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Multistress ageing of 28 kV Silicone Rubber Insulators under West and East Coast conditions of the USA

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Long term ageing of polymeric insulators was performed simulating coastal San Francisco and Boston. 28 kV silicone rubber insulators were used for this purpose. The same insulator (design and material) was compared at two different locations (West and East Coasts of the USA—San Francisco and Boston). Weather cycles simulating coastal San Francisco and Boston were developed. The various stresses applied include UV radiation, salt fog to simulate contamination from air-borne particles, clear mist, rain, heat, cold and electrical stress. Data acquisition of the leakage current and cumulative charge is also done by LabVIEW. High voltage divider was used to measure 20 kV using LabVIEW at 2V. They were aged for thousands of hours and their ageing and degradation were characterised using physical (discolouration, chalking, cracking, hydrophobicity), electrical (surface leakage current, cumulative charge and watts loss) and state-of-the-art material diagnostic techniques such as FTIR, SEM and XPS. Results indicate that silicone rubber insulators withstood these stresses well.

***Key words**: Polymeric insulators, silicone rubber, multistress, ageing, degradation*

1.0 INTRODUCTION

Ageing (weathering) is a major concern of utilities using polymeric insulators for outdoor insulation [1-6]. Polymers, being more organic than their ceramic counterparts are more susceptible to ageing, losing their original composition and function over time. Weathering and photo-degradation cause billions of dollars of polymer product damage and power outages each year [7]. Polymeric arresters and insulators in-service perform satisfactorily in the beginning, but with time, they have deteriorated due to continuous service stresses, both electrical and environmental. In order to develop materials that are resistant to weathering, it is necessary to understand their ageing mechanism and kinetics in a given service environment. This makes it worthwhile to investigate the performance of various polymeric insulators at their respective service conditions, simulating the various stresses encountered, known as multistress conditions, as insulators in the field experience synergistic effects of temperature, UV radiation, rain, clear mist and contamination [8-11].

2.0 MULTISTRESS AGEING

In multistress tests, various environmental stresses are applied in repetitive cycles to reflect real life conditions [8-10]. The stresses are created by simultaneous applications of varying combinations of voltage, UV radiation, moisture and contamination, just as in-service. Moisture

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is introduced in the form of humidity, fog or rain. Contamination is applied by various levels of salinity introduced with the moisture. Summer and winter weather cycles were developed to evaluate the arresters for their long-term performance under conditions that represent actual in-service environment [8-10]. The ageing cycles essentially identify the duration and the sequence of various stresses of interest. Meteorological data, such as maximum/ minimum temperatures, UV radiation intensity, number of clear days, hours of sunshine, amount of precipitation have been used for this purpose.

The overall weather pattern was developed using the Relative Ageing Factor (RAF) [8, 9], as

$$\text{Relative Ageing Factor (RAF)} = 2^{\left(\frac{T_{\max} - T_{avg\,\min}}{10}\right)} \quad (1)$$

where T_{max} is the maximum temperature of each month, $T_{avg\ min}$ is the minimum temperature of all average temperatures, both expressed in degrees Celsius. This is based on the assumption that the rate of ageing doubles for every 10°C increase in temperature.

3.0 EXPERIMENTAL INVESTIGATION

3.1 Multistress environmental chamber

Fig.1 shows the test setup along with the high voltage transformer and controller. The controls, water tanks, plumbing, and computer are all on the left side. Each water tank, clean water and salt water, holds 50 gallons. Part of the data acquisition system is shown on top of the computer. The gray box on the side of the chamber is the ballast and distribution box for the UVA lamps. The 4'x 2.5' door allows the operator to safely enter the chamber to change insulators or perform any maintenance in the chamber. Not shown in the picture is the cooler that was added later. Safety measures are provided as per standard industry practices.

3.2 High voltage power supply

The 0-100 kV, 40 kVA high voltage adjustable transformer and the controller are on the left.

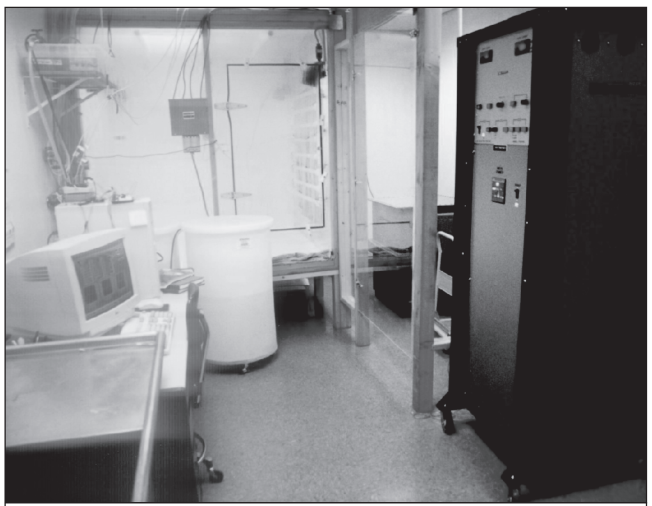


FIG. 1 MULTISTRESS TEST CHAMBER

The transformer controller allows to test insulators at a variety of line voltages up to 138 kV line to line. The voltage used in these tests was 16.2 kV line to ground.

3.3 LabVIEW controls and data acquisition

The environmental conditions are controlled through LabVIEW VI program, the industry standard instrumentation software. A second program running as a subVI (similar to a subroutine) of the main program acquires and stores the measured data. The LabVIEW program controls the lamps, fog and rain by cycling through a 24-hour cycle for a specified number of days. The UVA lamps control the heater indirectly; heating can only occur if the sun is shining. Therefore, the heater control attempts to maintain the temperature at the target temperature only when the UVA lamps are on. The cooler is turned on when the target temperature is below the present chamber temperature. Some hysteresis is provided within the program to ensure the heater and cooler do not interfere with each other to maintain the target temperature. Turning on the appropriate pump and opening the appropriate valves activates the salt fog and clean fog. Both fogs use the same nozzles so the source of the water is changed from one tank to the other. The compressed air is turned on whenever the cycle calls for either type of fog. The rain is turned on by opening the appropriate valve between the rain nozzles and the de-ionized water supply.

The manner in which the LabVIEW program controls the conditions is through the definition of a weather cycle. Each ageing factor has one or more time frames to be active during each 24-hour period. The program is designed to use the start and stop times for each factor. Each of the ageing factors has an enable switch to enable or disable each factor as required. There is also a master enable switch that is used to turn off all the ageing factors at one time. The season switch allows the user to select the seasonal weather cycle, summer or winter. The indicator lights on the control panel display the status of each of the ageing factors.

3.4 Insulators used

28 kV distribution class silicone rubber (SiR) insulators are used. Table 1 gives the salient dimensions of the insulator geometry. By using the same material for different locations, it is possible to compare the performance of the insulators under different environmental stresses and exposures.

TABLE 1

DETAILS OF SILICONE RUBBER INSULATORS USED

Item	Dimension (mm)
Leakage Distance	600
Diameter of Shed	96.1
Diameter of Sheath	25.3
Dry Arc Distance	283

3.5 Development of Monthly Weather Cycles for San Francisco—CA and Boston—MA

Multistress ageing normally uses summer (May –September) and winter (October–April) weather cycles to simulate the actual service environment [8, 14]. In our lab also, we have studied several service environments such as Detroit, Miami (Florida) using summer and winter weather cycles. This consists of averaging the meteorological data for these months which might skew at a time. For example, in the case of Florida, the month of October has noticeably more rain than the other winter months—November to April, but significantly less than the summer months—May to September. By averaging it to either winter or summer cycle, the rain data is skewed [14]. It is desirable to have monthly weather cycles which give a truer picture of the actual meteorology than averaging over a few or several months. Accordingly, in this research, monthly weather cycles were designed and developed and used for ageing study. Tables 2 and 3 give the monthly weather cycles for San Francisco and Boston respectively.

4.0 RESULTS AND DISCUSSIONS

4.1 Visual observation of the surfaces

Polymeric degradation includes colour change, strength loss, cracking, chalking, erosion and arcing [4, 14]. Visual observation helps to identify some of these changes.

By looking at the sample, we can sense the discolouration of the surface compared to the virgin sample. We can identify if there is cracking, chalking, or erosion. The amount and type of dust/dirt covered will be quantified using the soluble and non-soluble contamination indices, ESDD and NSDD respectively [15]. Table 4 shows the observations made for San Francisco and Boston. There was no noticeable change.

4.2 Hydrophobicity Classification (HC)

The surface hydrophobicity can be classified by spraying water on the insulator surface as per STRI guidelines [16] from HC 1 to HC 7. The HC 1 means highly hydrophobic and HC 7 is hydrophilic sheet of water. This method is one of the easiest and quickest ways to determine the status of the insulator surface.

Figs. 2A and 2B show reference HC 1 and HC 6, respectively. The hydrophobicity was observed immediately after the end of the test for each year. Fig. 3 illustrates the HC of aged insulators for coastal San Francisco. In general, silicones did not show much variation (HC 1-2).

TABLE 2

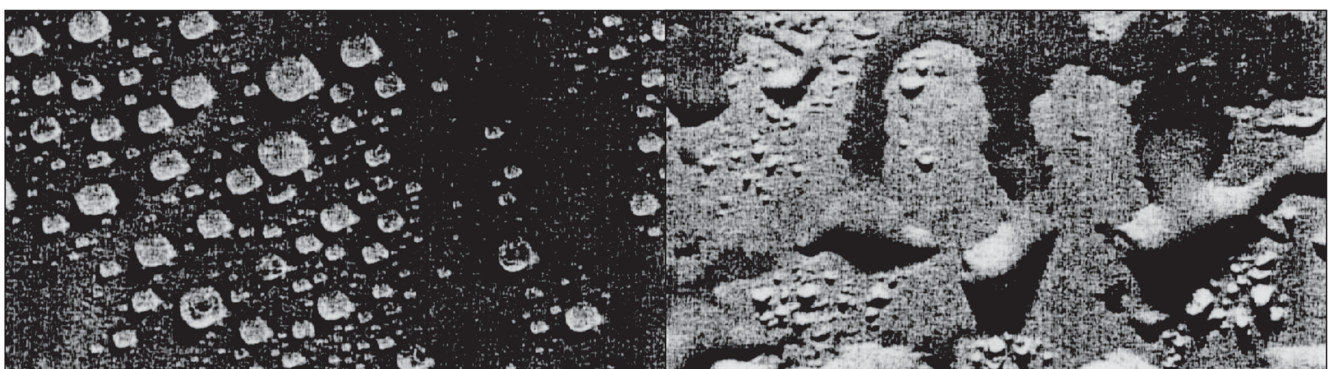
SAN FRANCISCO WEATHER CYCLE

Month	No. of days	Temp ºC	UVA hr/day	Rain hr/day	Salt Fog hr/day	Clean Fog hr/day
Jan	1.65	24	4.24	5 x 0.32	—	7 x 0.5
Feb	1.74	26	6.1	5 x 0.25	1 x 0.5	7 x 0.5
Mar	2.26	27	8	7 x 0.12	2 x 0.5	7 x 0.5
Apr	2.73	28	14.3	4 x 0.2	4 x 0.5	7 x 0.5
May	3.46	28	18	—	4 x 0.5	6 x 0.5
Jun	4.64	30	18	—	4 x 0.5	6 x 0.5
July	5.6	29	18	—	4 x 0.5	6 x 0.5
Aug	5.46	30	16.67	—	4 x 0.5	6 x 0.5
Sep	6.03	32	12.75	—	4 x 0.5	7 x 0.5
Oct	4.82	31	8.40	7 x 0.14	4 x 0.5	7 x 0.5
Nov	2.83	28	4.91	8 x 0.17	2 x 0.5	7 x 0.5
Dec	1.97	25	3.65	6 x 0.3	—	7 x 0.5

TABLE 3

BOSTON WEATHER CYCLE

Month	No. of days	Temp ºC	UVA hr/day	Rain hr/day	Salt Fog hr/day	Clean Fog hr/day
Jan	0.8	13	3.43	2 x 0.43	1 x 0.5	8 x 0.5
Feb	0.78	14	5.42	2 x 0.39	2 x 0.5	8 x 0.5
Mar	0.91	17	8.21	3 x 0.46	2 x 0.5	8 x 0.5
Apr	1.24	23	11.89	4 x 0.42	2 x 0.5	8 x 0.5
May	1.81	30	15.33	5 x 0.37	1 x 0.5	6 x 0.5
Jun	2.68	35	17.61	8 x 0.38	1 x 0.5	6 x 0.5
July	3.35	38	17.01	8 x 0.39	1 x 0.5	6 x 0.5
Aug	4.25	37	14.01	8 x 0.43	1 x 0.5	6 x 0.5
Sep	3.64	33	10.19	8 x 0.38	1 x 0.5	8 x 0.5
Oct	2.7	28	6.41	8 x 0.39	1x 0.5	8 x 0.5
Nov	1.13	20	3.66	3 x 0.43	1x 0.5	8 x 0.5
Dec	0.87	15	2.66	3 x 0.41	2x 0.5	8 x 0.5



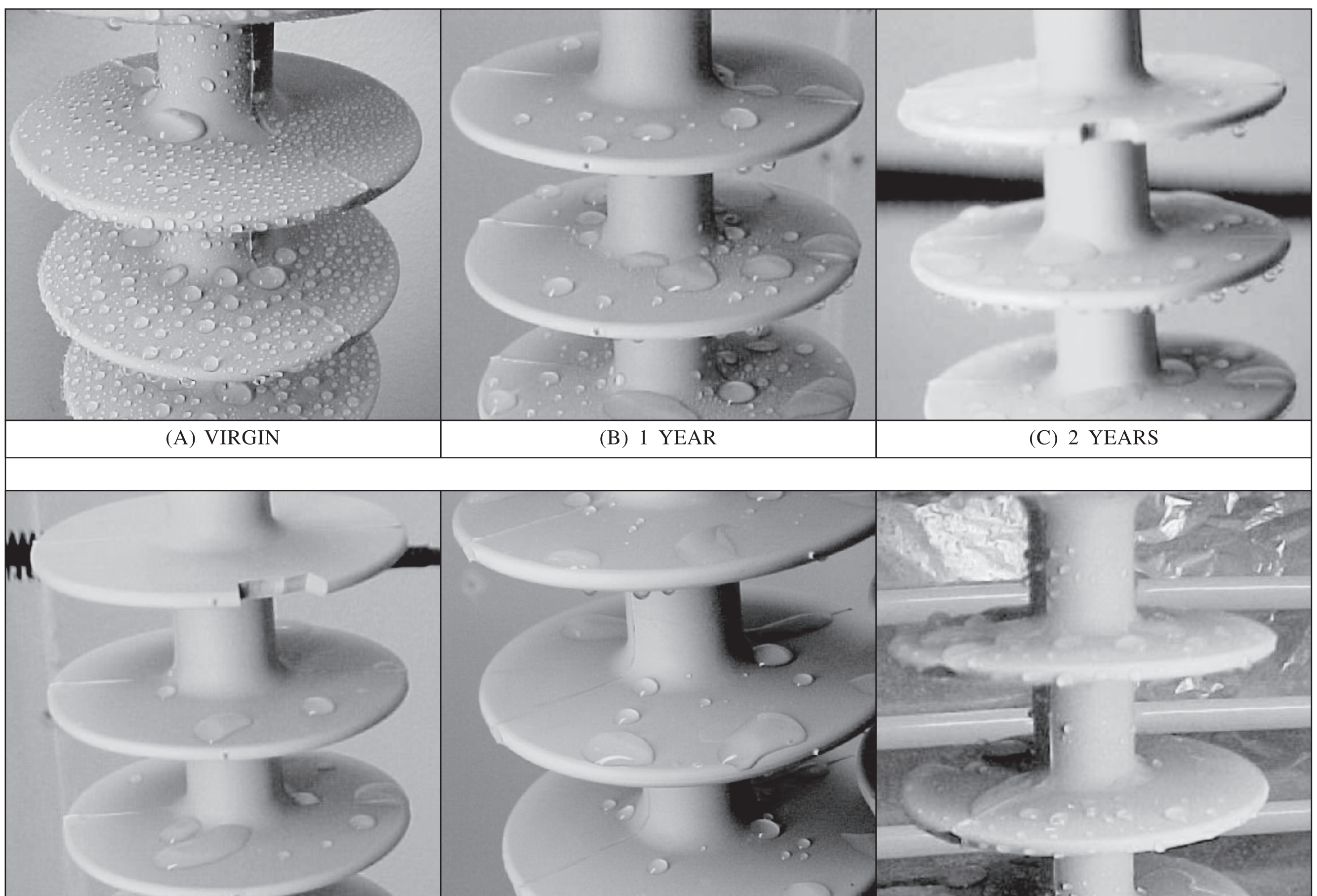
(A) HC 1 (B) HC 6

FIG. 2: HYDROPHOBICITY CLASSIFICATION CHART

TABLE 4

VISUAL OBSERVATIONS OF BOSTON AND SAN FRANCISCO

Item	Boston	San Francisco
Virgin	Water droplets (HC 1)	Water droplets (HC)
Year 1	No noticeable colour change No white salt deposit Droplets not too big (HC 2)	No noticeable colour change Some white salt patches on 2 skirts Droplets slightly bigger (HC 2-3)
Year 2	No noticeable colour change Some white salt patches on under skirts Droplets bigger than 1st year (HC 3)	No noticeable colour change Some white salt patches on 2 skirts Droplets bigger than 1st year (HC 3-4)
Year 3	No noticeable colour change Some white salt patches on under skirts Droplets bigger than 2nd year (HC 3-4)	No noticeable colour change Some white salt patches on 3 skirts Droplets bigger than 2nd year (HC 4-5)
Year 4	No noticeable colour change Some white salt patches on all skirts Droplets slightly smaller ($HC3^-$)	No noticeable colour change Some white salt patches on 2 skirts Droplets same as 3rd year (HC 4-5)
Year 5	No noticeable colour change Some white salt patches on all skirts Droplets almost same as 4th year (HC 2-3)	No noticeable colour change Some white salt patches on 2nd stem Droplets same as 3rd year (HC 4-5)



(A) VIRGIN (B) 1 YEAR (C) 2 YEARS

(D) 3 YEARS (E) 4 YEARS (F) 5 YEARS

FIG. 3 HYDROPHOBICITY CLASSIFICATION OF 6 YEAR LAB AGED INSULATORS—SAN FRANCISCO

5.0 ESDD/NSDD

The ESDD and NSDD were calculated by the standard method [16] and the results are shown in Tables 5 and 6.

TABLE 5

BOSTON AND SAN FRANCISCO, ESDD DATA

Year	ESDD—mg/cm²	
	Boston	**San Francisco**
1	0.001686	0.004167
2	0.001389	0.004407
3	0.001168	0.005755
4	0.002031	0.003200
5	0.005474	0.003873

TABLE 6

BOSTON AND SAN FRANCISCO, NSDD DATA

Year	ESDD—mg/cm²	
	Boston	**San Francisco**
1	0.014142	0.000
2	0.019641	0.034
3	0.033783	0.014
4	0.018070	0.060
5	0.020425	0.010

5.1 Electrical measurements

Leakage current data provide details about the surface conditions and hence the nature of ageing/degradation suffered by the sample, if any. In this research, the leakage current and the applied voltage were collected every minute, using which the cumulative surface charge (data not shown) and the watts loss were computed [12]. The leakage currents were acquired in ten bins so the number and magnitudes are known [14]. Fig. 4 shows the leakage current pulses obtained in the ten bins after 5 years ageing for both Boston and San Francisco conditions. The San Francisco environment had a large number of leakage current pulses in bins 1 (0.75mA to 1mA) and 2 (1-2mA) than the Boston environment.

Fig. 5 shows the watts loss computed for these two conditions. At year 1, there was less loss under Boston condition than at San Francisco, but they both became almost equal for years 3-5.

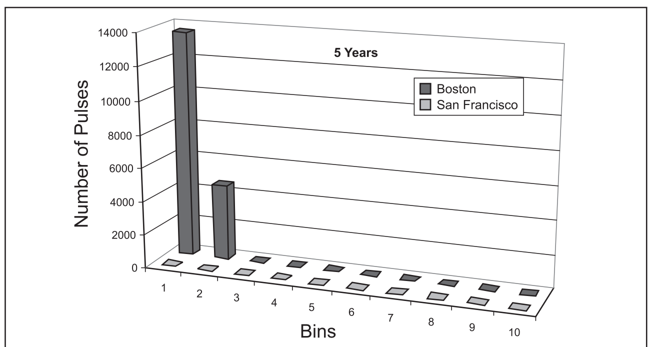


FIG. 4 LEAKAGE CURRENT PULSES FOR BOSTON AND SAN FRANCISCO

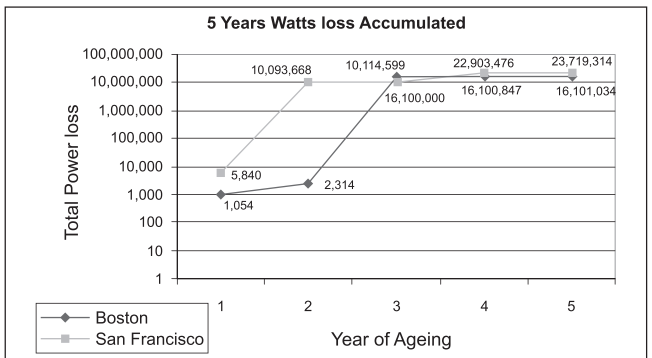


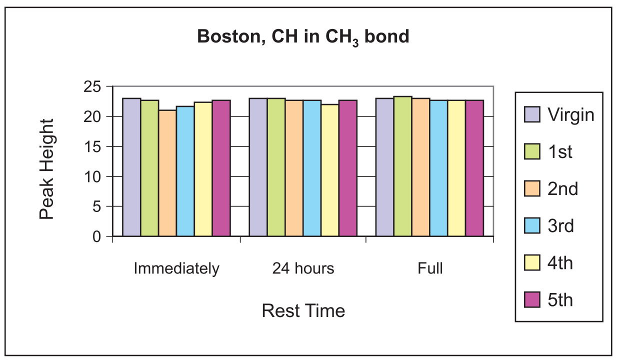
FIG. 5 POWER LOSS FOR BOSTON AND SAN FRANCISCO

5.2 Material characterisation

Because of ageing, polymeric surfaces change at the macro level due to local bond structure change with time causing interactions with other molecules at the micro level. The molecular structural changes were studied using state-of-the-art material analysis techniques, FTIR and SEM [4, 14].

5.3 FTIR

A Nicolet, AVATAR 360 FTIR E.S.P. Fourier Transform Infrared (FTIR) spectrometer with an attenuated total reflection (ATR) attachment and the Golden Gate single reflection Diamond was used to study the molecular structural changes of these aged surfaces. The size of the specimen was approximately 0.3x0.3 cm² cut from both the high voltage (HV) and the ground end. Tables 7 and 8 give the HV peak height variations for the two conditions. Fig. 6 illustrates the changes in CH molecules. Both the environments had almost similar changes.



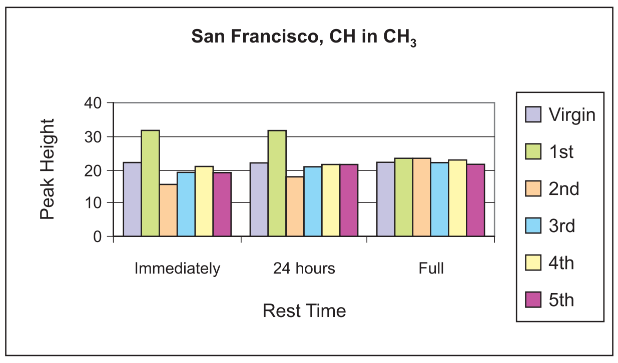


FIG. 6 COMPARISON OF CH IN CH_3 AGEING OF BOSTON AND SAN FRANCISCO – THE FTIR SPECTRA WERE TAKEN IMMEDIATELY AFTER THE AGEING FOR EACH YEAR, AFTER 24 HOURS AND THEN AFTER ONE MONTH (FULL) TO INVESTIGATE THE EFFECT OF RECOVERY.

TABLE 7

SAN FRANCISCO INSULATOR 1 HV FTIR PEAK HEIGHT VARIATIONS

	Wave Number	Vibration	Virgin	Year 1	Year 2	Year 3	Year 4	Year 5
1	3617	O-H Stretch	10.01	14.19	8.01	8.88	7.40	6.965
2	3525	OOH Stretch	19.13	21.19	15.93	15.06	13.05	12.40
3	3450	Silanol SiOH stretch	13.60	12.00	11.66	9.46	9.13	9.03
4	3371	Silanol SiOH stretch	3.48	4.01	3.23	3.35	3.04	2.76
5	2962	CH_3 asymmetric	16.95	17.67	14.39	14.57	15.49	14.79
6	2904	Methine C-H stretch	1.59	1.74	1.32	1.70	1.71	1.58
7	1577	Asymmetric CO_2 stretch	0.072	0.263	0.246	2.45	2.09	1.56
8	1540	Asymmetric CO_2 stretch	0.04	0.02	0.32	2.57	2.16	1.68
9	1413	CH_3 umbrella mode	6.35	12.08	3.80	4.39	4.45	4.35
10	1259	CH_3 umbrella mode in $Si(CH_3)_2$	46.61	48.03	44.13	42.54	44.48	42.66
11	1089	Si-O-Si Asymmetric stretch	12.78	12.55	12.50	10.56	11.27	10.03
12	1006	Si-O-Si Asymmetric stretch	30.22	25.28	31.97	29.09	28.94	27.87
13	788	CH_3 rock in $Si(CH_3)_2$	24.43	20.81	25.01	23.00	23.86	23.68
14	732	C-O in plane bend	8.58	6.67	9.22	8.55	8.11	8.36

TABLE 8

BOSTON INSULATOR 1 HV FTIR PEAK HEIGHT VARIATIONS

	Wave Number	Vibration	Virgin	Year 1	Year 2	Year 3	Year 4	Year 5
1	3617	O-H Stretch	11.23	10.63	9.64	11.56	11.11	10.48
2	3525	OOH Stretch	19.18	18.52	17.05	19.95	19.20	18.29
3	3450	Silanol SiOH stretch	14.42	14.66	12.72	15.34	14.72	14.55
4	3371	Silanol SiOH stretch	3.66	3.52	3.09	3.81	3.67	3.47
5	2962	CH_3 asymmetric	18.04	17.15	13.96	17.64	17.25	16.94
6	2904	Methine C-H stretch	1.52	1.0	1.15	1.55	1.45	1.63
7	1413	CH_3 umbrella mode	3.37	12.08	3.80	4.39	4.45	4.35
8	1259	CH_3 umbrella mode in $Si(CH_3)_2$	47.07	46.35	38.38	46.11	45.48	44.33
9	1089	Si-O-Si Asymmetric stretch	13.11	12.85	10.66	12.63	12.39	11.82
10	1006	Si-O-Si Asymmetric	32.29	32.26	27.15	32.18	31.78	31.18
11	788	CH_3 rock in $Si(CH_3)_2$	24.36	24.35	20.33	23.96	23.72	23.70
12	732	C-O in plane bend	7.64	7.75	7.39	7.49	7.62	7.98

In the case of San Francisco environment, there were 20–35% reduction of peak heights (indicating reduction in OH and Si-OH functional groups) of the first 4 bands and the 9th band. The other changes were 2 to 12%, indicating that the backbone remains unaltered in 5 years. There was a slight increase in years 2 and 3, but stabilised in years 4 and 5.

However in the case of Boston environment, due to relatively more rain, the salt got washed off and so there were less changes (1-10%) in all the bands indicating that the molecular structure was intact.

5.4 SEM

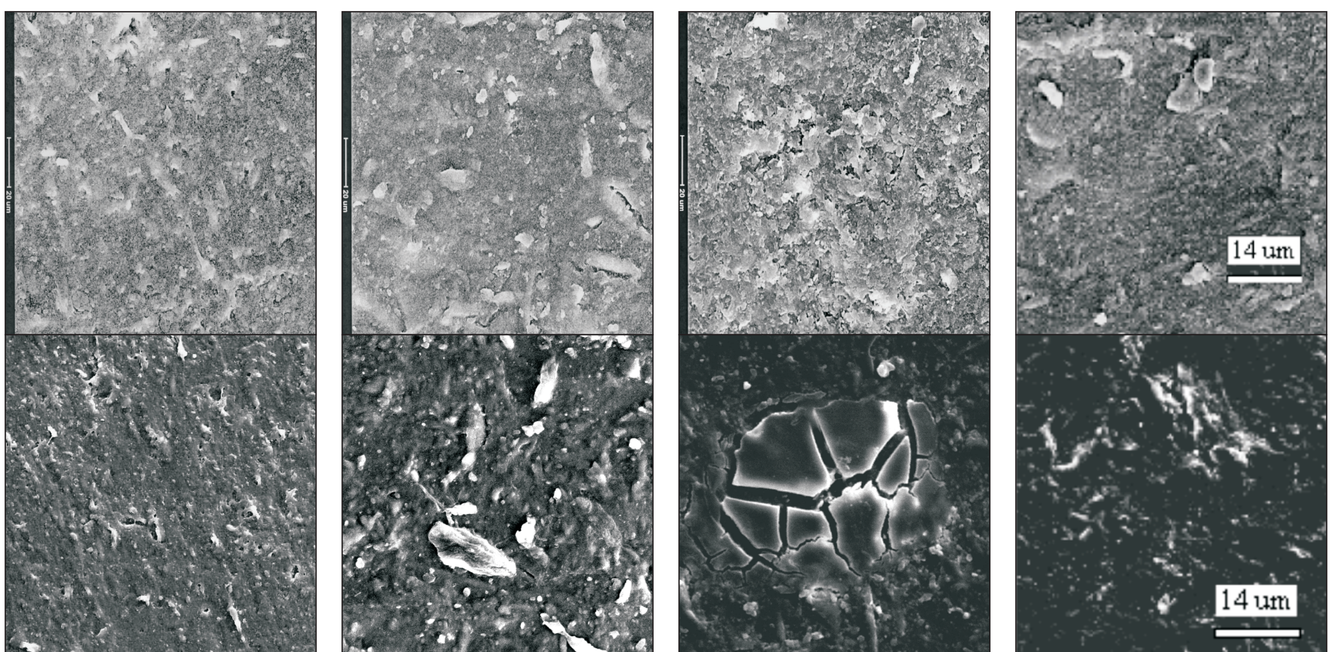
The topography of the insulators was studied using SEM. A JEOL 840 SEM equipped with an energy dispersive X-ray attachment (EDAX) at 20eV was used. Fig. 7 shows the SEM micrographs for San Francisco (top) and Boston (bottom) for years 1, 3 and 5 along with virgin at 700x. It can be seen that there was no change in year 1, started slight degradation in years 2 and 3, but stabilised back to almost original state in years 4 and 5. These changes corroborated the changes observed using FTIR technique.

5.5 Energy Dispersive X-ray (EDX)

EDX was used to monitor the transfer of degradation and hydrophobicity through the insulator surface layer by demonstrating the depletion of low molecular weight polymer chains on the surface of the aged material and counting the ratio of silicone to aluminium of the insulator.

Tables 9 and 10 show the San Francisco and Boston samples Si/Al ratio obtained using three different calculations, such as EDX counts, weight % and atomic % (Fig. 8). Si is the base material and Al is added as filler to take care of tracking and erosion.

In San Francisco ageing, the Si/Al ratio from EDX counts first increased from 1.215 (virgin) to 1.394 after 1st year ageing. It decreased to 0.943 after 2nd year ageing and increased to 1.206 after 3rd year ageing. After 4th year ageing, it increased dramatically to 1.924 indicating the surface now has more Si than before. These results are in line with SEM and FTIR results.



VIRGIN | YEAR 1 | YEAR 3 | YEAR 5

FIG. 7 SEM MICROGRAPHS OF SAN FRANCISCO (ABOVE) AND BOSTON (BELOW)

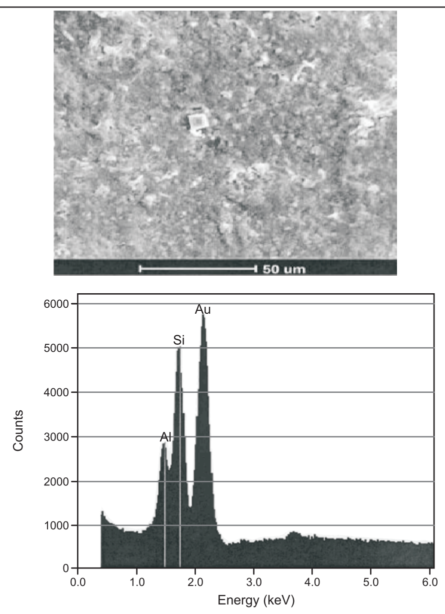


FIG. 8 EDX OF BOSTON—4th YEAR SAMPLE

TABLE 9

Si/Al RATIO, SAN FRANCISCO AGEING

Sample	EDX counts	Weight %	Atomic %
Virgin	1.215	1.152	1.107
1st Year	1.537	1.457	1.423
2nd Year	1.169	1.108	1.064
3rd Year	1.182	1.121	1.076
4th Year	1.660	1.575	1.513
5th Year	1.618	1.535	1.47

TABLE 10

Si/Al RATIO, BOSTON AGEING

Sample	EDX counts	Weight %	Atomic %
Virgin	1.215	1.152	1.107
1st Year	1.394	1.322	1.270
2nd Year	0.943	0.895	0.859
3rd Year	1.206	1.144	1.099
4th Year	1.924	1.825	1.753
5th Year	1.130	1.072	1.03

6.0 CONCLUSIONS

Study of long term ageing and degradation of polymeric insulators under multistress conditions, representing actual in-service conditions is the desirable way to understand the ageing and degradation of outdoor, high voltage insulators. In general, the leakage currents were very small in this study. There were no arcing or any discharge observed during ageing period, indicating that silicone rubber insulators undergo very little ageing. The changes in the same insulators aged for the same period, under San Francisco and Boston environments showed the effect of environmental stresses on the ageing and degradation of the insulator system.

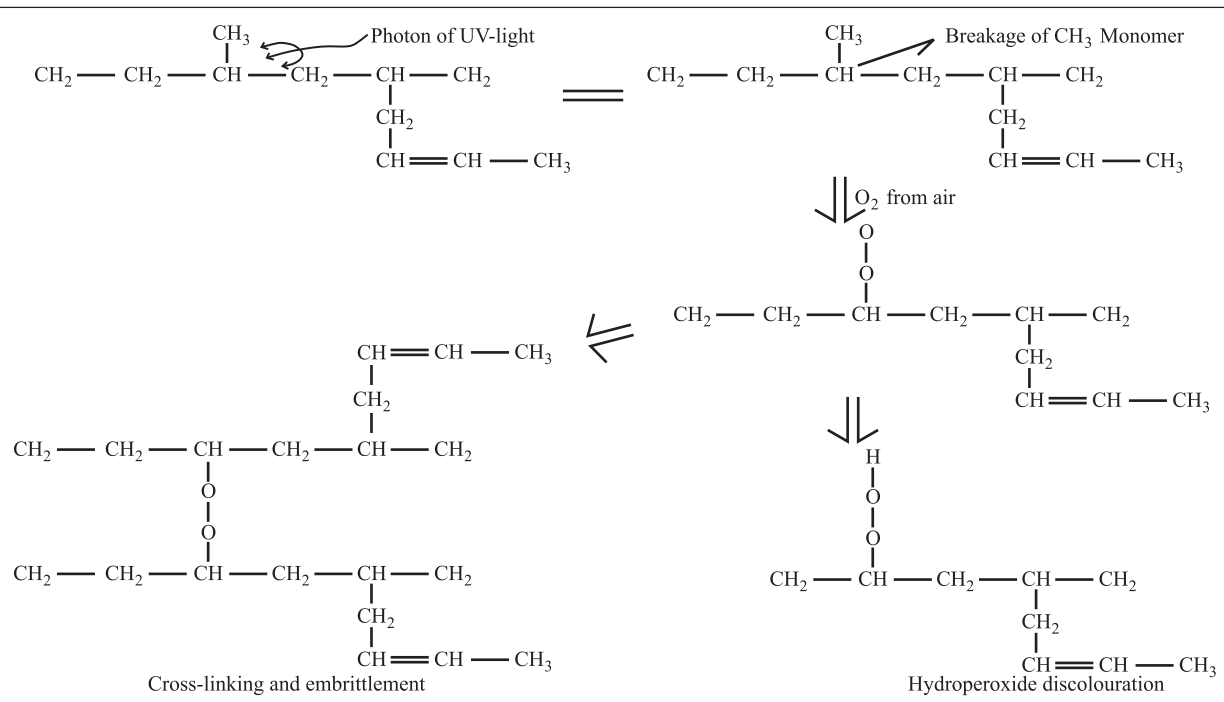


FIG. 9 MECHANISM OF AGEING OF POLYMERIC MATERIALS[4]

There was close correlation between FTIR, SEM and EDX techniques. This research threw more light on the performance of polymeric insulators, their design and material performance.

7.0 ACKNOWLEDGEMENT

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