Reliability and availability analysis of a 10 kW@20 K helium refrigerator

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Abstract. A 10 kW@20 K helium refrigerator has been established in the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. To evaluate and improve this refrigerator’s reliability and availability, a reliability and availability analysis is performed. According to the mission profile of this refrigerator, a functional analysis is performed. The failure data of the refrigerator components are collected and failure rate distributions are fitted by software Weibull++ V10.0. A Failure Modes, Effects & Criticality Analysis (FMECA) is performed and the critical components with higher risks are pointed out. Software BlockSim V9.0 is used to calculate the reliability and the availability of this refrigerator. The result indicates that compressors, turbine and vacuum pump are the critical components and the key units of this refrigerator. The mitigation actions with respect to design, testing, maintenance and operation are proposed to decrease those major and medium risks.

1. Introduction
A 10 kW@20 K helium refrigerator has been established in the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. This refrigerator allows the production of an equivalent cooling capacity of 10 kW at 20 K. This refrigerator has been accepted technically in May 2015. It has been operated more than 72 hours (three days) successfully several times to pass the technical acceptance. According to the project requirement document, the Mean Time to Failure (MTTF) of this 10 kW@20 K refrigerator should be at least 8000 hours. In order to evaluate and increase this refrigerator’s reliability and availability, a reliability and availability analysis is performed. An ITER Reliability, Availability, Maintainability and Inspectability (RAMI) program is adopted [1]. The failure data of the similar refrigerators’ components were collected. Software Weibull++ V10.0 is used to fit these failure data’s distributions. Software BlockSim V9.0 is used to calculate this refrigerator’s reliability and availability. The result indicates that compressors, turbine and vacuum pump are the critical components and the key units. The mitigation actions mainly about the preventive maintenance are given.

2. Overview of the 10 kW@20 K refrigerator
Figure 1 shows the Process Flow Diagram (PFD) of the 10 kW@20 K refrigerator. As shown in figure 1, this 10 kW@20 K refrigerator consists of two main parts, i.e. the compressor station and the cold box. The compressor station is composed of two screw compressors, an oil removal system (ORS), a helium
buffer tank and a gas management valve panel composed of three room temperature valves, CV-1, CV-2 and CV-3. The cold box is a vacuum insulated cold box which contains two heat exchangers, the first stage heat exchanger HEX1 and the second stage heat exchanger HEX2 and six control cryogenic valves and a turbine. Only two control cryogenic valves including a Liquid Nitrogen (LN) supply valve CV-4 and a turbine inlet valve CV-5 are shown in this diagram. E-3 is a dummy load which provides an electrical heating capacity of 10 kW. These two screw compressors are arranged in parallel. Each compressor provides half capacity of overall 400 g/s.

**Figure 1.** The Process Flow Diagram (PFD) of the 10 kW@20 K refrigerator.

3. **Functional analysis of the 10 kW@20 K refrigerator**

Based on the process flow diagram of this 10 kW@20 K refrigerator, a functional analysis is performed. The principal functionality of this 10 kW@20 K refrigerator is to provide 10 kW@20 K cooling power with the support of the auxiliary system. The simplified functional analysis of this refrigerator is summarized in figure 2.

The main function “To provide 10 kW@20 K cooling power” has been split into two parts, the first part is sub-function of the refrigerator “To provide cryogenic environment and 10 kW@20 K cooling power” and the second part is “To provide services and features to support main function of 10 kW@20 K refrigerator”.

3.1. **To provide cryogenic environment and 10 kW@20 K cooling power**

This functionality has been split into two main functions.

- To provide cryogenic environment;
- The turbine.
3.2. To provide services and features to support main function of 10 kW@20 K refrigerator

There are four sub-functions.

- To provide atmospheric temperature gas Helium;
- To provide auxiliary cold power;
- To control and monitor 10 kW@20 K refrigerator;
- To provide vacuum environment.

4. Reliability and availability calculation of this 10 kW@20 K refrigerator

4.1. General assumptions

The mission profile of this refrigerator, i.e. the purpose of this refrigerator, is to provide 10 kW@20 K cooling capacity which is the maximum cooling capacity of this refrigerator. To study the reliability and availability of this refrigerator, the following assumptions should be taken into account.

- The failure of each of two compressors leads to lack of cooling power which is provided by this 10 kW@20 K refrigerator;
- The failure of Liquid Nitrogen pre-cooling system leads to lack of cooling power which is provided by this 10 kW@20 K refrigerator;
- In a pessimistic approach, it is considered that failure of any valves (room temperature valves, CV-1, CV-2, CV-3 and all the six cryogenic valves including CV-4, CV-5) leads to loss of refrigerator’s cooling capacity;
- Only significant leakages of each of two heat exchangers lead to the stoppage of the refrigerator operation.

4.2. Refrigerator components’ failure rate distribution

The failure data of refrigerator components are important not only for reliability and availability calculation but also for failure modes, effects and criticality analysis (FMECA). Historical failure data in various sources should be searched and statistical assessments on components failures have been done [2]. Failure data are also collected from the manufacturer and the operating experience of other
cryogenic system [3, 4]. The experimental results and field data can also be analysed by graphical analysis using a Weibull plot [5].

In this paper, some refrigerator components, such as compressors, vacuum pump, Liquid Nitrogen pre-cooling system, Programmable Logic Controller (PLC) control system and turbine, the failure data of them are collected from several refrigerator users in China. These users include the Free Electron Laser Facility of Peking University (PKU-FEL), Shanghai Synchrotron Radiation Facility (SSRF) and Beijing Electron-Positron Collider (BEPCII). The other refrigerator components’ failure data, for example, the heat exchangers and the valves (room temperature valves and cryovalves), are cited from operating experience of other cryogenic system [3, 4]. The failure data composed of complete data and right censored data. Figure 3 shows the sketch of complete data and right censored data.

As figure 3 shows, when the Time to Failure (TTF) is equal to X, the failure data is a complete data. If the TTF is greater than X, TTF is unpredicted, the failure data is a right censored data. Only the complete data and right censored data are adopted to calculate the failure rate distribution in this research. The software Weibull++ V10.0 is used to fit the failure rate distribution. The following example illustrates how to fit the compressors’ failure rate distribution.

The compressors used in 10 kW@20 K refrigerator is designed and produced by MAYEKAWA. The collected failure data of similar screw compressors are used to calculate the compressor’s failure rate distribution. Table 1 shows the complete failure time of compressor (marked as F) and right censored data of compressor (marked as S).

| No. | F/S | Time to F or S (hrs) | No. | F/S | Time to F or S (hrs) |
|-----|-----|---------------------|-----|-----|---------------------|
| 1   | S   | 13140               | 5   | S   | 6888                |
| 2   | F   | 22344               | 6   | S   | 21144               |
| 3   | F   | 6504                |     |     |                     |
| 4   | F   | 22728               |

Software Weibull++ V10.0 is used to fit the compressor’s failure rate distribution. Maximum Likelihood Estimation (MLE) is adopted because there is right censored data. After calculation, the distribution of the compressor’s failure rate is 2P-weibull distribution, $\beta=2.94$, $\eta=22762.5$ hrs.

Failure rate ($t=1$ year) = 0.18
In this 10 kW@20 K helium refrigerator, there are two compressors. Each compressor provides half capacity of overall 400 g/s. To provide full capacity, each compressor should be available. Hence, in functional analysis, these two compressors are in series. Figure 4 shows the reliability block diagram of these two compressors.

![Reliability Block Diagram of two series compressors](image)

**Figure 4. Reliability Block Diagram of two series compressors.**

Failure rate of these two series compressors (t=1 year) = 0.35

This failure rate 0.35 will be used in the Failure Modes, Effects & Criticality Analysis (FMECA).

The other refrigerator components’ failure rate distributions are also fitted with the same method. Table 2 shows refrigerator components’ failure rate distribution and recover time for each component. That recover time is used to calculate the availability of this 10 kW@20 K helium refrigerator. That recover time is a mean time which is cited from Technical Institute of Physics and Chemistry (TIPC) repair experience.

| No. | Components               | Failure rate distribution | Source   | Time to recover (TIPC experience) |
|-----|--------------------------|---------------------------|----------|----------------------------------|
| 1   | Compressor               | Weibull-2P, β=2.94, η=22762.5 hrs | b        | One week, 168 hrs, with spare parts on sites |
| 2   | Room temperature valves  | 1P-Exponential, Mean Time = 76335877 hrs | a        | One week, 168 hrs, with spare parts on sites |
| 3   | LN precooling system*    | Log-normal-2P, Log-Mean=9.76 hrs, Log-Std=0.508 | b        | One day, 24 hrs, with spare parts on sites |
| 4   | Heat exchanger           | 1P-Exponential, Mean Time = 26315789 hrs | a        | With significant leak, half a year, 4380 hrs |
| 5   | Cryovalve                | 1P-Exponential, Mean Time = 76335877 hrs | a        | One week, 168 hrs, with spare parts on sites |
| 6   | Turbine                  | Weibull-2P, β=2.8, η=24061.1 hrs, Log-normal-2P, Log-Mean=9.93 hrs, Log-Std=0.923 | b        | One day, 24 hrs, with spare parts on sites |
| 7   | PLC control system       | Weibull-2P, β=1.34, η=29022.3 hrs | a        | One day, 24 hrs, with spare parts on sites |

|   |   |   |   |   |
|---|---|---|---|---|
| a | Cited from operating experience of other cryogenic system [3, 4]. |
| b | Fitted with collected failure data, using software Weibull++ V10.0. |
|   | LN precooling system doesn’t include valve CV-4, CV-4 is considered in cryovalves. |

4.3. Reliability and availability calculation of the 10 kW@20 K refrigerator

According to the functional analysis and the general assumptions, a Reliability Block Diagram (RBD) of this 10 kW@20 K refrigerator can be established. Figure 5 shows the Reliability Block Diagram (RBD) of this refrigerator. In figure 5, all the components which include two compressors, three room
temperature valves, one LN precooling system (not including valve CV-4), two heat exchangers, six cryogenic valves, one turbine, one PLC control system and one vacuum pump are all in series.

![Diagram of reliability block diagram](image)

**Figure 5.** Reliability Block Diagram of this 10 kW@20 K refrigerator.

According to the figure 5, Reliability Block Diagram and the table 3, refrigerator components’ failure rate distribution, the reliability of this refrigerator is calculated using software BlockSim V9.0. According to the recovery time of Table 2, the availability of this refrigerator is also calculated using software BlockSim V9.0 by Monte Carlo simulation (10,000 simulations). Table 3 shows the reliability and the availability of this refrigerator.

**Table 3.** The reliability and the availability of the 10 kW@20 K refrigerator.

| Component                  | Reliability for 3 months | Reliability for 1 year | MTTF (hrs) | Availability (for 1 year) | Time for 99.9% availability (hrs) |
|-----------------------------|---------------------------|-------------------------|------------|---------------------------|-----------------------------------|
| 10 kW@20 K refrigerator     | 95.8%                     | 51.0%                   | 9211       | 99.5%                     | 960                               |

Table 3 shows the Mean Time to Failure (MTTF) of this 10 kW@20 K helium refrigerator is 9211 hours, it is about one year. This refrigerator’s availability for one year is 99.5%. Time for 99.9% availability is 960 hours, it is 40 work days.

4.4. Reliability importance

The Reliability Importance (RI) is a parameter to show which component has the greatest effect on the whole refrigerator’s reliability. After the calculation using software BlockSim V9.0, the results show that in the short period of time within 2 years, compressor, LN precooling system, PLC control system, vacuum pump and turbine have more effect on the whole refrigerator’s reliability. In the longer period of time within 5 years, compressor has the most effect on the whole refrigerator’s reliability.

5. Failure modes, effects and criticality analysis (FMECA)

According to the functional analysis of this 10 kW@20 K refrigerator, a FMECA analysis was performed using a bottom-up approach to list the function failure modes and evaluate their risk level. The severity and occurrence rating scale is defined in Table 4 [6].

**Table 4.** Severity and Occurrence rating scale.

| Severity (S)                  | Rating scale | Occurrence (O) | Failure rate per year |
|-------------------------------|--------------|----------------|-----------------------|
| Less than 1 hour              | 1            | λ< 5×10−4      | (less than once in 2000 years) |
| Between 1 hour and 1 day      | 2            | 5×10−4 < λ< 5×10−3 | (less than once in 200 years) |
| Between 1 day and 1 week      | 3            | 5×10−3 < λ< 5×10−2 | (less than once in 20 years) |
| Between 1 week and 2 months   | 4            | 5×10−2 < λ< 5×10−1 | (less than once in 2 years) |
| Between 2 months and 1 year   | 5            | 5×10−1 < λ< 5   | (less than five times per year) |
| More than 1 year              | 6            | λ≥ 5           | (more than five times per year) |
The Criticality which is defined as the multiplication of Occurrence and Severity \((C=O\times S)\) is used to evaluate magnitude of each risk. According to its level, the criticality is divided into major risk, medium risk and minor risk, representing by red, yellow and green respectively. Criticality greater than or equal to 13 is considered to be major risk, mitigation actions are mandatory to reduce the criticality. Criticality between 7 and 13 is categorized as medium risk and mitigation actions are recommended to reduce the criticality. While criticality less than 7 is considered to be minor risk, mitigation actions are required to reduce the criticality (optional).

A detailed FMECA analysis is performed on this 10 kW@20 K refrigerator. Figure 6 and figure 7 show the initial and expected criticality matrix for this refrigerator. According to figure 6, there are 14 failure modes totally. There are 2 major risks and 6 medium risks in the initial criticality matrix. The corresponding failures modes of these two major risks are: the turbine can’t accomplish predetermined function and loss of function of compressor.

As shown in figure 7, in the revised criticality matrix, there are 0 major risk and 6 medium risks after implementing mitigation actions. The number of major risks is reduced.

6. Risk mitigation actions

The mitigation actions with respect to design, testing, maintenance and operation are applied to decrease those major and medium risks. These mitigation actions are as follows:

- Reinforced logistic and preventative maintenance is recommended for heat exchangers;
- A repair kit including shaft coupling, oil filter, gas filter for screw compressors must be available on site;
- A spare of vacuum pump must be available;
- Three turbines have been made, one is in operation and the others are as spares on sites. Quick mounting and dismounting technology is adopted.
7. Conclusion

A reliability and availability analysis has been performed on a 10 kW@20 K refrigerator which has been established in the Technical Institute of Physics and Chemistry, CAS. The failure data were collected from the similar refrigerators’ users in China and which distribution was calculated using software Weibull++ V10.0. The compressors, turbine and vacuum pump are the critical components and key units of this refrigerator. After the risk mitigation actions, the major risks are eliminated. The Mean Time to Failure (MTTF) of this refrigerator is 9211 hours which is greater than the target of 8000 hours.

References

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