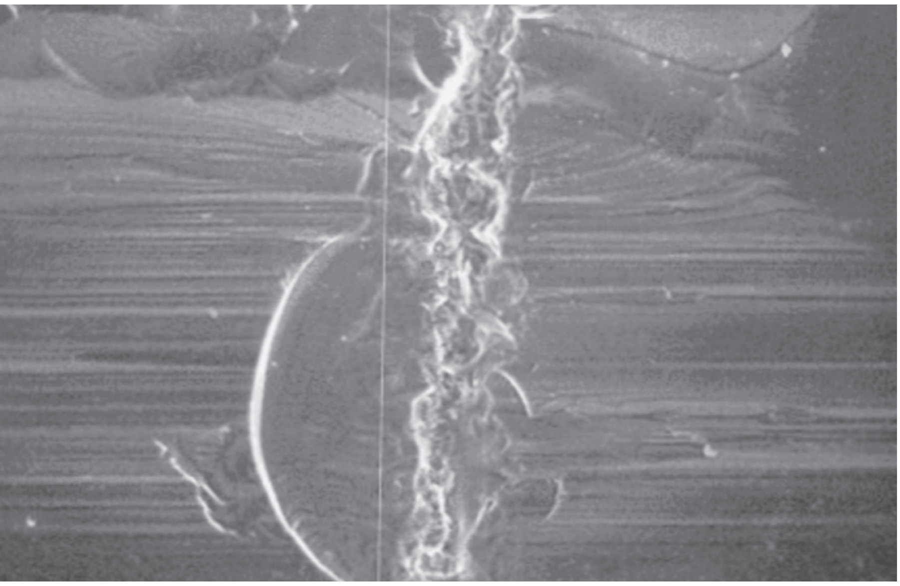
APPLICATION NOTE 5SYA 2061-02

Failure rates of fast recovery diodes due to cosmic rays



In the early 1990's a new failure mode for high current, high voltage semiconductor devices was discovered. The failure mode was of considerable practical significance and caused a series of equipment malfunctions in the field.
This failure mode affects all kind of devices like diodes, thyristors, GTOs, IGCTs, IGBTs, etc. It consists of a localised breakdown in the bulk of the devices and is not related to junction termination instabilities. The location of the breakdown spot on the wafer is random. The on-set of the breakdown occurs without a precursor within a few nanoseconds and there is no sign of early failures or wear out. The failure rate is, thus, constant in time but strongly dependent on the applied voltage and shows a small dependence on temperature.

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A molten channel through a silicon device created by a charge avalanche triggered by incident cosmic rays during blocking.

1. Introduction

Experiments in a German salt mine 140 m below ground did not show any of these failures, while experiments on the Jungfraujoch (3480 m above sea level) in the Swiss Alps yielded a much higher failure rate than in laboratories close to sea level. Furthermore, irradiation with heavy energetic particles creates the same failure patterns. All together it was concluded that “cosmic rays” are the root cause of this kind of failure and this conclusion is now supported by a vast number of experiments done all around the world.
Primary cosmic rays are high-energy particles, mostly protons, that are found in space and that penetrate our atmosphere. They come from all directions and have a wide energy range of incident particles. Most of these cosmic rays originate from supernovae. Originally the Austrian physicist Viktor Hess (Nobel Prize 1936) discovered cosmic rays because of the ionization they produce in our atmosphere. In fact, a primary cosmic ray particle usually does not reach the surface of the earth directly but collides with an atmospheric particle. There it generates a variety of other energy rich particles, which later collide with other atmospheric particles.

The process of a cosmic ray particle colliding with atmospheric particles and disintegrating into smaller pions, muons, neutrons, and the like, is called a cosmic ray shower. Most of the generated particles are harmless for semiconductor devices but some, mostly neutrons, may be lethal. Occasionally cosmic ray related events are observed, which do not lead to any perceivable damage but in general, the device is doomed even if fast fuses are used.
Today, ABB's high current, high voltage semiconductors are designed such that the failure rate due to cosmic rays is reduced to an “acceptable” level. Nevertheless, cosmic ray induced failures have to be taken into account for every power electronic circuit. In particular, semiconductors for applications with a high utilisation of the device's blocking capability and for equipment operating at high altitudes have to be assessed carefully. This application note is intended to provide a basis on which the power electronics designer can estimate failure rates, adjust parameters such as DC-link voltages or simply select the right semiconductor device for a particular application.

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2. Modeling the failure rates

In order to provide the user with a simple failure rate calculation tool, a mathematical model (Eq. 1) was developed that covers the three most important influences: blocking voltage, junction temperature, and altitude. The failure rate model consists of three multiplicands:

① the dependence on the DC-voltage (V_{DC} in volts, $V_{DC} > C_1$) at nominal conditions, i.e. 25 °C and sea level
② the dependence on the temperature (T_{vj} in degrees Celsius), term equals unity if T_{vj} equals 25 °C
③ the dependence on the altitude (h in meters above sea level), term equals unity if h equals 0, i.e. sea level.

The multiplicands ② and ③ are equal unity at nominal conditions (25 °C and sea level, respectively). Thus, the formula can be simplified for certain cases. If for example a converter operates only at sea level, multiplicand ③ can be neglected. The formula is only valid for DC blocking conditions. Varying blocking voltages, blocking duty cycles or overvoltage spikes due to switching operations should be addressed as described in paragraph 4. Other influences on the cosmic ray failure rate like dependence on the geomagnetic latitude or sun activity are neglected.
Please note:

- The model delivers failure rates in FIT, i.e. number of failures within 10^9 element hours.
- The formula is only valid if the DC-link voltage V_{DC} is larger than the parameter C_1 because the formula has a pole at C_1. For V_{DC} values below C_1 the failure rate is regarded as zero.
- The failure rate model describes only failures that are due to cosmic rays. The model does not cover failures due to other root causes

2.1. Voltage dependence

The formula for the voltage dependence (multiplicand ①) is a pure fit to measured data at DC-voltage. The formula has no physical background but fits the data almost perfectly. The model's parameters C_1, C_2, and C_3 are, therefore, characteristic values of the individual devices and can be looked up in the table in section 3. The parameters have also no physical meaning.

2.2. Temperature dependence

The formula for the temperature dependence (multiplicand ②) is again a fit to measured data. However, experiments indicate that the failure rates decrease exponentially with temperature and that this dependence is practically independent of the device type. Therefore, the formula does not require any device specific parameters.

2.3. Altitude dependence

The formula for the altitude dependence (multiplicand ③) assumes a screening of cosmic rays by the atmosphere and is, thus, based on the barometric formula. This implies that all devices are affected the same way, so again the formula does not contain any device specific parameters. The formula is valid up to an altitude of approximately 6000 m above sea level.

3. Failure rates of the individual FR diode types

The table on page 4 gives the device specific parameters for the individual diode types. The cosmic ray measurements were done with the smallest (corresponding to the D-housing) device type on wafer level. The model parameters were afterwards fitted to the measured failure rates scaled to the device area of the respective larger diodes. All values are typical values and may vary considerably. Section 3.1 gives two examples of how to calculate the failure rate by using the formula and section 3.2 shows some selected graphs for each product listed.

$$\lambda(V_{DC}, T_{vj}, h) = \underbrace{C_3 \cdot \exp\left(\frac{C_2}{C_1 - V_{DC}}\right)}_{①} \cdot \underbrace{\exp\left(\frac{25 - T_{vj}}{47.6}\right)}_{②} \cdot \underbrace{\exp\left(\frac{1 - \left(1 - \frac{h}{44300}\right)^{5.26}}{0.143}\right)}_{③}$$

—
Equation 1

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GTO Freewheeling Diodes	C_1 [V]	C_2 [V]	C_3 [FIT]
5SDF 05D2505	1780	8600	8.2 E+09
5SDF 11F2501	1800	8200	8.2 E+09
5SDF 07F4501	2720	3685	1.50E+06
5SDF 13H4501	2720	3685	2.70E+06
5SDF 10H6004	2900	16000	7.1 E+07

Snubber Diodes	C_1 [V]	C_2 [V]	C_3 [FIT]
5SDF 05D2501	1780	8600	8.2 E+09
5SDF 03D4501	2500	3650	7.60E+06
5SDF 07H4501	2500	3650	2.55E+07
5SDF 02D6002	2900	16000	2.0 E+07

IGCT Diodes	C_1 [V]	C_2 [V]	C_3 [FIT]
5SDF 03D4502	2720	3685	8.00E+05
5SDF 05F4502	2720	3685	1.50E+06
5SDF 10H4502 5SDF 10H4503 5SDF 10H4520	2720	3685	2.70E+06
5SDF 20L4520	2720	5000	3.0E+06
5SDF 28L4520	2720	5000	3.0E+06
5SDF 02D6004	2900	16000	2.0 E+07
5SDF 04F6004	2900	16000	3.7 E+07
5SDF 08H6005	2900	16000	7.1 E+07

3.1. Calculation examples

Assume a 4.5 kV diode in H-package (5SDF 10H4503) operated at a DC-link voltage of 3400 V, a temperature of 0 °C and at sea level. Because the altitude is at its nominal value the last multiplicand ③ can be ignored. Together with the parameters from the table above, the failure rate formula now reads:

$$\lambda(3400V,0°C,0m) \;=\; 2.7\cdot 10^{6}\,FIT\cdot \exp\left(\frac{3685}{2720-3400}\right) \;\cdot\; \exp\left(\frac{25-0}{47.6}\right) \;\approx\; 20220\,FIT$$

Equation 2

20220 FIT means 20220 failures within 10^9 element hours or an MTTF of $1/\lambda$ = 50000 h, i.e. 5.6 y. Assuming a converter output stage with six diodes, the MTTF reduces to 1 y and this is usually not regarded as sufficient reliability. Obviously, the targeted DC-link voltage is too high.

Assume again a 4.5 kV diode in H-package (5SDF 10H4503) that is operated now at a DC-link voltage of 2800 V, a temperature of 25 °C and at an altitude of 6000 m. Because the temperature is at its nominal condition the multiplicand ② can be ignored. Together with the parameters from the table above the failure rate formula now reads:

$$\lambda(2900V,25°C,6000m) \;=\; 2.7\cdot 10^{6}\,FIT\cdot \exp\left(\frac{3685}{2720-2900}\right) \;\cdot\; \exp\left(\frac{1-\left(1-\frac{6000}{44300}\right)^{5.26}}{0.143}\right) \;\approx\; 0.15$$

Equation 3

In this example the MTTF is $6.6\cdot 10^9$ h or 750’000 y. Even if the circuit contains a number of devices the overall reliability will not be affected by cosmic ray induced failures. Nevertheless, due to the statistical nature of the effect there might be cosmic ray failures in the field. Furthermore, the assumption of a constant DC-voltage is not realistic for typical applications. A variation of the DC-voltage due to e.g. input voltage variations or specific operations modes (breaking operation) is to be expected. Even more important is the repetitive over voltage the device has to withstand during switching. Dealing with this area is explained in more detail in section 4.

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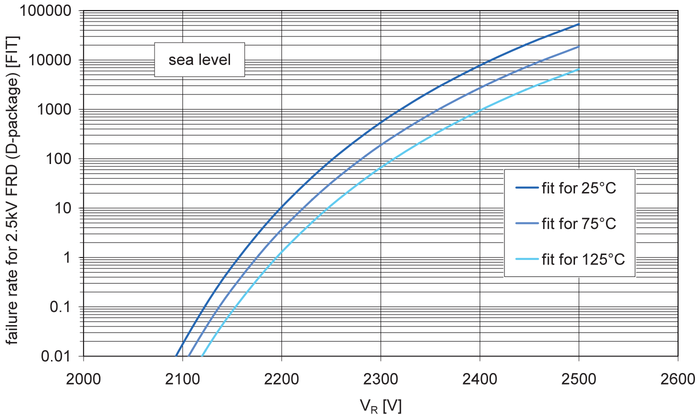
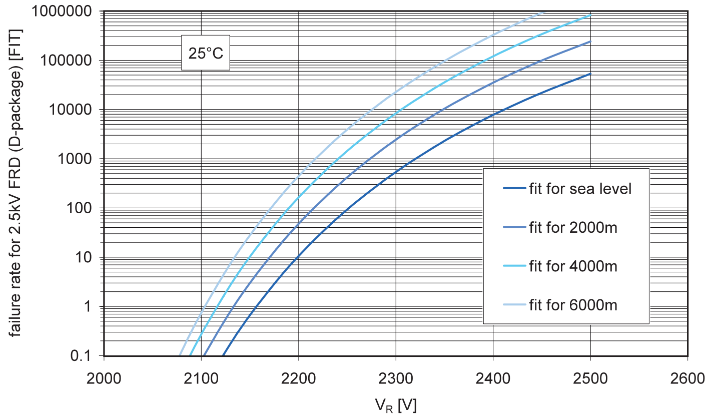
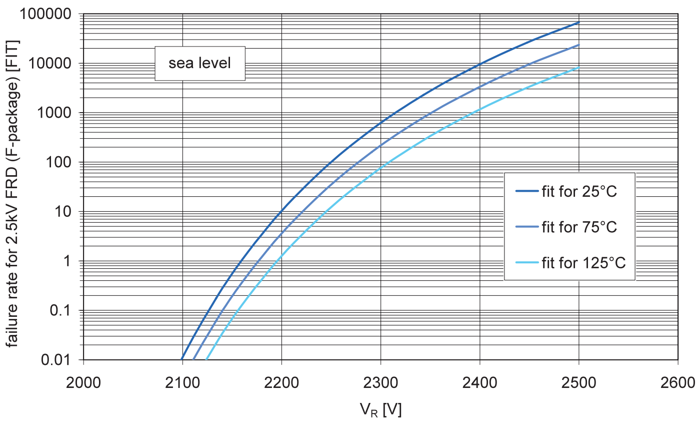
3. 2. Failure rate graphs for different diodes

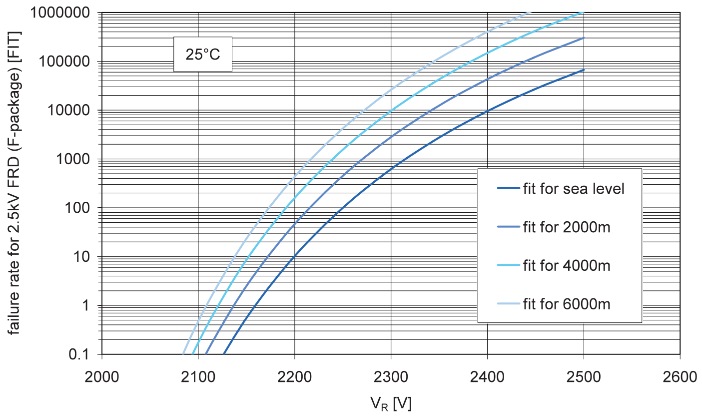
3. 2.1. SDF 05D2501 and 5SDF 05D2505 under DC – voltage condition





3.2.2. 5SDF 11F2501 under DC – voltage condition





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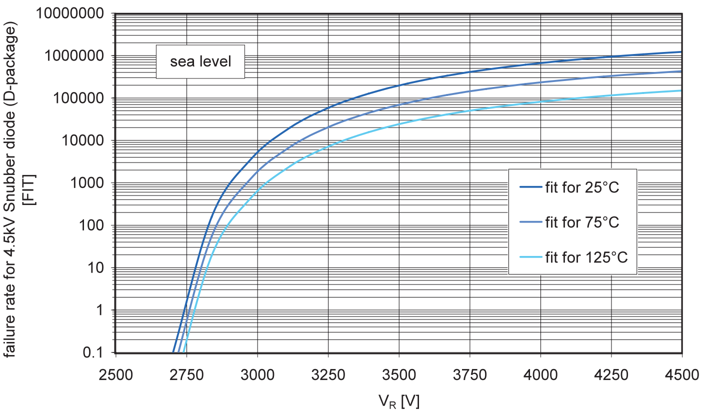
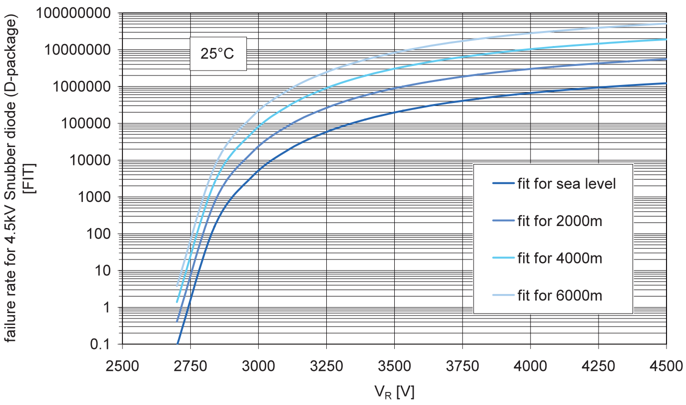
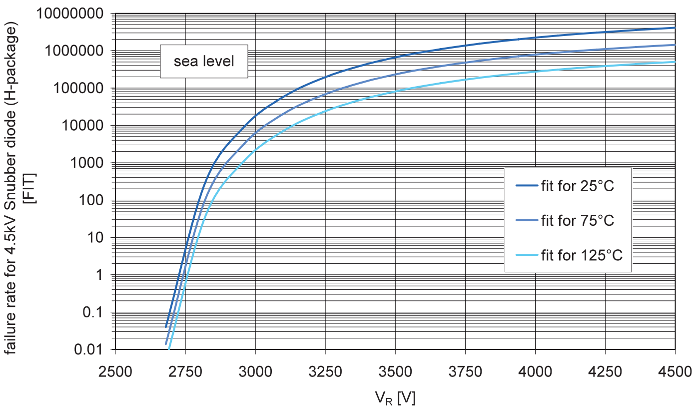
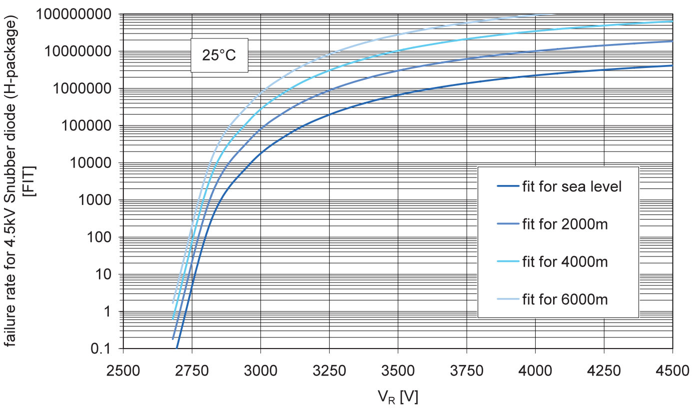
3.2.3. 5SDF 03D4501 under DC – voltage condition





3.2.4. 5SDF 07H4501 under DC – voltage condition





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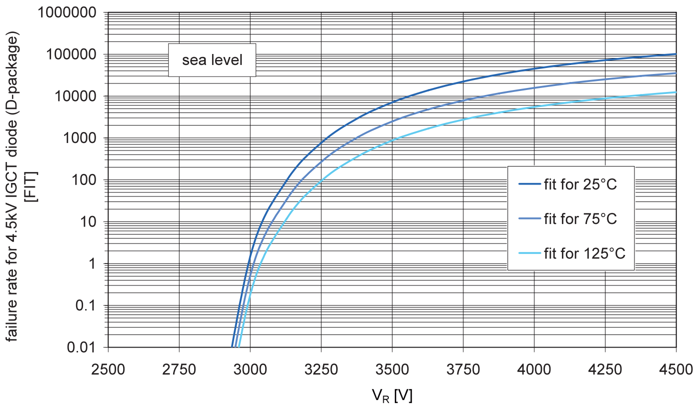
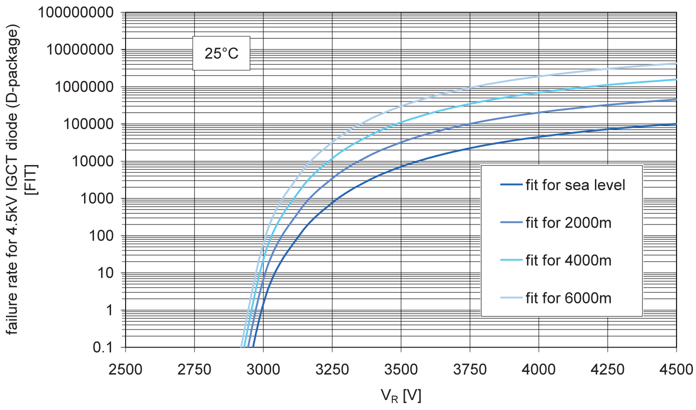
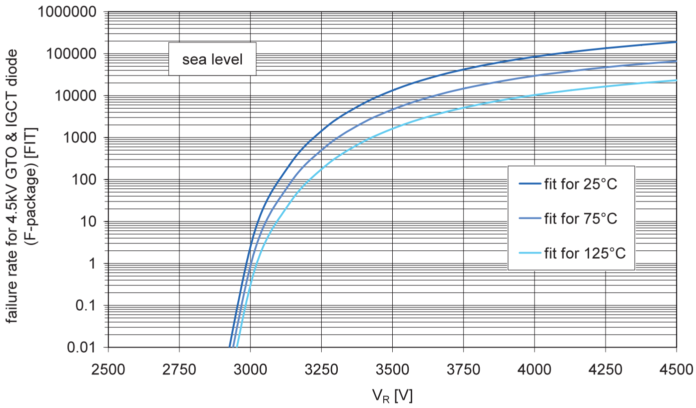
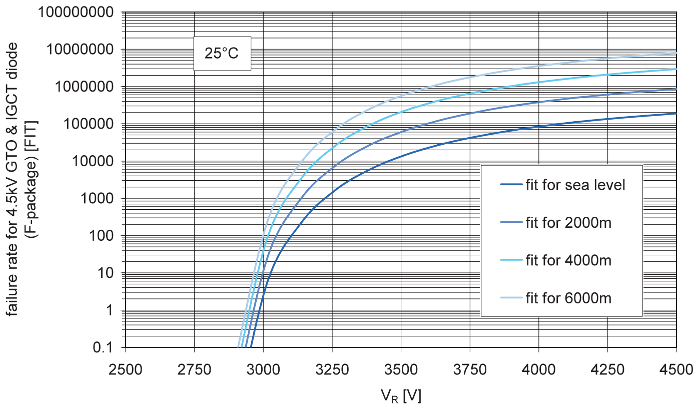
3.2.5. 5SDF 03D4502 under DC – voltage condition





3.2.6. 5SDF 07F4501 and 5SDF 05F4502 under DC – voltage condition





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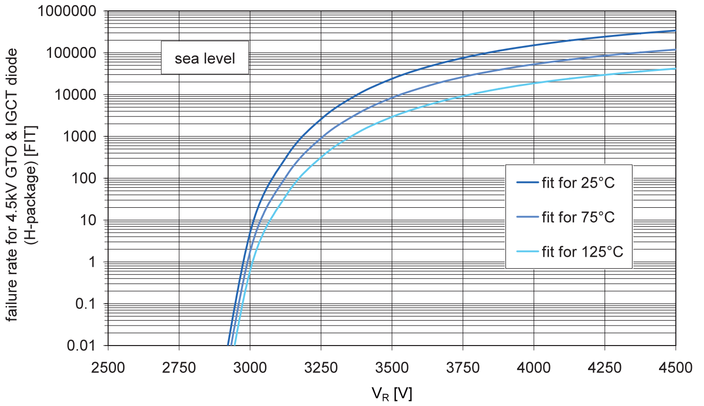
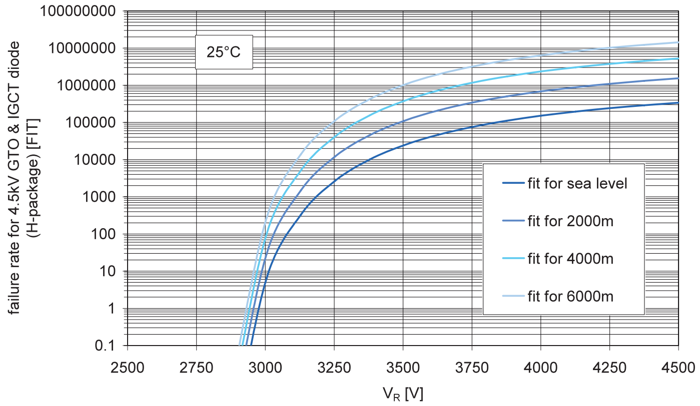
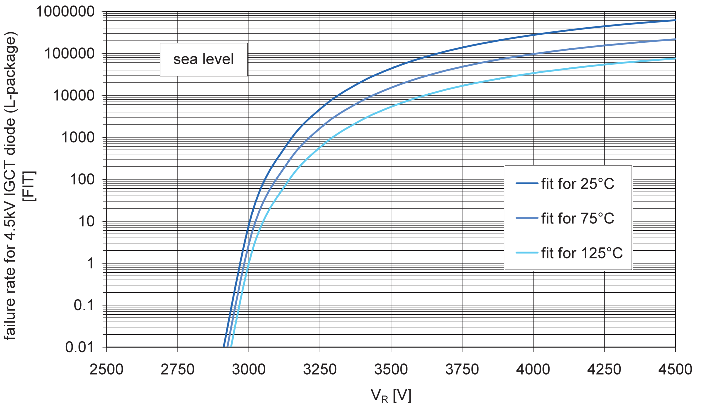
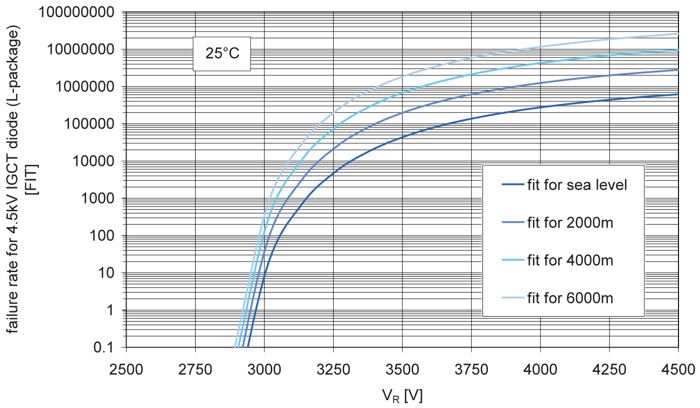
3.2.7. 5SDF 13H4501, 5SDF 10H4502, 5SDF 10H4503 and 5SDF 10H4520 under DC – voltage condition





3.2.8. 5SDF 20L4520, 5SDF 28L4520, 5SDF 20L4521, 5SDF 28L4521 under DC – voltage condition





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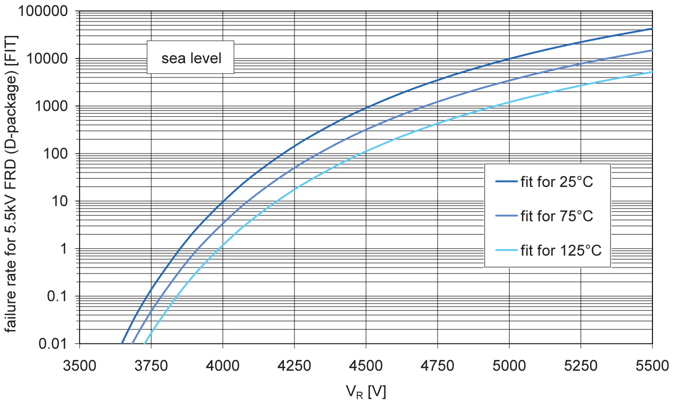
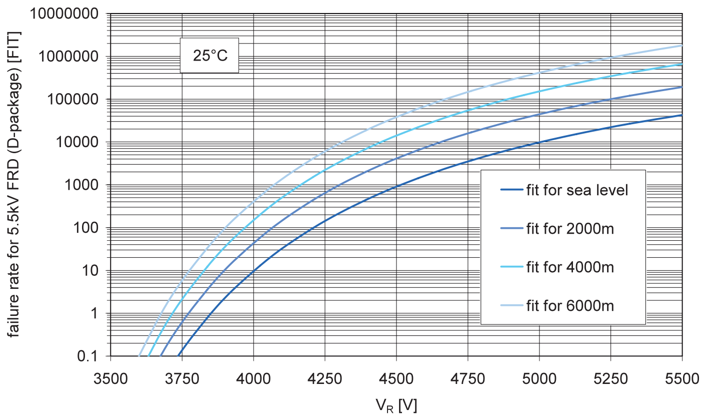
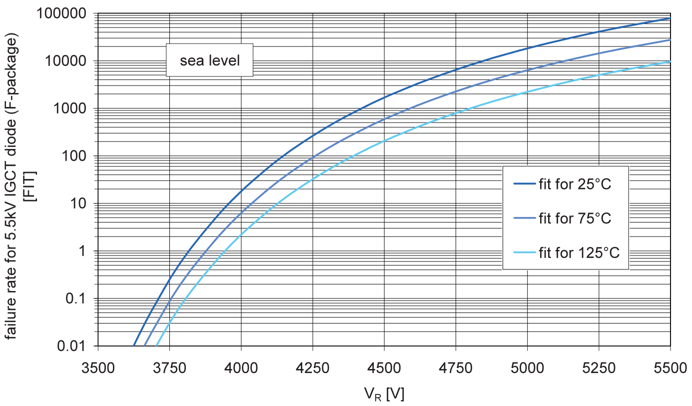
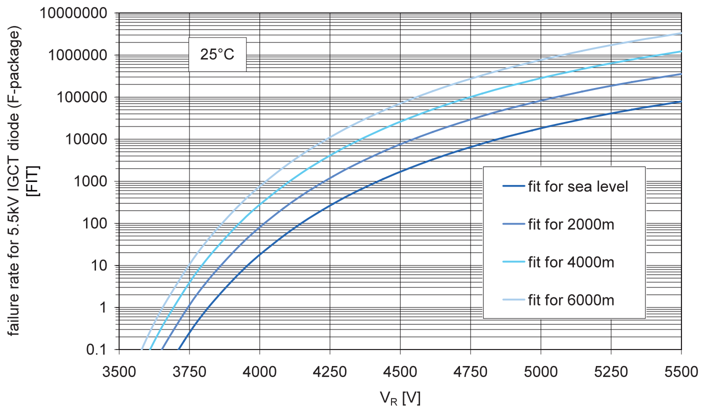
3.2.9. 5SDF 20L4520, 5SDF 28L4520, 5SDF 20L4521, 5SDF 28L4521 under DC – voltage condition





3.2.10. 5SDF 04F6004 under DC – voltage condition





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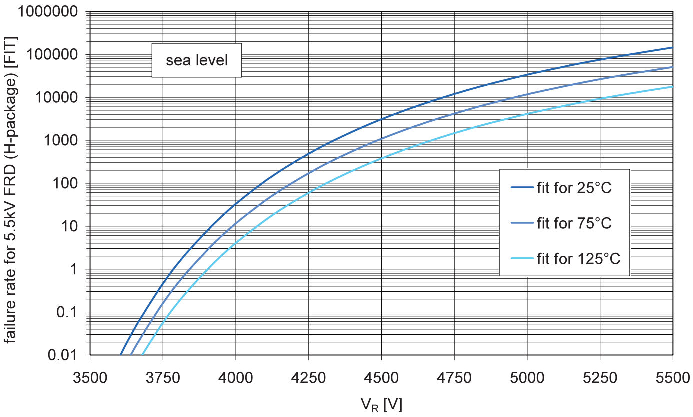
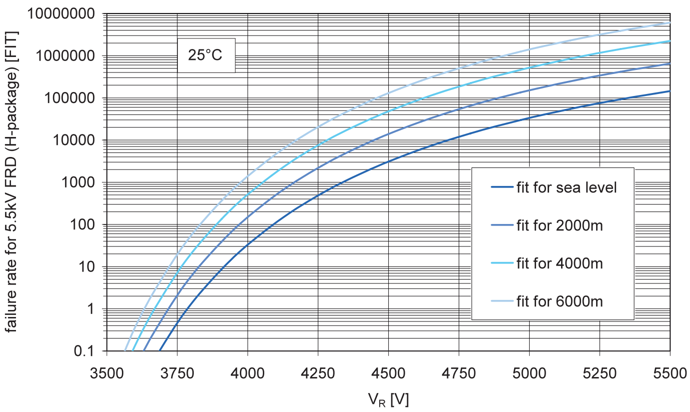
3.2.11 5SDF 10H6004 and 5SDF 08H6005 under DC – voltage condition





4. Varying voltages

The model assumes a DC-voltage. However, in most cases the applied voltage is not constant at all due to overvoltage spikes during switching or varying DC voltage during operation. Here a more sophisticated approach is necessary.
The diode life in the application has to be divided up in the different blocking situations. Let's assume a diode with a duty cycle of 50 % in blocking mode at 2.8 kV at an altitude of 1000 m and Junction temperature of 60 °C. The other 50 % the diode is in On-state mode. The diode is switched at a frequency of 100 Hz between blocking and On-state mode.
Let's analyse one second of the diode life:

1. On-stated period: The Failure probability is zero
2. Blocking period: The failure rate under 2.8 kV blocking condition is according to Eq1 negligible.
3. Switching events

The figure on page 11 shows a diode turn-off event of an IGCT diode (5SDF 20L4520) in a clamp circuit. During the turn-off event the diode is exposed to over voltages that are dependent on the switching characteristic of the diode itself and the design of the electrical circuit (dimensioning of clamp circuit, stray inductivities ...). Integrating the failure rate results in the failure probability during this switching event (see right graph on page 11). In this case the failure probability is 0.14 FIT*s per switching event. The repetition rate per second is 100 so the switching failure probability due to switching is 14 FIT*s
In total the failure probability during this second is 14 FIT*s. For a continuous operation under this condition the failure rate then is given by the failure probability during this second divided by one second.

Failure rate = 14 FIT

In reality the situation is often more complicated. The diodes typically are exposed to switching overvoltages of other devices in the circuit e.g. anti-parallel operated IGCTs. Additionally operation conditions are changing. But in principal this situation can be evaluated in the same way. The example shows, that the cosmic ray induced failure rate in many cases is determined by dynamic overvoltage loads.

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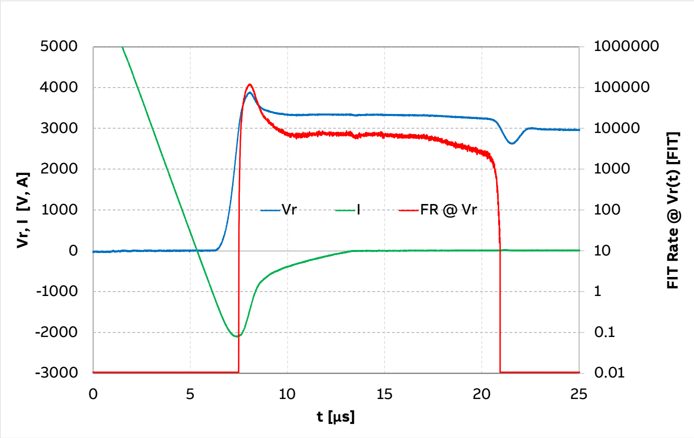

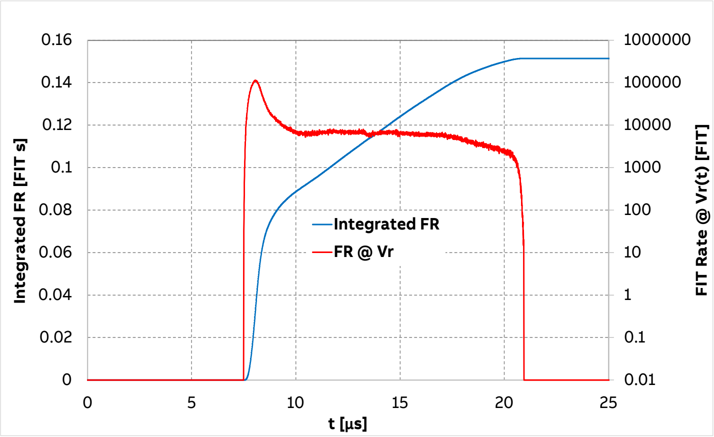

—
V_r and I with time (left scale, failure rate (FR) calculated with Equation 1 at the instant voltage (right scale)

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Failure rate (FR) as in left graph and failure probability (Integrated failure rate, left scale) for the turn-off cycle.

5. Revision history

Version	Change	Authors
00	initial release	Björn Backlund
01	10.2018	T. Stiasny, E. Tsyplakov
02	09.2019	C. Winter, E. Tsyplakov

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