Maximum Entropy Test Method for Sealing Reliability Evaluation of Extraterrestrial Celestial Body Sample Container

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Abstract: In order to solve the problem of sealing reliability evaluation of extraterrestrial celestial body sample container, by analyze and compare the current commonly used reliability evaluation methods, the maximum entropy test method with the minimum number of sample size is selected to evaluate its reliability and the evaluation process is introduced in detail. The method to choose the container seal leakage rate as the characteristics of sealing performance, through test and calculation in the critical point to implement reliability evaluation. At the same time, in view of the specialty of the seal leakage rate of numerical its margin value calculation method is proposed. The results show that the maximum entropy test method can be used to evaluate the sealing reliability of extraterrestrial celestial body sample container with only a small number of tests, which is better than 0.9999 (confidence level is 0.90), and the evaluation results is check calculated by means of the reliability evaluation by variables method, the results are consistent and credible.

1. Introduction
The sample collected from extraterrestrial celestial body has to be sealed in a high-vacuum environment during the entire mission, in order to ensure the accuracy of the original sample and ground data analysis[1]. Otherwise, after returning to the atmosphere, the entry of trace air will cause pollution and even chemical reaction to the sample, which will lead to the loss of scientific significance to the analysis of extraterrestrial celestial body sample and even the failure of the mission. Therefore, the sealing reliability of sample container is very important.

According to the investigation, at present, there is very few relevant data to evaluate the sealing reliability of sample container, and most of the existing evaluation methods are used to evaluate the reliability of initiating devices. In view of the current situation, this paper introduces and applies the commonly used reliability evaluation method in this field. After analysis and comparison, a small sample evaluation method is selected and the evaluation process is introduced in detail.

2. Evaluate task background
The sealing scheme of the sample container for extraterrestrial celestial body is referenced and adopted the mature sealing scheme of the lunar sample container. The sealing scheme using the metal knife edge squeezing seal as primary seal way[2], rubber ring seal as auxiliary seal way[3]for the redundancy seal.

Indium silver alloy and rubber ring are designed on the cover body, and the mouth of the container is machined into a ring knife edge. As in sealed container, need a locking mechanism can provide the vertical downward force to the cover body, which makes the container mouth knife edge blade into the
indium silver alloy on the cover body, at the same time, the rubber ring on the cover body squeezed into the sample container of cylinder body and the inner wall of the container form a radial seal[4], the cone of cover body and the cone of the sample container cooperate to form a mechanical limit. By this time, sample container complete the sealing action of the extraterrestrial celestial body sample. The schematic diagram of sealing scheme and sealing process is shown in Figure 1.

![Schematic diagram of sealing scheme and sealing process](image)

1-sample container 2-knife edge 3-indium silver alloy 4-rubber ring 5-cover body

(a)Before seal action
(b)After seal action

Figure 1. Schematic diagram of sealing scheme and sealing process

According to the requirements of the index, the sample container seal leakage rate must be not more than $1 \times 10^{-6}$Pa·m$^3$·s$^{-1}$, sealing reliability requirements not lower than 0.9999 (confidence level is 0.90).

3. Analysis and selection of reliability evaluation methods

Currently, the commonly used reliability evaluation methods are: attributes reliability estimating method[5], which adopts the success or failure model, without considering the characteristic parameters of the sample, and the evaluation results are relatively conservative[6]. Bayes reliability evaluation method[7-8], which also adopts the success or failure model; The maximum entropy method[9], the method is based on functional margin coefficient model; And also based on functional margin coefficient model reliability evaluation by variables method[5]. The above reliability evaluation methods are derived from the evaluation of reliability of the initiating devices. Their ideas and calculation models are different, resulting in a large difference in sample size. The specific method to be used needs to be analyzed and calculated.

3.1. Attributes method to evaluate the reliability

When the reliability is evaluated using the attributes method, the test is conducted under the design condition, namely test on sample container seal process and seal leakage rate, the seal leakage rate meet the requirements of index $(\leq 1 \times 10^{-6}$Pa·m$^3$·s$^{-1})$ as an acceptable and effective sample.

According to the look-up table and calculation, at least 29,957 test samples are required if the number of failures is 0 (namely, the seal leakage rate of each test product meets the index requirements), the reliability can meet the predetermined requirement. The above test quantity is obviously unaffordable for aerospace products with high production cost and testing cost. It is not realistic to use this method for evaluation.

3.2. Bayes method to evaluate the reliability

When the reliability is evaluate using the Bayes method, the test is conducted under the design condition also, namely test on sample container seal process and the seal leakage rate, the seal leakage rate meet the requirements of index $(\leq 1 \times 10^{-6}$Pa·m$^3$·s$^{-1})$ as an acceptable and effective sample.

According to the look-up incomplete beta function table and the calculation [11-12], at least 19,972 test samples are required in the case of the test failure number $F$ is 0. Although the method of algorithm is optimized and reduced the number of test, but the results still have large values, implementation difficulties also.
3.3. Variables method to evaluate the reliability
When the reliability of a product is mainly determined by a certain performance parameter, which has a certain design margin and is obeying the normal distribution, the reliability of the product can be calculated by using the statistical tolerance of normal distribution, that is, the reliability of the product can be evaluated by using variables method.

When variables method is used to evaluate the reliability of sealing performance, the calculation and evaluation can only be carried out after a certain number of tests have been completed, and even when the calculated value of reliability is close to the predetermined index, the calculation can be carried out while testing. This method cannot budget the test quantity in advance, makes the batch production of the product difficult, therefore it is not suitable for pre-evaluate of the reliability of small batch products, but can be used as a method for check calculated the reliability of the product after the completion of product reliability test.

3.4. Maximum entropy test method to evaluate the reliability
Maximum entropy test method is applicable to products with design margin, reliability determined by a certain performance parameter and the parameter obeying normal distribution. The most important feature of this method is that, unlike the traditional reliability evaluation method, it is not tested at the design value operating point, but at the critical operating point of performance parameters. The larger the actual performance margin of the product, the fewer number sample tests are required.

When using the maximum entropy test method to evaluate the reliability, the number of test samples required is small and can be calculated in advance. Since the sealing performance of sample container has included large margin in the design, the number of test samples required by this method is much smaller than that of traditional methods. This paper chooses this method to evaluate the sealing reliability of sample container.

4. Maximum entropy test method for the sealing reliability evaluation of sample container

4.1. Sample test method
In order to evaluate the sealing reliability of sample container, we should obtain relevant data through sample test as samples for reliability evaluation. The sample test method is as follows: the qualified product is fixed on the pressure tester, and the bottom of the container is connected to the helium mass spectrometry detector through the leak detection interface, as shown in Figure 2. In the test, the pressure tester puts a certain amount of vertical pressure on the cover body, the cone of cover body and the cone of the sample container cooperate to form a mechanical limit, the container mouth knife edge blade into the indium silver alloy on the cover body to complete the sealing process. Release pressure tester of compression force, the test piece installation gas shield for helium mass spectrometer leakage rate test[13], detection principle diagram as shown in Figure 3, a seal test is thus completed. The product after the seal test is discarded and cannot be used as the whole or part for the next test to avoid the impact on the real test results. Prepare the next set of qualified test products, repeat the above sealing and leakage rate testing process, and conduct the test in sequence, and record the leakage rate.

Figure 2. Diagram of Container seal test  Figure 3. Schematic diagram of leak rates measure system
of each test as a sample value.

4.2. Evaluation process

The maximum entropy evaluation method needs to select a characteristic quantity that can represent product reliability as the basis of measurement and calculation. For the sample container, the leakage rate index of seal which can best represent the sealing performance is selected as the characteristic quantity for measurement and calculation. According to the task index requirements, the lower limit value of the seal leakage rate of sample container is $1 \times 10^{-6}$ Pa·m$^3$·s$^{-1}$, which is very specific in comparison with the general characteristic quantity, and its value is very small and the smaller value indicates better sealing performance. For this characteristic, the margin level cannot be measured by simple multiple relation. In this paper, the margin relationship of seal leakage rate is determined by logarithmic calculation, and the calculation method is shown in formula (1).

$$M = \lg D - \lg T$$  \hspace{1cm} (1)

In the formula: $D$—Maximum design limit of seal leakage rate; $T$—The lower limit of the seal leakage rate, assignment $1 \times 10^{-6}$ Pa·m$^3$·s$^{-1}$; $M$—Seal leakage rate margin value.

According to the design report of sample container, the maximum design limit margin of seal leakage rate is 1.5 times. According to the above formula calculation to obtain $3.2 \times 10^{-6}$ Pa·m$^3$·s$^{-1}$. On the basis of ensuring that the sample test can be carried out successfully, and the larger the load strengthening coefficient is selected in the maximum entropy test evaluation method, the smaller the number of samples required. In this paper, the above two requirements are considered comprehensively, and the value of load strengthening coefficient $k$ assignment 1.3 times, which is calculated to obtain $5.0 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$. Through above the determination of load strengthening coefficient means that every time the seal leakage rate test results must be lower than $5.0 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$, can be accepted as an effective test sample. If one fails to meet this index, need to re-select the $k$ value and re-evaluate. According to the above test method, three experiments were carried out when the required number of tests was unknown, and the obtained three sample values were analyzed and the required number of samples was estimated. The seal leakage rate test results of the three tests are shown in Table 1.

| Serial number | 1      | 2      | 3      |
|---------------|--------|--------|--------|
| Leakage rate  | $1.95 \times 10^{-8}$ | $2.08 \times 10^{-8}$ | $2.03 \times 10^{-8}$ |

As can be seen from the above table, the test results are all lower than $5.0 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$, which can be accepted as qualified test samples. According to the calculation process of maximum entropy method, the required sample number can be estimated, and the calculation process is shown as follows.

The above three sample values were substituted into formula (2) to calculate the average leakage rate of the three test seals.

$$\mu = \frac{1}{n} \sum_{i=1}^{n} X_i$$  \hspace{1cm} (2)

In the formula: $\mu$—sample average value; $n$—sample number, assignment 3; $X$—each sample value.

It's calculated $\mu = 2.02 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$. Substitute the above three sample values into formula (3) to calculate the mean variance value of three tests seal leakage rate.

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\mu - X_i)^2}$$  \hspace{1cm} (3)

In the formula: $\sigma$—sample mean variance value; $n$—sample number; assignment 3; $X$—each
sample value;

It's calculated $\sigma = 0.065 \times 10^{-8}$ Pa·m³·s⁻¹. The calculated values above are substituted into formula (4) to calculate the dispersion value of three tests seal leakage rate.

$$\delta = \frac{\sigma}{\mu} = 3.25\% \quad (4)$$

Because the number of samples is less, it cannot accurately reflect the actual dispersion value of the product. In order to solve this problem, the envelope dispersion value is substituted into the formula. This value is only used for the calculation of the estimated sample number, which is the process value and does not affect the final evaluation result. According to literature [14], the corresponding envelope dispersion coefficient is 0.65, so the maximum envelope dispersion value is $\frac{\delta}{0.65} = 5.0\%$. The above parameters are substituted into formula (5).

$$N = \frac{\ln(1 - \gamma)}{\ln\left[1 - \Phi\left(k - \frac{\mu}{\sigma} - k\Phi^{-1}(R)\right)\right]} \quad (5)$$

In the formula: $N$ — number of test samples required to achieve the predictive reliability index; $\gamma$ — confidence level, assignment 0.9; $k$ — load strengthening coefficient, assignment 1.3; $\frac{\mu}{\sigma}$ — the reciprocal of sample dispersion value, assignment maximum envelope dispersion value $1/5.0\%$; $R$ — reliability, assignment 0.9999; $\Phi(\cdot)$ — normal distribution quantile symbol; $\Phi^{-1}(\cdot)$ — the inverse normal distribution quantile symbol.

It's calculated $N = 4.8$, take the integer value as 5. According to the above formula, it is concluded that five qualified tests are needed to achieve the reliability of 0.9999 at 0.9 confidence level in the condition of the actual leakage rate of sample container. We have done three qualified tests, and then we have to do two qualified tests to achieve the target reliability index. Two subsequent tests were carried out according to the above test methods. The test results are shown in Table 2.

Table 2. Seal leakage rate results of two tests

| Serial number | 1     | 2     |
|---------------|------|-------|
| Leakage rate  | 1.93×10⁻⁸ | 2.06×10⁻⁸ |
| value/Pa·m³·s⁻¹ |     |       |

As can be seen from the above table, the test results are all lower than $5.0 \times 10^{-8}$ Pa·m³·s⁻¹, which can be accepted as qualified test samples. By checking calculation using central limit theorem, the results of five test values are obeying the normally distributed. At this point, the number of test samples reaches the estimated value, and the sealing reliability of sample container can be calculated according to the above formula (2) ~ (4). The parameter definitions in the formula are described above and will not be repeated below.

A total of five test sample values are substituted into equation (2) to calculate the average value of five tests seal leakage rate.

$$\mu = \frac{1}{n} \sum_{i=1}^{n} X_i \quad (2)$$

It's calculated $\mu = 2.01 \times 10^{-8}$ Pa·m³·s⁻¹. Substitute the above five sample values into formula (3) to calculate the mean variance value of five tests seal leakage rate.

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\mu - X_i)^2} \quad (3)$$

It's calculated $\sigma = 0.0667 \times 10^{-8}$ Pa·m³·s⁻¹. Substitute the above five sample values into formula (3) to calculate the mean variance value of five tests seal leakage rate.
Finally, the above results are substituted into formula (6) to calculate the final seal reliability value.

$$R = \Phi \left( \frac{(k-1)\mu - \Phi^{-1}\left[1 - \exp\left(\frac{\ln(1-N)}{N}\right)\right]}{\sigma} \right)$$  \hspace{1cm} (6)

In the formula: $R$ — sealing reliability; $N$ — number of test samples, assignment 5; $\gamma$ — confidence level, assignment 0.9; $k$ — load strengthening coefficient, assignment 1.3; $\mu$ — average seal leakage rate value of five test samples, assignment $2.01 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$; $\sigma$ — mean variance value of five test samples, assignment $0.0667 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$; $\Phi^{-1}()$ — the inverse normal distribution quantile symbol.

The calculated sealing reliability $R$ of sample container is 0.99997 under confidence level of 0.9, which fully meet the requirements index.

5. Sealing reliability check calculate

When the test is completed, it is suitable to use the variables method to check calculate the seal reliability. According to the definition of variables method, as with the maximum entropy test method, the leakage rate index of seal is still selected as the characteristic quantity for measurement and calculation. The calculation process of sealing reliability is as follows.

By the formula (2) ~ (4) to calculate the five test sample average values and mean variance values, by the formula (7) to calculate the normal tolerance limit coefficient.

$$K_L = \frac{\bar{x} - L_L}{\sigma}$$  \hspace{1cm} (7)

In the formula: $K_L$ — normal tolerance limit coefficient; $\bar{x}$ — Average value of seal leakage rate, assignment $2.01 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$; $L_L$ — lower limit value of the seal leakage rate, assignment $1 \times 10^{-6}$ Pa·m$^3$·s$^{-1}$; $\sigma$ — mean variance value of the seal leakage rate, assignment $0.0667 \times 10^{-8}$ Pa·m$^3$·s$^{-1}$.

It's calculated $K_L = 29.98$. According to the standard[16], the reliability is 0.99999 in the table with confidence level of 0.90. This result is basically consistent with the results obtained by the maximum entropy reliability evaluation method.

6. Conclusion

According to the characteristics of the sample container, through comparing several kinds of commonly used method of reliability evaluation methods, this paper choose the maximum entropy test method to evaluate the sealing reliability. Through five sample tests, the evaluation reliability results reached 0.99997 (confidence level is 0.90), meeting the requirements of the index. The evaluation result is check calculated by means of the variables reliability method, the results are consistent and credible. The maximum entropy reliability evaluation method greatly reduces the number of sample container seal tests, saves the production and test cost, and has good operability and realization in engineering practice. At the same time, this paper also can be provided reference method and calculation basis for sealing reliability evaluation of other products.

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