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A KEY FOR THE CHOICE OF INSULATORS FOR DC TRANSMISSION LINES

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ABSTRACT

The first significant applications of the HVDC transmission line technology date back to the early fifties.

Since then, HVDC lines have become more and more attractive as compared to AC lines for the following reasons :

- lower construction costs (for a given energy transit)
- interconnection of separate networks operating at different frequencies (e.g. 50 Hz/60Hz)
- splitting of networks into independent systems for stability purposes.

Insulators have to withstand special stresses when installed on a DC line (electrical, pollutionwise, etc.).

The user and the line designer must take these special stresses into account when selecting the most appropriate and reliable insulators.

After evaluating the classical basic stresses applied to the insulators such as the thermal-mechanical stresses, overvoltage stresses, etc..., it is important to analyse the specific "DC stresses" due mainly to the fact that the flow of electric current in the insulator body is permanent and unidirectional and that the electric field distribution along the insulator string is not uniform.

Thermal runaway, ionic migration and accumulation can be possible modes of failure for insulators, specially in hot conditions.

Electrolytic corrosion can also lead to failures.

Due to the unidirectional electrical field on HDVC lines, the contamination accumulation is heavier than on AC lines in the same site. Depending on the conditions, the pollution parameter can be decisive in the cost of DC lines as the height of the towers depends on the length of the insulator strings.

However, some stresses are not so stringent on DC lines compared to AC lines, for example, in the case of radio interference.

This paper reviews and analyses the parameters which constitute a basis of thinking when choosing the most reliable insulators for DC transmission lines taking into account test performance and field experience.

1. INTRODUCTION

The first commercial High Voltage Direct Current (H.V.D.C.) transmission system was put into service in 1954 with a capacity rating of 30 MW. Since then, a total of thirty-five H.V.D.C. installations have been constructed throughout the world, with a total capacity of approximately 20 000 MW. The rapid growth of H.V.D.C. illustrates that it has gained worldwide acceptance as a reliable complement to the electric system.

When evaluating between a H.V.D.C. and a H.V.A.C. overhead transmission system, the D.C. line is sometimes the choice due to its lower cost and lesser environmental impact as compared to an A.C. line. In order to further reduce the cost, as well as minimize the maintenance requirements and outages on the line, it is essential to optimize the design of D.C. insulators. In this report , taking account of recent investigations, the improvements made on insulators to increase their thermal-mechanical and electrical reliability are developped. The various specific H.V.D.C. stresses applied on insulators are analysed and test recommendation are suggested to evaluate the behavior of insulators under D.C. stresses.

2. SPECIFIC H.V.D.C. STRESSES

H.V.D.C. insulators have to support particular electric stresses, due mainly to unidirectional flow of electric current in the insulator body and a non-homogeneous electric field distribution along the insulator string.

But the first parameter taken in consideration to choose insulators for a D.C. transmission line is the mechanical reliability. No risk of line drops shall be caused by a power arc initiated by lightning or pollution, or any other insulation damaging phenomenon.

Specific H.V.D.C. stresses are :

- The H.V.D.C. insulators are more contaminated than H.V.A.C. insulators for the same site.
- Unidirectional flow of the electric current can bring out various effects in the insulating material, in particular ionic accumulation.
- Non homogeneous electric field distribution along insulator string which amplifies the above stresses on the insulators at the line end.

The specific H.V.D.C. stresses will be defined to be taken into consideration for the choice of H.V.D.C. insulators.

3. PARAMETERS TO BE TAKEN INTO CONSIDERATION FOR THE CHOICE OF H.V.D.C. INSULATORS

3.1 General parameters

Basically, H.D.V.C. insulators must comply with the main standards used for High Voltage suspension insulators, such as IEC 383, BS 137, ANSI C29-1 and C29-2...

The insulators must undergo successfully different tests and inspections which check their ability to withstand electrical, mechanical and thermal stresses.

Most of these tests can apply as well on H.V.A.C. and H.V.D.C. insulators, as they check mechanical reliability and insulator string performance under impulses. Some tests are less important for H.V.D.C. insulators : for example, the Radio Influence Voltage level of an insulator string is much lower under D.C. stresses (either positive or negative polarities) than under A.C. stresses, as represented on fig. 1.

In addition to these standard tests, extra tests can be very useful to evaluate the behaviour of suspension insulators.

a) Thermal-mechanical tests check the compatibility of the different components of an insulator, dielectric, metal parts and cement under combined thermal and mechanical stresses.

Supplementary mechanical stresses in the dielectric material can result from differing thermal expansion coefficients of the component parts of certain insulators (see the thermal-mechanical endurance test described in IEC 575).

b) Overvoltage tests : when overvoltage stresses are induced by lightning strokes we can observe two possible events :

- An external flashover between the two external metallic parts of the insulator.
- A puncture (internal path). The insulation is destroyed and the energy of the power arc leads to the explosion of cap and pin insulators and the line drops.

The duration of application of a constantly increasing voltage (in kV/µs) necessary to reach sparkover depends upon the voltage rise-time. If the steepness of the impulse increases up to some thousands of kV/µs, the dielectric strength of the ceramic material can be exceeded (fig 2) : uppermost quality ceramics (toughened glass) can withstand up to 4,000 kV/µs, medium quality ceramics are punctured at about 2,500 kV/µs and ordinary ceramics at 1,000 kV/µs. This test of steep front impulse allows the selection of high quality materials.

c) Residual mechanical strength tests : any type of insulator can be damaged in service by external phenomena such as lightning, power arcs, ... or for more complex reasons associated with the ageing of certain brittle materials.

For toughened glass insulators, if any type of incident should become critical, the disc would automatically crumble away, leaving an insulator "stub" nearly as mechanically strong as the original insulator.At-a-glance inspection is sufficient to make sure that the electrical function of the insulator is fulfilled. From the mechanical point of view, as the toughened glass expands inside the insulator head when it breaks, new compressive forces are created because the fracturing pattern of toughened glass is invariably the same. Dispersion in the residual mechanical strength of broken insulators is very small. Usually, the average residual strength is close to the rated M&E strength (see ANSI C 29/2 or IEC 797 standards).

In the case of porcelain, numerous studies on subcritical crack growth have been published and the effect of stress, environment, cement growth and stress corrosion have been investigated [ref 1&2]. The direction of crack propagation is often random, but sometimes,some helicoidal cracks are capable of growing in the head of stressed insulators, inside the cap, with the shed completely unaffected. Fracture patterns are often unforseeable. Cracks remain hidden, only to become apparent when it is already too late and lead to a line drop [ref 3, about incident in Canada, for example] .

d) Electrical behaviour of broken insulators :

With toughened glass insulators, the electrical behaviour of a broken insulator ("stub") in a string is reliable. As the arcing distance in the air is very short, when an arc occurs, it sparks over externally (fig 3a).

In the case of porcelain, a microfracture of short length can exist inside the cap with no change in external appearance. In such a case the shortest path for the arc is through the microfracture inside the cap and it yields a molten channel in the porcelain (fig 3b). In the worst case, it can lead to an explosion of the cap. To be sure of their reliability in service, porcelain insulators have to be individually tested, more often necessitating the line to be de-energized. As this problem is really important, utilities or manufacturers of electrical material have had to develop highly sophisticated apparatus to perform live-line checking of porcelain insulators [ref 4 and 5].

With toughened glass insulators, safety in live-line work is excellent because it is easy to check the integrity of a string just by counting the amount of broken and entire insulators.

3.2 Specific parameters connected with environmental conditions of H.D.V.C. lines

Experience has shown that H.D.V.C. insulators are more contaminated than H.V.A.C. insulators under natural and/or industrial pollution in the same site.

In the case of H.V.A.C., it is often possible to measure the pollution severity on other existing lines in operation in the same general area. Unfortunatly, such information is much less useful for the design of a H.V.D.C. line as the contamination deposit is strongly affected by the D.C. electric field.

In our present state of knowledge, the most reliable way to choose the insulator string length is from results from a test station located on the future path of the line, in representative conditions. When such a test station is not avaible, the string length must be evaluated, based on :

- The estimated pollution level of the contamination on the line,

- The performance of the insulators in a laboratory test under uniform contamination [ref 6].

Among the various tests, the clean fog test is presentely used more widely than the others (see an example of test results on fig 4 where the 50% probability of flashover is given as a function of E.S.D.D., Equivalent Salt Density Deposit), [ref 7] . On overhead H.V.D.C. lines, the contamination is never uniform. The bottom surface of the insulators is more contaminated than the top surface. The ratio of the E.S.D.D. top / E.S.D.D. bottom is usually 1/2 to 1/3 and can be as low as 1/10, (see the curve 2 of fig 4). For real cases, we recommand to use the values of curve 1 (uniform contamination) to calculate the number of insulators of the string : this will give a safety margin.

For the same rating and the same leakage distance, toughened glass insulators have better pollution behaviour than porcelain insulators. The performance of toughened glass insulators is 15 to 20% higher than porcelain insulators. This difference comes mainly from the design of toughened glass insulators which have particular low rib thickness and low under rib tip radius. A recent study has demonstrated the importance of such a profile for H.V.D.C. insulator performance [ref 8]. Some H.V.D.C. specifications for polluted area require more porcelain insulators than toughened glass insulators for the same operating voltage in the same area.

Under polluted conditions, corrosion of the metallic parts can be a real problem because of the diminution of the mechanical strength arising from the reduction of the pin diameter. There is also a danger that corrosion products can induce cracks in porcelain material [ref 9]. The protection against electrolytic corrosion is made by attaching a sacrifial electrode (zinc sleeve) onto the metallic parts.

3.3 Specific parameters connected with ceramic insulating materials used in cap and pin insulators stressed by D.C.

Usual oxide glasses and electrical porcelains, which always contain a glassy phase occupying 50 to 70% of the volume, exhibit the same type of ionic conductivity. Under D.C. voltage, alkali ions can migrate through channels of the silica network forming the frame of the ceramic material. The ionic conductivity mainly depends on temperature, but is also function of :

- the amount of alkali ions,
- the nature of these alkalis (mainly sodium and potassium ions).

Different possible failure modes for H.V.D.C. insulator have been proposed by previous research work [ref 10] ; among these failure mechanisms, two seem of particular interest : thermal run-away and ionic migration.

a) Thermal run-away :

The resistivity of an insulating material decreases as the temperature increases. This material can, under certain conditions, undergo thermal run-away :

The first condition is that the electrical power dissipated inside the dielectric material by Joule effect has to be greater than the thermal power that the dielectric material can exchange with its environment.

The second condition is that the object must be submitted to a constant voltage so that the electrical power can increase as the temperature rises.

An increase in the resistivity of the material will reduce the electrical power dissipated in the dielectric.

The thermal run-away phenomenon is well known. The way it can develop in a string of insulators, with a number of units in series is less well known. The voltage accross an insulator is the product of the current and the ohmic resistance. If ~~this~~ insulator begins to run away, the internal temperature rises, leading to a reduction of its resistance. The current is limited by the ohmic resistance of the other units of the string and is almost constant. Thus the voltage accross the insulator decreases, which implies a reduction of the electrical power in the dielectric. A thermal equilibrium is therefore attained without puncture of the dielectric.

In laboratory tests, it is possible to obtain puncture of a single insulator unit by thermal run-away [ref 11] : it is sufficient to place the insulator in an oven and to apply a constant voltage from a sufficiently powerful supply. The initial temperature of the insulator, i.e. that of the oven, along with the applied voltage determine the electrical power which will be dissipated inside the dielectric. This power depends also on the resisitivity of the material being tested.

When the insulator can no longer dissipate the heat produced by the electrical energy, there is a rapid increase of the temperature of the dielectric in a narrow zone where the current density becomes higher and higher to reach a value such that the melting of the dielectric occurs in this zone. At this moment, the insulator no longer fulfills its insulating function ; it has been punctured by thermal run-away.

In spite of the fact that the phenomenon described above does not arise in service on power lines, this test is very useful for the characterisation of insulating materials whose resistivity varies inversely with temperature.

In service, conditions may arise such that thermal run-away begins in a string insulator unit. In this case, ionic conduction occurs inside the dielectric which ages the material (ionic accumulation).

b) Ionic migration

The passage of a unidirectional current through an insulating material submitted to a high D.C. voltage can bring about various effects in the material :

- Formation of a depletion layer [ref 12] where all the Na^+ cations have moved out under the effect of the electrical field. Previous studies [ref 10] have shown that this phenomenon cannot explain failures of H.V.D.C. insulators.

- Accumulation of ions at heterogeneities where they regain their electron and increase their volume, thus creating a mechanical stress [ref 13]. This mechanism is still under study in the laboratory.
- The presence of an heterogeneity may also help to start locally the phenomenon, leading possibly to the beginning of thermal run-away. Ionic conduction can thus begin in a very narrow zone of the dielectric ; this conduction ages the dielectric quickly in comparison with the case where the current is uniformly distributed and also leads to the development of high thermal stresses.

In laboratory, it is possible to verify the capability of the insulator to withstand ionic accumulation. Insulators will be subjected to a test at a combination of constant temperature and voltage such that the estimated charge passing through the insulating body for a desired life time, passed in a reasonable time.

This charge is calculated from the information about insulator temperature, insulator resistance and its variation with time and amount of voltage which are likely to occur. This charge in Coulombs is calculated from the following equation :

$$Q = U \int_0^{\tau} \frac{1}{R(t)} \cdot d\tau$$

U : the average value of the line to ground voltage (Volts)

R(t) : the resistance of the insulating body as a function of temperature (ohms)

τ : time (seconds)

Ionic accumulation tests performed in laboratory on porcelain insulators showed that a large number (66%) of the insulators were punctured at positive polarity (fig. 5) [ref. 10]. Under the same conditions, no puncture occurs in toughened glass insulators.

4. CONCLUSIONS

The insulator is a key element of a H.V.D.C. line. Its reliability and dimensioning must be taken into account by the designer.

Tests to evaluate the long term performance of insulators must be introduced into specifications, like the thermal-mechanical test and the impulse overvoltage test.

To reduce the effects of specific phenomena which appear under D.C. stresses, it is interesting to increase the resistivity of the material ; in addition, the increase in the resistivity reduces the harmfulness of the last very few heterogeneities that may still remain in the dielectric in spite of the drastic reduction of these defects due to the improvement of dielectric production technology.

NOTE : India will soon have access to the most sophisticated technology for the manufacture of toughened glass insulators. Manufacturing facilities are being set-up at FATEHPUR, a "no-industry" district of UTTAR PRADESH by India Insulators Private Ltd, a Compagny in which CERAVER has 40% equity participation.

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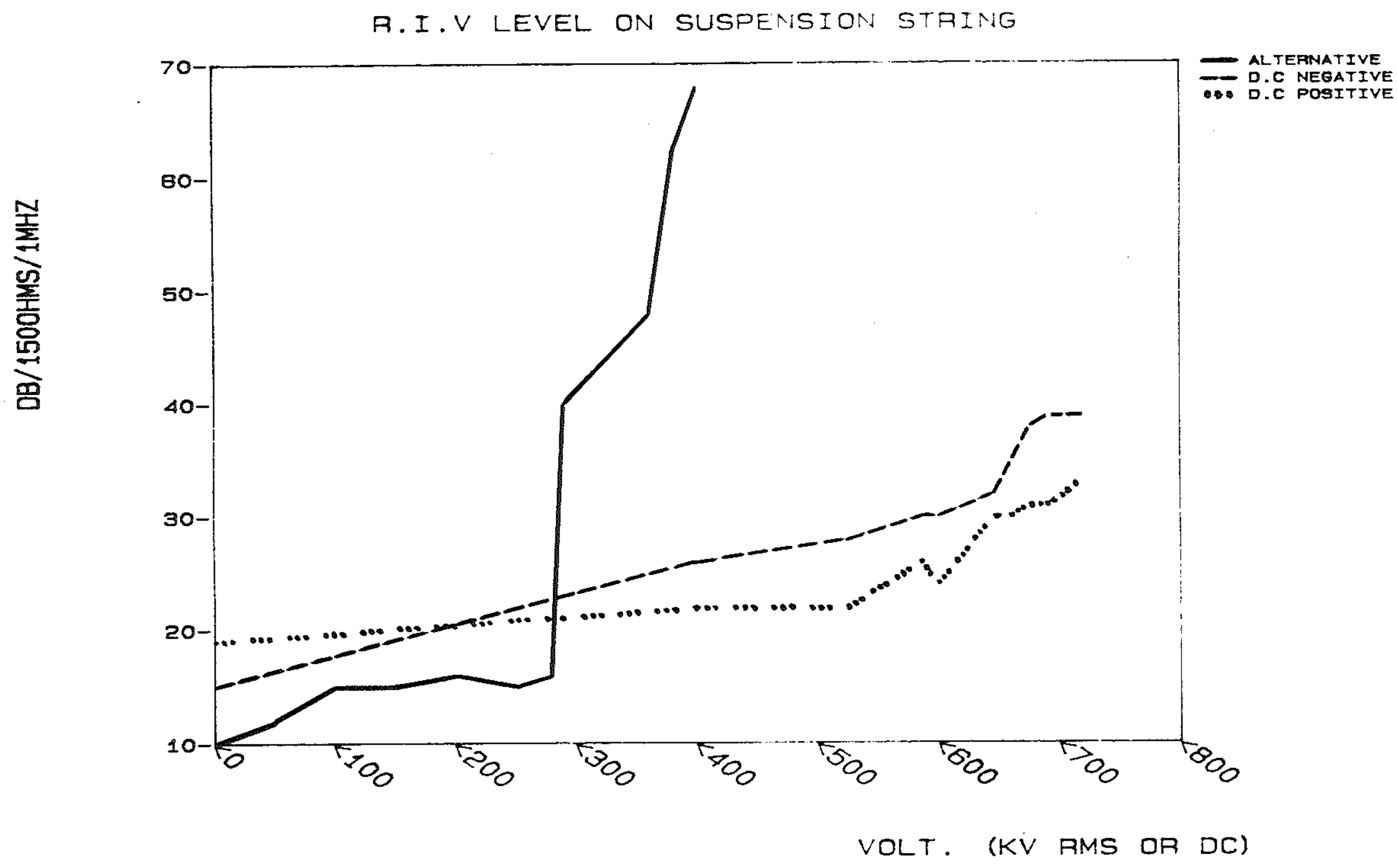

R.I.V LEVEL ON SUSPENSION STRING
DB/150OHMS/1MHZ
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
VOLT. (KV RMS OR DC)
ALTERNATIVE
D.C NEGATIVE
D.C POSITIVE

Figure 1

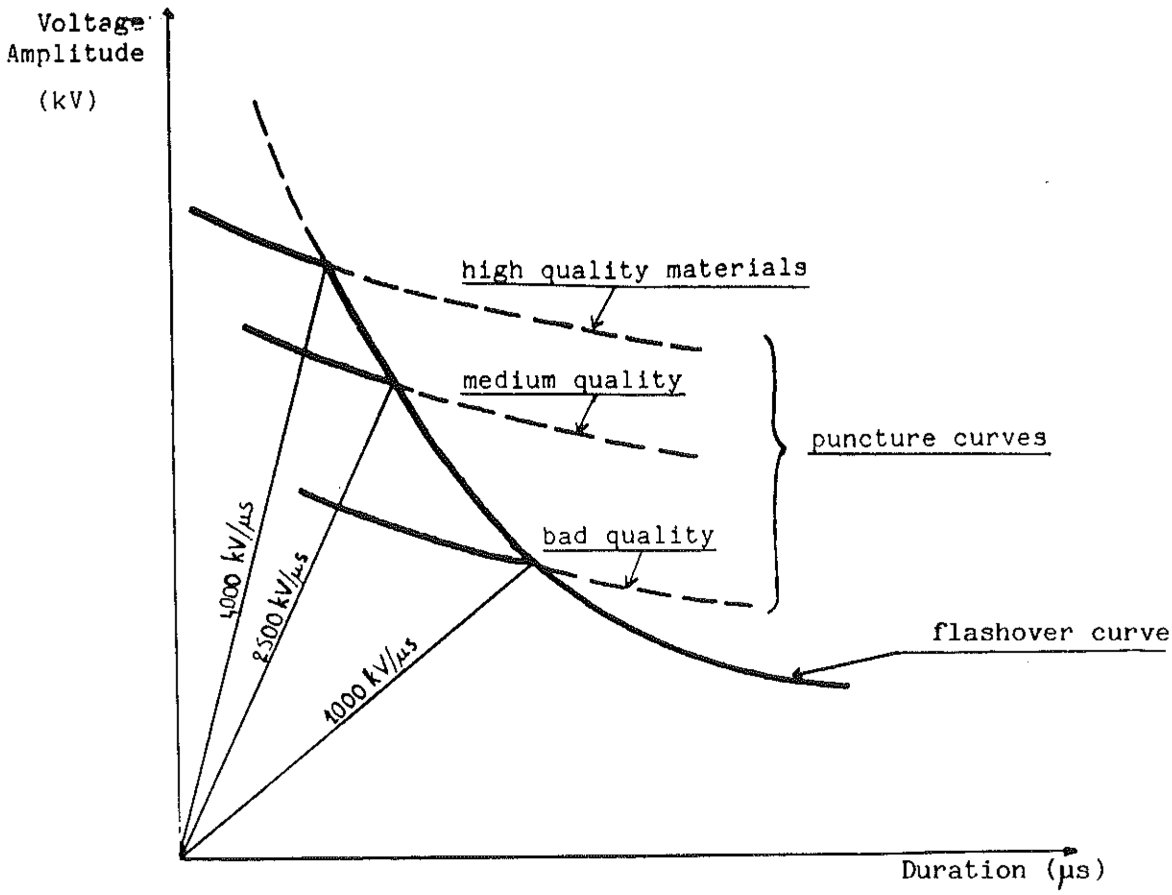
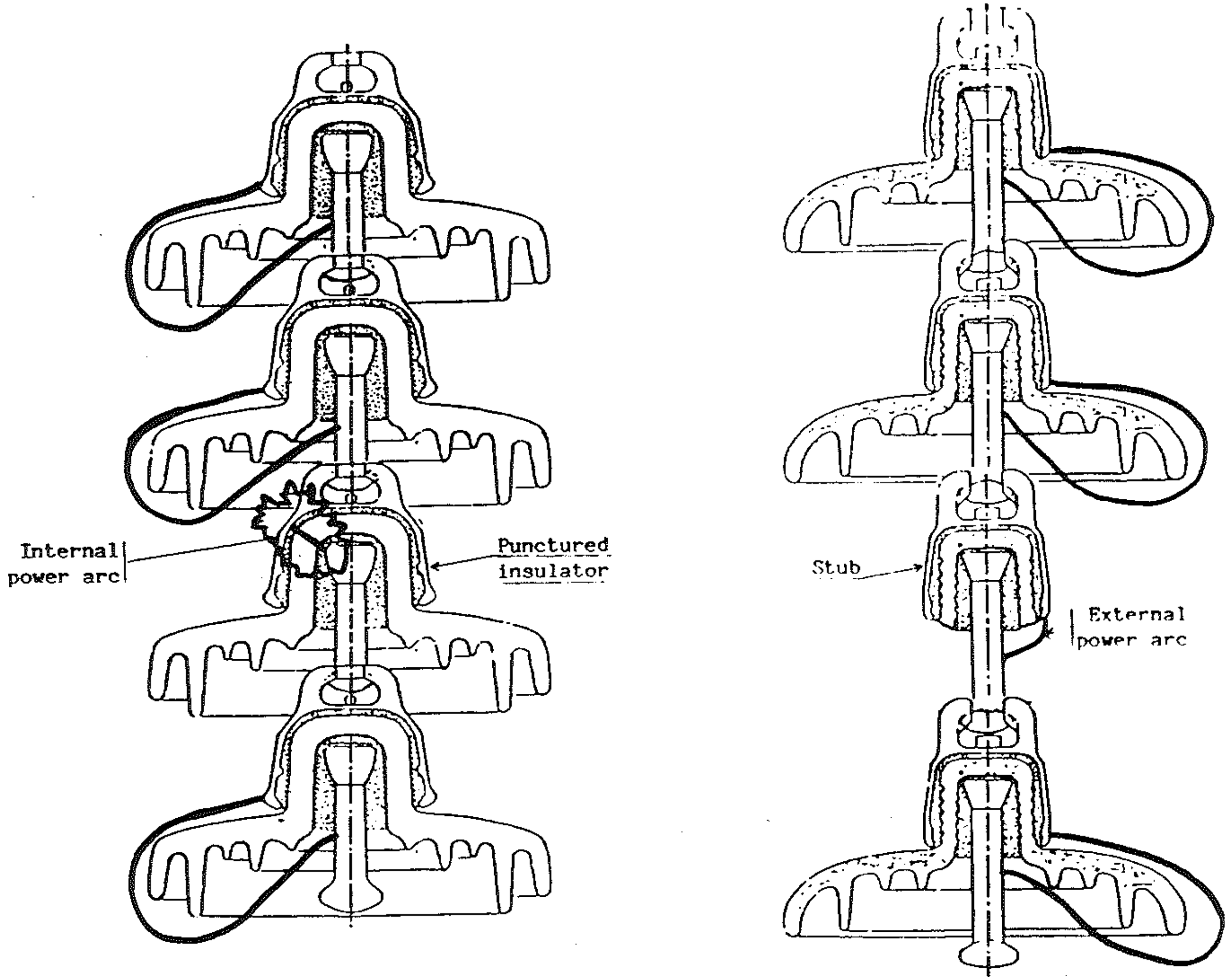


Figure 2 : Steep front impulse tests on cap and pin suspension insulators.

Note : For the same external shape, the flashover performance of cap and pin insulators made of different ceramic materials are almost identical.



PORCELAIN

TOUGHENBD GLASS

Figure 3

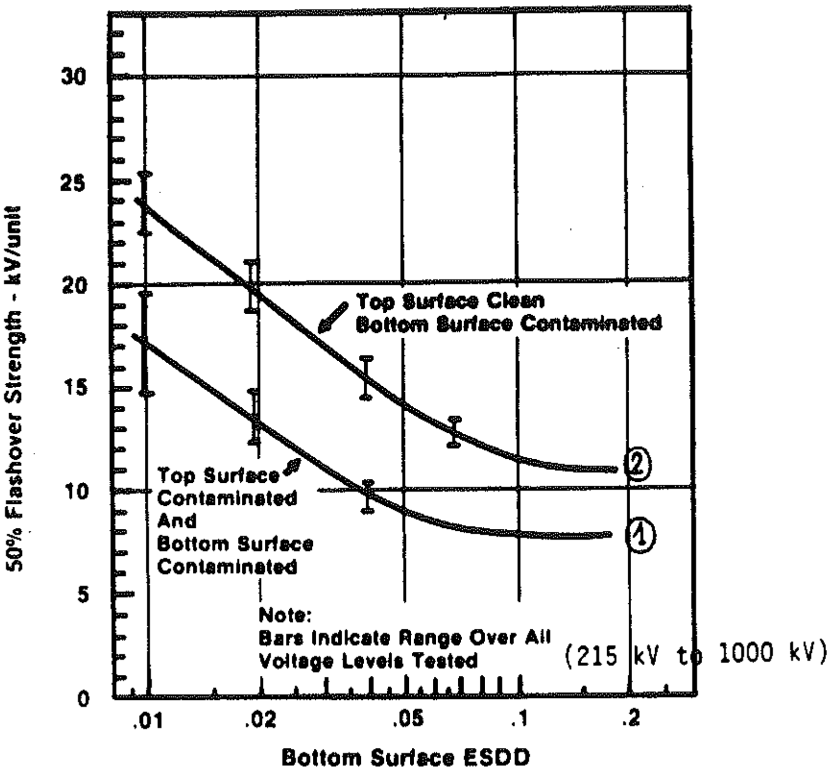


Figure 4 : 50% Flashover strength of a polluted cap and pin insulator :

① Uniformly contaminated

② With top surface clean and bottom surface contaminated

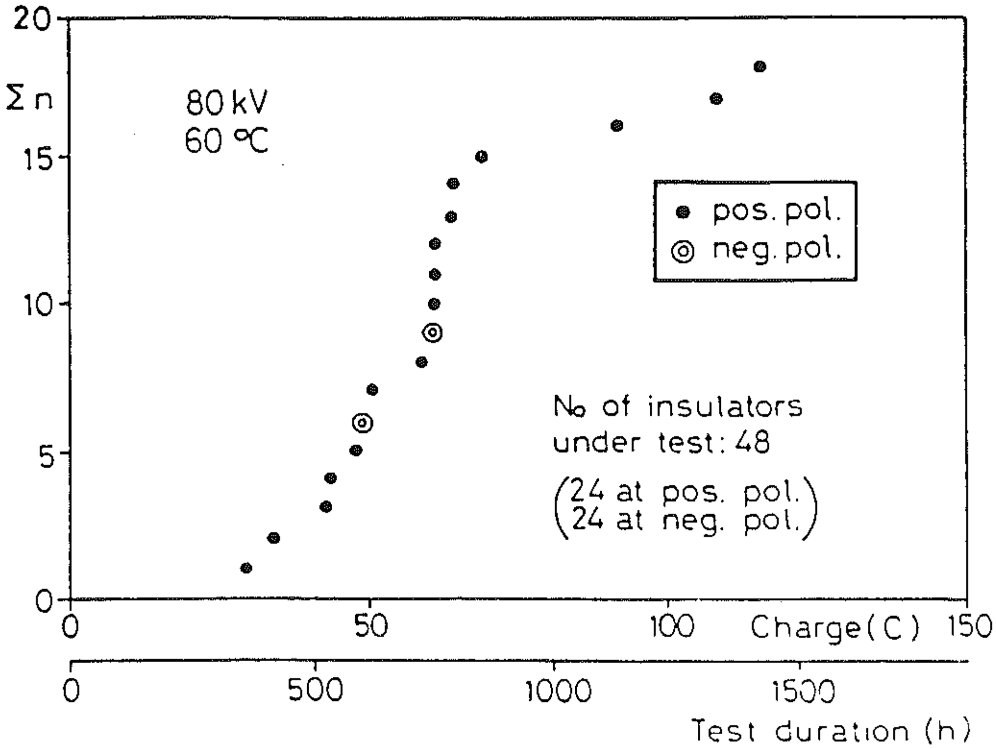


Figure 5 : Results of ion accumulation laboratory tests on porcelain insulators : number of failed units as function of the charge passed through the insulator (calculated according to test duration).

Under the same conditions no failure occurs in toughened glass insulators.