils and cases requiring several days delay to recover nominal operating conditions, which depend on the failure criticality. To reach a high reliability, the reliable industrially proven cryogenic and control components were adopted to constitute the EAST cryogenic system. Based on the control flow of the EAST cryogenic system and its operating experience over ten years, the cryogenic system function was analyzed and the fault modes of the EAST cryogenic system were summarized. The objective of this study is to assess the criticalities related to the fault modes and to present the risk mitigation actions for future operation and maintenance to promote the reliability of the EAST cryogenic system.
2. Functional analysis and control flow of the EAST cryogenic system

According to the ITER RAMI (Reliability, Availability, maintainability and Inspectability) analysis approach, the functional breakdown of the considered system is a top-down description of the system as a hierarchy of functions on multiple levels, from the main functions fulfilled by the system to the basic functions performed by the components [2]. Based on the latest process flow diagram of the EAST cryogenic system [3], the structure and relationship of its three subsystems including their function analysis are summarized in figure 1. The main devices are also illustrated in this figure.

In the compressor station, the warm helium screw compressors with the recovery & storage system are used to supply the high pressure of 2.0 MPa for refrigeration cycle of the whole helium refrigerator. The helium refrigerator of 2 kW@4.5K with one cold box which contains all the heat exchangers and helium turbine expanders in it, is used to produce the required cooling power. And the cryogenic distribution subsystem distributes the proper cryogenic power for the cold components including the toroidal field (TF) superconducting coils (SC), poloidal field (PF) SC, TF cases, the 80 K thermal shields (THS), high temperature superconductor current leads (HTS CL) with buslines, and the 4.4 K built-in cryopumps and pellet injection.

![Figure 1. Main devices and functional analysis of the EAST cryogenic system.](image1)

![Figure 2. Operational states and shift relationship of EAST cryogenic system.](image2)
Figure 2 illustrates the steady operational states (S0-S4) and their shift relationship of EAST cryogenic system, which shows the typical emergent fault modes and their criticality in the system. On the basis of the cool-down process and operational modes division, there are several temperature levels in EAST cryogenic system according to its cold components’ cooling requirement, including 80 K, 4.5 K and 3.8 K. Therefore, there are these steady operational states of different temperature levels. The compressors, turbines, Helium circulating pumps and the oil-ring pump are the critical mechanical equipments in EAST cryogenic system, whose start and stop status will change the cryogenic system’s final operation states. The EAST coils can be operated in 4.5K or 3.8 K. The dotted lines in figure 2 mean that the oil-ring pump doesn’t need to start if 3.8 K is not needed. The stop of the critical mechanical equipments will cause the cryogenic system can not keep in the current steady state, which will influence the physical experiments and also cause the helium refrigerator unstable or even damage other cryogenic equipments.

3. Fault modes, effects and criticality analysis (FMECA)

The fault mode analysis of the EAST cryogenic system was performed to translate the results of the function analysis. Based on the function analysis, FMECA was performed for each subsystem using a bottom-up approach [4]. Based on the operating experience over ten years, a statistic list of the typical function fault modes which have occurred in the operation of EAST cryogenic system was established, and their effects and criticality in terms of the basic functions were identified, which is shown in table 1. In accordance with the definition in the ITER RAMI program, the criticality C of a fault is defined as the multiplication of occurrence O and severity S (C = O × S) [4]. The criticality data was calculated based on the occurrence data of fault modes before the EAST cryogenic system’s upgrade [5].

| Fault modes              | O  | S  | C  | Effects in EAST cryogenic system                                      |
|-------------------------|----|----|----|---------------------------------------------------------------------|
| Compressors fault stop  | 4  | 4  | 16 | The cryogenic system cannot maintain operating in any operational mode, will return to S0 |
| Compressors protection  | 3  | 2  | 6  | The system will return to S0, but the compressors usually can be restarted again after a short while |
| One compressor fault     | 5  | 3  | 15 | Gas helium flow rate decreases, refrigeration power will decrease |
| One compressor protection| 3  | 2  | 6  | the compressor usually can be restarted again, so the system can keep in the current state |
| Turbines fault stop      | 6  | 3  | 18 | Cool-down can’t continue; can’t maintain the cooling, the magnets required discharge in 4.5 K steady state |
| Turbines protection stop | 4  | 2  | 8  | The cryogenic system can restore consuming some time after the turbines restarted again |
| One turbine TA/TD fault  | 5  | 2  | 10 | Can still remain in the current state with other operations in the cryogenic system |
| One turbine TA/TD protection | 4  | 2  | 8  | The cryogenic system can restore consuming several hours after the turbine restarted again |
| Helium circulating pumps | 3  | 3  | 9  | Can’t maintain the forced-flow cooling, the magnets required discharge in 4.5 K steady state |
| Oil ring pump            | 4  | 4  | 16 | Can’t maintain 3.8 K cooling, back to 4.5 K operation |
| Vacuum pumps             | 3  | 3  | 9  | Vacuum degree of cold box degrades |
Recovery compressor failure 4 2 8 Can’t recover gas helium in time, may cause economic losses
Leak (gas/oil) 5 2 10 Bring economic losses; oil leak may contaminate to the system which could cause other failures
Power supply failure 4 3 12 May cause compressors/turbines stop or damage to them or helium gas losses
Instrumentation 5 1 5 Influence process monitoring or automatic control
Valve (blocked/leak) 5 1 5 Blocked valve may cause the system stop; bring economic losses
Heat exchangers blocked 4 3 12 Decrease the efficiency or may cause the system stop
DCS failure(controller) 2 2 4 The cryogenic system cannot be operated or controlled
Gas supply failure 4 2 8 Control valve came into Fail state, could cause turbines protection stop or influence normal operation
Magnets quench 3 4 12 The refrigerator will be cut off with the magnets with the quench protection programs
Magnets failure cause too much return gas 3 4 12 May cause turbines protection stop if no control strategy applied
DCS program failure 3 1 3 Influence the automatic control

According to the FMECA results, there are 22 fault modes summarized in the system. A criticality matrix was plotted in figure 3 (a). There are 4 major risks, where criticality >=13; and 12 medium risks, where 12=< criticality <=8. The rules to classify the criticality are the same as the definition in ITER RAMI program [4]. The compressors and turbines fault stop both happened frequently before the upgrade, which mostly caused by their mechanical failure and usually cannot be restarted in short time again. To improve the reliability, the EAST cryogenic system has been upgraded and some risk mitigation actions was presented. The criticality matrix after upgrade was plotted in figure 3 (b). After the upgrade, the fault stop of new compressors and new turbines never occur again [5]. There are no more major risks, and the medium risks have also decreased.

Figure 3. The criticality matrix of EAST cryogenic system.
4. Risk Mitigation Actions

According to the EAST operation schedule, EAST cryogenic system has to put in operation continuously from three months to six months, which require a higher reliability and availability for the cryogenic system. In order to promote the reliability, the EAST cryogenic system was upgraded with new helium screw compressors and new dynamic gas bearing helium turbines as well as its control system, which are all the reliable industrially proven components [5]. And the seven old compressors were arranged as the spare main compressors and the spare recovery compressor on standby. In addition, the reparation spare including shaft coupling, gas filter for compressors and gas bearing valves for turbines as well as each type of instrumentation were also available on site. The vibration of new turbines has been monitored for diagnosing operation status.

For future higher reliability, the external purifier system will be reconstructed, and the adsorbers in the cold box will be processed next year. Additionally, the spare turbines on standby within the refrigerator cold box will be considered to allow resuming plasma operation in less than one day in case of turbines’ failure.

5. Conclusion

For better analyzing the system safety, the functionalities of the EAST cryogenic system have been analyzed in detail. And the operational states with their shift relationship of EAST cryogenic system, which represents the control flow of the cryogenic system, have also been summarized. Based on the system functional analysis and its operating experience over ten years, the fault modes and the effects have been identified. According to the ITER RAMI program, the occurrence O and severity S of each fault mode in the EAST cryogenic system before upgrade and after upgrade have been collected, and the criticality C has been calculated. The two criticality matrixes were plotted as a contrast to show that the upgraded EAST cryogenic system has higher reliability. The risk mitigation actions which have been performed already in the system were presented, and those actions plan to do in future will help the EAST cryogenic system to be more reliable.

References

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