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High Voltage Encapsulation Failure Modes

Steve Ainsworth, Director of Engineering for Dart Research, reveals the truth behind the "black art" of high voltage design.

Dart Research, based in Dartmouth UK, is a start-up that is currently developing high energy electron beam systems for use in x-ray inspection. It has a particular interest in difficult cross-disciplinary design problems.

Steve Ainsworth, founder and director of engineering, believes that modeling software is the essential component of any design engineer's toolkit. Ainsworth says that, "Wherever there is a significant risk in the design, it is always better to model first and build later as iterating the design on-screen is significantly more cost-effective. In the field of high voltage systems, I have seen a number of designs where this has clearly not been the case and as a result the products have been unreliable or oversized leading to further design work or, in the worst-case scenario, withdrawal of the product".

Since 2005 Ainsworth has relied on the accuracy of LORENTZ software for model analysis. Ainsworth says that, "LORENTZ offers the fastest design iteration time with on-screen model editing and self-determining analysis. Its accuracy has been proven over many designs".

He highlights three simple examples where modeling would prevent problems occurring. Though he says that more complex arrangements are likely to offer further revelations. In these examples, part or all of the design is encapsulated in a silicone potting compound designed for high voltage applications. Whilst this is a popular choice for many designs these examples equally apply to other materials, such as transformer oil.

The failure mechanism in silicone means a localised breakdown occurs in a very small region at the point of maximum electric field. This will vaporise and carbonise the silicone in this small region, resulting in a localised rupture by the gas pressure and some conductive carbon deposition. The outcome is usually a much greater electric field and the region rapidly grows, a continuous process that leads to a conductive path being formed across the potential gap. The path is sometimes erratic, and not in a direct line, but leads inextricably towards the opposite polarity accompanied by an audible crack and every high voltage engineer's nightmare.

Ainsworth has seen examples of breakdown paths exceeding 50mm long at 100kV, suggesting a material breakdown at 2kV/mm, whereas the actual material specification was nearly 10 times greater. The root cause was an electric field "hot spot" on a grounded case.

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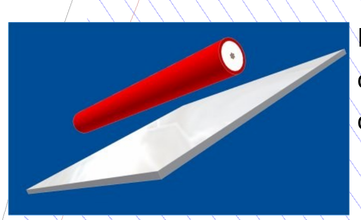
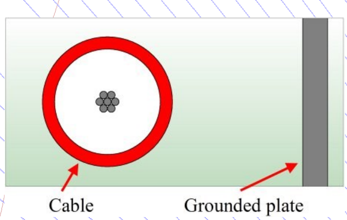
1. Potting high voltage components. It is often not understood that components rated in air do not have the same rating when potted. For example, a high voltage cable, often used on small supplies to connect to the outside world.



In Fig.1, a high voltage cable is shown, one cable diameter (5.2mm) from a grounded plate. The cable construction is 7/0.3mm core and the insulation is polyethylene with a PVC sheath. The cable is rated at 25kV and in this case, the potential difference is 20kV.



The cross-section is prepared for analysis as shown in Fig.2.

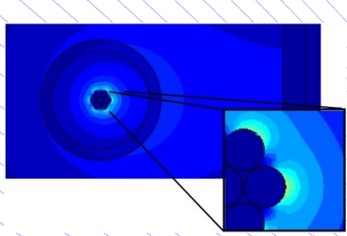


Fig.3 shows the cross-sectional analysis of the electric field with the system in air. The light-green areas around the core of the cable indicate a maximum stress of about 10kV/mm, which is within the material specification.

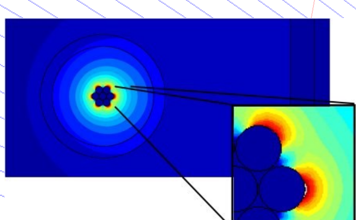
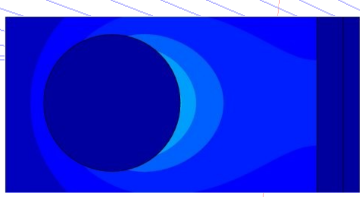


Fig.4 is the same cable potted in silicone rubber. The red areas around the cable core indicate a maximum electric field just exceeding 20kV/mm. This exceeds the insulation rating and it is unlikely that the cable would be reliable in this case. The proximity of the ground plate is not particularly significant.



One solution is to use a solid conductor of the same size as the cable, as shown in Fig.5, where the maximum electric field is around 5kV/mm.

This principle applies to any component designed to operate in air. It is also worth investigating the dielectric constant assumed for components designed for potting. In some commercial power supplies high voltage cable is used as the winding for isolation transformers. A typical application would be providing an elevated supply for grid or filament power in an electron beam gun. In this case, using modeling software for analysis is likely to yield a more optimum solution.

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2. Triple junctions. The enhancement of the electric field at a triple junction has been well understood for some time and the effect is often deliberately exploited, for example in field emission displays.

The example in Fig.6 is a 50kV vacuum feed-through where the central electrode is supported by a 100mm diameter ceramic disk. The front side is to be potted in silicone.

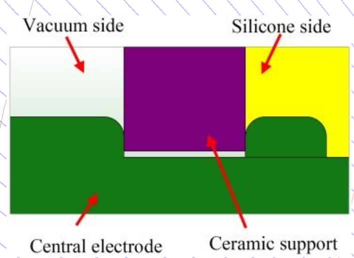
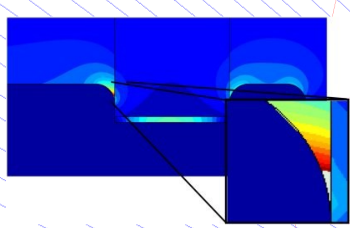


Fig. 7 shows a magnified cross-section view through the junction of the central pin and ceramic insulator. Here, the designer has recognised the need to avoid sharp edges and specified a radius on the turned shoulders.



The electric field analysis in Fig.8 shows the field enhancement around the triple junction of the metal pin, the ceramic disk and the vacuum. In this case the electric field exceeds 20kV/mm (shown in red) and could damage the ceramic, ultimately leading to total breakdown.

“An interesting point is the tolerance gap between the pin and the ceramic,” comments Ainsworth. “The electric field is 11kV/mm in this example and could easily cause a breakdown under certain circumstances. If, in a particular assembly, the gap were smaller, then the electric field would rise further. Although this is a stylised design, it does demonstrate the need for accurate and complete modeling.”

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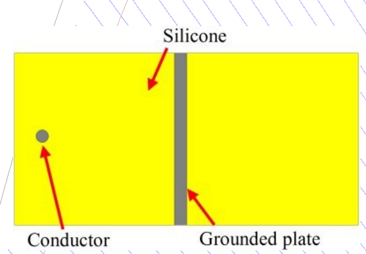
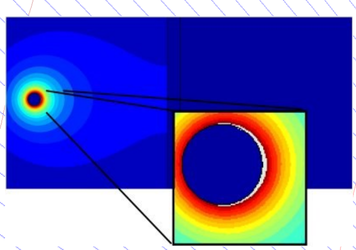
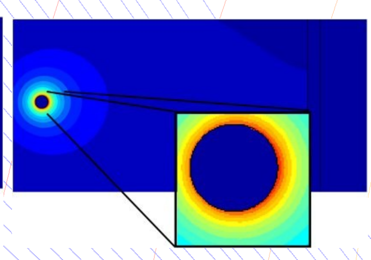
3. Minimising potting material. It is often assumed that increasing the thickness of insulation will improve the voltage rating of a particular design. Alternatively, where insulation has failed, the temptation can be to add more material. This approach is usually ineffective, unless the electric field has been modelled and the root cause clearly understood.



The example in Fig.9 shows a 40kV high voltage conductor of 1mm diameter encapsulated in silicone and located 10mm from a grounded plate. This is typical of electronic components used in voltage multipliers or dividers.





The analysis in Fig.10 shows a maximum electric field around the conductor of 21.9kV/mm. This is likely to result in a breakdown in the silicone. The effect of increasing the separation distance from 10mm to 20mm is shown in Fig.11. Here, the field has been reduced to 17kV/mm, a reduction of 22%, rather than the 50% which might have been expected.

Although the silicone may survive this electric field, in most cases it is beneficial to use shields to protect parts of the circuit from such stresses without the need for additional potting material.

Ainsworth concludes, "The use of electric field modeling software can be a very effective way of arriving at an optimum solution for a high voltage design. With electric field modeling even quite subtle problems are easily identified, changes quickly made and further testing done. It is also vital that the software is easy to use, fast and presents its results clearly. When looking at modeling software to iterate your design, LORENTZ from INTEGRATED Engineering Software meets these requirements. It is far better to select packages with specific features, than generic packages which require further 'programming' before being used for simulation. INTEGRATED's solution includes a CAD import facility, which is absolutely necessary, and it also allows one to quickly modify a design on-screen.

"For ease of use, calculations should be rapid and largely self-determining without the need to input any specific parameters such as meshing sizes etc. I would recommend that attention is paid to all aspects of the design, including such apparently benign components as screws and solder joints. Particular attention should be given to tolerances and fits of conductive and nonconductive materials.