



Product Safety Considerations for
Insulation Coordination of Low-
Voltage Equipment

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What is Insulation Coordination?

- From IEC 60664-1, Edition 1.2:

1.3.1

insulation coordination

mutual correlation of insulation characteristics of electrical equipment taking into account the expected micro-environment and other influencing stresses

NOTE Expected voltage stresses are characterized in terms of the characteristics defined in 1.3.5 to 1.3.7.

- So what does that mean in English?



What is Insulation Coordination? (cont.)

- From the IEEE Power and Energy Society, Surge Protective Devices Committee*:
- COORDINATION OF INSULATION
The process of correlating the insulation strengths of electric equipment with expected overvoltages and with the characteristics of surge protective devices: see ANSI 92.1–1982 [C62.2–1987 & C62.22–1991]

*Source: http://grouper.ieee.org/groups/spd/html/terms_c.html



What is Insulation Coordination? (cont.)

From Klaus Stimper:

“Insulation co-ordination implies the selection of the electric insulation characteristics of equipment with regard to its application and in relation to its surroundings.”

Source:

K. Stimper, "***The physical fundamentals of low-voltage insulation co-ordination***", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach vde-verlag 1991.



First Step of Insulation Coordination



First Step of Insulation Coordination (cont.)

- Define the Environment!
- Parameters that must be defined include:
 - Overvoltage Category
 - Pollution Degree (Macro and Micro Environments)
 - Working Voltages
 - Mains Configuration if Connection to AC Mains Present
 - Operating Altitude



Overvoltage Category

- At STP, air breaks down at approximately 3kV/mm
- According to IEC 60950-1, 2nd Ed., for a standard office environment, the minimum air gap between 120Vac mains and ground shall be 1.0mm.

Why?



Transient Overvoltages

Table 2J – AC mains transient voltages

AC MAINS SUPPLY voltage ^a up to and including	MAINS TRANSIENT VOLTAGE ^b V peak	
	Overvoltage Category	
V r.m.s.	I	II
50	330	500
100	500	800
150 ^c	800	1 500
300 ^d	1 500	2 500
600 ^e	2 500	4 000

^a For equipment designed to be connected to a three-phase, three-wire supply, where there is no neutral conductor, the AC MAINS SUPPLY voltage is the line-to-line voltage. In all other cases, where there is a neutral conductor, it is the line-to-neutral voltage.

^b The MAINS TRANSIENT VOLTAGE is always one of the values in the table. Interpolation is not permitted.

^c Including 120/208 V and 120/240 V.

^d Including 230/400 V and 277/480 V.

^e Including 400/690 V.

*Table from IEC 60950-1, 2nd Edition



Transient Overvoltages, IEC 60664-1

Table 1 – Rated impulse voltage for equipment energized directly from the low-voltage mains

Nominal voltage of the supply system ¹⁾ based on IEC 60038 ³⁾		Voltage line to neutral derived from nominal voltages a.c. or d.c. up to and including V	Rated impulse voltage ²⁾			
			Overvoltage category ⁴⁾			
Three phase	Single phase		I	II	III	IV
230/400 277/480 400/690 1 000	120-240	50	330	500	800	1 500
		100	500	800	1 500	2 500
		150	800	1 500	2 500	4 000
		300	1 500	2 500	4 000	6 000
		600	2 500	4 000	6 000	8 000
		1 000	4 000	6 000	8 000	12 000

- 1) See annex B for application to existing different low-voltage mains and their nominal voltages.
- 2) Equipment with these rated impulse voltages can be used in installations in accordance with IEC 60364-4-443.
- 3) The / mark indicates a four-wire three-phase distribution system. The lower value is the voltage line-to-neutral, while the higher value is the voltage line-to-line. Where only one value is indicated, it refers to three-wire, three-phase systems and specifies the value line-to-line.
- 4) See 2.2.2.1.1 for an explanation of the overvoltage categories.

*Table from IEC 60664-1, Ed. 1.2



Six (k) of One, Half a Dozen (k) of Another

IEC Approach (as explained by Klaus Stimper)

- Basis of tables in IEC 60664-1
- Literature study of more than 50 publications on transient overvoltages measured in European 230/400V systems (voltages induced by lightning strikes)
- Conclusion of study was that 6kV was rarely exceeded
- Surge arrestors along overhead lines in Germany are rated 2kV
- 1kV drop is assumed resulting from earth resistance of the arrestor
- Resulting 3kV surge could be doubled by reflections/constructive interference

IEEE Approach (as explained by Francois Martzloff)

- Analysis of data led to 3 categories relating # of surges/year and voltages
 - Categories are Low, High and Extreme Exposure
 - Noted that 6kV is typical wiring device sparkover
 - 6kV indicated as valid for indoor systems
-
- Both approaches concede that 6kV is not worst case, but higher voltages are improbable.
 - IEC approach appears to have gained more widespread acceptance.

Sources:

K. Stimper, "***The physical fundamentals of low-voltage insulation co-ordination***", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach vde-verlag 1991.

F. Martzloff, "***Protective Devices, Systems and Methods: Transient Overvoltage Protection in the Undefined Real-World Environment***", Solid State PowerConversion, Oxnard, 1979.



Definition of Overvoltage Categories

- Equipment of **overvoltage category IV** is for use at the origin of the installation.

NOTE Examples of such equipment are electricity meters and primary overcurrent protection equipment.

- Equipment of **overvoltage category III** is equipment in fixed installations and for cases where the reliability and the availability of the equipment is subject to special requirements.

NOTE Examples of such equipment are switches in the fixed installation and equipment for industrial use with permanent connection to the fixed installation.

- Equipment of **overvoltage category II** is energy-consuming equipment to be supplied from the fixed installation.

NOTE Examples of such equipment are appliances, portable tools and other household and similar loads.

- Equipment of **overvoltage category I** is equipment for connection to circuits in which measures are taken to limit transient overvoltages to an appropriately low level.

* Source: IEC 60664-1, Ed. 1.2, Clause 2.2.2.1.1



Pollution Degree

– ***Pollution degree 1***

No pollution or only dry, non-conductive pollution occurs. The pollution has no influence.

– ***Pollution degree 2***

Only non-conductive pollution occurs except that occasionally a temporary conductivity caused by condensation is to be expected.

– ***Pollution degree 3***

Conductive pollution occurs or dry non-conductive pollution occurs which becomes conductive due to condensation which is to be expected.

– ***Pollution degree 4***

Continuous conductivity occurs due to conductive dust, rain or other wet conditions.

* Source: IEC 60664-1, Ed. 1.2, Clause 2.5.1



Historical Background

- A paper was published in 1983 detailing results of collaborative experiments in the USA and Germany.
- Climatic conditions and measurements of corrosive gases in the air were taken at various sites, along with chemical analysis of test specimens' surface layers.
- Insulation resistance testing was performed to observe the influence of environmental conditions on insulation performance.
- IEC 60664-1 also draws from other studies.
- Summary of paper: The paper reports on a research project with the goal of ascertaining the effects of environmental pollution on insulating materials, to simulate these effects in the laboratory, to determine the insulating properties of synthetic materials commonly used in electrical engineering and thus to provide creepage distances for the design of products in the 0 to 1000 V range. As the first phase of this project, test boards with a total of over 24000 test positions are being subjected to various environmental conditions in locations throughout Germany and in two locations in the United States. Surface tracking and interelectrode resistance will be monitored periodically throughout the aging period; the dust, which settles on the test units, will be analyzed at the conclusion of the tests. Comparative tests in an artificial industrial atmosphere are intended to simulate the field trials at an accelerated pace.
- Schau, P.V.; Middendorf, W.H., “**An International Research Project to Determine New Dimensioning Rules for Creepage Distances**”, Electrical Insulation, IEEE Transactions on Volume EI-18, Issue 2, April 1983 Page(s):158 - 162



Effect of Humidity on Over-Surface Insulation

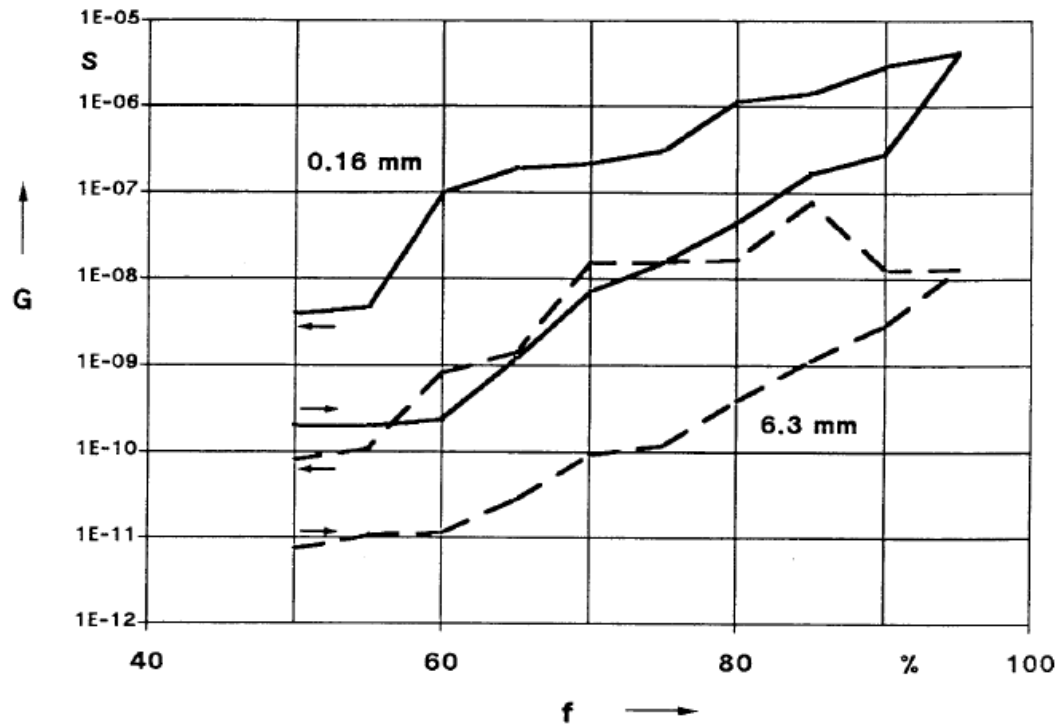


Figure 2.3.2. Dependency of the conductivity G of a polluted insulation on the relative humidity f during a step by step increase and later decrease of the surrounding humidity [13].
- insulation material: type 802 polyester resin moulding material

Source: K. Stimper, "***The physical fundamentals of low-voltage insulation co-ordination***", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach vde-verlag 1991.



Effect of Humidity on Breakdown of Air

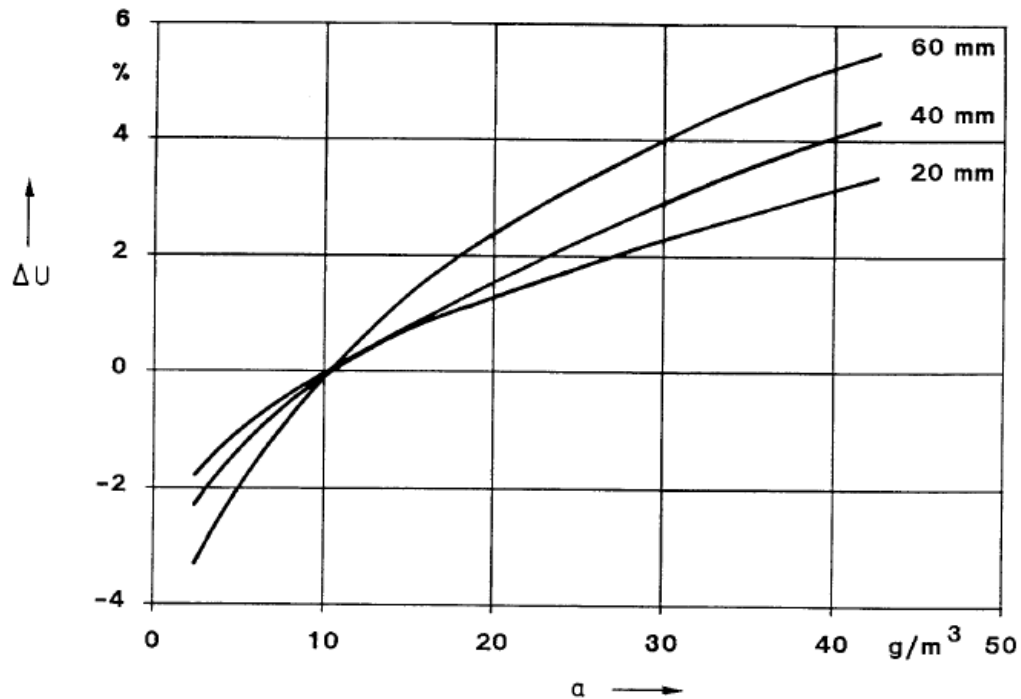


Figure 2.3.6. Dependency of the direct or alternating breakdown voltage U of a plate-plate-arrangement on the absolute humidity a at different spacings [12].

Source: K. Stimper, "***The physical fundamentals of low-voltage insulation co-ordination***", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach vde-verlag 1991.

Effect of Corrosive Components of Air

- Concentrations of SO₂, NO, NO₂, Cl⁻, F⁻ and O₃ measured as part of the data collection effort.
- In all cases, concentrations were significantly (orders of magnitude) below those concentrations that caused measurable insulation deterioration in the lab after several weeks.
- Deterioration is caused by slow chemical reactions.
- There was no correlation between data of corrosive gases to the chemical analysis of the pollution deposition on the test specimens.
- IEC 60664-1 disregarded the effect of corrosive gases in its requirements. Deterioration is considered mainly due to dust.



Effect of Dust Deposition on Insulation

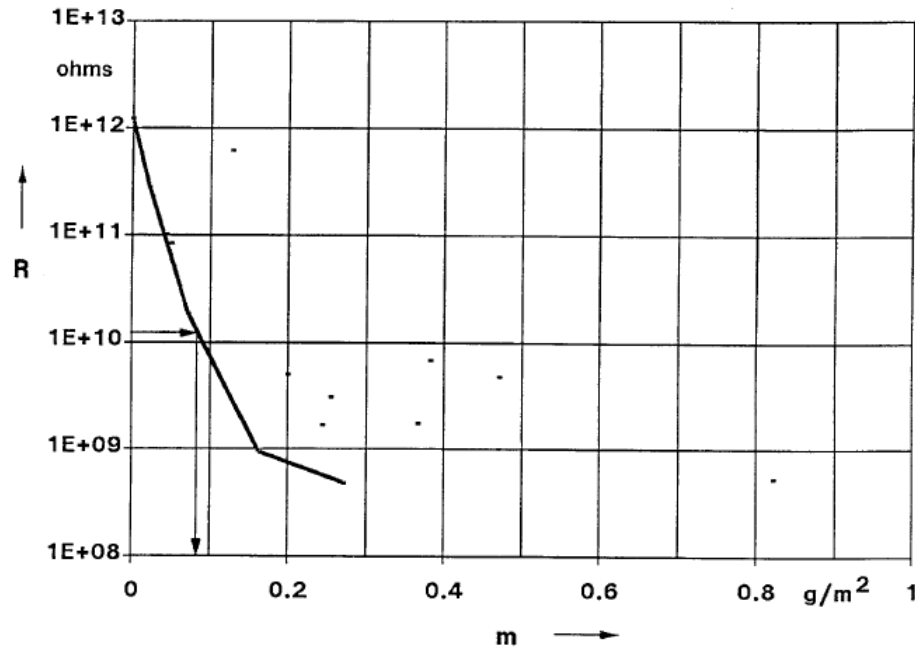


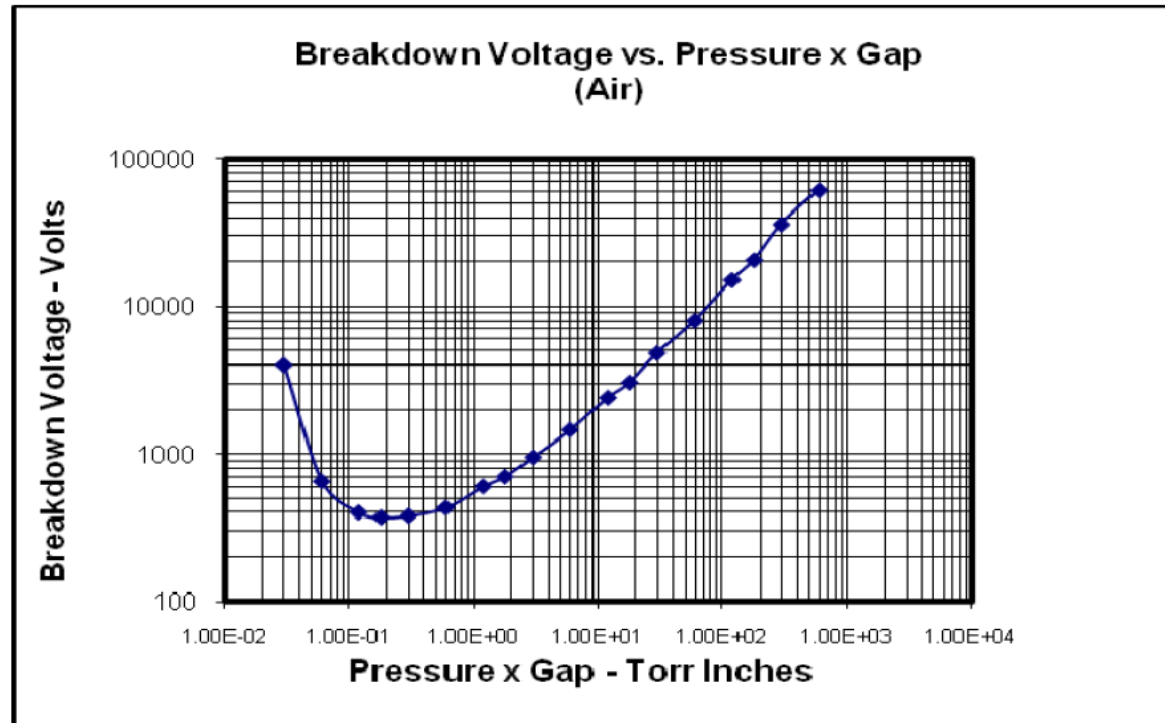
Figure 2.3.7. Insulation resistance R of polluted specimens exposed without voltage during the field trial of the research association "creepage distances" [14] depending on the salt deposition m . Each point refers to one of the locations and exposition durations listed in table 2.3.5. The lines and arrows explain the evaluation of the salt deposition threshold [13].

- insulation material: type 802 polyester resin moulding material
- creepage distance: 6.3 mm
- measuring climate: 23 °C / 83% relative humidity

Source: K. Stimper, "***The physical fundamentals of low-voltage insulation co-ordination***", VDE-Schriftenreihe, Vol. 57, Berlin, Offenbach vde-verlag 1991.



Effect of Air Pressure on Breakdown Voltage



- This is Paschen's Curve
- Technically, it is only accurate for homogenous fields, but IEC 60664-1 used the formula to convert results from laboratory elevation to 2000m.
- IEC 60664-1, Annex A, Table A.2 has altitude correction factors for clearances. For example, required clearance must be multiplied by 1.14 for 3000m
- The airport in El Alto, Bolivia sits at 4061m! 4000m elevation requires correction factor of 1.29



Clearance

- Clearance – shortest distance in air between two conductive parts
- Also referred to as Through-Air Spacings (in UL speak)
- Major factors affecting clearance:
 - Air Pressure (Altitude)
 - Temperature (if wide variation)
 - Overvoltage Category
 - From product safety evaluation point of view, working voltage
 - Homogenous vs. Inhomogenous Fields
 - Temporary overvoltages or recurring peak voltages



* Source for Photo: <http://www.electricalforensics.com/testing/testing.htm>



Creepage

- Creepage Distance – shortest distance along the surface of the insulating material between two conductive surfaces
- Also referred to as Over-Surface Spacings (in UL speak)
- Major factors affecting creepage
 - Pollution Degree
 - Humidity
 - Dust deposition
 - Material Properties (CTI)



Comparative Tracking Index (CTI)

- Tracking occurs when a surface leakage current is interrupted due to drying out of surface liquid, can cause progressive formation of conductive paths on surface of insulating material.
- CTI is relative measure of material propensity for tracking
- Inorganic materials (such as glass, ceramics) do not track
- 50 drops of 0.1% ammonium chloride solution dropped onto material, voltage measured for a 3mm thickness
- IEC standards classify materials according to material groups
- UL standards classify materials according to the PLC

CTI (in volts)	IEC Material Group	UL PLC
600 and greater	I	0
400 through 599	II	1
250 through 399	IIIa	2
175 through 249	IIIa	3
100 through 174	IIIb	4
Less than 100	IIIb	5




Basic Approach of Electrical Product Safety


- Assumption applied to Electric Shock Hazards:
 - Two levels of protection must be provided to protect operators from electric shock.
- Five different types of insulation are defined:
 - **Functional Insulation** – insulation between conductive paths which is necessary only for the proper functioning of the equipment
 - **Basic Insulation** – insulation applied to live parts to provide basic protection against electric shock
 - **Supplementary Insulation** - independent insulation applied in addition to basic insulation, in order to provide protection against electric shock in the event of a failure of basic insulation
 - **Double Insulation** – insulation comprising both basic insulation and supplementary insulation
 - **Reinforced Insulation** - single insulation system applied to live parts, which provides a degree of protection against electric shock equivalent to double insulation
- Protective Earthing is also considered a single level of protection.



Component Selection

- In a feedback circuit, we have an optocoupler between the AC mains and ungrounded safe circuitry. AC mains is OV cat III, PD 2, 480/277V. Is the component below an acceptable choice for product safety, per IEC 60664-1?





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H11F1M, H11F2M, H11F3M Photo FET Optocouplers

Features

As a remote variable resistor:

- $\leq 100\Omega$ to $\geq 300M\Omega$
- $\leq 15pF$ shunt capacitance
- $\geq 100G\Omega$ I/O isolation resistance

As an analog switch:

- Extremely low offset voltage
- 60 V_{pk-pk} signal capability
- No charge injection or latch-up
- $t_{on}, t_{off} \leq 15\mu S$
- UL recognized (File #E90700)

General Description

The H11FXM series consists of a Gallium-Aluminum-Arsenide IRED emitting diode coupled to a symmetrical bilateral silicon photo-detector. The detector is electrically isolated from the input and performs like an ideal isolated FET designed for distortion-free control of low level AC and DC analog signals. The H11FXM series devices are mounted in dual in-line packages.

Isolation Characteristics

Symbol	Characteristic	Test Conditions	Device	Min.	Typ.*	Max.	Units
V _{ISO}	Isolation Voltage	f = 60Hz, t = 1 sec.	All	7500			V _{AC} PEAK
R _{ISO}	Isolation Resistance	V _{LO} = 500 VDC	All	10 ¹¹			Ω
C _{ISO}	Isolation Capacitance	f = 1MHz	All		0.2		pF

*All Typical values at T_A = 25°C



Component Selection (Cont.)

- Component is UL Recognized, but it is not clear from the UL file what isolation voltage it is approved for.
- Assuming UL rating is identical to spec (7500Vpk isolation), then:
 - Impulse rating for this mains circuit is 4000Vpk per table 1
 - Impulse test voltage would be 4800Vpk at sea level per table 5
 - Assume manufacturer spec is tested at sea level
 - If product used up to 2000m, then must apply correction factor of 1.28 (table 8, inverse of 0.784) – gives 6144Vpk impulse test voltage
 - Looks OK, right?



Component Selection (Cont.)

- But mains to ungrounded safe circuitry requires Double or Reinforced Insulation. Test voltage must be based on next higher step impulse rating when based on standard impulse value. So impulse rating used must be 6000V, not 4000V.
- From table 5, impulse test voltage is 7300Vpk
- Applying correction factor for altitude, $7300\text{Vpk} * 1.28 = 9344\text{Vpk}$ required impulse test voltage

- Component is not acceptable for the application

- Other Considerations:
 - Thin Film Insulation
 - Component Spacings Requirements vs. End Product Spacings Requirements
 - Manufacturer Voltage Ratings



Can't we just hipot it?

Your product safety engineer's favorite question. Go ahead. Ask.



- Clearances can be evaluated by impulse or dielectric strength testing, simulating resistance to transients.
- Solid insulation can be evaluated by dielectric strength testing
- IEC 60664-1 requires clearances to be tested if they are below the values stipulated for inhomogenous fields.
- UL 840 has a similar provision
- No flashover breakdown allowed
- IEC 60664-1 also indicates testing for partial discharge and high frequency dielectric heating, but few product safety standards include these tests as requirements.



Combination of Insulating Elements

- Insulation consists of clearance, creepage and/or solid insulation
- What do to if a single point of insulation comprises multiple elements?
- **Example:** A trace near the edge of a PCB is a secondary circuit with 1000Vrms working voltage, pollution degree 2, overvoltage category II, 480/277V 3 phase mains, 1.0mm from trace to edge of board, then 0.5mm from edge of board through air to UL Recognized green/yellow protective bonding jumper rated 600V
- Solid Insulation – rated 600V
- Clearance Requirement (based on 2500V impulse) – 1.5mm
- Creepage Distance Requirement – 5.0mm
- Is this system compliant to the requirements of IEC 60664-1?



Combination of Insulation Elements (Cont.)

- Solid Insulation – 60% of required voltage rating
- Clearance – 33% of required distance
- Creepage – 20% of required distance
- Total: 113%

But this system is not compliant!

- Air gap is less than 1mm (PD 2), so is treated as creepage.
- Solid Insulation – 60%
- Clearance – 0mm – 0%
- Creepage – 1.5mm – 30%
- Total: 90%



Q&A





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