AN4589

Excess Failure Rate Calculation Due to Neutron Flux with SiC MOSFETs and Schottky Diodes

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1.0 INTRODUCTION

Neutron-induced failures in power electronics are of concern in many higher reliability applications. The following document describes the process by which a decrease in lifetime expectancy can be estimated based upon the usage of the device. This estimation is most accurate at an altitude between sea level and 15,000 meters (50,000 feet). It is not applicable to space-based applications. The document is applicable to Microchip's family of SiC MOSFETs and diodes.

The experimental data in this document is from three sets of tests by CoolCAD Electronics LLC of Microchip devices. Reports dated March of 2019, August of 2022 and October 2023 are available upon request.

2.0 THE PHYSICAL MECHANISM

The process by which neutron-induced failures occur starts with high-energy particles entering the earth's atmosphere. Most of these particles are charged and are deflected by the earth's magnetic field. For this reason, neutron-induced failures are latitude dependent.

Particles entering the atmosphere are various nuclear fragments, a combination of protons, helium, heavier nuclear ions, high-energy gamma rays, etc. Various nuclear interactions take place early in the process of entering the atmosphere. Energy is spread to other gas atoms. This reduces the energy of individual interactions and increases the number of involved particles subject to the conservation of energy and momentum for the overall system.

Deeper in the atmosphere, the most significant reaction product is neutrons. Neutrons are not charged. This allows them to penetrate through any solid, without interaction with other atoms. Charged particles are subject to what is referred to as the Coulomb barrier. Neutrons, not being charged, can penetrate the barrier easily.

When a neutron penetrates through the semiconductor crystal it sometimes collides with a lattice nucleus, kicking the atom out of the lattice and ionizing the atom. Free particles result from this collision. These free particles ionize other atoms that are still fixed to the lattice. The result is a stream of hole/electron pairs along the path of the atom. If the free particles reach a voltage blocking region, they will accelerate toward their terminal atoms. Electrons to the positive side, holes to the negative side. As they accelerate they can generate more hole/electron pairs, multiplying their effect. By this multiplication, an avalanche is formed. Avalanching generates heat and can destroy the device.

The avalanche process is voltage dependent. The probability of a device capturing a neutron is dependent on the volume of the device. Five factors influence the probability of neutron-induced failure.

From most important to least, these are:

- Operating voltage in relation to breakdown voltage
- Altitude
- Device volume, with a slight dependence upon device structure
- Latitude
- Duty factor, the device must be blocking voltage for a failure to occur.

3.0 FIT RATE STATISTICS

The semiconductor industry normalizes the FIT (Failure in Time) rate at over 10^9 hours. For example, a FIT rate of one means that at an average of 10^9 device-hours of functioning, one device is expected to fail. It can also mean that out of 10^9 devices it is expected that an average of one device would fail in one hour. Neutron-induced failures are a random occurrence that fit with this type of model. There are other sources of failures, which are not considered in this document:

- Infant mortality.
- Extended usage/wear out.
- Failures during normal usage related to stress caused by humidity or heat. These stresses may be expressed as a FIT rate or a wear out mechanism. These depend on the way the stress results in failure.

Some properties of FIT rates:

- FIT rates can be added. In a system with multiple devices the FIT rate of the individual components are added.
- FIT rates can be summed over time. An average FIT rate can be assigned by weighing the FIT rate under various operating conditions multiplied by the fraction of time the device is at that operating condition. Neutron induced failures are an example of this. If an aircraft spends 30% of its time at an altitude of 10 km and 70% at 1 km, the profile adjusted FIT rate equals 0.3 × FIT(10 Km) + 0.7 × FIT(1 Km).
- The system MTBF (Mean Time Between Failures) = 1 / the system summed FIT rate.

Experimental FIT rate data presented in this document were measured with devices of the given voltage and type. The FIT rate is proportional to device volume. A correction factor is applied to scale from the measured device to the application device.

4.0 FIT RATE CALCULATION

There are many ways to calculate neutron flux density. This aspect is caused by many sources of information, variation of measured results and the overall complexity of the problem. The calculations in the following sections are described in order to provide some background information on the sources.

4.1 Latitude Dependence

IEC TS 62396-1 2006, section 5.3.4 provides neutron flux as a function of latitude. This was curve fit to a tanh function and normalized to a value of one at a latitude of 45 degrees. 45 degrees is used to match the latitude of NASA (National Aeronautics and Space Administration) and Boeing altitude dependence measurements.

The latitude correction formula is:

EQUATION 1:

$$Flat\_numb = 0.857 + 0.559 \times \tanh\left(\frac{latitude - 42}{11.5}\right)$$

The range of this function is roughly from 0.30 to 1.40, domain 0 to 90. The result is unitless. The function plots as follows:

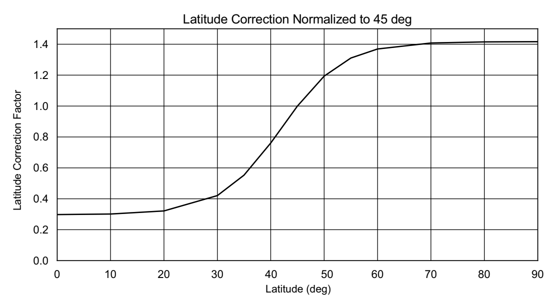

FIGURE 1: *Latitude Correction Chart.*

4.2 Altitude Dependence

There are two methods provided here to calculate altitude dependence. Both are only useful to about 15,000 meters (50,000 feet) due to high altitude effects. The first is by ABB referenced in ABB application notes 5SYA 2046-03 and 5SYA 2042-09.

EQUATION 2:

$$Falt\_numb = exp\left[\frac{1-\left(1-\frac{h}{44300}\right)^{5.26}}{0.143}\right]$$

The altitude “h” is measured in meters with a range from 0 to 15 km. This equation is unitless and is normalized to a value of one at sea level.

Equation 1 and Equation 2 can be used together to represent absolute flux density. For this, Equation 2 is modified with a multiplier of 13.3 to express flux density. in measurement units of n/cm^2/hr. This matched roughly with Boeing data presented in IEC TS 62396-1 2006. The resulting equation is presented below:

EQUATION 3:

$$Falt = 13.3 \times exp\left[\frac{1-\left(1-\frac{h}{44300}\right)^{5.26}}{0.143}\right]$$

The altitude "h" is measured in meters with a range from 0 to 15 km. As was explained above, the measurement units of this resulting function are n/cm^2/hr.

A second equation provided by CoolCAD follows. CoolCAD literature provides the equation in measurement units of n/cm^2/s with the altitude in units of feet. The final form provided here is adjusted to measurement units of n/cm^2/hr and altitude in meters:

The altitude "h" is measured in meters, which is immediately converted to feet with the 3.28 multiplier. This equation is discontinuous at zero. When calculating FIT below 300 meters it is recommended to use 300 meters.

The graphic below compares the Boeing simplified model presented in IEC TS 62396-1 with the two equations above by ABB and CoolCAD.

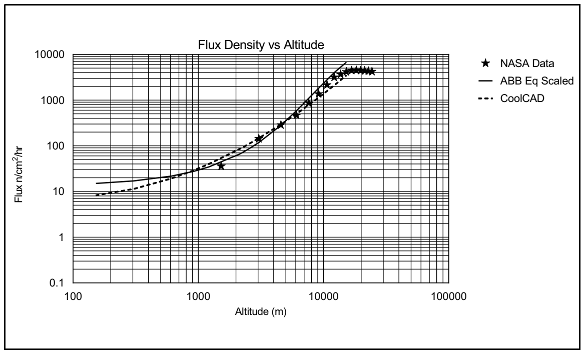

FIGURE 2: *Flux Density vs. Altitude.*

As can be seen in the NASA data, the flux density is very nonlinear above about 15,000 meters, which is the reason these equations should not be used in that case. The raw NASA data is available in IEC TS 62396-1.

4.3 Normalization of Neutron Flux Density

The process of FIT rate calculation starts by determining the effective neutron flux for an application. This can be done with a fixed position application with a known latitude and altitude. The product between Equation 1 and Equation 3 or Equation 4 can be used.

Automotive and aircraft applications are more complicated. A profile must be provided. Equation 1 together with Equation 3 or Equation 4 are used to calculate the neutron density for each element of the profile, multiplied by the fraction of time in that profile. The elements of the profile are then summed to yield the overall profile.

4.4 Using Normalized FIT Rate Charts

Section 5.0 and **Section 6.0** present experimental data for Microchip SiC MOSFETs and diodes respectively. Experimental data is presented together with an average FIT equation. The FIT rate graphics and equations presented are all normalized to a measurement unit of 13 n/cm^2/hr.

EQUATION 4:

$$Falt = 3600 \times 10^{0.2093 - 2.41511 \times \log 10(h \times 3.28) + 0.50386 \times \log 10(h \times 3.28) \times \log 10(h \times 3.28)}$$

These graphics are applied as follows:

1. Determine which graphic applies by matching the voltage class of the device in the application with the appropriate graphic. For example, when considering device MSC080SMA120J select MSCxxxSMA120, **Section 5.3**.
2. Determine the operating voltage in the application.
3. Multiply the FIT rate from the graphic by the volume correction table below the graphic to get the FIT rate for the specific device. This results in the FIT rate @ 13 n/cm^2/hr.
4. Multiply by the number of devices and the blocking voltage duty factor.
5. The result is the FIT rate for the application at a flux level of 13 n/cm^2/hr.

Based on the previous section, the average flux density is calculated by association with the application using Equation 1 together with Equation 3 or Equation 4.

The overall FIT rate = the device FIT rate calculated here × the application flux density divided by 13 n/cm^2/hr. That can all be done in one equation but doing so does not provide much insight into the calculation.

Example:

Assume an inverter operates at 1000V, 6.1 km altitude for eight hours a day, at 30 degrees latitude. It uses MSC025SMA120 in a half bridge arrangement.

- The graphic of **Section 5.3** puts the FIT rate for MSC040SMA120 at 2500.
- The die volume scaling factor to MSC025SMA120 is 1.6.
- The duty factor between the high side and low side transistors can be summed to one. If the desired FIT rate is per calendar time multiply by 8/24. If it is per operating time multiply by one.
- The latitude correction factor is approximately 0.35, per Equation 1.
- The CoolCAD calculated flux density is approximately 500 n/cm^2/hr, per Equation 4 above at 6.1 km.

The resulting calculated FIT rate is:

$$2500 \times 1.6 \times 0.35 \times (500/13) = 5384 \text{ failures per billion operating hours}$$

$$5384 \times (8/24) = 1795 \text{ failures per billion calendar hours}$$

5.0 SiC MOSFET FIT RATES

The graphs in the following sections express the FIT rate at sea level 45 degrees latitude for various devices.

This data is for multiple generations of devices. Data was taken at different times.

Each section title contains a reference to the part numbers of the applicable devices and the associated test report.

5.1 700V – p/n MSCxxxSMA070

The following graphics expresses FIT as a function of operating voltage for MSC035SMA070B, based upon the CoolCAD September 2022 report.

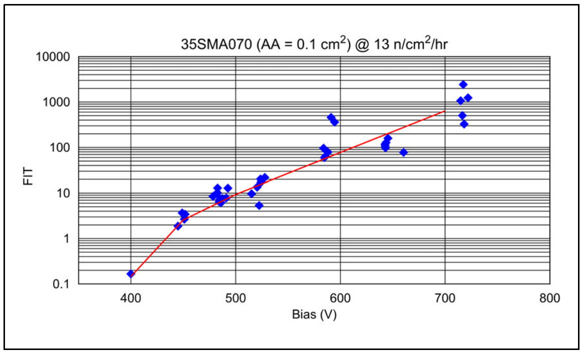

FIGURE 3: *FIT vs. Operating Voltage, MSC035SMA070B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.0211 \times Vds - 8.307)$$

$$FIT2 = exp(0.085 \times Vds - 36.029)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC090SMA070*	0.46
MSC060SMA070*	0.64
MSC035SMA070*	1
MSC015SMA070*	2.1

5.2 1200V – p/n MSC017SMA120

The following graphics expresses FIT as a function of operating voltage for MSC017SMA120B, based upon the CoolCAD October 2023 report.

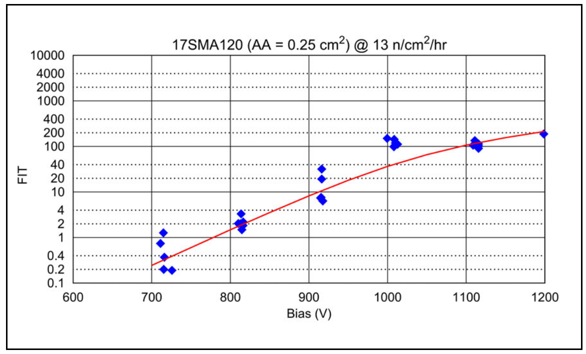

FIGURE 4: *FIT vs. Operating Voltage MSC017SMA120B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.004512 \times Vds - 0.05158)$$

$$FIT2 = exp(0.01827 \times Vds - 14.188)$$

No volume correction factor is required.

5.3 1200V – All Other MSCxxxSMA120

Excludes MSC017SMA120, MSCxxxSMB, MSCxxx-SMC.

The following graphics expresses FIT as a function of operating voltage for MSC040SMA120B. These measurements are based upon the CoolCAD March 2019 report.

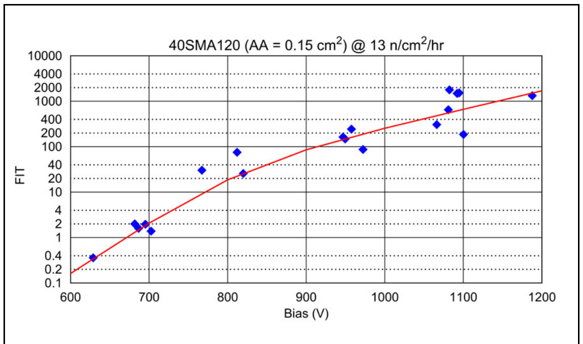

FIGURE 5: *FIT vs. Operating Voltage, MSC040SMA120B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.0093 \times Vds - 3.73)$$

$$FIT2 = exp(0.0266 \times Vds - 17.7)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC360SMA120*	0.19
MSC180SMA120*	0.31
MSC080SMA120*	0.60
MSC040SMA120*	1
MSC025SMA120*	1.60

5.4 1200V – p/n MSCxxxSMB120, MSCxxxSMC120

The following graphics expresses FIT as a function of drain voltage. These measurements are based upon the CoolCAD November 2023 report.

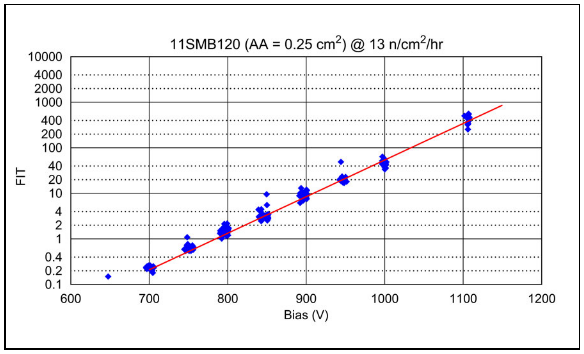

FIGURE 6: *FIT vs. Operating Voltage, MSC011SMB120.*

The curve fit shown above is:

$$FIT = exp(0.0185 \times Vop - 14.51)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC011SMB120	1
MSC011SMC120	1
MSC020SMB120	0.57
MSC025SMB120	0.45
MSC030SMB120	0.38
MSC040SMB120	0.29
MSC045SMB120	0.25
MSC060SMB120	0.19
MSC080SMB120	0.14

5.5 1700V – p/n MSCxxxSMA170

The following graphics expresses FIT as a function of operating voltage for MSC035SMA170B, based upon the CoolCAD March 2019 report.

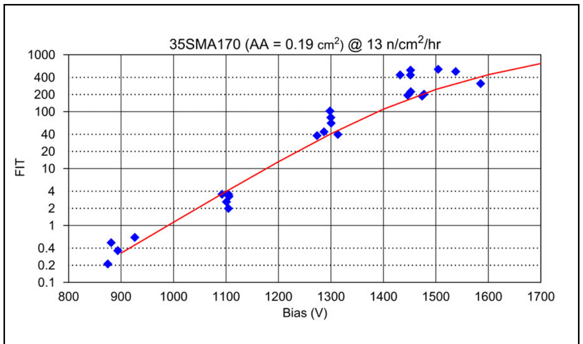

FIGURE 7: *FIT vs. Operating Voltage, MSC035SMA170B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.0126 \times Vds - 12.4)$$

$$FIT2 = exp(0.00326 \times Vds - 1.1)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC750SMA170*	0.115
MSC035SMA170*	1

5.6 3300V – p/n MSCxxxSMA330

The following graphics expresses FIT as a function of operating voltage for MSC080SMA330B, based upon the CoolCAD September 2022 report.

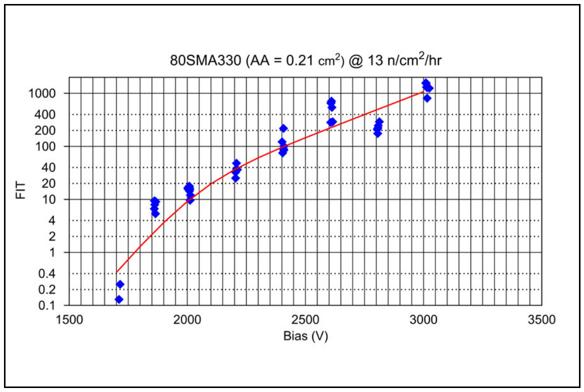

FIGURE 8: *FIT vs. Operating Voltage, MSC080SMA330B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.00395 \times Vds - 4.871)$$

$$FIT2 = exp(0.01198 \times Vds - 21.164)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC400SMA330*	0.42
MSC080SMA330*	1
MSC027SMA330*	1.58
MSC025SMA330*	1.58

6.0 SiC DIODE FIT RATES

The graphs in the following sections express the FIT rate at sea level 45 degrees latitude for various devices.

This data is for multiple generations of devices. Data was taken at different times.

Each section title contains a reference to the part numbers of the applicable devices and the associated test report.

6.1 700V – p/n MSCxxxSDA070

The following graphics expresses FIT as a function of operating voltage for MSC050SDA070B, based upon the CoolCAD March 2019 report.

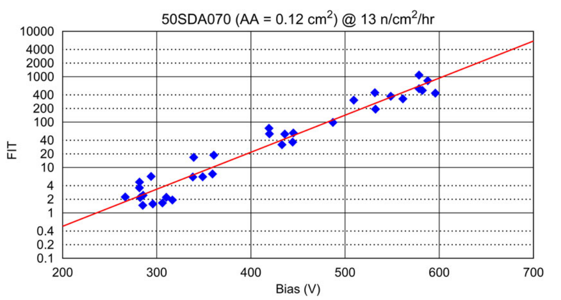

FIGURE 9: *FIT vs. Operating Voltage, MSC050SDA070B.*

The curve fit shown above is:

$$FIT = exp(0.0188 \times Vop - 4.44)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC010SDA070*	0.23
MSC030SDA070*	0.59
MSC050SDA070*	1
MSC2X50.,51SDA070J	1 for each half, 2 total if paralleled
MSC2X100 SDA070J	2 for each half, 4 total if paralleled

6.2 1200V – p/n MSCxxxSDA120

The following graphics expresses FIT as a function of operating voltage for MSC050SDA120B, based upon the CoolCAD March 2019 report.

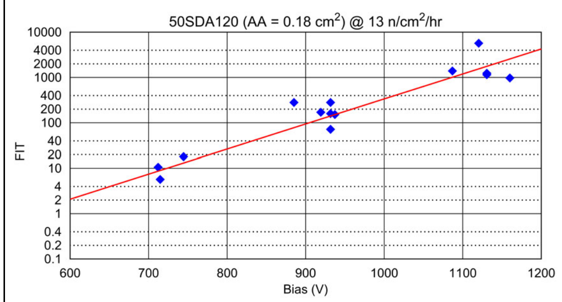

FIGURE 10: *FIT vs. Operating Voltage, MSC050SDA120B.*

The curve fit shown above is:

$$FIT = exp(0.0128 \times Vop - 6.88)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC010SDA120*	0.23
MSC015SDA120*	0.36
MSC020SDA120*	0.45
MSC030SDA120*	0.62
MSC050SDA120*	1
MSC2X50.,51SDA120J	1 for each half, 2 total if paralleled
MSC2X100 SDA120J	2 for each half, 4 total if paralleled

6.3 1700V – p/n MSCxxxSDA170

The following graphics expresses FIT as a function of operating voltage for MSC050SDA170B, based upon the CoolCAD March 2019 report.

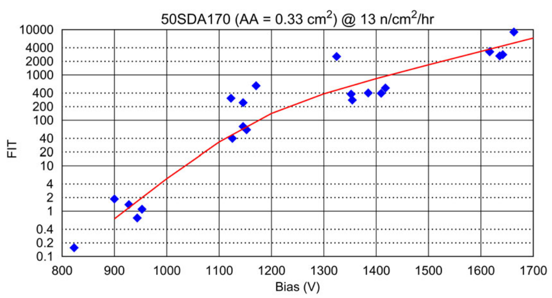

FIGURE 11: *FIT vs. Operating Voltage, MSC050SDA170B.*

The curve fit shown above is:

$$\frac{1}{FIT} = \frac{1}{FIT1} + \frac{1}{FIT2}$$

Where:

$$FIT1 = exp(0.00677 \times Vop - 2.72)$$

$$FIT2 = exp(0.0211 \times Vop - 19.4)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC010SDA170*	0.23
MSC030SDA170*	0.59
MSC050SDA170*	1
MSC2X30.,31SDA170*	0.59 for each half, 1.18 total if paralleled
MSC2X50.,51SDA170*	1 for each half, 2 total if paralleled

6.4 3300V – p/n MSCxxxSDA330

The following graphics expresses FIT as a function of operating voltage and altitude for MSC030SDA330B, based upon the CoolCAD September 2022 report.

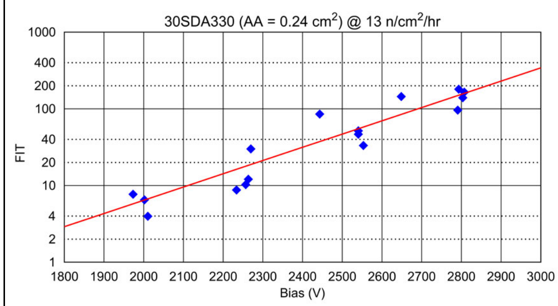

FIGURE 12: *FIT vs. Operating Voltage, MSC030SDA330B.*

The curve fit shown above is:

$$FIT = exp(0.006796 \times Vop - 12.89)$$

Use the following table to correct for die size:

Device	Volume Correction Factor
MSC030SDA330*	1
MSC090SDA330*	3.3

REFERENCES

1. CoolCAD Report, CoolCAD Electronics LLC, March 2019.
2. Technical Specification IEC TS 62396-1, Section 5.3.4, 2006.
3. Application Note 5SYA 2046-03, ABB, 2019.
4. Application Note 5SYA 2042-09, ABB, 2019.
5. CoolCAD Report, CoolCAD Electronics LLC, September 2022.
6. CoolCAD Report, CoolCAD Electronics LLC, November 2023.

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