The polychlorinated biphenyls (PCB's) which had excellent electrical properties were banned in the year 1972, as they were found to be toxic and non-biodegradable. Hence, the necessity arose for search of new liquids having properties equivalent to that of PCB's for use as capacitor impregnants. Keeping the above aspect in mind, the dielectric constant and dissipation factor of some of the available vegetable oils were studied. Among them castor oil was found to offer a higher dielectric constant with a lower dissipation factor and hence it was decided to study further the properties of castor oil to explore the possibilities of using it in place of PCB's. The measurements of physical, chemical and electrical properties of castor oil indicated that these properties are equivalent to that of a typical PCB excepting the dissipation factor which is slightly on the higher side. Hence to reduce the dissipation factor and at the same time to get a reasonable value of dielectric constant, the idea of mixing some other liquids with castor oil was thought off. Transformer oil (a derivative of mineral oil) has been the most widely used impregnating liquid for electrical insulation and was considered for mixing with castor oil, in the present study. The different properties of castor oil - transformer oil mixture, mixed in equal volume proportions (called as mixed oil) were studied. Most of the properties were found to be comparable to that of PCB's and some properties (viscosity and DC resistivity) were found to excel them. But, as expected, the dielectric constant of mixed oil was found to be less than either castor oil or PCB. Studies were also conducted with some organic additives of higher dielectric constants added in small percentage to castor oil. The results were not encouraging and hence this proposal was not pursued.

Having identified the castor oil and mixed oil to have properties equivalent to that of PCB's, they were considered as possible substitutes.
for PCB's, and further investigations were therefore made with castor oil and mixed oil impregnated systems and capacitors. Kraft paper (derivative of cellulose) and polypropylene (a synthetic polymer) are the widely used dielectrics in capacitors. The compatibility of castor oil and mixed oil with paper-polypropylene and all-polypropylene dielectric systems were assessed using Infra Red Spectrums taken for these oils before and after aging for 500 hours in the above dielectrics at high temperatures. The dielectric properties of paper and polypropylene systems under unimpregnated and impregnated conditions were studied and further studies were made on the encapsulated capacitors. For this purpose four different types of capacitors of the following details were fabricated:

- Paper-polypropylene capacitors impregnated with castor oil
- Paper-polypropylene capacitors impregnated with mixed oil
- All-polypropylene capacitors impregnated with castor oil and
- All-polypropylene capacitors impregnated with mixed oil

The dielectric properties including partial discharge levels and body temperature rise were measured for all the four different types of capacitors and a comparative analysis was made between the capacitors.

To make the investigations complete, the aging characteristics of these capacitors were studied by conducting accelerated life studies at higher than normal operating temperatures and electrical stresses. These studies were conducted,

- when thermal stresses alone were acting on the capacitors
- when both thermal and electrical stresses were acting together on the capacitors

The aging studies for thermal stresses alone were conducted at three temperatures and studies with combined thermal and electrical stresses were conducted at 4 different temperatures each at 4 different electrical
stresses. The end point criterion for thermal aging was chosen as the decrease in the DC dielectric strength to a value of 2 kV and for aging under combined thermal and electrical stresses, the criterion was the ultimate breakdown of the capacitors. Generally, the failure times of capacitors vary and are governed by extreme value statistics. Hence, order statistics was resorted to in the analysis of failure times (life data). Mathematical distributions (log-normal plot and Weibull plot) were fitted to represent the life data obtained under thermal aging and aging under combined stresses. The characteristic lives under different stress conditions were calculated from the above fitted distributions using relevant statistical procedures (in the present case, graphical and linear regression methods including Gauss Markov Technique). The thermal life and the life at constant electrical stresses were found to follow to a greater extent the Arrhenius relation. The electrical life at constant temperatures were found to follow both the power law relation and exponential relation. Based on the relations representing the thermal life and electrical life at constant temperatures and the practical constraints, a new model has been developed to represent the life of different types of capacitors in terms of temperature and electrical stress. The proposed model incorporates the Arrhenius relation in modified form for thermal stress, a product form incorporating the exponential law and modified power law for electrical stress and an exponential term combining electrical stress and temperature. The proposed model has been compared with two available models and found to be superior to both of them. The speciality of the proposed model also lies in addition to a better fit to the actual life data any non-linearity in the log life - log electrical stress plot can be taken into account.

From the studies conducted on the various aspects of liquid impregnants, liquid impregnated systems and the different types of capacitors, the following conclusions are drawn:

1. The physical, chemical and electrical properties of castor oil are comparable to that of typical PCB. Though the viscosity of castor oil is higher at low temperatures, at impregnating temperature the viscosity is very close to PCB and hence useful for good impregnation.
2. The different properties measured for mixed oil indicate that the mixed oil also has properties equivalent to that of PCB, excepting that the dielectric constant is lesser ($\varepsilon' = 3.5$). Further, the viscosity and the dissipation factor are less when compared to PCB. The reduced dissipation factor (and hence the dielectric losses) indicates better life performances. The reduced viscosity enables better impregnation than castor oil.

3. Most of the properties of mixed oil are in between those of castor oil and transformer oil, which shows that both liquids mix well with each other. The measured values of permittivity and dissipation factor for mixed oil were found to be in close agreement with the calculated values in terms of the permittivities and dissipation factors of component liquids in the mixture and this again confirms that, on mixing, castor oil and transformer oil forms homogeneous mixture.

4. From the measurements of dielectric constant and dissipation factor of mixed dielectric capacitors impregnated with mixture of castor oil and transformer oil in different volume proportions it is inferred that an impregnant mix with the above oils in equal volume proportions (i.e. 50%/50%) was found to be an optimum mix, yielding better dielectric properties.

5. The compatibility of mixed oil and castor oil with paper-polypropylene and all-polypropylene dielectrics was assessed by comparing the infra red (IR) spectrums of these oils taken before and after aging of 500 hours in the respective dielectrics at constant temperature of 100°C. A careful study of the IR spectrums indicated that there was no structural change in either mixed oil or castor oil due to aging and hence it is inferred that the compatibility of mixed oil and castor oil with paper and polypropylene dielectric is good.

6. The increase of dissipation factors of castor oil and mixed oil at high temperature indicate that the dielectric losses are mainly due to dipole relaxation in these liquids. The viscosity decreases with rise in temperatures facilitating the dipole movement.
7. Dielectric measurements were made on liquid mixtures with small percentage of organic additives - like toluene, ethylene glycol, ethyl acetoacetate and nitrobenzene - added to castor oil. These measurements indicated that though the dielectric constant of the mixture increased by about 10 percent, the dissipation factor increased to as high as 70 times. Hence, it was decided that these organic additives in its natural forms cannot be used with castor oil for impregnation.

8. The equivalence with which most of the physical, chemical and electrical properties of mixed oil and castor oil agree with typical PCB, indicates that mixed oil and castor oil can be considered as replacements for PCB's for use as capacitor impregnants.

9. The DC and AC dielectric strength measurements on paper and polypropylene dielectric impregnated with mixed oil and castor oil indicated that the breakdown strengths of polypropylene film are 4 to 5 times those of paper dielectric both under unimpregnated and impregnated conditions. The breakdown strengths with mixed oil impregnation and castor oil impregnation were found to be almost same.

The studies conducted on the different types of encapsulated capacitors led to the following:

10. Paper-polypropylene mixed dielectric capacitors impregnated with either oils (mixed oil and castor oil) have very low capacitance retrace from $5.025 \times 10^{-3}$ to $15.95 \times 10^{-3}$ whereas all-polypropylene capacitors have a higher value of about $45 \times 10^{-3}$.

11. As an encapsulated capacitor, the capacitors impregnated with mixed oil have higher DC and AC dielectric strength when compared to the capacitors impregnated with castor oil, whereas, earlier the dielectric strength of paper and polypropylene film impregnated with mixed oil was found to be almost equal to those impregnated with castor oil. This particular aspect encourages the use of mixed oil for impregnation in making encapsulated capacitors.
12. Though mixed oil has a dielectric constant of about 70% of that of castor oil, the capacitance values for the encapsulated capacitors (for same winding length) impregnated with mixed oil or castor oil differ very little.

13. The dielectric losses in (P + PP + CO) capacitors were found to be higher than the other types of capacitors and next in the decreasing order of losses are (P + PP + MO), (PP + CO) and (PP + MO) capacitors. This confirms that in paper-polypropylene capacitors in addition to the conductive losses and debye type losses, Maxwell-Wagner type losses (losses due to interfacial polarization) are also predominant, whereas in the case of all-polypropylene capacitors the losses due to interfacial polarization is absent. Again as expected, the losses in castor oil impregnated capacitors are more than mixed oil impregnated capacitors. Therefore, as predicted the maximum body temperature rose to 6.5°C for (P + PP + CO) capacitors and for (P + PP + MO), (PP + CO) and (PP + MO) capacitors the rise in temperatures were found to be 5.5°C, 3.5°C and 3°C respectively. The life performance is dependent on the dielectric losses and hence the rise in temperature during operation. In this respect, mixed oil impregnated capacitors are better when compared to castor oil impregnated capacitors.

14. The partial discharge inception stresses were found to be higher for capacitors impregnated with mixed oil when compared to the capacitors impregnated with castor oil.

15. Based on the dielectric strength and partial discharge measurements on the encapsulated capacitors, the safe operating stress for impregnated paper, paper-polypropylene and all-polypropylene capacitors were fixed at 16, 30 and 40 Volts per micron respectively.

The aging characteristics of the different types of capacitors were assessed by conducting accelerated life experiments at temperatures and electrical stresses of higher values than normal operating levels. The thermal aging tests were conducted at temperatures of 110°C, 130°C and 150°C. The aging tests under combined thermal and electrical stresses were conducted
at temperatures of 40°, 60°, 80° and 100°C and electrical stresses of 50, 60, 70 and 75 Volts per micron in the case of (P + PP) capacitors and 58, 70, 82 and 88 Volts per micron in the case of (PP) capacitors. Based on the life data distributions, a new model was developed to represent capacitor life at different temperatures and electrical stresses. The proposed model has been compared with available models developed by leading authors. The conclusions arrived from the above studies are as follows:

16. The failure times due to thermal aging could well be represented by log-normal plot.

17. A three parameter Weibull distribution is generally used to represent the failure times due to aging under combined thermal and electrical stresses. In the present study, the plotting of raw failure data on the X-axis itself yields a good fit. This implies that the location parameter \( \mu \) of three parameter Weibull distribution is zero and a two parameter Weibull distribution is found to be appropriate in the present case.

18. The statistical procedures - the graphical and linear estimation techniques including Gauss-Markov Technique - which were used to calculate the characteristic lives under aging due to thermal stresses only and aging due to combined thermal and electrical stresses yielded similar results.

19. The shape parameter \( \beta \) of Weibull distribution representing electrical failures at constant temperatures, was found to vary between 1.3 to 3.8, indicating variability in failures. This shows that the intra sample and inter sample failures were non-uniform.

20. The thermal life (i.e. the life when thermal stresses only were acting) followed Arrhenius relation, based on the degradation of dielectric due to chemical reaction. The life of capacitors, at constant electrical stresses also followed the Arrhenius relation to a great extent.
21. The data for electrical life, at constant temperatures, were well represented by both power law as well as exponential law. However, the very high values of regression coefficients calculated for the respective fits indicate that power law fits better than exponential law.

22. Under identical aging conditions, paper-polypropylene capacitors are found to have higher lives compared to all-polypropylene capacitors. Further mixed oil impregnation increases the life when compared to castor oil impregnation.

23. Paper-polypropylene capacitors impregnated with mixed oil are being manufactured by M/s. Electronics India Ltd., and are in service for the past four years. Not a single complaint was received from the customers on the above capacitors and this indicated that the mixed oil impregnant as suggested in this thesis work for capacitors is the suitable substitute for polychlorinated biphenyls (PCB's).

24. The proposed new model to predict the life of capacitors under combined thermal and electrical stresses fits well with the experimental life data for all the different types of capacitors. The normalised mean errors, taking into account the actual life and predicted life, were calculated for the proposed new model and were compared with Endicott et al. and Simoni models. The accuracies obtained using the new model were found to be much better when compared to the other two models.