Analysis of Reliability Prediction Technology for Aerospace Single Electronic Products

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Abstract. This paper analyzes the matters that should be paid attention to during the reliability prediction of aerospace electronic products, the corresponding relationship among mission profile, mission reliability model, and reliability prediction parameters, and the requirements for data and modeling to more accurately predict the reliability of products.

Keywords: Reliability Prediction · Aerospace Electronic Products · Mission Profile · Mission Reliability

1 Introduction

Reliability engineering has become an important part in the life cycle of aerospace equipment, which determines the success of equipment tasks [4]. Reliability also represents the ability of space equipment to operate, which directly affects the project approval, development, performance, and use of space equipment. Due to the complex structure of weapon equipment, it is needed to adopt a variety of advanced technologies, processes with high technical risks, which call for higher model requirements and reliability. In addition to the above characteristics, space products have special requirements for the space environment and demand more reliability.

Therefore, the requirements of reliability index are proposed by overall units and users of the aerospace system for products, which are taken as the acceptance criteria of the products. For example, the following figure showed the reliability index of a modeling task handbook.

Generally, the reliability verification of single-machine products is divided into two parts. The first part is the reliability prediction in the engineering development stage. During the evaluation of hardware design, the reliability prediction value should be larger than the specified value. The second part is the evaluation of reliability in the final stage by the statistical model for reliability according to the test data of the product. The value of this reliability evaluation lies in the accurate statistics of reliability indices of the product, which can help examine both the hardware and software design and the fulfillment ability of products. Therefore, in general, the reliability evaluation is lower than the expected one and can satisfy the minimum acceptable level [1].

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2 Principles of Mission Profile Establishment

The product data link of the equipment system is usually mounted on the aircraft missile or the missile launcher. Being on the missile launcher, the product data link usually has three mission stages: self-test, launch, and autonomous flight. When a data-link missile is mounted on an aircraft, it generally goes through four mission stages, including the mount, self-test, launch, and autonomous flight, which corresponds to silent, low power, medium power, and high power modes. Furthermore, the working modes of data link products can vary with task stages.

- In the silent mode, the missile-borne terminal can only receive forward service data and instructions while cannot send any backward data.
- In the low power mode, namely test mode, forward-reverse information, and image data can be exchanged. This mode is only used for ground testing.
- In the medium power mode, the missile-borne terminal machine can exchange forward and reverse data information while cannot send high-rate data, e.g. images.
- In the high power or task mode, the missile-borne terminal not only exchanges forward-reverse information and data, but also transmits the compressed image data.

According to the work process description of products, the task section is established as shown in Table 1. The reliability block diagram is shown in Fig. 1.

T0 refers to the time of missile launch; the time before T0 is to prepare for the missile launch, and the time after T0 is for the autonomous flight of the missile.

Table 1. Task stages and working modes.

No.	Task stage	Working mode	Component power
1	Self-test	Silent	Forward link components work with power on; the reverse link works without power on.
2	Hang a fly	Low power	The components of the front reverse link work with power on, while the high-frequency components work with low power. Image data work with power on.
3	Launch	In the power	The components of the front reverse link work with power on, while the high-frequency components work with low power. Image components work without power.
4	Autonomous flight	High power	The components of the front reverse link work with power, while the high-frequency components work with low power. Image components work without power.
5	Ground test	Low power	The components of the front reverse link work with power, while the high-frequency components work with low power. Image data work with power on.

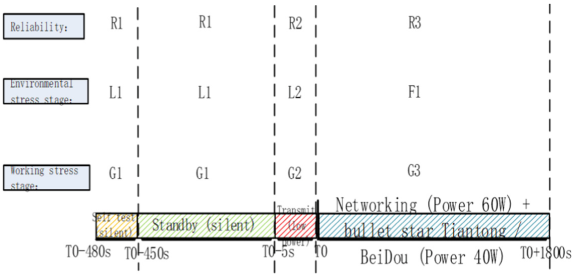

Fig. 1. Mission profile model. (Photo credit: Original)

Lm/Fn (m = 1, 2; N = 1):

- L1: In self-test and standby modes, the environment stress refers to the GF1 (ground, fixed, controlled) in GJB/299C.
- L2: Product stress at launch stage, while the environment stress means the missile launch in GJB/299C.
- F1: Product in free flight mode, environment stress denotes the missile flight in GJB/299C.

The working stress stage $G_{k.}$It can be divided into G1 to G3. At each stage, both the working time and stress of components are different under varied control voltages, e.g., some components are not powered on, while some are not working even though they are powered on.

- G1: The time period t1 = 30 s, t2 = 445 s; product self-test, standby; the product works at silent power, and the reliability block diagram is shown in Fig. 3.
- G2: time range t3 = 5 s; missile ready for launch; with 60W power and silent networking, the working block diagram of product reliability is shown in Fig. 4.
- G3: time segment t4 = 1800 s; missile free flight stage; the network works under 40W power, Tiantong or Beidou satellites work at 60W power,and the working block diagram of product reliability is shown in Fig. 5.

Only when the components of each module connect in series can we guarantee the success of the flight or launch mission.

3 Principles of Reliability Modeling

The product reliability basically reflects the required maintenance costs and logistics support resources if any module fails. Task reliability refers to the probability that a product will perform a required function in a specified task profile. The task reliability model can change with the task stage.

Depending upon the task stages, the working stress of components will be different in various working modes. For instance, the temperature rise of components can vary with the power consumption, causing different failure rates of components. To be more specific, in different task stages, some components should work with power while some without. Some components may require the operating voltage instead of applied voltage but deliver zero output. Hence, task stages and working modes of products should be fully considered in the prediction and modeling of reliability.

3.1 Reliability Block Diagram

Figure 2 describes the task reliability block diagram model for a certain task. Different mission profile models are shown in Fig. 1.

3.2 Block Diagram of Task Reliability in R1

In the figure:

- R1: Reliability of module 1 under general ground environment conditions;
- R2: Reliability of module 2 under general ground environment conditions;
- R3: Reliability of module 3 in general ground environment;
- R41: Reliability of module 4 in general ground environment1;
- R42: Reliability of module 4 in general ground environment2;
- R5: Reliability of module 5 in general ground environment;
- R6: Reliability of Module 6 in general ground environment;
- R711: Reliability of module 71 in general ground environment1 under silent working stage (different device working stress);
- R721: Reliability of module 72 in general ground environment2 under silent working stage (different device working stress);

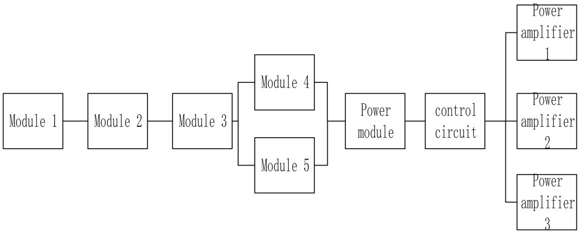

Fig. 2. Reliability block diagram.

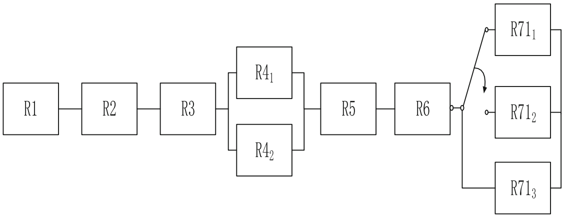

Fig. 3. The reliability block diagram of R1.

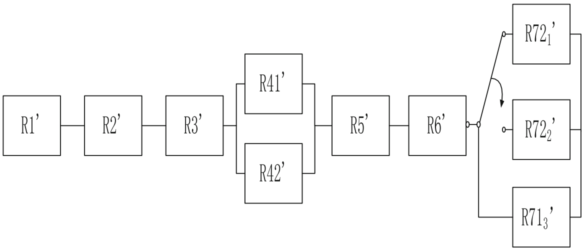

Fig. 4. The reliability block diagram of R2.

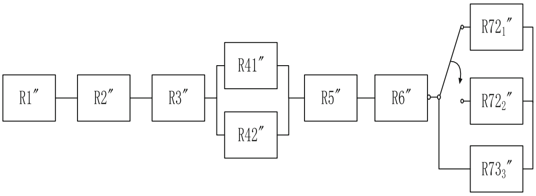

Fig. 5. The reliability block diagram of R3.

- R731: Reliability of module 73 in general ground environment3 under silent working stage (different device working stress);

Among them, the R71$_1$ and R71$_2$ side-link working models with R71$_3$ could constitute a parallel working model.

3.3 Block Diagram of Task Reliability in R2

In the figure:

- R1': Reliability of module 1 in launch environment;
- R2': Reliability of module 2 in launch environment;
- R3': Reliability of module 3 in launch environment;
- R41': Reliability of module 4 in launch environment1;
- R42': Reliability of module 4 in launch environment2;
- R5': Reliability of module 5 in launch environment;
- R6': Reliability of module 6 in launch environment;
- R712': Reliability of module 72 under launch environment conditions1 in 40W power;
- R722': Reliability of module 72 under launch environment conditions2 in 40W power;
- R732': Reliability of module 71 under launch conditions3 in the silent working stage;

Among them, R72$_1$' and R72$_2$' side-link working models with R71$_3$' could form a parallel working model.

3.4 Block Diagram of Task Reliability in R3

In the figure:

- R1”: Reliability of module 1 under missile flight conditions;
- R2”: Reliability of module 2 under missile flight conditions;
- R3”: Reliability of module 3 under missile flight conditions;
- R41”: Reliability of module 4 under missile flight conditions1
- R42”: Reliability of module 4 under missile flight conditions2;
- R5”: Reliability of module 5 under missile flight conditions;
- R6”: Reliability of module 6 under missile flight conditions;
- R712”: Reliability of module 72 under missile flight conditions1 in 40W power;
- R722”: Reliability of module 72 under missile flight conditions2 in 40W power;
- R732”: Reliability of module 73 under missile flight conditions3 in 60W power working stage;

Among them, $R72_1$” and $R72_2$” side-link working model with $R73_3$ could form a parallel working model (Table 2).

3.5 Task Stage, Working Mode, and Task Reliability

Based on task stages, the working modes can be divided into the normal stage, 40 W power, and 60 W power;

The environment stresses of R1 and R1’ are different while the working stress remains the same;

The environment stresses and working stresses of RJ and RK’ are varied.

3.6 Mathematical Model of Reliability

$$R(t) = e^{-\int_0 t\lambda\,(t)\,dt} \tag{1}$$

In the formula above, λ(t) means the failure rate function, R(t) refers to the reliability function, and t indicates the working hours.

Belonging to electronic products, the failure rate function of components and equipment follows an exponential distribution. To ensure the success of the task, the modules and components are in series, where the value of λ(t) of the module is the sum of the failure rates during all periods, and the R(t) equals the multiplication of successive reliability values, as shown in Formula 2.

$$R_i(t) = \prod_{j=1}^{n} R_{ij}(t) = e^{-\sum_{j=1}^{n} t_i\lambda_0} \tag{2}$$

Among them, $R_i(t)$ signifies reliability of the i-th period, j means the j-th component, N denotes the number of components, $R_{ij}(t)$ refers to the reliability of the j-th component at the time period i, t_i indicates the working time of the i-th period (the base time of each period is 0), and λ_{ij} suggests the failure rate of the j-th component at the time period i;

Table 2. Environment stress and working modes.

Components	Environment stress	Working mode	Reliability
Module 1	Generally the ground	Self-check/Normal	R1
Module 2	Generally the ground	Self-check/Normal	R2
Module 3	Generally the ground	Self-check/Normal	R3
Module 4	Generally the ground	Self-check/Normal	$R4_1$
Module 5	Generally the ground	Self-check/Normal	$R4_2$
Power supply module	Generally the ground	Self-check/Normal	R5
Control circuit	Generally the ground	Self-check/Normal	R6
Power amplifier 1	Generally the ground	Self-check/Normal	$R71_1$
Power amplifier 2	Generally the ground	Self-check/Normal	$R72_1$
Power amplifier 3	Generally the ground	Self-check/Normal	$R73_1$
Module 1	Missile launch	Normal	R1’
Module 2	Missile launch	Normal	R2’
Module 3	Missile launch	Normal	R3’
Module 4	Missile launch	Normal	R41’
Module 5	Missile launch	Normal	R42’
Power supply module	Missile launch	Normal	R5’
Control circuit	Missile launch	Normal	R6’
Power amplifier 1	Missile launch	40W	$R71_2$’
Power amplifier 2	Missile launch	40W	$R72_2$’
Power amplifier 3	Missile launch	40W	$R73_2$’
Module 1	Missile flight	Normal	R1”
Module 2	Missile flight	Normal	R2”
Module 3	Missile flight	Normal	R3”
Module 4	Missile flight	Normal	$R4_1$”
Module 5	Missile flight	Normal	$R4_1$”
Power supply module	Missile flight	Normal	R5”
Control circuit	Missile flight	Normal	R6”
Power amplifier 1	Missile flight	60W	$R71_3$”
Power amplifier 2	Missile flight	60W	$R72_3$”
Power amplifier 3	Missile flight	60W	$R73_3$”

Wherein, the failure rate of the j-th component in the time period i and the working stress G in the time period during which the component works $\lambda_{ij\ \mathrm{k}}$, the environment stress $\mathrm{L_m/F_{n.}}$So should be calculated separately.

$$\mathrm{R_s(t)} = \Pi^3_{(i=1)}\mathrm{R_i(t)} \tag{3}$$

The reliability model during each time period is in series, and the product reliability in the whole task stage is shown in Formula 3:

$= \prod_{\mathrm{i=1}}^{2} \mathrm{R_i(t)}$ Then, the launch reliability before T0 is illustrated in Formula 4:

$$\mathrm{R_L(t)} \tag{4}$$

The flight reliability model $\mathrm{R_F(t)}$ and the full-stage reliability model $\mathrm{R_s(t)}$ are included in Formula 3.

4 Estimated Component Reliability at Each Task Stage

The components of various task stages may operate at different levels of voltage, operating current, and power, as well as task periods.

4.1 Expected Approach

Referring to the component stress analysis in GJB/Z299C Electronic Equipment Reliability Prediction Manual, the reliability prediction in this project is carried out [5]. The expected principles are as follows:

The parameters of reliability prediction mainly refer to the device manual and project schematic diagrams; for parameters and components that cannot be located in GJB/Z299C, those values of similar components could be used for prediction.

Being an electronic product, the failure function of this project follows an exponential model to have a constant failure rate at each task stage. That is:

$\mathrm{R(t) = e^{-\lambda t}}$, λ is the product failure rate of the task stage;T is task time; R(t) is the product reliability.

The series work of various components during each time period t in the flight mission profile (after T0) and launch mission profile (before T0)i, and the calculation methods are suggested in Formula 2, 3, and 4. The failure rate of the j-th component at the time period i was calculated based on the stress analysis of components as indicated in GJB/Z299C. The failure rate of components λ_{ij}, the work stress in the period of components G λ_{ij} k, and the environment stress Lm/Fn It all matter. The environment stress Lm/Fn means the environment coefficient in GJB/Z299C as can be seen in the previous section. The specific values of working stress can be referred to the manual of components.

The software reliability evaluation is built upon the delivery and use of previous software models of analog circuits as well as the qualification of software development unit. For example, the software reliability is 0.99950.

As this paper only considers the design reliability this time, the process implementation reliability is valued as 1.

When the components operate in different task stages, their work stresses will be varied, and the condition with the greatest influence on the reliability will be adopted in the estimation.

If the predicted parameters are unavailable, the worst-case reliability will be employed for estimation.

4.2 Expected Parameters of Components

According to the component failure rate model described in GJB/Z299C,the inherent and service parameters of components are collected and predicted [2], e.g. the information collection table. The standard of GJB/Z299C is based on MIL217F,a failure rate model simulated by the failure statistics sourcing from sufficient corresponding components. Thus, the failure rate model has certain reference values. The following points should be noted when collecting the information:

In accordance with the component classification of GJB/Z299C, if the category of the target component is unclear, e.g. the semiconductor digital circuit may also be FPGA, the results of both types should be calculated and the one with a higher failure rate is selected as the final result. If the target component is excluded in the component classification of GJB/Z299C, we will turn to the manufacturer for failure rate data;

Accurate information is essential to correct failure rate results. As an example, the junction temperature of components can be obtained by thermal simulation, or by shell temperature, heat consumption, and thermal resistance [3]. Chapter 3 provides the analysis of heat consumption. In different task stages and working modes, the heat consumption result will be varied from junction temperatures and failure rates (Yu Jianzu 2008);

The collection of information is prone to be a challenge in the actual situation. As the result, we should try to obtain accurate data from component manuals or manufacturers;

See Tables 3, 4, 5, 6, 7 and 8 for examples of reliability prediction information of components.

Table 3. Semiconductor monolithic analog integrated circuit.

Bit Number	Component model	Category	Number	Quality grade	Maturity	Circuit type NV	Values of VS.	Setting mode of junction temperature	Junction temperature	Maximum power consumption	Shell temperature	Thermal resistance to the tube shell[4]	Thermal resistance is determined in package form	Number of transistors	Packaging form	Number of legs
U7	B9122E	Semiconductor monolithic analog integrated circuit	1	A3	Stable product	CMOS, $3V \le VDD \le 18V$, if $Vs < 8V$	3.3 V	To calculate	175 ℃	1.5 W	60 ℃	1.1 ℃ / W	Sealed, chip carrier (LCC) package;	500000	Sealed, surface mounted (chip carrier) package	72

Table 4. Eeprom, FLASH.

Bit Number	Component model	Component name	category	Number	Quality grade	Maturity	Circuit type NV	Values of VS.	Setting mode of junction temperature	Junction temperature	Power consumption	Shell temperature	Thermal resistance to the tube shell	Thermal resistance is determined in package form	Digits	Packaging form	Number of legs	Number of programming cycles in the lifetime
F1	MT28EW01GABA1HPC-0SIT	NOR flash memory	FLASH	1	B2	Stable product	CMOS, 3V ≤ VDD ≤ 18V, if Vs < 8V	5	To calculate	125 ℃	0.5 W	85 ℃	15℃ / W	Sealed, ball grid array (CBGA) package;	128000	Sealed, plug array (including PGA, BGA, and others)	64	10000

Table 5. Rf coaxial connectors

Bit Number	Component model	Component name	Category	The number of	Quality grade	Work environment temperature	Temperature rise	Material type	Actual number of contacts used	Jack structure	Insertion and removal times / 1000 hours	Connector type
J1	SMP-JHD	The connector	Radio frequency connector	2	B2	60 ℃	2℃	I	2	pinhole	10	A single

Table 6. Rectangular connectors.

Bit Number	Component model	Component name	Category	Number	Quality grade	Work environment temperature ℃	Temperature rise	Material type	Actual number of contacts used	Jack structure	Insertion and removal times / 1000 hours	Connector type
J2	J30J-15ZKN-J-P5	The connector	Rectangular connector	1	B2	60 ℃	2℃	I	1	pinhole	40	A single

Table 7. Semiconductor digital integrated circuit.

Bit Number	Component model	Component name	Category	The number of	Quality grade	Maturity	Circuit type NV	Values of VS.	Setting mode of junction temperature	Junction temperature	Maximum power consumption W	The shell temperature ℃	Thermal resistance to the tube shell	Thermal resistance is determined in package form	Circuit type	Gate number	Packaging form	Number of legs
U29	JCDCV304	Clock buffer	Semiconductor digital IC	1	A3	Stable product	CMOS, 3V ≤ VDD ≤ 18V, if Vs < 8V	3.3 V	To calculate	150 ℃	0.15 W	60 ℃	20 ℃ / W	Sealed, small shape (SO) package;	MOS	500	Sealed, surface mounted (chip carrier) package	8

Table 8. Hybrid integrated circuit

Bit Number	Component model	Component name	Category	Number	Quality grade	Maturity	Circuit function type	Process types	Temperature environment	Temperature	Network complexity failure rate	Failure rates of thick and thin film resistors	Substrate area cm^2	Membrane resistance number
U47	DBP9282A		Hybrid IC	1	A3	Trial production or new products	Microwave > 1 GHZ	Thick film - thin film mixture	Temperature of the package base	60 ℃	Thin film	Thin-film resistor	1.107	4

5 Conclusions

On the basis of the above analysis, it can be concluded that the following points deserve more attention in the reliability prediction of aerospace electronic components:

It is necessary to establish the task profile of electronic products to analyze different task stages, work modes of products and components, as well as to determine the work stress including the levels of power, voltage, etc.;

Following the environment classification of GJB/Z299C, the environment π coefficient can be adjusted appropriately;

By strengthening the secondary screening, DPA detection, and inspection management, the quality grade coefficient can be reduced appropriately;

The information collection of components, especially for quality grade, power consumption, junction temperature, gate number (bits, transistor number), leg number, package form, should all be accurate;

More accurate reliability evaluation of electronic products needs to be evaluated by using statistical model combined with more test data in the later stage, and the results are more in line with the real value of product reliability.

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References

1. Elsayed, translated by Yang Zhou, reviewed by Kang Rui; Reliability Engineering (2nd Edition),Beijing, electronic industry press, 2013;
2. GJB/Z299C Electronic equipment reliability prediction manual, General Armament Department of the Chinese people's Liberation Army, 2006.
3. Yu Jianzu, Gao Hongxia, Xie Yongqi, Thermal design and analysis technology of electronic equipment (2nd Edition), Beijing, Beijing University of Aeronautics and Astronautics Press, 2008;
4. Zeng Shengkui, Zhao Tingdi, Zhang Jianguo, Kang Rui, Shi Junyou; System reliability design and Analysis Course; Beijing; Beijing University of Aeronautics and Astronautics Press, 2001;
5. Zhang Zengzhao, Pan Yong, Reliability prediction of electronic products, Beijing, Science Press, 2007.