Failure modes, effects and criticality analysis of a 3kW@4.5K helium refrigerator

Y W Zong¹,², Z W Zhou*¹, Q Y Zhang¹, Z G Zhu¹, P C Yang¹,² and B Hu¹,²

¹Institute of Plasma Physics Chinese Academy of Sciences, Hefei 230031; ²University of Science and Technology of China, Hefei 230036

E-mail: yiwen.zong@ipp.ac.cn, zzw@ipp.ac.cn

Abstract: The comprehensive research facility for key systems of fusion reactors was included in the “13th Five-Year Plan” priority project in China. In order to meet the requirements of cryogenic testing of large superconducting magnets, it is proposed to build a 3kW@4.5K refrigerator and carry out research on 3kW@4.5K superfluid helium cryogenic system. In order to evaluate the reliability of the 3kW refrigerator, the FMECA analysis was performed on the helium refrigerator. The refrigerator system is divided into three subsystems: the compressor system, the monitoring and control system and the cold box, to identify the failure mode and the impact on the refrigerator system related functions. The critical value is calculated and the critical matrix is drawn by the severity and the occurrence of the rating criteria. Identify the parts with high and medium risks and propose corresponding risk mitigation measures.

1. Introduction
The comprehensive research facility for key systems of fusion reactors is included in China’s “13th Five-Year Plan”, among which the proposed 3kW/4.5k (1kW/3K) helium refrigerator will be used for the cryogenic test of large superconducting magnets of CFETR in the future.

Large cryogenic systems are widely used in key systems of fusion reactors. However, the failure of helium refrigerator not only affects the operation of the cryogenic system, but also affects the large superconducting magnet system. Therefore, the helium refrigerator must have high reliability. FMECA analysis of the refrigerator is carried out to ensure the stable operation of the cryogenic system so as to ensure the normal and safe physical experimental operation of large scientific devices [1].

FMECA analysis method is widely used in the reliability analysis of cryogenic systems. In order to achieve the overall inherent usability of 60%, ITER carried out failure modes, effects and criticality analysis (FMECA) on ITER system in its conceptual design stage, and proposed the evaluation criteria
of FMECA applied to all ITER systems [2]. D Henry et al. conducted FMECA analysis on the three subsystems of ITER cryogenic system, namely, cryogenic distribution system, refrigerator system and cryolines, and finally obtained 18 high-risk failure modes and adopted corresponding mitigation measures to reduce risks [3].

At present, the reliability analysis of large helium cryogenic refrigeration systems has been paid more and more attention in China. By analyzing the reliability and availability of the 10kW @20K helium refrigerator designed by the technical institute of physics and chemistry, Chinese academy of sciences, it is concluded that compressor, turbine and vacuum pump are components of the refrigerator with high risks, and corresponding mitigation measures are adopted to reduce these major and moderate risks [4]. Meanwhile, the technical institute of physics and chemistry, Chinese academy of sciences adopted the same method to analyze the reliability and availability of 250 W@4.5K helium refrigerator. The reliability analysis of the cryogenic cooling system of the superconducting tokamak experimental device (EAST) was conducted by Hefei institute of physical sciences, Chinese academy of sciences using fault tree analysis (FTA) [5].

The integrated research facility of the key system of the fusion reactor at the institute of plasma physics, Chinese academy of sciences is currently in the preliminary design stage. In order to evaluate the reliability of the 3kW@4.5K helium refrigerator in its cryogenic system, it is necessary to establish the failure mode, effect and criticality analysis (FMECA) model of the 3kW@4.5K helium refrigerator, analyze the fault mode of the helium refrigerator and its corresponding influence and risk, and evaluate its safety, so as to propose and implement risk mitigation measures.

2. 3kW@4.5K helium refrigerator process

The flow chart of 3kW@4.5K helium refrigerator is shown in figure 1. The refrigerator is mainly composed of three subsystems: compressor system, refrigerator cold box system and helium refrigerator monitoring and control system. The compressor system consists of helium storage tanks, four screw compressors, oil filters, adsorbers, regulating valves, etc. The refrigerator cold box is composed of 4 turbo expanders, 9 plate-fin heat exchangers, 2 80K adsorbers, regulating valves and independent vacuum system. The monitoring and control system enables the helium refrigerator to operate fully automatically, and can also be switched to manual mode, and provide a safety interlocking system to ensure the safe and stable operation of the refrigerator.

The working process is as follows: The helium gas first passes through the compressor station, compresses the helium gas through the two-stage screw compressor set, and then passes through the filtration and purification of the oil-removal system before entering the refrigerator cold box.

After the compressed high-pressure helium gas enters the cold box, it is divided into two paths. One path, high-pressure helium gas passes through heat exchanger HX9, liquid nitrogen pre-cooling and turbo expander T4 to obtain 50K cold helium gas to cool the thermal shield. Another path high-pressure helium gas is mainly used for cooling expansion to cool the magnet. After heat transfer by heat exchanger HX1, liquid nitrogen pre-cooling and heat exchanger HX3, it is further divided into two parts: One path, helium gas enters into turbo expander T1 to expand and cool down. The expanded gas is further cooled by heat exchanger HX5 to further reduce the inlet temperature of turbo expander T2. The cooled gas enters the turbine T2 to expand and cool down and finally returns to the low pressure circuit. The return gas is used to cool the heat exchanger HX6, HX5, HX4, HX3 and HX1, and finally return to
the low pressure compressor inlet. The other high-pressure helium gas is cooled by the heat exchangers HX3, HX4, HX5 and HX6 and then enters the turbine T3 to expand and cool down. The gas after the turbine T3 expansion directly cools the superconducting magnet.

Figure 1. 3kW@4.5K helium refrigerator process diagram

3. Functional analysis
Perform FMECA analysis on the refrigerator, first perform functional analysis on the refrigerator. Based on the general process flow diagram (PFD) of the cryogenic system, the system is functionally decomposed according to the top-down description. The compressor station, the refrigerator cold box and the control system include the three sets of functions summarized in figure 2.

Each set of functions is divided into two parts: the first part describes the main functions of each subsystem; the second part describes the services required to achieve the main functions of the 3kW@4.5K helium refrigerator.

Figure 2. Functional analysis of the 3kW@4.5K refrigerator
4. Failure modes, effects and criticality analysis

4.1 FMECA risk assessment standard
Classification criteria for severity and occurrence used by the International Thermonuclear Experimental Reactor (ITER) \(^1\) are adopted.

Draw the risk matrix diagram of the subsystem according to ITER RAMI program. The critical \(C\) of failure is defined as the product of occurrence \(O\) and severity \(S\) (\(C=S \times O\)). According to the calculation result, the critical \(C\) is classified into the following three types:

- Low risk, \(C<7\). Mitigation measures are optional, represented by the green areas in the risk matrix.
- Medium risk, \(7\leq C<13\). Mitigation measures are recommended to reduce hazards, represented by the yellow areas in the risk matrix.
- High risk, \(C \geq 13\). Mitigation measures must be taken to reduce the level of hazard, represented by the red area in the risk matrix.

4.2 FMECA analysis results
FMECA analysis of each component of 3kW@4.5K helium refrigerator is shown in table 1. Through ITER cryogenic system and EAST cryogenic system failure data, severity and occurrence rating standard are used to obtain the severity and occurrence data in the table.

There are 22 failure modes. There were four high-risk failures and 14 medium-risk failures. The corresponding fault modes are:

High risk failure: screw compressor can not operate normally; turbo expander failure; power supply; failure of sensors including signal conditioning.

Medium-risk failure: helium buffer tank leakage; room temperature valve failure; recovery compressor failure; liquid nitrogen precooling system failure; heat exchanger failure; vacuum system failure; cryogenic valve failure; cryogenic pipeline rupture; cold box rupture; helium dewar fracture; throttle valve failure; input/output hardware failure; data communication loss; Loss or air or He leak tightness.

According to the FMECA analysis, the initial risk matrix and the improved risk matrix are plotted, as shown in figure 3.

| Sub-function | Number | Failure mode | Reason | Result | \(S\) | \(O\) | \(C\) |
|--------------|--------|--------------|--------|--------|-------|-------|-------|
| Compressor station | 1 | Screw compressor does not work properly | Bearing or motor failure | Loss of subsystem refrigerator power | 4 | 4 | 16 |
| | 2 | Helium buffer tank leak | Material flaw or mechanical fatigue | Helium gas loss, causing economic losses | 4 | 3 | 12 |
| | 3 | Room temperature valve failure | Blocked or broken | Lead to loss of refrigerator’s cooling capacity | 3 | 3 | 9 |
| | 4 | Recovery compressor | Mechanical | Unable to recover | 3 | 3 | 9 |

Table 1. FMECA analysis of 3kW@4.5K helium refrigerator
|   |   |   |   |
|---|---|---|---|
| 5 | The oil-removal system cannot fulfill the intended function | Saturation by oil or regeneration failure | Loss of pure He availability |
| Cold box | 6 | Liquid nitrogen pre-cooling system failure | Heat exchanger rupture or liquid helium tank operation failure or valve, pipeline rupture | Resulting in insufficient cooling power provided by the cold box |
|   |   |   |   |
|   |   |   |   |
|   |   |   |   |
|   |   |   |   |
| 7 | Heat exchanger failure | Corrosion causes water leakage | Reduce efficiency or cause the system to stop |
|   |   |   |   |
|   |   |   |   |
| 8 | Vacuum system failure | Molecular pump or mechanical pump failure | Lower vacuum of cold box |
|   |   |   |   |
|   |   |   |   |
| 9 | Cryogenic valve failure | Blockage or leak | Lead to loss of refrigerator’s cooling capacity |
|   |   |   |   |
|   |   |   |   |
| 10 | 80K adsorber failure | Adsorbers saturation by impurities or regeneration failure | Risk of system breakdown |
|   |   |   |   |
|   |   |   |   |
| 11 | Cryogenic pipe rupture | Material flaw or mechanical fatigue | Bring economic loss |
|   |   |   |   |
|   |   |   |   |
| 12 | Turbo expander failure | Turbine bearing is damaged, the rotor is holding the shaft, and it is stuck. | Cooling cannot continue, system stops |
|   |   |   |   |
|   |   |   |   |
| 13 | Cold box rupture | Material flaw or mechanical fatigue | Insulation vacuum loss increases the thermal load of the cold box |
|   |   |   |   |
|   |   |   |   |
| 14 | Liquid helium dewar ruptured | Material flaw or mechanical fatigue | Loss of cooling power, resulting in economic losses |
|   |   |   |   |
|   |   |   |   |
| 15 | Power supply | Power failure or fluctuation | Full breakdown |
|   |   |   |   |
|   |   |   |   |   |
|---|---|---|---|---|
| 16 | Throttle failure | Rupture or misoperation | Reduced cooling efficiency | 3 3 9 |
| 17 | Cooling water system failure | Carbonate deposit | Efficiency loss | 2 3 6 |
| Monitoring control system | 18 | Input/output hardware failure | Affect process control or automatic control | 3 3 9 |
| 19 | Data communication loss | Communication line fault or poor contact and communication equipment fault | Impact automatic control | 3 3 9 |
| 20 | Centralized data processing system failure | Data server, processing, or storage failure | Operation disturbing | 2 3 6 |
| Measuring actuating | 21 | failure of sensors including signal conditioning | sensors actuators, signal conditioners and transmitters failure | Cooling power loss until subsystem failure | 3 5 15 |
| 22 | Loss or air or He leak tightness | Loss of He or pollution by impurities | 3 3 9 |

(a) Initial criticality matrix  
(b) Revised criticality matrix

**Figure 3.** Initial and expected criticality matrix for the refrigerator

5. Risk mitigation measures

In order to improve the reliability of 3kW@4.5K refrigerator, it is necessary to propose improvement measures in the design stage of the system to reduce high risk and Medium-risk failure mode. These improvements are as follows:
(1) Reduce compressor maintenance interval and instrumentation. Repair kits for couplings and gas filters for compressors should be available on site.

(2) The vibration of the turbo expander should be monitored and a spare of the turbo expander must be provided.

(3) Pipes and valves are inspected regularly and spare parts are on site.

(4) Spare parts and specific assistance contract for intervention.

(5) Redundancy of critical sensors, spare parts and logistics on site.

(6) Overcapacity or redundancy of rough pumping, policy on seals, gas exhaust analysis.

(7) Partial redundancy of power supply.

6. Conclusion
In the design phase, in order to evaluate the reliability of the 3kW@4.5K refrigerator, the failure modes, effects and criticality analysis of the refrigerator were performed. The analysis results show that the compressor, turbo expander, cooling water system and power supply are the key components that affect the reliability of the 3kW@4.5K refrigerator. For the above key components, corresponding risk mitigation measures are proposed at the design stage to reduce risks, thus ensuring stable operation of the cryogenic system.

7. References:
[1] J Li, L Y Xiong, L Q Liu 2016 Failure modes, effects and criticality analysis of a 250W@4.5K helium refrigerator. Cryogenics. 4 35-40.
[2] D V Houtte, Okayamak, F Sagot 2010 RAMI approach for ITER. Fusion Engineering and Design. 85 1220-1224.
[3] D Henry, J Trouve, C Chodimella 2012 RAMI approach for ITER cryoplant and cryodistribution systems. AIP Conference Proceeding1434. 1551-1558.
[4] J Li, L Y Xiong, L Q Liu 2016 Reliability and availability analysis of a 10kW@20K helium refrigerator. ICEC26-ICMC2016.
[5] X H Cao, L Q Hu, Y Z Li 2009 Fault tree analysis of EAST cryogenic system. Chinese Journal of Nuclear Science and Engineering. 2 170-175.
[6] ITER documentation 2011 RAMI analysis of cryodistribution. WBS-34 summary report ITER_D_476UDV v1.2.
[7] ITER documentation 2011 RAMI analysis of cryoplant. WBS-34 summary report ITER_D_45VHQV v1.0.