IMPULSE DIELECTRIC STRENGTH OF NONINFLAMMABLE TRANSFORMER FILLED WITH SYNTHETIC OIL

By

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I. INTRODUCTION

The advantage of noninflammable-oil transformer has long been accepted as follows:

1) It is noninflammable and nonexplosive, therefore it is suitable for the substation in centre of a city, underground room of building, ship and mine etc.
2) The noninflammable-oil is chemically stable. It is not deteriorated by oxidation as seen in mineral-oil. Therefore it can keep the initial high dielectric strength for many years.
3) Because of improvement of the potential distribution by the high dielectric constant of noninflammable-oil, the reliability against dielectric strength is large.

On the contrary, T. W. Dakin[1] reported recently that the impulse ratio has a value of 1.38 for the noninflammable-oil and of 1.2 for the impregnated pressboard, therefore the third advantage of noninflammable-oil transformer seems to be lacking.

In order to resolve this question, we investigated anew about both the properties of materials and insulation design. The summary of the results is as follows:

1) The dielectric strength of noninflammable-oil is slightly higher than that of mineral-oil both at a-c and impulse voltage and its impulse ratio does not differ from mineral-oil.
2) In the case of thin sample, the dielectric strength of noninflammable-oil impregnated paper is higher than the mineral-oil impregnated and its impulse ratio does not differ from the mineral-oil impregnated.
3) In the case of thick sample, the impulse dielectric strength of noninflammable-oil impregnated pressboard is lower than the mineral-oil impregnated and its impulse ratio is only slightly higher than unity, about 1.2.
4) For the insulating construction of transformer, however, because of the advantage that the potential distribution of the noninflammable-oil transformer is equalized as compared to the mineral-oil transformer and the dielectric strength of noninflammable-oil is higher than mineral-oil, the safety factor against dielectric test of the noninflammable-oil transformer is larger.[2]

II. DIELECTRIC STRENGTH OF NONINFLAMMABLE-OIL

There are few reports about the breakdown of noninflammable-oil, among them the reports by F. M. Clark[3,4] are most famous. In his reports, he showed that a-c breakdown voltage of noninflammable-oil is higher than that of mineral-oil. But he did not test at impulse voltage. In this section shall be shown the results of breakdown test about mineral- and noninflammable-oil, not only with alternating voltage, but also impulse voltage.

Table 1. Sample oil

Classification	Name
Mineral oil	High voltage insulating oil # 2*
Noninflammable oil	Fuji Synclor**

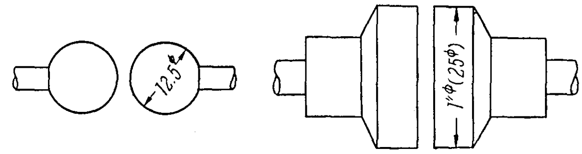
* JIS C 2320.

** Correspond to Pyranol 1470, Aroclor 1232, Clophen T-64. 60% pentachlorodiphenyl 40% trichlorbenzene.

1. Test procedure

As the breakdown voltage of oil is seriously affected even by small degree of impurity, breakdown test must be conducted at exactly identical condition. The sample oil, showed in Table 1, were filtered at vacuum through ♯3 filter-glass and conducted to closed glass vessel for test. In consequence the sample oil were kept at clear condition during the test. Two kinds of electrode were used, one was JIS (Japanese Industrial Standard) electrode (Fig. 1 (A)), the other was ASTM electrode (Fig. 1 (B)).

Impulse (1×40 microsecond wave) and a-c 1 minute breakdown voltage were measured by interpolating method. In the case of a-c short-time breakdown voltage measurement, applied voltage were increased at the rate of 3 kV per second.



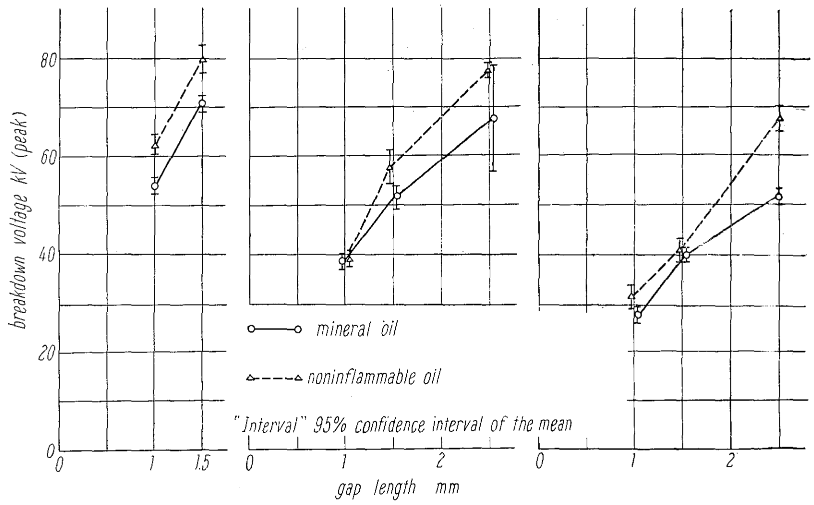
(A) JIS electrode (B) ASTM electrode

Fig. 1. Electrode

2. Experimental results

In Fig. 2, one example of experimental results is shown. According to them, we find that the dielectric strength of non-inflammable oil is somewhat higher than that of mineral oil, not only at alternating voltage, but also impulse voltage and that there is no difference in impulse ratio between noninflammable- and mineral-oil (see Table 2).

On the contrary, according to T. W. Dakin, it has been shown that the impulse ratio of non-inflammable-oil is smaller than that of mineral-oil (see Table 3). The reason why our experimental results do not coincide with Dakin, in spite of same kind of the sample and the test method, cannot be explained, for we can not exactly know his test method. As the breakdown voltage of the noninflammable-oil in same one cup decreases with number of tests, we changed the specimen every puncture. From this test manner, we can never find the phenomena like that he said.



(A) Impulse (B) A-c short time (C) A-c 1 minute

Fig. 2. Breakdown voltage of insulation oils (ASTM electrode)

Table 2. Impulse ratio of oils

Electrode	Gap length (mm)	Oil	Impulse ratio	
			Average	95% confidence interval
JIS 12.5 ϕ	1.0	Mineral	2.65	2.40~2.89
		Noninflammable	2.17	1.90~2.39
ASTM 1″ ϕ	1.0	Mineral	1.94	1.80~2.08
		Noninflammable	1.98	1.81~2.14
	1.5	Mineral	1.76	1.71~1.81
		Noninflammable	1.96	1.83~2.13

Table 3. Impulse ratio of oil
(by T. W. Dakin)

Mineral oil	2.00
Noninflammable oil*	1.38

* Same composition as expressed in Table 1.

III. DIELECTRIC STRENGTH OF NONINFLAMMABLE-OIL IMPREGNATED PAPER

1. Experimental results of breakdown voltage

1) Test procedure

Kraftpaper (thickness 0.15 mm) and pressboard (thickness 0.8 and 1.6 mm, all kraft pulp) were used in our test. All samples were vacuum-dried and vacuum-impregnated with mineral- and noninflammable-oil. Two kinds of symmetrical 50mm diameter electrode were used one having square edge, the other 6 mm radius edge. The test was conducted in ungrounded large tank. The breakdown voltage at impulse (1×40 microsecond wave), 50 cycle 1/10 second and 50 cycle one minute was measured by interpolating method.

2) Experimental results of breakdown voltage

Voltage-time characteristics are shown in Fig. 3 and 4, impulse ratio in Table 4. In the case of kraftpaper (which represents the thin sample) the breakdown voltage of the noninflammable-oil im-

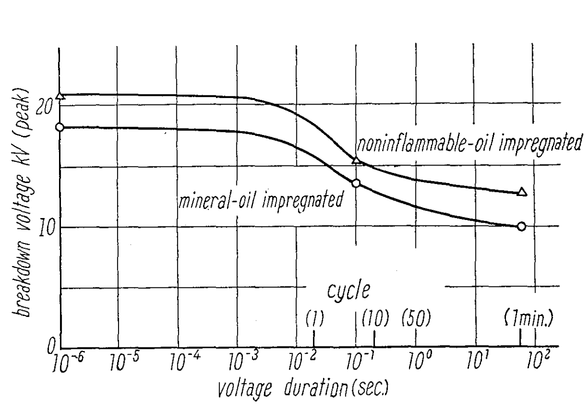


Fig. 3. Voltage-time characteristics of oil-impregnated kraft-paper (0.15 mm) (electrode: 50ϕ 6R and 50$\phi\angle$R)

pregnated is higher than that of the mineral-oil impregnated at impulse voltage as well as at alternating voltage, the impulse ratio of the former is almost equal to the latter. These phenomena are agreeing with the original concept. On the contrary in the case of pressboard (which represents the thick sample) the abnormal phenomenon like that T. W. Dakin has found occurs. The 50 cycle-longtime breakdown voltage of mineral-oil impregnated pressboard is considerably lower than the noninflammable-oil impregnated, but it progressively increases inversely proportional to the voltage duration, and its impulse breakdown voltage becomes higher than the noninflammable-oil impregnated. For that reason the impulse ratio of the noninflammable-oil impregnated is small and only slightly higher than unity.

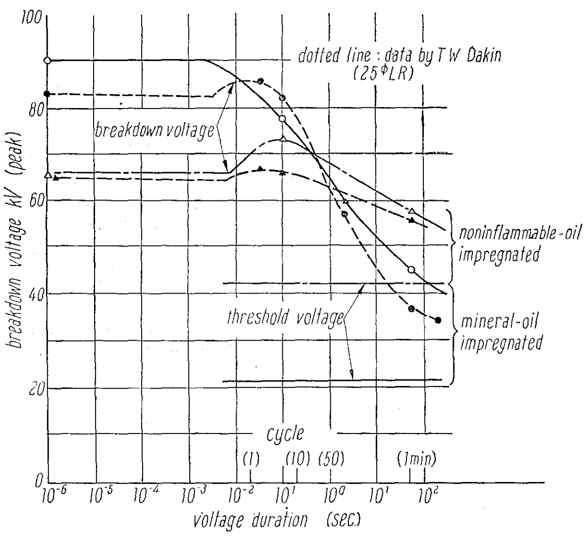


Fig. 4. Voltage-time characteristics of oil-impregnated pressboard (0.8 mm) (electrode: 50φ∠R)

The mechanism of those phenomena will be discussed later. Shortly speaking it is concluded that the mineral-oil impregnated pressboard can resist well to short time voltage and the noninflammable-oil impregenated pressboard to long time voltage. These differences are due to the manner of corona discharge and the resistivity against corona discharge.

2. Relation between corona discharge and breakdown

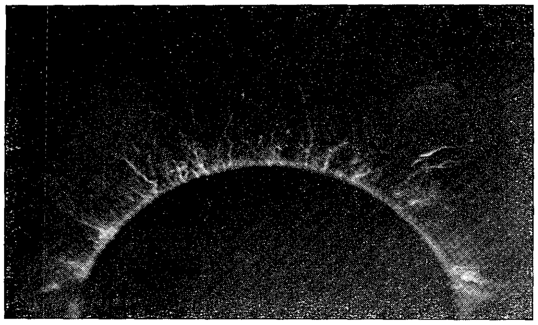
1) Progress of corona discharge

Fig. 5 is the photographic records of corona discharge that appears near the electrode edge when impulse or a-c voltage is applied. Between the mineral- and noninflammable-oil impregnated pressboard, an essential difference can be found in the manner of corona dischage. The corona discharge at the surface of the mineral-oil impregnated pressboard propagates radially and uniformly from electrode edge to considerable distance. On the other hand, at the noninflammable-oil impregnated the corona discharge propagates circumferentially rather than radially and appears intermittently alone at one or two locations. Near over the threshold voltage it breaks down without the progress of corona. These phenomena are summarized in Fig. 6 (A).

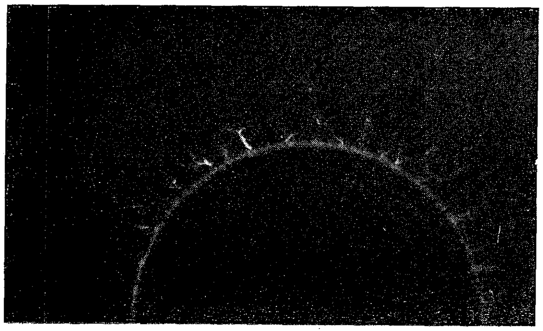
Table 4. Impulse ratio of oil-impregnated papers

Sample	Electrode	Impregnant	Impulse ratio	
			Average	95% confidence interval
Kraftpaper 0.15 mm	50φ6R	Mineral oil Noninflammable oil	1.82 1.65	1.73~1.86 1.58~1.72
	50φ∠R	Mineral oil Noninflammable oil	1.70 1.65	1.60~1.80 1.58~1.76
Pressboard 0.8 mm	50φ6R	Mineral oil Noninflammable oil	1.97 1.18	1.88~2.06 1.12~1.24
	50φ∠R	Mineral oil Noninflammable oil	2.00 1.14	1.90~2.10 1.09~1.19
Pressboard 1.6 mm	50φ∠R	Mineral oil Noninflammable oil	2.06 1.21	1.95~2.16 1.15~1.27

(A) Mineral-oil impregnated pressboard) (3.2 mm)

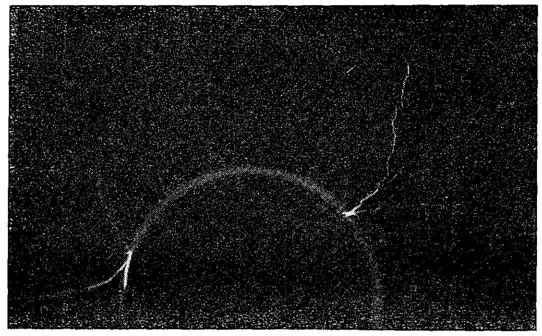


Impulse 170 kV

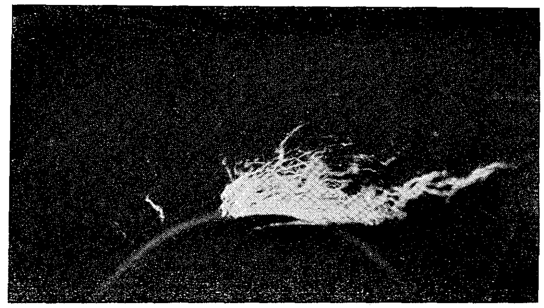


50c/s 100 kV (peak) 3 sec.

(B) Noninflammable-oil impregnated pressboard



Impulse 100 kV (1.6 mm)



50 c/s 100 kV (peak), 20 sec. (3.2 mm)

Fig. 5. Ionization patterns (electrode 50 $\phi \angle$R)

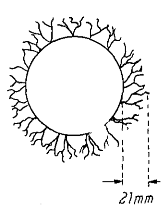
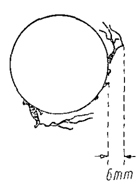
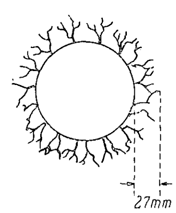
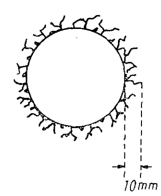
	(A) When immersant is equal to impregnant		(B) When immersant differs from impregnant	
	A-1 Mineral-oil impregnant and immersant	A-2 Noninflammable-oil impregnant and immersant	B-1 Mineral-oil impregnant, noninflammable-oil immersant	B-2 Noninflammable-oil impregnant, mineral-oil immersant
Corona figure		 Black points are mark of carbonizing of noninflammable-oil		 Black points are mark of carbonizing of noninflammable-oil
Progress of corona streamer	Propagate radially with many blanches, continuous	Appear at one or two locations, not radially but circumferentially, intermittent	Propagate radially to longest distance, glow white, continuous	Radially but not long, intermittent
Trace	White trace (may be by gasifing of oil) disappears gradually, and very few black trace	White trace and black trace (may be by carbonizing of noninflammable-oil)	White trace and very few black trace	White trace and black trace

Fig. 6. Corona figures of mineral- and noninflammable-oil impregnated pressboard (0.8 mm) (electrode 50ϕ 6R)

2) Relation between corona discharge and breakdown

The breakdown voltage of oil impregnated paper is seriously affected by corona discharge. It can be considered generally that the corona discharge is the direct cause of the breakdown of oil impregnated pressboard. Because almost 100 percent of failures occur at the electrode edge when corona appears. However, the deteriorating action of corona discharge differs between the mineral- and noninflammable-oil impregnated. It is considered that this is the cause of the difference of the breakdown voltage characteristics. The threshold voltage is shown in Table 5. In noninflammable-oil insulation, oil and pressboard have nearly close dielectric constant (see Table 6). Therefore the electric field intensity at the electrode is equalized and the threshold voltage is higher than in mineral-oil insulation. This is the merit of noninflammable-oil insulation. However the higher threshold voltage does not always set up the higher breakdown voltage. The mineral-oil impregnated can resist to 3 times of its threshold voltage at impulse and a-c short time voltage (see Table 5), but the noninflammable-oil impregnated fails near over its threshold voltage. This tendency is clarified by next explanation.

Table 5. Threshold voltage and breakdown voltage of oil-impregnated pressboard (0.8 mm)

Electrode	Impregnant	Threshold voltage (kV) (peak)	Impulse breakdown voltage (kV)
50φ6R	Mineral oil	26.3	88.8
	Noninflammable oil	50.6	73.4
50φ∠R	Mineral oil	21.0	90.0
	Noninflammable oil	41.7	65.9

Table 6. Dielectric constant (20°C)

Sample	50 c/s	250 kc
Mineral oil	2.20	2.20
Noninflammable oil	4.80	4.76
Mineral-oil impregnated pressboard	4.1	4.1
Noninflammable-oil impregnated pressboard	5.2	5.2

In the case of mineral-oil impregnated pressboard, the threshold voltage with square edge electrode is smaller than with round edge electrode, but there is no difference in breakdown voltage. This is perhaps due to the grading effect at the pressboard surface. While in the similar experiment with the noninflammable-oil impregnated, the breakdown voltage is proportional to its threshold voltage. Therefore we can say in the case of the latter that the corona discharge immediately causes the breakdown.

Concerning to the long time breakdown voltage, we can say as follows. The breakdown voltage decreases with voltage duration, and approaches to the threshold voltage. With the noninflammable-oil impregnated where threshold voltage is higher, the decrease is not so much, while the mineral-oil impregnated where threshold voltage is lower, it is very remarkable. For that reason it can be said that in both the mineral- and noninflammable-oil impregnated pressboard the breakdown voltage is affected by corona discharge, however the former can well resist to corona if time is short.

3) Phenomenon when immersant differs from impregnant

The above mentioned explanation will be more clarified by investigating on the combination of mineral-oil immersant and noninflammable-oil impregnant and on the reversed.* It is expected from the dielectric constant that the threshold voltage is highest for the combination of noninflammable-oil immersant and mineral-oil impregnant and lowest for mineral-oil immersant and noninflammable-oil impregnant. The test results coincide to this as seen in Table 7. From the data given we can calculate the breakdown voltage of the oil-film between electrode and pressboard. According to Table 8, which indicates the dielectric strength of thin oil-film, it can be seen that there is no appreciable difference of dielectric strength between mineral- and noninfiammable-oil, agreeing to the mentioned in Chapter II.

Note: * It can be shown that the impregnant is not replaced by the immersant if immersing time is not long. The dielectric constant of mineral-oil impregnated pressboard does not alter at all even after the sample has been immersed in noninflammable-oil about 15 hours. For the noninflammable-oil impregnated the same is true.

Table 7. Threshold voltage of oil-impregnated pressboard (0.8 mm) in (kV) (peak)

Immersant	Mineral-oil impregnated pressboard	Noninflammable-oil impregnated pressboard	
Mineral oil	26.3	25.0	Electrode 50φ6R
Noninflammable oil	54.8	50.6	Voltage 50 c/s

Fig. 7 indicates the voltage-time characteristics of the oil-impregnated pressboard and Fig. 6 (B) the progress of corona discharge. The threshold voltage of the combination of noninflammable-oil immersant and mineral-oil impregnant increases, whereas the

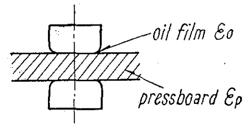
Table 8. The threshold stress* of immersant

Pressboard	Oil film	kV (peak)/mm
Mineral-oil impregnated	Mineral oil	64.5
	Noninflammable oil	61.6
Noninflammable-oil impregnated	Mineral oil	77.7
	Noninflammable oil	72.2

Electrode 50ϕ6R, Voltage 50 c/s

* Threshold stress of oil film

$$=\frac{\text{threshold voltage}}{\text{thickness of pressboard}}\times\frac{\varepsilon_p}{\varepsilon_0}$$



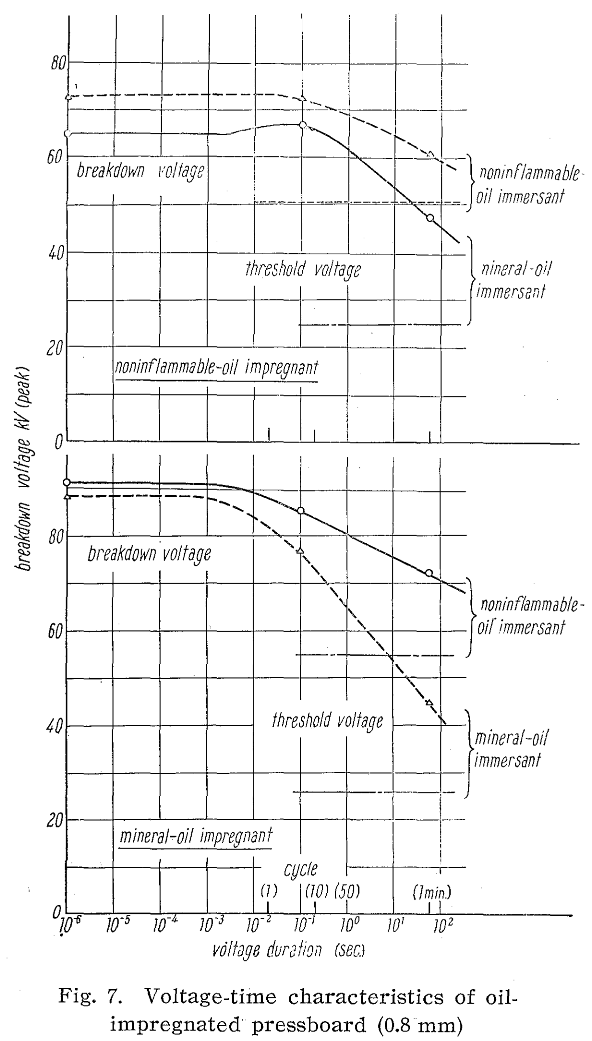


Fig. 7. Voltage-time characteristics of oil-impregnated pressboard (0.8 mm) (electrode 50ϕ 6R)

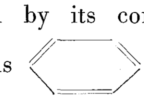
short time breakdown voltage does not, indicating that the breakdown voltage of the mineral-oil impregnated is not affected by slight variation of corona discharge, if the voltage application is short.

On the other hand, for the combination of mineral-oil immersant and noninflammable-oil impregnant, the short time breakdown voltage decreases corresponding to the threshold voltage, being directly affected by corona discharge.

The long-time breakdown voltage, however, is affected by corona discharge in both combination. In consequence, we can find even the facts that the impulse ratio for the mineral-oil impregnated is only slightly more than unity and for the noninflammable-oil impregnated increases to some extent.

4) Why noninflammable-oil impregnated pressboard can not well resist to corona

It may be considered that why the noninflammble-oil impregnated pressboard can not well resist to corona is due to its essential property. T. W. Dakin showed that a chlorinated compound-impregnated pressboard has relatively a low impulse dielectric strength, from his series of the test with various kinds of halogenated liquid. G. M. L. Sommerman[5] found that for the chlorocarbon liquid the positive streamer propagates more rapidly than hydrocarbon liquid, corresponding to the lower impulse dielectric strength.

We consider about this question as follows. Everyone, conducting the breakdown test of noninflammable-oil, will find without fail that the noninflammable-oil yields much more isolated carbon by breakdown as compared to mineral-oil. This may be caused by its composition, consisting in benzene nucleus . As indicated in Fig. 6, the mineral-oil impregnated are only slightly carbonized by exposure to corona, but for the noninflammable-oil impregnated the carbonized trace is very remarkable. If this carbonizing process by corona discharge propagates from electrode edge to the oil space of interior of pressboard, a conducting path will be established, leading to the breakdown even a short time. This is appeared to the cause of its low impulse strength.

5) Kraftpaper

For the kraftpaper the abnormal phenomenon can not be found as mentioned in Chapter III, 1. This is due to the fact that the effect of corona to short time breakdown voltage is negligible small, because its thickness is small, 0.15 mm, and therefore the applied voltage is relatively lower, less than 20 kV. Even the case of kraftpaper, we can find the same phenomenon as pressboard, by forming more than about 0.8 mm in layers.

IV. DISCUSSION ABOUT TRANSFORMER INSULATION DESIGN

We shall calculate the safety factor against dielectric test on a representative transformer insulation-model, showed in Fig. 8 (A). When the test voltage is applied to the insulation, expressing the equivalent circuit as Fig. 8 (B), the voltage across the oil-impregnated pressboard and oil-duct E_1 and E_2 respectively will be

$$E_1 = \frac{\dfrac{\varepsilon_2}{1-k}}{\dfrac{\varepsilon_1}{k} + \dfrac{\varepsilon_2}{1-k}} \cdot E \quad \text{...........(1)}$$

$$E_2 = \frac{\dfrac{\varepsilon_1}{k}}{\dfrac{\varepsilon_1}{k} + \dfrac{\varepsilon_2}{1-k}} \cdot E \quad \text{...........(2)}$$

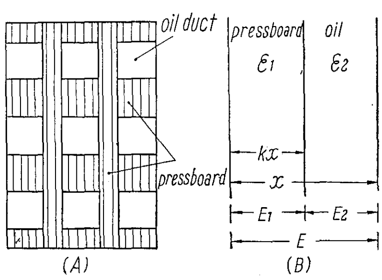


Fig. 8. Transformer insulation with oil-duct

But the breakdown voltage of the equivalent circuit in Fig. 8 (B) is lower than that of Fig. 8 (A), where pressboard and oil-duct are piled up alternatively. This is due to the fact that the breakdown voltage does not increase linearly proportional to the total thickness. So the breakdown voltage must be considered about Fig. 8 (A) instead of Fig. 8 (B).

As an example we shall examine about the insulation-model, consisting of three layers of oil-duct and two layes of pressboard. Expressing the breakdown voltage of pressboard $\left(\text{thickness} = \frac{1}{2}kx\right)$ and oil-duct $\left[\text{thickness} = \frac{1}{3}(1-k)x\right]$ respectively by V_1 and V_2, the safety factor will be $V_1 \Big/ \frac{1}{2}E_1$, $V_2 \Big/ \frac{1}{3}E_2$.

If the total thickness of insulation x is calculated by

$$E = 9\ x^{0.7}\ \text{kV} \quad \text{..............................(3)}$$

where E = a-c 1 minute test voltage

the safety factor against a-c 1 minute dielectric test is expressed by Fig. 9 (A). Here it is assumed that the dielectric strength of noninflammable-oil is equal to that of mineral-oil, but in practice it is more higher. Therefore it may be considered that the safety factor of noninflammable-oil insulation is higher than Fig. 9 (A). In the same manner calculated safety factor against impulse dielectric test, applying 2.5 E, is presented in Fig. 9 (B). Here as the impulse ratio is used Table 2 for oil and Table 4 for pressboard.

From the curve given, we can note for the noninflammable-oil transformer that the potential distribution between oil-duct and pressboard is equalized and the safety factor of oil-duct, which is the weak point of the mineral-oil transformer, become larger. This is the advantage of noninflammable-oil transformer, which is due to the high dielectric constant of noninflammable-oil. (The safety factor of pressboard illustrated in Fig. 9, which is calculated in regard to the potential distribution before the puncture of oil, is only apparent and temporary. The true safety factor is decided only by that of oil-duct).

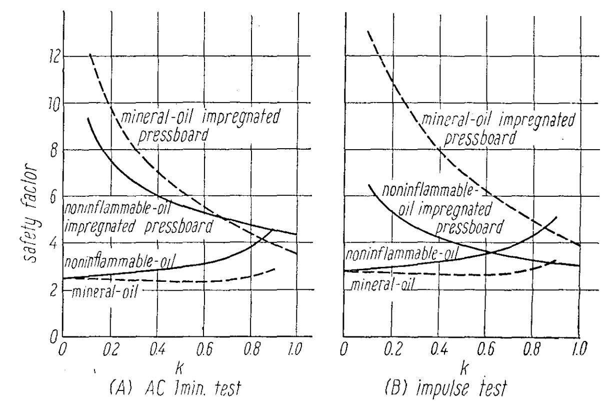


Fig. 9. Safety factor against dielectric test

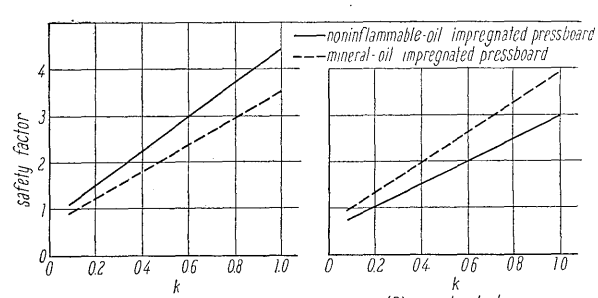


Fig. 10. Safety factor of pressboard (when oil breaks down at dielectric test)

For the weak points except the insulating part with oil-dust, for example the turn insulation of high voltage terminal side, it is easily resolved by reinforcing, that is, increasing the thickness of pressboard by 20 or 30% more than mineral-oil insulation. The noninflammable-oil is not deteriorated by running and can keep the initial high dielectric strength, but supposing that by any chance the oil-duct should breakdown by mixing of impurity and the others, the full voltage would be impressed to pressboard and the safety factor would become to Fig. 10.* Only on that occasion, the safety factor of noninflammable-oil transformer against impulse voltage will be lower than mineral-oil transformer. If it is requested for even such occasion that the safety factor of noninflammable-oil transformer is in same grade as that of mineral-oil transformer, it is necessary to increase the portion of pressboard by about 20% from Fig. 10 (B). (At the same time the safety factor of oil-duct inevitably increases.) By such special design the cooling effect will become into question, but the noninflammable-oil will scarcely be deteriorated even at higher temperature, differing from the mineral-oil, so the such design may be allowed.

V. CONCLUSION

Among the noninflammable transformer, the dry type transformer has an defect that it has low dielectric strength especially for impulse voltage. It has been supposed that the noninflammable-oil transformer has the same or more dielectric strength as compared to the mineral-oil transformer. However, recently it was felt unsafe for this point, so in order to resolve this question, we tested the dielectric strength of mineral- and noninflammable-oil and impregnated into pressboard, and considered about the dielectric strength of representative transformer insulation.

Note: * This assumption is the worst case. All parts of the oil-ducts can not usually breakdown at the same time.

From above-mentioned, in spite of the somewhat lower impulse dielectric strength of noninflammable-oil impregnated pressboard, it has been confirmed that in the noninflammble-oil transformer the field intensity is equalized and it has higher corona starting voltage and dielectric strength.

Noninflammable-oil has the advantage that it is not detriorated under high temperature and keeps the initial high dielectric strength. Therefore it is suitable for the high voltage transformer not only at less than 20 or 30 kV in ordinary use, but also even at more than 60 kV. Regarding to the dielectric strength of the transformer insulation, in addition to the breakdown by penetration above given, the surface flash-over strength must be considered. About this question, we have already finished the investigation, which will be published later.

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