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Space product assurance

Worst case analysis

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Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

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Scope

This handbook provides guidelines to perform the worst case analysis. It applies to all electrical and electronic equipment. This worst case analysis (WCA) method can also be applied at subsystem level to justify electrical interface specifications and design margins for equipment. It applies to all project phases where electrical interface requirements are established and circuit design is carried out.

The worst case analysis is generally carried out when designing the circuit. For selected circuitry, worst case analysis (WCA) can be used to validate a conceptual design approach.

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References

ECSS-ST-00-01	ECSS system - Glossary of terms
ECSS-E-ST-10-02	Space engineering -Verification
ECSS-Q-ST-30	Space product assurance - Dependability
ECSS-Q-ST-30-11	Space product assurance - Derating - EEE components
ECSS-Q-TM-30-12	Space product assurance – End-of-life parameters drifts - EEE components
ECSS-Q-ST-30-02	Space product assurance - Failure modes, effects and criticality analysis
ECSS-Q-ST-40-02	Space product assurance - Hazard analysis
ECSS-Q-TM-40-04	Space product assurance - Sneak analysis
ECSS-Q-ST-40-12	Space product assurance - Fault tree analysis – Adoption notice ECSS / IEC61025
CRTAWCCA	Worst Case Circuit Analysis Application Guidelines, 1993 Reliability Analysis Center, Rome NY, U.S.A
JPL D-5703	Jet Propulsion Laboratory Reliability Analyses Handbook

3
Terms, definitions and abbreviated terms

3.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply and the terms specific to the present document.

3.2 Terms specific to the present document

3.2.1 ambient temperature

temperature of a medium surrounding the component

3.2.2 biased variation value

value with a deterministic direction or sign whose amplitude and direction of variation are known

3.2.3 component parameters

electrical performance parameters of EEE parts

3.2.4 component specification

specification of the EEE part used for procurement of the EEE part

3.2.5 design lifetime

duration for which the circuit is designed to work within a particular mission

3.2.6 effective ageing data

ageing data extrapolated from the lifetime assumed in database to the design lifetime

3.2.7 lifetime assumed in database

lifetime for which the parameter variation due to ageing and environmental effects is valid

3.2.8 radiation

phenomenon by which energy, in form of waves or particles, emanates from a source into space

Example Trapped electrons, trapped protons and solar protons.

3.2.9 random variation value

value with no preferred direction or sign whose amplitude alone is known

3.2.10 reference condition

relative condition where the parameter variation is assumed to be zero

3.2.11 temperature assumed in database

temperature for which the parameter variation is given in the database

3.2.12 variation factors

factors which affect component parameters over its lifetime

NOTE For details see subclause 5.1.1.

3.2.13 worst case

highest or lowest boundary value of a given control parameter established in a validation or qualification exercise

NOTE Failures or single event effects are not covered by the worst case.

3.2.14 worst case analysis (WCA)

performance prediction of the circuit in the worst case condition

3.2.15 functional block

within a circuit, set of components which perform a specific function

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
CDR	critical design review
EEE	electrical, electronic, electromechanical
EMC	electromagnetic compatibility
EOL	end-of-life
EVA	extreme value analysis
E_A	activation energy
k	Boltzmann constant
MCA	Monte-Carlo analysis
PCB	printed circuit board
PDF	probability density function
PDR	preliminary design review
RF	radio frequency
RSS	root-sum-square
SEE	single event effect
T_j	junction temperature
WCA	worst case analysis

4
General methodology

4.1 Introduction

The worst case analysis (WCA) is performed on electronic and electrical equipment to demonstrate that it performs within specification despite particular variations in its constituent part parameters and the imposed environment, at the end of overall lifetime (EOL).

A good survey of worst case circuit analysis can be found in CRTAWCCA “Worst Case Circuit Analysis Application Guidelines, 1993 Reliability Analysis Center, Rome NY, U.S.A.”.

4.2 Flow diagram of WCA

The worst case analysis is used to demonstrate sufficient operating margins for all operating conditions in electronic circuits.

A flow diagram of WCA is shown in Figure 4-1.

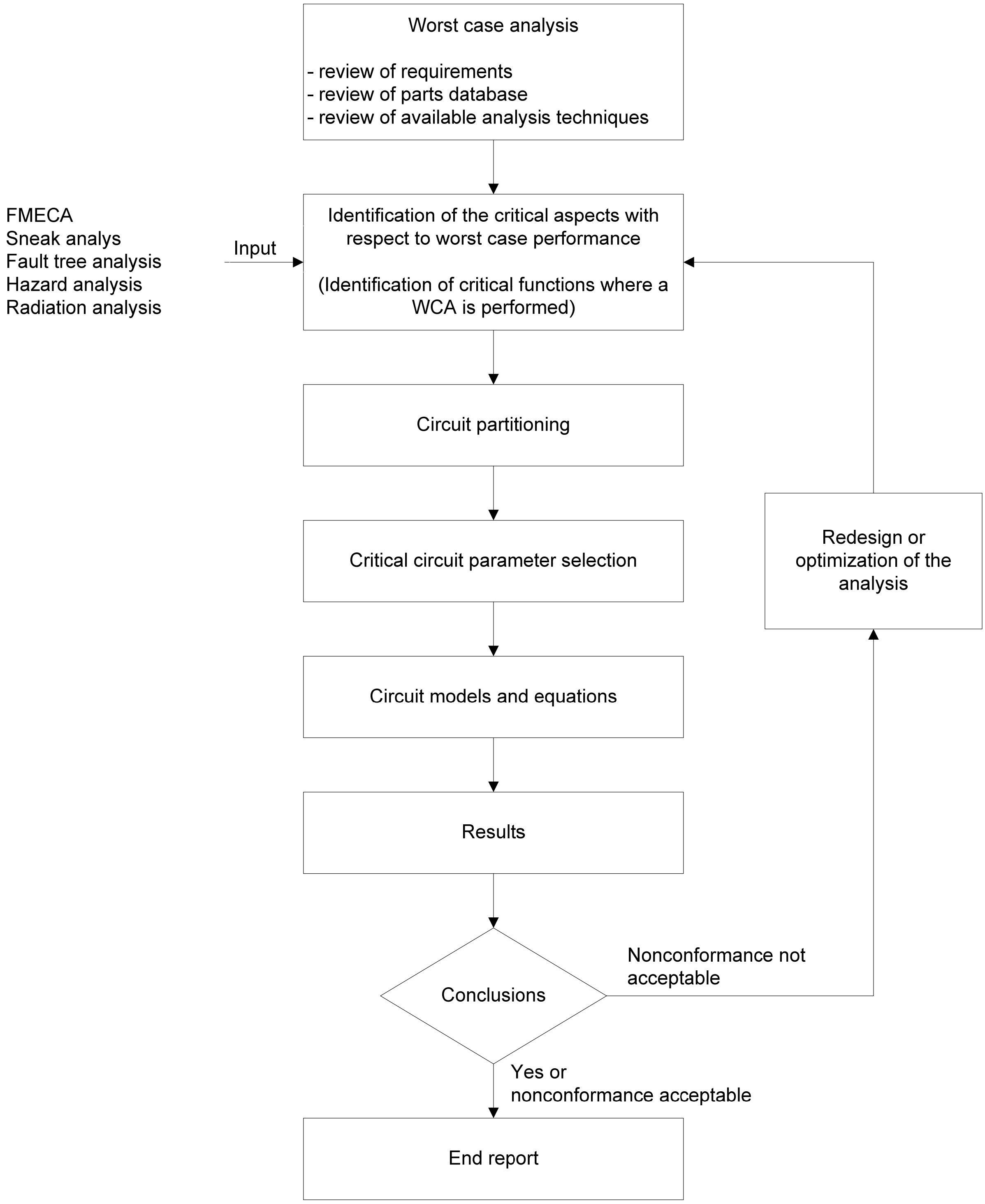

Figure 4-1: Flow diagram of WCA

4.3 Identification of the critical aspects w.r.t. worst case performance

The critical aspects with respect to worst case performance and the critical circuit parameters should be identified. These critical aspects can be identified from results of other analyses:

- FMECA,
- sneak analysis,
- fault tree analysis,,
- hazard analysis,
- radiation analysis.

The sources of parameter variation are in general:

- initial tolerances,
- ageing,
- temperature,
- electrical interfaces,
- radiation, and
- EMC.

However, in some cases the effects of the above sources can be negligible.

To justify which effects influence the result and which can be neglected, a sensitivity analysis or appropriate other method can be carried out.

4.4 Evaluation of worst case performance

The following basic tasks should be performed:

- partitioning of large circuits into smaller circuits which are better manageable (functional blocks);
- selection of critical circuit attributes;
- mathematical simulations of circuit behaviour;
- application of a worst case numerical analysis technique.

To facilitate the performance of the WCA, the analyst can reduce complex circuits into smaller functional blocks. When a circuit is reduced to these functional blocks, performance requirements for the inputs and outputs of each functional block can be established. These requirements serve as the evaluation criteria for the WCA results for the functional blocks. If such criteria exists in another document (e.g. design verification requirements document), reference to the source document should be made. Some of the requirements for the functional blocks derive from higher level specification requirements. In that case, the method of deriving these requirements should be clearly shown.

Non-linear effects: Within the process of splitting up the unit circuit into functional blocks the contractor should consider non-linear effects resulting either from components intrinsic non-linearity (according to the components specification), or effects resulting from reciprocal interaction of the functional blocks (e.g. power supply variations induced by load changes, and load effects of the power supply drifts). Otherwise the WCA should justify the absence of such effects, or should quantify such effects as negligible, in comparison to other error sources.

A combination of testing and analysis may be employed to obtain results through actual measurements.

4.5 Comparison of WCA with requirements

The WCA should conform to all requirements, both on the functional block level and at the circuit level. Variations from these requirements should be noted explicitly and any proposed solutions outlined as part of the report. Proof of conformance to certain less significant requirements may be omitted provided that adequate justification for the specific omission is given in the WCA report. As a summary the analysis results should be compared with the requirement specification.

5
Analysis parameters and technical issues

5.1 Definition of worst case parameters within parts database

5.1.1 Variation factors

5.1.1.1 General

For each physical parameter of the component affecting the worst case parameter analysed, the value of the variation linked to each environment or interface stimulus should be determined. Sources of variation include:

- the reference value (e.g. typical and adjusted),
- the initial tolerance,
- sensitivity to electrical interfaces (e.g. power supply, shared mode on inputs and output loads), and
- sensitivity to ageing and environmental conditions (e.g. temperature, radiation and EMC).

5.1.1.2 Selection of reference condition

The variations of a component parameter due to radiation, ageing, temperature and tolerance are applied to the reference condition. The reference condition should be chosen such that data is available. This is usually room temperature (22±3) °C at beginning-of-life.

5.1.1.3 Compensation

If the circuit compensates initial tolerance or environmental variations (such as temperature) the analysis report should include a justification for the residual variation.

5.1.1.4 Radiation

5.1.1.4.1 Radiation total dose effect

Under the influence of total dose radiation parametric degradations or variations can be expected in particular for active electronic components. The electrical parametric changes can either be of a permanent or temporary nature, depending upon the component technology. Radiation affects parameter variations of active components only (those that have a semiconductor junction).

These parametric changes are related to the influence of the accumulated total dose radiation received throughout the mission lifetime.

5.1.1.4.2 Assessment of the radiation total dose

Using dedicated shielding and radiation analysis tools (radiation sector analysis), the local accumulated total dose on each single individual component level can be assessed and calculated. The accumulated total dose received on individual parts depends on the mission lifetime, the radiation environment (usually a function of the spacecraft orbit) and the shielding. For this document, the shielding and total dose radiation analysis is an input to the worst case analysis even though in practice it may be incorporated into the WCA.

5.1.1.4.3 Assessment of the component parameters drift

Given the assessed and calculated accumulated local total dose level, the associated parameter drift values of each of the components should be derived. The applicable parameter drift values, which depend on the accumulated total dose received, can only be determined by performing radiation testing on components from the parts lots used on the spacecraft. The parameter drift is linked to the technology of the component and can vary from one manufacturer to another and from one lot to another. The following methods are available for the determination of the parameter drift values.

a. The parameter drift values can be taken from radiation tests that were performed under appropriate conditions on parts lots used on the spacecraft. In this case the reference of the document containing the test results should be included in the list of normative documents.

b. If the parameter drift values are derived from component radiation test data (not within the lot of the parts used on the spacecraft), an appropriate margin should be considered for a difference in parameter performance variations between the tested lot and the actual lot of the components used on the spacecraft.

    1. If the component to be used on the spacecraft is from the same manufacturer and the same established manufacturing process as the tested part, a 20 % margin is considered sufficient for parameters such as gain, threshold voltage, resistance or conductance.

    2. If the component to be used on the spacecraft is from a different manufacturer or process than the tested sample, a margin of more than 100% should be considered. Thus, three or more sample components from the manufacturer should be tested to the expected radiation level with the same process used for the other parts of the spacecraft to confirm the correctness of the assumptions for the WCA.

c. The component specification can also be used as the information source. In this case the specification usually contains and specifies the parameter drift of total dose radiation up to given accumulated levels (including initial tolerance).

5.1.1.4.4 Radiation dose testing and verification

Within the WCA and, if applicable, the assumed component parameter drift (due to total dose radiation) should be verified to correlate to the performance drift specified in the component specification for the assessed and calculated accumulated total dose level.

The component radiation test results should show that the associated parameter drift values of the tested components are within the parameter drift limits assumed in the WCA.

During total dose testing, the bias condition should be adopted such as to simulate the electrical properties on the spacecraft.

The parameter drifts due to radiation are biased variation values.

5.1.1.4.5 Single event effects

Single event effects (SEE) are anomalies and thus not a variation factor to be considered in the scope of the WCA. If the SEE assessment of the circuit requires countermeasures for SEE, these should be described in a design justification document. If, as a result of SEE assessment, a protection circuit is included to prevent circuit failures or degradation during SEE events, certainly for nominal operation, this circuit should be considered in the WCA.

5.1.1.5 Temperature

a. Parameter variations due to temperature variations are applicable to all passive and active components.

b. The parameter variations are taken from the component specification, manufacturer’s specifications, data sheet or test results. These parameter variations generally have biased values and are expressed as a delta per degree Celsius (in % or in value) with respect to the value within the component specification at the reference condition. There can also be a random part with respect to the bias value. For passive parts the parameter variation over temperature is usually a fixed value.

c. Often the component specification does not contain the parameter variation in the necessary parametric form required for the evaluation of the worst case performance of the circuit. In this case, the parameter variations should be derived considering, for instance, measurement data and component physics.

d. In the component specification these variations generally apply over the complete temperature range of the component (-55 °C to +125 °C). The thermal analysis of the equipment is provided as an input with the actual temperature range of each component, which is usually lower than this complete temperature range. The thermal analysis considers the temperature rise between the PCB temperature, the case temperature and the junction temperature.

e. Within the WCA the temperature of the component is the ambient temperature when the equipment thermal interface varies over the acceptance temperature range. In the worst case analysis, the minimum temperature of each component is the minimum acceptance environmental temperature of the equipment. The maximum temperature is the temperature determined within the thermal analysis for the extreme acceptance temperature of the equipment. As long as the results from the thermal analysis are not available, the component can be assumed to operate at the maximum operating temperature.

5.1.1.6 Initial tolerance

Parameter variations due to initial tolerance concern all passive and active components.

If the circuit compensates initial tolerance variations, the WCA should include an analysis of the residual variation.

The variations are taken from the applicable component specifications and have a random distribution.

5.1.1.7 Ageing

5.1.1.7.1 Introduction

Parameter variations due to ageing concern all passive and all active components.

This variation is a function of time and temperature, junction temperature for active components, and case temperature for passive components.

The ageing effects are specific to each family of components.

The variations are taken from the component specifications, life test data or worst case parameter database.

5.1.1.7.2 Extrapolation of ageing data from the lifetime assumed in database to the design lifetime

If the design lifetime is different from the lifetime assumed in the database, the effective ageing data should be extrapolated from the data available in the database:

The linear extrapolation (conservative approach) should be applied. The use of other extrapolations may be adopted with adequate justification.

For a design lifetime shorter than the database, the database value for the next longer time interval should be assumed. The parameter variation data should not be interpolated between database values without justification, as the ageing process cannot be assumed a priori to be linear.

5.1.1.7.3 Extrapolation of ageing data from the temperature assumed in the database to the maximum temperature of the component in the application

To extrapolate ageing data from the temperature assumed in the database to the maximum temperature of the component for the same duration, the law of Arrhenius should be used:

$$q_2 = q_1 \exp\left[\frac{E_A}{k}\times\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$

where

q_1 and q_2	are the parameters at temperature T_1 ant T_2, respectively;
T_1 and T_2	are the temperatures in Kelvin at which q_1 and q_2 are measured, respectively;
E_A	is the activation energy in eV;
k	is the Boltzmann constant (8,62 10^{-5} eV/K);
$exp(x) = e^x$,	where e is the base of the natural logarithm.

The use of other extrapolations may be adopted with adequate justification.

Some typical activation energy values are (these are default values; with the appropriate justification and reference, other values can be used):

Semiconductors

GaAs	1,4 eV
Silicon	1,1 eV

Resistances

Metal film, thin film	1,35 eV
Carbon	1 eV
Wirewound	1 eV

Capacitances

Ceramic	1,67 eV
Porcelain, glass, mica	1,1 eV

Film, plastic	3,4 eV
Tantalum	0,43 eV

NOTE For a mission duration of 10 years, we want the drift in ageing of V_Z at T_2 = 85 °C. We take an activation energy of 1,1 eV (semiconductors).

We know that $q_1 = \pm 2$ % at $T_1 = 110$ °C, what is the value of q_2 ?

$$q_2 = \pm 2 \exp\left[\frac{1{,}1}{8{,}62\times 10^{-5}}\left(\frac{1}{273+110}-\frac{1}{273+85}\right)\right] \quad \Rightarrow \quad q_2 = \pm 0{,}195\%$$

At T_j = 85°C, the voltage V_Z varies by ±0,195 % in 10 years.

5.1.1.8 EMC and variation of electrical signals

Worst case variations of the signal at the electrical interfaces (including conducted EMC) should be considered. These variations depend on the design of the equipment and are generally random in nature.

The extreme values are taken from the interface specification and the EMC requirements.

The interest of the worst case is to verify that the parameter variations of the components selected for conducted EMC reduction and the components that generate conducted EMC allow the EMC requirements to be satisfied.

The circuit behaviour for the EMC aspects can be determined either by simulation , or by tests or by combination of both.

5.1.2 Summary on deviations

Table 5-1 summarizes the various possible parameters deviations and their attributes.

Table 5-1: Deviations and attributes summary

	Initial tolerance	Ageing	Temperature	Radiation	EMC and variation of electrical signals
Components concerned	All	All	All	Active only	All
Type	Random	Biased (sometimes random)	Biased (sometimes random)	Biased	Biased (sometimes random)
Function of	Intrinsic	Time, temperature	Temperature range	Dose received	Design
Where to find the data?	Component specification	Worst case parameter database	Component specification	Component specification radiation tests	Interface specification and EMC requirements
Specific case	Compensation by alignment	-	Temperature compensated circuit	-	-

5.2 Phase and timing considerations within the WCA

5.2.1 Introduction

This clause provides inputs to take into account the phase and timing problems. Some specific problems are detailed in this clause. Nevertheless, other timing problems (such as reset duration and voltage level) should be analysed in the WCA.

Within the WCA it should also be demonstrated that the timing conditions of the signals are such that the circuit operates properly together under simultaneous worst case source and load conditions. It is suggested that particular attention be paid to noise margin at the interface when performing the worst case analysis.

5.2.2 Timing of transient pulses

5.2.2.1 General

All sequential circuits should have a worst case timing diagram made to determine the effects of variation in switching times of the installed circuits. There are many factors that affect timing. They include supply voltage, capacitive loading, clock or oscillator instability, and slope of clock rising and falling edge.

5.2.2.2 Signal delays (and response times in digital circuits)

The limits of the propagation delays for the circuit being analysed should also be shown in the WCA. For example, response times in digital circuits should conform to the required response times identified in the requirements. For circuits that have no specific delay or response times at the unit level, the worst case response times should be explored in further detail during the system level worst case analysis to determine if design constraints should be levied "from the top down". The total delay of a circuit is the sum of its propagation delay and a transition time effect.

5.2.2.3 Phasing of repeating waveforms (such as sinusoidal signals)

In circuits such as DC/DC converters or RF circuits, the timing of the signal waveforms can be critical. In this case, the WCA should include an evaluation of the required phase and gain margins.

5.3 Numerical analysis techniques

5.3.1 Approach

The worst case analysis can be performed using four different approaches:

- extreme value analysis;
- extreme value analysis combined approach;
- root-sum-squared analysis;
- Monte Carlo analysis.

5.3.2 Extreme value analysis

The extreme value analysis (EVA) technique is the best initial approach to worst case analysis. The extreme value analysis assesses circuit performance when each component exhibits its most extreme variation; if the circuit passes an EVA, it always functions properly. If the circuit fails, the circuit can be modified to meet the performance. Alternatively, a less conservative approach can be applied, such as the extreme value analysis combined approach, the root-sum-squared analysis or the Monte Carlo analysis. EVA uses the limits of variability and the circuit directional sensitivities to determine the worst case results.

5.3.3 Extreme value analysis combined approach

This method uses as an initial approach when the minimum and maximum values of the variables are not available, but only their nominal values and their deviations. This method is based on the fact that some variations are random (the variation has no preferred direction or sign) and others are biased (with a deterministic direction or sign). This approach is valid for standard deviations (moment methods), but is not always valid for maximum values.

5.3.4 Root-sum-squared analysis

The root-sum-squared (RSS) approach to the worst case analysis provides a more realistic evaluation technique by employing a statistical approach. An RSS analysis provides a probability that manufactured circuits work within specification (the manufacturing yield). The results are in the form of parameter bias and standard deviation, so that the three-sigma limits of performance can be determined.

5.3.5 Monte Carlo analysis

The Monte Carlo analysis (MCA) technique is a computer simulation of circuit performance to provide statistically significant results that estimate the percentage of circuits that operates successfully under expected field conditions.

This method uses actual part tolerance distributions, if available. If these distributions can be utilized, then this approach is the most realistic of the three.

If the circuit parameter probability distribution is unknown or if it is difficult to select the reference one appropriately, a binomial process can be used. But this process requires a higher number of iterations than the normal distribution.

The working hypothesis on the applicable distribution significantly reduces the effort.

The simulations should be performed to assure, at least, P = 99,5% (in line with the three-sigma limits – P = 99,73% - of the RSS approach) with a confidence level of 95%, where P is the probability that the circuit operates successfully.

The number of iterations to be performed (n) is given by the Kolmogorov-Smirnov rule and is function of the confidence level (1-α) and the maximal error on the confidence level (Δ) :

$$n = \left(\frac{d\left(n, a\right)}{\Delta} \right)^2$$

$d(n, \alpha) = 1{,}36$ for $\alpha = 0{,}05$ (confidence level = 95%)

$d(n, \alpha) = 1{,}68$ for $\alpha = 0{,}01$ (confidence level = 99 %)

The advantages of the approaches are shown in Table 5-2

Table 5-2: Numerical techniques and value summary

	Advantages	Disadvantages
EVA	Provides most readily obtainable estimate of worst case performance. Does not require statistical inputs for circuit parameters. Database need only provide part parameter variation extremes.	Results in pessimistic estimate of circuit worst case performance. If circuit fails, there is insufficient data to assess risk.
EVA combined approach	Results in more realistic estimate of worst case performance than EVA. This method can be implemented with simple calculations.	Valid for standard deviations (moment methods) but not always valid for maximum values. Requires accurate knowledge of piece part parameter PDF. It is strictly valid only for Gaussian variables. Risk of over-dimensioning is as high as for EVA.
RSS	Results in more realistic estimate of worst case performance than EVA. Knowledge of parameter PDF not required. Provides some degree of risk assessment in terms of percentage of units to pass or fail.	The computation of the standard deviation of piece part parameter's probability distribution. Assumes circuit sensitivities remain constant over range of parameter variability. Uses approximation: circuit performance variability is normally distributed (central limit theorem).
Monte Carlo	Provides the most realistic estimate of true worst case performance of the three methods. Provides additional information which can be applied to risk assessment.	Consumes large amount of CPU time.

For selection of the appropriate method for the first three techniques, see subclause 5.2.3 of CRTAWCCA (Worst Case Circuit Analysis Application Guidelines, 1993 Reliability Analysis Center, Rome NY, U.S.A.).

6
WCA and project phases

A detailed WCA during the design phase can be used to find design problems that were not found during the test phase due to temperature extremes, age or radiation.

For selected circuitry, a preliminary WCA should be available to validate a conceptual design approach at PDR.

The assumptions and approach to be used in the analyses should be checked against reliability assessments prior to the performance of the analyses.

The critical aspects with respect to worst case performance and the critical circuit parameters should be identified. These critical aspects can be identified from results of other analyses (e.g. FMECA, sneak analysis). The circuits models and equations should be defined. If a nonconformance is identified, a redesign of the circuit can be proposed to achieve conformance or an optimization of the analysis can be investigated.

If design changes are made, either as a result of the WCA or for other reasons, the WCA should be updated using the new circuit.

Results of such an analysis are generally presented in the frame of the circuit CDR.