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AN5948
Reliability of High Power Bipolar Devices
Application Note

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INTRODUCTION

The question is often asked, "What is the MTBF or FIT rating of a particular diode or thyristor?" This cannot be answered without knowing how the device is intended to be used in a system and the conditions of its operation. In other words, it is necessary to know the "Mission Profile".

MTBF is the "**M**ean **T**ime **B**etween **F**ailure" and is the measure of an average time for a second component to fail after the failure of a first component in a system. MTBF usually applies to a repairable system consisting of many components. Knowing the MTBF allows the system designer to recommend a repair or maintenance schedule and thus deduce the running cost of the system. For semiconductor devices MTTF (**M**ean **T**ime **T**o **F**ail) is generally appropriate, however, MTBF and MTTF have the same value if the time to repair a system is negligible. Thus, MTBF is loosely used to mean MTTF for semiconductor devices.

FIT (**F**ailure un**IT** or **F**ailure **I**n **T**ime*)* is a unit for the measure of failure rate (λ) of the components and is equal to one failure per billion hours (10^9 hours). Both MTBF and λ are statistical quantities and if the failure pattern assumes a normal distribution, then one is the reciprocal the other (MTBF = $1/\lambda$). The failure rate is useful for predicting the life of a device.

The purpose of this Application Note is to discuss the reliability of high power bipolar devices (diodes, thyristors and GTOs) and how it relates to the different failure mechanisms, materials used in the construction of the devices and the manufacturing processes. Also, different methods used to predict the reliability and the pros and cons of each method are discussed.

DEVICE CONSTRUCTION

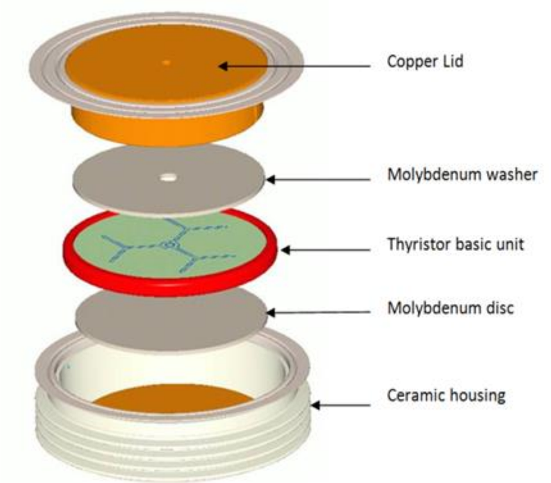

Fig. 1: Pressure contact thyristor construction.

Fig. 1 shows the typical construction of a fully-floating pressure contact thyristor and the materials used. The silicon wafer is sandwiched between a molybdenum washer and disc, thus providing electrical contact to the active parts of the device. These are further sandwiched between two copper pole-pieces, one in the ceramic housing and the other in the lid. The housing is backfilled with inert gas and the copper lid is cold welded to the ceramic housing. In a non-fully-floating construction, the molybdenum disc is alloyed to the silicon wafer. Electrical and thermal contact is made by clamping the pole-pieces under pressure.

THE CONCEPT OF RELIABILTY

Reliability is a design engineering discipline, which applies scientific knowledge to assure a product will perform its intended function, for the required duration, within a given environment. This includes designing in the ability to maintain, test and support the product throughout its total life cycle.

There are several definitions of reliability. IEC 50(919):1990 defines reliability performance as “The ability of an item to perform required function under given conditions for a given interval of time.”

The fundamental understanding of the reliability of any product requires a basic understanding of failure mechanisms and how the failure rate is determined.

FAILURE MECHANISMS

The pressure contact power semiconductor failures can be classified into two main categories namely:

- Random failures
- Wear-out failures

Random failures

These failures are caused by external accidental events such as particle radiation, voltage transients and damage by service actions leading to momentary over-stress. This type of failure is not related to the length of service or the age of the device. Fig. 2 shows a typical failure site due to cosmic ray activity.

Wear-out failures

These types of failures are attributed to the accumulation of incremental physical damage under the operating load (stress) conditions, altering the device properties beyond the functional limit. These are mechanical wear-out due to expansion and contraction caused by cyclic power loading and ionic drift in the junction passivation leading to an increase in leakage current and eventual voltage breakdown.

Depending on the application and the duty cycle within that application, any one of these failure mechanisms can dominate.

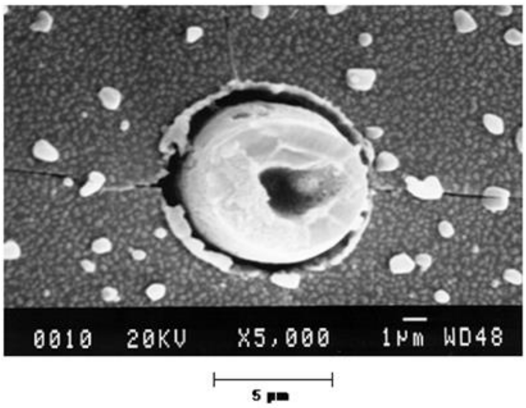

Fig. 2: Failure due to cosmic rays causing damage to the silicon crystal lattice which gives rise to immediate and catastrophic failure of the device.

Cosmic Ray induced failure

Failure due to cosmic rays was first postulated in the early 1990s to explain an unexpectedly high failure rate of GTOs in railway locomotives running with higher than previous DC-link voltages. Failures were seen to be random, sudden, and without any previous overload condition or signs of wear-out. The cause of this failure mechanism is postulated to be neutrons, produced when cosmic rays collide with the upper atmosphere, which have energies above 10MeV. When one of these neutrons hits the silicon lattice it will generate electron-hole pairs. If the electric field is high enough, the electrons and holes will be accelerated to sufficient energy to cause avalanche multiplication and consequent device breakdown.

Because the failure rate is exponentially related to the bias voltage and proportional to the time spent at that voltage, it is only in applications where the device sits at high DC volts relative to its rating that this failure mechanism needs to be considered. There is no easily applied universal formula for the failure rate because it depends upon the electric field profile within the silicon basic unit which in turn depends upon the design philosophy. Devices intended for such applications may have a figure for the maximum DC voltage, for a rating of 100 FITS at 100% duty cycle, quoted in their datasheets.

Mechanical Wear

In a power semiconductor, increases and decreases in the temperature of the device will cause the various internal components to expand and contract. Table 1 gives the linear temperature coefficient of expansion for materials commonly found inside such devices. In large diameter, high reliability devices, where the internal components are pressed together by a clamp, molybdenum buffers are used between the silicon wafer and the copper electrodes, but in some smaller diameter products the copper electrode is in direct contact with the silicon wafer. The difference in the coefficient of thermal expansion causes movement of one component relative to its neighbours with a resultant scrubbing action. This scrubbing will eventually lead to degradation of the device characteristics, initially an increase in the forward voltage drop, but eventually the silicon becomes chipped and the voltage blocking capability of the device is lost.

Table 1: Material properties

Material	Linear coefficient of expansion @ 20°C ($x10^6$ per °C)
Silicon	4.2
Copper	16.5
Aluminium	23.95
Molybdenum	5.2
Silver	18.9

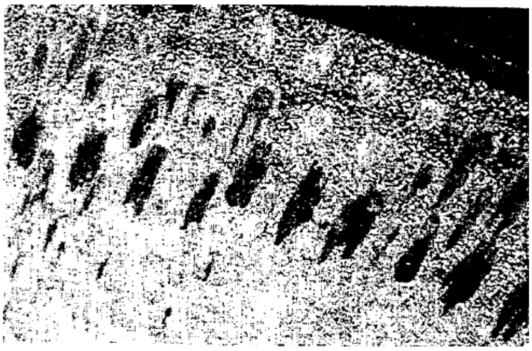

Fig. 3a: Thermo-mechanical wear-out.

Fig.3b: Expanded view of the wear-out.

Figs. 3a and 3b show a typical example of thermo-mechanical wear-out failure. Note that in fig. 3a the wear-out marks are radial with respect to the centre of the device. In the expanded view of the failure site (fig. 3b) the scrape marks from the sliding action can be seen at the bottom of several wear areas.

Ionic Drift in the passivation

The surface of the silicon that supports the blocking voltage of devices is passivated with one of a number of different compounds, depending on the structure, that has several functions. Primarily it is a high dielectric material used to confine the electric field but it also locks up mobile ionic charge that may be present on the surface of the silicon. If this ionic charge drifts, under the influence of the applied electric field, into a region of high field strength it can cause excess leakage current to be observed and a resultant degradation in the voltage blocking performance of the device.

This phenomenon is largely limited to very high voltage devices. Manufacturers of these products will subject their devices to a short “burn-in” to precipitate early life failures due to this mechanism. After any early failures the failure rate is extremely small.

PREDICTIVE RELIABILITY

Many engineering disciplines incorporate reliability engineering that employs tools and methodology such as predictive reliability, Weibull analysis, reliability testing and accelerated life testing. The purpose of predictive reliability is to evaluate the failure rate (λ) or the MTBF of the device for a specified lifetime. The failure rate of a large population of similar and non-repairable items shows a typical “bathtub” curve (fig. 4) with the following three phases:

1. *Early failures*: where λ(t) generally decreases rapidly with time. The failures in this phase are attributed to randomly distributed weaknesses in materials, components or production processes. To eliminate early failure, burn-in or environmental stress screening is used. This phase is also called infant mortality.
2. *Useful life:* where failure rate is approximately constant and is useful for calculations. The failures are intrinsic and random (mainly related to failure of silicon material).
3. *Wear-out failures:* where λ(t) increases with time. The failures in this phase are attributed to degradation phenomenon due to aging, fatigue, wear-out, etc.

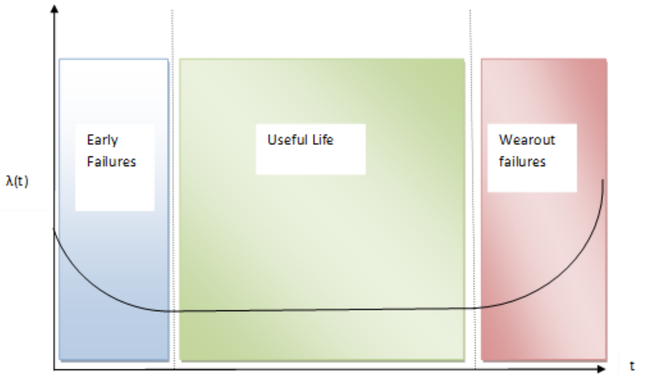

Fig. 4: Bathtub Curve

Some of the methods used in the semiconductor industry to predict reliability are:

- Field failure experience
- Qualification procedure
- Theoretical calculation
- Physics of failure method

Field failure experience:

This method involves collection and analysis of all field failures and also system integration. The advantage of this method is that it gives the best reliability evaluation. The main drawback is the difficulty in collecting data and its integrity (use duration, failure context, quantity of parts used with reliable accuracy). This method may not be suitable for small or medium volume power semiconductor manufacturers as quantities involved may not be statistically significant.

Qualification procedure:

The principle behind this method is to qualify a product based on a test plan according to defined conditions such as international standards and/or some reference test plan. The obvious advantages of this method are having the same evaluation process for all companies in the same industry sector and no additional cost for study (test plan definition). The major disadvantage is that the test plan becomes obsolete when considering new technology. The test plan can be very general and not specifically adapted to the application (constraint choice).

Table 3 shows the standard qualification tests (based mainly on the IEC Standard) adopted by Dynex during the product release stage and the maintenance of the qualified product.

Theoretical calculation:

The traditional method of calculating failure rate uses an accelerated life testing of the device. The method involves testing devices from a random sample obtained from the parent population followed by a stress test, under accelerated conditions, to promote failures. The acceleration factor (AF) thus obtained is then extrapolated to end-use conditions by means of a predetermined statistical model to give an estimate of the failure rate in the field application. For thermally/electrically activated failures, modified Arrhenius equation [1] is used in conjunction with Chi square statistical model equation [2].

$$AF = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right) \times \left(\frac{V_2}{V_1}\right)^{\beta} \qquad [1]$$

$$\lambda = \frac{\chi^2}{2T_D AF} \times 10^9\, FIT \qquad [2]$$

Where:

AF	= acceleration factor	E_a	= activation energy (eV)
T_{use}	= application temperature (°C)	T_{stress}	= stress temperature (°C)
V_1	= application voltage	V_2	= test voltage
λ	= failure rate (FIT)	β	= constant for voltage stress
χ^2	= chi square confidence value	k	= Boltzmann-factor (J/K)
T_D	= Total device hours		

From equation [2], a higher value of device hours (T_D) gives a lower value of failure rate. Hence, in order to accumulate a high number of device hours, large numbers of devices in test are required and/or much longer time for the test. This form of statistical data is acquired over a number of years of regular testing of the product. The unknown parameters in equation [1] are the activation energy E_a and β. E_a is a constant in the Arrhenius equation and is related to the kinetics of the underlying physical process under temperature stress, while β is a constant related to the voltage stress. These constants are experimentally determined.

For cyclic stress, the Coffin Manson equation [3] is used. This model predicts the number of cycles to fail due to thermo-mechanical cyclic stress.

$$N = \left(\frac{A}{\Delta T_{j-c}}\right)^{B} \qquad [3]$$

Where:

N	= number of cycles to fail	A	= fitting parameter
B	= fitting parameter	ΔT_{j-c}	= temperature difference, junction to case

For pressure contact high power devices, the fatigue life depends upon:

- Wafer diameter
- Temperature change
- Device construction
- Mounting force

Somos et al [1] have derived an empirical formula for thermal fatigue based on the Coffin Manson equation, giving rise to the number of cycles to failure N_f.

$$N_f = K \times (300/\Delta T)^9 \qquad [4]$$

Where:

K = constant ∆T = temperature difference

This is visualised in the graph, fig. 5. This graph assumes that the devices are clamped evenly at the recommended force so that the relative expansion takes place radially outwards from the centre. If the device is clamped unevenly, then one point on the circumference of the silicon will be hard clamped and the diametrically opposite point will move twice as far as for the evenly clamped case. Thus, an unevenly clamped 50mm device will follow the curve for a 100mm evenly clamped device.

This type of failure mechanism should be evaluated for slowly cycling thermal loads such as traction locomotives or pulsed power supplies.

To use this graph in practice, temperature variations due to the duty cycle have to be converted into an equivalent number of cycles at a set temperature excursion.

There are several hand-books created to help predict the reliability of electronic components. The Military Hand-Book 217 (MIL HDBK 217F) entitled “Reliability Prediction of Electronic Equipment” is the most popular and well received document. The method given in this handbook to calculate the failure rate λ_p is as follows:

$$\lambda_p = \lambda_b * \pi_t * \pi_r * \pi_s * \pi_q * \pi_e \qquad [5]$$

Where:

λ_p = the specific failure rate

λ_b = base failure rate (0.002)

π_t = temperature factor

π_r = current rating factor

π_s = voltage stress factor

π_q = quality factor

π_e = environmental factor

For modern-day high power semiconductors, this can to be reduced to a function of the temperature and the blocking voltage of the device, i.e. failure rate, λ_p is given by equation [6].

$$\lambda_p = A.T^b \qquad [6]$$

Where A is related to the voltage stress level and b is related to the temperature stress level.

The graph in fig. 6 [2] was developed in the 1960s under US Government sponsorship for the MINUTEMAN intercontinental ballistic missile program. It used a large statistical sample for a high degree of confidence. Although the devices were small compared to today’s high power products, semiconductor manufacturers have verified that this information is still valid for present day use. One investigation of thyristors used in High Voltage DC Transmission (the single largest population of devices in one equipment) indicated actual, in service, failure rates of 0.0057% to 0.029% per thousand hours of operation, which compares very well with the calculations for the device application. Again, to use the graph, the actual duty cycle must be known.

In the past MIL HDBK 217F was updated periodically but recently it has not been and it is now very much outdated.

Physics of failure method

This is a relatively new approach to the design and development of a reliable product to prevent failure, based on the knowledge of root cause failure processes. The concept is based on a good understanding of relationships between the requirements and the physical properties of the product and any variation in the production processes. Also encompassing how the product materials react and interact under the applied stresses at the application conditions and their effect on the reliability. The product is designed with built-in reliability, which is quantified by the physics of failure models for each failure mechanism. Although this method is at infancy stage, it is gaining some popularity.

MISSION PROFILE

Mission profile refers to a set of operational and environmental conditions that are experienced during the operating life of a device. Any of these conditions or combination of these conditions has influence on the failure rate and the wear-out of the device.

An example of a mission profile for a high-speed rail traction application is shown in table 2.

The operating life of a product is determined for the given operational and environmental conditions. Experiment and simulation methods are used to determine this. This method gives a better estimation of the device under the real application conditions.

SUMMARY

The reliability of high power, pressure contact, bipolar devices depends on the construction and the components used, their material properties, and their interactions with external and internal stresses imposed by the operating and environmental conditions. There are several methods available to predict the failure rate of the device, each having its advantages and disadvantages. The physics of failure is an emerging method and will require some time before it is fully accepted. The most meaningful method of predicting reliability is the use of "mission profile".

CONCLUSION

A brief introduction to the concept of reliability related to high power bipolar devices is given. The methods used to quantify reliability are explained. Also, it has been emphasised that the mission profile method gives the best reliability prediction.

Table 2: Typical Mission Profile for rail traction application

Stress condition	Temperature range	Cycles over 30yr life
Overnight shed stop	-40°C to operating temperature	Worst case 10,000
Station stop	Heat-sink to operating temperature	~3.5E5
Traction/braking	Experimentally measured at 30°C	~3.4E7
Power cycling	< 1°C	~7E11

Dynex can provide service to calculate FIT and lifetime for a given customer "mission profile" upon request.

References:

(1) Power Semiconductors Empirical Diagrams Expressing Life as a Function of Temperature Excursion. Istvan Somos, Dante Piccone, Lawrence Willinger & William Tobin. IEEE Transactions on Magnetics, Vol 29, No 1, January 1993.

(2) Power Conversion – Application Handbook. A.C Stevenson private publication 1997.

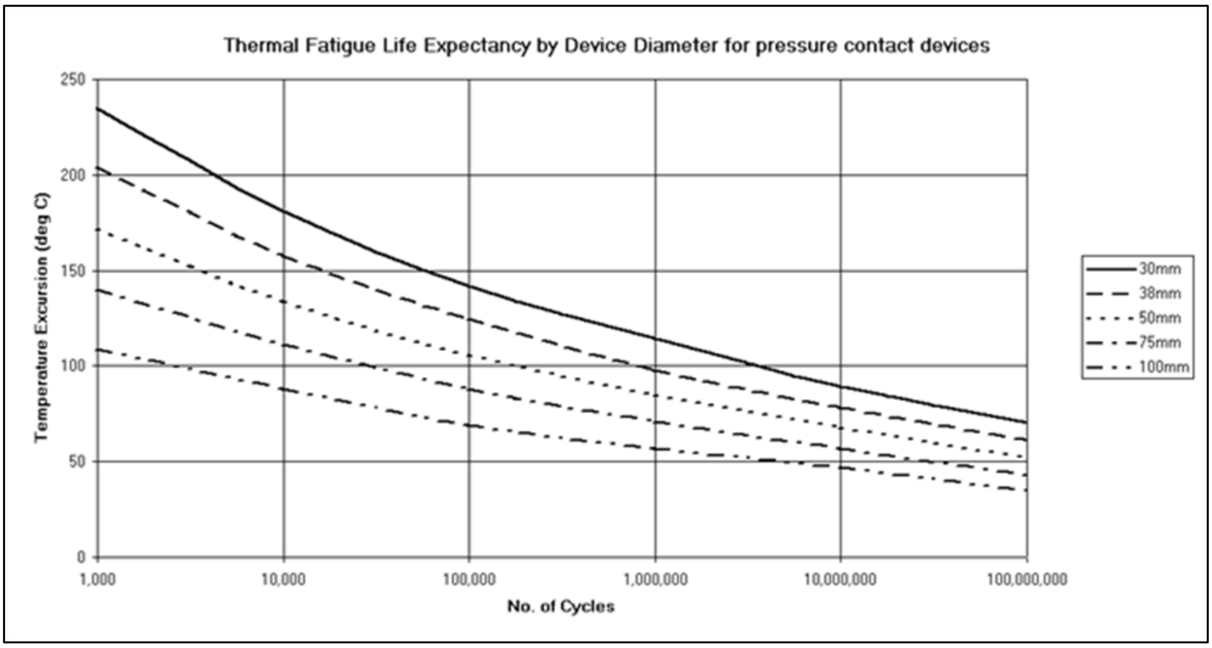

Fig. 5: Thermal fatigue life failure.

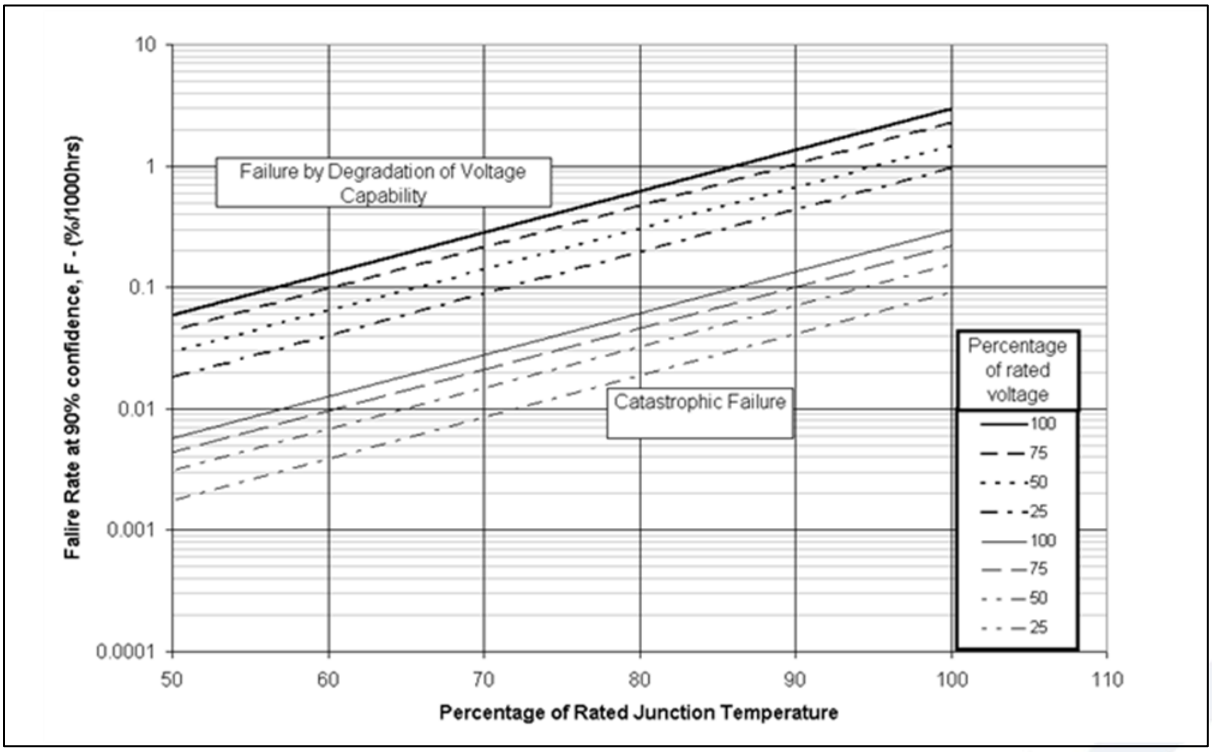

Fig. 6: Voltage failure rate.

Table 3: Qualification Tests for Pressure Contact Bipolar Devices.

	Qualification Test	Test Method	Test Conditions	Qual Standard
Electrical Assessment	High Temperature Blocking Life	IEC60747-2 (Diodes) IEC60747-6 (Thyristors) IEC60749-23	T = Max T_j 90% V_R (Diodes) 80% V_{DRM}/V_{RRM} (Thyristors)	1000 hours
	Thermal Cycling/Power Cycling	IEC60747-2 (Diodes) IEC60747-6 (Thyristors) IEC60749-34	Equivalent to Δ60°C	Equivalent to 175,000 cycles
Environmental Assessment	Temperature Cycling	IEC60068-2-14 Na IEC60749-25	-55°C to 125°C, 2 hours dwell, 2 min transition	5 cycles
	Vibration	IEC60068-2-6 IEC60749-12	f = 50 to 500Hz, a = 10g	2 hours in each of 3 mutually perpendicular axes
	Mechanical Shock	IEC60068-2-27 IEC60749-10	a = 40g, t = 6ms half-sine	5000 shocks
	High Temperature Storage	IEC60068-2-2 IEC60749-6	T = T_{stg} max	1000 hours
	Damp Heat, Steady State	IEC60068-2-78 Cab IEC60749-4	T = 85°C, RH = 85%	168 hours

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