PC and TC Diagrams

About this document

Scope and purpose

This application note replaces AN2010-02, “Use of Power Cycling Curves for IGBT4” [1] and is applicable for the following products: industrial power modules (with/without base plate), Intelligent Power Modules (IPM), and discrete devices.
It provides all required information on the use of Infineon’s power and thermal cycling diagrams and how to apply the rainflow-counting algorithm for proper cycle counting.

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1 Introduction

Different load conditions with varying thermal conditions can lead to different levels of thermal stress in applications using the same type of industrial power module, IPM module, and/or discrete device. Specification is a necessary procedure to warrant the required lifetime of a power semiconductor device. Load-generated stress should not exceed the limits defined by the corresponding diagrams.

There is a distinction between two types of cycling capability, the junction temperature ΔT_{vj}-related power cycling (PC), and the solder joint and case temperature ΔT_C-related thermal cycling (TC).

This application note provides a better understanding of the underlying failure mechanisms, and the corresponding power and thermal cycling diagrams.

In particular, the application note discusses in detail the use of both power and thermal cycling diagrams for industrial power modules.

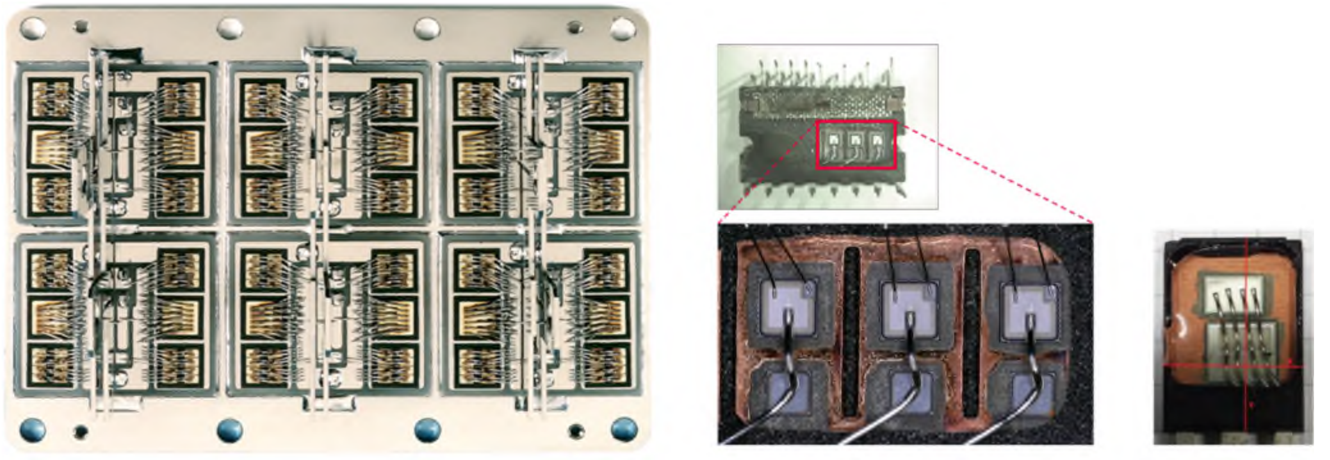
With regard to IPM modules and discrete products, the application note focuses exclusively on the power cycling diagrams. Hence, the thermal cycling information discussed in the document is not applicable for these products.

Therefore, as the application note covers different type of products that differ in construction, current density, size, and semiconductor technology, for example, it is important to use the specific reliability curves for the selected product.

2 Power cycling

Typically, the wire-bonding process is used for the electrical interconnections of the specific products discussed in this document, i.e. industrial power modules, IPMs, and discrete devices, as illustrated in Figure 1.

For instance the IGBT power module sample shown in Figure 1 comprises approximately 450 wires together with 900 wedge bonds. For many years, the reliability of this contact technology had been a concern.



Industrial power module (with base plate) Intelligent power module (IPM) Discrete device

Figure 1 **Internal view of an industrial power module with base plate, intelligent power module (IPM), and co-pack IGBT discrete device (typical appearance)**

Considerable work has been concentrated on accelerated power-cycling tests, analysis of failure mechanisms, and improvements in bonding and die attach technology. Developments in the composition of wire, the shape of bonding tools, bonding parameters, chip metallization, and the mold compound as well as the introduction of improved die attach processes, such as diffusion soldering and sintering, have led to considerable improvements in the reliability and lifetime of the power semiconductor devices.

Power cycling raises and lowers the chip-junction temperature at relatively short intervals in a timeframe of seconds. It mainly puts stress on the bond wires on the silicon chips, and the soldered joints below the silicon chips. The power-cycling capability of power semiconductor devices is dependent on the absolute junction temperature T_{vj}, the temperature swing ΔT_{vj}, the duration t_{cyc} and the on-time t_{on} of the cycle. Typically, as in this case, during the power cycling test the same conditions such as load current and T_{vjmax} are periodically repeated.

In case of products not having the on-time t_{on} PC curve like IPM, the time-dependent PC impact can be omitted for simplification.

2.1 Key definitions and terms

Definition of T_{vj}

The junction temperature T_{vj} is the temperature of the semiconductor junction region. Since the junction temperature can only be determined either by indirect measurement or calculation, it is termed “virtual junction temperature.”

Definition of $T_{vj,max}$

The maximum junction temperature $T_{vj,max}$ is the maximum allowed value for the specific device to be reached during the temperature cycles shown in the power-cycling diagram. The higher the maximum junction temperature $T_{vj,max}$, the higher is the stress on the device, which results in a reduced number of cycles.

Definition of $T_{vj,mean}$

The mean junction temperature $T_{vj,mean}$ is the arithmetic mean value of the minimum and maximum T_{vj} during the power cycling test, i.e. $T_{vj,mean} = 0.5 * (T_{vj,min} + T_{vj,max})$.

Definition of t_{off}

The time t_{off} is the period without load. It is adjusted so that the temperature T_j drops down to the level needed to achieve the desired ΔT_j. The typical t_{off} time is in the same range as the heating time t_{on}.

Definition of t_{on}

The turn-on time t_{on} is the period during which power losses are generated in the device, resulting in a steady temperature rise of T_{vj} e.g. during the acceleration phase of a motor drive. The longer the turn-on period, the higher the temperature rise and the corresponding stress to the device, which results in a reduced number of cycles during lifetime. This can be explained by the viscoplastic deformation energy in the material layers that undergo thermomechanical cycling for longer turn-on periods. For instance, for industrial power modules, a typical t_{on} time for the short cycle PCsec test is 1.5 s.

Definition of t_{cyc}

The time t_{cyc} is the period of one power cycle of $t_{on} + t_{off}$. For industrial power modules, a typical t_{cyc} time for short-cycle PCsec tests is 3 s.

The following Figure 2 shows an example of a power-cycling diagram. It displays the achievable stress (= number of temperature cycles) vs. temperature swing during the lifetime of the bond contacts described above. The junction temperature, which can be measured either under lab conditions or simulated under application conditions, is used as a measure.

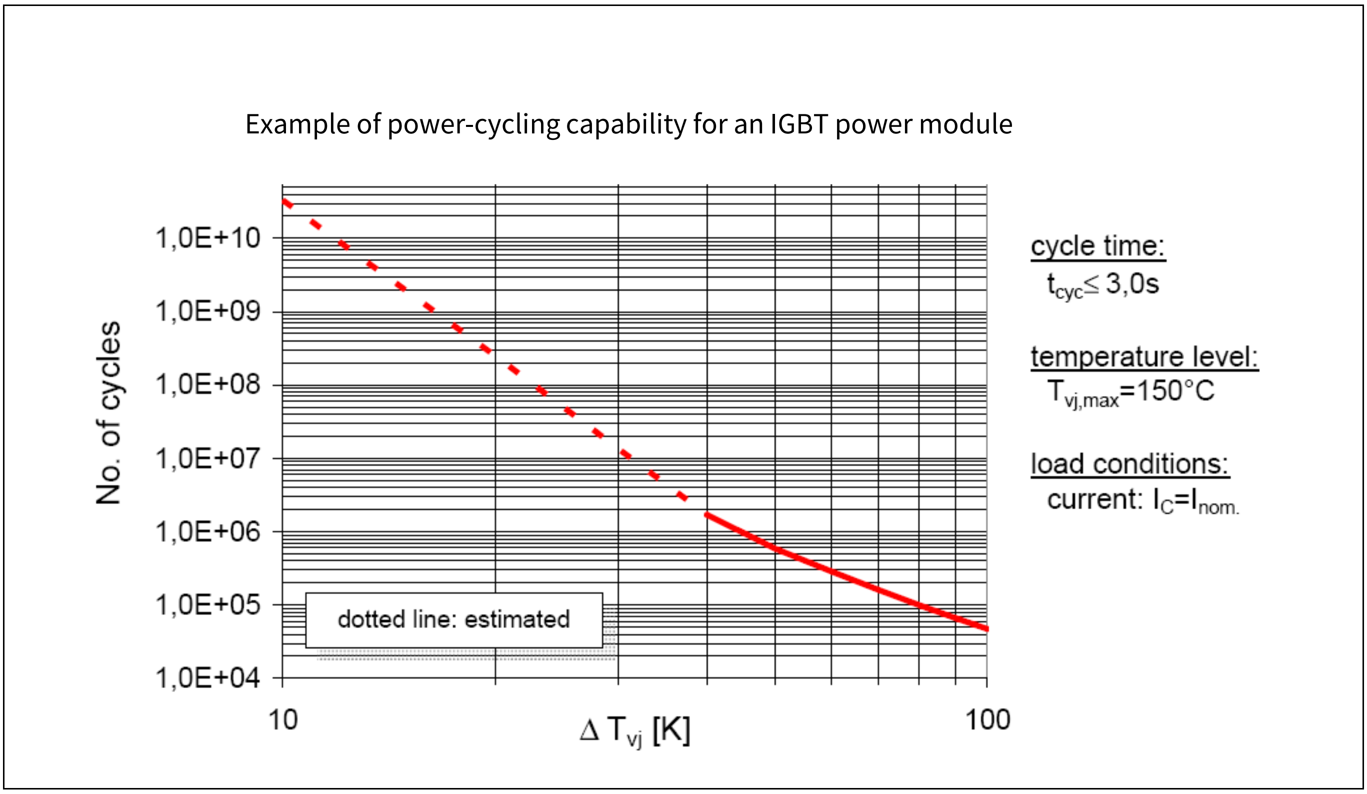


Figure 2 **This diagram depicts an example of the number of cycles versus the junction temperature rise for power-cycling stress at maximum junction temperature**

For a repetitive junction temperature swing of e.g. ΔT_j=60 K, we can read from the diagram that the device can withstand 300,000 cycles. For a correct interpretation of such diagrams from different manufacturers, it is important to know the underlying conditions.

Definition of I_{nom}

In the case of discrete devices, the current through the device has a significant impact on the power-cycling test. Hence, an additional power-cycling diagram is provided as a function of nominal current, I_{nom}. The nominal current is the amplitude value of the current through the device during the t_{on} period in the power-cycling test.

Furthermore, the nominal current corresponds to the chosen current by design for device characterization. It serves as a reference for specifying main electrical parameters in the data sheet such as V_{CEsat} and safe operating area (SOA) for IGBT devices and $R_{DS(on)}$ for MOSFET devices. Very often, in the case of IGBT devices, the nominal current value is included in the name of the product and specified as the DC collector current parameter at T_C = 100°C in data sheets as well.

Note that for co-pack IGBT discrete devices (IGBT and diode die in the same package, similar to the sample shown in Figure 1.) the nominal current I_{nom} for the diode is the same one as the IGBT regardless of the diode current rating.

In order to find the corresponding power-cycling diagram the applicable nominal current I_{nom} is equal to the RMS current through the device.

What is the **failure criterion**?

Infineon uses an increase of the R_{th} by 20% or an increase of the on-state voltage by 5% as a failure indicator. With this, the parameters of a "failed" device are still within the limits of the data sheet for products with a 0h value close to the typical value.

What is the **temperature level** for which the curve is valid?

Infineon shows "worst-case" curves, assuming that every temperature swing reaches the maximum allowed junction temperature T_{jmax}.

What is the **failure rate**?

The failure rate is the probability with which devices in the field will show any failure according to the above criterion. Typically, Infineon uses a failure rate of 5% for determining the PC curves. However, in the case of discrete devices, there are PC curves released showing 1%, 5% and 10% failure probabilities.

What are the **cycle times** which should be considered relevant for PC?

Specifically for industrial power modules, the tests at Infineon are performed with cycle times of $t_{on} + t_{off} = 3$ s. Infineon's investigation cover t_{on} times from 0.1s ... 60s. For this regime, a typical dependency can be given as shown in Figure 3. As an approximation, the derating factors reached at the limits of the 0.1 … 60s interval should be used also for t_{cyc} extending the regime. For shorter cycles this would be regarded as a conservative approach; for longer cycles, the approximation is based on the assumption that viscoplastic deformation saturates for t > 60 s.

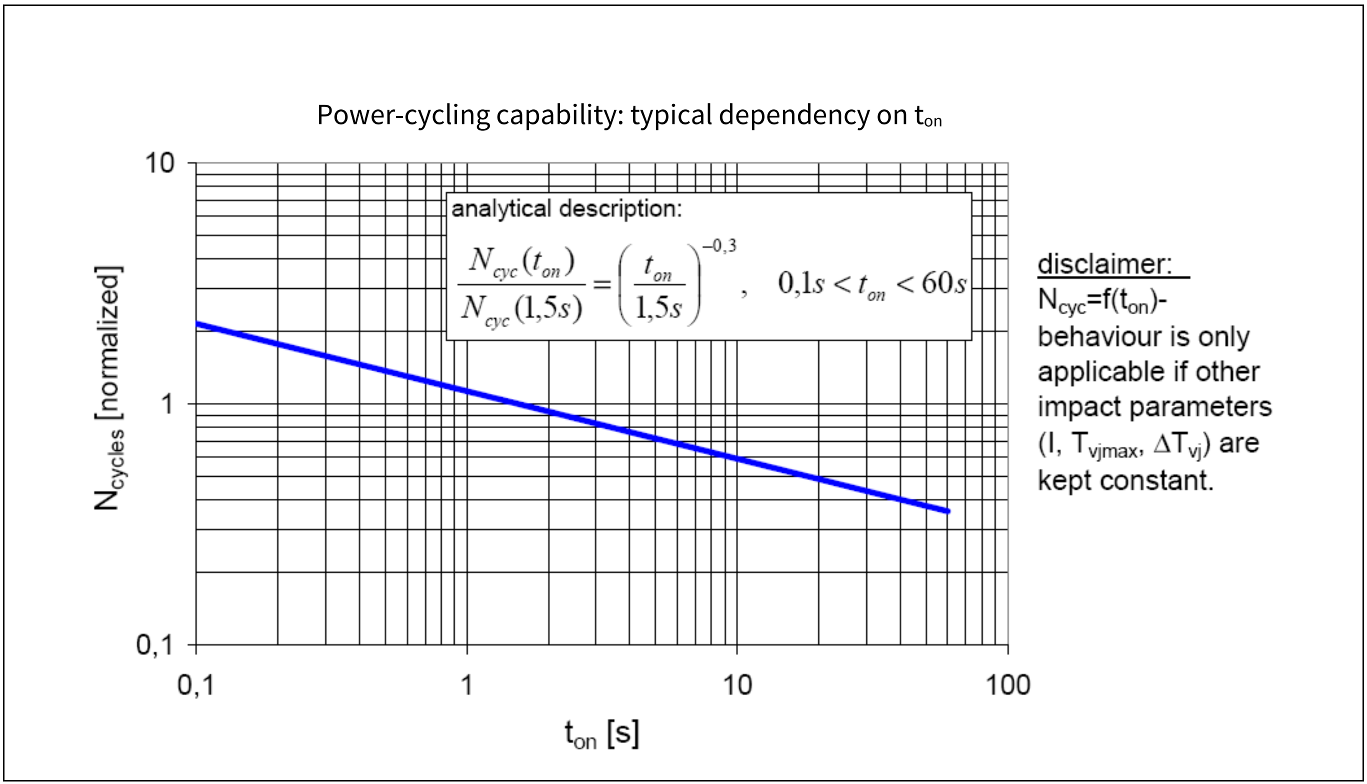


Figure 3 This diagram depicts the typical dependency of the cycling capability on the turn-on time t_{on} for IGBT4 industrial power modules

Power-cycling diagrams from competitors might depict higher number of cycles without naming the "disguised" conditions and applied failure criterias. This is a common practice and may therefore not allow a direct comparison. Ways to virtually "improve" test results and the corresponding reliability diagrams:

- raise the failure criterion to the level of real malfunction
- show diagrams with higher failure rate
- use lower temperature levels for T_{jmax}
- test single chips instead of complete modules to avoid inhomogeneity, which is unavoidable in multi-chip modules
- apply a test strategy that controls losses or heating time t_{on} to keep ΔT_j constant, whereas in a real application, losses and t_{on} remain constant and ΔT_j is allowed to rise as a consequence of R_{th} degradation
- reduce the stress on the bond connections by partly generating heat by switching losses. As a result, the same losses (temperature swings) can be generated at the same time by lower current loads, and therefore lower the stress to the bonds

2.2 Application examples

The following examples illustrate how to use the power-cycling diagrams to define the number of power cycles capability of a device in typical application conditions. The method used for finding the power-cycling capability in each example is applicable for any of the products discussed, i.e. Industrial power modules, IPM's, and discrete devices.

Example 1

An industrial power module is used in a motor drive inverter with an intermittent operation, a turn-on period of 10 s and a cycle time of 60 s. The load leads to a junction temperature rise from 85°C to 125°C in the IGBT. This means a repetitive junction temperature swing of ΔT_{vj}=40 K.

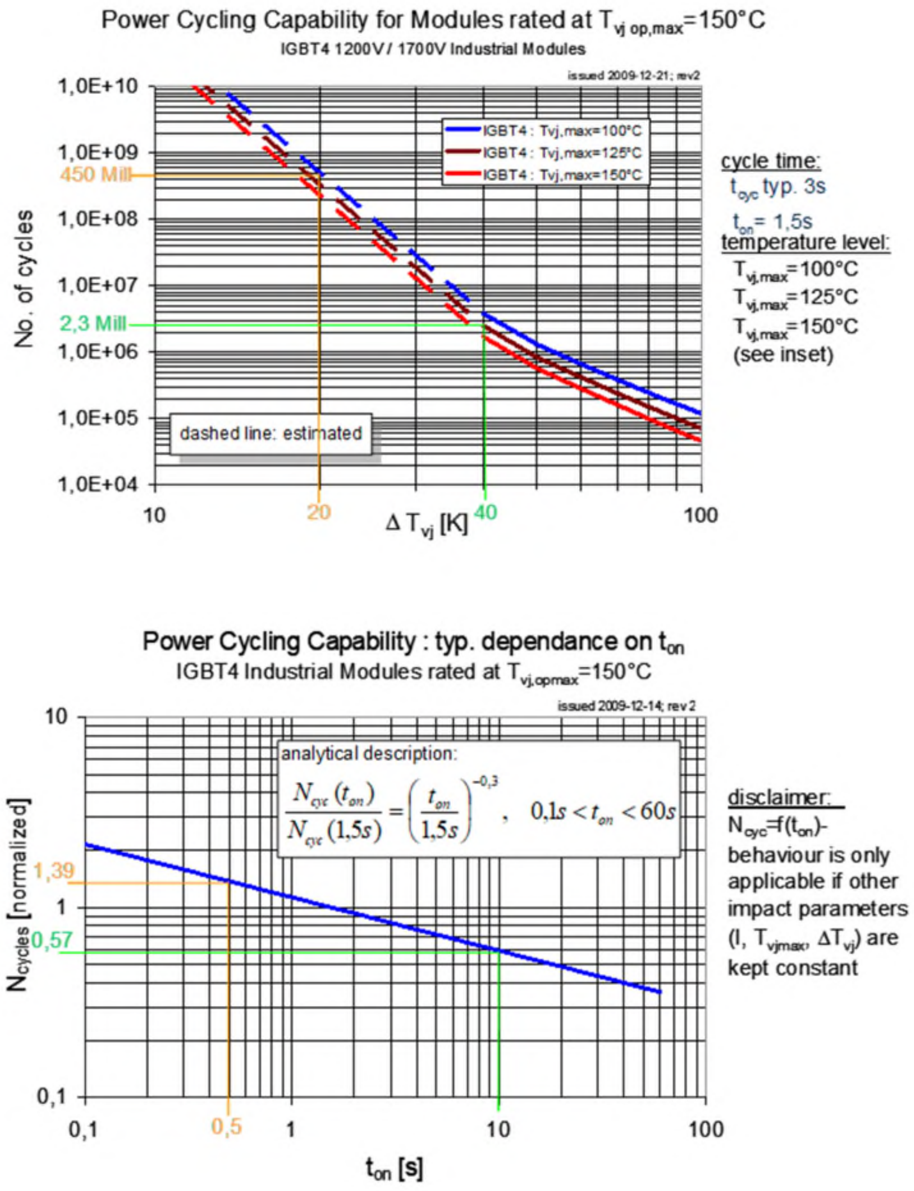


Figure 4 **Example of the reliability specifications for IGBT 4 industrial power modules**

As seen in the first diagram, one obtains 2.3 million cycles at ΔT_{vj}=40 K and T_{vjmax}=125°C. Due to the on-time of t_{on}=10 s, the value has to be multiplied with a correction factor of 0.57 from the second diagram. This finally results in a lifetime of 1.3 million power cycles. At continuous operation with a cycle time of 60 s, a lifetime of 21,600 operation hours can be expected under these application conditions.

Example 2

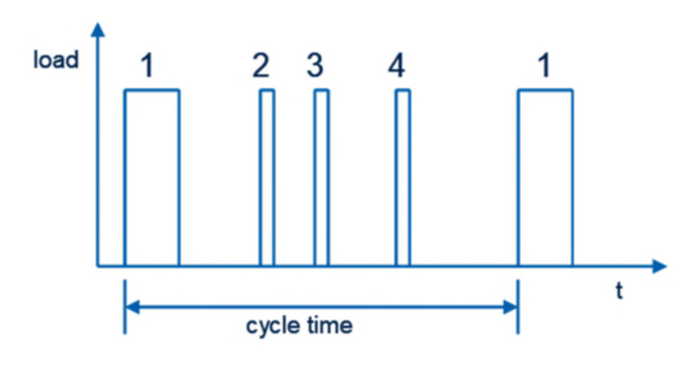


Figure 5 Example of a load train with pulses of different lengths

The same industrial power module as in the previous example is used in a motor drive inverter with intermittent operation and varying loadd per cycle. The first turn-on period of 10 s leads to a junction temperature rise from e.g. 85°C to 125°C in the IGBT. The following three turn-on periods of 0.5 s each lead to junction temperature rises from 85°C to 105°C in the IGBT. The “off” period between each load period exceeds 2 s. The cycle time of this load train is 60 s.

This results in a junction temperature swing of ΔT_{vj}=40 K for the first pulse and 3 times a swing of ΔT_{vj}=20 K per cycle. The upper diagram in Figure 4 shows 2.3 million cycles at ΔT_{vj}=40 K and T_{vjmax}=125°C. Due to the turn-on period of t_{on}=10 s, the value has to be multiplied with a correction factor of 0.57 from the bottom diagram in Figure 4. This results in a lifetime of 1.3 million power cycles.

So far, this is the same result as in example 1. But further load periods have to be considered as well. In the PC diagram, there are 450 million cycles for ΔT_{vj}=20 K. With a load period of t_{on}=0.5 s, the value has to be multiplied with a correction factor of 1.39. This results in an estimated lifetime of 626 million pulses.

Each single load pulse consumes a lifetime. The total number of achievable cycles for this load train of four pulses per cycle has to be calculated using the following formula:

$$N_{cycle} = \frac{1}{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \frac{1}{N_4}}$$

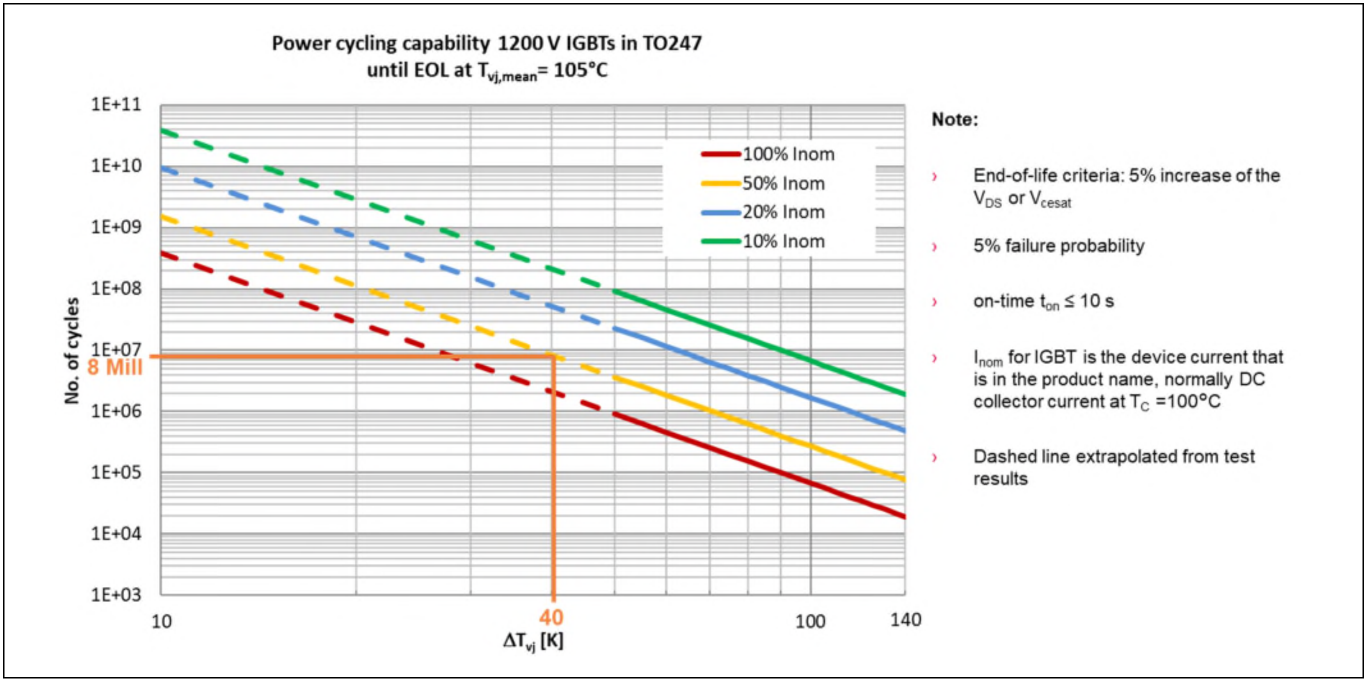
With the derived values above, this results in an estimated lifetime of

$$N_{cycle} = \frac{1}{\frac{1}{1{,}3} + \frac{1}{626} + \frac{1}{626} + \frac{1}{626}} = 1.294\,mio\ cycles$$

At continuous operation with a cycle time of 60 s, a lifetime of 21,560 operation hours can be expected for this application. It can be seen that 99.4% of the total lifetime is used up by the high temperature swing of the first load, and only 0.6% by the three subsequent load periods with lower temperature swings.

Example 3

A 50 A rated IGBT discrete, IKQ50N120CH3 is conducting 25 A RMS in a servomotor drive inverter. The turn-on time operation, t_{on} is 1 s and the time t_{off} is 9 s, i.e. 10 s cycle time operation. During the drive inverter operation, the IGBT junction temperature rises from 85°C to 125°C. This means a repetitive junction temperature swing of $\Delta T_{vj} = 40$ K and a temperature $T_{vj,mean} = 105$°C.



Note:

- End-of-life criteria: 5% increase of the V_{DS} or V_{cesat}
- 5% failure probability
- on-time $t_{on} \leq 10$ s
- I_{nom} for IGBT is the device current that is in the product name, normally DC collector current at T_C =100°C
- Dashed line extrapolated from test results

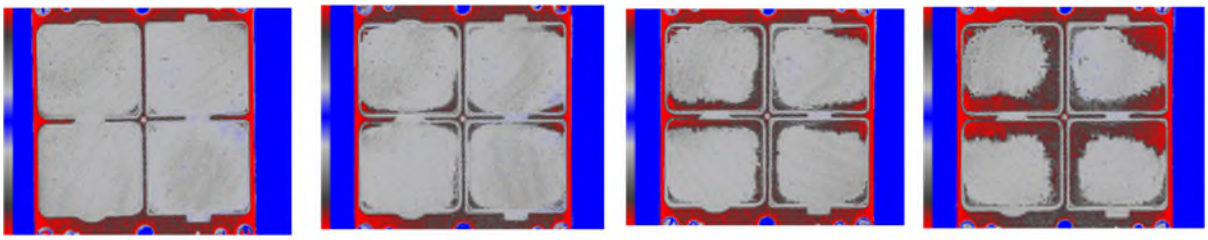
Figure 6 **Example of IGBT discrete device PC capability using nominal current I_{nom}**

First, checking the data sheet of IKQ50N120CH3 IGBT [2] and the I_{nom} definition, it is confirmed $I_{nom} = 50$ A. Following the same process as the previous examples, and using the trend line information for 50% I_{nom}, the power-cycling capability resulted in 8 million cycles at $\Delta T_{vj} = 40$ K and $T_{vj,mean} = 105$°C.

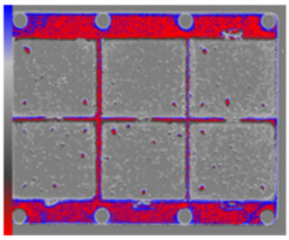
3 Thermal cycling

The use of copper as base plate material is common for its well-known advantages with regard to easy mechanical handling and high thermal conductivity. A disadvantage is the mismatch of the coefficient of thermal expansion (CTE) to the ceramic substrates. Different CTEs of the materials, together with thermal stress, generate mechanical strain on the solder. Repetitive, heavy load cycles will create solder cracks, and therefore an increase of the thermal impedance between chip and base plate.

A relatively stiff material such as AlSiC, with its low deviation of the CTE to the substrate ceramic, solve the described problem. Furthermore, the diminished bimetallic effect results in a well-balanced contact surface to the heat sink. The most outstanding advantage can be seen in the gain of reliability. At highly accelerated cycling tests at $\Delta T_c = 80$ K, the solder layer between the copper base plate and ceramic shows severe delamination at the edges of the substrate after some few thousand cycles, while modules with AlSiC base plates exceed this value by far.



200 cycles (Cu) 1000 cycles (Cu) 2000 cycles (Cu) 4000 cycles (Cu)



20 000 cycles (AlSiC)

Figure 7 **Comparison of TC with copper (top) and AlSiC (bottom) showing a stable thermal interface by use of AlSiC base plate**

Thermal cycling raises and lowers the case temperature at relatively long intervals in a time frame of minutes. It mainly puts stress on the soldered joints between DCB substrate and module baseplate.

Figure 7 shows examples of thermal-cycling diagrams, which provide information on achievable stress (= number of temperature cycles) vs. temperature swing during the lifetime of the solder joint described above. The case temperature of the presumably hottest chip position, which can be either measured in the base plate under lab conditions or simulated under application conditions, is used as a measure.

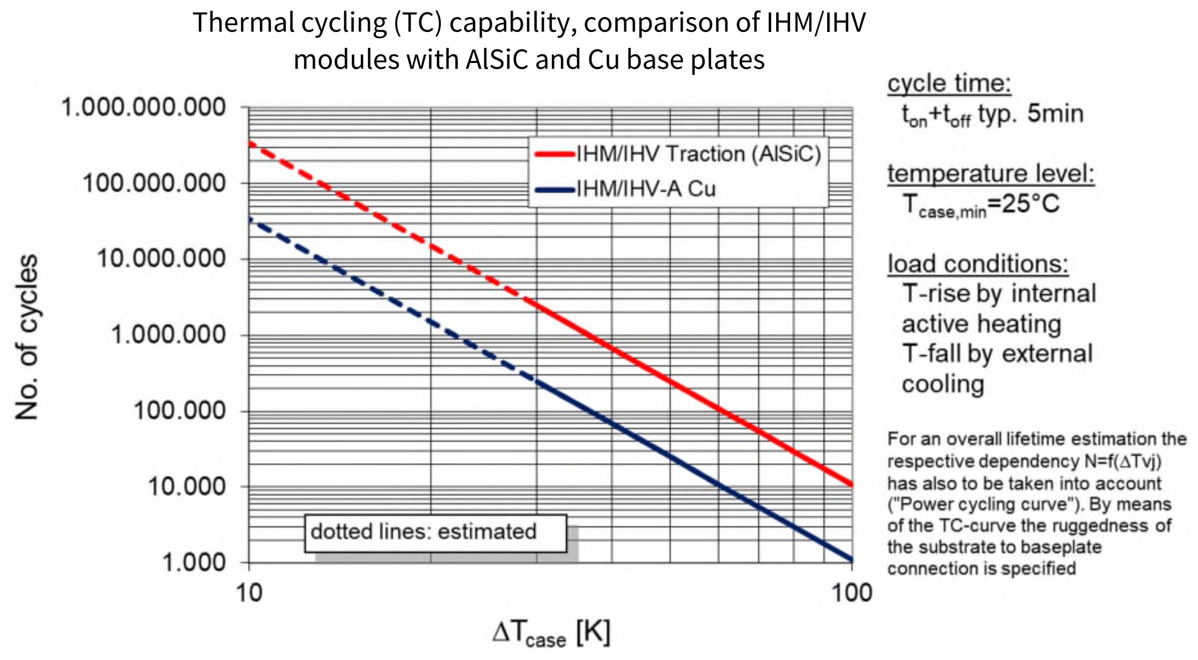


Figure 8 **Example for thermal-cycling capability of industrial modules with Cu base plate and traction modules with AlSiC base plate versus the case temperature rise at a fixed minimum case temperature**

Corresponding diagrams for other Cu module types like PrimePACK™ or or EconoPACK™ are available on request.

With a repetitive case temperature swing of e.g. ΔT_c=80 K, an IHM-A device with copper base plate can withstand 3,000 cycles, while the corresponding AlSiC device is specified for 30,000 cycles.

Again, for judging or comparing such diagrams, it is important to know their underlying conditions.

The **cycle times,** which can be considered relevant for TC, are in the time frame of several minutes. Shorter temperature fluctuations in a time frame of just seconds do not activate the solder joint-related failure mechanism, and can be neglected in the considerations.

The TC curve is not applicable for IPM products; for lifetime calculations only the PC curve needs to be used.

4 Rainflow-counting algorithm for calculating lifetimes

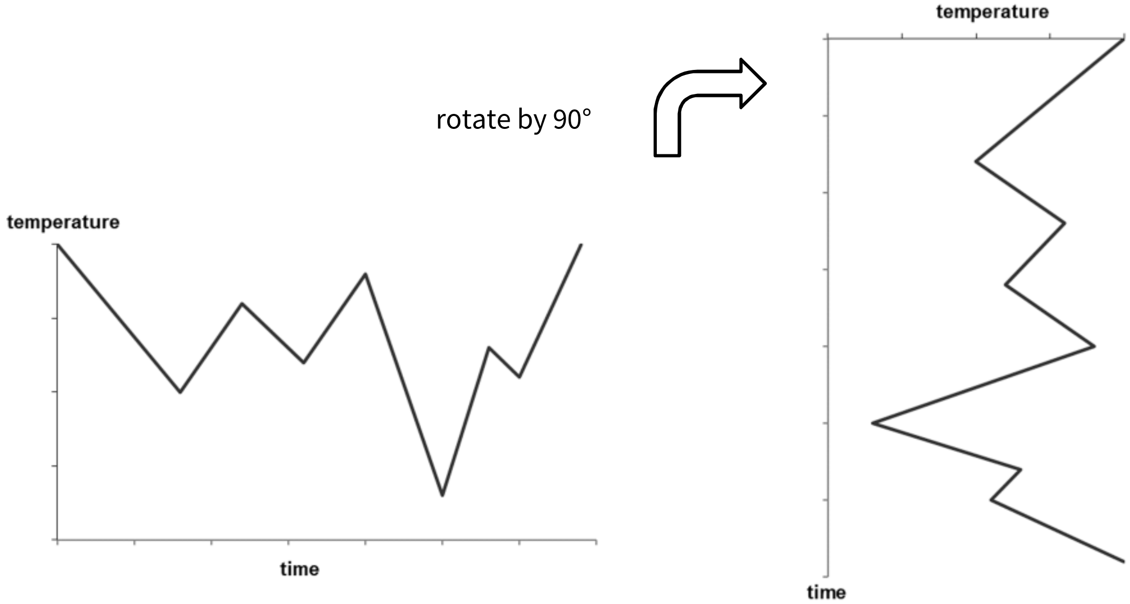
To determine the expected lifetime of an application, it is necessary to sum up the number of temperature cycles within the scope of the junction temperature $T_{vj}(t)$ to check the power cycling, or in the scope of the case temperature $T_c(t)$ to check the thermal cycling.

For this the load-cycle calculation function of the Infineon IPOSIM tool is available on the internet.

For load cycles with a complex, varying temperature profile, the rainflow-counting algorithm is used in the analysis of fatigue data in order to reduce the spectrum of varying stress into a set of simple cycle numbers. With these numbers, the fatigue life can simply be calculated from the cycling diagrams as described previously.

The approach of the rainflow algorithm is as follows: reduce the time history to a sequence of tensile peaks and compressive troughs.

For this, turn the temperature cycle clockwise 90°:



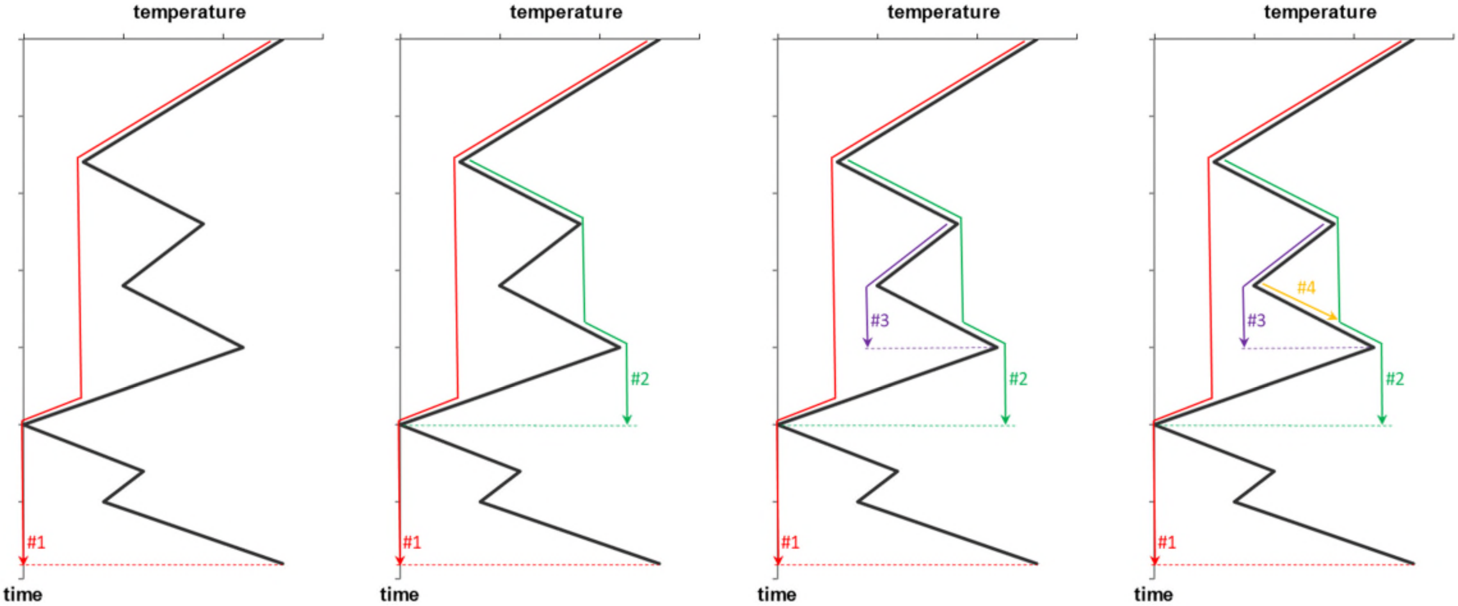
Each peak is imagined as a source of water that drips down. Let “drops” start from each maximum and minimum, and stop if the flow terminates, when the “drop” …

- starts from a minimum and reaches a maximum, which is equal or higher than the one passed before
- starts from a minimum and passes a minimum, which is equal or lower than the starting point
- starts from a maximum and reaches a minimum, which is equal or lower than the one passed before
- starts from a maximum and passes a maximum, which is equal or higher than the starting point
- reaches the run of another drop / merges with a flow that started at an earlier peak
- reaches the end of the time history or “falls out”

Record the number of half-cycles and their magnitude (the difference between start and termination point).

Example (t_{ON} time curve for simplification is not applied)

We analyze the cycle here by means of the rainflow approach.

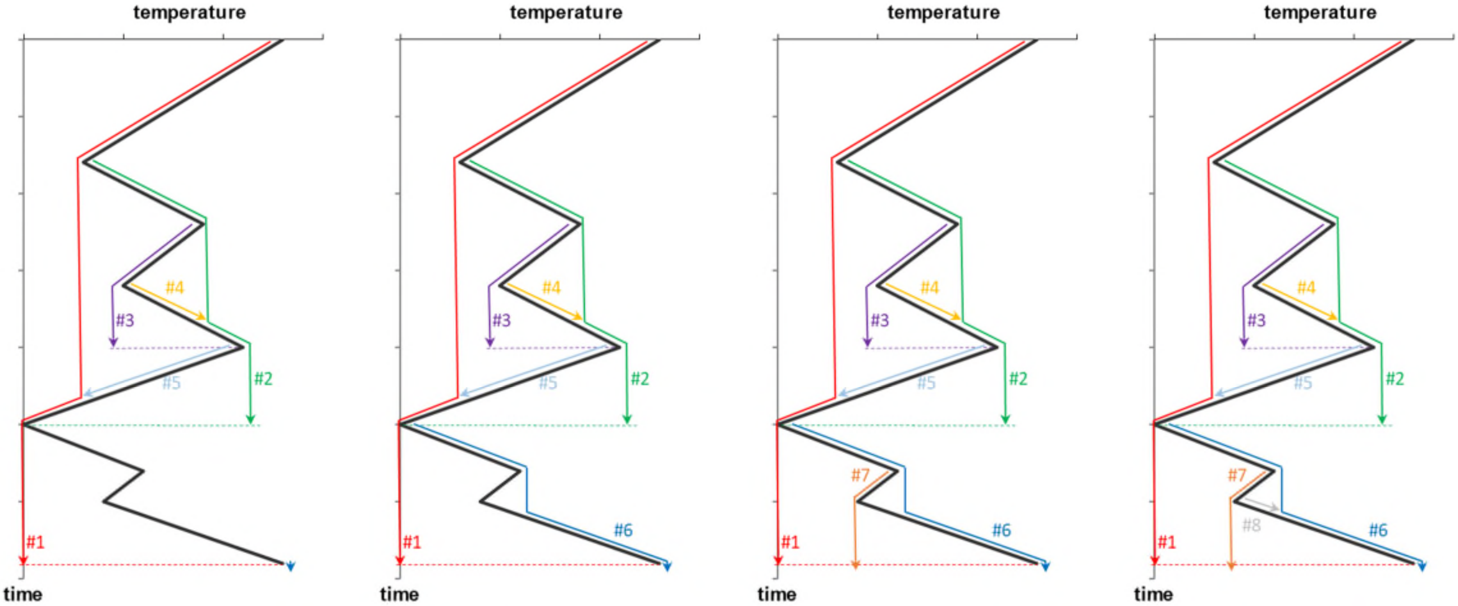


#1 reaches a minimum, which is lower than the previous one

#2 reaches a maximum, which is higher than the previous one

#3 passes a maximum, which is higher than the starting point

#4 reaches the run of drop 2



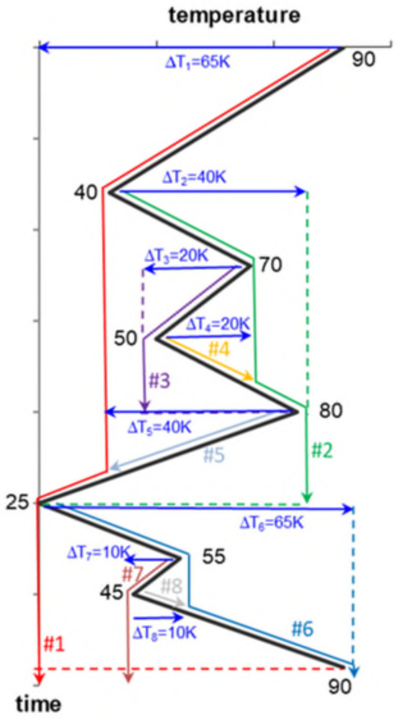
#5 reaches the run of drop 1

#6 “falls out“

#7 “falls out“

#8 reaches the run of drop 6

Now we sum up half-cycles of identical magnitude, but in the opposite sense, to count the number of complete cycles.



number of ΔT´s:

2x 65 K

2x 40 K

2x 20 K

2x 10 K

The raindrop counting method always generates pairs of identical temperature cycles. It emphasizes the large temperature fluctuations more than the simple approach.

The rule, sometimes called Miner's damage hypothesis, states that if there are *k* different stress magnitudes in a spectrum, each contributing n_i cycles, then if N_i is the number of cycles to failure of a constant stress, a failure occurs when $\sum_{i=1}^{k}\frac{n_i}{N_i}=C$ with *C* assumed to be 1.

In practice, you usually calculate the lifetime consumption from the cycling diagram for each pair of up and down temperature swings ΔT, and sum up the individual results.

The load cycle analyzed previously should be performed 25,000 times during a lifetime.

The thermal cycling diagram in Figure 7 allows for 75,000 cycles @ 65 K or 650,000 cycles @ 40 K during a lifetime.

The resulting lifetime consumption is 25,000/75,000 = 33.3% by the 65 K cycles and 25,000/650,000 = 3.8% by the 40 K cycles.

In total, 37% of the available lifetime will be consumed by the investigated load cycle. The contribution of the 20 and 10 K cycles are negligeable.

5 References

[1] AN2010-02 Use of Power Cycling Curves for IGBT4

[2] IKQ50N120CH3 IGBT data sheet, https://www.infineon.com/dgdl/Infineon-IKQ50N120CH3-Data sheet-v02_04-EN.pdf?fileId=5546d4625bd71aa0015bd817b0150536

[3] K.Mainka, M. Thoben, O.Schilling: „Lifetime calculation for power modules, application and theory of models and counting methods“. EPE 2011

Revision History

Major changes since the last revision

Page or reference	Description of change
Chapter 1 & 2	Intelligent power modules (IPM) and discrete devices added

The cycling diagrams shown above are the result of an extrapolation based on Infineon’s current tests and simulations, or on tests done in cooperation with external partners who are highly competent in the field of power cycling. Such information is provided as a guideline for the implementation of the Infineon products in question. Product-life calculations and estimates are to be verified by Infineon’s customers before implementation of the relevant Infineon products, as actual operating conditions and environmental factors may differ from Infineon’s assumptions. Therefore, Infineon is not responsible for the correctness of the lifetime calculations or estimates based on these cycling diagrams. Please note that the technical specifications of Infineon’s products are conclusively determined in the respective Infineon data sheets. Please contact your sales partner for Infineon products if you require further information.

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Edition 2021-02-1919
Published by
Infineon Technologies AG
81726 Munich, Germany

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AN2019-05

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