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PREDICTION OF MTTF OF ROTARY MICROCRYOGENIC GAS MACHINES (MICROCRYOCOOLERS) BASED ON THE WEIBULL DISTRIBUTION LAW

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Abstract

In this paper, we analyze the methods for predicting the MTTF of microcryocoolers of various manufacturers based on the Weibull law. The values of the shape and scale parameters of the Weibull distribution law for rotary microcryocoolers of various foreign manufacturers and a method for calculating the shape and scale parameters of this law are applied to the data obtained from experimental studies of microcryocooler samples. The limiting values of the shape variable were estimated and the methods for calculating the scale parameter needed to predict the MTTF of the microcryocooler both at the stage of improving existing models and at the stage of designing newly developed samples are presented. It seems that the approach to predicting the MTTF of the microcryocooler described in the work will allow us to determine the parameters of the Weibull distribution function for specific values set by the customer of the MTTF of the created microcryocooler sample, which in turn will allow the selection of machine components (assemblies and details) also for a specific values of MTTF

Keywords

Rotary microcryocooler, reliability, life time, MTTF, the Weibull distribution

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Introduction. The rapid development of infrared detectors of satellite navigation and communication systems is the reason for the increase in the requirements for the reliability and life time of rotary microcryocoolers (RMC), cooling photosensitive elements [1]. These systems are complex and non-recoverable due to their specialized application in space: mean time to failure (MTTF) of such machines is from 10 000 to 50 000 hours, depending on the purpose of the device.

Expensive testing in situ of machine samples and the requirements for a constant increase in the life time of the RMC make us look for new methods for predicting reliability (MTTF) already at the design stage.

Literature review. Methods for calculating the predicted reliability of RMC are presented by various manufacturers of cryogenic equipment. RMC manufacturers Thales Cryogenic, Ricor use a methodology for estimating MTTF by the Weibull distribution law, based on the contribution of each component or factor to the overall reliability of the device [2, 3]. Assembly units and elements of the RMC are selected from the list of commercially available components and parts, or are developed (improved) to achieve the specified reliability directly by the manufacturers of the RMC. BAE Systems Company uses the experimentally obtained graphical relationship between the power consumption of each prototype and MTTF for estimating uptime for fixed operating frequency and fill pressure [4]. The disadvantage of this method is the need for a large number of tests to build a graphical relationship, as well as the inability to exclude the influence of random factors.

The accuracy of determining the predicted MTTF depends on a large extent on the availability of a database of accumulated data on failures in the main assembly units of the RMC experimental samples and on the connection of the causes of failures with external factors such as ambient temperature, operating frequency, and fill pressure.

It is known that statistical probability theory is used to assess the probability of failure-free operation of mechanical devices in batch production. For newly developed machine designs, the application of the statistical theory of probability in estimating uptime is possible only when components and assembly units (assemblies) are batch produced. Since RMC are systems that include elements that are produced both commercially and singly, and the MTTF of each test sample is complex, time-consuming and, most importantly, a long process, forecasting, as a rule, does not allow to obtain reliable values of the MTTF at the initial stage of testing a new model.

Weibull distribution law. The probability of failure of complex mechanical devices is best described by the Weibull distribution law. The probability density function for the Weibull distribution $f(t)$ as applied to the RMC illustrates the number of failed devices per unit time, related to the total number of tested samples. The function has two positive parameters: shape variable β; scale parameter η

$$f(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-(t/\eta)^{\beta}}. \tag{1}$$

The Weibull distribution characterizes the dependencies of the shape variable β and mechanical failure, and is universal, because depending on the values of the shape variable β it can be modified into an exponential, normal, and

Rayleigh distribution. Fig. 1 shows the relationships between the probability density distribution according to the Weibull distribution law over time of models of rotary RMC with a payload of up to 1 W at a cooling temperature of up to 77 K from Thales Cryogenic and RICOR. The values of β and η were obtained in various test modes, both accelerated and standard (Table 1).

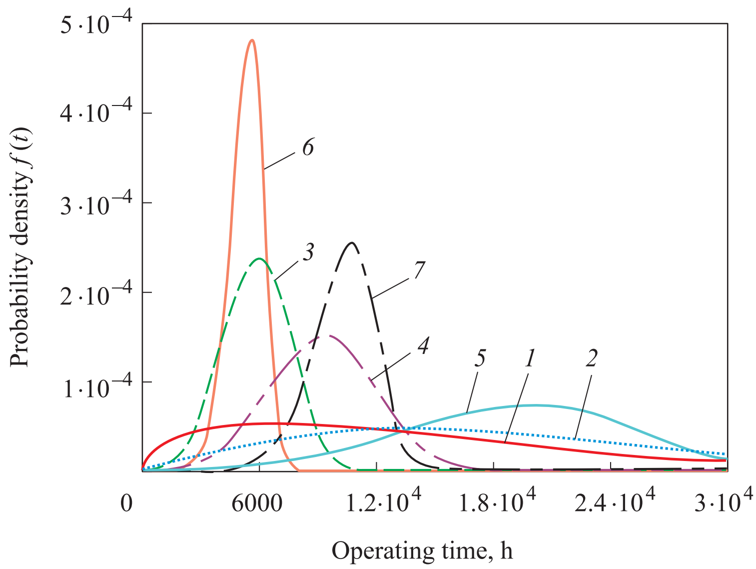

Fig. 1. Probability density according to the Weibull distribution law for RMC models with payloads up to 1 W at a cooling temperature of 77 K

Table 1

The values of β and η were obtained in various test conditions, both accelerated and standard

The curve index in Fig. 1	RMC index and manufacturer	Shape variable, β	Scale parameter, η	Test conditions
1	RM-2, Thales Cryogenic	β = 1.5	η = 15 000 h	A20 [5]
2	RM-2 new design, Thales Cryogenic	β = 2	η = 19 000 h	STP profile [5]
3	K508, Ricor	β = 4	η = 6 500 h	Acceleration life test & 80 °C [6]
4	K508N, Ricor	β = 4	η = 10 250 h	Acceleration life test & 80 °C [6]
5	RM-2, Thales Cryogenic	β = 1.7	η = 29 000 h	A20 [2]
6	K560, Ricor	β = 7.5	η = 5 780 h	GF & 36 °C [3]
7	K562S, Ricor	β = 7.5	η = 11 000 h	GF & 36 °C [3]

Fig. 2 shows the function of changing the failure rate of the RMC $\lambda(t)$ in time determines the number of failures in the average number of operating devices in a certain time interval and is presented in the form of a bath shaped curve with a characteristic bend.

$$\lambda(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}. \tag{2}$$

The value of the shape variable β makes it possible to evaluate the failure rate $\lambda(t)$ at each of the stages of RMC life time depending on the operating time. Fig. 2 also shows the results of the analyses of the relationship between the shape variable and the failure rate of the RMC using the example of the values η = 20 000 h obtained during the RMC tests and various values of the shape variables β.

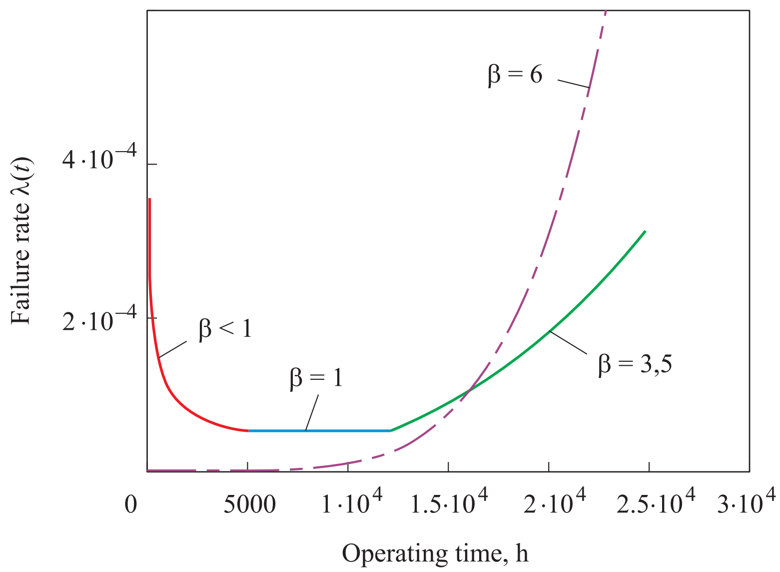

Fig. 2. The failure rate λ (t) of RMC at η = 20 000 h and $\beta < 1$, $\beta = 1$, $\beta = 3.5$, $\beta = 6$

During the running-in of parts and assemblies (0–5000 h), the shape variable takes values less than unity $\beta < 1$, the distribution density functions $f(t)$ and the failure rate $\lambda(t)$ are decreasing. The main focus of designers on production tests of prototypes is focused on reducing the likelihood of failures at this stage. Design errors, technological and manufacturing defects associated with errors in the manufacturing technology of assemblies of assemblies and parts of the RMC (for example, piston group), and problems of quality control of manufactured parts are identified and eliminated. Thales Cryogenics conducts various intermediate production tests to eliminate failures during this time period [7]. During normal operation (5 000–12 120 h) $\beta = 1$ — the failure rate decreases and is conditionally constant. Failures in this period are random, time-independent, and arise due to a combination of adverse factors, for example, service errors, external influences, human factors, the possible presence of mixed data on several types of failures. Weibull's distribution law turns into exponential. During the period of increased wear of the mechanical parts of the RMC (from 12 120 h for $\beta = 3.5$) $\beta > 1$, an increase in the function of the failure rate $\lambda(t)$ is observed. Accidental failures are superimposed on gradual failures associated with the accumulation of wear of mechanical parts and assemblies. For $\beta = 2$, the Weibull distribution turns into a Rayleigh distribution, and for $\beta = 3.3$ it is close to the normal distribution. The shape variable β determines the slope of the curve of the distribution density function and the failure rate. With parameter values $1 < \beta < 4$, the increase in failures due to mechanical wear is of a slowly growing nature and is the main range of research for designers, since the RMC contains components that undergo slow mechanical wear. For values of $\beta > 4$, a sharp increase occurs, i.e., rapid aging of the assembly or part of the RMC. For given values of β, failures during the period of increased wear will occur in a more limited period of time than for $\beta < 4$, and, consequently, the accuracy of determining the MTTF of RMC is higher, and the result is more predictable.

Fig. 1 the value of the shape variable β for Ricor's K560, K562S, K508 models, calculated according to the test results, significantly exceeds $\beta > 4$. Despite this, Ricor suggests that it is unlikely to provide $\beta = 7.5$ in real conditions it is possible, since non-stationary modes of operation of the RMC are predominant during operation and, in reality, the parameter β is in the range from 2 to 3, and it is recommended to take it equal to two [8].

Note that it is impossible to predict the reliability of a part, assembly, or the entire assembly with respect to one shape variable β, and it is necessary to take into account the values of the second scale parameter η.

RMC tests are a complex, expensive and time-consuming process, and obtaining data on the nature of the distribution of failures is possible only after completion of tests on the mean time between failures of a batch of machines. In spite of the fact that the majority of RMC manufacturers use accelerated tests [9–11], their duration is also significant. As noted earlier, the requirements for the service life of cryogenic systems for cooling photosensitive elements, under given operating conditions of the device, are 10 000–50 000 h, depending on the purpose. Weibull analysis is well suited to determine the failure density function of a assemble, part, or entire assembly unit with a small sample and a minimum number of failures. This method allows, on the basis of the obtained statistical data on failures during testing of tested samples, to proceed to the determination of two Weibull distribution parameters: shape variable β and scale parameter η.

The scale parameter η can be calculated using the maximum likelihood method during the test, when not all the samples have failed and censored data are available, according to the following relationship:

$$\eta = \left[\sum_{i=1}^{n} \frac{t_i^{\beta}}{r} \right]^{1/\beta}, \tag{3}$$

where t_i is the sample run time; r is the number of failed RMC during this period; β is the shape variable.

The maximum likelihood method for determining the scale parameter η gives good results when improving the RMC model, provided that the β value for the previous models is known — Weibayes analysis [7].

The scale parameter η is proportional to the MTTF:

$$\text{MTTF} = \eta\Gamma\left(1 + \frac{1}{\beta}\right), \tag{4}$$

where $\Gamma\left(1 + \frac{1}{\beta}\right)$ — Euler tabular gamma function (see Table 1), depending on the shape variable β, are presented in Table 2.

Table 2

Euler gamma function values

$1 + \frac{1}{\beta}$	$\Gamma\left(1 + \frac{1}{\beta}\right)$	$1 + \frac{1}{\beta}$	$\Gamma\left(1 + \frac{1}{\beta}\right)$	$1 + \frac{1}{\beta}$	$\Gamma\left(1 + \frac{1}{\beta}\right)$
1	1	1.35	0.89115	1.7	0.90864
1.05	0.97350	1.40	0.88726	1.75	0.91906
1.10	0.95135	1.45	0.88566	1.8	0.93138
1.15	0.93304	1.50	0.88623	1.85	0.94561
1.20	0.91817	1.55	0.88887	1.9	0.96177
1.25	0.90640	1.60	0.89352	1.95	0.97988
1.30	0.89747	1.65	0.90012	2	1

For β = 1, the MTTF value is η; however, with increasing β, the gamma function is less than unity and MTTF < η.

One of the main indicators of RMC reliability is MTTF, with the help of which models of the same type are compared with identical technical and thermodynamic characteristics.

The MTTF of RMC values given by various manufacturers are difficult to compare, since there is no internationally agreed standard for testing and a method for determining the MTTF. The values of the Weibull distribution parameters β and η are calculated according to data obtained under various standard and accelerated test modes with various ambient temperature parameters, the number of start and stop modes, various payloads, fill pressure, and rotor speed.

Test conditions and modes of RMC. Thales Cryogenic test conditions: STP profile and A20. Thales Cryogenic conducts RMC tests in the modes: STP profile test and accelerated tests A20 test.

The STP profile mode is close to the typical operational profile of the RMC operation [12, 13]. During testing in the STP profile, the test sample is turned on and off with a certain frequency when the outside temperature changes from 20 to 55 °C.

Due to the length of the standard tests, the company since 2012 has mainly used accelerated A20 tests based on accelerated aging and statistical data [5]. Accelerated RMC tests in A20 mode include two aging factors: an increased rotor speed of 3 000 rpm and the continuous operation factor of the RMC test sample at 20 °C outside temperature. The accelerated rotation of the RMC engine increases the load on the bearings and piston coating. Every 500 hours of operation, RMC test samples are checked for compliance with the technical data sheet according to the following parameters: cooling time or power consumption. If the required parameter values indicated in the RMC passport go beyond the boundaries, the tests are terminated.

To recalculate the data obtained as a result of accelerated tests (test A20), empirical coefficients are used to determine the mean time between failures during the basic MTTF base operation mode [12]. The RMC operating conditions differ from both accelerated and standard test conditions. The MTTF app RMC is converted according to empirical coefficients in accordance with the operating profile, taking into account the operating temperature, environmental conditions, the number and duration of on and off cycles, as well as the total required service life of the RMC. The value of these empirical coefficients is determined by the Thales Cryogenic ICM manufacturer during long-term tests for various operating modes [7].

RICOR's RMC test conditions are GF (Ground Fix) and Accelerated Life test. The manufacturer RMC RICOR conducts tests of rotor type samples in various modes. RMC tests in GF mode are close to the operation of the device in ground conditions at a given outdoor temperature [14]. As an example, Fig. 1

shows the distribution functions of the failure probability density of the RMC over time for the K560 and K562S models, tested ground use at an outdoor temperature of 36 °C.

The technical conditions that allow to accelerate the RMC tests during the MTTF by RICOR (Accelerated Life test) include [14]:

• an increase in the operating frequency to 60 Hz, which is equivalent to an increase in the rotor speed to 3 600 rpm;

• temperature control of the motor casing in the climate chamber at the level of 80 °C.

Accelerated tests are carried out on experimental samples with increased test loads, in order to reduce test time. Moreover, the methodology for conducting these tests does not affect the nature and causes of failures.

The accelerated test method alone does not allow us to evaluate the reliability of the new RMC design. First, it is necessary to compare the RMC test failure time with the known reliability tested under standard conditions with the results of tests carried out under accelerated tests. To assess the reliability of the improved RMC model, the MTTF values of the prototypes are compared with the updated models obtained under the conditions of accelerated reliability tests, and the conversion factors are used to estimate the uptime for normal operation.

Conclusion. In the paper, the limiting values of the shape variable were estimated and methods for calculating the scale parameter needed to predict the uptime of the RMC at the stage of improving existing models and at the stage of designing newly developed samples were presented.

The Weibull distribution shape variable for specific customer-specified MTTF is in the range $1 < \beta < 4$, which is well illustrated by tests conducted by manufacturers of RMC.

The determination of the scale parameter of the Weibull distribution law is possible at the stage when not all the samples have failed in the test using the maximum likelihood method for the known values of β of the previous model of the RMC. This method is known as Weibayes analysis. However, when developing a new RMC sample, it is necessary to test a series of samples until the complete life cycle of all RMCs is completed.

MTTF is one of the main indicators of RMC reliability, with the help of which models of the same type are compared with identical technical and thermodynamic characteristics. The presented MTTF RMC values are difficult to compare, since there is no internationally agreed standard for testing and a method for determining the mean time to failure. The values of the Weibull distribution parameters β and η are calculated according to the data obtained for various normal and accelerated test modes with different ambient temperature parameters, the number of start and stop modes, and various payloads (see Fig. 1). Manufacturers introduce correction factors for translating MTTF for standard conditions (STP profile) or (GF — GROUND Fix) compared to conditions in accelerated tests, such as test A20.

The approach to predicting the RMC uptime described in this paper will allow us to determine the parameters of the Weibull distribution function for specific customer-specified mean time to failure (MTTF) of the created RMC sample, taking into account the field of application. This, in turn, will allow the selection of components (components and parts) of the machine for a specific value of the mean time to failure.

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