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Process management for avionics – Atmospheric radiation effects – Part 4: Design of high voltage aircraft electronics managing potential single event effects

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FOREWORD

International Standard IEC 62396-4 has been prepared by IEC technical committee 107: Process management for avionics.

This International Standard is to be used in conjunction with IEC 62396-1:2012.

This first edition cancels and replaces IEC/TS 62396-4 published in 2008. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Change to title.

b) Clause 4 inclusion of SEGR.

c) Inclusion of 6.5 concerning SEB due to thermal neutrons.

d) Consideration of alternative materials to silicon in 6.6.

The text of this international standard is based on the following documents:

FDIS	Report on voting
107/211/FDIS	107/221/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 62396 series, published under the general title *Process management for avionics – Atmospheric radiation effects,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual edition of this document may be issued at a later date.

INTRODUCTION

This industry-wide international standard provides guidance and requirements to design high voltage aircraft electronics for electronic equipment and avionics systems. It is intended for avionics system designers, electronic equipment manufacturers, component manufacturers and their customers to manage the single event effects produced in semiconductor devices operating at high voltage (nominally above 200 V) by atmospheric radiation. It expands on the information and guidance provided in IEC 62396-1:2012.

The internal elements of semiconductor devices operating at high applied voltage will be subject to high voltage stress. The incident radiation causes ionisation charge within the device, and the high voltage stress may cause a large increase (avalanche) in this charge, which may be destructive. Within this part of IEC 62396 two effects are considered: single event burnout (SEB), and single event gate rupture (SEGR).

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 4: Design of high voltage aircraft electronics managing potential single event effects

1 Scope

This part of IEC 62396 provides guidance on atmospheric radiation effects and their management on high voltage (nominally above 200 V) avionics electronics used in aircraft operating at altitudes up to 60 000 ft (18,3 km). This part of IEC 62396 defines the effects of that environment on high voltage electronics and provides design considerations for the accommodation of those effects within avionics systems.

This part of IEC 62396 provides technical data and methodology for aerospace equipment manufacturers and designers to standardise their approach to single event effects on high voltage avionics by providing guidance, leading to a standard methodology.

Details are given of the types of single event effects relevant to the operation of high voltage avionics electronics, methods of quantifying those effects, appropriate methods to provide design and methodology to demonstrate the suitability of the electronics for the application.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62396-1:2012, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62396-1:2012 apply.

4 Potential high voltage single event effects

An N-channel power MOSFET can have two different types of destructive effects induced by the deposition of charge from a single energetic particle, single event burnout (SEB) and single event gate rupture (SEGR). Different tests performed on several devices show that is difficult to induce SEB in P-channel MOSFET [1], [2] [1]. In addition to this kind of power MOSFET, other power devices, such as insulated gate bipolar transistors (IGBTs), bipolar power transistors and diodes, which have large applied voltage biases and high internal electric fields, are susceptible to SEB.

In SEB, the penetration of the source-body-drain region by the deposited charge can forward bias the thin body region under the source. If the bias applied to the drain exceeds the local

1 Numbers in square brackets refer to the Bibliography.

breakdown voltage of the parasitic bipolar elements, the single event induced pulse initiates avalanching in the drain depletion region that eventually leads to destructive burnout SEB. SEB can be induced by heavy ions, high energy protons [3] and high energy neutrons [4].

SEGR applies to N- and P-channel MOSFETs. It is explained via the transient plasma filament created by the energy deposition track when the MOSFET is struck through the thin gate oxide region. As a result of this transient track filament, there is a localized increase in the oxide field which can cause the oxide to break down, leading first to gate leakage and finally to gate rupture. The SEGR failure mechanism has been widely studied by heavy ion testing and effects have been identified on different devices with various levels of sensitivity [2]. For the time being, experiments show also that SEGR induced by heavy ions is more an issue for space systems, and guidance for heavy ion SEGR testing is available [5]. As a consequence of the atmospheric neutrons, SEB is the major threat to high voltage electronics.

There remains a paucity of data on the question of neutron-induced single event gate rupture (SEGR) in power devices. In the late 1990s one study looked for, but did not find, SEGR in 500 V power MOSFETs during accelerated spallation neutron testing [1]. Shortly afterwards, however, dielectric breakdown was observed in 60 V power MOSFETs during 44 MeV and 200 MeV proton irradiation [6]. As the gate ruptures in these devices were almost certainly caused by charge deposition from recoil ions, rather than by direct ionisation from the very low LET protons, sensitivity to neutrons was implied.

Data published more recently show more direct evidence of neutron-induced SEGR in devices rated at ~1 kV. Hands *et al.* observed significant gate damage to a 1 kV power MOSFET at a spallation neutron facility, with a dependence on gate bias consistent with SEGR [7]. Griffoni *et al.* tested a variety of devices, including IGBTs, SiC MOSFETs and superjunction (SJ) MOSFETs in quasi-monoenergetic neutron environments, and observed SEGR only in the SJ MOSFETs [8]. Interestingly, in this latter case the SEGR failure rate was sometimes higher than the SEB failure rate, though no dependency on gate bias condition was investigated to characterise the relative susceptibilities. These results demonstrate that fast neutrons (and protons) are very capable of causing damage to the gate regions of power devices and, where conditions are right, this damage can lead to dielectric breakdown and catastrophic failure. Therefore this failure mode should be considered and, where appropriate, quantified during accelerated testing of HV devices.

Although at the outset this threat to the power system in an aircraft from SEB from the atmospheric neutrons may appear to be remote or even far-fetched, the experience of breakdowns in the high voltage electronics on electric trains in Europe before 1995 shows that SEB can be real and has happened in the field. In that case, European and Japanese manufacturers of high voltage semiconductors noticed that some of their devices were undergoing burnout failures in the field during normal operation of newly developed train engines [9, 10]. The diodes and GTO thyristors (gate turn-off thyristors) used on the trains were rated at 4 500 V, and were normally operated at 50 % to 60 % of rated voltage. They were designed for terrestrial use for > 35 years, so when the failures first appeared in the field after only a few months, this was puzzling. The failure mode was investigated in great detail and eventually a set of experiments was carried out at three different locations (salt mine, top-floor laboratory and basement); the results convinced the investigators that the cause of the failures was the cosmic ray neutrons. Since that time, the manufacturers of these very high voltage devices have been careful in recommending the voltage at which the devices can be operated safely without SEB.

In addition, these manufacturers have followed the methodology established by an experienced radiation effects group [1] by carrying out tests in the WNR beam at Los Alamos National Laboratory to characterize the response of their devices to a simulated high-energy neutron environment. Because the atmospheric neutron flux is higher by about a factor of 300 at aircraft altitudes compared to sea level, it is clear that the same effect can occur in high voltage electronics in aircraft. The reason that, as far as is known, such failures have not been experienced previously in the field in aircraft power electronics is that the bus voltage used in aircraft systems has always been low enough to preclude SEB or SEGR.

Generally, the highest voltage used in aircraft power systems has been 270 V, and a practical lower onset limit for most high voltage devices is 300 V. This practical lower limit stems from the fact that with SEB there is a threshold voltage for the effect to occur; if V_{ds} is kept below the threshold voltage, there will be no SEB. Thus for 270 V operation, devices rated at 400 V or 500 V would be used, resulting in a situation in which the devices are being operated at a derating factor of 67,5 % and 54 % respectively. Since the devices are being used at < 300 V and with a derating factor of < 70 %, these conditions are sufficient to preclude any single event burnout in the high voltage electronics.

However, in advanced designs for avionics systems significantly higher voltages are being considered for the bus voltage in order to reduce the overall weight of the system. The voltage will thus be > 300 V and in fact 600 V has often been mentioned as a practical bus voltage. Thus, in order to preclude SEB from occurring in the high voltage electronics of such advanced avionics systems, a sufficiently low derating factor will have to be used, and the adequacy of the derating factor will have to be demonstrated through testing.

5 Quantifying single event burnout in avionics for high voltage devices

Thus, the problem becomes that avionics vendors are asked to provide systems that will operate at higher voltages, e.g., 600 V, and there has been virtually no guidance for them to use in developing the designs that will avoid the potential of SEB in the high voltage devices such as power MOSFETs and IGBTs.

In reality, the situation with SEB in high voltage electronics is relatively similar to that of single event upset (SEU), in low voltage devices (< 5 V) such as random access memories (RAMs), microprocessors and FPGAs. The threat of SEU from the atmospheric neutrons in the low voltage devices has been dealt with very extensively in the technical literature and in IEC 62396-1:2012. The approach in IEC 62396-1:2012 is that the rate of the single event effect, in this case SEU, in the devices, can be estimated by the following equation:

$$\text{SEE rate per device (per hour)} = 6\,000\ (\text{n/cm}^2\text{h}) \times \text{SEE cross section (cm}^2 \text{ per device)} \qquad (1)$$

The 6 000 n/cm^2 per hour flux is a nominal value for the cosmic ray neutrons with energy > 10 MeV, at 40 000 ft (12,2 km) altitude and 45° latitude. It shall be adjusted for different altitudes and latitudes using the data tables in Annex D of IEC 62396-1:2012. For RAMs especially, a great deal of SEU cross section data has been published, allowing users of the standard to estimate the SEU rate, and some SEU cross section data is also available for microprocessors and FPGAs.

The same Equation (1) shall be used for SEB rates in high voltage devices provided that SEB cross sections are known for specific devices operated at a specified voltage. This part of IEC 62396 recommends the use of Equation (1) for calculating SEB rates even though it is recognized that this is conservative. There is very little published data on the SEB cross sections, but the data that does exist [1], [4] suggests that the SEB cross section is significantly reduced at lower neutron energies compared to e.g. 200 MeV. The most suitable facilities for measuring SEB cross sections are spallation sources with maximum energy above 200 MeV. Thus the minimum neutron energy threshold for calculating the SEB rate (energy at which the SEB cross section is similar to that at high energy, e.g., 200 MeV) is 100 MeV. The available SEB cross section data is documented in Clause 6.

For avionics applications it should be recognized that assuming the high voltage electronics will be operating at a single voltage is unrealistic. First, the airplane power system is expected to experience power transients and spikes during flight. The transients typically last for less than 1 s, during which time V_{ds} could increase from 270 V to 350 V. The cascading power spikes can increase the voltage to even higher levels above nominal, although the duration is much shorter, usually < 100 µs.

Secondly, the operating details of the high voltage equipment are important in evaluating its susceptibility to SEB. For example, in the case of certain types of DC-DC converters, the voltage across the MOSFET is not continuous. The MOSFET cycles between off and on states, and the voltage across the MOSFET during the off state is higher than during the on state due to an inductive voltage associated with the mechanism that allows the magnetic energy to be discharged [11]. The highest voltage across the MOSFET is during the off state, but its magnitude depends on several operational parameters of the converter (e.g., V_{in}, V_{out} and output current). Thus, a true evaluation of the SEB susceptibility should take into consideration the voltage across the MOSFET throughout the complete duty cycle and set of operating conditions of the converter. Other high voltage components may have similar variations in their operating conditions.

The use of the WNR beam to perform accelerated SEB testing of very high voltage devices [1] has spurred considerable additional testing of the very high voltage devices (> 2 kV) by the microelectronics companies that manufacture these devices. This testing has used the WNR facility as well as other sources of neutrons. The other neutron sources include the quasi mono-energetic neutron beam created by a proton beam on a lithium target (e.g., at the Svedberg Laboratory in Sweden) or high elevation research stations (Sphinx Laboratory at Jungfraujoch, Switzerland, 11 300 ft (3,4 km) high). However, the results of such testing are usually considered proprietary and not published, or if a few are published, it is in a little known publications [12], [13]. In addition, for these vendors having ground level applications, their results are often put into the format of a FIT (failure in time) rate, 1 FIT being equal to one failure in 10^9 device hours of operation [1].

The key points are that none of these very high voltage devices are relevant to avionics applications currently and that some vendors treat their SEB data as proprietary. However, the familiarity of these HV electronics vendors with the overall SEB issue from neutrons means that if they also manufacture lower voltage devices, devices that are relevant to avionics applications, they may have SEB data, but this data will often be considered proprietary.

6 Relevant SEB data and applying it to avionics

6.1 SEB data from heavy ion testing is not relevant

It is surprising that when it comes to SEB induced by high-energy protons and neutrons, there are only a limited number of IEEE papers [1], [2], [4] that discuss this subject and present useful data, despite the fact that the first evidence of proton-induced SEB in MOSFETs was documented in a 1988 report [3]. Since the 1988 report, almost all data published concerning SEB in power devices has been based on single event effects testing using heavy ions to simulate the cosmic rays rather than with protons and neutrons. The results of heavy ion testing are not relevant to the situation with high energy neutrons and protons. This heavy ion SEB data could theoretically be used if the SEB cross section induced by the heavy ions was measured, but in most cases this isn't done, only the values of V_{ds} and V_{gs} are presented at which no SEB occurs.

However, even if heavy ion SEB cross sections were known, applying them to avionics applications would be extremely conservative, and would result in highly conservative SEB rates for avionics applications. For example, just looking at the V_{ds} threshold value at which no SEB occurs, in a 500 V device that was tested with both high energy protons and heavy ions, the threshold was 330 V with WNR neutrons and 300 V with heavy ions. In addition, for a 400 V device, the threshold was 280 V with WNR neutrons and 220 V with heavy ions. Thus, the heavy ion results are overly conservative and there is really no substitute for SEB cross sections in high voltage devices measured using a high energy neutron or proton source.

6.2 SEB data from high energy neutron and proton testing

SEB cross section data from tests using high energy neutron and proton with 400 V and 500 V MOSFETs are shown in Figure 1. The data comes from testing by Boeing [1], [4] and Fermilab, the Fermi National Accelerator Laboratory [14]. For some of the parts the SEB cross sections are similar to one another at some values of V_{ds}, but for other parts there are some distinct differences. Figure 1 includes data taken by Boeing on various specific devices using both the WNR neutron beam as well as 149 MeV protons (Harvard cyclotron). The Fermilab data in Figure 1 was obtained using 200 MeV protons from the Indiana University Cyclotron Facility (IUCF). None of these Fermilab devices are identified as a specific part type.

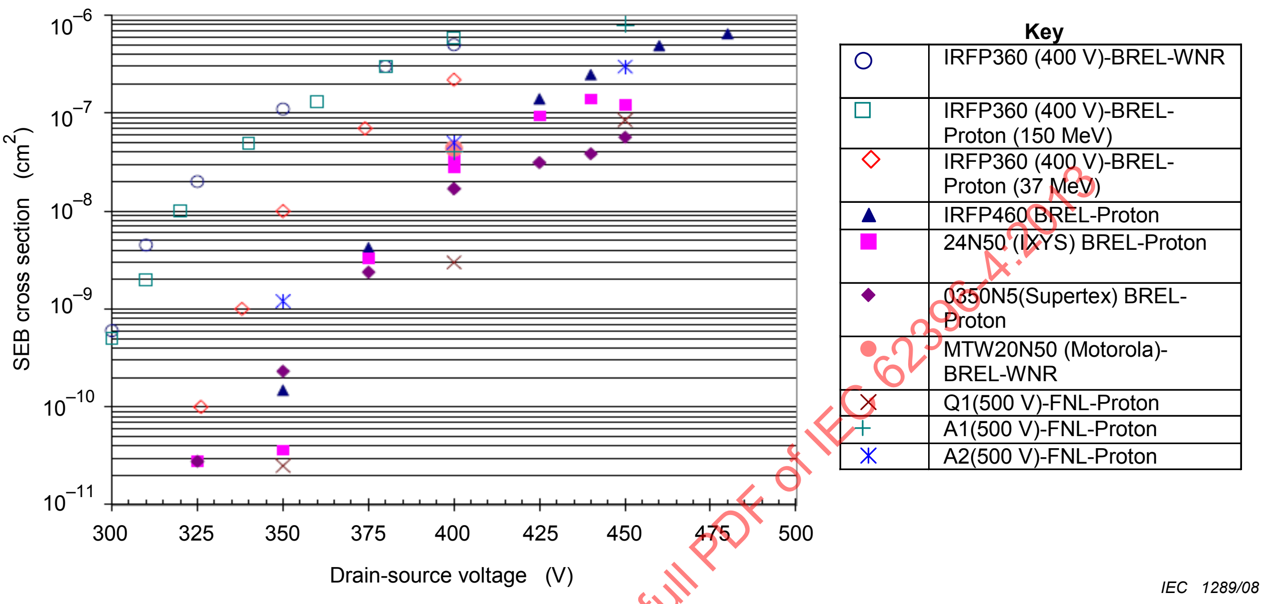


Figure 1 – SEB cross sections measured in 400 V and 500 V MOSFETs for WNR neutron and proton beams

In looking at Figure 1, it is clear that the voltage threshold for the 400 V IRFP360 is < 300 V. In reference [9] the threshold is given as 280 V, meaning that at 280 V there will be no SEB events, but that at higher voltages there will be. Figure 1 also shows that the SEB response of the IRFP360 is very similar when using the WNR neutron beam and a 150 MeV proton beam. However when using lower energy protons, e.g., 37 MeV protons, the SEB response is far too low compared to that with the WNR beam, some values of V_{ds} being too small by 1 to 2 orders of magnitude.

In a similar manner, the IRFP360 (rated at 400 V) has also been tested with 14 MeV neutrons [1]; in this reference it is clear that the SEB cross section induced with 14 MeV neutrons is much lower compared to the SEB cross section from WNR neutrons. With the IRFP360 in the WNR beam, the SEB cross section was 1×10^{-7} cm^2 per device at $V_{ds} = 350$ V and 5×10^{-10} cm^2 per device at $V_{ds} = 300$ V, whereas with 14 MeV neutrons, the SEB cross section was 3×10^{-9} cm^2 per device at $V_{ds} = 350$ V and no SEB could be induced at $V_{ds} = 300$ V. Thus, 14 MeV neutrons should not be used in SEB testing for avionics applications.

For the four different 500 V MOSFETs tested by BREL (Boeing), the SEB cross sections are generally within an order of magnitude of one another, even though there may be significant differences between them, such as the size of the die and the maximum allowable current. At some values of V_{ds}, the SEB cross sections are actually quite close for several of the devices. Of the three devices tested by FNL, one of these, Q1, exhibits a markedly smaller SEB cross section than all of the other devices, while the responses of the other two devices, A1 and A2, are much closer to the response of the devices tested by BREL.

Similar data for higher voltage parts, mostly 1 000 V MOSFETs and two 1 200 V IGBTs are presented in Figure 2. This data shows that there appears to be greater variation in the SEB cross section with the higher voltage devices compared to the 500 V MOSFETs in Figure 1. There is SEB cross section data on one part, the IRFPG50, using both 200 MeV protons and WNR neutrons. There is fairly good agreement between the two sets of measurements, with the proton SEB curve higher than the neutron curve by a factor of 2 to 3.

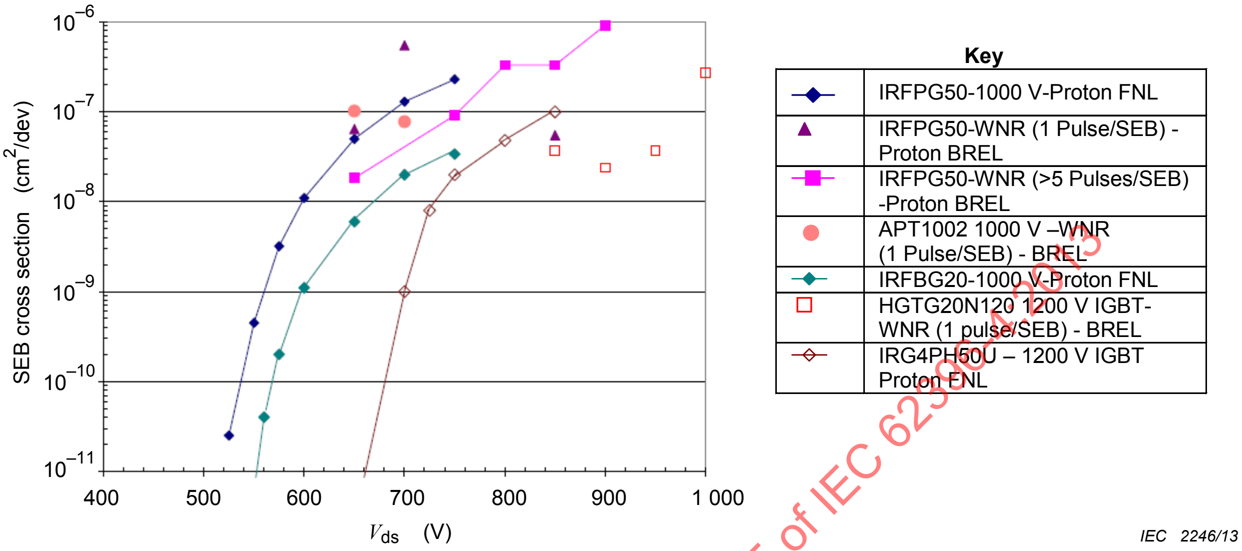


Figure 2 – SEB cross sections measured in 1 000 V MOSFETs and 1 200 V IGBTs with WNR neutron and 200 MeV proton beams

Two sets of SEB measurements were made with the WNR neutrons and these illustrate the importance of having good statistics (adequate number of burnout pulses) in calculating the SEB cross section. The SEB neutron curve that seems to parallel the proton curve was made on a single part with the burnout protection mechanism on the test card still operational so numerous burnout pulses could be counted during each neutron exposure. After the burnout protection mechanism was no longer operational, each burnout pulse destroyed the test sample, so there was only one burnout pulse per device. Since there were only a few samples available of each part type, the SEB cross section was based on a very small number of burnout pulses. For that reason, the SEB cross sections based on such a small number of pulses are not considered to be very accurate.

Although Figure 2 contains data on only two 1 200 V IGBTs, it clearly shows that the SEB cross sections for these devices are lower than those for 1 000 V MOSFETs by at least a factor of 10 and possibly more at lower voltages. However, since this is based on only two data points, such a generalization cannot be applied to other specific devices.

It also should be emphasized that most of the data in Figure 2 for the 1 000 V to 1 200 V devices are on devices from one vendor, International Rectifier, IR. The figure also includes data on one device from Harris and one from APT, but this is not adequate for the figure to be viewed as being representative of the SEB behaviour of comparable devices from all of the vendors that produce such devices. A similar caution needs to be applied to Figure 1, although this figure clearly has a wider range of high voltage manufacturers included in it. Figures 1 and 2 should be viewed only as giving the overall behaviour of the SEB cross section curve as a function of applied voltage. These figures cannot be used in place of data obtained from the testing of actual devices that are being considered for use in specific systems.

SEB cross section is also dependent on the temperature test conditions. Indeed, for N-channel power MOSFETs the SEB cross section is worse at 25 °C than at higher temperature [15]. This dependence of failure rate on temperature is also confirmed on high voltage diodes [16] and on IGBTs as a decrease with temperature increase but is not a general feature. This contribution has to be considered before testing or using cross section data for calculation of SEB rate at system level.

6.3 Calculating the SEB rate at aircraft altitudes

With the SEB cross sections shown in Figures 1 and 2, examples can be given on how to calculate the SEB rate for power devices. If it is assumed that a 500 V MOSFET is needed to operate at 400 V within an aircraft, from Figure 1 it can be observed that an upper bound SEB cross section would be ~5 × 10^{-8} cm^2 per device, so that the SEB rate at 40 000 ft (12,2 km) would be, following Equation (1), 3 × 10^{-4} burnout per device·hour. However, a much more reliable scenario would be to limit the MOSFET operating voltage to 300 V, in which case an upper bound on the SEB cross section would be 3 × 10^{-11} cm^2 per device leading to an upper bound SEB rate at 40 000 ft (12,2 km) of 2 × 10^{-7} burnout per device·hour. However, with better data or by extrapolating the limited data in Figure 1 more carefully, much lower values for the SEB cross section could be obtained. For example a SEB cross section that is at least a factor of 10 lower than 3 × 10^{-11} cm^2 per device could be obtained, or even further it could be assumed that 300 V is below the SEB threshold, in which case there would be no SEB at 300 V. This emphasizes the importance of having good SEB cross section data on specific parts of interest in order to obtain SEB rates in which confidence can be established.

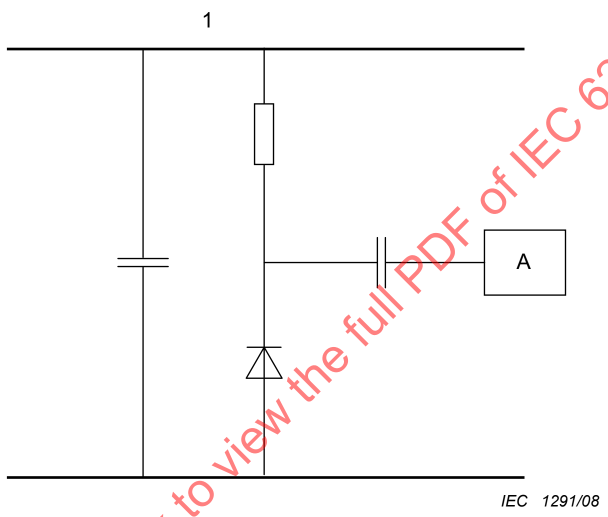
For advanced avionics systems that might operate at 600 V, from Figure 2 it can be observed that a reasonable value for the SEB cross section of a 1 000 V MOSFET would be 1 × 10^{-8} cm^2 per device. This would lead to SEB rate of 6 × 10^{-5} burnout per device·hour in the nominal neutron environment (IEC 62396-1:2012) at 40 000 ft (12,2 km) and 45° latitude. However, in looking at Figure 2, the data can also be extrapolated to 1 000 V to obtain an upper bound estimate on the SEB cross section that is an order of magnitude larger, in which case it would lead to a SEB rate of 6 × 10^{-4} burnout per device·hour. For the 1 200 V IGBTs, the data on the IRG4PH5OU would indicate that 600 V is below the threshold of this specific device, in which case no SEB would be expected from the atmospheric neutrons. The very limited data on the other IGBT, the HGTG20N120, is not adequate to allow extrapolation to voltages below 850 V, so no conclusion may be drawn as to the SEB susceptibility of this device at 600 V. Thus again, these examples emphasize the importance of having good SEB cross section data on specific parts of interest in order to obtain SEB rates in which confidence can be established.

6.4 Measurement of high voltage component radiation characteristics, EPICS

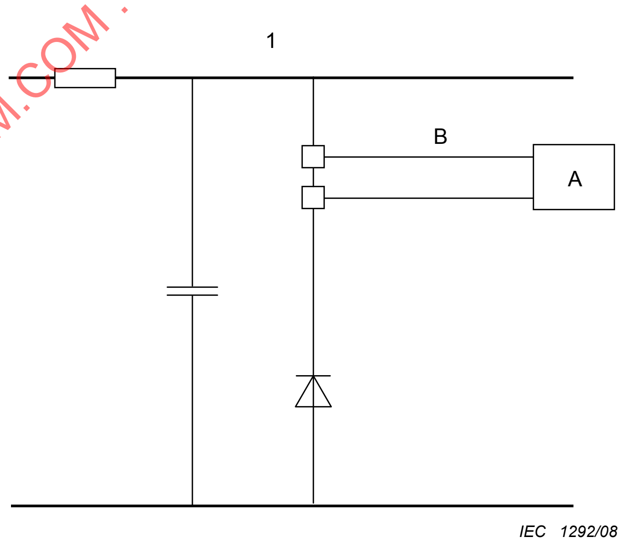
EPICS (energetic particle induced charge spectroscopy) is primarily a non-destructive technique [17] when the applied voltage is limited below the SEB threshold, which shall be used to determine the charge or current response of high voltage devices under applied voltage to radiation. The technique was developed to assist in the understanding of the mechanisms behind charge multiplication within high voltage electronic devices and shall be used to determine derating margins for devices operating at high applied voltages under radiation.

The basis of the measurement technique is shown for a high voltage diode in Figure 3 (a) and b)) using a charge and current measurement technique respectively. The high voltage (labelled 1 in the figures) is provided with a suitable storage capacitor. In the charge measurement technique a charge sensitive amplifier, CSA (A in Figure 3a)) is used in combination with a multi-channel pulse height analyser, to record the radiation induced event charge at different applied voltages. Alternatively, the radiation induced event current may be measured using transformer current probes B of differing current ranges in combination with, for example, a digital oscilloscope (A in Figure 3b)) employing suitable input sensitivity to provide a wide current monitor range [18].

The results are normally plotted as the number of events per charge or current interval in a logarithmic scale against the logarithm of the charge or current. In Figure 4 for results taken at TRIUMF using the arrangement of Figure 3b), the X axis is the logarithm to base 10 of the event current in milliamperes. The technique has the benefit that each measured event contributes to the graph. A typical EPICS plot for current measurement under simulated atmospheric neutron radiation (TRIUMF, NIF maximum energy 400 MeV) of a 1 200 V diode is shown in Figure 4 where the curves at each applied voltage have been normalised to the same fluence ($3,5 \times 10^9$ neutrons per cm^2) at each voltage. Above 300 mA (2,5 on the logarithmic scale) the diodes potentially burn out (SEB). This is a measure of the critical current (charge). As the applied voltage increases the number of events rises (see Figure 4), the event cross section is rising and the peaks move to the right (increasing current and charge). For an applied voltage of 800 V and below there were no single event burnout (SEB) events, at a neutron fluence of 10^9 neutrons per cm^2. This equates to a neutron cross section of less than 10^{-9} cm^2 at 800 V. At a higher applied voltage of 900 V SEB can occur. Figure 5 clearly demonstrates the effect of increasing voltage stress when both the number of recorded events (increasing cross section) and the value of the induced currents rise. At lower voltage stress near to 50 %, for these parts the potential for destructive avalanche is very small. The EPICS technique shall be used in a similar way to measure the SEE response of power MOSFET, IGBT and bipolar transistors in order to determine voltage margins and cross sections for SEB, single event burnout.



a) Application of EPICS to the measurement of radiation event induced charge



b) Application of EPICS to the measurement of radiation event induced current

Figure 3 – Measurement of radiation event charge and current

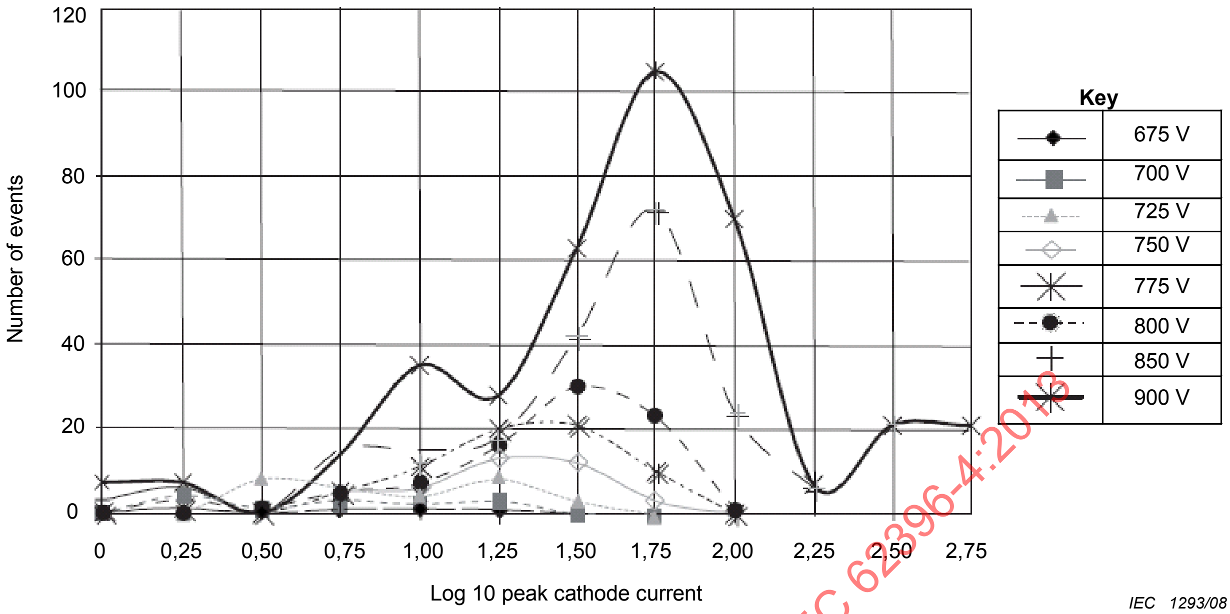


Figure 4 – EPICS plot of 1 200 V diode numbers of events at currents taken at different applied voltages for a neutron fluence of approximately 3,5 × 10^9 neutrons per cm^2 measured at energies greater than 10 MeV

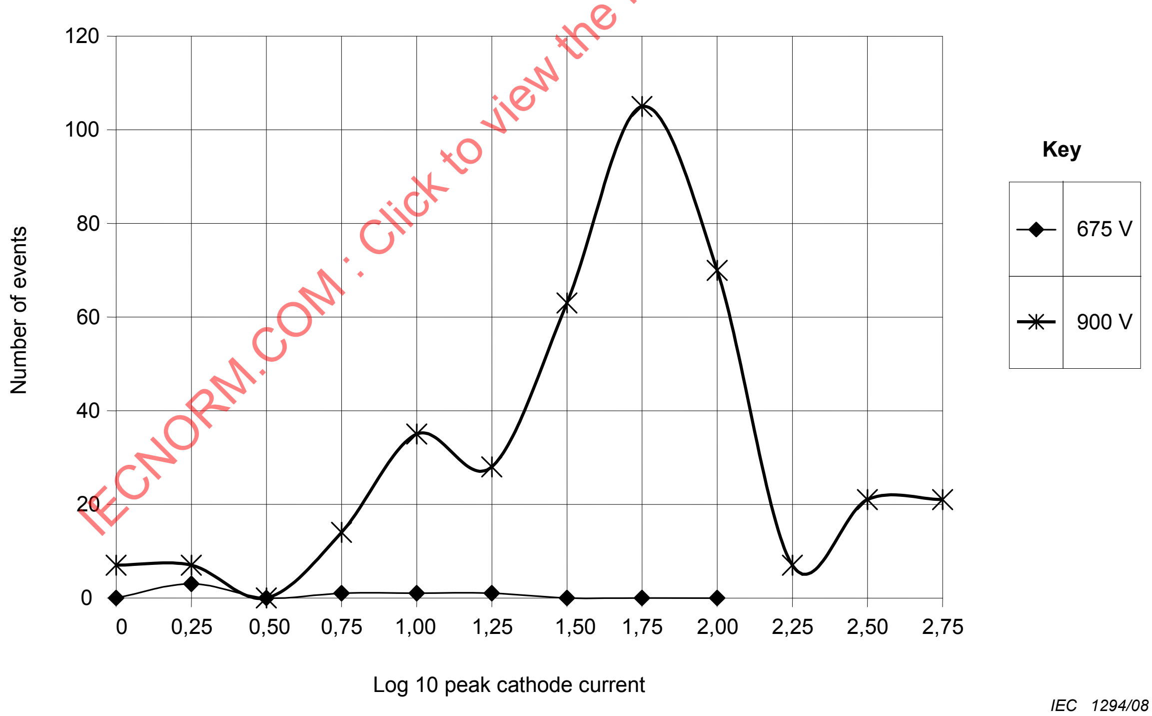


Figure 5 – EPICS plot of 1 200 V diode numbers of events at currents taken at 675 V (56 %) and 900 V (75 %) applied voltage (stress) demonstrating the difference between low and high voltage stress – Fluence as per Figure 4

6.5 Single event burnout due to thermal neutrons

Recently it has emerged that thermal neutrons are also capable of inducing SEB in high voltage components. Prior investigations into SEB induced by relatively low energy (< 10 MeV) fast neutrons implied that the level of energy deposition required in the sensitive volume of a power MOSFET to trigger SEB is lower than previously thought [19]. This introduced the possibility of thermal neutron effects via interaction with boron-10 in the device structure, where the reaction products are of similarly low energy. Experiment confirmed that, in some cases, thermal neutrons are indeed capable of inducing SEB in N-channel MOSFETs [7]. A likely cause of this is the fact that boron dopant is, by definition, located in the p-body region of an N-channel MOSFET, which is also the location of the sensitive volume for charge deposition leading to SEB. This phenomenon was observed in devices operated at their maximum-rated (breakdown) voltage ranging from 800 V to 1 000 V. Limited derating measurements were performed with no observations of SEB, implying that the effectiveness of derating is greater for thermal neutrons than for fast neutrons or heavy ions.

In the atmospheric environment thermal neutrons are at relatively low levels due to absorption by atmospheric nitrogen. However, thermalisation by local structural materials has been shown to cause significant enhancement to thermal neutron fluxes in aircraft [20]. In spite of this, due to the relatively low cross sections measured for thermal SEB, the implied failure rates in a typical aircraft neutron environment are orders of magnitude lower than for fast neutron-induced SEB. In combination with the un-quantified but probably significant effect of derating, this means that thermal neutrons are unlikely to be a significant hazard to the operation of power devices in avionics equipment, even when systems move to higher voltages. However, manufacturers shall be aware of the existence of this effect so that where appropriate it is incorporated into wider SEE reliability analyses.

6.6 Alternative semiconductor materials to silicon

Silicon carbide (SiC) has been used for some high voltage devices mainly due to its wide energy bandgap of 3,23 eV. SEE testing of SiC diodes using high energy protons [21] and of SiC power MOSFETS using high energy neutrons [22] has been carried out. Due to the large energy bandgap SiC devices are expected to be inherently immune to SEE. However, during trials with 70 MeV protons (which are equivalent to 70 MeV neutrons) and 30 MeV protons, single event burnout (SEB) of the Schottky barrier diodes was observed [21]. The proposed mechanism causing burnout is an anomalously large charge collection. The collected charge increased as the bias voltage was increased, and permanent damage was observed at higher bias voltage. The testing produced evidence that destructive SEB events are caused by a single proton at high voltage stress [21], [23], [24]. More recent testing with 50 MeV and 80 MeV neutrons at neutron fluxes of $1,5 \times 10^4$ n/cm^2/s and $5,7 \times 10^4$ n/cm^2/s, respectively, indicates the tested SiC devices are robust to neutron-induced SEE [22], however these results were obtained below the recommended minimum neutron energy to test devices for SEB which is over 100 MeV.

Although not directly applicable to the avionics environment, additionally SiC and silicon Schottky barrier diodes have been compared for high radiation (proton) space applications [25] where the charge carrier removal rate (increasing resistivity) is higher for SiC than silicon, at high neutron fluence levels.

Terrestrial neutron-induced SEB testing [26] of SiC power diodes with the same voltage rating from two different manufacturers showed an order of magnitude difference in SEB tolerance between two manufacturers. Monte Carlo simulation indicates that energetic carbon nuclei generated by high energy neutron impact with the SiC substrate may play an important role in the triggering of SEB in SiC power devices.

7 Conclusion

Single event burnout (SEB) in high voltage devices has been discussed with regard to the possibility that the high energy neutrons ($E > 10$ MeV) in the atmosphere can induce this effect. The key factor is the value of voltage stress, for example V_{ds} that is applied for power MOSFETs (or V_{ce} for IGBTs). The concept of the SEB cross section has been introduced and the limited data of the SEB cross section has been reviewed. An Equation (1) has been presented that shall be used to determine the SEB rate to be calculated for aircraft altitudes,