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TECHNICAL REPORT

Process management for avionics – Atmospheric radiation effects – Part 7: Management of single event effects (SEE) analysis process in avionics design

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 7: Management of single event effects (SEE) analysis process in avionics design

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IEC TR 62396-7, which is a technical report, has been prepared by IEC technical committee 107: Process management for avionics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
107/300/DTR	107/304/RVDTR

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

This document 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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 7: Management of single event effects (SEE) analysis process in avionics design

1 Scope

This part of IEC 62396, which is a technical report, describes a process to account for the effects of atmospheric radiation on electronic equipment. Single event effects (SEE) due to atmospheric radiation are one class of possible failure mechanisms that are addressed in the safety and reliability analyses of electronic equipment and associated functions.

This document focuses on electronic components, electronic equipment and associated electronic functions. System level analysis is not addressed in this document.

This document is intended to describe an approach to accounting for SEE in electronic equipment design, design review, and it can provide aid in the aerospace certification process. This document establishes an example process for assessing electronic components in the atmospheric radiation environment, evaluating for mitigations/protections/utilizations, and addressing the electronic equipment impacts of the SEE. The process is intended to support an SEE analysis for electronic equipment.

It does not describe, in detail, methods used to mitigate the effects of SEE in the electronic equipment design.

NOTE 1 IEC 62396-3 provides further details for this process.

NOTE 2 IEC 62396-2 provides further details for SEE testing.

This document, by itself, is not a program requirements document, i.e. it does not contain the word “shall.” However it describes a process that can be used, for example, at the discretion and agreement of the users, to aid in the preparation and the maintenance of an electronic components management plan (see [1][1] and [7]). The output of the process described in this document provides data as an input into the product safety and reliability analyses.

Although developed for the avionics industry, this document can be used by other industrial sectors at their discretion.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62396-1:2016, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

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1 Numbers in square brackets refer to the Bibliography.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

NOTE For the purposes of the document, the term “device” can be used in place of “electronic component”.

3.2 Abbreviated terms

BIT	built-in test
BoM	bill of material
COTS	commercial off the shelf
CRC	cyclic redundancy check
E	Energy
ECC	error correction code
EDAC	error detection and correction
FoM	figure of merit
FPGA	field-programmable gate array
IEEE	Institute of Electrical and Electronics Engineers
I/O	input/output
JEDEC	JEDEC Solid State Technology Association
JESD	JEDEC standard
L1/L2	level 1 / level 2 (related to microprocessor cache memories, "level 1" cache memory being usually built onto the microprocessor chip itself, “level 2” cache memory being usually on a separate chip or expansion card)
MBU	multiple bit upset (in the same word)
MCU	multiple cell upset
MTBF	mean time between failure
P/SSA	preliminary/system safety assessment
RAM	random access memory
SDRAM	synchronous dynamic random access memory
SEB	single event burnout
SEE	single event effect
SEFI	single event functional interrupt
SEL	single event latch-up
SET	single event transient
SEU	single event upset
SSA	system safety assessment
TLB	translation lookaside buffer
µP	microprocessor

4 Radiation analysis process

4.1 General

Electronic components and integrated circuits have become increasingly susceptible to atmospheric radiation causing SEE. These phenomena are the result of interaction of high energy cosmic rays with silicon-based components. The resulting single event effects may cause various conditions; such as data corruption. Additional types of undesirable effects may include:

- damage to hardware;
- corrupted software residing in volatile memory;
- corrupted data in memory;
- microprocessor halts and interrupts;
- writing over critical data tables;
- unplanned events.

The industry trend is for continued decreases in electronic component feature size and operating voltages, while the number of gates on a given device continues to increase, which entails focusing attention on the radiation effects. As this trend continues to deep sub-micron feature sizes, electronic component designs are achieving higher densities and lower voltages, resulting in smaller active charge regions. In general, for decreasing feature size of silicon based cells, the expected critical charge decreases and the sensitivity to radiation may increase.

The radiation effects analysis example process described in this document assesses the radiation effects susceptibility of the electronic components and the effects at the electronic equipment level. This includes radiation effects assessment of the electronic components, mitigation analysis, and test of electronic components and electronic equipment if needed. This information may be utilized as input to a safety and reliability assessment of the electronic equipment.

An overview of the radiation analysis process is provided as example. The remainder of the document provides one way to perform a radiation analysis with 4.2 to 4.10 providing further details based on the radiation process shown in Figure 1.

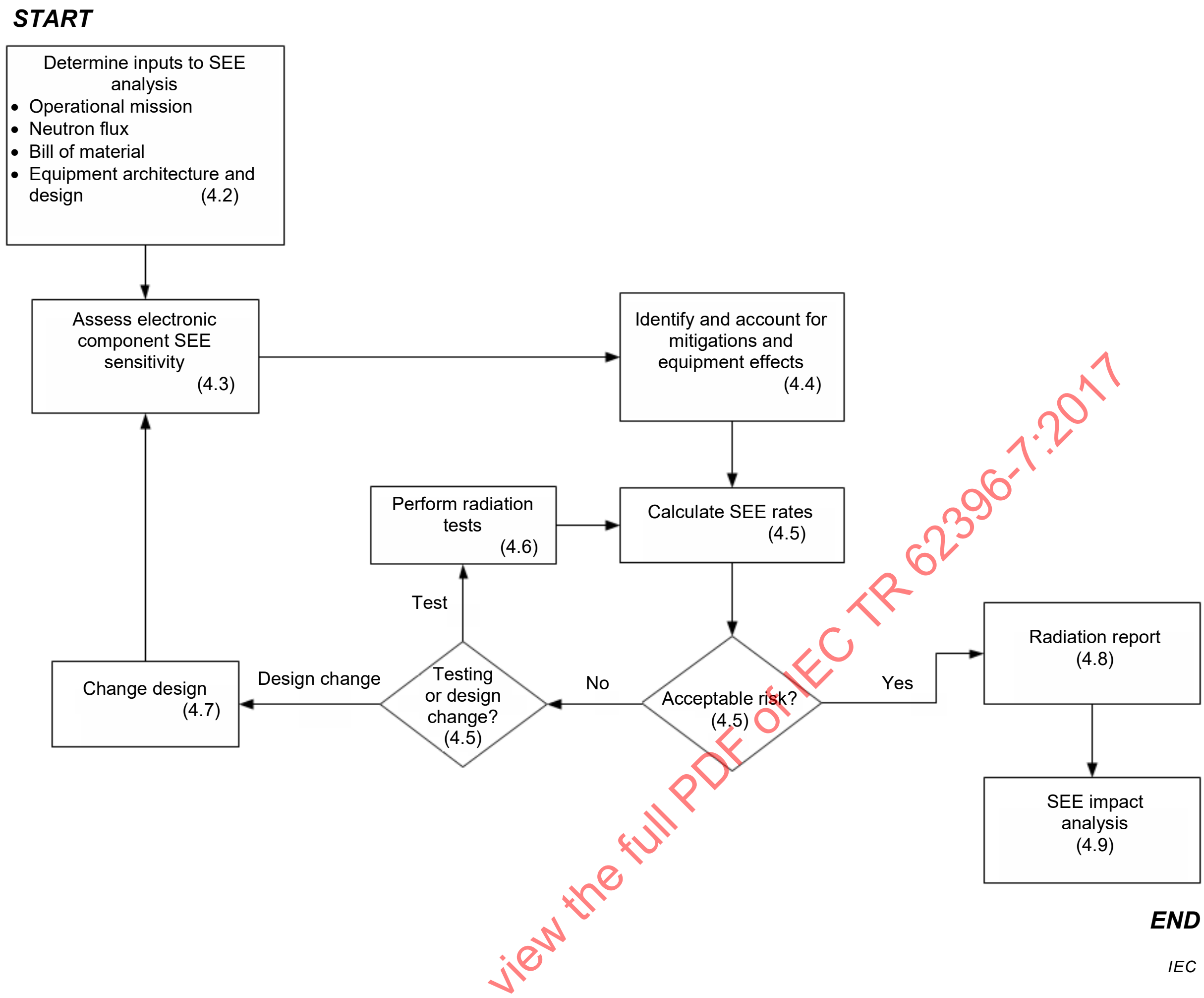

Figure 1 – Radiation analysis process overview

The process starts with the operational mission and data definition (e.g. atmospheric radiation environment, BoM…), and ends with a summary of the SEE effects data to be utilized as input for safety and reliability assessments. An atmospheric radiation analysis plan may be included in the planning for a new program. This analysis may be appropriate for new electronic equipment development, electronic equipment upgrades, and electronic component replacement programs.

Annex A provides, for information, a detailed radiation analysis process flowchart. This diagram expands on the steps defined in Figure 1. Additional detailed descriptions of the electronic component assessment, evaluation, electronic equipment impact analysis, and on-going electronic component management steps are provided,

4.2 Determine inputs to SEE analysis

Inputs to the SEE analysis may include various electronic equipment and operational mission definition, and detailed electronic equipment design information.

The atmospheric radiation definition may include the environment in which the electronic equipment operates and the flux densities under consideration based on operational missions. In the absence of such definition, the default levels of IEC 62396-1 are recommended.

The equipment design information may include the electronic equipment bill of materials (BoM), schematics and electronic equipment design material. In addition, existing and available SEE rates for known susceptible electronic components may be included.

4.3 Assess electronic component SEE sensitivity

Each electronic component on the electronic equipment BoM is assessed for its susceptibility to SEE, and classified according to its susceptibility to the various relevant SEE types (for example SEB, SEL, MCU, MBU, SEU, SEFI…; for more details see IEC 62396-1).

For all sensitive electronic components, cross-section data is obtained if possible. If no data is available, conservative estimates may be utilized for this initial step. Table B.1 provides a template for recording the components typically considered sensitive and which may result in a SEE analysis. Notes may be added to the table to indicate the source of the cross-section rates. This table may be used throughout the SEE analysis process, starting with the electronic component assessment, evaluation of mitigations/protections and SEE impact analysis.

Electronic components assessment process steps may include:

a) Classification of each electronic component as being either SEE-sensitive (identifying all applicable SEE types) or not SEE-sensitive.
b) For the sensitive electronic components, the column “Component SEE sensitivities” of Table B.1 is populated. Sources of data may include:
   1) test data (from a source such as high energy neutron beam; see list of facilities provided in IEC 62396-1 for example);
   2) industry data;
   3) in-service flight data;
   4) figure of merit (FoM) calculations based on test data from other sources (proton and heavy ion);
   5) conservative estimates.

   For more details related to these sources of data, one can refer to IEC 62396-1:2016, Annex G, and IEC 62396-2.
c) For each sensitive electronic component, describe the SEE sensitivity and provide all the SEE cross-section data for each applicable SEE type for the electronic component. Details on calculating the SEE rates in avionics are provided in IEC 62396-1.

The cross-section data, such as test data, vendor data or in-service data may be recorded into the template proposed in Table B.1, column “SEE cross-section data (cm^2/bit)” or column “SEE cross-section data (cm^2/device)”.

The SEE response of an electronic component is characterized as the SEE cross-section of that component. The SEE cross-section unit is cm^2/device or cm^2/bit. This cross-section, which is obtained through test, is the number of radiation events divided by the fluence of particles (particle/cm^2, particle flux integrated over the exposure time) to which the electronic component was exposed.

The SEE rate is calculated by multiplying the SEE cross-section and the integrated neutron flux rate. Generally, 6 000 neutron/cm^2h (E > 10 MeV) and 9 300 neutron/cm^2h (E > 1 MeV) are used for these calculations. The 1 MeV rate and greater is utilized for electronic components with feature sizes less than 150 nm.

This flux value represents the nominal high energy neutrons at 40 000 ft and 45° latitude, and is a recognized industry standard value. Details on calculating SEE rates in avionics are provided in IEC 62396-1. Thermal energy neutron background information is provided in IEC 62396-5.

The cross-sectional area is a figure of merit that establishes how sensitive the electronic component is to the effects of atmospheric radiation. The different types of effects, such as SEU, SEL or SEFI, have independent cross-sections. SEFI rates are often defined on a per-device basis as the total number of registers in the electronic component; usually they are not shared by the original electronic component manufacturer.

To establish a normalized standardized flux for avionics calculations, refer to IEC 62396-1 for guidance about when different flux rates should be used (consideration of different altitudes and latitudes, etc.). This is the standard number for quantitative calculations. Actual flux varies according to altitude, latitude, and solar activity. For example, one electronic component SEE rate can be approximated as follows (if its feature size is more than 150nm):

SEE rate per electronic component = Bit upset per electronic component hour = 6 000 neutron/cm²/h x electronic component cross-section for E > 10 MeV.

A more accurate calculation integrates the flux and the cross-section curves.

4.4 Identify and account for mitigations and electronic equipment effects

Using the results for 4.3, the impact of SEE on the electronic equipment functionality may be determined, taking into account the electronic component cross-sections, electronic equipment design and implemented mitigations, protections and utilizations

This evaluation includes information related to the SEE rates of the electronic components which have been deemed both susceptible and critical. The radiation evaluation provides an assessment of the impacts of mitigations/protections/utilizations on SEE rates. Early in the development program, electronic components selection and architectural decision are not final. Therefore, the evaluation process may be started during this timeframe and may provide aid in the assessment of proposed electronic components. In the later phases of the development program, this process may further quantify SEE rates.

SEE rates can be adjusted for the conditions used within the design. Examples may include accounting for the number of bits/registers utilized, on-chip error mitigation and electronic equipment level error mitigation. Mitigation options and techniques may include electronic component-level technology solutions, hardened circuit designs, and fault-tolerant electronic equipment architectures.

Examples of mitigations/protections, which can be accounted, include:

a) Device / bit utilizations:
   – include only the bits utilized in the design;
   – account for the total number of control registers in components such as FPGAs.
b) Timing aspects:
   – active monitors;
   – watchdog timer, bit-stream CRC check; periodic CRC check of an FPGA may not be considered fully mitigation unless the CRC is fast enough to catch the SEE before a failure condition can be realized.
c) Electronic component level mitigations:
   – SEU tolerant finite state machine;
   – triple modular redundancy;
   – on-chip EDAC or ECC;
   – scrubbing (error correction technique which uses a background task that periodically inspects memory for errors).
d) Electronic equipment level mitigations:
   – data scrubbing;
   – voting;
   – triple modular redundancy (made by hardware or software);

- reasonableness testing;
- CRC;
- watchdog timers;
- controlled power cycling.

e) Protections:

- filters, exposure window, data range-checking, continuous monitoring and exception handling;
- redundancy, watchdog supervisory logic, error correction, and partitioning.

Software techniques may be utilized to mitigate the effects of SEE induced errors. Examples include replication of program execution, results checking, refreshing and monitoring configuration, data range checking, input data filtering, program and constant refreshing, and process partitioning.

If the mitigated electronic components, utilizing conservative cross-section estimates, meet the electronic equipment safety and reliability objectives then the evaluation may be considered complete. If the initial SEE rate does not meet objectives, and has included conservative cross-section estimates for untested electronic components, testing of the high risk electronic components, or a re-design, may be an option.

If a statistically significant amount of existing flight data is available for the electronic components under analysis, then in-flight results may be another input into the radiation evaluation. This method may need customer's agreement in advance.

4.5 Calculate SEE rates and analyse risk

The final SEE rate calculations are completed for each susceptible electronic component. This may take into account all applicable cross-sections rates and the adjusted rates taking into account mitigations/protections/utilizations. The "Evaluation" columns in Table B.1 may be used to complete these SEE rate assessments. All mitigations/protections/utilizations factors may be noted, with associated justifications and the updated SEE rates.

Each electronic component is reviewed to determine if the SEE rate is acceptable. This is an estimate and review of the electronic components rates in terms of overall safety and reliability objectives for the electronic equipment is considered. The review may be made on a single electronic component basis or cumulative electronic component basis. After the SEE rates have been calculated using the available component cross-sections, device utilizations, protections, and mitigations, it can be determined if the resulting SEE rate is acceptable. For example, if the SEE rate is an order of magnitude less than the overall hardware failure rate then it may be able to be considered negligible.

During this evaluation phase of the process it may not be possible to complete a final analysis to verify that all objectives have been met, however there may be enough information to determine if it is reasonable to proceed with the SEE analysis or if further steps are useful to obtain better SEE rates. While a final decision cannot be made as to whether or not all safety or reliability objectives can be met, a reasonableness check may be performed for identifying potential risks. For example, if conservative electronic component SEE rates, utilized because no test data is available, account for a disproportionate percentage of the safety or reliability objectives, then this may not be an acceptable risk.

Several actions may be taken if it has been determined the initial SEE rates are not acceptable. More accurate electronic component SEE rates may be obtained by performing radiation tests or the design may be changed.

4.6 Perform radiation tests

With the completion of the SEE rate calculations, it may be determined that there is continued risk for not meeting electronic equipment SEE rate objectives. One option is to test the electronic component to obtain cross-section data. Testing may be needed when an electronic component is both critical to the electronic equipment performance and sensitive to radiation, and initial conservative estimates do not meet electronic equipment safety/reliability objectives. When an electronic component is replaced by another component, due to obsolescence or design modification, the replacement component is also considered for SEE-susceptibility. It is important to note that data from one electronic component may not be used reliably to estimate the SEE susceptibility of similar electronic components which may have different characteristics.

The SEE cross-section rates of a tested component are based on actual measurements, generated by exposing individual devices to a particle beam relevant to the atmospheric conditions (see IEC 62396-1 and IEC 62396-2 for more details). Testing may also be performed at the equipment level, however, the rates obtained are specific to the equipment under test and provide the equipment level effects rates rather than the component level cross-section rates.

The purpose of the testing is to obtain the cross-sections of the device, including the cross-section of each bit type and SEE sensitivity within the device. As shown in Table B.1, this may mean multiple SEE rates to be measured for the electronic device under test, based on bit type and functionality.

For example, testing may be performed on an electronic component or at the electronic equipment level to validate mitigations/protections. Additionally, testing may be performed by testing both legacy and replacement electronic components when an electronic component level change is made and no cross-section information is available for either the legacy or new device.

Radiation testing of electronic components and electronic equipment for SEE susceptibility utilizes specialized test facilities capable of conducting such tests. A list of such facilities is provided in IEC 62396-1 allowing selection of the relevant source and is also discussed in [11]; this does not constitute an endorsement of any test facility by IEC.

JEDEC JESD89-3, provides an outline of the test method and setup for radiation testing. It describes procedures for beam calibration, stress conditions and a minimum test sequence. IEC 62396-2 also discusses electronic component testing.

Multiple factors are taken into account when estimating beam time estimates including the confidence level needed, acceptable SEE impact level affecting the electronic equipment MTBF, and mission operational definition. With this highly accelerated testing, experiments often take several days to complete.

4.7 Design change

If the initial SEE rates indicate that there is an unacceptable risk in meeting the safety/reliability objectives, a design change may be warranted.

Design change options include:

- an electronic components selection change; or
- additional mitigations and protections, either through hardware or software implementation; or
- re-design of the electronic component itself (generally difficult), or re-design of an architecture to include additional mitigation(s).

If a design change is made, an incremental analysis is useful to verify the updated SEE rates.

4.8 Radiation report

A radiation report, which includes Annex B data, may contain the following information that is used as input to the SEE impact analysis:

a) Atmospheric radiation environment, for example operational mission, customer requirements, nominal environment (see IEC 62396-1).
b) Electronic components assessments for all identified susceptible components. If no data is available, conservative estimates may be utilized.
c) Sources of data which include:
   – test data from high energy neutron source;
   – electronic component manufacturer and/or industry data;
   – figure of merit (FoM) calculations based on test data from other sources (proton and heavy ion);
   – conservative estimates from IEC 62396-1:2016, Annex G, can be used.

As an example, the radiation effects evaluation of mitigations and protections are also provided in Table B.1. The evaluation is based on cross-section data for each susceptible electronic component, the operational mission environment, and the reliability and safety objectives. Mitigations, protections, utilization factors and electronic equipment design are examples of information provided in the evaluation columns.

If testing was performed, the report may be updated to include the new rates. The radiation report may include completed "Component SEE sensitivities" and "Evaluation" columns of Table B.1. The remaining column, "Equipment impact analysis" may be completed as part of the SEE impact analysis phase.

4.9 SEE impact analysis

With the radiation report and data from Annex B, a final SEE impact analysis may be performed. A final column in the radiation evaluation table shown in Table B.1 is provided to complete this impact analysis step. The results of the electronic equipment impact analysis may be recorded into the template proposed in Table B.1 at the column "Equipment impact analysis" level, and may be utilized as input into the reliability and safety assessments. If it is determined, after the completion of the electronic equipment impact analysis, that the safety/reliability requirements have not been met then the SEE analysis would be performed again.

Data and functional design considerations for the SEE impact analysis include:

- Determination of how information flows in the electronic equipment and how data are calculated and results in messages transmitted from the electronic equipment.
- Identification of all routines and data blocks that contribute to these data.
- Identification of which memory blocks contribute to an equipment impact.
- Accounting for design factors which may be utilized in determining electronic equipment robustness.

Examples of electronic equipment design actions or considerations for the SEE electronic equipment impact analysis include:

a) Identification of recoverable or non-recoverable events which result in an electronic equipment level effect. Address each electronic equipment impact.
b) Does a reset or reconfiguration recover the electronic equipment operation?
c) Are SEEs in control logic and other variables detectable and/or correctable? (The analysis may be difficult as control logic and some variables can be non-documented within the electronic components' data-sheets).

d) What is the discoverable time period for detectable SEEs?

e) Is there an avenue for a comparison of a mismatch in a dual path; does a failure to recovery force a flag and an opportunity for a higher level equipment recovery attempt?

f) Identification of persistent and non-persistent events; hard failures and latch up conditions which require a power reset.

g) Determination of watchdog timeout impact to availability (as applicable).

h) Determination of probability of false watchdog timeout (as applicable).

i) Determination of impact of I/O and memory access being disrupted, both partially and completely.

j) Determination of impact of CRC.

The information developed as a result of completing the SEE electronic equipment impact analysis may be utilized as input to the preliminary/system safety assessment (P/SSA).

4.10 On-going component management

Monitoring of potential changes made by the electronic component manufacturer to potentially SEE-sensitive components is useful throughout the manufacturing and operating service life of the electronic equipment; this is generally part of the electronic equipment manufacturer electronic component management plan. This monitoring of change may be useful because design, feature size, or fabrication changes to the electronic components may affect their SEE sensitivity. Where such changes at electronic component level occur, reassessment of the SEE sensitivity of that electronic component is proposed. A subsequent SEE impact analysis of the new electronic components and affected electronic equipment may also be necessary.

Annex A
(informative)

Detailed radiation analysis process

Figure A.1 provides a detailed radiation analysis process flowchart.

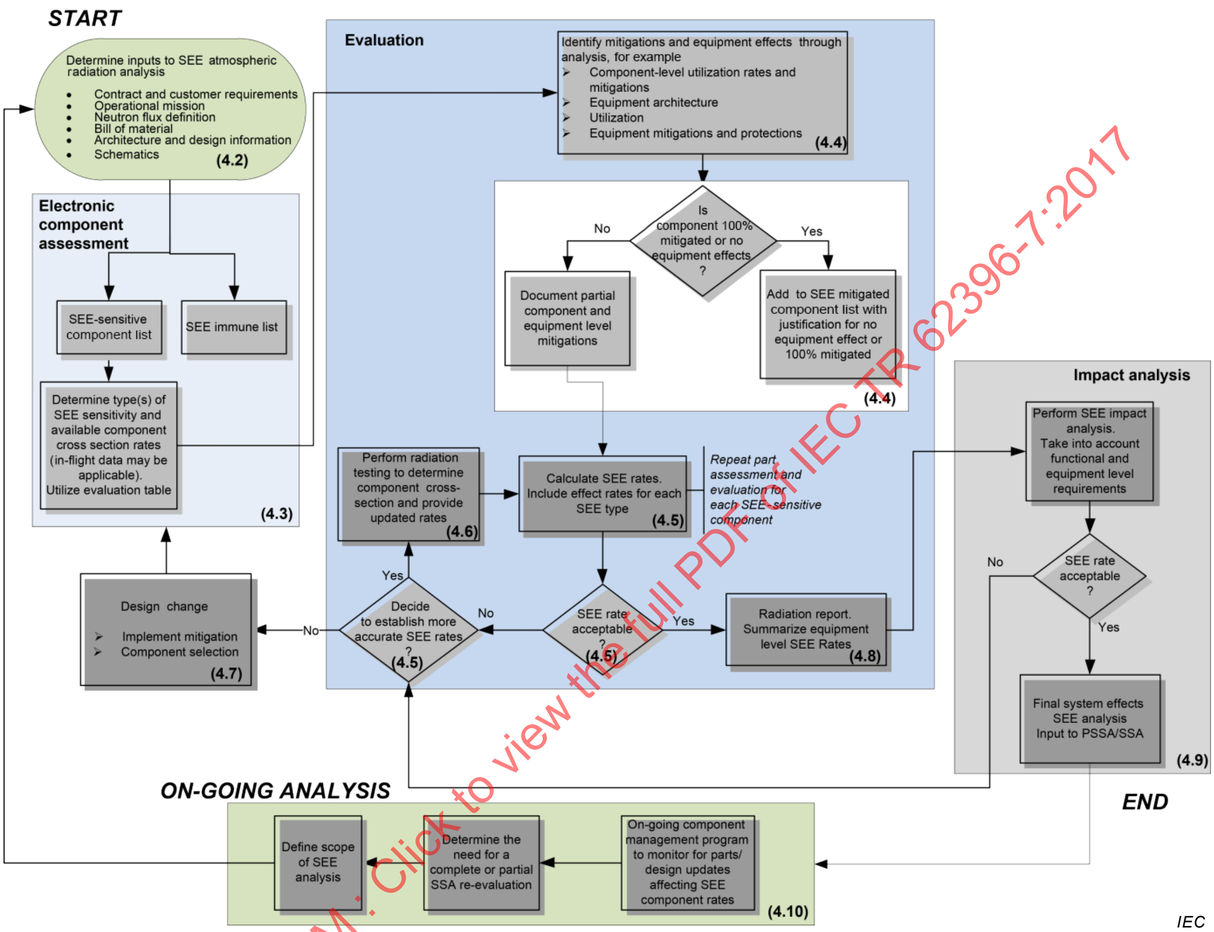

Figure A.1 – Detailed radiation analysis process flowchart