Standard/Handbook for Multipactor Breakdown Prevention in Spacecraft Components

May 28, 2014

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Prepared for:

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Contract No. FA8802-14-C-0001

Authorized by: Space Systems Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Program Mission Assurance Improvement Workshop.

Distribution Statement A: Approved for public release; distribution unlimited.

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Executive Summary

This document (Aerospace TOR-2014-02198) is intended to provide a standardized process for mitigation of radio frequency (RF) breakdown within spacecraft components. It is directed toward component designers, satellite system engineers, as well as the customer community to provide worst-case conditions, margin requirements, and verification of those requirements using state-of-the-art methodologies. In addition, recommended methods are provided, with examples, to ensure proper requirement verification for all satellite RF components susceptible to RF breakdown.

The importance of applying the processes and risk mitigation strategies of this document continue to grow with the increase in component power levels. Multipactor and ionization breakdown can lead to device damage and/or significant mission impact; as such, this document provides methodologies to minimize potential risks in applicable RF systems and components. Many of the recent RF breakdown related issues can be traced back to a lack of standard processes for analysis and test. The processes described in TOR-2014-02198 are focused on predicting bounding, worst-case conditions for known system parameters and applying these conditions to a broad range of components and RF systems. This new and alternative approach removes excessive, hidden, or stacked margins by using bounding case calculations and measurable/available data for the particular system and component under investigation. Worst-case conditions are combined with standard analysis and test processes to minimize device susceptibility to RF breakdown.

The document is organized to follow this process in a typical component development flow, starting with high-level component definitions and determination of worst-case system parameters. Subsequent sections continue the process by providing margin requirements and then minimum requirement verifications. These minimum verification requirements utilize state-of-the-art tools for both analysis and test, and they are necessary to avoid many of the failures observed in recent history. Lastly, recommended analysis and test guidelines are provided to illustrate industry best practices and considerations for different component types. A reference geometry for analysis and test validation is also provided as a standard to the industry for comparison purposes.

This document provides new benefits to customer, contractor, and supplier groups by providing clear margin definitions and requirements, while removing excessive margin through the application of this bounding case process. Proper implementation of the latest analysis techniques can, in some cases, eliminate the need for expensive qualification/acceptance testing with more accurate and representative numerical analysis. Adherence to test requirements will provide risk reduction and early issue identification and prevent expensive failures late into the integration cycle. By following the requirements and process outlined in this document, multipactor risk within spacecraft components should be minimized throughout the component life cycle.

In summary, multipactor risk mitigation is made possible via this document through proper and careful analysis processes, test methods, and application of the process detailed in this document.

Acknowledgments

Contents

Figures

Tables

1. Introduction

1.1   Purpose

This document is intended to serve as a standard and handbook for the prevention of multipactor and ionization breakdown in spacecraft components and systems. The document provides minimum requirements for risk definition, system analysis, and component analysis and test. Supporting documentation describes proper design, analysis, and test guidelines while also providing the requirements for defining the proper system engineering to identify RF breakdown risks within susceptible components. The document framework is based on defining worst-case parameters as general inputs to analysis or test criteria for all components within the RF system. Using hardware-specific values, these worst-case parameters are defined separately from margin requirements.

With properly defined worst-case conditions, the document addresses required margins for analysis and test for multiple devices categories. Subsequent sections provide minimum verification requirements to demonstrate the margin recommendations for both analysis and test. Applicability of different analysis and test methods to the device class categories is provided, with special cases and considerations.

Multiple appendices based on state-of-the-art industry best practices are also provided as guidelines to aid manufacturers and contractors. Typical approaches including examples for both design and test are provided. A reference geometry is described along with corresponding analysis and test data. This information can be used as a benchmark standard, such that component vendors and manufacturers can have a standard example for RF breakdown.

Incorporating this document and its improved process into the development and test cycles of an RF component will reduce the risks associated with RF breakdown failure. The document goal is to concurrently reduce program risk as well as elevated cost of excessive margin requirements. This document shall serve as a baseline and minimum set of criteria for low-risk development and verification of RF spacecraft components.

1.2   Document Applicability and Features

This document is intended for RF and microwave satellite systems and component manufacturers. TOR-2014-02198 provides an overall process approach for RF breakdown mitigation using new tools, data, and current industry best practices. Some of the highlighted features of TOR-2014-02198 are:

- A device classification structure is given, allowing more specific margin requirements to be levied on the different groupings. The classifications are separated such that verification plans can be tailored to the analysis level of the device and certainty of the electric fields and multipactor regions.

- A system analysis process to determine the bounding input power for each device under consideration is provided. Parameters such as voltage enhancement due to voltage standing wave ratio (VSWR) can be accurately predicted, or evaluated, from the actual system hardware.

- Margin requirements for component analysis and test are given. Using a complete system and component process, over-conservatism is minimized using improved system knowledge, application of new simulation tools, and refined test methods.

- New and expanded minimum verification requirements for analysis and test are provided. Recommended methodologies using the latest technologies and tools are given for reference. Analysis verification requirements utilize classification by device analysis level to allow tailored application of different analysis methods and techniques

1.3 Document Tailoring

In general, high-powered RF systems within the space environment are complex and diverse and require the strict governance and controls within this document to prevent RF breakdown. However, if the methodology or limits within the standard do not account for a unique manufacturing or design solution of an RF product, then a specific tailoring within this standard may be considered by the customer or governing authority. The characteristics of the product, its system applications, and the rationale that reduces the performance risk must be documented, reviewed and approved by the governing authority prior to any requirement tailoring.

1.4 General Document Structure and Process Overview

A generalized RF system suitable for evaluation using this document is provided in Figure 1.1. This simple example illustrates a general RF system with an amplifier and N number of components. Component examples include connecting transmission lines, cable assemblies, filters, isolation devices, antenna and other devices in the RF path. This document provides a process in which the applicable power for each component is determined, an appropriate margin is chosen for the device class, and analysis and test requirements are verified.
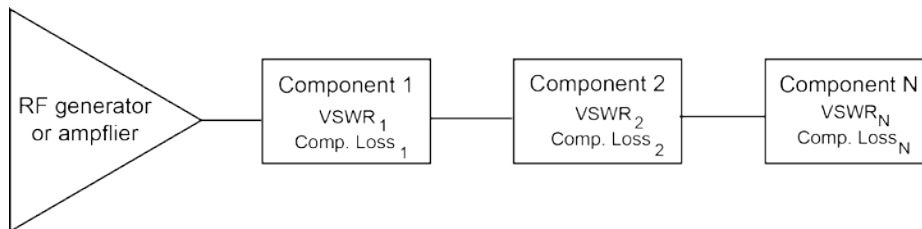
Figure 1.1.   Simplified schematic of an RF system

The goal is to determine realistic but worst-case voltages that could be present in each susceptible component. Because many of the system parameters such as component losses and voltage standing wave ratio (VSWR) are known, these can be applied to the analysis directly rather than arbitrarily applied to the margin allocation for each component. Once this power is determined, an appropriate margin for the device class and verification method (analysis or test) is then applied to this worst-case condition.

Figure 1.2 illustrates the document structure and the overall process for RF breakdown mitigation. In general, each section provides foundational analysis and requirements that are required for each subsequent section. As such, the document is intended to be used as a complete set of requirements with each section requiring previous section requirements be met. The intent and process flow of each of the sections is summarized below.

- *Section 2: Minimum Multipactor Criteria and Device Classification* – Provides minimum criteria determining under what conditions RF components shall be deemed susceptible to multipactor breakdown. Additionally, components are divided into types as well as analysis levels. These classifications allow the ability to group different types of components to

specific margin requirements and respective verification processes for that particular group. This approach allows better tailoring of margin requirements as well as analysis and test techniques.

- *Section 3: System Analysis Requirements* – Presents an analysis methodology that applies to the RF system as a whole (e.g. from the amplifier to the antenna). The goal of this section is to determine the worst-case but realistic power to each multipactor susceptible component within the RF system using available data. The requirements and margins specified in the subsequent section require worst-case power to be defined for each component using the method given in this section.

- *Section 4: Margin Requirements* – Specifies the margin requirements for analysis and test, assuming devices have been classified by the methods in Section 2 and worst-case power to each component has been determined by Section 3.

- *Section 5: Analysis Verification* – Provides a minimum set of analysis requirements to verify the margins provided in Section 4. Different analysis methods are outlined for the Analysis Levels defined in Section 2.

- *Section 6: Test Verification* – Provides a minimum set of test requirements to verify the margins provided in Section 4. These requirements shall apply to all multipactor tests for spacecraft components.

- *Section 7/8: Recommended Analysis/Test Methodology* – Illustrates state-of-the-art and current best-practices for analysis and test methods. Section 7 provides examples of analysis methods that can be implemented to meet the minimum requirements given in Section 5. Similarly, Section 8 provides additional guidance on multipactor testing and examples to meet the requirements of Section 6.

- *Appendix A: Background* – Supporting basic principles of multipactor breakdown

- *Appendix B: Multipactor mitigation process comparison* – Comparison of TOR-2014-02198 to historical or other RF breakdown mitigation processes including ECSS-E-20-01A Rev.1.

- *Appendix C: Reference Geometry for Analysis and Test* – Provides a standard geometry with corresponding analysis and test data. This device can be used as a reference geometry for analysis and test benchmarking as well as test facility verification.

- *Appendix D: References*

Section 2

| Minimum Multipactor Criteria and Device Classification | Define multipactor susceptibility and type of device/geometry |

Section 3

| System Analysis Requirements | Determine worst case voltage/electric fields for each component within RF system |

Section 4

| Margin Requirements | Apply appropriate margin to each RF component based on device class/verification method |

Section 5

| Analysis Verification | Minimum analysis criteria to successfully demonstrate margins (Section 4) to worst case conditions (Section 3) |

Section 6

| Test Verification | Minimum test criteria to successfully demonstrate margins (Section 4) to worst case conditions (Section 3) |

Section 7

| Recommended Analysis Methodology |

Section 8

| Recommended Test Methodology |

| Supporting Appendices |

Figure 1.2. Applicability and document implementation for a typical RF system.

1.5 Ionization Breakdown

Ionization breakdown shall be considered in all components that can have sufficient gas pressure to support plasma discharge. This shall include all RF components that operate during launch, such as transponders and other associated devices. Venting requirements for devices that do not operate during launch should allow sufficient vacuum conductance to maintain internal device pressures below 1×10^{-4} Torr before and during operation of each component. If such venting is provided, ionization breakdown requirements shall not apply.

Future document revisions/volumes will provide specific ionization breakdown requirements.

2. Minimum Multipactor Criteria and Device Classification

This section provides a description for multipactor susceptible geometries as well as defining device categories for which different margin, analysis, and test requirements are imposed. This section is divided into three sub-sections:

1. Minimum Multipactor Criteria
    a. Provides requirements to define multipactor susceptible components and geometries
2. Device Type
    a. Three device types are given, including:
        i. Type 1: Multipactor between metal-only electrode surfaces
        ii. Type 2: Dielectric materials within line-of-sight of multipactor region
        iii. Type 3: Variable geometries
3. Analysis Level
    a. Analysis levels are provided to apply appropriate analysis requirements for different components. The analysis level depends on device complexity, which refers to the relative departure of the RF fields when compared to those obtained in the 1-D parallel plate case. Additionally complexity refers to the relative knowledge of the specific multipactor location as compared to the 1-D parallel plate case. Three analysis levels are defined in Section 2.3.

2.1 Minimum Multipactor Criteria

For multipactor breakdown, this document shall apply to all components within spacecraft RF systems with minimum frequency of 5 MHz and local internal RF voltages greater than 5V peak. This will be referred to as the 5/5 rule[1]. A minimum power level is not applicable as the voltage is the defining parameter for multipactor breakdown. Local field analysis must be used to determine specific voltages in actual device geometries. No multipactor requirement is necessary for devices below the 5 MHz/5V peak internal voltage threshold.

2.1.1 Multipactor Susceptible Frequency Selection

Each susceptible gap within the RF system shall be evaluated for multipactor breakdown at the following frequencies:

- Lowest single carrier tone within RF bandwidth

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[1]Basis for the 5/5 rule: At 5 MHz, supporting data indicate gaps smaller than 8cm cannot support multipactor with any electrode surface due to low frequency-gap (fd) cutoff. If the region of interest for multipactor susceptibility exceeds 8cm for 5V voltages, then the 5/5 rule cannot be applied. Additionally, the 5V requirement is based upon the first crossover energy of the SEY. The first crossover energy (E1) for the majority of materials including those studied for this effort was larger than 10eV. As such, the 5V requirement would yield electron energies less than 10eV and insufficient electron growth for typical SEY values. Exceptions may occur in geometries when resonant electron motion in non-linear electric fields or magnetic field regions allows harmonic positive acceleration leading to higher impact energies for 5V accelerating voltage – although they have not been experienced by the authors.

- If the frequency-gap (fd) product of any geometry is less than 0.5 GHz-mm at the lowest single carrier tone within the bandwidth, evaluate at the highest single carrier tone within the RF bandwidth (see Section 2.1.4).

  - For large bandwidth systems: If the range of possible frequencies is larger than 0.5 GHz mm divided by the largest possible gap, d_{max}, then each gap shall be evaluated at frequency steps,

$$\Delta f = \frac{0.5 \; GHz \cdot mm}{d_{max}}.$$

Evaluation of other frequencies within the available bandwidth shall be considered if more susceptible combinations of fd and voltage are possible between the lowest and highest single carrier tones.

2.1.2 Multipactor Gap

Each gap within all components and transmission line structures satisfying the 5/5 rule shall be independently evaluated for multipactor breakdown. A susceptible gap shall be considered any open, non-filled gap between metal/metal, metal/dielectric, or dielectric/dielectric surfaces for which the 5/5 rule is satisfied. The two surfaces under consideration shall be within line of sight of multipactor electron trajectories of a possible discharge. Two surface multipactor shall be considered the primary breakdown mode, with special cases (magnetic devices and/or DC bias systems) where single surface multipactor could be possible within typical spacecraft systems.

For design and analysis, it is necessary to examine all possible gaps, including those caused by tolerance variations. Small changes due to geometric tolerances can affect significant changes in the multipactor threshold. Tolerances shall be reviewed for multipactor susceptibility including all possible gaps within the tolerance band.

2.1.3 Multipactor Frequency-Gap (fd) Product

A frequency-gap (fd) product shall be defined and provided for analysis/test verification for the frequencies defined in Section 2.1.1 and all gaps satisfying criteria in Section 2.1.2.

2.1.4 Minimum Frequency*Gap (fd$_{min}$) Product Criteria

With lower frequency-gap products (fd), there is a physical cutoff for which the multipactor criteria for electron growth cannot be met. This is referred to as the low fd cut-off or fd$_{min}$, and it has primary dependence on the secondary electron yield (SEY) [1]. fd$_{min}$ is proportional to $\sqrt{E1}$, the square root of the first crossover energy of the SEY [2]. The parameter fd$_{min}$ is also referred to as "gap-too-small". This minimum fd product is depicted in Figure 2.1.

- fd < 0.50 GHz-mm shall not be considered for multipactor breakdown.

- fd products > 0.5 GHz mm shall be considered for multipactor breakdown if also satisfying the 5/5 rule.
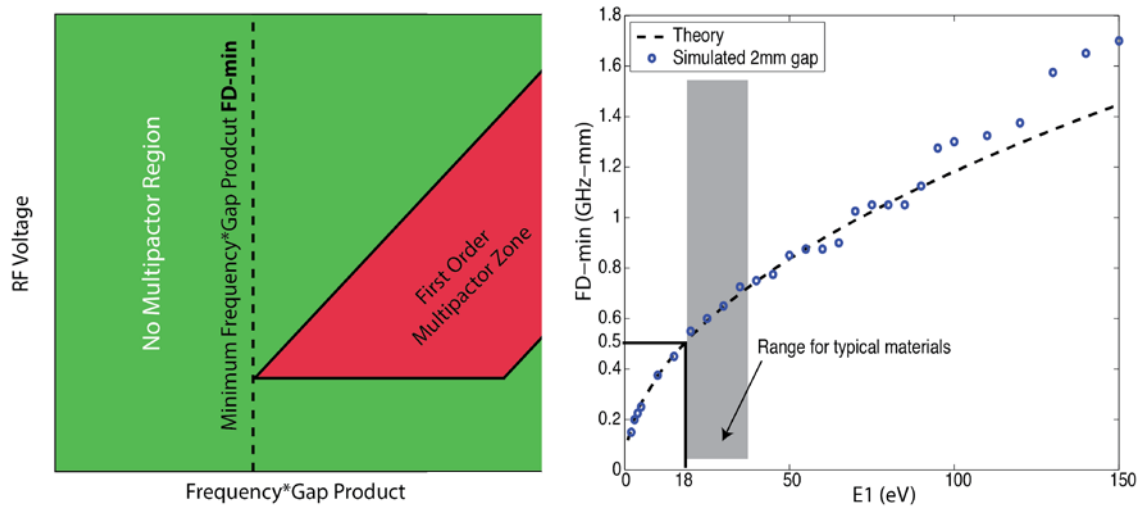
Figure 2.1.   Illustration depicting the "no multipactor region" below fd$_{min}$. Actual values of fd$_{min}$ will depend on the first cross over energy of the SEY, E$_1$.

2.2   Device Type

All susceptible components defined from Section 2.1 shall fall into the following device types, for which different margin and verification requirements apply.

Table 2.1. Device types For Multipactor Test and Analysis

Device Type	Description
1	Two surface, metallic conductors
2	Two surface, dielectric within line of sight
3	Uncontrolled geometries, filled devices

2.2.1   Type 1 Component

Electron trajectories shall be defined between metallic electrodes in the susceptible voltage region. Dielectrics shall be outside the line-of-sight (straight-line electron trajectory) of the multipactor discharge region. Metal oxides shall be considered metallic surfaces unless the oxide layer exceeds 10 skin depths. All gaps shall have a well-defined vent path per Section 3.6.

2.2.2   Type 2 Component

Electron trajectories shall be between metallic and dielectric surfaces and/or two or more dielectric surfaces within line-of-sight of the breakdown region. Organic dielectrics (containing carbon) as well as non-organic dielectrics (such as ceramics) shall be considered part of Type 2 components. All gaps shall have a well-defined vent path per Section 3.6.

Special consideration shall be taken for dielectric to dielectric interfaces that are in-plane or parallel with the possible multipactor electron trajectory.

2.2.3 Type 3 Component

This type includes components with undefined or uncontrollable gaps that include unit-to-unit variation, workmanship, and geometric tuning elements. In these cases, the multipactor gap cannot be clearly determined for all units or geometric variation can occur during the component life, including ground-test and on-orbit operation.

Examples include potted components and hermetically-sealed devices in which multipactor gaps are intentionally filled or pressurized to prevent resonant electron motion. Special consideration is required due to inability to prove multipactor mitigation through analysis due to workmanship variability.

Uncontrolled geometry examples include tuning screws, dielectric tuning elements, or variable coupling geometries. In most cases, such devices allow tunability of resonant devices. Special consideration is required due to unit-to-unit variation and differences between analysis and actual flight hardware.

Any component that does not fit the description of a Type 1 or 2 device shall be considered Type 3.

2.3 Device Analysis Level

For purposes of device analysis, components are categorized by complexity. The device analysis levels are intended to provide a means to tailor different analysis techniques to different component categories. Different analysis techniques include analytical field determination, numerical field determination, and particle tracking simulation. Proper application of the appropriate tool is necessary to verify the Section 3 margin requirements. The selection of device analysis level is based on departure from the canonical 1-D parallel plate, linear electric field case described by Vaughan [3]. Component assemblies shall be defined by the worst-case analysis level for any susceptible gap within the device. Analysis levels are summarized below in Table 2.2.

For *test* verification, all device analysis levels shall meet the same margin and verification requirements.

Table 2.2. Summary of Device Analysis Levels used for Analysis Verification

Analysis Level	Device features	Voltage Determination Method (Section 5)	Multipactor Threshold Comparison (Section 5)
1	Parallel surfaces with one possible electron trajectory[2] possible	Analytical voltage determination	Required Hatch and Williams (Figure 5.1)
2	Non-parallel surfaces or multiple electron trajectories[2] possible	Numerical, multi-dimensional voltage determination	Required Hatch and Williams (Figure 5.1), Particle sim. recommended
3	3-D electron trajectories[2], multidimensional structures, static electric/magnetic fields	Numerical, three-dimensional voltage determination	Required Particle Simulation

2.3.1 Analysis Level 1

Analysis Level 1 components shall meet all of the following considerations:

- Multipactor susceptible region can be clearly defined between two parallel surfaces
- Only one possible electron trajectory path[2] exists, with known gap dimension within the susceptible region
- Analytical determination of local RF voltage in multipactor region is possible

Examples include simple transmission line structures such as parallel plate or coaxial geometries. Resonant transmission line structures that require additional analysis to determine local fields are not considered Analysis Level 1. Presence of dielectrics may require higher analysis level due to changes in the local impedance.

2.3.2 Analysis Level 2

Analysis Level 2 components include any one of the following criteria:

- More than one possible multipactor gap/electron trajectory[2] within two dimensions
- Non-parallel surfaces
- Voltages must be determined by numerical field solutions (including multi-dimensional field solvers)

Examples include composite transmission line structures, impedance transformer geometries, and coaxial filters of varying gap size.

2.3.3 Analysis Level 3

Analysis Level 3 components include any one the following criteria AND any one of the Analysis Level 2 criteria:

- Three-dimensional electron trajectories[2] possible
- Diverging electric field vectors from multipactor region ("fringing field" [4][5] or aspect ratio limited geometries)
- Multi-dimensional resonant structures
- The presence of sufficiently large static magnetic fields [6] (See Section 2.3.5)
- Combined DC and RF electric fields within susceptible multipactor region

Examples include cavity filters, resonators, waveguide to coaxial adapters, isolators/circulators, and DC biased transmission lines.

Analysis Level 3 components shall require multidimensional particle simulation to verify analysis margin requirements (see Section 5). Any device that does not fall into one of the three Analysis Levels cannot be qualified by analysis.

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[2]Assuming electron emission normal to the bulk electrode surface

Static magnetic or electric fields as well as resonating RF fields can lead to complex electron motion; therefore, multipactor analysis by electric field integration and comparison to breakdown curves is not sufficient. This is due to the lack of applicability of these breakdown curves, which are based on parallel plate, linear electric field geometries.

2.3.4   Analysis Level Considerations

Analysis Level 1 refers to simple transmission line structures with clearly defined multipactor trajectories. In many cases, more complex, multidimensional structures may fall into either Analysis Level 2 or 3 categories. Described in detail in Section 5, Analysis Level 2 and 3 components rely on multi-dimensional, numerical models to determine the electric fields. For Analysis Level 2, the gap voltage is determined via line integration along any and all trajectories subjectively determined to be multipactor susceptible. Uncertainty can exist in the subjective nature of choosing these integration lines. These calculated voltages are compared to the parallel plate Hatch and Williams curve [2] (See Figure 5.1). Over-conservatisms may exist in the parallel plate assumptions, and under-conservatisms may exist if improper integration lines are selected.

Analysis Level 3 requires particle tracking simulation, removing the subjective nature of choosing electron trajectory paths. All possible trajectories are included in the particle simulation assuming proper 3-D electric and magnetic field determination. Over-conservatisms are removed by including electron loss mechanisms not included in the parallel plate assumptions in the Hatch and Williams curve (See Figure 5.1).

2.3.5   Special Cases and Examples

The following provide some special cases for which the analysis levels may not directly apply due to unit-to-unit variation or alternative multipactor suppression approaches. Definitions of other examples are also included.

Filled devices: Any component or sub-assembly that implements an insulating or nonconductive filling process is categorized as a potted device. Examples include high power isolators, circulators, and combiners with dielectric fill. Even if the potting material serves as a compound to strengthen shock and vibration performance or curtail effects from ground level moisture and oxidation, its effect must be considered for multipactor. Potting material must be present in one or more gaps within regions of the device exposed to the RF electric fields. Potting material examples include room temperature vulcanizing silicone (RTV), foam, or other potting compounds that are intended to eliminate all gaps in breakdown sensitive regions. Filled devices are considered either Type 2 or 3 devices based on the tolerance control and variability in the dielectric fill. Analysis level may not apply for cases in which gaps are dielectric filled due to the inability to perform multipactor analysis on gaps that are not included in component design.

Hermetic devices: A hermetic device is any device designed to maintain atmospheric pressure while in vacuum or space operation. Examples include cables or filter devices sealed with 760 Torr nitrogen internal pressure with trace concentration of helium (typical) for leak detection. The primary failure mode for these devices is ionization breakdown, rather than multipactor breakdown. Leaks in the hermetic devices can lead to reduced internal pressures capable of supporting a plasma discharge [7]. Verification of hermetic devices must include a leak rate measurement from the device and ensure sufficient internal pressures over the entire life of the mission. Unit testing should be performed over worst-case conditions including the lowest expected temperature. Sufficient internal pressure is based on the appropriate margin to ionization breakdown. Hermetic devices shall be considered Type 3 as each component margin requirement must be verified for each flight component. Analysis Level as

defined in this document does not apply to hermetic devices, as the RF breakdown analysis is more applicable for ionization breakdown rather than multipactor breakdown.

Magnetic devices (Analysis Level 3): In this context, a magnetic device is any device using external or internal static magnetic fields for device operation. Examples include isolators, circulators, and TWTs that depend on custom static magnetic fields for the tuning of the device. Any device with static magnetic field such that electron cyclotron frequency exceeds 10% of the RF frequency shall be considered in this device class.3

DC biased system (Analysis Level 3): A DC biased system is a collection of RF devices that rely on the application of a fixed DC voltage to preclude multipactor via perturbation of the electron motion in all component gaps. DC biased systems are only applicable to multipactor discharge and require additional verification for ionization breakdown due to the presence of the DC electric field in combination with the RF fields.

2.4   Process Flow Chart for Multipactor Qualification/Acceptance and Verification

The generalized process for device verification is provided in Figure 2.2 below. System analysis provides worst-case powers, which are used in analysis and testing processes. The appropriate processes are dependent on device type and analysis level. Section numbers relevant to each step are provided in the flow chart for easy reference.
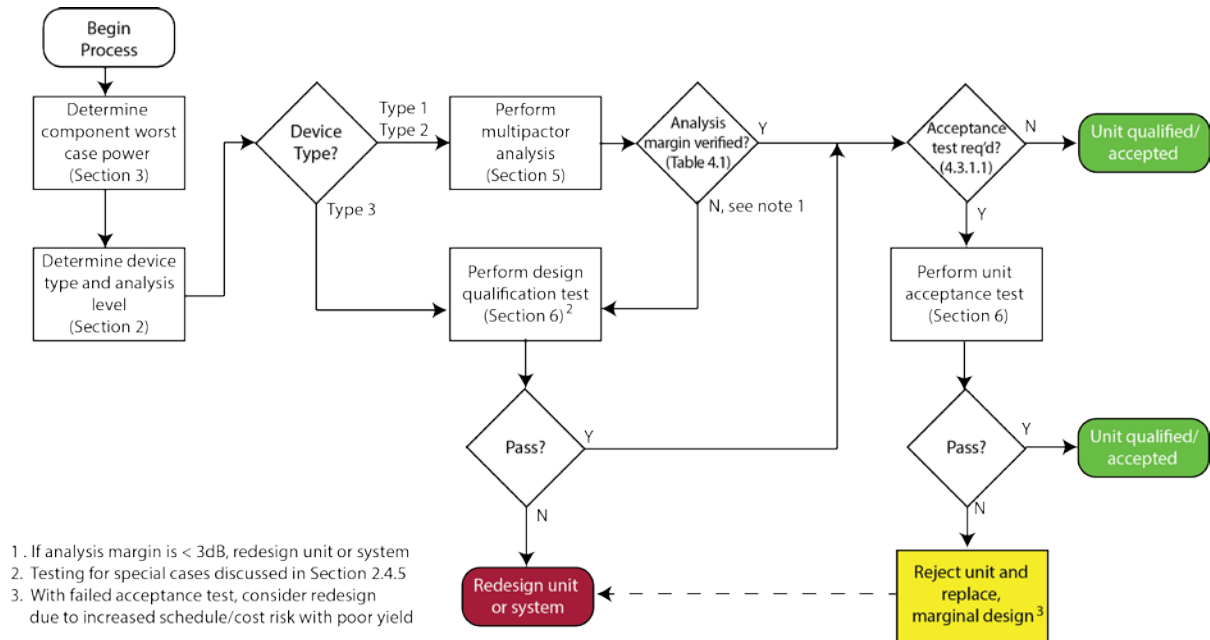
Figure 2.2.   Flow chart for margin determination and verification process.

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[3]Magnetic fields will dominate electron trajectories when electron cyclotron frequency approaches the RF frequency. A cutoff is defined at 10% of the RF frequency such that:

$$B = \frac{\pi m f_{RF}}{5q}$$

A device must be treated as Type 3 when magnetic fields exceed this critical value.

3. System Analysis Requirements

The worst-case instantaneous peak power and average power applied to each component in the high power chain shall be computed with consideration given to waveform (single carrier, modulated, multicarrier), component losses, system voltage standing wave ratio (VSWR), and fault conditions. These values can then be applied when deriving average and peak power test requirements and when computing the internal maximum voltages in determining multipactor and ionization breakdown margins.

In the simple, single carrier case shown in Figure 3.1, this section provides requirements to determine the bounding RF power to each component within the RF system. In this example, a worst-case amplifier output power is determined, and this power is decreased by component losses as it is passed downstream through the different components. Concurrently, downstream VSWR, assuming in-phase voltage addition, will lead to higher voltages within the components. All these system parameters are measureable and predictable in a bounding-case fashion, and they shall be included in determination of the applicable power to each component in the system susceptible to RF breakdown.
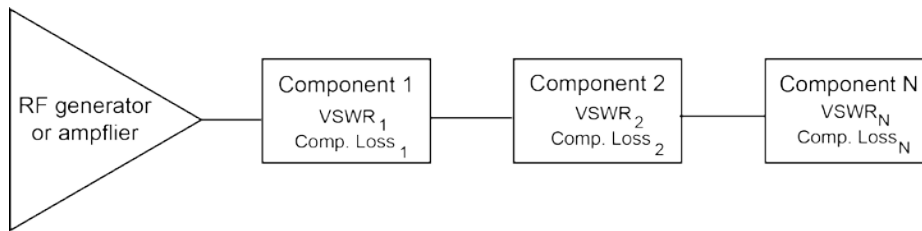
Figure 3.1.   Example of a single carrier RF system for which component N must be evaluated for multipactor breakdown.

The following requirements and process flow are provided in detail for the RF system analysis:

- Section 3.1: Determine credible, yet recoverable failure modes to define which components, losses, and VSWR effects to include in the analysis

- Section 3.2: Determination of the worst-case output power from system amplifier(s)

- Section 3.3: Component losses based on ohmic losses of all upstream components

- Section 3.4: VSWR effects to each component from downstream reflections, assuming worst-case, in-phase voltage addition

- Section 3.5: Requirement for defining effective power for each system component

- Section 3.6: Other Requirement Considerations

- Section 3.7: Venting Requirements

3.1   Definition of Failure Modes

Fault conditions shall be considered in order to specify conditions that could affect voltages in the system components. These conditions may result from standing waves due to failed components, unintended redundancy switch matrix configurations, overdrive scenarios, unintended out-of-band power reflected back from downstream narrowband components, unintended thermal conditions, test system or procedural failures, or other conditions specific to the system being analyzed. The test

power limits shall only consider single fault conditions, not the cumulative effect of multiple simultaneous faults. Fault conditions considered shall be credible and recoverable. If the failure is not recoverable, then consideration may not be necessary.

3.2 Worst-case Amplifier Power

The maximum instantaneous applied power calculation for several common amplifier configurations is described in this section.

3.2.1 Single Amplifier (Single Carrier, Modulated or Multicarrier)

The worst-case instantaneous power output from a single amplifier shall be defined as the maximum saturated output power. It is not dependent on the number of carriers or modulation. The worst-case voltage shall be determined by instantaneous power and local impedance of the device under consideration.

3.2.2 Non-resonant Combining of Amplifiers (Example: Multiport Amplifier)

Multiport amplifiers combine the power of individual amplifiers using non- resonant combiners (example: butler matrices at the input and output). Any downstream component from the non-resonant-combining matrix shall be evaluated at a power level equal to n*P, where n is the number of amplifiers and P is the saturated output power (Section 3.2.1) of each amplifier. Any upstream component from the non-resonant combining matrix shall be evaluated for a single amplifier per Section 3.2.1.

Special consideration and analysis is necessary to determine the appropriate power levels for components and devices within the non-resonant combining matrix.

3.2.3 Resonant Combining of Amplifiers (Example: Output Multiplexers)

Resonant combining of amplifiers using output multiplexers can result in instantaneous maximum peak powers equal to the voltage summation of the individual amplifier powers, represented as an peak power, n^2P, where n is the number of amplifiers combined, and P is the saturated output power of each amplifier. The time duration for which these high instantaneous peak powers may occur may be short depending on the number of carriers and the frequency spacing.

New research for requirements definition applicable to multicarrier systems is currently in progress. No specific requirement reduction from n^2P is provided in this version of the document.

For devices that constitute part of the resonant combining circuit, care should be taken to analyze each channel filter's last several output cavities as a multicarrier region since they also are exposed to multiple carriers. The penetration of individual carrier energy in any given channel filter would be a function of the filter design and manifold junction geometry.

3.3 Component Loss

The worst-case input power to the component shall be determined by reducing the maximum instantaneous peak power from the amplifier (Section 3.2) by the sum of the ohmic losses, *L*, for each upstream component. The expression below for ohmic loss assumes conjugate matching for maximum power transfer as a bounding case.

$$L(dB) = \left| S_{21}(dB) - 10log_{10}\left(1 - 10^{\frac{S_{11}(dB)}{10}}\right)\right|$$

S parameters shall be selected for minimum possible or expected ohmic loss.

3.4   VSWR/Reflected Power Enhancement

Mismatch at the output of the device will cause a voltage standing wave within the device resulting in higher voltages with in-phase voltage addition. Reflected power/VSWR contributions for each device shall be included in the worst case system power analysis. The largest downstream VSWR component specification shall be used to scale the effective device power to account for higher gap voltages.

The power enhancement due to in-phase voltage addition, E_{VSWR}, is given below in dB

$$E_{VSWR}(dB) = 20 \cdot log_{10}\left(\frac{2 \cdot VSWR}{VSWR+1}\right) = 20 \cdot log_{10}\left(1 + 10^{-\frac{RL}{20}}\right)$$

As in Section 3.3, downstream power reflections will also be reduced by ohmic losses. Assuming lossless components for reflected power enhancements shall be considered a bounding case.

3.5   Effective Component Power for Analysis and Test

The worst-case power requirement for each component shall be calculated via the following equation:

$$P_{WC}(dB) = P_{amp}(dB) - L(dB) + E_{VSWR}(dB)$$

where P_{wc} is the worst case component power, P_{amp} is the bounding amplifier(s) power given in Section 3.2, L is the ohmic loss calculated in Section 3.3, and E_{VSWR} is the reflected power enhancement given in Section 3.4.

3.6   Other Requirements and Considerations

3.6.1   Test VSWR Environment

The component may be exposed during factory testing to load environments that are different than the operational environment and these must be taken into account when specifying the test power. Examples include poor matching conditions due to TVAC chamber feedthrough connections or test equipment conditions such as test cabling and imperfect loads. Components tested in conjunction with antennas need special consideration of the radiating environments during test. Imperfect absorber mismatch and consideration of multiple reflections in a thermal vacuum environment should be assumed when determining the reflected power from downstream components.

3.6.2   Other Ground Test Considerations

When specifying the power handling of components that can outgas or are dimensionally affected by thermal loading, both the average power (thermal) and the peak instantaneous power (modulation, multicarrier) conditions should be specified.

Some highly resonant components may be capable of handling more power at vacuum than at a pressure of one atmosphere at the humidity levels in ground test. Care should be taken to review both

the vacuum operation power handling and the ground test power handling conditions when specifying test conditions.

3.7 Venting Requirements

The device under test shall be vented to ensure an internal pressure of 1×10^{-4} Torr or less in order to avoid ionization breakdown. The time required to ensure this internal pressure shall be added to the requisite vacuum soak time. Each cavity in the device shall be individually vented. Regions in the device featuring gaps that are susceptible to multipactor shall be locally vented to accommodate a local diagnostic method when possible.[4] Vent holes shall be placed for direct venting to vacuum region.

The venting rate is defined by the ratio of the device or cavity volume divided by the total vacuum conductance of all venting from this region. In order to accommodate outgassing that could occur during early operation or higher thermal loading, sufficient venting shall be incorporated to maximize the venting rate and prevent sufficient pressure rise to reach ionization breakdown pressure threshold.

Initial on-orbit operation should consider outgassing rates and possible tailoring of power profiles to allow more gradual outgassing and subsequent lower internal pressures.

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[4]The amount of time needed to ensure the device is at a sufficiently low pressure can be determined from vent hole conductance, volume, and the difference in pressure within the device and pressure in the vacuum chamber. The conductance of a vent hole with length L and diameter D is given by the long tube approximation:

$$C = 12.2 \frac{D^3}{L} \text{ [liters/sec]}$$

where D and L are given in centimeters. Parallel conductances add such that if a device has fifteen identical vent holes with conductance C_1, total conductance will be $15*C_1$. The pressure inside the device changes at a rate $Q = d(PV)/dt$ described by:

$$Q = C*(P_D - P_C) \text{ [Torr-liters/sec]}$$

where P_D is the pressure inside the device and P_C is the pressure in the vacuum chamber. [8]

4. Multipactor Margin Requirements

4.1 Margin Requirements

Table 4.1 provides minimum power margin requirements for analysis and test of multipactor breakdown.

- These margins shall only be appropriate when verified using the methods and requirements given in Section 5, Analysis Verification Requirements, and Section 6, Test Verification Requirements.

- These margins shall be based on input power defined using the methods and requirements given in Section 3.

- All components and multipactor susceptible geometries satisfying the minimum multipactor criteria (Section 2) shall have a baseline analysis conducted prior to performing acceptance or qualification testing.

- Type 3 components shall have documentation providing rationale for classification as well as analysis limitations for the specific component

Table 4.1. Multipactor Margin Requirements for Analysis and Test

Analysis Level	Analysis Margin (dB)			Test Margin (dB)	
	Type 1	Type 2	Type 3	Type 1/2/3	Example
1	3	3	N/A	3	1-D Transmission Line
2	3	6	N/A	3	Stepped Impedance
3	3	6	N/A	3	Isolator

4.2 Factors Influencing Margin Requirements

Multiple factors are incorporated within the device analysis levels as well as device types in order to reduce excessive conservatism in choosing the appropriate margin requirement for analysis and test. Analysis requirements for the different levels and device classes are set based on accuracy and ability to compute the appropriate accelerating voltage as well as determining the multipactor location.

In terms of device types, higher analysis margins are required with dielectrics present due to a higher risk of component failure and uncertainty of the dielectric effects on the multipactor threshold (SEY and/or surface charging). Multipactor margin requirements for Type 3 components with unit-to-unit variability cannot be solely verified by analysis; as such, acceptance testing is required for these component types. With more complex devices, such as Analysis Levels 2 and 3, voltage determination typically requires a multi-dimensional model to accurately determine local gap voltages. For Analysis Level 2 and 3 devices, an additional 3 dB margin for analysis is required over simpler Analysis level 1 devices due multiple possible electron trajectories and overall component complexity in electric field determination. Analysis Level 3 requires improved multipactor modeling using state-of-the-art particle simulation tools that can remove the subjective nature of choosing susceptible trajectories and also more accurately simulate complex electron motion.

For test, margins are the same across all device types and Analysis Levels. These margins are appropriate as long as the device under test is identical to the intended flight component and power levels are based on the system analysis requirements of Section 3. Margins are identical with and

without dielectrics assuming that the device adequately represents the materials, geometry, and configuration of the actual component.

4.3   Margin Verification Methods

Margins specified in Table 4.1 shall be verified by component qualification and, when applicable, acceptance test (Section 2.4). Qualification shall be required for all components. Definitions and requirements for qualification and acceptance are provided below. Minimum margin verification requirements for qualification/acceptance via analysis or test are provided in Sections 5 and 6, respectively.

4.3.1   Component Qualification

Component qualification is intended to demonstrate adequate margin for multipactor in terms of component design and manufacturing processes. Qualification also ensures the acceptance program will produce hardware that will meet the component requirements with margin. Qualification testing validates the acceptance verification process including validation of test techniques, equipment, and procedures [9].

Component qualification shall be required for all device types. Qualification by analysis shall be considered for device types 1 and 2 only. Any component operating at a new frequency with respect to prior qualification conditions shall require additional qualification at these new conditions. Operation at higher power levels shall require additional qualification if there is insufficient margin per Table 4.1 at the increased level with respect to prior qualification power levels.

For new component development, risk-reduction testing on an engineering model/prototype is recommended prior to proceeding into production of qualification units. Upper-limit capability tests, in which the component power is increased until breakdown is observed, is also recommended for new designs.

4.3.1.1   Lot Acceptance by Qualification

The following criteria shall be met in order for qualification analysis/test to verify acceptable margins for all identical flight units within a manufacturing lot. For this case, unit-level acceptance testing (Section 4.3.3) is not required.

- Worst-case component voltages shall be computed per Section 3
- Qualification by test: Performed on unit identical to flight component(s)
- Qualification by analysis: Model shall be representative of worst-case geometry and local voltages expected within all flight components
- Bounding worst-case conditions in terms of multipactor susceptibility
- No unit-to-unit variability between qualification and flight units (Type 1 and Type 2)

4.3.1.2   Qualification by Similarity

Qualification by similarity shall be possible for consideration if geometries affecting multipactor performance and the frequency of interest are determined to be identical to prior qualification. Description of any device changes and similarity to prior qualification shall be provided to the

17

customer. The customer shall provide approval on "qualification by similarity" applicability to each component under consideration.

4.3.2 Component Proto-qualification Testing

Qualification test conditions may induce overstresses to the component (electrical, thermal or mechanical) that may make it unsuitable for flight without refurbishment and retest at acceptance temperatures. Proto-qualification test conditions shall demonstrate the required multipactor margin with no overstress to allow the component to be accepted and used for flight.

Qualification may include conditions in which device temperatures may exceed the unit capability due to the combination of qualification baseplate temperature (hot) plus peak RF power dissipation. Proto-qualification may include tailoring of the thermal conditions and power profile to prevent overstress to the component.

4.3.3 Flight Component Acceptance Testing

Component acceptance testing is conducted to demonstrate multipactor-free operation with margin for each deliverable unit. Testing shall demonstrate workmanship and manufacturing is sufficient to eliminate multipactor breakdown under worst-case flight conditions plus margin. Acceptance testing should envelop worst-case conditions and applications, and test conditions are designed to allow repeated testing of the component with no degradation [9].

Acceptance of flight components shall be applicable by test only. All Type 3 components shall undergo acceptance testing of each flight unit to verify workmanship and manufacturing/unit-to-unit variations. Any component not satisfying conditions in Section 4.3.1.1 shall satisfy margin requirements via acceptance test per Table 4.1.

The following criteria shall be met for valid component acceptance:

- Performed on each flight unit
- Worst-case component power shall be computed per Section 3
- 3 dB test margin shall be demonstrated to Section 3 worst case power
- All minimum test verification requirements (Section 6) are met

4.4 Risk Management Process

This document is designed to minimize multipactor risk, and thus stipulates a suitable approach to analyzing and testing hardware. Any departure from margin requirements (Table 4.1) or deviations from the outlined process (Figure 2.2) shall require specific and documented disposition and technical rationale for the acceptance of higher risk associated with lower margin requirements. Customer and supplier shall agree on additional risk imposed by a departure from specified requirements.

5.   Analysis Verification Requirements

This section describes the minimum verification criteria required to validate multipactor mitigation by analysis, per the performance margins outlined within Section 4.

Each paragraph for verification requirements contains the general criteria for each analysis of multiple device classes and for application of different analysis methods to different analysis levels. Table 5.1 provides a list of the minimum criteria for analysis verification

Table 5.1. General List of Analysis Verification Requirements

Section	Analysis Requirements	Description/Summary
5.1	Geometric evaluation	Determine all regions requiring analysis
5.2	Frequency selection	Determine analysis frequencies
5.3	Local field analysis	Voltage in all susceptible regions
5.4	System parameters for analysis	Application of Section 3 Worst-case Power
5.5	Analytical margin determination	Determination of multipactor margin by comparison to known/modeled threshold
5.6	Material evaluation	Baseline SEY requirements
5.7	Ineligible Components	Type 3 components

5.1   Geometric Evaluation

Each device and each gap satisfying the multipactor criteria in Section 2 shall be evaluated for multipactor. Analysis for devices below fd_{min} (Section 2.1.4) shall require disposition of "gap-too-small" for multipactor breakdown.

Analysis shall not be sufficient for Type 3 devices (by definition) due to workmanship and/or unknown locations/geometries for breakdown.

5.2   Frequency Selection

An analysis shall be performed for each frequency specified by Section 2.1.1. Additional analyses may be necessary for cases with other frequencies of concern and/or consideration.

5.3   Implementing System Parameters into Analysis

For each component and susceptible gap, the worst-case input power shall be derived via methods provided in Section 3 for baseline internal voltage/electric field determination. Voltages and/or electric field maps derived in Section 5.4 shall be scaled to input power levels given in Section 3.

5.4   Local Electric Field/Voltage Analysis

For each component and susceptible geometry, electric fields local to the specific multipactor region shall be determined. Minimum requirements for determining these fields are categorized by device Analysis Level, which are tailored by different analytical methods as described below.

5.4.1   Analysis Level 1

As described in Section 2.3, Analysis Level 1 components shall have analytically-determined voltages in the multipactor susceptible region. Level 1 components shall have no gap variation within

the region with parallel electrodes, such that analytical expressions for the voltage shall apply across the entire region.

Analysis Level 1 components shall have a single computed voltage for the multipactor-susceptible region. The multipactor assessment for the entire region will be based on this voltage and comparison to known thresholds (Figure 5.1).

In cases with dielectric layers of different dielectric constants (or stacked dielectrics), the voltage shall be calculated in the vacuum gap region including impedance changes due to the presence of the dielectric layers. Application of Analysis Level 2 methods shall be required if analytical solutions are not available or possible for the vacuum gap region.

5.4.2   Analysis Level 2

Analysis Level 2 components have more than one possible gap and/or length of electron trajectory (assuming emission normal to surface) within a multipactor region. Electrode surfaces may also be non-parallel. As such, determination of the local voltages requires numerical field solutions from multi-dimensional field solvers. Level 2 components shall have electric fields within the multipactor gap modeled with numerical solvers. Voltage determination shall be performed via line integration of the electric field for each possible electron trajectory or gap within the region that could potentially support multipactor.

Analysis Level 2 components may have multiple computed voltages for each multipactor-susceptible region. A multipactor assessment is required for each voltage with comparison to known thresholds (Figure 5.1). In the event that it is not possible to identify electron trajectories or gaps within the region, which could support multipactor, then the application of Analysis Level 3 methods shall be performed on the device.

5.4.3   Analysis Level 3

Analysis Level 3 components require three dimensional (3-D) electric field solvers or tools to determine all internal electric fields for the component. In these cases, voltage calculation is not required because susceptible gaps and/or electron trajectories are not well defined.

Analysis Level 3 components shall have a 3-D electric field map that can be incorporated into particle tracking simulation tools to determine multipactor thresholds. The breakdown power threshold shall be determined by the particle tracking software, applied to all potentially susceptible geometries within the device.

5.4.4   Analysis Level Considerations

While a low analysis level device can be analyzed using a higher analysis level process, analysis margin cannot be verified in cases where a higher analysis level device is analyzed using a lower analysis level process. An example is a magnetic device (Analysis Level 3) which requires particle tracking and the Analysis Level 3 process. The lower Analysis Level process can be performed for risk assessment (Section 7.3), but it cannot be used for margin verification. Exceptions may be possible for some devices falling between Analysis Levels 2 and 3. For multi-dimensional devices with 3-D electric field solutions, Analysis Level 3 is recommended, but Analysis Level 2 may be used if conservative parallel plate assumptions satisfy analysis verification requirements and all possible electron trajectories have been bounded in the analysis.

5.5 Analytical Margin Determination

5.5.1 Analysis Level 1 and 2 Components

Each voltage computed in Sections 5.4.1 or 5.4.2 shall be compared to the baseline threshold voltages given in Figure 5.1. Multipactor margin shall be computed for each fd product by the equation below.

$$Margin \ (in \ dB) = 20 log_{10} \frac{V_{\text{threshold}}}{V_{\text{local}}}$$

where $V_{\text{threshold}}$ is the voltage from Figure 5.1 at the determined fd location, and V_{local} is the computed voltage from Sections 5.2.1/5.2.2. All voltages are given in peak voltage.
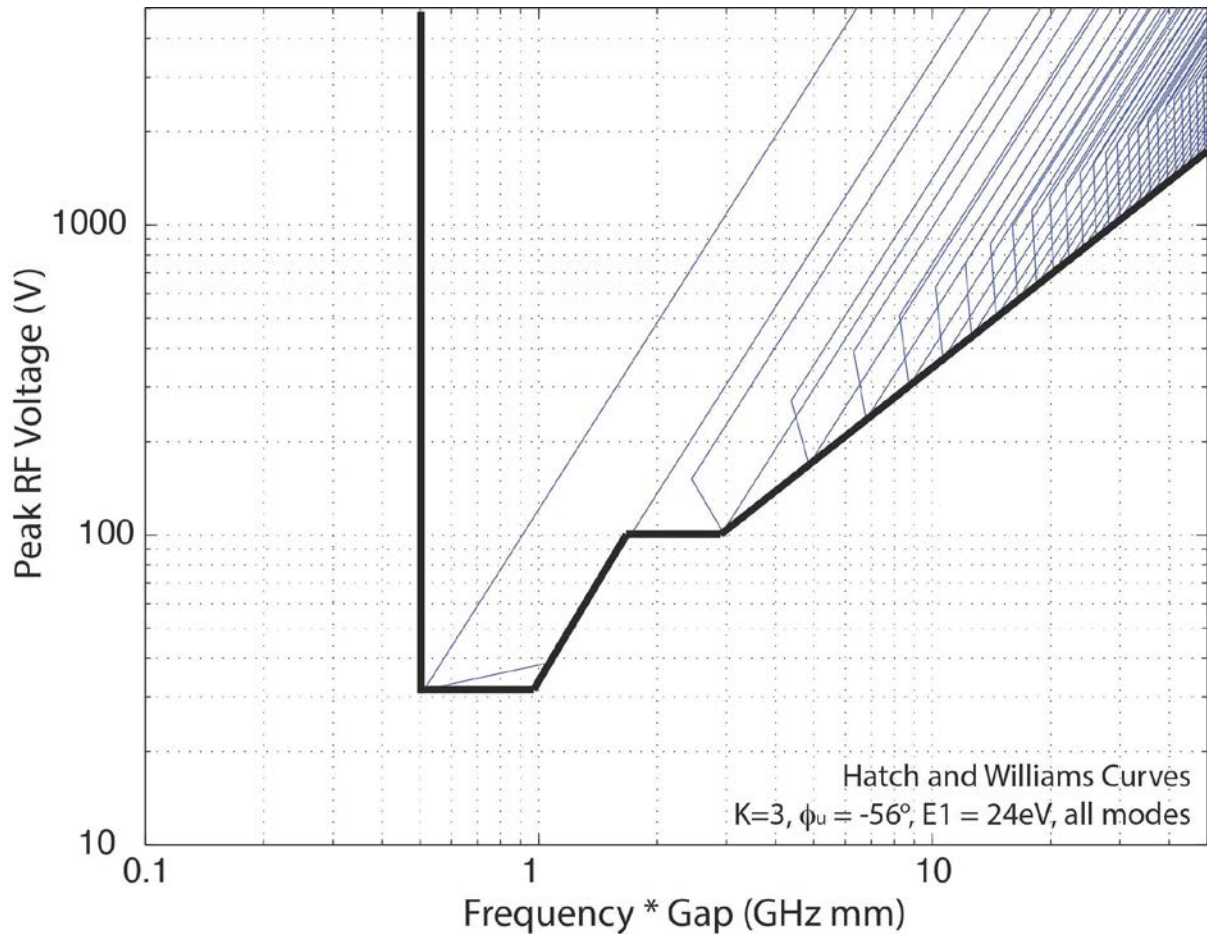
Figure 5.1.   Baseline multipactor threshold curves for analysis. RF voltage shown is peak RF voltage.

Analysis Level 1 and 2 component voltages shall be compared to the black curve shown in Figure 5.1 as a baseline. The curve is represented by the equations given in Table 5.2.

Table 5.2. Threshold Voltage Equations by Frequency-Gap Product.

fd Region (GHz-mm)	Threshold Voltage Equation
0.50 to 1.0	V = 31.65 (constant)
1.0 to 1.67	V = 34 fd ^{2}
1.67 to 2.9	V = 100.6
2.9 to 50	V = 34.6 fd

This curve is generated using the standard Hatch and Williams relationships assuming linear electric fields for multiple half-cycle multipactor modes [2]. SEY considerations are discussed in Section 5.6.

5.5.2 Analysis Level 3 Components

Analysis Level 3 components cannot be adequately compared to parallel plate analyses for multipactor breakdown due to highly non-uniform and/or non-linear electric fields, presence of magnetic fields, or other effects that can lead to large uncertainties in the electron trajectories. As such, Level 3 component voltages calculated via numerical solvers cannot be simply compared to the Hatch and Williams curves shown in Figure 5.1.

For level 3 components, the multipactor threshold shall be determined via multi-dimensional electron/particle simulation. A bounding SEY ($E_1 \leq 24$ eV, $\delta_{max} \geq 2.9$, $E_{max} \leq 150$ eV) (Section 5.6, see Figure 5.2) shall be used in simulation to provide a bounding analysis case. Simulation of space charge effects is not required but may provide more accurate results in some cases. Once a threshold has been determined, margin is computed via the equation below and compared to the margins given in Table 4.1:

$$Margin\ (in\ dB) = 10log_{10}\frac{P_{analysis}}{P_{worst\ case}}$$

5.6 Material/SEY Evaluation

The bounding SEY[5] used in Figure 5.1 is required for baseline analysis due to uncertainty and variation in surface preparation, contamination over component life, and SEY variation between plating processes. Figure 5.1 is based upon a baseline SEY that bounds the majority of plating variations for common metal surfaces as well as normal contamination such as water adsorption and other possible thin films. Foreign contamination sources such as oils, outgassing residue, or potting compounds may not be bracketed by Figure 5.1; as such, proper contamination sensitivity and vacuum cleanliness shall be strictly practiced [20][21].

Alterations of the multipactor threshold based on electrode material shall not be considered for worst-case analysis. This is based on strong sensitivity of the multipactor threshold to surface variability from different plating processes and/or uncontrollable, thin-film contamination layers [10]. Plated surfaces with the same baseline atomic composition (e.g. silver plating) can have different SEY values and subsequent multipactor thresholds. Figure 5.1 is intended to encompass the majority of typical surface variations.

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[5]A worst-case SEY shall be required for analysis due to uncertainty and variation in surface preparation and contamination that can occur over the life of the component. With even the most strict assembly and manufacturing procedures, the majority of satellite hardware will be exposed to ambient atmospheric conditions as well as other contamination sources associated with outgassing on the spacecraft, test facility, or other adjacent materials. Thin contamination layers can have a significant effect on the SEY [10].

The required worst-case SEY is plotted against electron energy in Figure 5.2 ($E1 = 24$ eV, $\delta_{max} = 2.98$, $E_{max} = 150$ eV, and $E_0 = 14$ eV)[6]. The curve is generated using the formulae provided by Rodney [17] and Vicente [19].
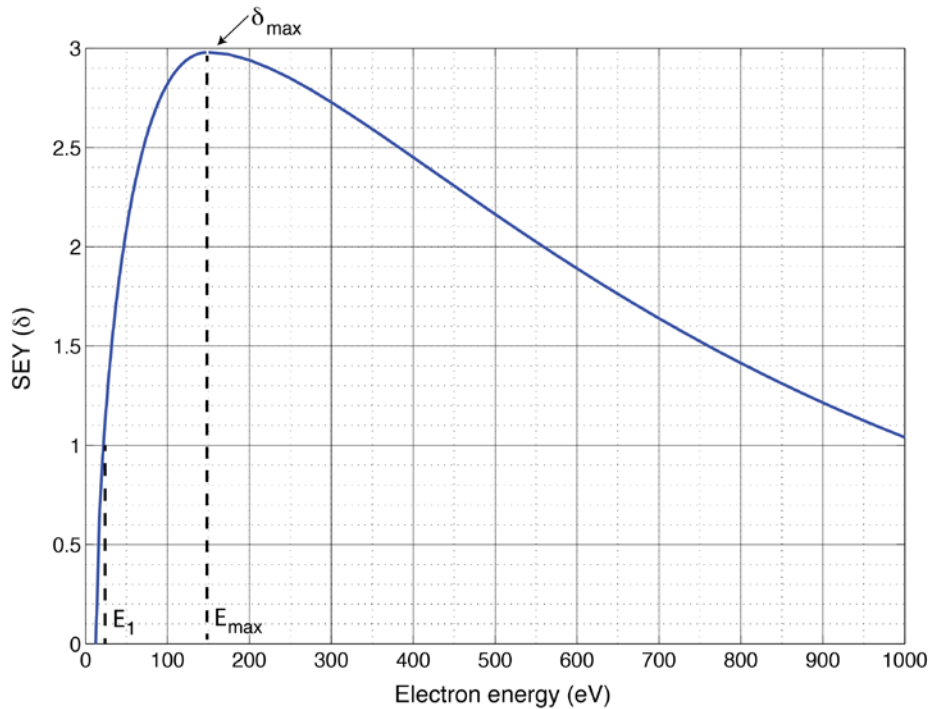
Figure 5.2.   Worst-case secondary electron yield.

5.7   Components Not Eligible for Qualification by Analysis

Type 3 components including potted, hermetically-sealed, dielectric-filled, or uncontrolled geometries shall not be qualified by analysis. This shall be documented for any possible multipactor gaps with workmanship variation or unknown gap sizes in voids or uncontrolled geometries associated with tuning elements or similar configurations. Acceptance test screening is required for these components to ensure proper operation over life.

5.8   Analysis Process

The following describes the general process for multipactor margin verification by analysis.

1. Identify the necessary method to determine the local electric field in the susceptible gap region.

    a. Analysis Level 1: Analytically determine the gap voltage in the susceptible region

    b. Analysis Level 2: Numerically determine the electric fields in the multidimensional region. Calculate the local voltage by line integration of the electric fields for any and all possible multipacting electron trajectories

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[6]Below E_0 the SEY can be assumed to be equal to 0.5 [19].

    c.   Analysis Level 3: Numerically determine the 3-D electric fields in the multidimensional region. (In some simulation tools, field analysis is done concurrently with particle tracking simulation)

2. Analysis Level 1 and 2: Scale each determined gap voltage to the worst case power by the following equation, where $P_{worstcase}$ is calculated in Section 3, and $P_{analysis}$ is the input power used in the analysis:

$$V_{scaled} = V_{analysis} \sqrt{\frac{P_{worstcase}}{P_{analysis}}}$$

Compare the scaled voltage(s) to known threshold(s) given in Figure 5.1. Determine margin by the equation in Section 5.5.1.

3. Analysis Level 3: Input the 3-D electric field model into a particle tracking tool. Determine the threshold breakdown power and compare to $P_{worstcase}$ derived in Section 3.

4. If margins in Table 4.1 are satisfied, then margin verification is **<u>complete</u>**

5. If margins in Table 4.1 are not met, then determine if evaluation at a higher Analysis Level is possible/needed (Analyze Level 2 component as Level 3). If so, repeat process starting with step number 1.

6. Type 3 components as well as any component not meeting the analysis verification requirements shall undergo redesign or verification by test.

The flow diagram in Figure 5.3 summarizes the baseline analysis process above. Other hybrid analysis approaches may be possible, and some examples and recommendations are provided in Section 7.
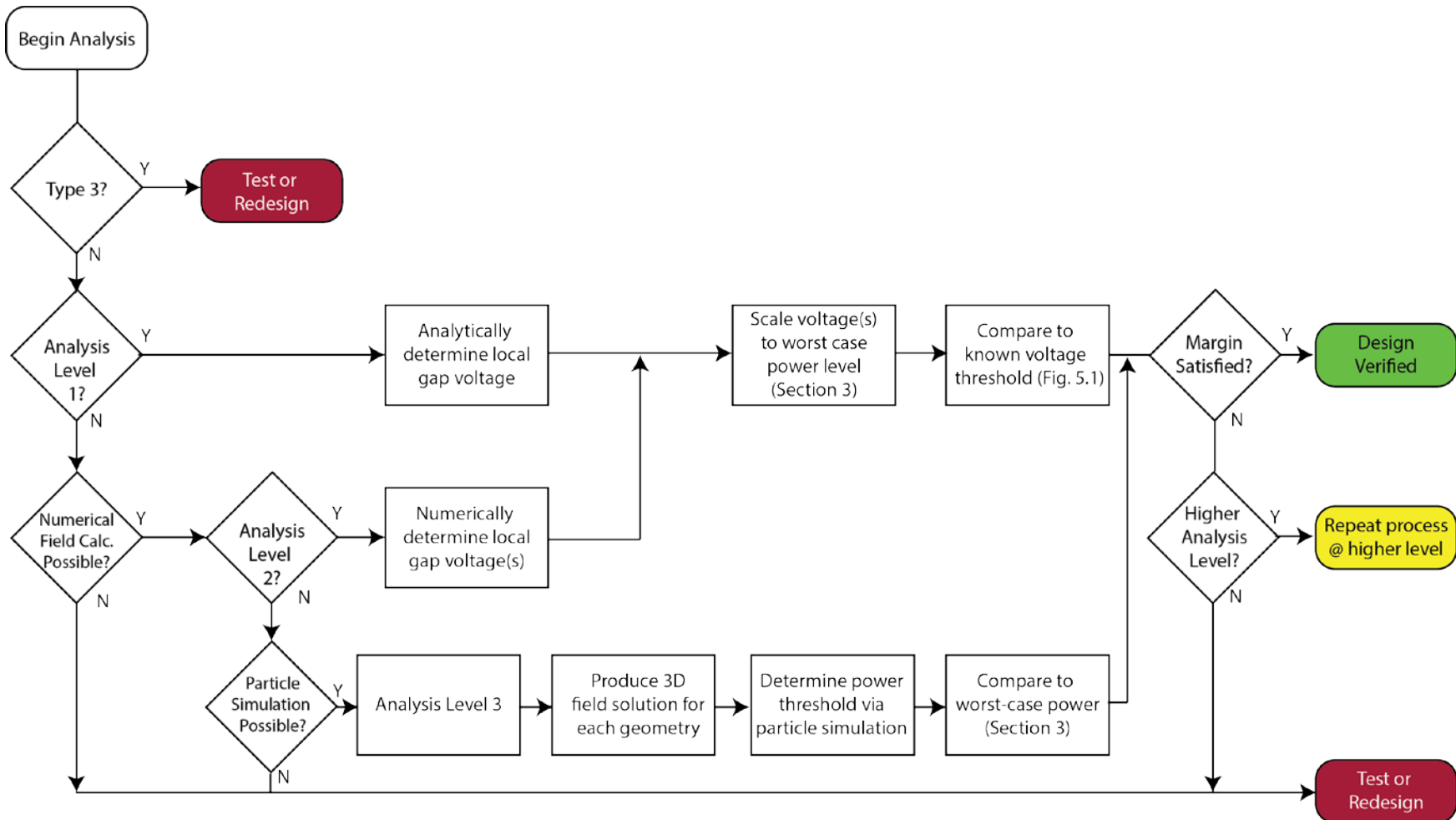
Figure 5.3.   Minimum analysis verification process.

6. Test Verification Requirements

This section outlines the basic minimum criteria for requirement verification via multipactor test. The requirements are summarized in Table 6.1.

Table 6.1. Summary of Minimum Test Requirements for Margin Verification

Section	Test Requirements	Description/Summary
6.1	Documentation	Detailed test plan
6.2	Breakdown detection methods	2 global, 1 local when possible; high sensitivity
6.3	Test setup verification	RF breakdown-free test setup Demonstration of multipactor detection
6.4	Duty cycle	Based on simultaneous application of average and peak power with margin
6.5	Pulse length	1 microsecond minimum, must be detectable
6.6	Electron seeding	Required for pulse lengths less than 1 ms
6.7	Vacuum	Vacuum defined as below 10^{-4} Torr 24 hours at ambient air before test 12 hour minimum soak at ambient temperature and vacuum before test
6.8	Thermal	Baseplate temperatures based on unit acceptance, proto-, or qual. Temperatures Pre-test thermal vacuum temperatures constraints
6.9	Data acquisition	Continuous monitoring at sampling rates fast enough to detect breakdown on one pulse
6.10	Pass/fail criteria	Simultaneous detection on at least 2 methods

6.1 Documentation

A detailed multipactor test plan shall be provided for each flight device that meets the criteria of this section. The customer shall approve the test plan prior to test start.

6.2 Breakdown Detection Methods

Multipactor events shall be detected by means of global and/or local diagnostics. Global diagnostics are defined as detection of multipactor occurring the test equipment and device under test. This diagnostic cannot typically determine the specific location of the multipactor breakdown. Local diagnostics are defined as detection of the local electron current or photo-emission directly from the multipacting electrons or local plasma. Diagnostic sensitivity is defined in Section 8.4.

The detection methods that are required for multipactor testing shall include:

- At least 2 high-sensitivity global multipactor detection methods

- At least 1 high-sensitivity local multipactor detection method, where possible

The device monitors that are required for multipactor testing shall include:

- Incident power monitor (peak and average)

- Reflected power monitor (peak and average)

- Output power monitor (peak and average, if available)

- Temperature of unit

- Chamber pressure

Peak power may be used as a detection method only if high-speed detection (such as with a diode detector) is used. Local diagnostics shall be implemented when access to internal geometries is available. During unit design, consideration should be given to locating vent holes near susceptible locations to provide local diagnostic access. Local diagnostics are not required for fully-filled, potted, or complete dielectric-loaded devices where internal geometries are inaccessible.

6.3   Test Setup Verification

Prior to flight article testing for RF breakdown margin verification, the test setup shall be verified via a demonstration of multipactor-free operation within the setup and demonstrated breakdown of a known breakdown device.

6.3.1   Setup Verification

With no DUT present, RF energy shall be applied to the test setup at the test frequency and at least the maximum test power to demonstrate multipactor-free operation within the test components, system, and test diagnostics. Setup verification can be done at ambient temperature unless specific concerns exist. There shall be no evidence of multipactor breakdown.

6.3.2   Known Breakdown Device

A known multipactor device with a known breakdown threshold shall be tested in the identical test configuration as the DUT. The verification test shall be performed at the same frequency as the device under test. Evidence of successful breakdown detection shall be demonstrated for at least 2 global, high-sensitivity diagnostics as well as any local diagnostics, simultaneously. Evidence of successful breakdown detection with the known multipactor device shall be demonstrated before and after flight unit testing.

6.4   Duty Cycle

To verify Section 4 margins by test, the average maximum power (Section 3) will be exceeded by the specified margin of +3 dB. For CW components, testing the component at +3 dB average CW power may overstress the device thermally. In such cases, a duty cycle shall be employed to match worst-case average power (0 dB) with peak power provided at the +3 dB level. For the 3 dB margin case, this equates to a 50% duty cycle. The average power shall be maintained at the 0 dB power level, with one exception. The duty cycle may be reduced in cases when extreme cold temperatures cannot be achieved with the nominal duty cycle.

No additional average power margin requirement is provided in this document.

6.5   Pulse Length

The minimum pulse length shall be greater than 10,000 RF cycles for the specific test frequency of interest. In no case shall the pulse width be less than 1 microsecond. The detectability of the chosen pulse width shall be confirmed by the known breakdown device from Section 6.3.

For test configurations in which electron seeding levels are lower than on-orbit (e.g. all laboratory radioactive sources), test-like-you-fly exceptions should be considered to allow longer pulse lengths for testing. Longer pulse lengths can decrease the sensitivity to electron seeding and provide more time response for common diagnostics.

6.6 Electron Seeding

Electron seeding is defined as the introduction of free electrons to the local, multipactor susceptible regions within the DUT. The minimum requirements for electron seeding in multipactor testing for the test conditions below shall be as follows:

- Pulsed testing
  - Electron seeding is required when the pulse width is less than 1 millisecond or for duty cycles less than 5%.
- Continuous wave (CW) testing
  - Electron seeding is not required, but is recommended when possible.

The electron seeding source shall provide local electrons to breakdown risk area. Consideration for the seed strength shall include radioactive isotope selection, DUT housing material, wall thickness, as well as physical access to internal geometries.

6.7 Vacuum

All components shall have a minimum of 24 hours ambient, atmospheric (not dry nitrogen) exposure in the expected component or spacecraft test environment prior to starting pumpdown for the multipactor test thermal vacuum cycle[7].

Manufacturing bake-out processes or other high temperature thermal vacuum tests shall be performed separately from the thermal vacuum cycle for multipactor testing.

For initial vacuum chamber pump-down, soak periods shall be started once vacuum chamber pressures reach 5×10^{-5} Torr.

To minimize the risk of ionization breakdown, components shall be soaked in vacuum at a pressure less than 5×10^{-5} Torr and at ambient (about 25 degrees Celsius) temperature for minimum of 12 hours prior to applying power to the device under test. Vacuum soak times may be extended for items with volatile compounds or poorly defined vent paths.

Chamber pressure shall not exceed 5×10^{-4} Torr during any portion of testing when RF is applied. Exceeding this pressure point shall impose a restart of the vacuum soak period due to ionization breakdown risk.

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[7]The majority of RF components are exposed to ambient, atmospheric (air) conditions prior to on-orbit operation; as such, some degree of recontamination of water vapor and other species present in ambient air will occur. Once on-orbit, these gases can persist for many months given low component temperatures prior to RF operation. This requirement exists to provide a test-like-you-fly condition for the multipactor test, providing a realistic surface condition and outgassing scenario similar to the first application of power for the component on-orbit.

6.8 Thermal

During the vacuum soak period described in Section 6.7 and prior to application of RF power, DUT and baseplate temperature shall not exceed the larger of the maximum on-orbit component temperature prior to RF operation or ambient chamber temperature.

Flight representative thermal cycle profiles are required during multipactor component level testing. Devices shall be subjected to thermal cycling with RF power applied. The temperature extremes shall be determined by the applicable acceptance, protoflight, protoqualification, or qualification temperatures of the device.

The minimum dwell times at a temperature shall be at least 10 minutes after thermal stabilization. Ramp rates shall be at least as fast as operational predictions.

For the thermal profile test conditions, the device shall be tested at the cold extreme temperature prior to the hot extreme temperature. This is required to maintain bounding and test-like-you-fly conditions based on first on-orbit application of RF power to the component.

6.9 Data Acquisition

All items listed in Section 6.2 shall be continuously monitored and recorded throughout test for post-test review. Data acquisition rates for detection methods (local and global diagnostics) shall be sufficient to measure transient multipactor events [10] occurring within a single pulse. Other parameters, such as temperature and pressure, shall be monitored at a reasonable rate with respect to the speed of changes during test. Further recommendations are given in Section 8.9.

6.10 Pass/Fail Criteria

Pass/fail criteria are specific to the attributes of the device under test and chosen detection methods and shall be stipulated as appropriate for that detection method.

RF breakdown shall be indicated by simultaneous detection on a minimum of two global diagnostics or a single local diagnostic. Simultaneous increase of any duration over a pre-determined threshold shall be considered positive indication of RF breakdown. Threshold levels shall be specified within the test documentation (Section 6.1). Detection on single global diagnostic shall be dispositioned in the test report.

In order to successfully verify margins by test, the full-recorded data history (Section 6.9) shall be provided to verify component performance with no simultaneous detection of breakdown at any point. Additionally, evidence of successful detection on the known breakdown device shall be provided.

Short bursts of multipactor or ionization breakdown that are not sustained and/or difficult to repeat shall be fully considered and evaluated by the pass/fail criteria. If dispositioned as positive indication of breakdown and test failure, no subsequent testing on the failed DUT shall be considered to exonerate the original failure.

7.   Analysis Methodology

This section describes methods and consideration for performing multipactor analysis for an RF device or assembly. The following topics are addressed below:

- Steps for determining multipactor breakdown threshold at the device level

- Guidance and considerations for applying analysis techniques

- Analysis methods for risk assessment

The foundation of any multipactor analysis is knowledge of the electromagnetic field distribution within the device. An analytical or numerical model capable of providing accurate field quantities and distributions is the baseline requirement of all analysis methods. In support of a field solution, the basic inputs of frequency, RF geometry, and RF material parameters are required for any multipactor analysis. Minimum requirements for these inputs are described in Section 5.

The baseline method of analysis chosen for a device depends upon the Analysis Level for the device as outlined in Section 2. However, a device may be analyzed as if it were of a higher Analysis Level (provided it is not Analysis Level 3). An analysis performed at a lower level is for risk assessment purposes (Section 7.3) and cannot be used for margin verification.

Table 7.1. Summary of Analysis Verification by Analysis Level

Analysis Level	Device features	Voltage Determination Method (Section 5)	Multipactor Threshold Comparison (Section 5)
1	Parallel surfaces with one possible electron trajectory[2] possible	Analytical voltage determination	Required Hatch and Williams (Figure 5.1)
2	Non-parallel surfaces or multiple electron trajectories[2] possible	Numerical, multi-dimensional voltage determination	Required Hatch and Williams (Figure 5.1)
3	3-D electron trajectories[2], multidimensional structures, DC electric or magnetic fields	Numerical, three-dimensional voltage determination	Required Particle Simulation

7.1   Analysis Level 1 and 2

The process of verification analysis for Analysis Level 1 and 2 devices differs only in the method of obtaining gap voltages. For this reason, analysis methodologies for these two device levels are considered together in this section. Two equivalent processes for verifying analysis margin are outlined below.

7.2   Steps for Verification Analysis using Worst-case Power (Section 3)

When performing a verification analysis, there is a worst-case power (Section 3) for which the device is being verified. Recommended steps for this process are outlined below:

1. Calculate the surface to surface RF gap voltages within the device

    a. Voltage calculated based on field solution ($V_{analysis} = \left| \int_{l_{Gap}} \vec{E} \cdot \overrightarrow{dl} \right|$)

        i. Analysis level 1 – analytical field solution for a single gap

        ii. Analysis level 2 – numerical field solution for multiple gaps

    b. Calculated gap voltages must be consistent with a user defined input power ($P_{analysis}$)

2. Use system level analysis to produce worst-case input power: $P_{worst\ case}$ (Section 3)

3. Scale device level voltage analysis to determine worst case voltages:

$$V_{worst\ case} = V_{analysis} \cdot \sqrt{P_{worst\ case}/P_{analysis}}$$

4. Use baseline multipactor threshold curve from Section 5.4 to determine the predicted breakdown voltage at each fd product under analysis: (V_{BD})

5. Determine if device meets the power margin (Section 4)

$$MP_{margin} = 20 \cdot log_{10}(V_{BD}/V_{worst\ case})$$

7.2.1   Steps for Determining Expected Breakdown Power

In cases where no known worst-case power known, or when the analysis goal is the predicted breakdown power level for a device, a different process is used. The expected breakdown power level is calculated in absence of all system factors that contribute to a worst-case power analysis in Section 3 (e.g. VSWR). Recommended steps for this process are outlined below:

1. Calculate the surface to surface RF gap voltages within the device

    a. Voltage calculated based on field solution ($V_{analysis} = \left| \int_{l_{Gap}} \vec{E} \cdot \overrightarrow{dl} \right|$)

        i. Analysis level 1 – analytical field solution for a single gap

        ii. Analysis level 2 – numerical field solution for multiple gaps

    b. Calculated gap voltages must be consistent with a user defined input power ($P_{analysis}$)

2. Use baseline multipactor threshold curve from Section 5.4 to determine the predicted breakdown voltage at each fd product under analysis: (V_{BD})

3. Compute the power breakdown threshold by scaling the analysis to expected breakdown voltage

$$P_{BD} = P_{analysis} \cdot \left(V_{BD}/V_{analysis} \right)^2$$

7.2.2   Gap Selection for Field Integration

For Level 1 and 2 analyses, the goal is find the worst-case power breakdown threshold for the device. This requires selecting the worst-case gaps and worst-case portion of the gap to perform the voltage integration. For Analysis Level 2 devices, it is necessary to perform multiple voltage integrations

across multiple gaps to sufficiently demonstrate that the worst-case breakdown threshold has been determined.

7.2.3   Limitations and Considerations

The accuracy of Analysis Level 1 and 2 methods relies on the applicability of the theoretical voltage breakdown curve shown in Figure 5.1 (Section 5.5). The curve assumes a constant electric field across the gap with infinite parallel plate electrodes. For gaps where the electric field distribution is not constant, electrodes are no longer parallel, or electrode size becomes small compared to the gap distance, the accuracy of this analysis method decreases.

Examples include situations where higher order multipactor modes (large fd) can exist in non-uniform field cases such as high impedance coaxial geometries or similar. In such cases, Level 1 or 2 analysis methods may be insufficient due to the unsuitability of parallel plate assumptions.

7.3   Analysis Level 3

Similarly to how there are a multitude of electromagnetic field solution methods, there are multiple different particle tracking algorithms that may be allied for multipactor analysis. At a minimum, the algorithm must accurately simulate electron trajectories based on the impact of the modeled fields.

7.3.1   Recommended Steps for Analysis

1. Generate a representative 3-D RF device model to anchor numerical EM field solution

   a. At a minimum, the model must be capable of demonstrating accurate RF electrical performance (S-Parameters) matching RF designed specifications or measurements

   b. Some algorithms compute the time harmonic electromagnetic fields before invoking time-domain electron tracking algorithm. For these methods, the time harmonic RF fields within the device are computed at this point.

2. Invoke a particle tracking algorithm using the RF device model to determine P_{BD}

3. Determine power margin

   a. Calculate the device multipactor margin using the worst case power obtained from Section 3.2

$$MP_{margin} = 10 \cdot log_{10}(P_{BD}/P_{worst-case})$$

7.3.2   Particle Simulation Guidelines

Particle simulation codes directly compute the number and positions of electrons within the gap over time. Particle tracking methods can vary in application method and fidelity depending on the electromagnetic algorithm used to generate the field solution.

The following considerations should be made to ensure a valid result from the particle simulation analysis. It is important to pay attention to the electron sourcing used, the power levels selected for analysis, the SEY inputs used, and the criteria used to determine breakdown.

7.3.2.1　Considerations for Initial Electron Sourcing

For correct prediction of the worst-case multipactor breakdown level, it is necessary for an initial source, or seed, electron population to be present in the correct gap with the correct initial energy.

For algorithms that automatically seed the entire vacuum volume of the device under analysis, a sufficient number of initial electrons are required to ensure that enough make it into the critical gap for accurate results to be produced. It may be desirable to break the RF device volume into separate regions and perform analysis on the regions separately in order to ensure accurate results.

For algorithms that require or allow the user to specify the location and properties of initial electron sources, a Level 2 analysis is useful to determine where the critical gaps are that might require seeding.

7.3.2.2　Determining Power Levels for Analysis

Particle tracking algorithms require the input power level of the device to be selected before an analysis step is performed. If too low or too high of an initial power level is chosen, then breakdown will not be predicted. To determine the minimum breakdown power level for the device by analysis, it is necessary to avoid stepping over the minimum multipactor breakdown region for the device.

It is a good practice to go through a Level 2 analysis process to obtain an expected starting breakdown power level for the device. This informs the starting power levels for analysis to ensure that the minimum breakdown level of the device is not stepped over.

7.3.2.3　SEY inputs

The secondary electron yield properties are implicit inputs into the particle tracking code. For all surfaces, use worst-case breakdown criteria (see Section 5.5).

7.3.2.4　Multipactor Breakdown Criteria and Accuracy

At any given input power level, the required output of a particle tracking code is number of particles over time. Assuming the model has reached steady state, any amount of electron growth over time indicates sustained multipactor breakdown. A decrease in electron population indicates that there is no breakdown.

Depending upon the initial electron sourcing method and the particle tracking algorithm used, there may be initial decay or growth early on in simulation time. Over several RF cycles the particle count over time should begin to trend. It is necessary to allow sufficient simulation time for the initial electron conditions to stabilize before determining the breakdown state of the device. The number of RF cycles required to reach steady state behavior will be higher for higher order multipactor (larger fd products).

Multiple simulations should be performed to demonstrate repeatable results. Due to the probabilistic nature of secondary electron emission and, often, initial electron seeding, some variation in electron growth curves can be expected. Large differences in breakdown results for subsequent analysis runs could result from poor electron sourcing, too few particle tracking time steps per RF half-cycle, and/or not enough mesh points to capture the RF field variations in the breakdown region. In this manner, running multiple simulations can help identify issues with simulation methodology.

The desired breakdown threshold accuracy determines the power step size of the final analysis runs. The difference between the lowest power at which multipactor is detected and the highest power at which multipactor is not detected, must be less than the desired accuracy.

7.4   Analysis for Risk Assessment

In cases where verification by analysis is not permitted or possible, a simplified analysis for risk assessment is recommended to provide some basic confidence in the device design. **These methods are not intended for device qualification by analysis.** Examples of risk assessment analysis include: applying a lower level analysis method to higher level device, and by applying a hybrid RF circuit model approach as outlined below.

7.4.1   Hybrid RF Circuit Model Approach

In cases where a complete component full-wave electromagnetic analysis may not be practical with available computing resources, the following technique is provided as a hybrid approach to build confidence in the design. This technique describes a method for breaking a larger device composed of identical coupled resonators into smaller parts for analysis.

For electrically large periodic devices such as filters, a full wave analysis may not be possible. Coupled filter cavities can often be modeled using an RF circuit lumped element model. This method finds the resonator with the most stored energy and performs a Level 2 analysis on that specific resonator. In such cases, the following steps outline a method that will help predict resonator breakdown. [19]

1.   Generate a RF equivalent circuit model for the device.

2.   Using the circuit model, calculate the voltage and corresponding stored energy for each resonator in the device relative to a set input power ($P_{analysis}$).

3.   Determine the resonator containing the highest stored energy.

4.   Generate a 3-D EM field solution for a filter resonator section (Eigenmode solution).

5.   Calculate the critical gap voltages as if performing a level 2 analysis (Section 7.1)

6.   Calculate the total stored electrical energy in the 3-D EM resonator model.

7.   Scale the eigenmode voltages to the circuit model using the worst case resonator energy from the circuit model. This produces gap voltages ($V_{analysis}$) relative to $P_{analysis}$.

8.   Use the gap voltage due to input power numbers as in Section 7.1 to determine margin of breakdown threshold.

7.4.2   RF Hybrid Model Limitations

While this method is effective at capturing main resonator breakdown, it fails to account for resonator to resonator coupling features and variable tuning elements that may vary from resonator to resonator. For this reason it is considered a risk assessment analysis method only and not for margin verification.

8.   Test Methodology

This section describes recommended test methods that can be used to meet the minimum test requirements given in Section 6. The section guides the user through the diagnostic options and basic steps required to establish the multipactor test bed and verify performance of the device under test (DUT). The section also outlines the general test set and instrumentation requirements used for multipactor testing.

8.1   Test Equipment Considerations

Recommended multipactor test setups consist of the following major functional blocks:

- **High Power RF Generator:** This consists of signal generators, amplifiers (SSPA or TWTA), multiplexors, isolators, and pulse generators. This functional block should be capable of delivering RF signals that best simulate the inputs that the device will see in normal operation. It should be capable of delivering RF power above the maximum operating power that will be seen in normal operation to demonstrate required margin. RF test set losses also need be considered to meet delivered power test requirements at the device under test.

- **High Power RF Test Set:** This consists of the RF input and output couplers, filters, chamber feedthrough(s), cables and/or waveguides and loads. These parts should be rated to the maximum RF generator peak and average power while having known and repeatable performance over the range of input power and frequency. Parts inside the chamber should be adequately vented and multipactor-free at the test power levels. Special considerations should be taken for the input couplers operating into a shorted termination (internal loads may not be rated for full power in the reverse direction).

- **Environmental Systems:** This includes vacuum chamber and pump systems, thermal controls and measurement and electron seeding. These systems should be capable and verifiable to achieve the required test levels. Elevated chamber pressures or complete loss of vacuum can lead to destructive RF ionization; fail-safe protection or interlock systems for critical hardware should be considered.

- **Global Diagnostic Instrumentation:** This consists of the RF test equipment generally used to monitor the outputs of the RF test set (e.g., spectrum analyzers, RF diode detectors, and RF power meters). These devices must have known and repeatable performance over the test dynamic range and bandwidth.

- **Local Diagnostic Instrumentation:** This consists of sensitive instruments to detect multipactor events within the device under test at the specific breakdown location (e.g., current probes, photon detectors).

- **Data Acquisition:** This consists of autonomous data sampling and recording equipment that are used for event-triggered test controls and output products for test reporting.

- **Test Equipment Block Diagrams:** There are several main types of tests that are outlined in this section. These include CW and pulsed systems followed by resonant-ring test setups.

- **DUT measurements:** S-parameter measurements should be taken on the device under test before and after the test to verify expected performance as well as no indication of damage during the test.

For CW and pulsed systems, the following diagram outlines the standard system implementation for multipactor testing. This is a single source system and requires the source to deliver power levels that meet the margin test requirements in the test set.

Example Multipaction Test Block Diagram
(CW/Pulsed Systems)

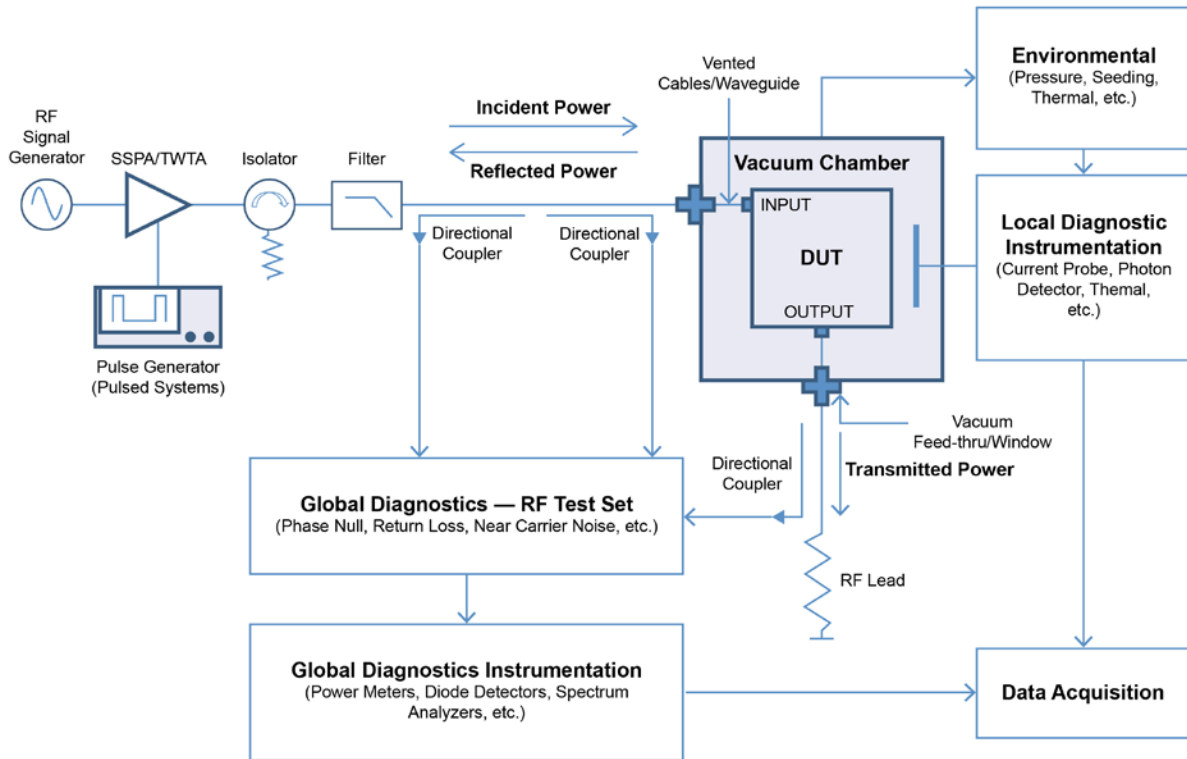Figure 8.1.   Example of a multipactor test block diagram.

In order to practically provide high levels of power in excess of typical amplifier capability, a resonant ring may be used. The ring uses the resonant voltage addition within a tuned transmission line to effectively achieve the required power levels. This method is generally narrower band and specific for a single tone frequency [22].

Example Multipaction Test Block Diagram
(Resonant Ring)
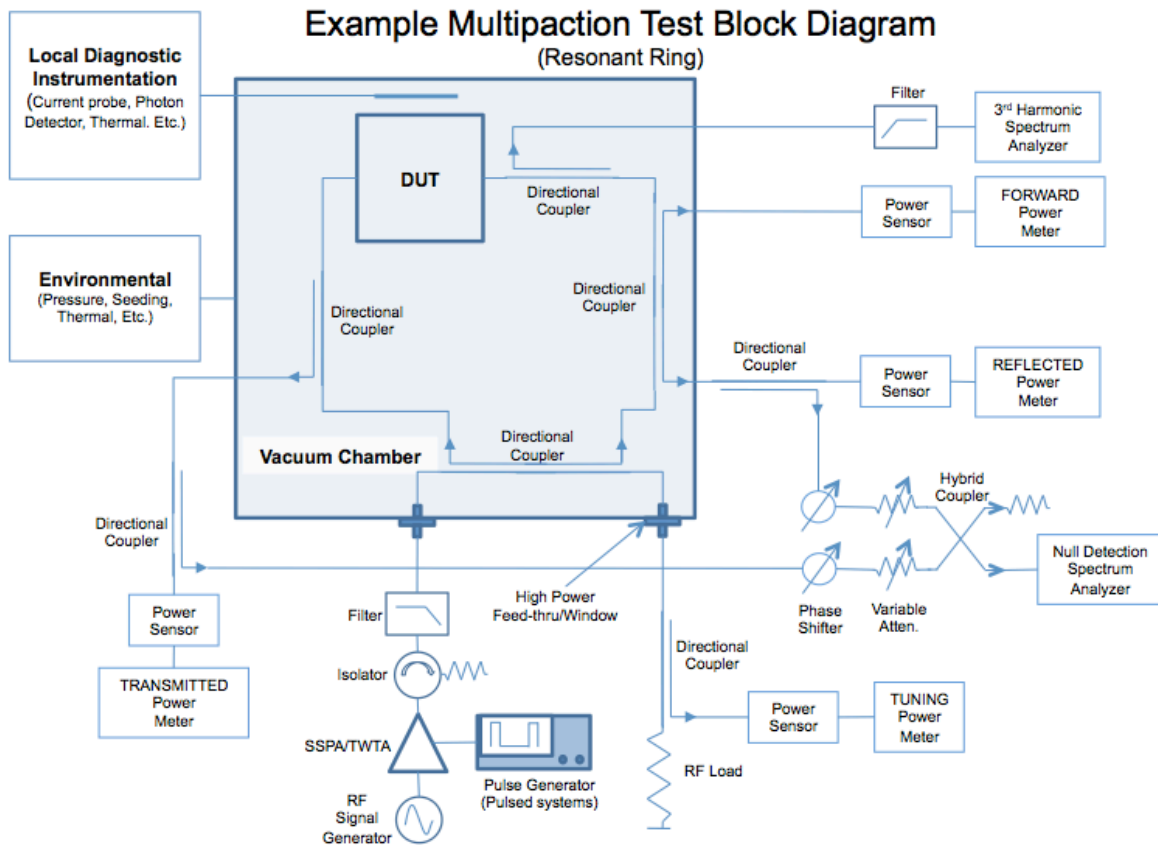
Figure 8.2.   Ring resonator test block diagram.

Considerations that should be addressed in the design and setup of multipactor test equipment are provided below:

- **Return Loss:** The input return loss of the test set should be ideally less than that of the device to be tested. If the test set input return loss is worse than the DUT, then additional power is required to meet the test requirements to accommodate for potential out-of-phase voltage addition resulting in lower than intended voltage at the device under test. In general, well-matched test equipment is available and should be used. Upstream VSWR considerations may be necessary to fully accommodate for all possible voltage additions from different sources.

- **RF Power Meters:** Typical RF Power meters are generally too slow to capture fast-occurring or transient multipactor events shorter than 100-500 ms. While not used as a primary, high sensitivity multipactor diagnostics, they provide necessary and calibrated input and output power measurements at the device.

- **Diode detectors:** Schottky diode detectors can be used for waveform monitoring and multipactor detection. They have fast rise times, reasonable sensitivity and dynamic range. The best rise time is achieved when operated into low impedance such as 50 ohms, at the expense of sensitivity. Additional sensitivity can be gained by the use of an LNA to drive the diode input.

- **Isolation:** Isolation of the diagnostic instruments from the high power source is an important consideration to minimize false positives and diagnostic noise. The use of filters and isolators

in the system may be needed to achieve proper isolation between test equipment and diagnostics.

- **Venting:** Especially on cables, waveguide, and feedthroughs, connectors inside the vacuum envelope should have sufficient venting to avoid localized pressures leading to unintended ionization breakdown. Ohmic losses within the test equipment can also cause thermal rises that can increase outgassing rates. The test components inside the vacuum envelope should be well vented.

- **Thermal:** Thermocouples are typically used to monitor unit, chamber and test equipment temperatures. It is important to monitor the unit in multiple locations, especially where it is predicted that extremes will occur. It is important to also monitor the input test equipment predictions indicate service temperature limits may be reached. When possible, the thermal control thermocouple should be placed on the device under test as close to the thermal interface as possible.

8.2 Test Setup Validation

The following steps should be considered in the validation of multipactor test set equipment.

8.2.1 Multipactor-Free Verification

When constructing the test setup for multipactor testing, the setup should be evaluated for multipactor-free operation at the specific test frequency and power levels. This verification should incorporate the entire block diagram intended for the full component test. The device under test should be replaced with a surrogate device or multipactor-free connector to join the test cables with minimal impact on the overall RF parameters of the system. This test system should be tested in vacuum at the same frequency and to at least the maximum test power. All diagnostics should be monitored for RF breakdown evidence with the same parameters as the component test. This test is determined to be successful with the detection of no RF breakdown events after applicable soak times at each power level. This validation does not necessarily need to be performed before each component test, but it is good practice to repeat periodically, as system components, such as cables and connectors, can change between DUT installations or other system alterations. If a failure is observed in test, it is recommended to re-run the test setup verification as part of the troubleshooting process after consent to break configuration is granted.

8.2.2 Ability To Detect Multipactor

As required in Section 6.3, a known multipactor breakdown device should be tested in vacuum in the identical system as the component test. The RF power should be incremented until breakdown is detected on all detection methods to verify successful and simultaneous operation of all detection methods. Some detection methods may be more sensitive than others; as such, power shall be increased until the required detection methods observe breakdown.

The known breakdown test should be run at the same frequency as the device under test. Any breakdown power level can be used. An example reference geometry is provided in Appendix C. The KMD should have accessible internal geometries or open structures for local diagnostic method verification if also used on the DUT.

This known multipactor device test is performed before and after the actual unit test to demonstrate no change in detection capability for the duration of the test.

8.3   Multipactor Diagnostic Methods

There are two types of multipactor test diagnostics. The first is a local diagnostic. A local diagnostic can provide indication of multipactor in a specific location if the collector is placed sufficiently close to the breakdown region. The second is a global diagnostic. This type can detect that multipactor is occurring somewhere in the device, but it cannot generally pinpoint the location of the breakdown within the component. Additional information on both local and global diagnostics can be found in [4][11].

8.3.1   Local Diagnostics

Table 8.1. Local Diagnostic Methods

Method	Effectiveness	Sensitivity	Advantages	Disadvantages	When to Use
Current Probe	High	High	Reliable, simple, inexpensive	Requires placement within vicinity of multipactor region	Vented or open geometries
Photon Detector	Medium	High	Non-perturbative	Requires line of sight, sufficient neutral collisions for detection	Open geometries which are unsuitable for current probe

8.3.1.1   Current Probe

In the majority of cases where it can be applied, the most sensitive diagnostic to detect multipactor is a simple current probe. This diagnostic has the added advantage of being straightforward to implement while robust over a wide range of operating power and frequency. It also has a strong advantage in clear interpretation as multipactor current is directly measured.

Probe placement depends upon the geometry tested. In a component with limited access to internal geometries, vent holes can be used to access multipactor regions. In some cases, it may be necessary or beneficial to add additional or specific vent holes to accommodate this local diagnostic. A separate qualification unit can be used with specific current probe access if flight designs cannot accommodate. The probe can be inserted into the vent hole with minimal penetration into the DUT. Care should be taken to minimize impact to the RF fields by the probe itself as well as RF coupling to the probe.

A metallic collector or current probe placed in the vicinity of the DUT is biased with a positive DC voltage relative to the input of a picoammeter or electrometer. Bias is generally implemented by use of a simple battery in series with the probe collector and the input to the picoammeter. In cases with an open geometry, a larger probe area can be connected to the probe electrical connection to allow for a larger collection area. If current probes are implemented in vent hole geometries, semi-rigid cables can be used to match the vent hole size and wall thickness in order to control the overall probe penetration into the unit. In some cases, multiple current probes with known collection areas can be used to determine the local region of breakdown if multiple geometries are suspected. Multipactor/RF breakdown is said to occur when electron current can be measured clearly above the noise floor.

It is generally recommended to perform a "touch-test" on each current probe, in which the probe tip is physically touched briefly to provide electron current to the setup. This can be used to verify connections and data acquisition.

8.3.1.2 Photon Detector

Electron bombardment from multipactor can cause excitation or ionization of trace gases or molecules on the device wall. This can lead to localized photon emission that can be detected either with an optical probe or intensified charge-coupled device (ICCD).

Like the current probe, the use of a photon detector requires optical access to the multipactor site. Detection is also contingent upon local, neutral gas excitation/ionization and sufficient photon counts to be measured by the detector.

8.3.2 Global Diagnostics

Table 8.2. Global Diagnostic Methods

Method	Effectiveness	Sensitivity	Advantages	Disadvantages	When to Use
Phase Null	High	High	Reliable and most sensitive global diagnostic.	Quality factor (Q) of device affects sensitivity. Requires retuning during test.	Well matched devices and single tone.
3rd Harmonic	Medium	Medium (low for pure multipactor breakdown).	Fast, reliable. Can be used for multicarrier.	Noise can be generated by other issues. Filtering can lower sensitivity.	All instances, but not combined with near carrier noise.
Near Carrier Noise	Low	Medium	Suitable for single and multicarrier systems.	Noise can be generated by other issues. Custom filtering required.	All instances, but not combined with 3rd harmonic.
Transmitted/ Reflected Power (high-speed).	Low	Medium (low for pure multipactor breakdown).	Low-cost components via Schottky diodes.	Least reliable indicator of multipactor in group.	Ionization breakdown or multipactor-induced plasma.

8.3.2.1 Phase Null

A conventional phase null system (Figure 8.3) uses coupled RF signal from the test setup to monitor for global changes in relative amplitude or phase changes between two RF signals. The presence of a multipactor or plasma discharge can change the local impedance in the discharge location, leading to near instantaneous changes in the phase and/or amplitude of either the reflected RF signal or through RF signal (measured downstream of the device under test).

As shown in Figure 8.3, the output of the combining hybrid to create the signal "null" is commonly monitored by a spectrum analyzer set to zero space at the center, fundamental frequency. A video out option is often used to monitor the signal level in real time and record the analog data stream with a digital data acquisition system. If a spectrum analyzer is used, it is critical to monitor the signal in "zero-span", as transient multipactor events can be missed if the spectrum analyzer is monitoring off the main carrier at the time of the breakdown.
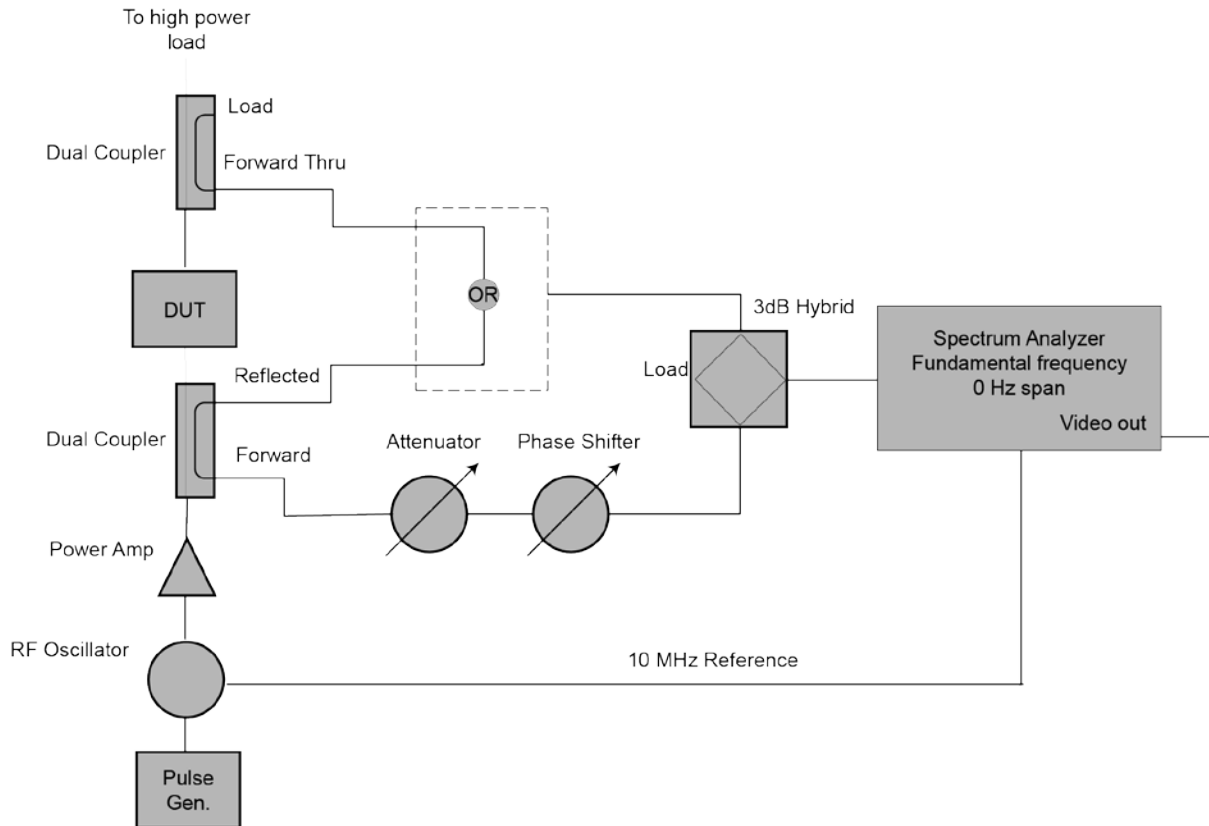
Figure 8.3.   Example block diagram for a phase null diagnostic.

One disadvantage of the conventional phase null is manual tuning to maintain the low signal levels for sensitivity. Null detuning can occur with thermal or power changes, both of which happen throughout a typical multipactor test. To maintain low null levels for best sensitivity, the test operator is required to constantly tune the attenuator and phase shifter to account for these variations. Null responses to RF breakdown can typically be discriminated from thermal or power changes based on much faster rise time and overall amplitude in the change of the phase null signal from a breakdown event.

The overall sensitivity of the phase null is dependent on the density of the multipactor or plasma, the physical size of the multipactor or plasma region, and the frequency of the RF signal. A typical electron-ion plasma is denser than a multipactor discharge, and thus a phase null will respond stronger to a plasma event than a pure or transient multipactor discharge. For the case of pure multipactor (electron population only) with breakdown region much smaller than the RF wavelength, phase shift is the dominant factor influencing the null response. As the density increases and the plasma frequency approaches the RF frequency, changes in the relative amplitude (reflection/attenuation) can occur. Similarly, amplitude changes can occur for electron-neutral collision-dominated plasmas or plasmas with plasma frequency larger than the RF frequency. Phase null sensitivity is generally an order of magnitude higher or more for ionization breakdown (including multipactor induced) than for pure multipactor, but will depend on the overall size and density of the plasma for specific sensitivity.

8.3.2.2   Near Carrier Noise

Multipactor is known to produce noise near the carrier frequency. Using a spectrum analyzer, low-noise amplifier, and special notch filtering, the carrier frequency can be filtered out and the noise floor of a nearby band monitored. Multipactor will be associated with a rise in near-band signal above this noise floor. The detection of near carrier noise is typically fast, making it well suited for either single carrier or multicarrier detection. Care must be taken with pulsed discharges such that harmonics are not generated in the measurement band. In addition, it can be difficult to ensure that observed noise is due to multipactor and not other issues with the test setup, such as loose connectors [11]. Additionally, care must be taken to ensure that the detection frequencies are within the passband of the test device.

Care should be taken when using near carrier noise concurrently with third harmonic detection as the only two global diagnostics. This is because the same non-multipactor events can cause false readings in both detection methods, possibly creating a condition for a falsely failed test.

8.3.2.3   Third Harmonic

During a multipactor discharge, noise is not only generated at the carrier frequency but also at harmonics of the carrier frequency. Detected increase in harmonics of the carrier frequency is a common diagnostic for RF breakdown. While other harmonics may be considered, the third harmonic is typically most sensitive and widely used. A filter for the high power input signal is typically required to reduce harmonic noise from the amplifier(s) and maintain a sufficiently low signal to noise ratio for harmonic detection as a multipactor diagnostic.

Implementation of the third harmonic diagnostic is similar to that for near carrier noise, with different system filtering. Third harmonic detection is often fast and readily accessible through common RF coupled ports. It can be used in both single and multicarrier systems. Care must be taken to filter out harmonic noise products from the amplifier as well as any passive intermodulation products that could be generated within the system. Like the phase null, the third harmonic signal is typically monitored on a spectrum analyzer set to zero Hz span (same rationale as phase null). The spectrum analyzer output is then monitored via video/analog out that can be monitored with other high-sensitivity diagnostics.

Third harmonic is generally adequate for detection of ionization breakdown (including multipactor induced), but, in some cases, cannot detect pure or transient multipactor. For threshold multipactor, open-geometry devices, or geometries which support pure electron multipactor, third harmonic detection (as well as other harmonics) can be insufficient for detection.

As mentioned in Section 8.3.2.2, care should be taken when using near carrier noise concurrently with third harmonic, as a non-multipactor distortion generating event can cause false readings in both detection methods, possibly creating a condition for a falsely failed test.

8.3.2.4   Transmitted/Reflected Power

Using available RF coupled ports, transmitted and reflected power signals can be monitored via Schottky diodes/crystal detectors. As analog measurement devices, these diodes can monitor fast changes in transmitted and reflected signals that can correlate with a RF plasma discharge (including multipactor-induced plasma). The analog DC output of these detectors can typically be monitored by the same data acquisition system as other high-sensitivity diagnostics. Commonly, RF transmitted

power through the DUT may drop, while the RF reflected power may increase in the presence of a plasma. Specific amplitude changes will depend on the plasma size and density.

8.4 RF Breakdown Observations

Other observations may occur with initiation of RF breakdown. The following observables can be used for correlation to RF breakdown, but they are often insufficient and unreliable for high-sensitivity and real-time detection.

8.4.1 Chamber Pressure Increase

Electric bombardment on device walls can cause gas desorption leading to an increase in chamber pressure. Pressure monitor diagnostics are an essential diagnostic for vacuum systems, and these monitors can be used to correlate signs of multipactor or ionization breakdown. A pressure rise can be caused by other events including device heating. As a result, pressure monitoring should be used only in conjunction with other global diagnostics as a correlating diagnostic. Pressure rise can be observed with pure multipactor or ionization breakdown.

8.4.2 DUT Temperature Increase

Multipactor leading to ionization breakdown (or pure ionization breakdown) can cause localized heating of the device in the breakdown region. Timescales for temperature rise observables are large compared to high-sensitivity diagnostics, and they will depend on the thermal time constants of the DUT. In many cases, thermal detection via external-mounted thermocouples on the DUT is far too slow to prevent internal damage.

8.4.3 Visual Indication

In the event of open or visually-accessible geometries, ionization breakdown (including multipactor induced) can provide visual cues via localized glow discharge of the plasma. Additionally, observation of localized damage to the device walls post-test can be seen in some cases. Discoloration is commonly due to dielectric carbonization and redeposition onto metallic walls by means of the plasma discharge. Such discoloration can provide evidence of the location of the plasma breakdown, but may not correlate to multipactor discharge occurring else where that could lead to pressure increase and a subsequent plasma discharge.

8.4.4 RF Performance Changes

If a breakdown occurs and damages the part, it is possible that the RF performance, such as S-parameters, may change as a result. It is recommended to measure S-parameters before and after the test.

8.5 Relative Diagnostic Sensitivity

The following is based on typical RF configurations outlined in Section 8.1.

For pure electron multipactor discharge, the highest sensitivity diagnostics may be necessary for detection.

- Local diagnostic – most reliable is current probe with signal levels commonly well above measurable noise floor

- Phase null – Phase changes associated with the electron density can be observed in common analog null detection, with ultimate null sensitivity based on physical size of the discharge, electron density, and the DUT configuration.

Other diagnostics such as harmonic detection and/or changes in reflected or transmitted power generally may not detect multipactor breakdown until the discharge has transitioned to a plasma [12]. In situations without transition to plasma or for detection of threshold multipactor, current probe detection and phase null global monitors are often most sensitive for common devices and test configurations.

For ionization breakdown or multipactor-induced plasma, local diagnostics, phase null, harmonic or near-carrier noise detection, and fast changes in reflected/transmitted power may all provide indication of breakdown with fast rise time and sufficient signal to noise ratio. Diagnostic configurations should be sufficiently fast to measure fast rise times of order 1 ms, and care should be taken to prevent damage to components from the destructive plasma (Section 8.7). Relative sensitivity will depend on the plasma density, physical size of the plasma, and specific component impedance.

RF breakdown measurement via digital power meters, pressure rise, DUT thermal increase have typically insufficient response times to measure short duration plasma events. Multipactor-induced plasma and ionization breakdown events with durations less than 10 ms can occur and be rendered undetectable via typical slow global monitors. Use of these measurements and indicators is not recommended for primary breakdown detection.

8.6   RF Shut-down Protection System

Multipactor-induced plasma and ionization breakdown can cause significant local heating leading to internal melting, deposition, carbonization, and other damaging situations. Use of an RF shutdown protection system [13] should be incorporated to lower the probability of device damage. The system should be designed to shutdown the high power RF signal if a pre-defined threshold is exceeded. Response time should be as fast as possible, with millisecond or better time response to prevent damage and surface conditioning. A shutdown system can be incorporated to minimize multipactor conditioning and changes to the local SEY. This, in turn, can lead to repeatable breakdown events for diagnosis purposes. Without fast shutdown protection, changes in the surface may alter the threshold, making repeatable detection and diagnosis difficult.

Shutdown systems should be triggered by the most sensitive and reliable diagnostic in the test configuration. Multiple diagnostics can be incorporated into the shutdown logic when possible. In many cases, current probes can be the most reliable in use with the shutdown system due to the large signal to noise ratio with occurrence of a breakdown event.

8.7   Electron Seeding

The following considerations such as sources, radioactive levels and device thicknesses should be considered when employing electron seeding:

- Radioactive source (Typically Cesium-137 or Strontium-90)
- Electron gun
- UV source

Electron seed selection is a complex determination beyond the scope of this document. Additional references: [11][15][16]

8.8   RF Test Operation

For successful verification of RF breakdown handling, the DUT should be simultaneously exposed to maximum expected average power and maximum peak voltages at both cold minimum and hot maximum temperatures as well as transitions.

RF power at the DUT should be increased from 30 dB_m typical to the desired test level with a minimum step size to ensure all susceptible powers are tested and the multipactor threshold is not missed. Diagnostic sensitivity should be considered when choosing power step sizes, as smaller step sizes may yield lower probability of false positives for diagnostics such as the phase null.

Minimum soak time at each power level should be no shorter than 5 minutes per step.

It is recommended to perform the multipactor verification testing as late in the test sequence as possible, after all environmental tests such as random vibration and thermal cycling have been completed. It may be permissible to include multipactor testing as part of thermal vacuum testing assuming requirements in Sections 6.7 and 6.8 are met.

8.9   Data Acquisition and Reporting

8.9.1   Data Recording

As mandatory data items, the outputs of the multipactor detection methods, power meters, pressure, and temperatures should be recorded continuously. If spectrum analyzers are used, the continuous analog output proportional to the measured signal should recorded. This is typically through a "video out" output connector. The screen "maximum hold" feature alone is not sufficient data collection due to insufficient resolution and video bandwidths that can lead to missing data and incomplete multipactor detection.

8.9.2   Sampling Rates

Sampling rates for data recording vary amongst test equipment. The detection methods should be fast enough to capture events at the threshold of sensitivity for that particular method. This depends on the pulse width. The sampling rate should be fast enough to capture an event on any pulse. For example, a 500 microsecond pulse width requires a 4 kHz sampling rate in order to ensure that every pulse has at least 2 data points. To capture the entire envelope and transitions with optimal resolution, an even higher sample rate is advised. Larger pulse widths used during testing can thereby reduce sampling rates.

For CW testing, the sample rate should be perceptive enough to capture the envelope or duration of the multipactor event. A rate of at least 1 kHz is recommended.

For other equipment, such as a power meter, thermocouple, or pressure gauge, sampling can occur at a much slower rate. A typical sampling rate for a power meter or thermocouple is 1 Hz.

For situations in which large and difficult-to-manage data files are produced, triggered data storage may be implemented for the faster data rates, though continuous monitoring of the maximum possible signals for all diagnostics should be maintained.

8.9.3 Minimum Data Items Required

- Continuous data recording of all detection methods, power meters, pressure and thermocouples.

- Evidence from each of the detection methods showing the breakdown of the known breakdown device.

- Evidence that temperatures and pressures were within specification limits during the test and that all dwell times were met.

- If any events were recorded on the DUT, there should be images of the events on the detection methods and detailed descriptions of the test conditions during the event(s).

8.9.4 Test Report Guidelines

A test report shall be of typical scientific or laboratory format. At a minimum, the following sections should be included:

- Executive Summary
- Purpose
- Reference Documents
- Unit Description
- Test Description
- Test setup
- Setup verification
- Vacuum soak
- Known multipactor test
- Multipactor test details
- Known multipactor test
- Conclusions

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Appendix A.   Background

A.1 Background

RF breakdown, including multipactor [3] and ionization breakdown [7], continues to be a growing technology risk with higher available powers, high bandwidth, and larger number of carriers in satellite RF systems. With increasing powers comes increased risk for both multipactor and ionization breakdown within critical satellite systems. Avoidance is paramount for continued mission success and US component development. With development of new technology, there is a need for a more standard and robust approach to RF breakdown analysis and test in order to ensure mission success across many US mission classes, including military, commercial, and civil programs. Lessons-learned as well as new available tools need to be incorporated across the industry and RF high power community to aid in improved design and manufacturing yield.
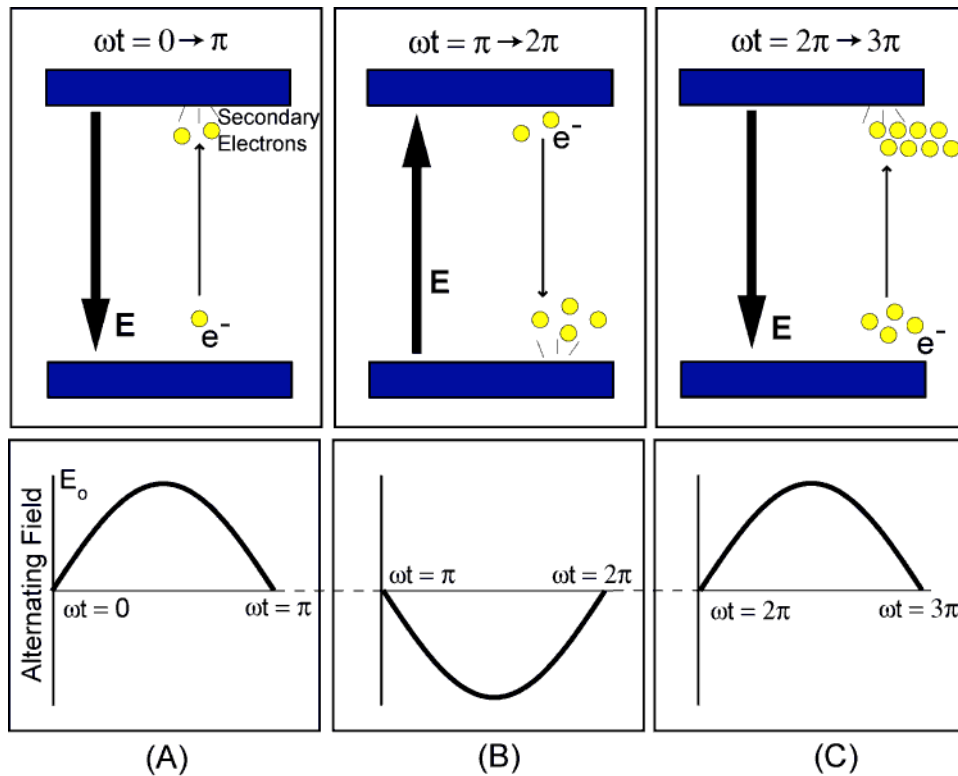

Figure A.1.   Cartoon representation of simple, parallel plate multipactor breakdown.

Multipactor breakdown is a resonant condition that can exist when electrons impact one or more electrode surfaces in resonance with the RF electric field. Under certain conditions, electron density can grow with each successive impact by means of secondary electron emission as depicted in Figure A.1. In general, multipactor occurs when electron growth by secondary emission is greater than electron losses from the local region of interest. The number of emitted electrons is governed by the secondary electron yield (SEY), which is defined as the number of emitted or "secondary" electrons per incoming or "primary" electrons. The SEY curve is a function of the primary electron energy, which is given on the X-axis for Figure A.2. For a theoretical and infinitesimal geometry, the average secondary electron yield (SEY) for all impacting electrons, shown in Figure A.2, is greater than unity. Multipactor can occur if electrons impact surfaces between the first and second cross-over energies, defined as E_1 and E_2. For more realistic and finite conductor geometries, this SEY value must be large enough to overcome electron losses from the multipacting region, and depending on the losses, this can require an average SEY larger than unity. Incorporation of new modeling and simulation techniques described in this document allow new insight into SEY and geometric loss effects.
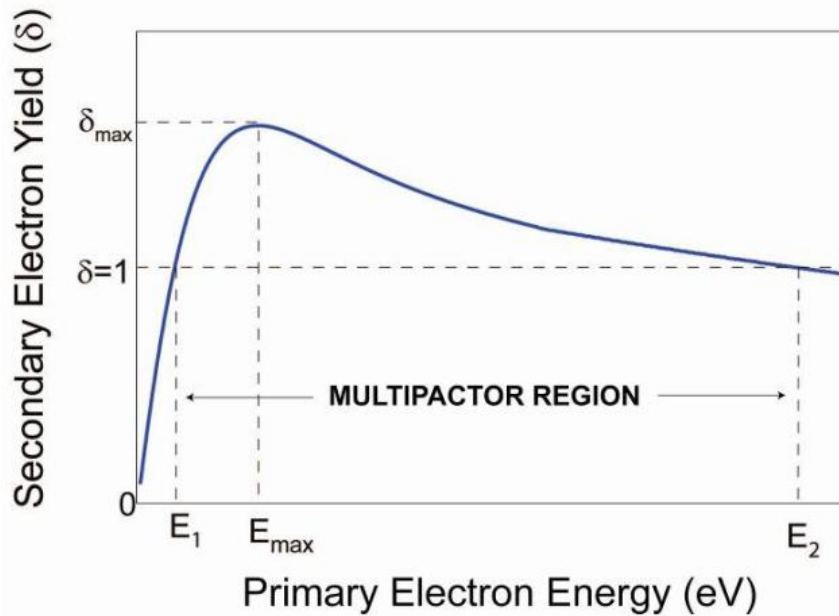
Figure A.2. A general secondary electron yield (SEY) curve showing the theoretical multipactor region for electron density growth.

As such, multipactor breakdown, also called multipaction, is dependent on the RF frequency, the electrode spacing or gap, and accelerating RF voltage. With the dependence on SEY, multipactor is also dependent on the material properties of the actual surface within the RF device. For typical systems (RF voltages 10-5000V), electron penetration depths may be only 1-2 nanometers of the electrode surface. This can make the SEY and subsequent multipactor breakdown also strongly dependent on very thin, adsorbed layers of residual gases or contamination from outgassing products.

Multipactor breakdown can lead to significant risks for spacecraft components and systems. These risks are manifested in noise or perturbations to signal integrity that can be generated by the discharge. In many cases as electrons impact surfaces, local adsorbed gases are released from the surface, which in turn can raise the local pressure in the device. A multipactor-induced plasma can cause significant local damage, component melting, and physical destruction of devices. In majority of spacecraft components, the transition from multipactor to plasma breakdown is uncontrolled as gases rapidly desorb from surfaces and local heating leads to increased outgassing of the internal materials. With this uncontrolled process, any measured multipactor discharge can have the potential to transition to plasma and cause permanent damage to the device. As such, this document treats any detected RF breakdown, including transient multipactor breakdown, as potential failure with need for full mitigation in order to fully reduce risks of on-orbit damage or system impact.

Ionization Breakdown

Ionization breakdown is not explicitly treated in this standard. This document will be revised in future revisions for ionization breakdown guidelines.

Appendix B.   Comparison of Different Multipactor Risk Mitigation Processes

TOR-2014-02198 is intended as a stand-alone document to provide RF and microwave components with low risk for RF breakdown. This document provides a new end-to-end process that includes the RF system to determine worst-case power conditions for each device. The analysis and test verification requirements are based on known and predictable worst-case conditions.

Some of the requirements in this document differ from older literature or the ECSS-E-20-01A Rev. 1, Space Engineering: Multipaction Design and Test. The following illustrates some of the differences and supporting rationale.

Device Classification

- TOR: A new structure of device classes is given, allowing more specific margin requirements to be levied on these classes. The classes are separated such that verification plans can be tailored to the analysis level of the device and certainty of the electric fields and multipactor regions. The tailoring process allows incorporation of the latest modeling tools and techniques. Similarly to ECSS-E-20-01A Rev.1, this document distinguishes between devices with and without dielectrics exposed to RF breakdown.

  - ECSS-E-20-01A Rev.1: Device classes are divided into three classes – metallic devices, devices with dielectrics, and any other device. No consideration is provided for special cases. Verification of margin requirements is applied to their three device classes, with same requirements and verification methods for all components that, for example, have metallic-only electrodes. The same higher margin requirement is levied on all components with dielectric, regardless of the type of device or geometry.

Worst-Case System Analysis

- TOR: Providing worst-case analysis process to determine voltage or electric field at the device under consideration. Given the ability to specify worst-case conditions for device RF fields, parameters such as voltage enhancement can be accurately predicted, or evaluated, from the actual system hardware. These effects can then be implemented ultimately into the device power requirement. TOR-2014-02198 also provides a system-wide process to account for combined effects of multiple components such as VSWR and component losses.

  - ECSS-E-20-01A Rev.1: System effects such as VSWR and voltage enhancement are applied as a general margin to include the majority of general devices. These effects (and their uncertainty) are then accounted in additional lumped-margin requirement. No specific treatment is provided for system wide analysis for RF breakdown. Overconservative margin requirements may exist due to overestimation of the VSWR effects, or underconservative margins where worst-case powers are not truly worst-case.

Margin Requirements

- TOR-2014-02198 margin requirements rely on a full system analysis to determine the worst case conditions. Hidden or unknown margins are removed, yielding lower overall margins for both test and analysis as compared to ECSS. Lower margins are also derived by incorporating better analysis tools and strict test requirements for proper breakdown detection. Margins for analysis and test are compared between ECSS and the TOR in Tables B.1 and B.2.

Table B.1.   Comparison of Margin Requirements for Analysis Between TOR and ECSS

Analysis Level	TOR Analysis Margin (dB)			ECSS Analysis Margin (db)		
	Type 1	Type 2	Type 3	Type 1 (ECSS)	Type 2 (ECSS)	Type 3 (ECSS)
1	3	3	N/A	8	10	12
2	3	6	N/A			
3	3	6	N/A			

Table B.2.   Comparison Of Margin Requirements for Test Between TOR and ECSS

Analysis Level	TOR Test Margin (dB)	ECSS Test Margin (dB)		
	Type 1/Type 2/Type 3	Type 1 (ECSS)	Type 2 (ECSS)	Type 3 (ECSS)
Qual	3	6	6	10
Batch acceptance	3	4	4	6
Unit acceptance	3	3	3	4

Multipactor Analysis Requirements

- TOR-2014-02198: Different analysis requirements are provided using multiple different techniques to eliminate excessive margins and take advantage of newly available analysis tools. Additionally, the Hatch and Williams curve has been modified for Analysis Level 1 and 2 devices with additional margin removed, and a bounding SEY. This bounding SEY is used as there is uncertainty in plating processes that can lead to a wide variation in SEY for a similar base plating material. Additionally, analysis methodology recommendations are provided, outlining the advantages and disadvantages of different techniques and tools.

  – ECSS: No specific analysis requirements are provided. The ESA/ECSS Multipactor Calculator scales the Hatch and Williams curves to match specific material data, but these curves will not apply universally to all plating types and surfaces.

Figure B.1 depicts a comparison between the TOR-2014-02198 multipactor threshold baseline and that for the ECSS document. The ECSS curve shown is for the assumed aluminum surface, yet recent studies have shown that applying a single multipactor curve for a single electrode material does not universally apply. The TOR-2014-02198 shown below removes any hidden margin, and also matches more closely to the curves between the N=1 and N=2 multipactor modes.

Multipactor Test Requirements

- TOR-2014-02198: Minimum test requirements are provided to ensure proper detection and test-like-you-fly requirements to best match the worst-case expected mission environment. These include minimum requirements for diagnosis, data collection, and test conditions. Recommended test techniques, similar to other references [11], with modern best practices are described. The minimum requirements are more stringent and specific as compared to ECSS, allowing the lower margin values described above.
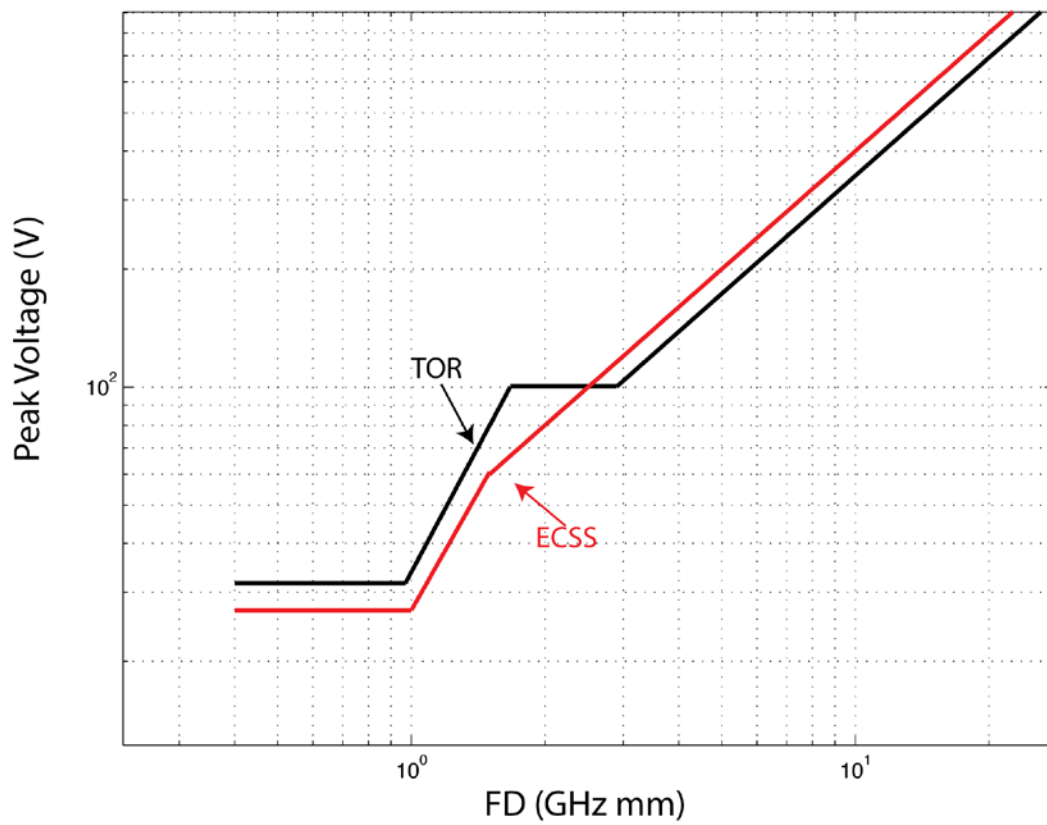
Figure B.1.   Comparison between TOR and ECSS multipactor threshold.

Appendix C.   Reference Geometries for Analysis and Test Setup Validation

In this appendix, a reference geometry is presented and used to demonstrate suitable analysis and testing techniques. Drawings accompany the device such that the user can manufacture a Known Breakdown Device (KBD) for validation of their own analysis and test methodology. The two devices presented represent simple coaxial and parallel plate geometries, with a The device has a coaxial 1.5 mm gap region with both surfaces comprised of aluminum.

Device Specifications

A cross-section of the coaxial Known Breakdown Device (KBD) is provided in Figure C.1. The aluminum outer conductor is 30 mm in diameter, with a 13.4 mm inner diameter that tapers to 7 mm inner diameter at the center. TNC connectors mount to the sides of the outer conductor. The aluminum inner conductor is press-fit over the TNC connector pins. The inner conductor is 4 mm in diameter, giving a minimum gap distance of 1.5 mm. Drawings for the outer and inner conductor are given in Figures C.2 and C.3. There is a single 0.096" diameter venting hole drilled through the outer conductor.
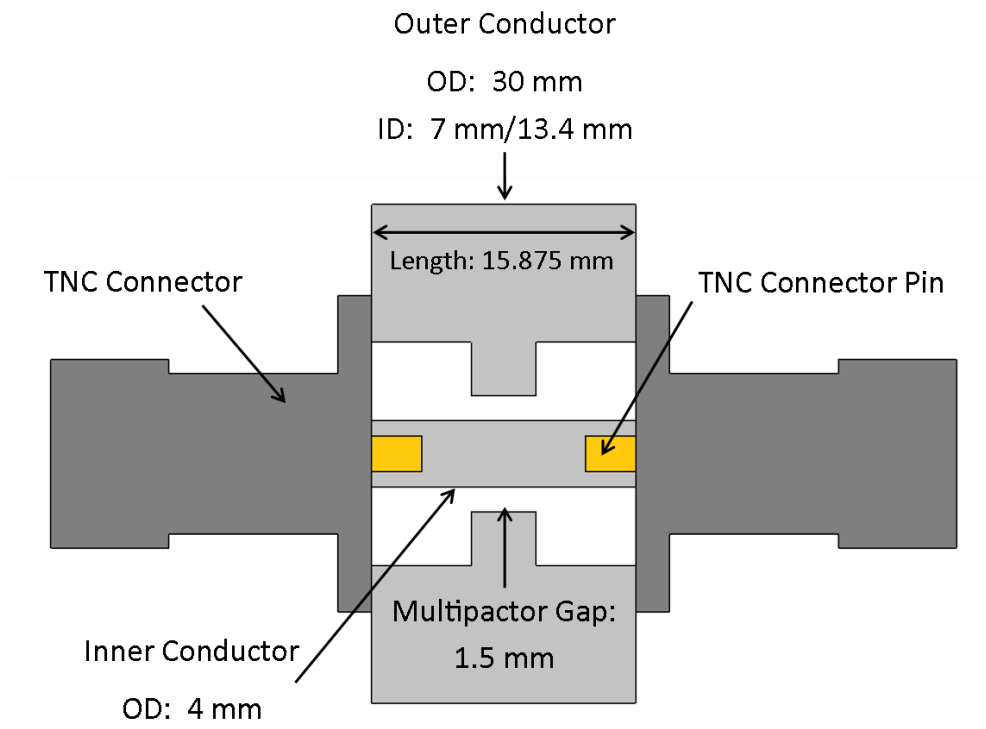
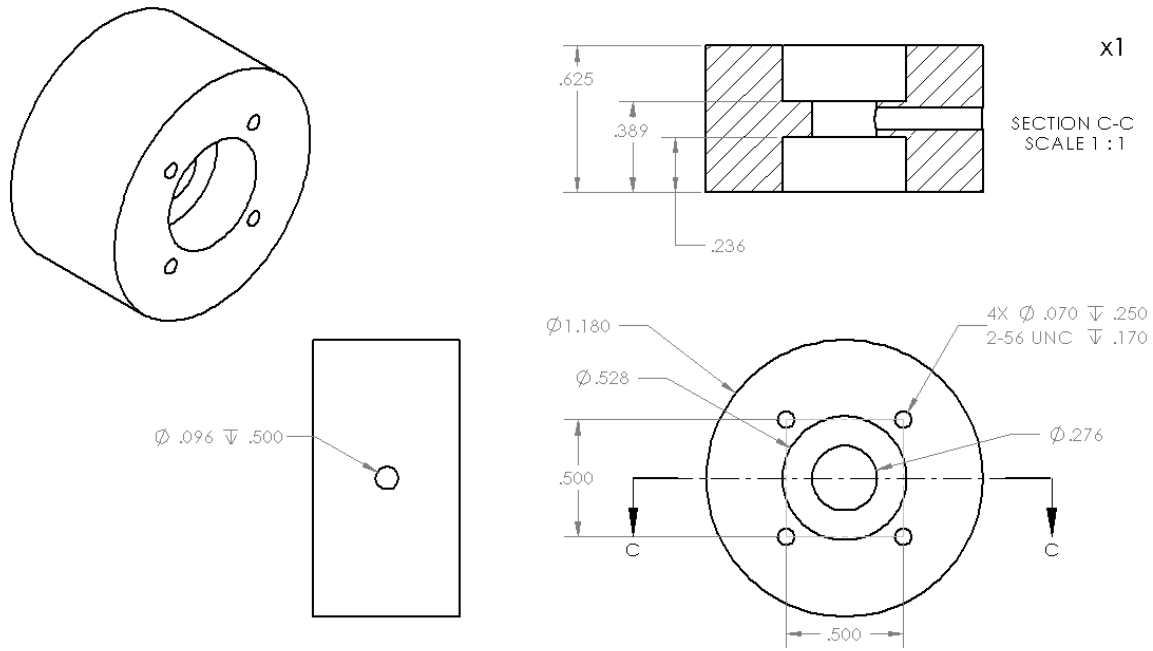Figure C.1.   Annotated cross section of coaxial device.

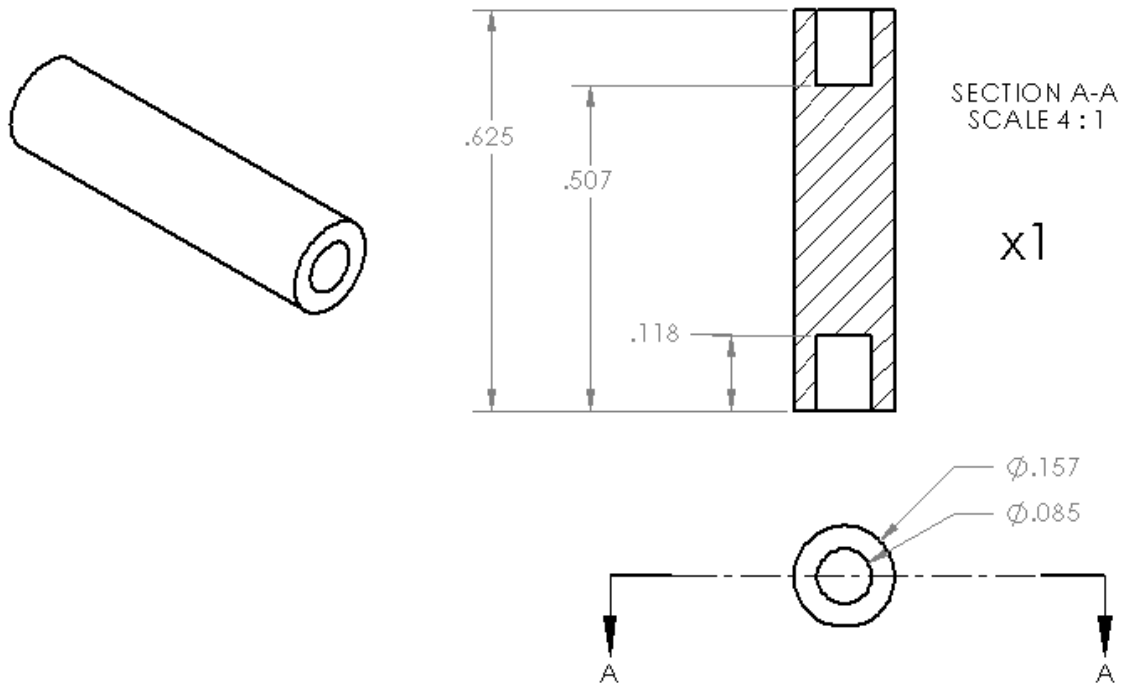Figure C.2.   Dimensional drawing of outer conductor piece.

Figure C.3.   Dimensional drawing of inner conductor piece.

Analysis

The following section will provide an example analysis of the coaxial RF breakdown device from 0.5 to 2.5 GHz. The device is identified as Analysis Level 2. The coaxial steps occur at a rate small compared to a wavelength, meaning the device surfaces cannot be considered entirely parallel. For analysis level 2 the local fields in the device are calculated using a method capable of capturing the full 3-D field effects. This device must be modeled in a 3-D electromagnetic CAD tool to determine the local fields within the device (Figure C.4).
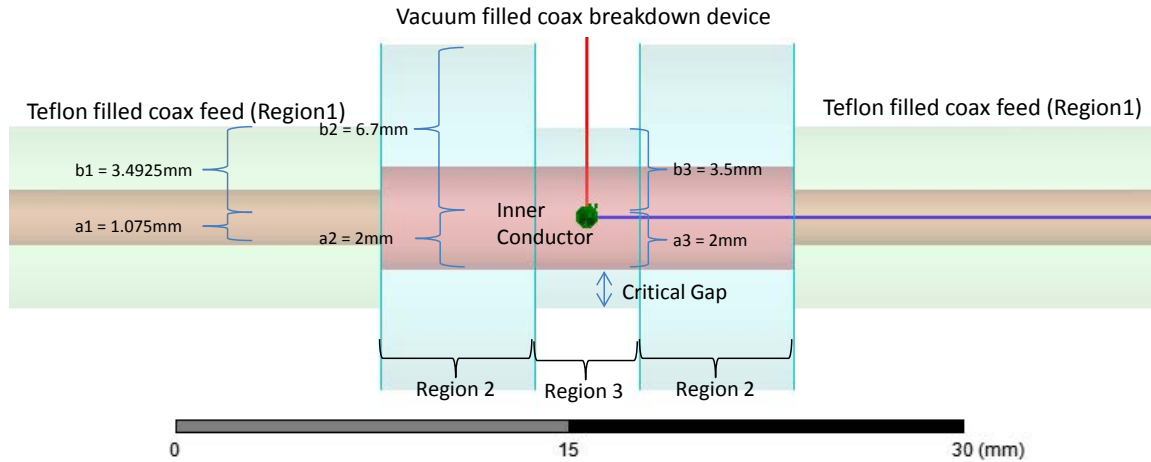

Figure C.4.   Device geometry.

Observing that the dominant fields are all normal to the inner conductor, integration lines are defined between the inner conductor and outer conductor at various locations along the inner conductor length in both Region 2 and Region 3. Using a 1 watt average power source for purposes of modelling, the peak voltages are calculated from the computed electric field values by: $V_{Gap} = \left| \int_0^{l_{Gap}} \bar{E} \cdot \overline{dl} \right|$. These voltages are plotted across the frequency band in Figure C.5.
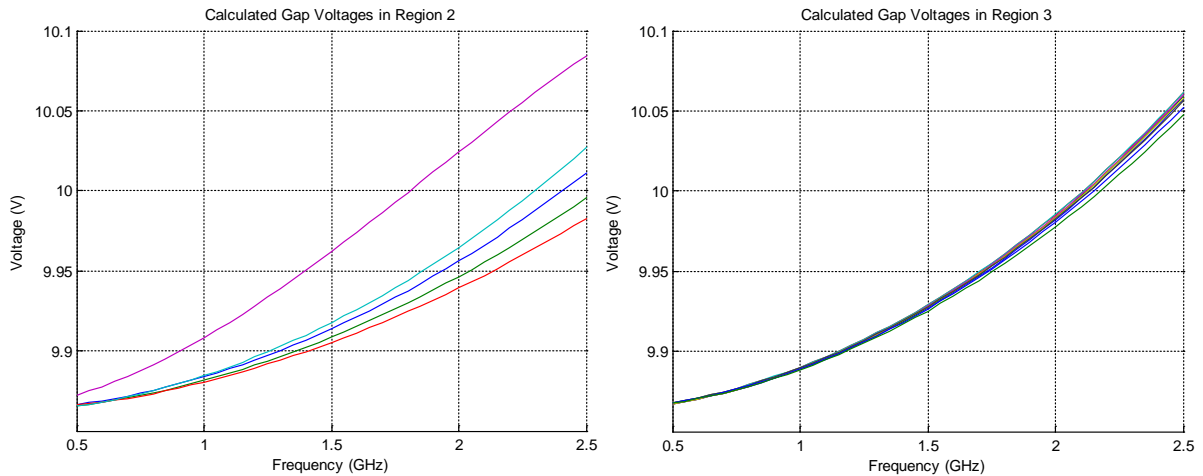

Figure C.5.   Calculated gap voltages from electromagnetic analysis.

The worst-case voltages in each region will be are used to determine the breakdown level.

The breakdown gap in Region 2 is 4.7 mm, and the Region 3 gap is 1.5 mm. These gap values are used to calculate the f*d product for each frequency of interest. Using the f*d product, the peak RF breakdown threshold (V_{BD}) is determined using Figure 5.1. The expected breakdown power is then calculated by scaling the calculated gap voltages ($V_{analysis}$) to the voltage breakdown threshold numbers: $P_{BD} = P_{analysis} \cdot \left(V_{BD}/V_{analysis}\right)^2$

The predicted breakdown power level for the two regions is shown in Figure C.6. It is clear that the breakdown in the defined frequency band is expected to initiate only in Region 3.
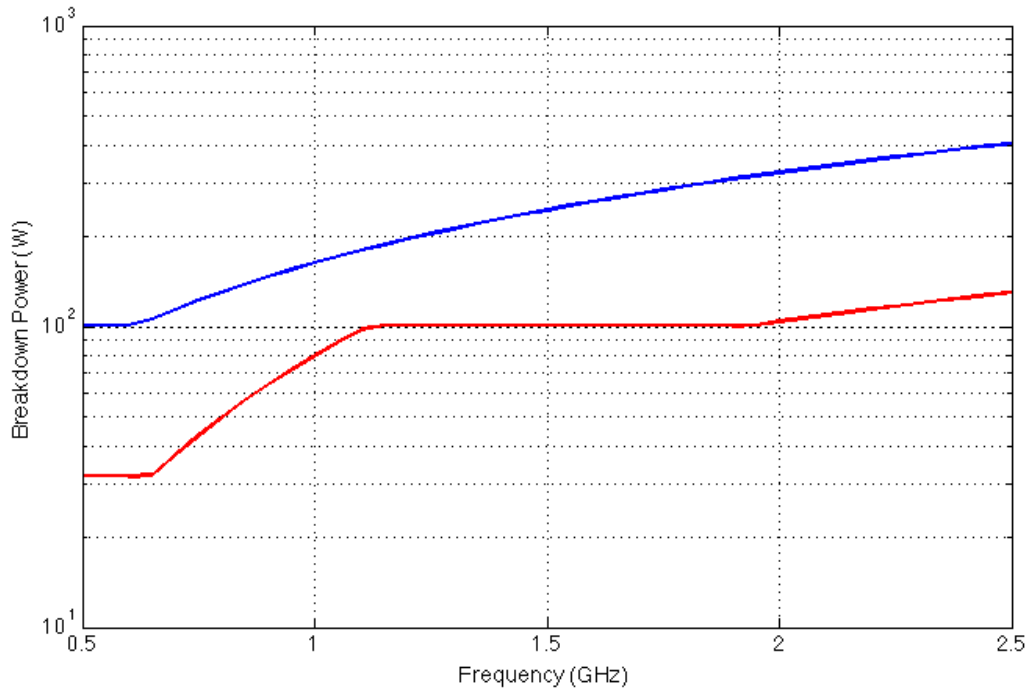

Figure C.6.   Breakdown power versus frequency in Regions 2 and 3.

Test Setup and Breakdown Measurements

Breakdown measurements of the KBD were obtained using the test setup depicted in Figure C.7.
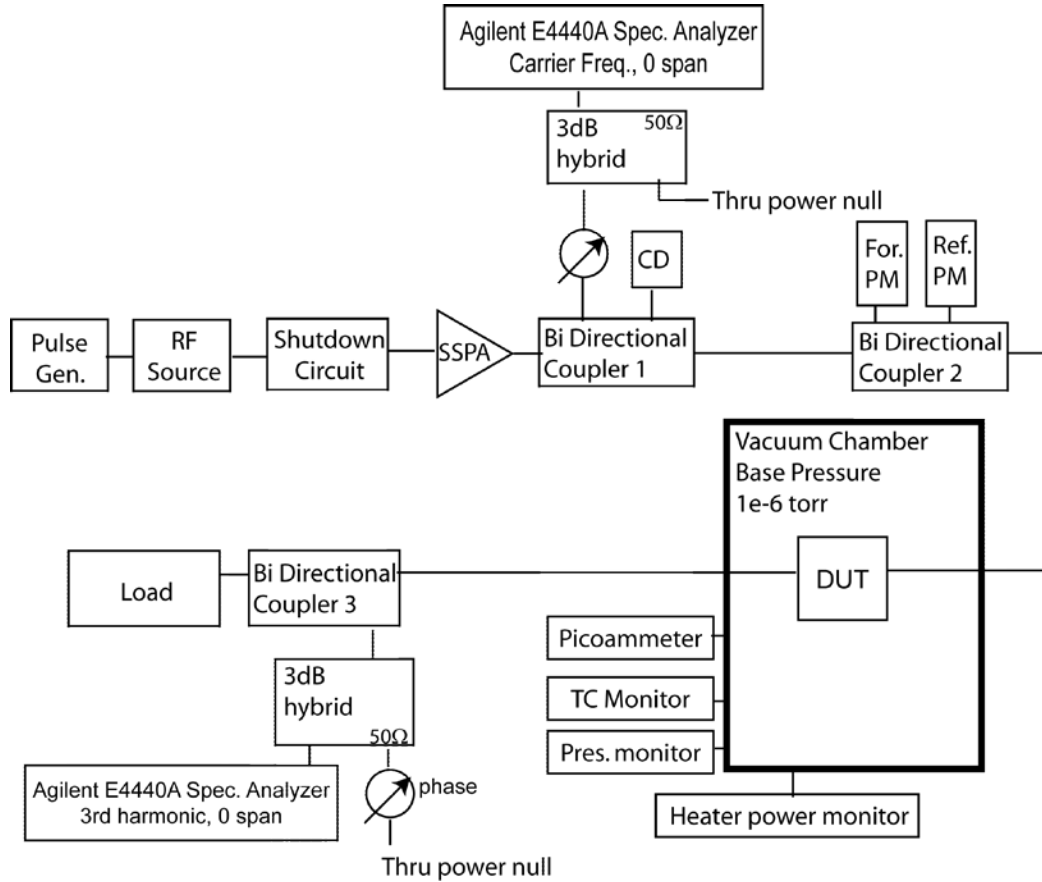

Figure C.7.   Test schematic for multipactor testing on the coaxial KBD.

A 0.5" diameter planar current probe was placed in the vicinity of the KBD vent hole. Additional global diagnostics include reflected power diode, third harmonic, and through power null. A high speed RF power shutdown circuit was utilized to prevent device conditioning across testing. S-parameters for this device are satisfactory across a bandwidth of 100 MHz – 2 GHz (Figure C.8). Measurements were made from 500 MHz (fd = 0.75 GHz-mm) to 1.25 GHz (3 GHz-mm).
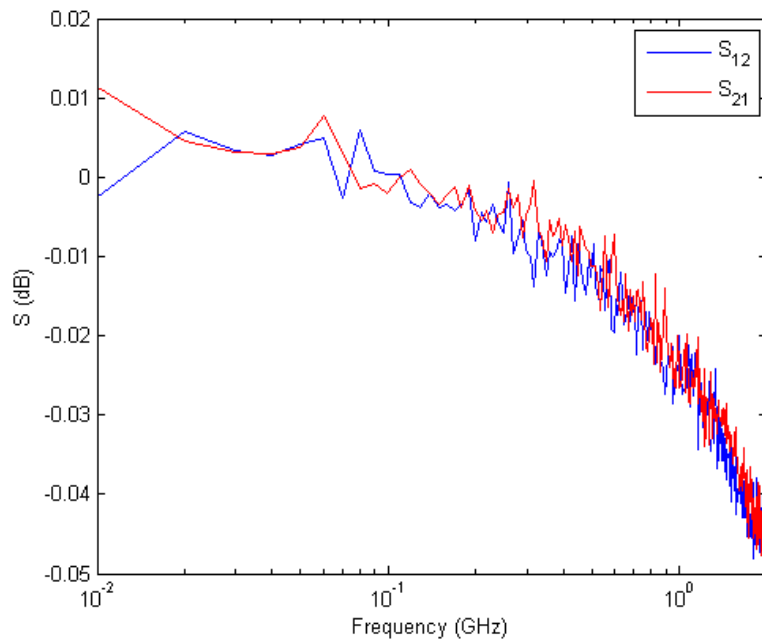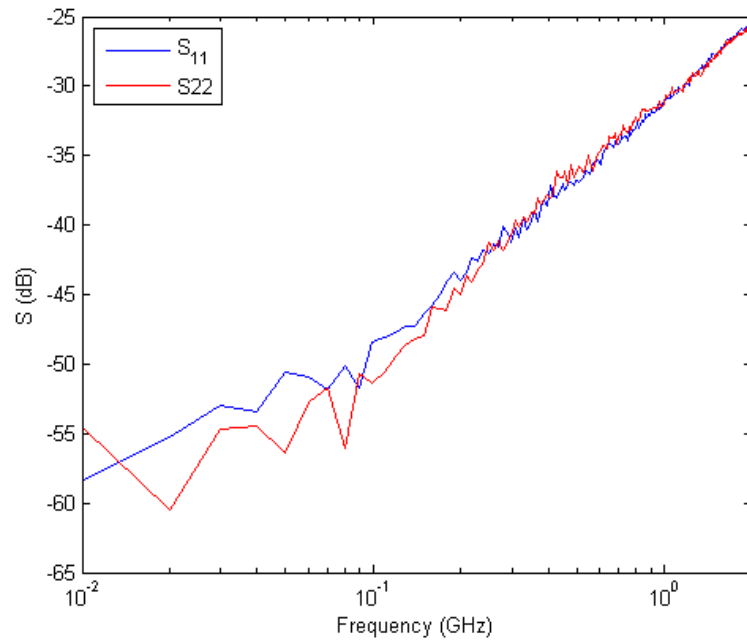
Figure C.8. S-parameters for coaxial KBD.

Input power was increased at a rate of 0.1 dB$_m$/sec with 0.1 minute soak times at intervals of 10 W. The current probe diagnostic triggered the shutdown circuit in all tests. Breakdown power is plotted versus frequency in Figure C.9. The breakdown power in Region 3 provided by analysis and breakdown power predicted by AuroraSAT's SPARK3-D multipactor prediction tool is included in this figure. Measured breakdown power is also provided in Table C.1.

Figure C.9.   Breakdown power test data in coaxial KBD.

Table C.2. Breakdown Power Test Data in Coaxial KBD.

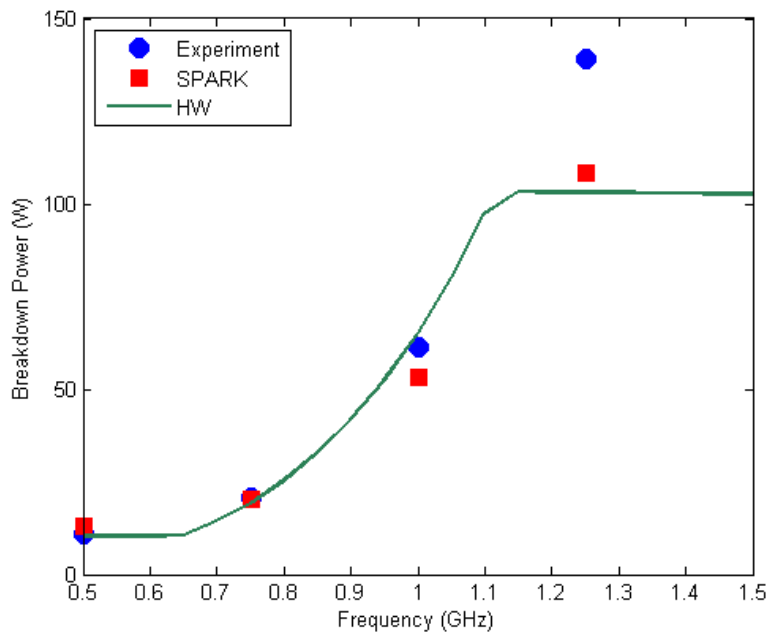| Frequency (GHz)	fd (GHz-mm)	Breakdown Power (W)
0.5	0.75	10.8
0.75	1.125	20.9
1	1.5	61.3
1.25	1.875	139

Standard/Handbook for Multipactor Breakdown Prevention in Spacecraft Components

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SK0674

External Distribution

REPORT TITLE		
Standard/Handbook for Multipactor Breakdown Prevention in Spacecraft Components		

REPORT NO.	PUBLICATION DATE	SECURITY CLASSIFICATION
TOR-2014-02198	May 28, 2014	UNCLASSIFIED

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