PC and TC Diagrams

About this document

Scope and purpose

This application note replaces AN2010-02 “Use of Power Cycling Curves for IGBT4” [1].
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

In applications, various load conditions with different thermal conditions could lead to different thermal stress for the same type of module. Considering its reliability, specification is a necessary procedure to warrant the required lifetime of a power electronic device. The 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 shall provide a better understanding of the underlying failure mechanisms, and the corresponding power and thermal cycling diagrams.

2 Power cycling

An IGBT module as 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.

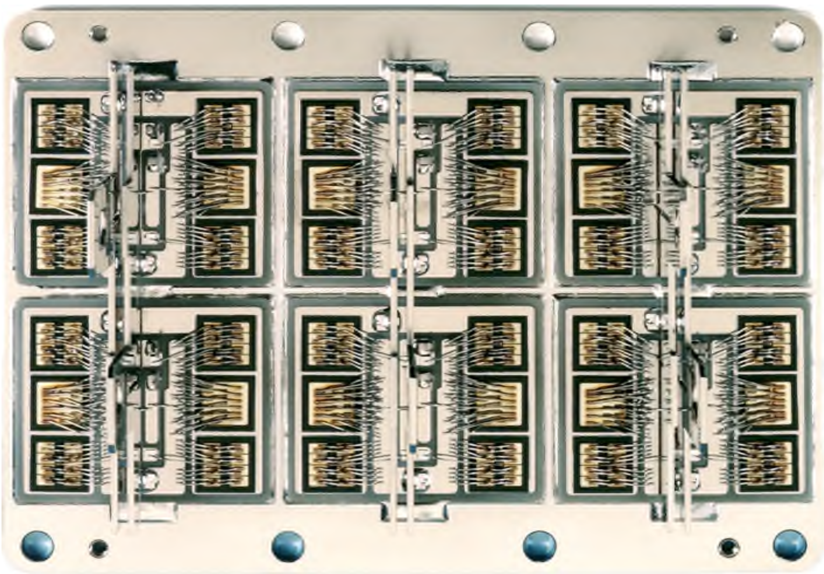


Figure 1 Internal view of a power module (typical appearance)

Considerable work has been concentrated on accelerated power-cycling tests, analysis of failure mechanisms, and improvements in bonding and die attach technology. Developments on the composition of wires, shape of the bonding tools, the bonding parameters, the chip metallization as well as the introduction of sintering have led to considerable improvements in the module reliability and lifetime.

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 modules 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. During the power cycling test, the same conditions such as load current, T_{vjmax} are periodically repeated.

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_{vjmax}

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

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 of 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 visco-plastic deformation energy in the material layers that undergo thermomechanical cycling for longer turn-on periods. 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}. A typical t_{cyc} time for short cycle PCsec tests is 3 s.

The following figure 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 either measured under lab conditions or simulated under application conditions, is used as a measure.

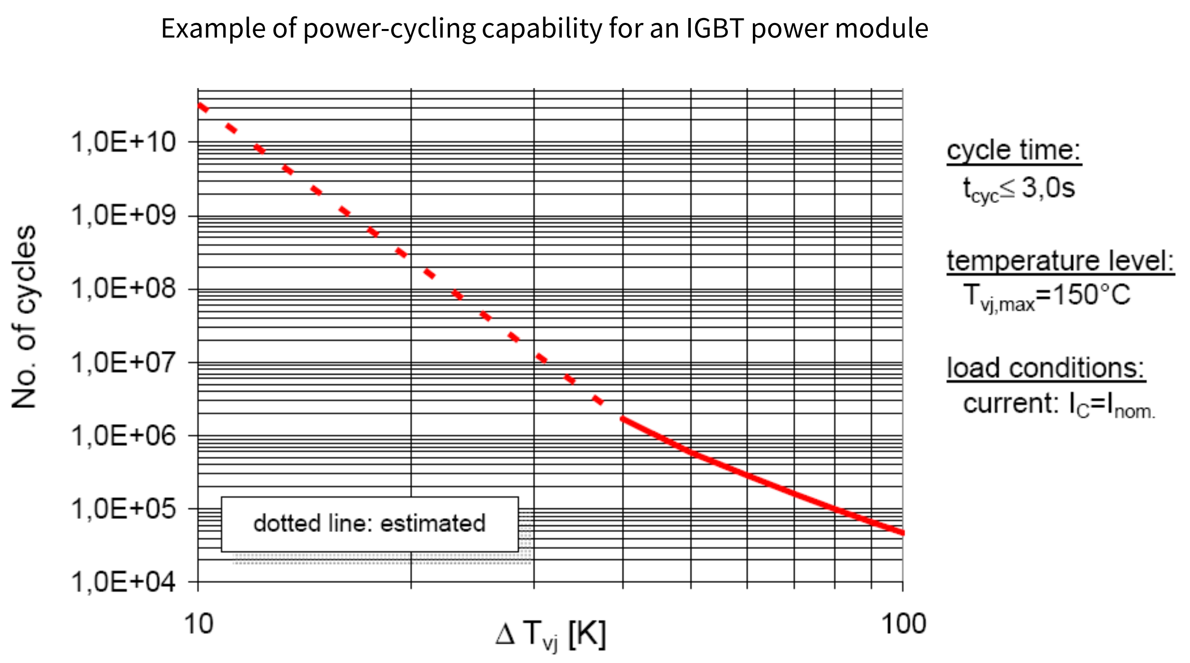


Figure 2 **This diagram depicts an example of the number of cycles versus the junction temperature rise for power-cycling stress at maximum junction temperature**

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 their underlying conditions.

What is the **failure criterion**?

Infineon uses an increase of the Rth by 20% or an increase of the on-state voltage by 5% as a failure indicator. With this, the parameters of a "failed" module are still within the limits of the data sheet for products with a 0h value close to the tyical 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 modules in the field will show any failure according to the above criterion. Infineon uses a failure rate of 5% for determination of the PC curves.

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

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 issued as shown in Figure 3. As an approxmation 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.

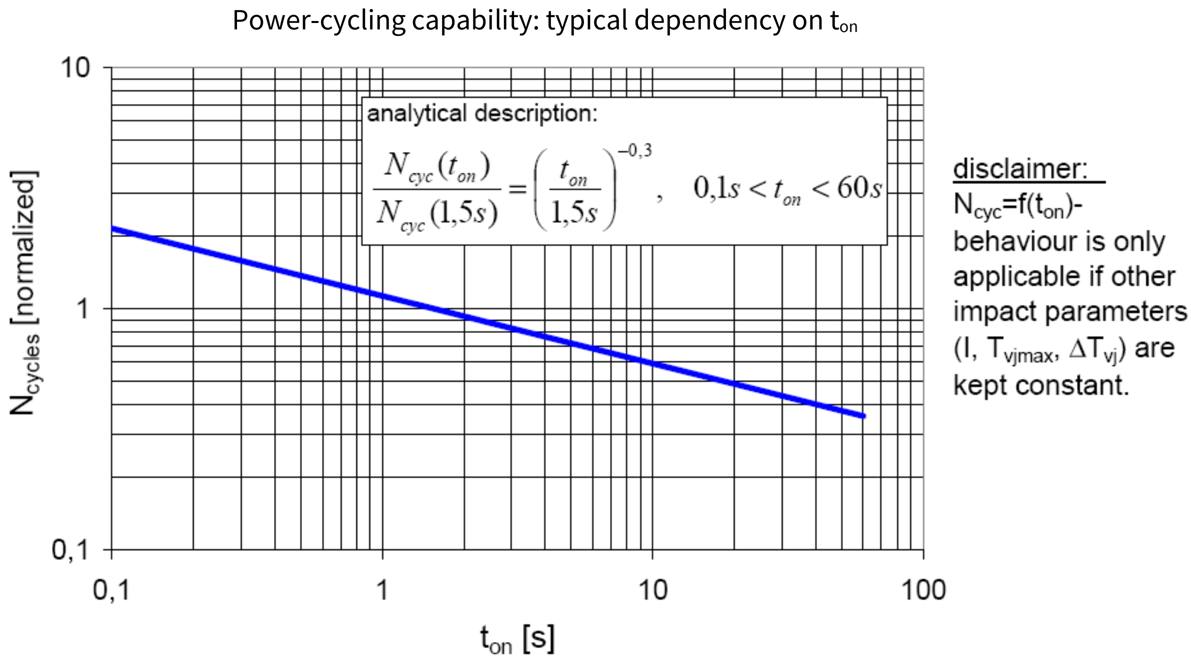


Figure 3 **This diagram depicts the typical dependency of the cycling capability on the turn-on time t_{on} for IGBT4 modules**

Power-cycling diagrams from competitors might depict higher number of cycles but without the concealing conditions and the applied failure criterias. This is a common practice, and may therefore prohibit 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 a 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

2.1 Application examples

Example 1

A 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.

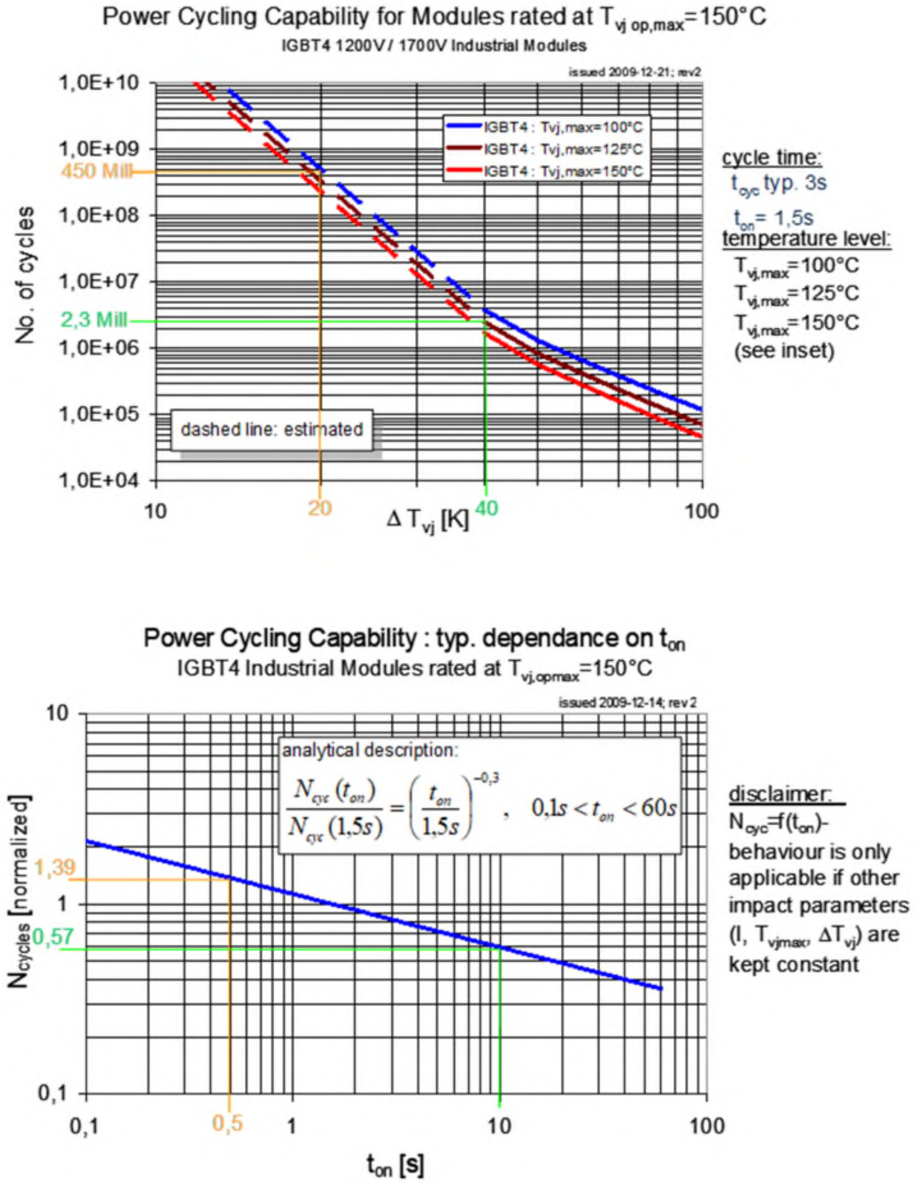


Figure 4 Example of the reliability specifications for IGBT 4 industrial modules

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

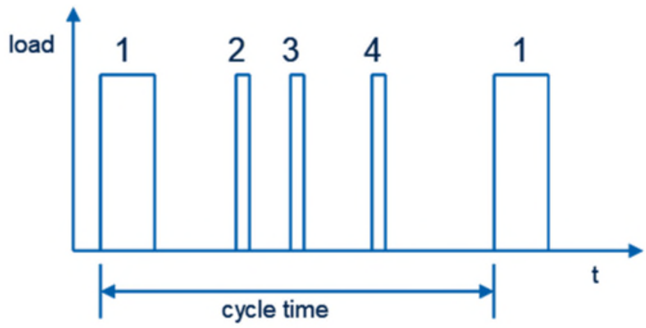


Figure 5 Example of a load train with pulses of different lengths

The same module as in the previous example is used in a motor drive inverter with intermittent operation and varying load 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.

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. Disadvantageous 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 ΔT_c = 80 K, the solder layer between 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.

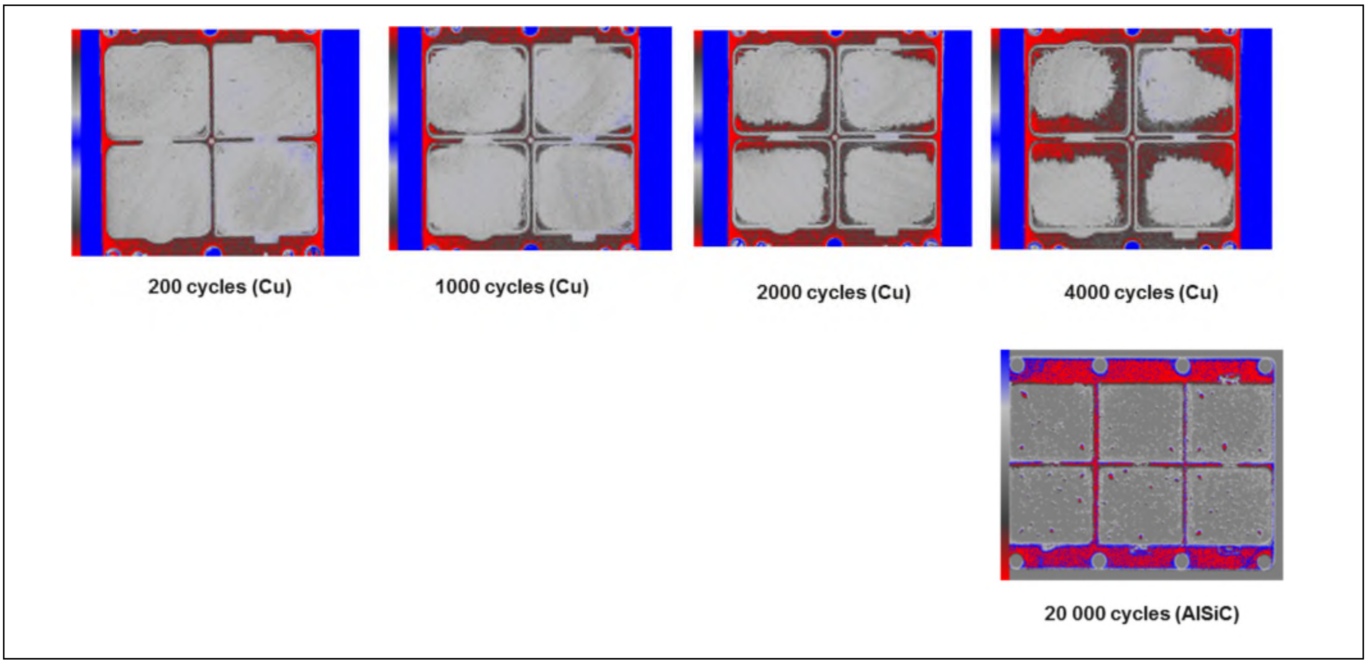


Figure 6 Comparison of TC with copper (top) and AlSiC (bottom) showing a stable thermal interface by use of AlSiC base plate

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.

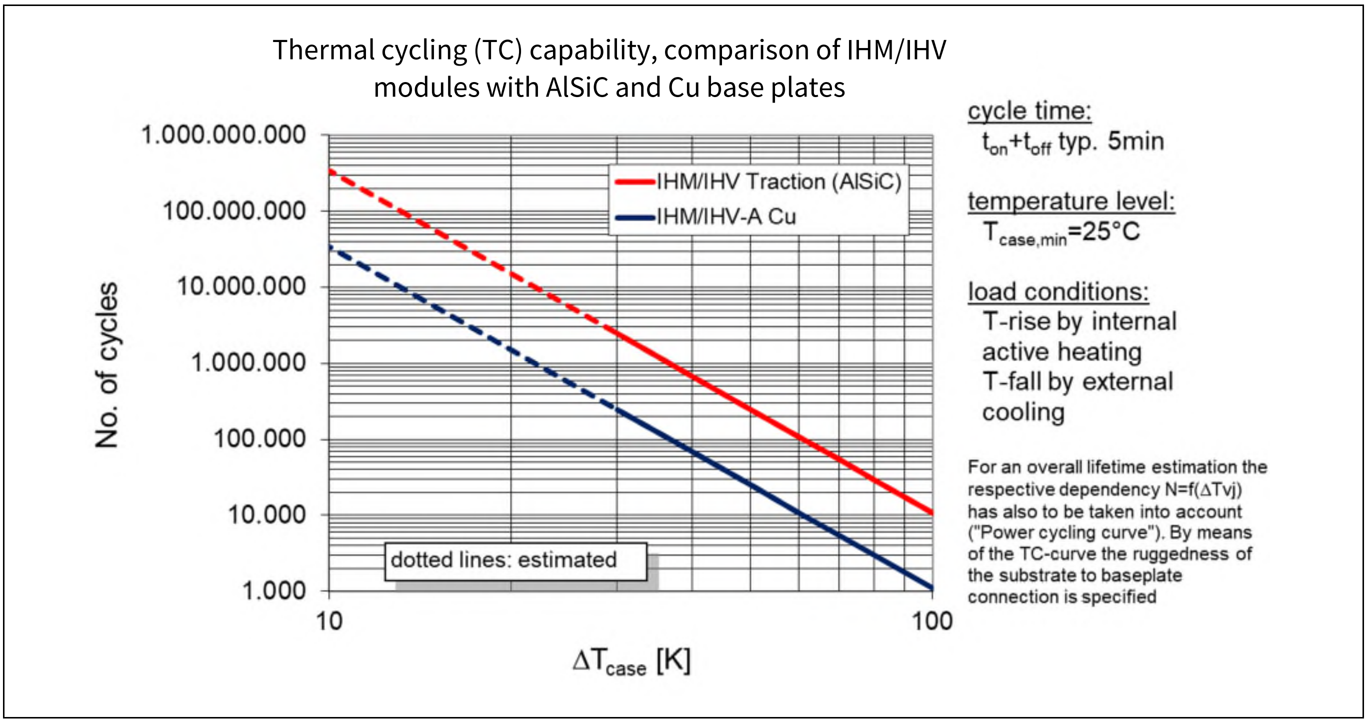


Figure 7 Example for thermal cycling capability of industrial modules with Cu base plate and traction modules with AlSiC base plate versus the case temperature rise at a fixed minimum case temperature

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.

4 Rainflow-counting algorithm for calculating lifetimes

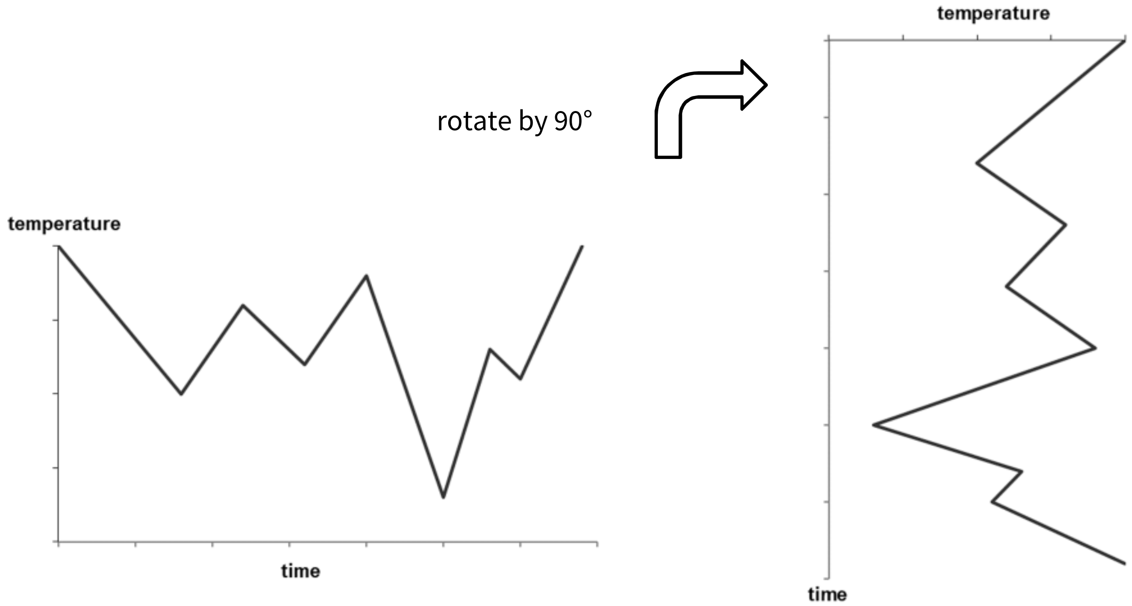
To determine the expected lifetime of an application, it is necessary to sum up the number of temperature cycles within the scope of the junction temperature $T_{vj}(t)$ to check the power cycling, or in the scope of the case temperature $T_c(t)$ to check the thermal cycling.

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

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 a spectrum of varying stress into a set of simple number of cycles. 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°:



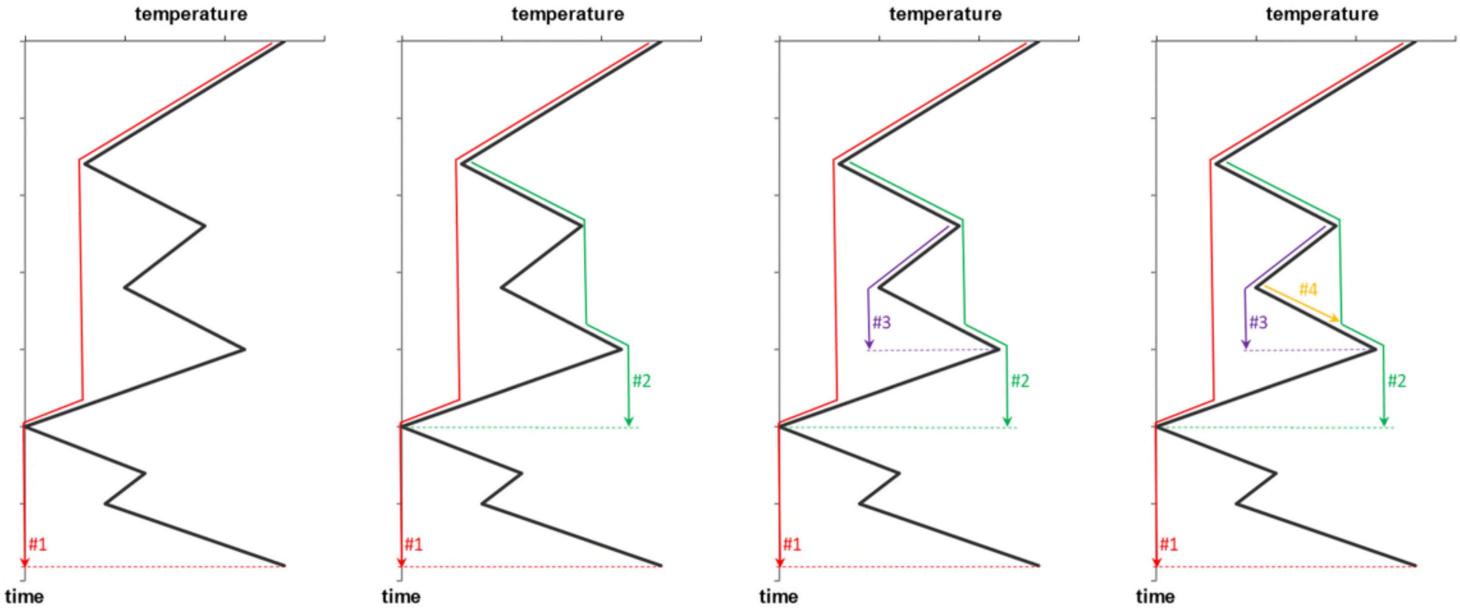
Each peak is imagined as a source of water that drips down. Let "drops" start from each maximum and minimum, and stop if the flow terminates, when the "drop" …

- 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

We will now analyze the cycle by means of the rainflow approach.

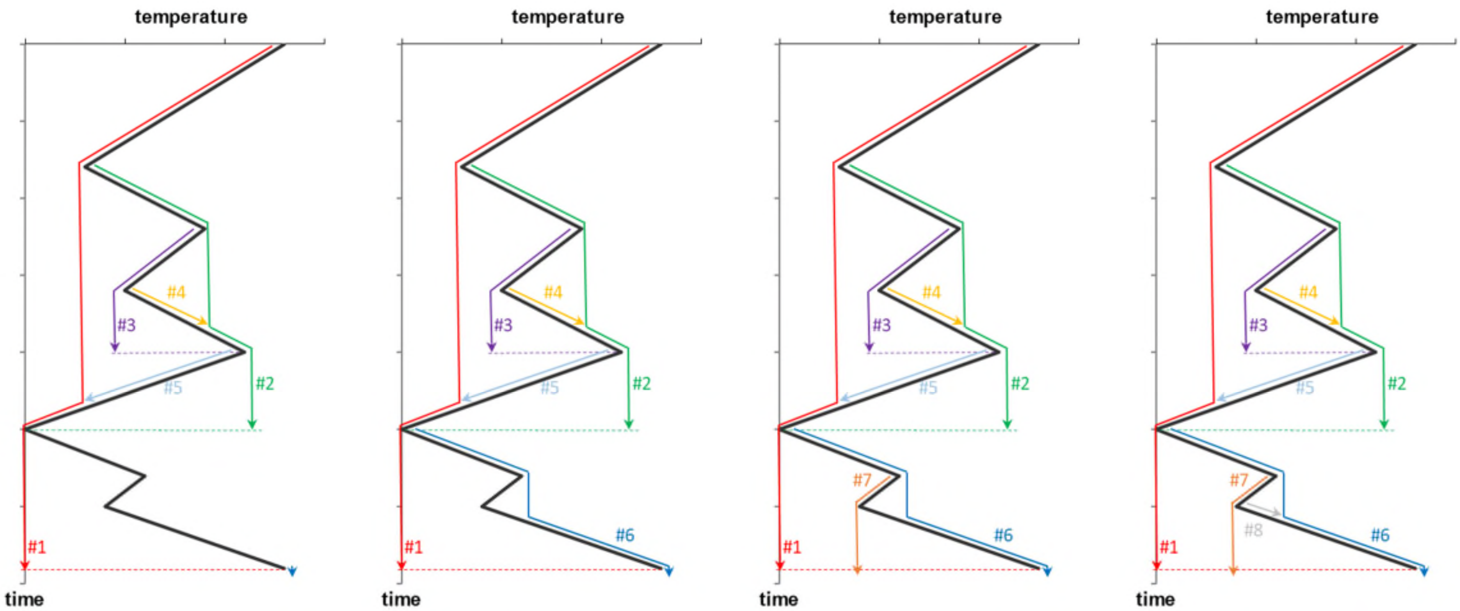


#1 reaches a minimum, which is lower than the one passed before

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

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

#4 reaches the run of drop 2



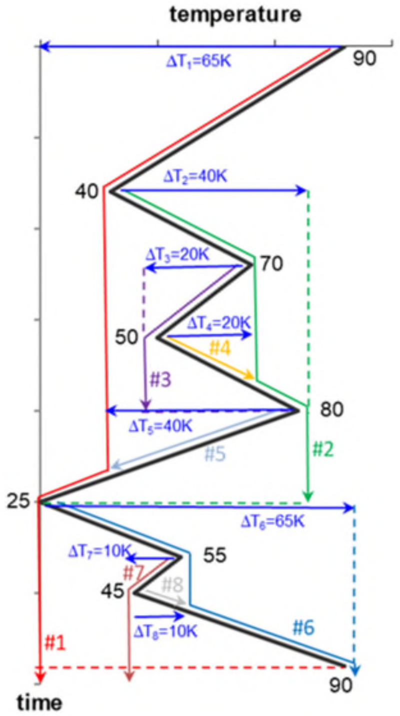
#5 reaches the run of drop 1

#6 “falls out“

#7 “falls out“

#8 reaches the run of drop 6

Now we sum up half-cycles of identical magnitude, but 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] 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

The before shown cycling diagrams are the result of an extrapolation based on Infineon's current experimental tests and simulations. Such information is given as a hint for the implementation of the relevant Infineon products only. Lifetime calculations and estimations shall be verified by Infineon's customers before implementation of the relevant Infineon products, as actual operating conditions and environmental factors differ from Infineon's assumptions. Therefore, Infineon is not responsible for the correctness of any lifetime calculations or estimations that are based on these cycling diagrams. Please note that the technical specifications of Infineon's products are conclusively stated in the applicable Infineon data sheets. Please contact your sales partner of Infineon products for further information.

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Do you have a question about this document?

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