

# Considering Failure Rates and the Impact of Cosmic Radiation

## Objectives

This white paper describes methodologies to include the influence of cosmic radiation on the estimation of failure rates. Cosmic radiation is a natural phenomenon and consists of high-energy charged particles, x-rays, and gamma-rays produced in space by stars like our sun. These charged particles react with the earth's atmosphere and produce a cascade of secondary radiation which reaches our planet's surface.

Interaction between these charged particles and power semiconductors can lead to failure in the sequence displayed in Figure 1.

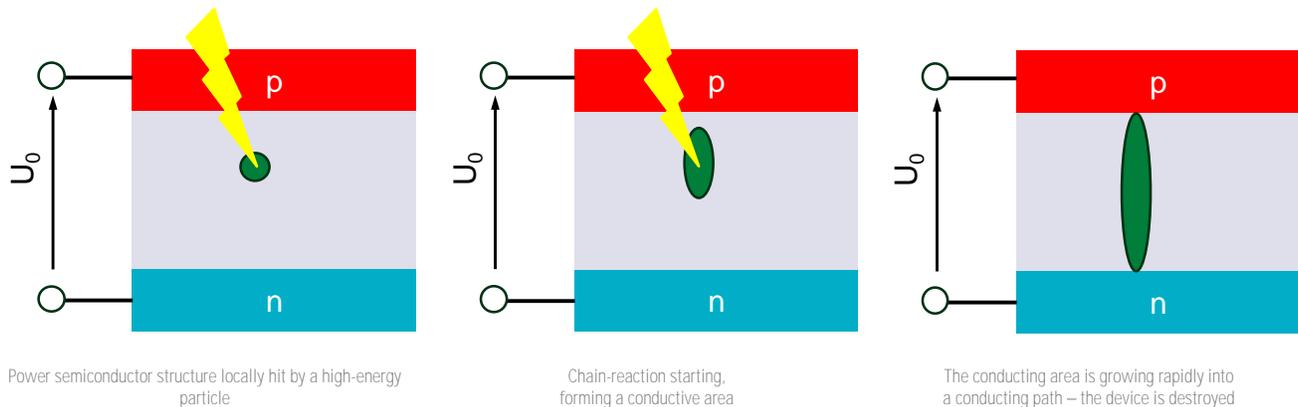


Figure 1. Failure development due to Cosmic Radiation

## Applications

The information compiled in this document is relevant for the power semiconductor itself and thus for all its applications.

## Target Audience

This document is intended for all developers, design- and test-engineers involved in building power semiconductor applications. It is also meant for personnel working in failure analysis.

## Contact Information

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## Introduction

Cosmic radiation is emitted by stars like our sun and exists, strictly speaking, only in open space. Large amounts of particles are ejected by our sun but most of the particles direct to our planet are deflected by earth's magnetic field before reaching the atmosphere. Those that enter the atmosphere collide with other particles, transferring energy to them. These accelerated particles again hit further particles, creating a cascading effect. This cascading effect multiplies the number of high-energy particles and in turn, the chance that some of them will collide with semiconductors.

As the sum of energy remains constant, there is a correlation between the energy per particle, the particle density, and the altitude at which the particles are observed. Therefore, physically, it is not the initial cosmic radiation that impacts electronic components. Commonly, to be more precise, the effect is also described as high-altitude phenomena.

It is within the nature of these high-energy particles, that shielding a device in most cases is not a viable option. Experiments done in 1929 by Walther Bothe and Werner Kolhörster revealed that even a gold-layer of 4 cm thickness remains insufficient.

Cosmic radiation first got into the focus of power electronic developers when in the early 1990s power converters in traction applications started failing for no obvious reasons. A famous experiment to support the hypothesis of radiation being the root cause was conducted. The core of the experiment was to compare failure rates in devices in higher altitude to devices operated in underground salt caverns [1].

The results gathered were unambiguous. Cosmic radiation was concluded to be a cause for toggling bits in memory chips but also was determined as having an impact on power devices, especially when high electric field strength is present. These conditions are found in all power semiconductor devices in blocking condition and therefore, cosmic radiation affects active switches like MOSFETs, IGBTs, and thyristors in the same way as diodes.

## 1. Standards used in Failure Rate Estimation

There are dedicated standards to refer to if it comes to testing and qualifying semiconductor devices:

- JEDEC82 is a standard for DDR Memory modules. Though cosmic radiation is a known source of toggling single bits in memory devices, the high-altitude phenomena is not considered in this work.
- IEC 60749-Parts 23 and 39 are standards describing processes and tests to be done to quantify the robustness of power semiconductors. They include stress-tests and environmental tests but do not dive into high-altitude testing.
- The MIL-Handbook 217F [2] includes both, airborne and space application and gives valuable parameters to determine a failure probability. However, it explicitly excludes failure due to ionizing radiation.

Failure rates for the remainder of this documents are probability values, also called FIT-rates. FIT is the abbreviation for *Failure In Time*. In industrial use, *Time* is commonly defined as  $10^9$  hours.

Thus, a FIT-rate of 100 for a single device means that this one device will probably fail within  $10^7$  operating hours, representing more than ten years of permanent operation. It also means that from  $10^9$  such devices in the field, 100 pieces failing per hour can be expected.

FIT-rates do not tell the user anything about when a certain device will fail or which device within a group will be affected. FIT-rates remain a statistical information. Additionally, FIT-rates do not consider failures in line with the so-called bath-tub curve, correlated to early failures and end-of-life effects.

The military handbook 217F refers to the failure rate as  $\lambda_p$ -value given as the number of failures to be expected within  $10^6$  hours only. Therefore, the correlation used within the industry is  $FIT = \lambda_p \cdot 10^3$ .

The failure rate derived from these values still needs to be modified to better reproduce the influence of high altitude. This is done in a final step after calculating the FIT-rates for use at sea-level.

The procedure and values used in this whitepaper are based on the military handbook 217F and further, publicly available sources.

## 2. Estimating FIT-rates

There are several factors which influence the result, which need to be included in the calculation which can be summarized as:

$$\lambda_p = \lambda_b \cdot \prod_{i=1}^n \pi_i$$

In this formular,  $\lambda_p$  is the resulting failure rate. It is calculated from a base failure rate  $\lambda_b$  which is modified by acceleration factors  $\pi_i$ . The acceleration factors vary for different technologies or applicational fields. For all factors, information can be found to choose reasonable numbers for different power semiconductor classes, including:

- Diodes in low-frequency operation as in rectifiers
- Diodes in high-frequency operation like RF or microwave applications
- Bipolar transistors in low-frequency operation < 200MHz
- Si-based field-effect transistors (FETs) operating < 400MHz
- Unijunction transistors
- Low-noise, high-frequency bipolar transistors operated at >200MHz
- GaAs-based FETs operated at  $\geq$  1GHz
- Thyristors, SCRs and TRIACS

As an example, the relevant acceleration factors  $\pi_i$  for diodes in low-frequency operation are given in Figure 2.

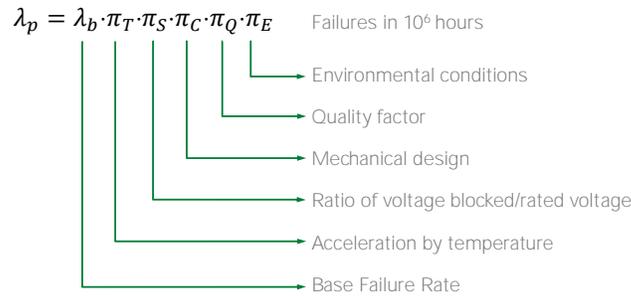


Figure 2. Failure calculation for diodes in low-frequency applications

The handbook also includes tables with the values to be used for the various acceleration factors.

## 3. Exemplary Calculation

FIT-rates for a rectifier diode operated in a mobile application at 1000 V<sub>dc</sub>, carrying 18.5 A in an application located in altitudes between 400 and 2000 m above sea level at case temperatures of -40, 25, and 85°C have to be estimated. The base failure rate can be taken from Table 1 as 0.0038.

Table 1. Base failure rates for diodes in low frequency operation

| Diode Type/Application  | $\lambda_b$     |
|---|-----------------|
| General Purpose Analog  | 0.0038          |
| Switching   | 0.0010          |
| Fast Recovery Power Rectifier                                 | 0.025           |
| Power Rectifier/Schottky Power Diode                          | 0.0030          |
| Power Rectifier with High Voltage Stack                       | 0.0050/Junction |
| Transient Suppressor/Varistor                                 | 0.0013          |
| Current Regulator   | 0.0034          |
| Voltage Regulator and Voltage Reference (Avalanche and Zener) | 0.0020          |

The temperature dependence factor  $\pi_T$  is given as a look-up table and as analytic expression, both seen in Table 2. The function  $\pi_T=f(T_J)$  is plotted in Figure 3.

Table 2. Acceleration factor  $\pi_T=f(T_J)$

| $T_J$ [°C] | $\pi_T$ | $T_J$ [°C] | $\pi_T$ |
|------------|---------|------------|---------|
| 25         | 1       | 105        | 9       |
| 30         | 1,2     | 110        | 10      |
| 35         | 1,4     | 115        | 11      |
| 40         | 1,6     | 120        | 12      |
| 45         | 1,9     | 125        | 14      |
| 50         | 2,2     | 130        | 15      |
| 55         | 2,6     | 135        | 16      |
| 60         | 3       | 140        | 18      |
| 65         | 3,4     | 145        | 20      |
| 70         | 3,9     | 150        | 21      |
| 75         | 4,4     | 155        | 23      |
| 80         | 5       | 160        | 25      |
| 85         | 5,7     | 165        | 28      |
| 90         | 6,4     | 170        | 30      |
| 95         | 7,2     | 175        | 32      |
| 100        | 8       |            |         |

$$\pi_T = e^{-3091 \cdot \left( \frac{1}{T_J+273} - \frac{1}{298} \right)}$$

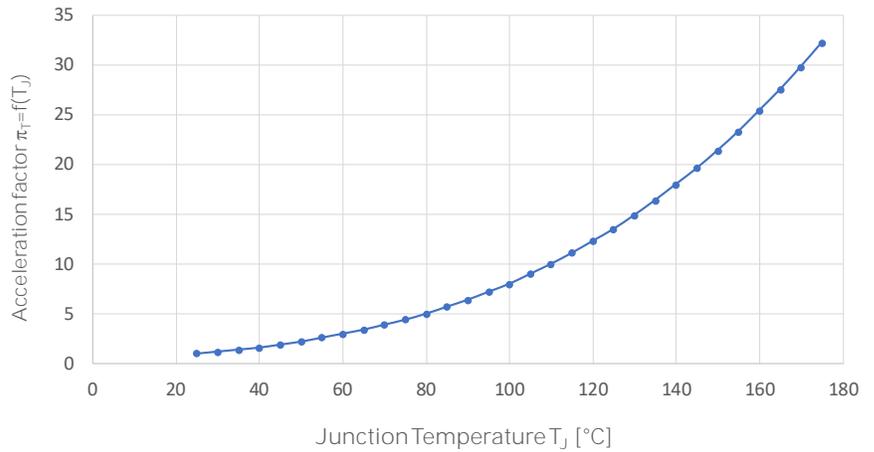


Figure 3. Plotted function  $\pi_T=f(T_J)$

The factor  $\pi_T$  accounts for the influence of changing temperatures and relates to the device’s junction temperature. In case the device is actively carrying current, losses, thermal resistances, and cooling capabilities need to be considered. For the device in blocking condition, the situation is determined by the case- or housing-temperature. Heating due to leakage currents can usually be neglected.

To attribute the voltage stress, the factor  $\pi_S$  takes the ratio  $V_S$  of voltage applied and the diode’s rated blocking voltage into account. Here too, a table and an analytical expression are given as summarized in Table 3 and sketched in Figure 4.

Table 3. Electrical Stress Factor  $\pi_S$

| Stress   | $\pi_S$ |
|--|---------|
| Transient Suppressor,<br>Voltage Regulator,<br>Voltage Reference,<br>Current Regulator | 1       |
| All others:  |         |
| $V_S \leq 0,30$  | 0,054   |
| $0,3 < V_S \leq 0,40$  | 0,11    |
| $0,4 < V_S \leq 0,50$  | 0,19    |
| $0,5 < V_S \leq 0,60$  | 0,29    |
| $0,6 < V_S \leq 0,70$  | 0,42    |
| $0,7 < V_S \leq 0,80$  | 0,58    |
| $0,8 < V_S \leq 0,90$  | 0,77    |
| $0,9 < V_S \leq 1$   | 1       |

$$\pi_S = 0,54 \quad (V_S \leq 0,3)$$

$$\pi_S = V_S^{2,43} \quad (0,3 < V_S \leq 1)$$

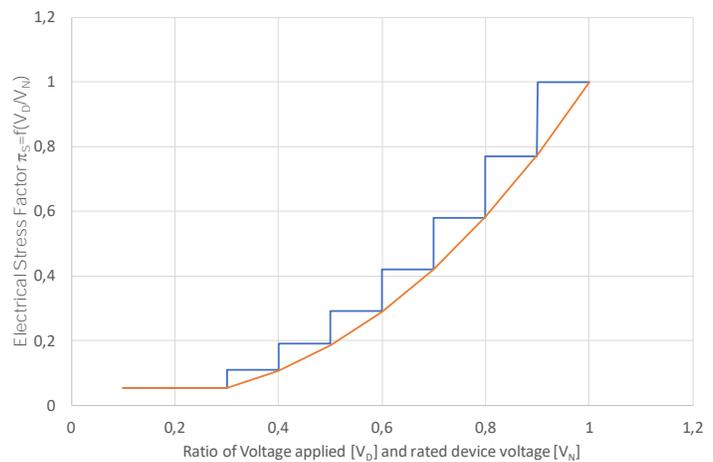


Figure 4. Electrical Stress factor  $\pi_S=f(V_S)$

Though an exact value for  $\pi_S = f(V_S)$  can be calculated from the analytical expression, a stepwise increase for  $\pi_S$  is considered for every 10% increase in  $V_S$ .

It is these two factors  $\pi_T$  and  $\pi_S$  that can be influenced best and in a wide range by choosing components with suitable blocking voltages and care for adequate cooling.

Contact Construction Factor  $\pi_c$  and Quality Factor  $\pi_Q$  are parameters related to the mechanical characteristics of the component in question. The available options are summarized in Table 4.

Table 4. Contact Construction and Quality Factor

| Contact Construction                                  | $\pi_c$ | Quality | $\pi_Q$ |
|---|---------|---------|---------|
| Metallurgically Bonded                                | 1.0     | JANTXV  | 0.7     |
| Non-metallurgically Bonded and Spring Loaded Contacts | 2.0     | JANTX   | 1.0     |
|   |         | JAN     | 2.4     |
|   |         | Lower   | 5.5     |
|   |         | Plastic | 8.0     |

The final element to be considered here is the factor  $\pi_E$  to capture the impact by the surrounding environment as described in Table 5.

Table 5. Environmental symbol, description, and acceleration factor  $\pi_E$

| Environment    | $\pi_E$ -Symbol | Equivalent HIL-HDBK-217E, Notice 1 $\pi_E$ -Symbol | Description   | $\pi_E$ -Value |
|----------------|-----------------|--|---|----------------|
| Ground, Benign | $G_B$           | $G_B$<br>$G_{MS}$                                  | Nonmobile, temperature and humidity controlled environment readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes, and missiles and support equipment in ground silos.   | 1.0            |
| Ground, Fixed  | $G_F$           | $G_F$  | Moderately controlled environment such as installations in permanent racks with adequate cooling air and possible installation in unheated buildings; includes permanent installation of air traffic control radar and communications facilities.                                 | 6.0            |
| Ground, Mobile | $G_M$           | $G_M$<br>$M_p$                                     | Equipment installed on wheeled or tracked vehicles and equipment manually transported; includes tactile missile ground support equipment, mobile communication equipment, tactile fire direction systems, handheld communications equipment, laser designations and range finders | 9.0            |

For the given boundary conditions in this example, a variety of diodes can be chosen. To demonstrate the impact of the chip temperature, a reasonably sized 30 A / 2200 V device DNA30E2200NA is compared to a potentially oversized 70 A-version DNA70E220NA. Both devices feature the same diode technology, the same interconnections, and the same housing.

### 3.1. Calculation and Comparison

For the two diodes considered, the first important information is the thermal development in the application. The chip temperature swing  $\Delta T$  can be calculated from the conduction losses and the thermal resistance. Conduction losses are the product  $V_F \cdot I$  and the correlating forward voltage at a given temperature can be taken from the datasheets' diagrams.

The corresponding values and results as well as the acceleration factors  $\pi_T$  related to them are summarized in Table 6.

Table 6. Thermal development and  $\pi_T$ -factor for two different diodes

|  | DNA70E2200NA | DNA30E2200NA |     |
|--|--------------|--------------|-----|
| Rated Voltage                                  | 2200         | 2200         | V   |
| Rated Current                                  | 70           | 30           | A   |
| $V_F$ (18.5 A, $T_J \sim 85^\circ\text{C}$ )   | 0.91         | 1.09         | V   |
| $V_F$ (18.5 A, $T_J \sim 25^\circ\text{C}$ )   | 1.02         | 1.16         | V   |
| $P_{\text{conducting @ } 100^\circ\text{C}}$   | 16.835       | 20.165       | W   |
| $P_{\text{conducting @ } 25^\circ\text{C}}$    | 18.87        | 21.46        | W   |
| $R_{th}$                                       | 0.6          | 0.9          | K/W |
| $\Delta T @ 85^\circ\text{C}$                  | 10.101       | 18.1485      | K   |
| $\Delta T @ 25^\circ\text{C}$                  | 11.322       | 19.314       | K   |
| $\pi_T @ 85^\circ\text{C} / 120^\circ\text{C}$ | 7.2          | 9            |     |
| $\pi_T @ 25^\circ\text{C} / 45^\circ\text{C}$  | 1.2          | 1.9          |     |

As both diodes are 2200 V-devices, the voltage stress factor is the same for both. The two cases to be considered are related to the instantaneous operating conditions blocking or conducting mode. For comparison, the stress factor for a 1200 V device is also given. All values are compiled in Table 7.

Table 7. Electrical stress parameter  $\pi_S$  for the chosen example

| Diode  | 2200 V  | 1200 V  |
|--|---|---|
| Blocking mode<br>$\frac{\text{Voltage applied}}{\text{rated voltage}}$         | $\frac{1000}{2200} = 0.45 \Rightarrow \pi_S = 0.19$ | $\frac{1000}{1200} = 0.83 \Rightarrow \pi_S = 0.77$ |
| Conducting mode<br>$\frac{\text{Voltage applied}}{\text{rated voltage}} < 0.3$ | $\pi_S = 0.054$                                     | $\pi_S = 0.054$                                     |

With a metallurgically bonded structure, the contact construction factor  $\pi_c$  is 1.0 and the molded housing qualifies as lower quality and a correlating quality factor  $\pi_o$  of 5.5.

Designed into a mobile application operating on ground, the environment factor  $\pi_E$  results in 9.0.

With these numbers known, the equation for the failure rate can be populated for the different cases and the  $\lambda_p$ -value can be calculated, as shown in Table 8:

Table 8. Failure rate calculation

| Diode type   | Failure rate in 10 <sup>6</sup> hours   | FIT-rate |
|--|---|----------|
| 2200 V / 70 A, blocking mode<br>T <sub>J</sub> ~T <sub>C</sub> =85°C | $\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E = 0.0038 \cdot 5.7 \cdot 0.19 \cdot 1.0 \cdot 5.5 \cdot 9.0 = 0.20346$ | 204      |
| 2200 V / 70 A, conducting mode<br>T <sub>J</sub> =96°C               | $\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E = 0.0038 \cdot 7.2 \cdot 0.054 \cdot 1.0 \cdot 5.5 \cdot 9.0 = 0.0731$ | 73       |
| 2200 V / 30 A, blocking mode<br>T <sub>J</sub> ~T <sub>C</sub> =85°C | $\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E = 0.0038 \cdot 5.7 \cdot 0.19 \cdot 1.0 \cdot 5.5 \cdot 9.0 = 0.2035$  | 204      |
| 2200 V / 30 A, conducting mode<br>T <sub>J</sub> =103°C              | $\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E = 0.0038 \cdot 9 \cdot 0.054 \cdot 1.0 \cdot 5.5 \cdot 9.0 = 0.091$    | 91       |
| 1200 V / 70 A, blocking mode<br>T <sub>J</sub> ~T <sub>C</sub> =85°C | $\lambda_p = \lambda_b \cdot \pi_T \cdot \pi_S \cdot \pi_C \cdot \pi_Q \cdot \pi_E = 0.0038 \cdot 5.7 \cdot 0.77 \cdot 1.0 \cdot 5.5 \cdot 9.0 = 0.826$   | 826      |

### 4. The High-Altitude Impact

The high altitude can be included into the failure rate analysis by adding a further acceleration factor into the equation. The real measurement of the failure rate as a function of the geographical height above sea level is extremely complex and has only been carried out holistically by a few institutions in the past. From the data obtained here [3], the accelerating factor as given in Figure 5 can be used.

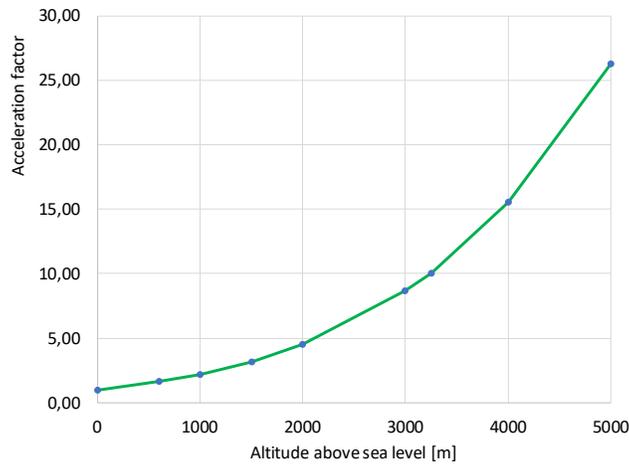


Figure 5. Acceleration factor to consider cosmic radiation [3]

By multiplying the calculated FIT-rate with the acceleration factor for high altitude, the final FIT-rate for an application depending on its geographical mounting position can be estimated. If a mission profile is given and the percentages of operating altitudes during the lifetime are known in detail, the weighted FIT-rate for a given equipment can be estimated as well.

The effect can best be demonstrated by an example: A system that has a FIT-rate of 10<sup>4</sup> is likely to fail within 10<sup>5</sup> operating hours, representing 10 years of permanent operation if mounted at sea level like in New York, Singapore, or Shanghai. If instead, the same system is mounted in La Paz, administrative capital of Bolivia which is located 3869 meters above sea level, the FIT-rate grows by a factor of 15. In turn, the system can be expected to fail in less than 8 months.

These correlations deserve special attention when considering power electronics for aircrafts or even satellites.

## 5. Conclusion

Cosmic radiation is a well-known and well-documented natural phenomenon describing high-energetic particles and their interaction with atmospheric particles forming secondary radiation. This secondary radiation poses a very real threat to power electronic components, as shielding cannot be considered a viable option. To still develop designs that operate reliably and durable in high-altitude environments, special care needs to be taken when choosing components.

The best options to enhance the resilience of a design in regards of cosmic rays is oversizing the components. Keeping a larger margin between the device's rated voltage and the voltage to be expected in the application is the best option. Oversizing in current carrying capability and in turn reducing the temperature swing within the component is the second option to choose from.

When properly done, successfully designing applications that can operate in these demanding situations can be achieved.

## 6. References

- [1] H. Kabza, H.-J. Schulze, Y. Gerstenmaier, P. Voss, J. Wilhelmi, W. Schmid, F. Pfirsch und K. Platzöder, "Cosmic Radiation as a Cause for Power Device Failure and Possible Countermeasures," *Proc. of the 6th International Symposium on Power Semiconductor Devices & IC's*, Davos, Switzerland, 1994
- [2] Military Handbook 217F, Reliability Prediction of Electronic Equipment, Department of Defense, Washington
- [3] Application Note 5SYA 2042-09, Failure rates of IGBT modules due to cosmic rays ABB Power Grids Switzerland Ltd, 2019

For additional information please visit [www.Littelfuse.com/powersemi](http://www.Littelfuse.com/powersemi)

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