

Design of a Cylindrical High-Voltage High-Temperature Vacuum Insulator

Robert J. Pahl and Mark A. Shannon

University of Illinois at Urbana-Champaign
Department of Mechanical and Industrial Engineering
MC244, 1206 W. Green St., Urbana, IL, 61801 USA

ABSTRACT

A design for a high temperature, HV insulator is presented. This design exploits the temperature dependent thermal and electrical properties of alumina and a unique structural insulator design to increase the high voltage hold-off characteristics of the insulator, reduce thermal flux through the insulator, and alleviate stresses caused by mismatch between insulator and electrode thermal expansion coefficients. The designed insulators insulate graphite electrodes at temperatures approaching 1000°C and potentials up to 50 kV. In this paper, the general methodology of designing these insulators is explored, and some limited performance data is presented.

Index Terms — High voltage, high temperature, insulation, vacuum, design, cylindrical insulator.

1 INTRODUCTION

STANDARD HV vacuum insulating ceramic materials, such as alumina, have been used extensively as HV vacuum insulators because of their electrical and structural properties [1]. Such ceramics also have good high temperature mechanical properties and are used as structural members in high temperature applications. In research on the effects of transverse electric fields on thermal emissions, an insulator is needed to electrically insulate and structurally support large graphite electrodes at temperatures approaching 1000°C. Limited information on the design of high temperature HV insulators exists since such applications where high temperatures and high voltages are simultaneously present are usually avoided.

In this paper, the design methodology used to create cylindrical alumina HV insulators for HV, high temperature application is presented. In this description, first a listing of the design criteria of this application is given. Based on this criteria, the material properties of the insulator material and structural analysis are used to design insulators which meet our design goals. In this design methodology, it is shown how the non-linear thermal and electrical properties of alumina can be used to aid in improving the HV hold-off characteristics of the insulator and to reduce the thermal flux through the insulator. The structural analysis then will show how a careful choice of

insulator design can be used to alleviate the stresses in the electrode and insulator caused by the inherent mismatch in thermal expansion coefficients. Although the analysis presented here is for a specialized case, the design approach described could be used for other high temperature-high voltage insulator design applications as well as other HV systems undergoing a substantial temperature change, such as in cryogenic systems.

2 DESIGN CRITERIA

The design criteria that govern the design of our insulators are established by the size and orientation of the electrodes. Our application consists of two concentric cylindrical graphite electrodes, each supported by a cylindrical alumina insulator. The graphite cylinders are shown along with the final design of the alumina insulators as a cross-sectional view in Figure 1. The outer graphite cylinder is 250 mm long with an outer diameter of 180 mm. The graphite cylinders are heated to temperatures approaching 1000°C and the other, grounded, end of the insulators will be kept below 100°C by a water based cooling system. At these elevated temperatures, the outer graphite cylinder is grounded and the inner cylinder will be brought to a steady potential varying from 5–50 kV, depending on the magnitude of the thermal electron emission current and limitations of the HV power supply. The HV gap between the graphite cylinders is 5 mm. The large size of the electrodes result in a vertical gravity load of ~60 N on the outer insulator and ~45 N on the inner insulator. In

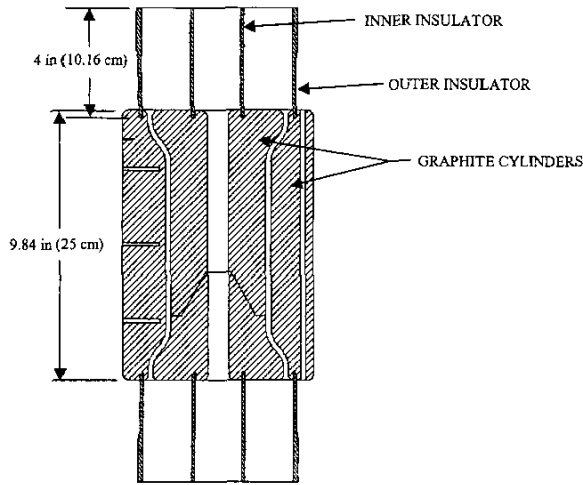


Figure 1. Cross-sectional drawing of assembled graphite electrodes and alumina insulators.

In addition to this mass load, the insulators must support any horizontal electrostatic forces caused by non-concentric misalignment of the inner and outer cylinders. An expression derived elsewhere [2,3] relating the magnitude of this force per unit length, F , to the horizontal misalignment distance, d , is

$$F = \frac{V^2 d \pi \epsilon_0}{\left[\cosh^{-1} \left(\frac{R^2 + r^2 - d^2}{2Rr} \right) \right]^2 \cdot \sqrt{\left(\frac{R^2 + r^2 - d^2}{2Rr} \right)^2 - 1} \cdot Rr} \quad (1)$$

where V is the applied voltage, ϵ_0 is the permittivity of free space, R the inner radius of the outer cylinder, and r is the outer radius of the inner graphite cylinder. Using the geometry of the electrodes, the maximum horizontal electrostatic force on the insulators is estimated at 7 N for a 1 mm misalignment under a 50 kV potential. To support these forces, the wall thickness of the cylindrical insulators is 2.5 mm. The diameter of the inner and outer ceramic insulators are 50.8 mm and 152.4 mm, respectively, and all components are operated in a high vacuum environment.

3 DESIGN METHODOLOGY

Holding components at high voltages while at elevated temperatures requires the consideration of many factors such as high temperature material behavior, thermal expansion and structural performance, and HV hold-off characteristics. Given the above design criteria, the design methodology for the design of the insulators for the concentric cylinder graphite electrodes involves first looking at the thermal properties of the insulators and then at

how these thermal properties affect the electrical and structural behavior of the insulators. The details of this design methodology are now presented in depth.

3.1 THERMAL ANALYSIS

The first step in the design of the insulators is the analysis of the thermal behavior of the insulators. The material chosen for the insulators here is alumina because of its commercial availability. This material has had extensive use in the past [1] as a HV vacuum insulator. Alumina also has excellent high temperature structural properties in that high purity (99.7%) alumina has a structural working temperature of over 1500°C, which far exceeds our 1000°C objective.

When holding the graphite electrodes at high temperatures, it is advantageous to keep the heat flux through the insulators to a minimum to reduce heat transfer to the surroundings. Reducing heat flux can be done by reducing the cross-sectional area of the insulators and by reducing the temperature gradient in the insulators. To reduce the cross-sectional area, the insulators are thin-walled cylinders with a wall thickness of 2.5 mm. To reduce the temperature gradient in the insulators between the high temperature electrode and cooled ends of the electrodes, the electrodes can be lengthened. The heat flux then, in most cases, decreases linearly with insulator length for an insulator with a linear thermal conductivity. However, in addition to its high temperature capabilities, alumina has unusual thermal material properties in that its thermal conductivity decreases dramatically with increasing temperature [4]. In addition to lowering the overall heat flux through the cylinders when compared with a material having a linear conductivity, this property also causes most of the temperature drop to occur at the high temperature end of the insulator with a large fraction of the cylinder remaining at temperatures near the insulator base temperature. A plot of the temperature, temperature gradient, and thermal conductivity as a function of insulator position is shown in Figure 2.

At high temperatures, it has been shown [5] that surface breakdown events increase with surface temperature, and so if the electric field strength is too large over a portion

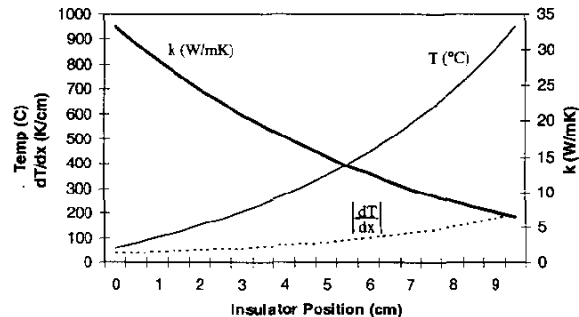


Figure 2. Thermal characteristics of alumina insulators.

of the insulators having higher temperatures, there is an increased likelihood that the insulators will break down. The non-linear thermal conductivity of alumina means that lengthening the insulator increases the fraction of the support at lower temperatures ($< 200^\circ\text{C}$). Lengthening the insulators therefore has the additional effect of improving the HV hold-off characteristics. The length of the insulators (101.6 mm) has thus been tailored so that at the upper temperature limit of operation, the length of the relatively cool part of the insulators ($< 200^\circ\text{C}$) is ~ 30 mm. It has been shown [6] that a 13 mm alumina segment can hold off potentials > 60 kV, and so the cool length of our insulator is more than sufficient to hold off our maximum potential of 50 kV.

Another electrical aspect related to HV hold-off is the current leakage through the bulk insulator. If this current leakage is too large, charge concentrations can develop in the insulator, thereby increasing the local field strength on the insulator, which could lead to an increased probability of electrical breakdown. To find the leakage current, first the current density through the insulator, J , must be found. Assuming a one-dimensional system, J can be expressed as

$$J = -\sigma(x) \frac{d\phi}{dx} \quad (2)$$

where ϕ is the overall potential across the insulator and $x=0$ corresponds to the grounded end of the insulator ($\phi=0$). The conductivity of the insulator as a function of position, $\sigma(x)$, can be derived using the temperature data from the thermal analysis and temperature-dependent electrical conductivity data [4]. The results of this analysis can best be expressed as an exponential function,

$$\sigma(x) = Ae^{Bx} \quad (3)$$

where $A = 2 \times 10^{-20} (\Omega \text{ cm})^{-1}$ and $B = 2.73 \text{ cm}^{-1}$. Equation (2) can then be solved to find the current density through the insulators

$$J = \frac{AB\phi}{1 - e^{-BL}} \quad (4)$$

For our system having a length of $L = 101.6$ mm holding a potential of $\phi = 50$ kV, the current density through the insulator is $2.7 \times 10^{-15} \text{ A/cm}^2$ corresponding to a leakage current of $1 \times 10^{-14} \text{ A}$. This value again shows that our prescribed insulator length is more than sufficient to hold off our maximum potential.

The last thermal property of alumina having an impact on the insulator design is the thermal expansion coefficient, α . For alumina, $\alpha = 7.7 \times 10^{-6} \text{ m/m}^\circ\text{C}$. This value is much lower than most materials used in HV design and so care must be taken so that the alumina supports are not structurally damaged during operation. In the design presented here, however, the material mating with the alumina insulators is graphite, having a thermal expansion

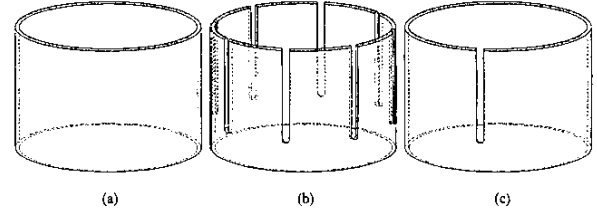


Figure 3. Three cylindrical insulator designs. a, Solid cylinder design; b, Multi-slit cylinder design; c, Single-slit design.

coefficient of $4.0 \times 10^{-6} \text{ m/m}^\circ\text{C}$. Although the thermal expansion coefficients in this application are similar, the difference between the two materials is still sufficient to cause structural damage to the insulators, as will be shown in the next section.

3.2 STRUCTURAL ANALYSIS

The second step in the insulator design is the structural analysis of the insulators. The main concern in this step of the design is alleviating the thermal stresses in the insulator caused by the mismatch in thermal expansion of the materials. Failure to design for thermal expansion could lead to the eventual structural failure of the insulators or electrodes.

This problem of structurally supporting a high temperature, HV component with a cylindrical insulator can be approached with three designs. The insulator can be a solid cylinder (Figure 3a), a multi-slit cylinder (Figure 3b), or a single-slit cylinder (Figure 3c). Each design has ranges of applicability depending on the diameter of the insulator-electrode junction, the difference in thermal expansion between the insulator and component, and the temperature range covered.

The first of these insulator designs considered is a solid cylindrical support, as shown in Figure 3a. The insulator is sized to have the same radius of the mating insulated electrode. Since, in this application, the thermal expansion of the insulator, α_i , is greater than that of the electrodes, α_e , the insulator will be inserted into the electrode so that the outer diameter of the insulator and the inner diameter of the electrode mating groove are in contact. As the temperature of the insulator and graphite electrode are increased, the insulator will be under compressive stresses, and the electrode will be under tensile stresses. The maximum stresses in the electrode, σ_e , and insulator, σ_i , in the tangential direction can be estimated by [7]

$$\sigma_e = P \frac{r_e^2 + R^2}{r_e^2 - R^2} \quad (5)$$

$$\sigma_i = P \frac{R^2 + r_i^2}{R^2 - r_i^2} \quad (6)$$

where r_e is the outer radius of the electrode and r_i is the inner radius of the insulator after thermal expansion. The

transition radius, R , is estimated by taking the average of the outer radius of the insulator and the inner radius of the electrode after thermal expansion. The contact pressure, P , between the insulator and electrode due to thermal mismatch is given by

$$P = \frac{\delta}{R} \left[\frac{1}{E} \left(\frac{r_e^2 + R^2}{r_e^2 - R^2} + \nu_e \right) - \frac{1}{E} \left(\frac{R^2 + r_i^2}{R^2 - r_i^2} - \nu_i \right) \right]^{-1} \quad (7)$$

where E is Young's modulus and ν is Poisson's ratio of the graphite electrode and alumina insulator. The total interference between the two parts, δ , is given by

$$\delta = r_i - r_e = r\Delta T(\alpha_i - \alpha_e) \quad (8)$$

where r is the room temperature radius of the insulator-electrode junction and ΔT is the temperature change experienced by the insulator-electrode junction.

Using equations (6-8) the compressive stress in the smaller diameter insulator is estimated to be 500 MPa, which is well below the compressive yield strength of alumina (>2000 MPa). The corresponding stresses in the graphite electrode are estimated at 60 MPa, which is above the estimated tensile strength (45 MPa) of the grade of graphite used in the electrodes. At the outer insulator-electrode junction, the compressive stress in the insulator is estimated to be 310 MPa and the corresponding tensile stresses in the graphite electrode is estimated to be 71 MPa. Clearly, even if brittle fracture mechanisms are ignored, a solid cylinder design would result in structural failure of both electrodes at high temperatures and so the shape of the insulator must be modified.

The second insulator design is one having multiple slits cut into its sides as shown in Figure 3b. In this design, the difference in thermal expansion is absorbed by the bending of the insulator in that the slits create individual "beams" that are deflected to absorb the thermal mismatch between the insulator and electrode. In this manner, the stress and strain in the graphite electrodes due to thermal mismatch is kept well below the yield strength. As in the solid-cylinder design, the resulting stresses in the insulators should be determined to insure that structural failure does not occur. From simple beam theory [8], a relationship estimating the maximum tensile stresses in the insulator is

$$\sigma_{imax} = \frac{2E\delta}{L^2} \left[r_i - \frac{2}{3} \frac{\sin(\pi/N)}{(\pi/N)} \left(\frac{r_{out}^3 - r_{in}^3}{r_{out}^2 - r_{in}^2} \right) \right] \quad (9)$$

where L is the length of the beams created by the slits, N is the number of slits or beams, and r_{out} and r_{in} are respectively the outer and inner radii of the insulator. Equation (9) assumes that the width of the slits cut into the insulator is small compared to the width of the beams made by the slits, and that the stress due to the weight of the insulator is negligible compared to the stress due to bending. Using equation (9) and the yield strength of alumina, ~ 200 MPa, it is found that if the slit length is made

to be 75% of the total insulator length ($L = 76.2$ mm), and for a large number of slits, $N = 10$, the estimated maximum tensile stresses in the small and large diameter insulators is 25 MPa and 115 MPa respectively. These values are both below alumina's yield strength, and the resulting factor of safety for the large diameter insulator, s_{yield}/s_{max} , is ~ 2 . However, the brittle nature of alumina necessitates a fracture analysis in addition to this simple yield strength analysis. The maximum allowable crack size in the beam surface, a , can be estimated by

$$a = \left(\frac{K_{IC}}{4\sigma_{imax}} \right)^2 \frac{1}{\pi} \quad (10)$$

where K_{IC} is the fracture toughness of alumina (4-5 MPa $m^{1/2}$). s_{imax} is found from equation (9), and the factor of 4 is a combination of safety factor ($n = 2$) and estimated stress concentration factor ($= 2$). The resulting maximum allowable crack length is ~ 30 μm . This is on the order of the grain size for this high purity grade of alumina, and so this value of a is unacceptable. As equation (9) suggests, the stress value can be decreased by either adding more slits, or increasing the length of the insulator. In this application, however, both of these solutions could not be used because of space and cost of construction limitations. In addition, adding too many additional slits will reduce the vertical load carrying capability of the insulator, possibly leading to structural failure.

The third and final insulator design considered is a combination of the solid cylinder and multiple-slit designs. In this final design, only one slit is made in the insulator. This single slit design allows the insulator to absorb the thermal mismatch between the insulator and electrodes by flexing laterally around the circumference of the insulator instead of undergoing a beam-like deflection. In this manner, the stresses are not concentrated on any one area of the insulator and the stress and strain in the graphite electrodes due to thermal mismatch are still absorbed by the insulator. In addition, the cost of construction is much lower than the multiple-slit design in that only one slit is cut into each insulator. Unfortunately, the complex three-dimensional nature of the stresses in this new design does not lend to a simple analytical expression relating stresses to part dimensions and material properties. Instead, experimental evidence is used to validate the design. After the insulators were constructed, the insulators were compressed well beyond their expected deflection range. The insulators did not fail indicating that design is sufficient to prevent any structural failure during normal operation.

4 SUMMARY AND CONCLUSIONS

IN this paper, we have shown a simple method of constructing a high temperature, HV insulator. The nonlinear thermal conductivity of alumina was shown to im-

prove the HV hold-off characteristics of the insulator at high temperatures by creating a low temperature zone at the cool end of the insulators long enough to ensure that the insulator will hold off the required potential. In addition, the non-linear thermal properties also reduce heat flux through the insulator, thereby reducing the amount of power needed to heat the electrodes. Further to the insulator material, the shape of the insulator is critical to the operation of the HV insulation system in that the mismatch in thermal expansions of the insulator and electrode can cause unacceptable stresses in either part. In our system, these stresses were relieved by an insulator design consisting of a cylinder with one slit cut in the side of the cylinder. In most other systems, the electrodes would be made out of a metal or another material with thermal expansions larger than that of the ceramic insulator. In these cases, the direction of stresses most likely would be reversed in that the insulator would expand less than the electrode as temperature increases. However, the methods used here should be applicable and the general insulator design ideas presented here could be used after additional analysis.

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