Clearance and Creepage in Circuits Up to 1500 V_{DC}, Considering Cost and Space Requirements for Film Resistors

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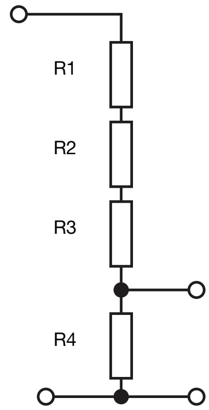
INTRODUCTION

Resistors are commonly used in voltage measurement circuits as voltage dividers. Depending on the voltage level that is applied in today's automotive and industrial applications (e. g. 400 V, 800 V, or 1200 V) [LVD], different requirements need to be fulfilled. Nowadays, many component engineers and electrical circuit designers are faced with requirements that call for resistors with voltage ratings well above the common values associated with standard surface-mount devices. Until now, there has not been a broad variety of SMD resistors available that are capable of handling voltages higher than about 200 V. This paper will discuss such components, ranging in size from 0805 with a 450 V rating to 2512 with a 3000 V rating.

This white paper is intended to provide design engineers - especially PCB designers - with guidance on the difficult topic of applying the right creepage and clearance distances. Selecting the appropriate tables in the standard and applying them properly to a design are key to avoiding related issues later on. The overall target is to safeguard the reliability and stability of the application, taking space and cost requirements into consideration.

Furthermore, this white paper explains the creepage and clearance requirements of surface-mount resistors that are capable of handling high voltages. It also provides layout recommendations to enhance a design's robustness and ensure compliance with safety standards.

Voltage Divider Circuit



Generic voltage divider schematic

Due to new eMobility applications and their space constraints, the common 200 V voltage rating for devices such as resistors in the 1206 case size is no longer sufficient. There are several resistor series in the market that allow the circuit designer to use fewer components to do the same task, while using less space in the final application. These components are available within different technologies.

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The RCV-AT e3 high voltage thick film chip resistor series can handle up to six times the voltage of a standard thick film chip resistor in the equivalent case size. This includes 800 V in the 1206 size, 2000 V in the 2010, or even 3000 V in the 2512.

The TNPV e3 high voltage thin film chip resistor series can handle up to five times the voltage level of a standard thin film chip resistor in the equivalent case size, with excellent long term stability of ± 0.05 %. The series includes voltage levels of 450 V in the 0805 case size, 700 V in the 1206, and 1000 V in the 1210.

The MM HV AT high voltage thin film MELF resistor series can handle up to 1200 V - 3.5 times the voltage of a standard thin film MELF resistor in the equivalent case size - with a high ohmic value range up to 10 MΩ to meet requirements for high insulation resistance values. In general, MELF resistors have the advantage of higher pulse load capability compared to thin film chip devices.

CASE SIZE	SERIES		
	RCV-AT E3	TNPV E3	MM HV AT
0805		450 V	
1206 (0204)	800 V	700 V	700 V
1210		1000 V	
2010	2000 V		
2512 (0207)	3000 V		1200 V

EXCURSE 1

Which Technology Is Doing the Job: Thick Film Chip, Thin Film Chip, or Thin Film MELF?

Thick film chip resistors are mainly used to detect a malfunction in the application or as an additional measurement topology to be compliant with safety integration level requirements. The basic standard is IEC 61508 for the functional safety of electrical / electronic / programmable electronic safety-related systems. If the requirements for the drift (or better measurement accuracy over lifetime) of the voltage divider is higher than ± 6 %, this technology can be used as well.

Thin film chip resistors are used if the application must be precise over its lifetime. In this case, a ≤ ±1 % drift of the divider network is frequently required. This cannot be achieved by thick film chip resistor technology.

Thin film MELF resistors are used if the voltage measurement circuit must be precise over its lifetime, with a ≤ ±1 % drift, and if the voltage divider must be capable of withstanding transients (high voltage spikes) within a burn-in test or the final application.

With the use of smaller components with higher voltage ratings, insulation requirements are becoming increasingly important. In addition, there is the issue of achieving the correct clearance and creepage distances. Many standards in the market describe the handling of voltage and insulation. These include IEC 60071 for insulation coordination in three-phase applications above 1 kV, and IEC 60664-1 for insulation coordination in equipment within low voltage supply systems up to 1000 V_{AC} or 1500 V_{DC}.

In the automotive industry, electrical test standards to verify the safety and electrical parameters of components in electric vehicles include ISO 21498 (voltage class B systems and components), ISO 21782 (electric propulsion components), and LV 123 (components in HV on-board networks). In addition, there are also several national standards available, such as SAE, KMVSS, GB/T, TRIAS, and DIN. For assessing the right distances under a defined working voltage level in the final application, various parameters must be considered.

Basic Definitions: Clearance and Creepage

Any insulator can become electrically conductive if the voltage applied exceeds a critical level. Insulators are used in all electrical devices to separate electrical conductors from each other without allowing current to flow between them. The performance of the insulation must be so good that the insulator withstands the electric stress over a long time in the application environment. Insulation can be implemented as clearance, creepage, solid insulation, or a combination of these three.

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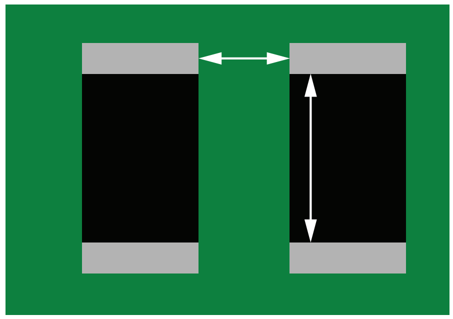


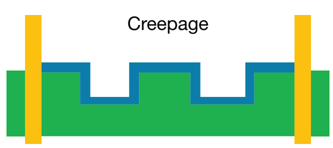
Insulation issues must be considered between components, from component to surroundings, and even between contacts of the same component

Clearance distance is the shortest distance between two conductive parts (or between a conductive part and the bounding surface of the equipment) measured through air.

Visualization of clearance distance between two conductive elements through air. The distance should be visible to the eyes

Clearance distance helps prevent dielectric breakdown between electrodes caused by the ionization of air. The dielectric breakdown level is further influenced by construction of the electrodes, air pressure (altitude), relative humidity, temperature, and degree of pollution in the environment. The clearance must always be large enough that flashover is prevented during operation.

Creepage distance is the shortest path between two conductive parts (or between a conductive part and the bounding surface of the equipment), measured along the surface of an insulating material. A proper and adequate creepage distance protects against tracking - a process that leads to a partially conductive path of localized deterioration on the surface of an insulating material - because of the electric coronal discharges on or close to an insulation surface.



Visualization of creepage distance between two conductive elements along the surface of the unit

In addition to dust, protection (for example coating), salt, water, and nominal voltage, the ability of a bulk insulator to withstand partial discharges is of great importance for the correct dimensioning of the creepage distance. The ability of a bulk insulation material to withstand partial discharges over time is referred to as the comparative tracking index (CTI), which can be tested in accordance with IEC 60112.

Used for electrical insulating materials, the CTI provides a numerical value of the voltage that will cause failure by tracking during standard testing. IEC 60112 provides a full explanation of tracking and the CTI.

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Comparative Tracking Index (CTI)

This value is used to assess the relative resistance of bulk insulating materials to tracking. It is determined by increasing a test voltage until a specified leakage current flows in a defined test setup. The more resistant a material is, the higher the CTI value and the shorter the creepage distance can be. Determining the CTI for a thin resistor coating layer is not applicable, as CTI testing is typically designed for bulk materials. The CTI test involves exposing a defined sample size of the insulation material to partial discharge stress to assess its ability to withstand tracking and electrical breakdown.

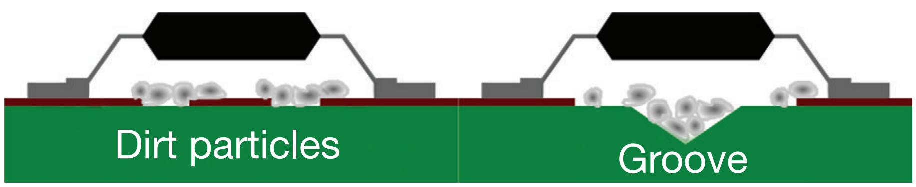
However, when dealing with thin coating layers, especially those applied to electrical resistors, other electrical and material properties become more relevant for evaluation than the CTI:

- Dielectric strength measures the maximum electric field a material can withstand without electrical breakdown
- The adhesion of the coating to the substrate and resistive material is essential. Poor adhesion can lead to discontinuities of environmental protection properties and electrical failures
- The operating environment - including temperature, humidity, and the presence of liquid solvents or contaminants - can significantly affect the protective performance of thin coatings

In practice, assessing the suitability of a thin coating layer for electrical resistors often involves a combination of electrical testing, material characterization, and consideration of the specific application requirements, as shown in the datasheet.

Pollution Degrees and Overvoltage

According to IEC 60664-1:2020 clause 4.5.2, pollution degree is divided into four categories. The environmental conditions correlate with four degrees of pollution.



Dirt particles can accumulate underneath a component or in notches of the PCB

- Pollution degree 1
  No pollution or only dry, non-conductive pollution occurs. The pollution has no influence (example: sealed or potted products)
- Pollution degree 2
  Normally only non-conductive pollution occurs. Occasionally a temporary conductivity caused by condensation can be expected (example: the product used in a typical office environment)
- Pollution degree 3
  Conductive pollution occurs, or dry, non-conductive pollution occurs that becomes conductive due to expected condensation (example: products used in heavy industrial environments that are typically exposed to pollution such as dust)
- Pollution degree 4
  Pollution generates persistent conductivity caused, for instance, by conductive dust, rain, or snow

The peak voltage is considered by the overvoltage category, also known as installation category, of the equipment, which is the degree for the expected overvoltage. There are four overvoltage categories according to IEC 60664-1:2020 clause 4.3.2.

In special protected circuits, expected voltages are lower (= low category level) than in circuits where lightning strikes can occur (= high category level).

- Overvoltage category I
  Signal level (special equipment or parts of equipment) equipment shall not have direct connection to a mains supply
- Overvoltage category II
  Energy consuming equipment supplied by the fixed installation
- Overvoltage category III
  Equipment in fixed installations and for cases in which the reliability and the availability of the equipment is subject to special requirements
- Overvoltage category IV
  Equipment for use at the origin of the installation

Typically, most standards are based on pollution degree 2 and overvoltage category II. It is important to note that creepage and clearance distances also increase with increasing working voltage, pollution degree, overvoltage category, and altitude.

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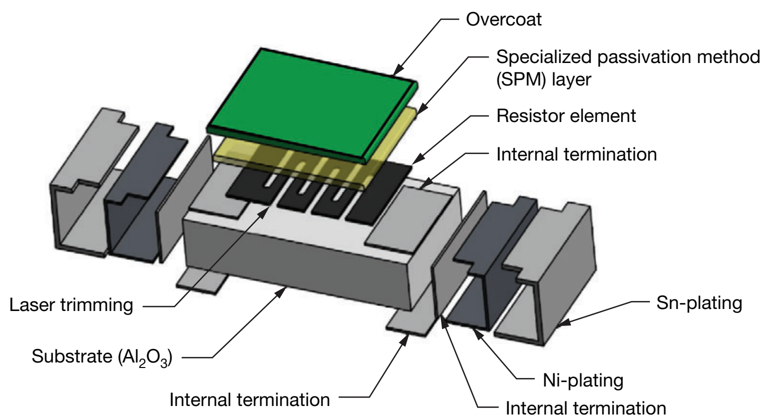
EXCURSE 2

How Is a Chip Resistor Constructed? Explained Here Using a Thin Film Chip Resistor

The resistor element is a homogeneous film of special metal alloy deposited on a carrier ceramic substrate (Al_2O_3). Specially designed inner contacts are deposited on both sides. Laser cutting is used to achieve the target value by smoothly fine trimming the resistive layer without damaging the carrier ceramics. The resistor element is covered by a protective coating layer - applied in a thickness of several µm - designed for electrical, mechanical, and climatic protection. The terminations receive a final pure matte tin on nickel plating.



Internal construction of a thin film chip resistor

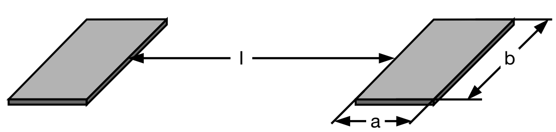
How Are Clearance and Creepage Distances Determined?

Clearance:

In addition to the generic safety standard IEC 60664, various device standards provide information on the required clearance based on different voltage levels. In Annex A of IEC 60664-1:2020, Table A.1 shows the clearance distance for several rated RMS voltages and their source test voltages for homogenous fields and altitudes of up to 2000 m above sea level (800 mbar). For higher altitudes, Table A.2 offers a correction factor for altitudes of up to 20 000 m.

In Annex 5 of IEC 60664-1:2020, Table F.1 shows the normative overload test voltages according to their overvoltage category, which is followed by Table F.2 with the clearance distances related to pollution degrees. Reinforced insulation shall be dimensioned and tested by one step higher out of the preferred source pulse levels, as defined in clause 4.2.2.1.

For printed wiring material or PCBs, clearance between two electrical potentials is defined by the distances of the recommend solder pads or in the respective IEC and IPC standards. Besides the recommended solder pads, professional EDA software provides adjustable parameters in its design rules checklist to guarantee the correct distances between tracks with different electrical potentials.



Solder pad dimensions of SMD resistors

Note: from the electrical view, a resistor cannot be classified as an insulator. A resistor is a conductor and will have an impact on the behavior of the insulation between the solder pad's electrodes.

Resistors have been tested with source pulses and due to its resistance value, the maximum applicable source pulse voltage is shown in the pulse load diagram.

For PCBs used in SMD designs, creepage dimensions are of higher concern than clearance dimensions.

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Creepage:

The creepage distance is influenced by different factors in the final application.

- Voltage
- Pollution degree
- Material group
- Orientation and location of the creepage distance
- Shape of the insulating surface
- Duration of the voltage stress
- Floating conductive parts
- Use of ribs
- Components mounted on printed wiring material (PCB)
- etc.

For non-tracking material like glass, ceramics, or other inorganic insulating materials, the creepage distance need not be greater than the associated clearance.

A guidance flow chart (informative) for defining the required distances for clearance and creepage can be found in IEC 60664-1 in Annex G and H.

For Printed Wiring Materials:

A reduced creepage distance for printed circuit material across a component under pollution degrees 1 and 2 is allowed and may be selected out of Table F.5 of IEC 60664-1:2020. However, it is still important to pay attention to the reduced creepage distance via the component.

EXCURSE 3

IEC 60112 Purpose and Testing Procedure

The scope of standard IEC 60112 ("Method for the determination of the proof and the comparative tracking indices of solid insulating materials") is the definition of the test method for determining the verification and comparative tracking indices of **solid and bulk insulating materials** on parts of equipment, and on material plates using alternating voltages.

How to Determine the CTI of Solid Insulation Materials

The upper surface of the test specimen is supported in a horizontal plane and subjected to an electrical stress via two massive electrodes. The surface between the electrodes is exposed to a series of electrolyte drops until either the overcurrent device operates, a persistent flame occurs, or the test period has elapsed. An alternating voltage between 100 V and 600 V is applied to these electrodes. Furthermore, the other dimension of the test specimen is specified to prevent the electrolyte from being lost over the edges of the specimen (normally 20 mm x 20 mm), including a minimum thickness of the tested material of 3 mm. According to this test method, the material can be divided into four different groups.

- Material group I: $600 \leq CTI$
- Material group II: $400 \leq CTI < 600$
- Material group IIIa: $175 \leq CTI < 400$
- Material group IIIb: $100 \leq CTI < 175$

In conclusion, IEC 60112 classifies different material groups for:

1. Micro-characterization of a material
2. Solid insulation material (piece of part)
3. With an outer dimension of 20 mm x 20 mm
4. With a minimal thickness of 3 mm

It cannot be used for:

1. Macro-characterization of a complete electrical device
2. Very thin materials (which cannot be stacked up to 3 mm)
3. Material systems (different stacked materials)
4. Interactions of interfaces between materials

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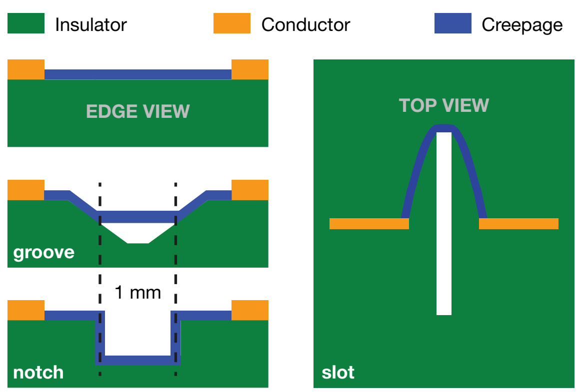
Which Category Is Used for Creepage Distances?

The bottom side of the resistor is made of ceramic, whereby the standards stipulate that the creepage distance should not be greater than the associated clearance. The top side of the chip resistor is protected by a very thin layer (a few µm) of a special protective coating, which cannot be used to create or stack a 3 mm thick sample for testing the material properties. In addition, the interconnection of the ceramic substrate, the resistive element (which is electrically conductive), and the coating would not be evaluated at all.

The category of printed wiring materials [IEC 60664-1] is used to specify the creepage distances of resistors. The process of manufacturing such components is basically the same as for printed circuits, whereby the electrically conductive parts are also covered by a coating material (layered structure). In addition, the CTI is a pure material classification and does not include connections between different materials.

How to Increase the Clearance and Creepage?

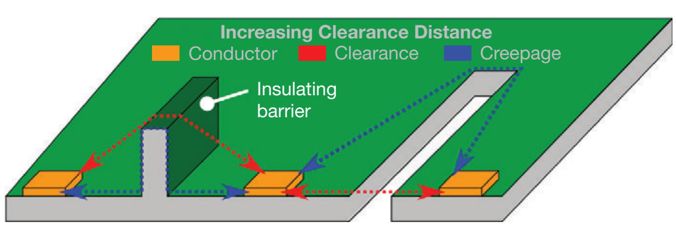
As products continue to get smaller and PCB space is considered in the cost calculation of an application, it is more important than ever to have an optimized PCB design that not only reduces electromagnetic interference emissions, but also reduces creepage and clearance issues through its layout. If lack of space on a PCB is an issue, techniques such as slots or grooves can be used to attain the desired creepage distance. Slots must be wider than 1 mm, otherwise they are considered unacceptable. For a groove (> 1 mm wide), the only depth requirement is that the existing creepage plus the width of the groove and twice the depth of the groove must equal or exceed the required creepage distance. The slot or groove should not weaken the substrate to such an extent that it no longer meets the mechanical test requirements.



Different ways to increase creepage distances

The clearance can be increased by adding additional insulating barriers between the high and low potential sides of two different components. A higher number of components in the voltage divider can also increase the final clearance of the entire system.

The creepage can be increased by grooves, notches, or additional insulation barriers, as well as by an additional coating or molding of the entire PCB [refer to application note “Preserving Precision: Conformal Coatings Applied to Thin Film Resistors”: www.vishay.com/doc?28960]. To effectively increase the insulation, a material with higher CTI than the PCB material should be selected. This improves the pollution classification and leads to fewer components being required for the voltage divider.



Different ways to increase clearance or creepage distances

WHITE PAPER

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Example

According to the standard IEC 60664-1, the corresponding minimal creepage in a 1000 V system, for example, is defined as 3.2 mm for pollution degree 1 and 5.0 mm for pollution degree 2. When using a high voltage component, the following assessment for case size e. g. 1206 (0204) can be performed:

SERIES	CLEARANCE AND CREEPAGE FOR SINGLE COMPONENT	MINIMUM QUANTITY FOR POLLUTION DEGREE 1	MINIMUM QUANTITY FOR POLLUTION DEGREE 2
RCV1206-AT	1.7 mm	2	3
TNPV1206 e3	1.5 mm	3	4
MMA 0204 HV AT	1.8 mm	2	3

For standard components (which do not have the higher voltage rating) the minimum quantity in terms of creepage will remain with the same case size, but the maximum voltage level of these components is defined as only 200 V. This finally leads to the use of at least five components to fulfill the same task as described above.

SUMMARY

Increasing voltages in industrial and automotive designs result in special requirements for the components used. To be competitive, new technologies must be used to decrease the system cost of the final application. For high voltage circuits, a possible way is the use of specially designed high voltage components that can replace multiple standard components.

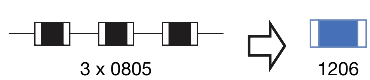
On one hand, the requirements in regards to creepage and clearance distances must be evaluated intensively by using the guidelines in the given standards, while keeping in mind that the CTI concept cannot be applied for resistors having only a thin layer of protective coating. Instead, the guidance from IEC 60664-1 must be used where:

- From the electrical view, a resistor cannot be classified as an insulator. A resistor is a conductor and will have an impact on the behavior of the insulation between the solder pads' electrodes
- Resistors have been tested with source pulse and due to its resistance value, the maximum applicable source pulse voltage is shown in the pulse load diagram

Table 4 of IEC 60664-1 presents a guide for using the right distances under different voltage conditions.

On the other hand, a lot of other benefits can be achieved with fewer or smaller components in the application:

- Reduce system costs
- Improve the reliability of the circuit with fewer solder joints that must be evaluated
- Improve thermal cycling performance
- Reduce the assembly cost of the circuit, which is approximately 10x the product cost
- A reduction of the expensive multilayer PCB space



Example for 500 V

VOLTAGE RATING	STANDARD SIZE		REPLACEMENT			x TIMES SMALLER
			THICK FILM	THIN FILM	MELF	
150 V	0805		RCC0603			≈ 2x
200 V	1206		RCC0805			≈ 2x
200 V	1210		RCC0805			3x
400 V	2010	2 x 1206	RCV0805	TNPV0805		5x / 3.6x
500 V	2512	3 x 0805	RCV1206 AT			4x / 1.7x
700 V		3 x 1206	RCV1206 AT	TNPV1206	MMA 0204 HV AT	3x
1000 V		5 x 1206	RCV1210	TNPV1210	MMA 0207 HV AT	3x
2000 V		10 x 1206	RCV2010 AT			3.6x
3000 V		6 x 2512	RCV2512 AT			6x

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DIN EN IEC 60664-1:2022-07
Insulation coordination for equipment within low voltage supply systems
Part 1: Principles, requirements, and tests

DIN EN IEC 60112 VDE 0303-11:2022-11
Method for the determination of the proof and the comparative tracking indices of solid insulating materials

IEC 60068-2-67:1995+AMD1:2019 CSV (Consolidated Version)
Environmental testing - Part 2-67: Tests - Test Cy: Damp heat, steady state, accelerated test primarily intended for components

MIL-STD-883 Method 5011
Electrical test method standard for microcircuits: Evaluation and acceptance procedures for polymeric adhesives

J-STD-004
Guidelines for the testing of solderability and the reliability of electronic assemblies

ASTM D257
Surface resistivity, volume resistivity, test method determines surface resistivity and volume resistivity of insulating materials

IEC 61508
Functional safety of electrical / electronic / programmable electronic safety-related systems

LV 123, VW 80303
Electrical and electronic high voltage components in motor vehicles - electrical requirements, test conditions, and tests // test sequences for components in HV on-board network

IEC 60071:2023
Insulation coordination in three-phase applications above 1 kV

IEC 60664-1:2020
Insulation coordination for equipment within low voltage supply systems up to rated voltages of 1000 V_{AC} or DC 1500 V_{DC}

ISO 21498:2021
Electrically propelled road vehicles - Electrical specifications and tests for voltage class B systems and components

ISO 21782:2023
Electrically propelled road vehicles - Test specification for electric propulsion components

Anwenderforum Passive Bauelemente; Dr. Hauke Lehmann; VISHAY DBR
2020: “Resistors in high voltage applications”
2021: “Precise (and) high voltage dividers”

Low Voltage Directive 2014/35/EU and EN 61010-1
Product-certification, electromagnetic-compatibility, electrical-safety

Vishay Application Note on Conformal Coating:
“Preserving Precision: Conformal Coatings Applied to Thin Film Resistors”
www.vishay.com/doc?28960