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Field Analysis of SF_6 Gas Insulated Cables and Its Application to Spacer Design

Takayoshi MISAKI*, Hideki YAMAMOTO*
and Koshi ITAKA**

Synopsis

This paper describes the spacer design for SF_6 gas insulated cables. The maximum electric stress within the cable is calculated by a numerical method, and it is recognized that the breakdown voltage depends linearly on the calculated values. Moreover, the effects of varying the shape of the spacer are made clear in this study for designing an optimum spacer.

1. Introduction

The problem of compressed gas insulated cables has been studied by many reseachers from different points of view. Lately, the number of these reports has been increasing. The authors were given many useful suggestions by several papers which explained the breakdown characteristics in a compressed gas such as SF_6. [1,2,3,4]

The purpose of this paper is to investigate by calculation and experiment the effects of the insulating spacers upon the breakdown characteristics and also to present basic data of a practical spacer design. Each phase of the cable system consists of a single conductor, a cylindrical metal sheath, the spacers which support the conductor within the sheath, and SF_6 gas between two metal electrodes. In this case two relative dielectric constants exist: that of the epoxy spacers and that of the surrounding SF_6 gas.

* Department of Electrical Engineering
** Sumitomo Electric Industries, Ltd.

The spacers have direct effects upon the breakdown characteristics. One of the effects is caused by its cohesion with electrodes and shielding electrodes. These problems and countermeasures are presented in an IEEE paper. [5]

The problem treated here is the effects of varying the shape of the spacer upon the field distribution in the cable. If epoxy spacers are introduced into a uniform field, the field is distorted. The potential distribution becomes complicated, and the maximum electric stress occurs near the spacers. A numerical analysis based on digital computation is helpful in solving such a problem. [6,7,8,9] Here, equations to be used in the calculations are derived directly from the familiar Gauss'theorem.

After calculating the potential distribution, the point where the maximum electric stress occurs and its value are obtained. Then the relation between the shape of the spacer and the breakdown voltage can be estimated. Comparing the calculations with the breakdown tests, the effects of varying the shape of the spacer upon the breakdown characteristics may be made clear, and these results may be used in a practical spacer design.

2. Procedure of Numerical Analysis

Fig.1 shows the cross section of SF_6 gas insulated cables. This cable has axial symmetry and has two different dielectrics;that is, epoxy resin and SF_6 gas.

The problem region, that is, R-Z plane, is subdivided by a rectangular mesh, and each grid-intersection point is numbered. A set of algebraic equations is obtained by using Gauss' theorem around a point (i,j) as shown in Fig.2.

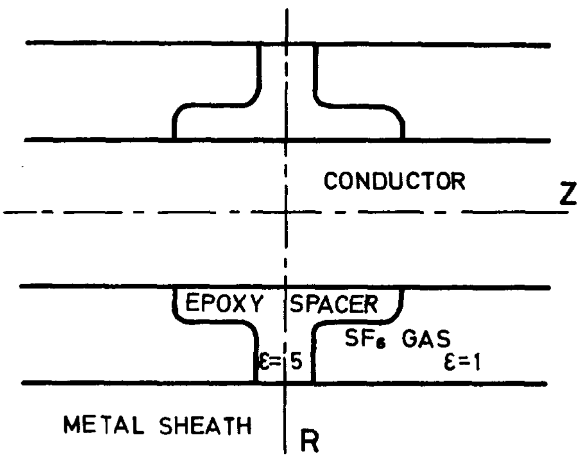


Fig.1 Cross section of SF_6 gas insulated cables

$$a_1V(i,j+1)+a_2V(i-1,j)+a_3V(i,j-1)+a_4V(i+1,j)-a_5V(i,j)=0 \qquad (1)$$

where

$$a_1=\frac{1}{h_1}\{\varepsilon_1 h_2(1-\frac{h_2}{4R(i,j)})+\varepsilon_8 h_4(1+\frac{h_4}{4R(i,j)})\}$$

$$a_2=\frac{1}{h_2}(\varepsilon_2 h_1+\varepsilon_3 h_3)(1-\frac{h_2}{2R(i,j)})$$

$$a_3=\frac{1}{h_3}\{\varepsilon_4 h_2(1-\frac{h_2}{4R(i,j)})+\varepsilon_5 h_4(1+\frac{h_4}{4R(i,j)})\}$$

$$a_4=\frac{1}{h_4}(\varepsilon_6 h_3+\varepsilon_7 h_1)(1+\frac{h_4}{2R(i,j)})$$

$$a_5=a_1+a_2+a_3+a_4$$

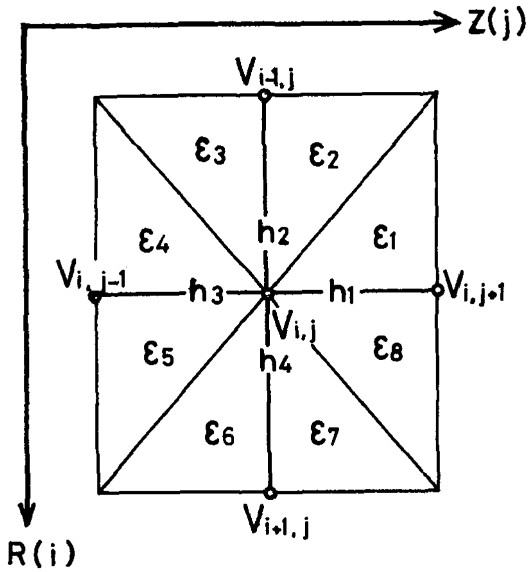


Fig.2 Interface nodal configurations

$R(i,j)$ represents the radial distance from a point (i,j) to the Z axis. ε_1, ε_2, $\cdots$, ε_7 and ε_8 are the relative dielectric constants, and h_1, h_2, h_3, and h_4 are the distance between grid-intersection points on the rectangular region. The boundary conditions are as follows:

(1) The potential V on the $R=R_i$ line in Fig. 3 is given by
$V=V_a$
where V_a is the applied voltage.

(2) The potential V on the $R=R_0$ line in Fig.3 is given by
$V=0$

(3) It can be considered that there is no effect of the spacer near the line $Z=2Z_c$. The potential V on the $Z=Z_0$ line in Fig.3 is given by

$$V=\frac{Va}{\ln(Ro/Ri)}\times \ln(Ro/R(i,j)) \qquad (2)$$

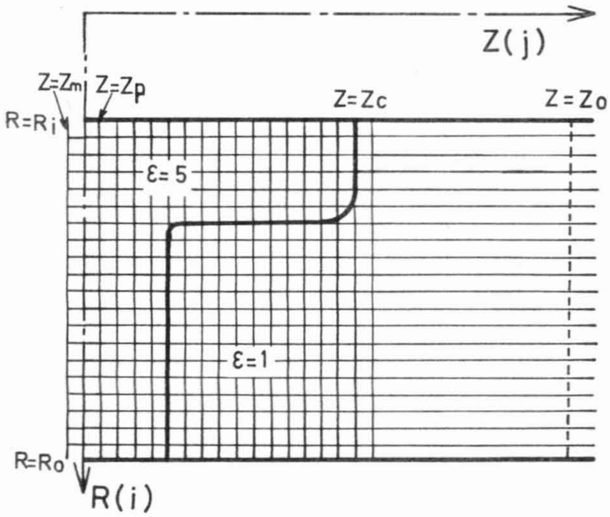


Fig.3 Determination of boundary conditions

(4) The potential V on the $Z=Z_p$ line and the potential V on the $Z=Z_m$ line are symmetric with respect to the R axis.

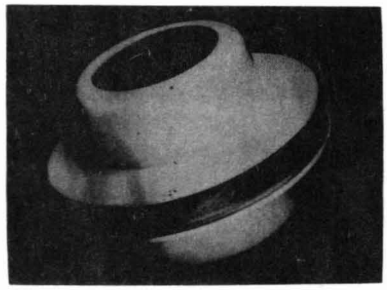
The usual method of solving Eq.(1)by iteration techniques is to set up the iteration procedure.

$$V^{k+1}_{(i,j)}=V^{k}_{(i,j)}+\frac{\omega}{a_5}(a_1V^{k}_{(i,j+1)}+a_2V^{k+1}_{(i-1,j)}+a_3V^{k+1}_{(i,j-1)}+a_4V^{k}_{(i+1,j)}-a_5V^{k}_{(i,j)}) \qquad (3)$$

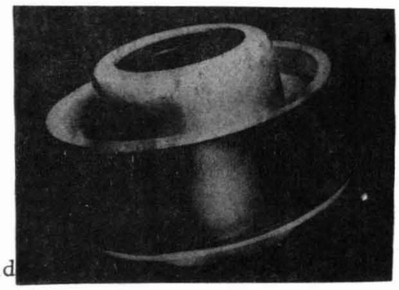
where

ω = accelerating factor

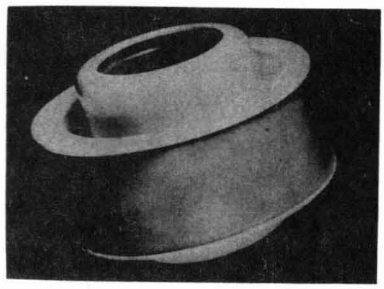
k = order of iteration



SPACER NO.1



SPACER NO.2



SPACER NO.3

Fig.4 Typical profiles of spacers

3. Computer Solutions and Discussion

Making use of the above method, the potential distributions within SF_6 gas insulated cables may be calculated.

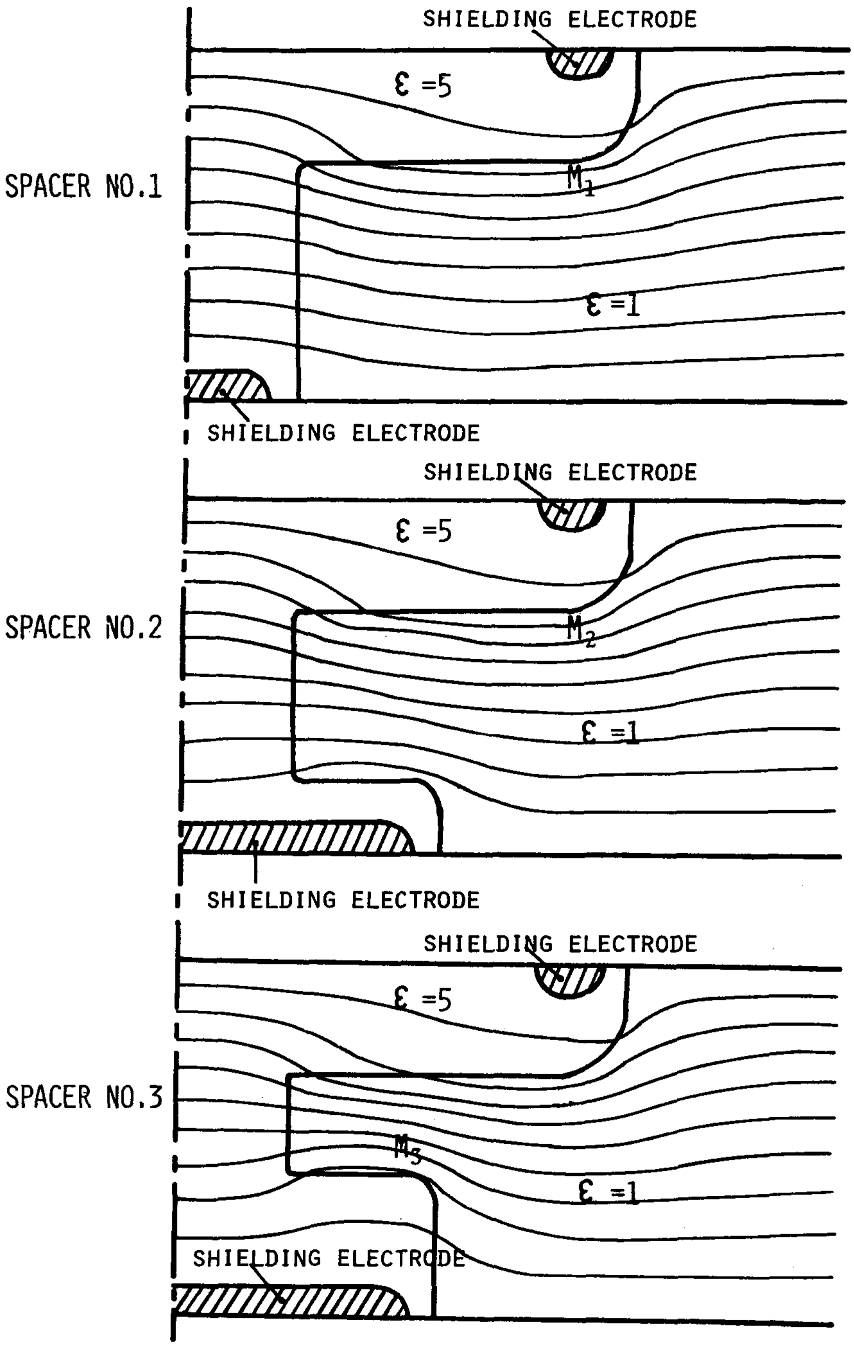


Fig.5 Potential distributions within cables

Now the cable chosen as a numerical example consists of a single conductor of radius=20mm, a cylindrical metal sheath of radius=45mm, the epoxy spacers of relative dielectric constant=5, and the surrounding SF_6 gas of relative dielectric constant=1. The typical profiles of the spacers are shown in Fig.4. By using the above method, the potential distributions within the cable are obtained as shown in Fig.5.

The value of the maximum electric stress can be obtained from the potential distributions, and also the effects upon the maximum electric stress of varying the shape of the spacer can be made clear. Table 1 shows the values of the maximum electric stress obtained by the calculation. Where β is normalized stress in case the applied voltage is 100. From these results, it is predicted that the breakdown voltage of spacer No.1 will be highest and that of spacer No.3 lowest. Table 2 shows the test results. In the tests, 60-Hz AC voltage was applied between two electrodes. Fig.6 gives the relationship between maximum electric stress (Table 1) and breakdown voltage (Table 2). In this figure, it is recognized that the breakdown voltage depends linearly on the calculated values.Moreover, the traces of flashover in the tests are shown in Fig.7. With the No. 1 spacer, the flashover occurs directly through the gas. However, with the No.3 spacer, the flashover occurs along the surface of the spacer. These results correspond to the predicted results from Fig.5. Therefore this method may be very useful for designing an optimum spacer.

Table 1 Numerical results of model spacers

Spacer Number	Maximum Electric Stress(β)
No.1	8.5
No.2	8.65
No.3	9.67

Table 2 Test results of model spacers

Spacer Number \ Test Number	Test Results (kVeff) 1	2	3	4	5
No.1	160	150	175	165	—
No.2	160	170	160	150	—
No.3	100	130	100	130	120

SF6 Gas Pressure : 1.5 kg/cm^2 Gauge

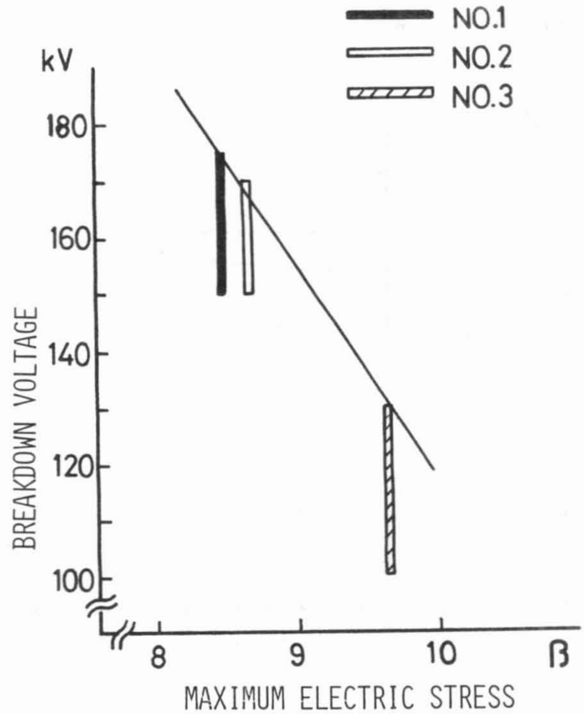
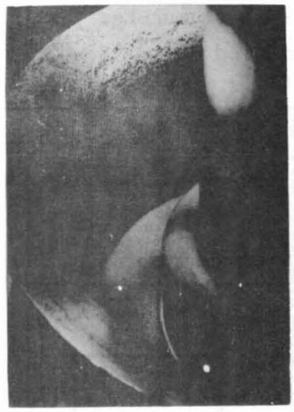
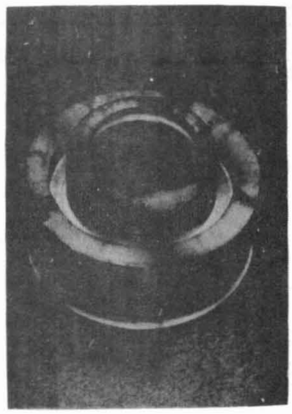


Fig.6 Relations between maximum electric stress and breakdown voltage



SPACER NO.1



SPACER NO.3

Fig.7 Traces of flashover

Fig.8 to Fig.15 shows an example of spacer design. In this design, parameters selected are as follows:

case 1

R_3/R_2, R_4/R_3, Z_2/Z_1 in Fig.8

case 2

Z_3/Z_1, R_5/R_1, R_6/R_5 in Fig.12

In each case, the results obtained are shown in Fig.9 to Fig.11 and Fig.13 to Fig.15. In Fig.9, when R_3/R_2=5/17,8/17, the maximum electric stress occurs near the point B, and when R_3/R_2=9/17, the maximum electric stress shifts to the point A. When R_3/R_2=10/17, the maximum electric stress changes to the point C, and in this case, the value of stress becomes highest. From all the results obtained (Fig.9 to Fig. 11 and Fig.13 to Fig.15), the spacer shown in Fig.12 is most preferable with respect to its shape. As for R_5 in Fig.12, the smaller the value is, the better the dielectric characteristic is, and in this case, the value of Z_3 should be about 5 times that of Z_1.

Moreover, it was made clear that in case the shielding electrode on sheath is smaller the maximum electric stress near the spacer is also decreased.

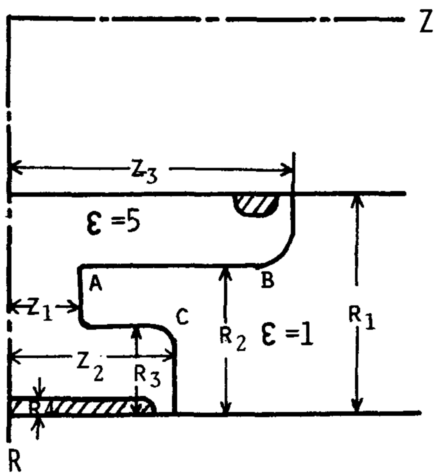


Fig.8 Example of spacer design

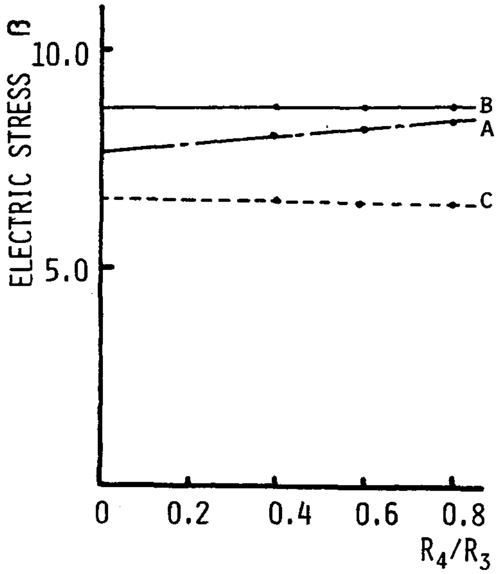


Fig.10 Calculated results

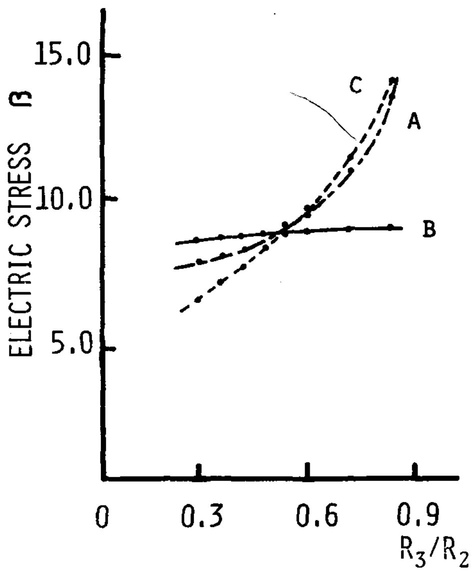


Fig.9 Calculated results

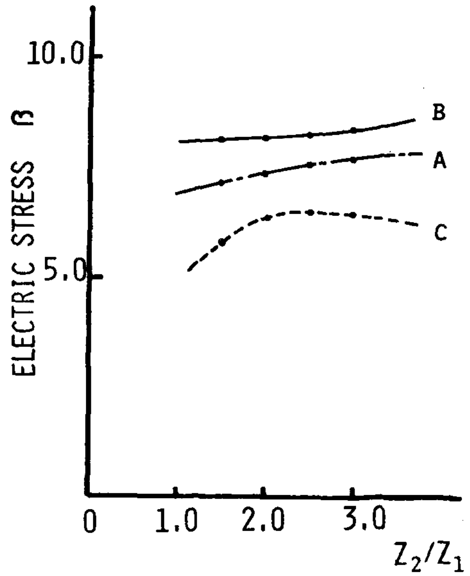


Fig.11 Calculated results

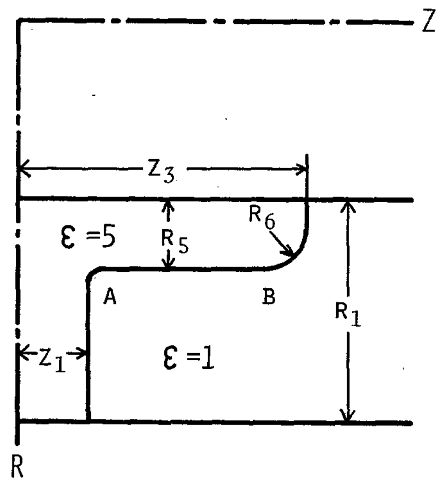


Fig.12 Example of spacer design

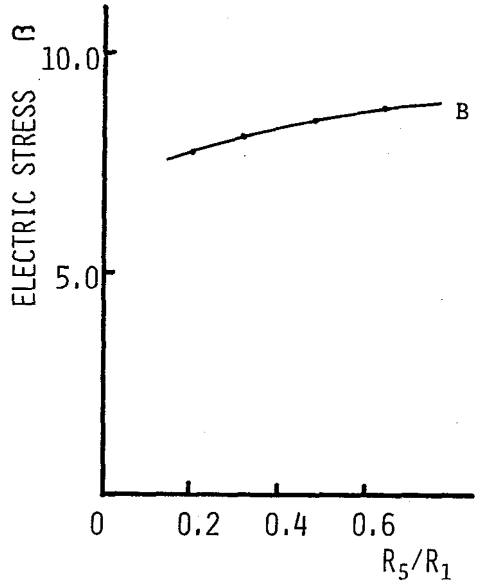


Fig.14 Calculated results

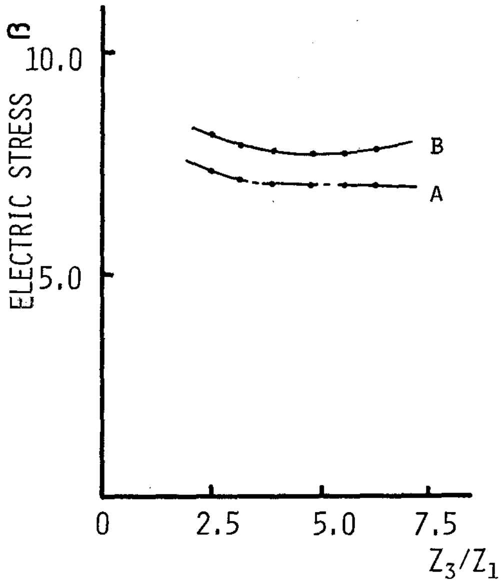


Fig.13 Calculated results

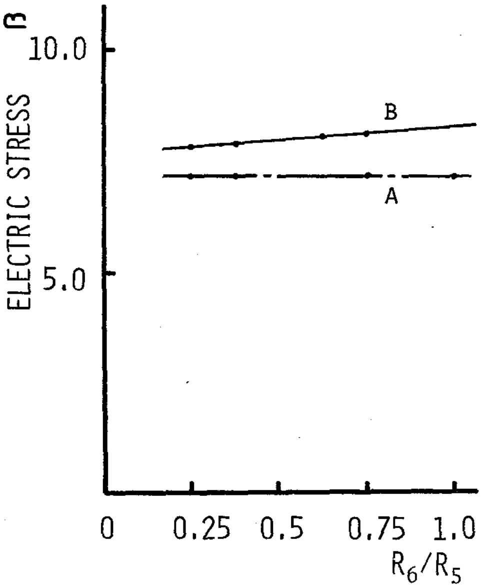


Fig.15 Calculated results

4. Conclusions

In this paper, the potential distribution and the maximum electric stress within SF_6 gas insulated cables having various shaped spacers were obtained by using a numerical method. The conclusions can be summarized as follows:

1. It is recognized that the breakdown voltage depends linearly on the calculated values.
2. If electric stresses for the various parameters are obtained by a numerical method, optimum spacer design may become possible.
3. For the application to the EHV cables, it will be necessary to continue experiments to get full scale data.

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