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FUJI F-CLASS STABILASTIC INSULATION (NEW F-CLASS INSULATION FOR HIGH VOLTAGE ROTATING MACHINERY)

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I. INTRODUCTION

In recent years, there has been a remarkable development and expansion in application of heat resistant insulation materials. With the progress made in design and production techniques, research and development of devices with high heat resistance is proceeding rapidly. However, with the great industrial expansion, the demands for rotating machinery have increased and their conditions of use have become very severe. For example, in the chemical industry, there are increasing demands for insulation resistant to chemical and moisture, as well as moisture resistance for auxiliary equipment in various types of plants. In response to these requirements, Fuji Electric employs F-resin Insulation and Fuji Stabilastic Insulation with good results.

Research and development is being carried out to improve the insulation reliability considering light, compact machinery and other factors. As a result, the F-class Stabilastic Insulation has been developed as heat resistant F-class insulation for high voltage rotating machinery. This F-class Stabilastic Insulation is based on the techniques for former Stabilastic Insulation, but the insulation structure and the manufacture method has been improved and the heat resistance is also better. In particular, deterioration by partial discharge under high temperature has been investigated and this has been completely solved in respect to turn insulation which often causes a problem in high voltage machinery with high temperature.

II. CHARACTERISTICS OF F-CLASS STABILASTIC INSULATION

1. Construction

A characteristic of Stabilastic Insulation is that insulation sheets are wrapped around the slot part, high pressures are applied for heat curing and the sheets are formed into a molded insulation layer. Almost the same method is used to manufacture F-class Stabilastic Insulation. In other words, the insulation sheets consist of heat resistant film and

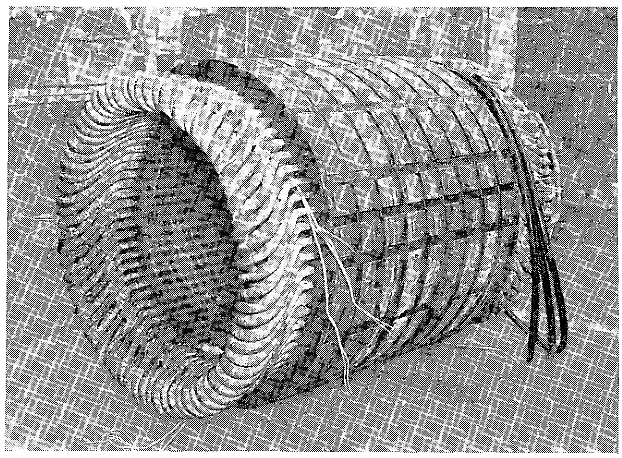

Fig. 1 Stator winding of F-class Stabilastic insulation 3,300 V, 530 kW 8 poles induction motor

mica paper stuck together by epoxy resin. The epoxy resin which is applied to the sheets contains no solvents and is maintained in a semi-cured condition. These sheets are wrapped around the coil and molded by the application of heat and pressure. After this, the end insulation is applied, various tests are performed and the coil is installed in the machine. There are two methods for the end insulation. One is the mica-tapewinding method using semi-cured adhesive resin, and the other method is the solventless resin impregnation method using a special tape. In both cases, high quality resins are used and there are no weak points in the connection parts, etc. because of the development of special manufacturing techniques. Moisture resistance is also excellent as the results of subsequently described water submerging tests will show. *Fig. 1* shows a stator winding with F-class Stablilastic Insulation of the new type.

2. Wire Characteristics

For some time, the failure of turn insulation in high voltage machines has been one of the main causes of insulation troubles. Along with the recent popularity of vacuum switches, it can be expected that high switching surges will occur and therefore, demands for improved reliability of turn insulation have increased. The points of difficulty in turn insulation are that setting of the insulation level is not clear because the peak value and the rates of rise of the surge voltage is not constant, and if the turn insulation thickness would be thicker the machine becomes more uneconomical and the space factor is therefore bad. In respect to the former problem, it has been reported that the main part of the crest value of an impulse established in 0.1 to 0.2μs is applied to the initial turn[(3),(4)], because of the surge impedance of the machine and the propagation speed due to the progressive wave theory. In addition, deterioration due to the occurrance of internal discharge must be considered in high voltage machinery and therefore careful investigations must be carried out since the partial discharge is promoted by the temperature. When the F-class Stabilastic Insulation was developed, careful consideration was given to the selection of the electrical wires because of the above points. Since the wires are wrapped in heat resistant film or are heat resistant enamel wires wrapped heat resistant film and also have a double layer of glass fiber, the breakdown voltage between the wire when the coil is completed is 1 to 1.5 times the rated voltage of the machinery. In order to investigate the influence of the partial discharge on the turn insulation, a high voltage was applied for a long period at 155°C to a 6kV coil with F-class Stabilastic Insulation and variations of the turn insulationn dielectric strength were obtained. In order to promote deterioration, an AC power source of 500 Hz was employed. The results are as shown in *Fig. 2*. Even when a field strength of 5 kV/mm, which is more than twice the field strength under operating conditions, is applied to the insulation layers, there is only a slight drop in turn insulation dielectric strength. There was almost no drop at 3.75 kV/mm that is 1.5 times the field strength. To observe stability after heat treatment, the same test was performed after the coil had undergone heat aging at 170°C for 2,000 hours. The results are as shown in *Fig. 3*. There was no change in the turn insulation dielectric strength after heat aging.

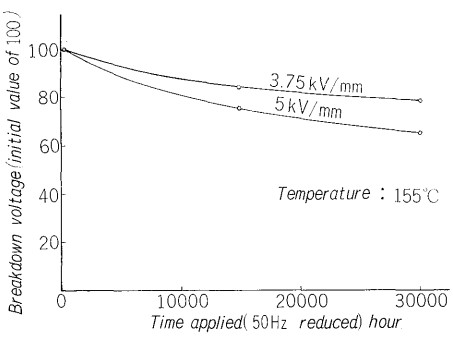

Fig. 2 Aging test of turn insulation

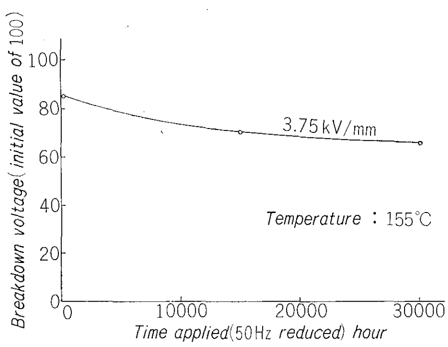

Fig. 3 Aging test of turn insulation after coil heat treatment

3. Coil Insulation Layer Characteristics

1) General characteristics

Table 1 **Chemical resistivities of insulating layers**

Item	Slot part		Coil end part	
	Flexural strength (kg/mm²)	Volume resistivity (Ω-cm)	Flexural strength (kg/cm²)	Volume resistivity (Ω-cm)
Initial value	28.7	7.5×10^{15}	18.8	7.5×10^{15}
Water	—	1.3×10^{15}	—	1.7×10^{15}
5% H_2SO_4	22.4	1.1×10^{15}	21.4	2.1×10^{14}
5% NaOH	25.0	7.5×10^{14}	17.5	2.5×10^{15}
5% NH_4OH	29.7	8.0×13^{13}	18.7	9.1×10^{13}

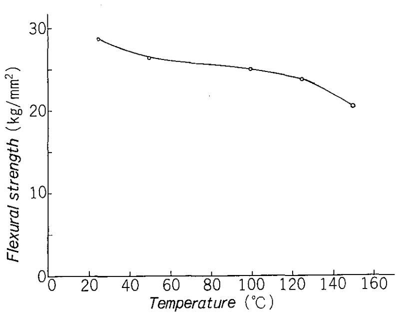

Fig. 4 Flexural strength vs. temperature characteristics

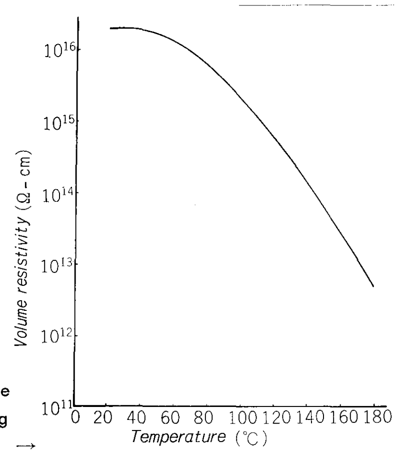

Fig. 5 Volume resistivity vs. temperature characteristics of coil insulating layers →

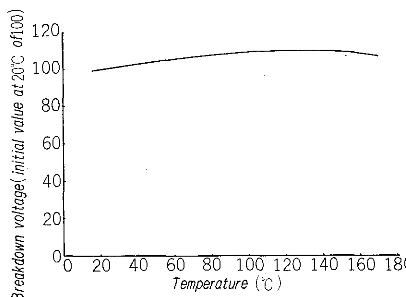

Fig. 6 Breakdown voltage vs. temperature characteristics of coil insulating layers

Fig. 4 shows the flexural strength, *Fig. 5* the volume resistivity and *Fig. 6* the breakdown voltage all in relation to the temperature characteristics of coil insulating layers using F-class Stabilastic Insulation. Excellent characteristics at high temperatures were observed in all cases.

2) Water and chemical resistance.

When the insulation layers were submerged in water and various chemicals, any changes in flexural strength and volume resistivity were observed. The results are shown in *Table 1*. However, there were almost no changes which prove that the insulation has good water and chemical resistance.

4. Coil Characteristics

1) Tanδ and partial discharge characteristics

In the case of high voltage coils, it is necessary that the initial tan δ—voltage characteristics and the partial discharge characteristics be good and also that they remain unchanged during operation. *Fig. 7* shows a typical example of the tanδ vs. voltage characteristics. *Figs. 8* and *9* show the frequency percent curves during manufacture for tan δ and the partial discharge respectively, at the rated voltage. The tanδ vs. voltage characteristics are flat until the rated voltage. The average of maximum partial discharge at the rated voltage is extremely small, less than 10^{-10} coulomb. Therefore, no partial discharge occurs at the operating voltage. The voltage withstand characteristics of the insulation layers can generally be seen from the v-t characteristics. This test was also conducted for the F-class Stabilastic Insulation and the results are shown in *Fig. 10*. When the field strength is low, the linear characteristics deviate and there is a tendency for longer life. However, even in the case of exterpolation to a straight line in consideration of the field strength during operation, the life of the insulating layers was still over 100 years.

2) Coil moisture resistance characteristics

Moisture resistance characteriseics are very important for coil insulations along with heat and partial discharge resistance. Even when there is no problem concerning the previously described water and chemical resistance of the material, the moisture resistance is vert important in relation to the insulation system of the coil. Therefore, Fuji Electric has performed water submerging tests on coils for a long time and the results have shown complete moisture resistance. The same water submerging test was also performed for Stabillastic Insulation. *Fig. 11* shows the changes in insulation resistance

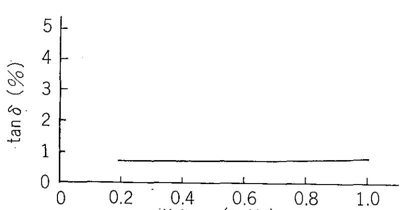

Fig. 7 Tanδ vs. voltage characteristics

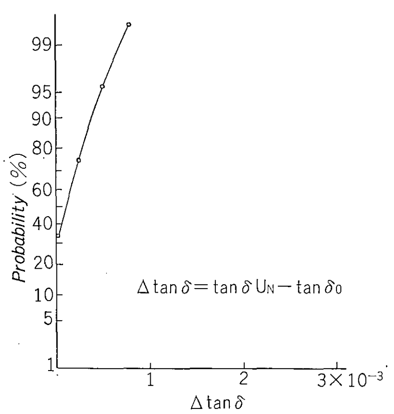

Fig. 8 Frequepcy percent of Δtanδ

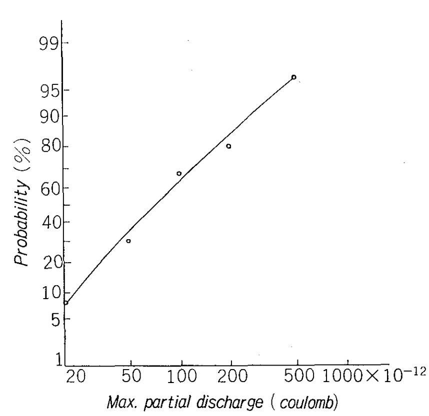

Fig. 9 Frequency percent of corona discharge

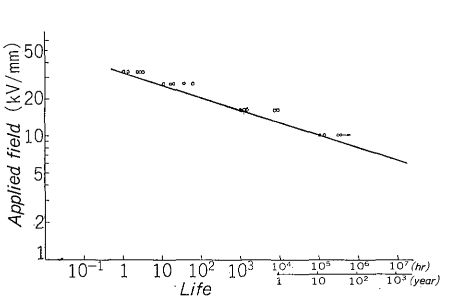

Fig. 10 Voltage endurance characteristics of F-class stabilastic insulation

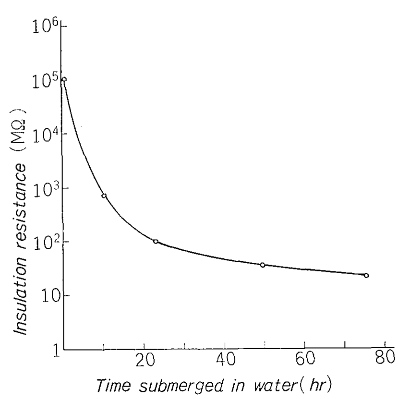

Fig. 11 Insulation resistance submerging test

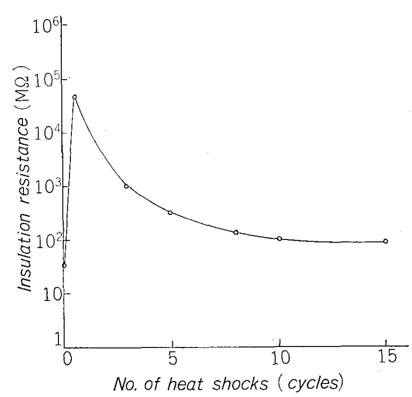

Fig. 12 Insulation resistance submerging test after heat shocking

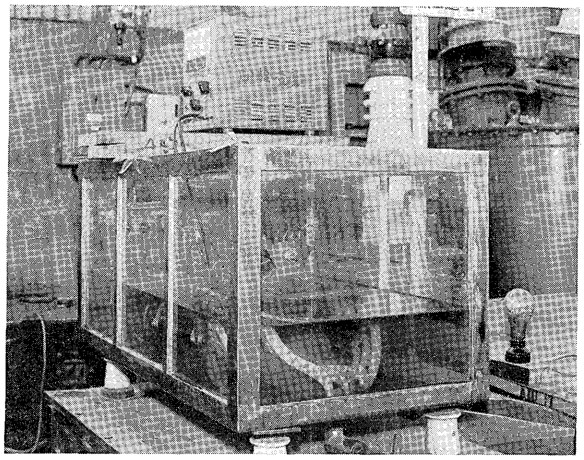

Fig. 13 Coil submerging test

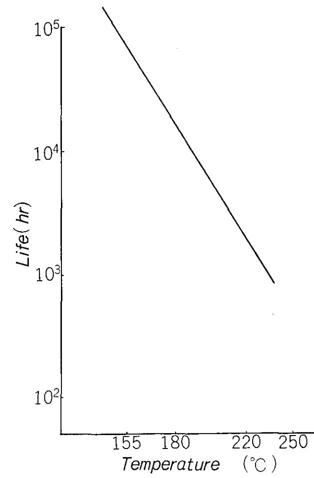

Fig. 14 Life-temperature relationship of wire

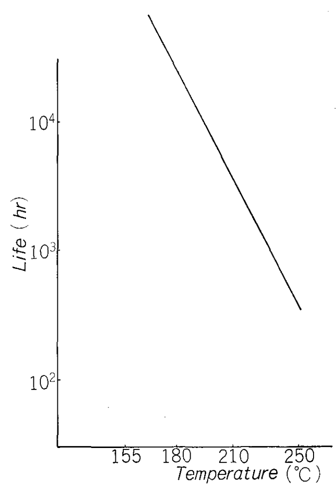

Fig. 15 Life-temperature relationship of coil insulation layers

when the coil was submerged in water for 80 hours and *Fig. 12* shows the changes in the insulation resistance for a coil submerged in water for 80 hours after being submitted to a severe heat shock repeated for five hours at 160°C. The insulation resistance remained good after this heat shock and no defects such as cracks occurred. *Fig. 13* shows the coils during a water-submerging test. These tests prove the superiority of the moisture and chemical resistance of the F-class Stabilastic Insulation and this means that the reliability is high. The range of application of the open type and open drip-proof type is therefore very wide and maintenance is very easy.

III. HEAT RESISTANCE CHARACTERISTICS OF F-CLASS STABILASTIC INSULATION

As was described previously, the F-class Stabilastic Insulation has excellent initial, characteristics resistance of particel discharge, moisture resistance and chemical resistance characteristics. The heat resistance and heat cycle resistance characteristics are also excellent. Insulation deterioration in rotating machinery includes heat and moisture deterioration, chemical deterioration due to various chemicals, gases and oils, deterioration due to mechanical stress and vibrations and electrical and chemical deterioration due to partial discharge, etc. All of these factors together result in overall deterioration. Generally, however, the major effects are considered to be due to heat, partical discharge and heat cycle deterioration. For this reason, heat and heat cycle resistance of F-class Stabilastic Insulation will now be described.

1. Heat Resistance Characteristics of Wires and Insulating Layers

As is well known, when evaluating the heat resistance of insulating materials, it is necessary to consider the items related to the limit values decided by the temperature alone, i.e. form stability at high temperatures and heat resistance deterioration when heat is applied for long periods at relatively high temperatures. Since the latter deterioration in heat resistance is also influenced by factors such as mechanical stress during actual use, vibrations, inner stress due to thermal expansion and the absoprtion of moisture, sufficient consideration just also be given to these. It is also very important to evaluate it as a so-called insulation system. Therefore, various tests methods related to heat resistance were devised and since a long period is required generally for tests related to heat resistance, recently, methods of evaluating the heat resistance life in short periods have also been attempted. However, at present, there is no complete method of this type. The test method must be selected in accordance with the type of machinery and conditions and a wide range of tests must be conducted over a long period at temperatures near to those used under actual operating conditions. For F-class Stabilastic Insulation, many tests including heat deterioration test on each material to functional evaluation tests for the wires, coil insulating layers and insulating system were performed. In this way, an insulation system with a high heat resistance has been developed. First, thermal deterioration tests

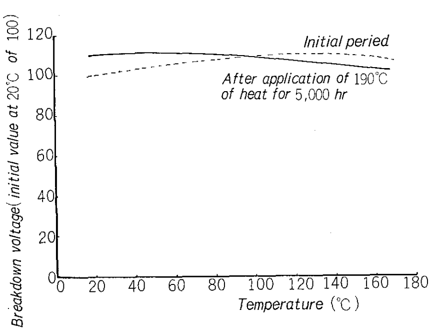

Fig. 16 **Breakdown voltage vs. temperature characteristics after coil heat treatment**

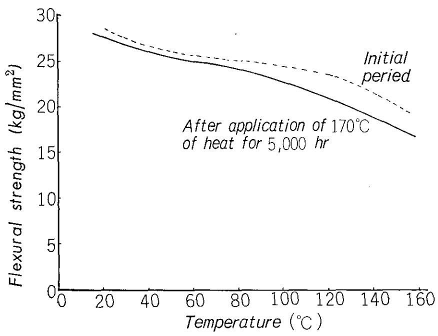

Fig. 17 **Flexural strength vs. temperature characteristics after coil heat treatment**

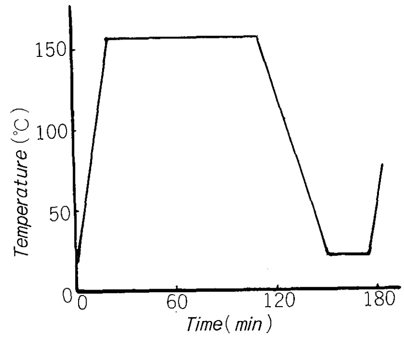

Fig. 18 **Diagram of heat cycle**

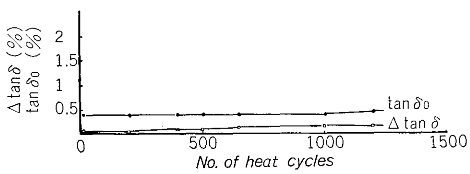

Fig. 19 **Change by heat cycle of tanδ characteristics**

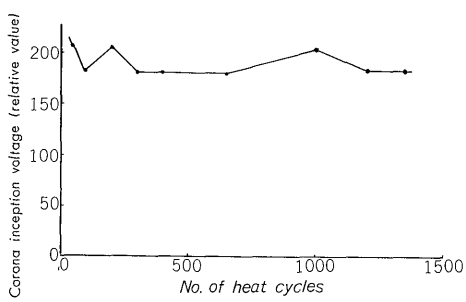

Fig. 20 **Change by heat cycle of discharge inception voltage**

with heat shocks using a model coil were performed for the wires and changes in the insulation breakdown voltage between two wires at various temperatures were obtained. Typical results are shown in *Fig. 14.* This figure shows the relation between temperature and the time of heat application when the breakdown voltage between the two wires drop to 6 kV. This proves that the wires used for F-class Stabilastic Insulation have a high voltage resistance over long periods even at temperatures of more than 155°C. Therefore, considering this heat resistance and the previously described voltage resistance, the reliability of the turn insulation is very high. An example of the heat resistance of the coil insulating layers is shown in *Fig. 15.* This figure gives the relation between the temperature and the life until the flexural strength is decreased by half. The results show that the time required to reduce the flexural strength by half at 180°C is more than 20,000 hours. In ordinary thermal deterioration test, it is usual to trace the changes in the characteristics at normal temperatures but actually, the problem is the characteristics at the actual temperatures used and therefore, it is necessary to investigate the characteristics at high temperatures after application of heat. *Fig. 16* shows the temperature characteristics vs. the insulation breakdown voltage after application of 190°C for 5,000 hours for F-class Stabilastic Insulation. *Fig. 17* shows the temperature characteristic vs. flexural strength after application of 170°C for 5,000 hours. In both cases, the initial value under normal temperature is shown as 100. These curves show that there is almost no drop in the breakdown voltage or flexural strength at high temperatures even after exposure to high temperatures for long periods.

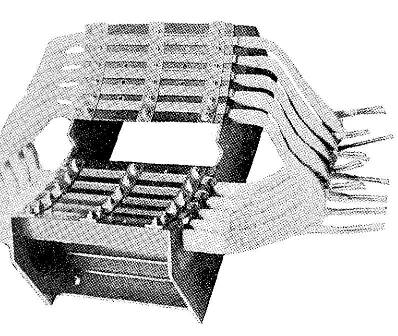

Fig. 21 **Model coils of I.E.E.E. No. 275 Motorette test**

2. Heat Cycle Resistance Characteristics

Conductor used in machinery undergo repeated thermal expansion and contruction. Stress is also applied to the insulating layers because of differences in the temperature and thermal expansion coefficient between the conductor and the insulating layer. Therefore, voids between the conductor and the insulating layer or cracks in the insulating layers often occur, harmful partial discharge arises and the breakdown voltage often decreases. When the F-class

Stabilastic Insulation was developed, various heat cycle tests were performed and the stability of the insulations was confirmed. The test method was the application of the rated voltage to the coil unit without attaching a model slot or cramping plates. The heat cycle conditions were as shown in *Fig. 18*, *Figs. 19* and *20* show the tests results using a 6 kV coil. *Fig. 19* shows the changes of $\tan\delta_0$ and $\Delta\tan\delta$ (difference between $\tan\delta$ at the normal voltage and $\tan\delta_0$) due to the heat cycle test. *Fig. 20* shows the changes in the discharge inception voltage due to the heat cycle test. These curves show that there is almost no change in $\tan\delta_0$ and excellent characteristic of the coil insulating layers are maintained. Almost no voids or cracks occur in the insulating layers due to changes in $\Delta\tan\delta$ and the discharge inception voltage.

3. Heat Resistance Life Evaluation Using a Motorette

The I.E.E.E. No. 275 motorette test is widely used as a functional tests for machinery with formed coils. There are considerable differences in the deterioration factors during use and this method is not completely satisfactory. However, rather significant data are obtained for comparison with former insulation system and in respect to the life test of actual equipment. At present, various types of mechanical factors are added to the test to approximate actual conditions as much as possible and the test method is under investigation. Here, the results of the former motorette test (I.E.E.E. No. 275) on the F-class Stabilastic Insulation will be described. The test was performed using the model coils shown in *Fig. 21* under the following conditions:

1) Heat applied: {210°C 2 days; 190°C 7 days; 170°C 28 days}
2) Voltage resistance check: 7,000 V (one minute)
3) Vibrations (one hour): {Amplitude 0.2 mm; Frequency 25 cps; Acceleration 1.5 g}
4) Moisture absorption (48 hours): {Temperature 40°C; Humidity (relative) over 95%}
5) Voltage resistance check: 7,000 V (10 minutes)

From the results of the test, the regression line for temperature and life was obtained by the method of least square. This line is shown in *Fig. 22*, which also includes results for standard B-class insulation. Several methods for evaluating the heat resistance from these characteristics can be considered. When compared with the ordinery B-class insulation, the temperature of 155°C presents no problem for the F-class insulation. For example, in cases when the life is over 20,000 hours as was often mentioned previously, the corresponding heat resistant temperature is approximately 170°C.

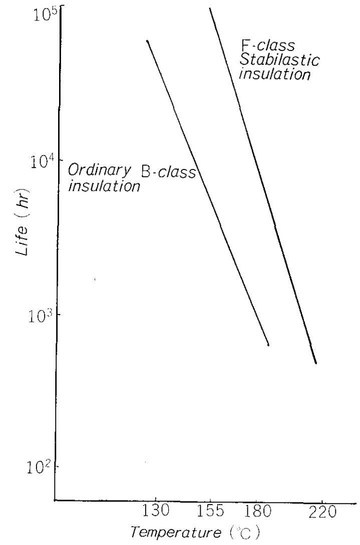

Fig. 22 Life-temperature relationship of F-class Stabilastic insulation

IV. CONCLUSIONS

The Fuji Stabilastic Insulation for high voltage rotating machinery developed in 1966 by Fuji Electric can be applied in machinery with voltages of 3,300 to 11,000 V and capacities of 55 to 8,400 kW. Already, this insulation has proven satisfactory in over 1,000 applications. Recently, a new F-class Stabilastic Insulation has been developed and it is described in this article. This F-class Stabilastic Insulation employs materials with high characteristics and highly reliable heat resistance is obtained by special manufacturing techniques. Careful consideration has been given to deterioration by partial discharge and turn insulation. Fuji Electric has used F-resin Insulation for over 10 years in large generators with good results. Considerable research is being performed on this F-resin Insulation and the reliability is being increased through the addition of various improvements. The authors hope to describe this insulation for large scale generator in another article.

References:

(1) Shimizu, Taniguchi, Iseki: Fuji Electric Journal 31, No. 5 (1958)
(2) Yamaguchi, Tani, Natsume: Fuji Electric Journal 40, No. 10 (1967)
(3) R. Sextor: Proceedings of 7th Electrical Insulation Conference (1967)
(4) C. J. Mole and G. L. Moses: I.E.E.E. No. 31, 67 (1967)