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AN ASSESSMENT OF THE LONG TERM CAPACITOR  
REQUIREMENTS FOR STATIC POWER CONVERSION EQUIPMENTS

by

C. E. Mugford

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SUMMARY

The recent trends in conversion equipments towards higher powers and smaller sizes highlights the need for more advanced components. This paper discusses the equipment designer's requirements for capacitors in the next decade.

The paper consists of three main sections dealing with commutation, filters and the environmental conditions of capacitors.

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- FIG. 1A & 1B Current and voltage waveforms for commutation capacitors.  
 FIG. 2 Peak voltage and capacitance for commutation capacitors.  
 FIG. 3 Percentage change in capacitance with temperature.  
 FIG. 4 Insulance change with temperature.  
 FIG. 5 Peak voltage and capacitance for ripple filter capacitors.  
 FIG. 6 Reliability of capacitors.

## 1. INTRODUCTION

- 1.1 The future requirements for Static Power Conversion Equipments appear to be very extensive both in Military and Civil applications. At present the short-comings of semiconductors and capacitors limit the theoretically high efficiencies possible with this type of equipment and it is considered that improvements in these devices are necessary if high efficiency and compactness are to be realized.
- 1.2 Semiconductors have already been discussed in S. R. D. E. Report No. 67006 and this paper is intended to cover the main aspects of capacitor performance in conversion equipment.
- 1.3 It is hoped that, by indicating what improvements are necessary, the capacitor manufacturers will endeavour to meet these requirements, as it is anticipated that large quantities will be required.
- 1.4 This report was compiled in consultation with the design teams of Establishments and Equipment Manufacturers who are at present producing static conversion equipment.

The figures quoted are not intended to show a specific requirement, but rather an indication of the general requirements of the designers.

## 2. APPLICATIONS OF CAPACITORS

The report consists of the following sections:-

- (a) Commutation capacitors.
- (b) Filter capacitors, sub divided into:-
  - (i) Ripple suppression filters.
  - (ii) Harmonic suppression filters.
  - (iii) Radio interference suppression filters.
- (c) Physical requirements for capacitors including reliability.

Sections (a) and (b) describe the likely electrical conditions that the capacitors will experience and Section (c) discusses the merits of the various capacitor types available at present. An indication is then given of how presently available types could be improved, or increased use made of newer types of capacitor.

## 3. COMMUTATION CAPACITORS

### 3.1 Introduction

- 3.1.1 The process of switching an S. C. R. off is called commutation. In order to do this either the forward current has to

be reduced to below the holding current value, or the anode to cathode voltage reversed. Commutation can either be natural or forced, and there are various classes of forced commutation employed in conversion circuits.

Capacitors have an important role in commutation and this section describes likely electrical conditions that these capacitors will encounter.

- 3.1.2 Capacitors are not designed specifically for this application and equipment manufacturers have said that choosing a capacitor for commutation depends to a large extent on experience.

The reason for this situation is that although r. m. s. currents and voltages can be measured, peak values can occur which can damage capacitors chosen merely with the nominal parameters in mind. It may be necessary therefore, to specify to the capacitor manufacturer the waveform that the capacitor will experience so that a suitable component can be offered.

- 3.1.3 Capacitors for commutation are non-polar types.

## 3.2 Electrical Conditions

### 3.2.1 Capacitance and Voltage Ratings

The capacitance values required by the majority of firms ranged up to 200  $\mu\text{F}$ ; however, one firm suggested values up to 400  $\mu\text{F}$  and another up to 1000  $\mu\text{F}$  but these were considered exceptional.

The voltage requirements are extremely difficult to quote as can be seen from Figs. 1A and 1B, which show the waveform for a 40  $\mu\text{F}$  capacitor on and off load. These waveforms are not sinusoidal but asymmetrically trapezoidal. The harmonic content of this type of waveform would also be important when considering voltage spike information. Voltage ratings have been quoted by many firms and the figures below show the average requirements:-

Max. d. c. voltage:	300 to 400 volts
Max. (r. m. s.) a. c. voltage:	400 to 800 volts
	(560 to 1120 volts peak)

Voltages up to 860 or even 1500 volts may be expected for some commutation applications.

In order to depict what capacitance and voltage is required of the same capacitor, Fig. 2 shows the total peak voltage against capacitance, with an indication of some specific requirements.

### 3.2.2 Series Inductance and Resistance

Lower series inductance and resistance values are required for commutation capacitors in order to reduce losses.

The following figures are suggested:

2.5  $\mu\text{H}$  for the 10  $\mu\text{F}$  capacitor

50  $\mu\text{H}$  for the 200  $\mu\text{F}$  capacitor.

(It is important to note that in some instances series inductance is added to commutation capacitors in order to control the initial rate of rise of anode current through the S. C. R.)

### 3.2.3 Peak current Rating

Although peak voltages have been mentioned (para. 3.2.1) it is vitally important that capacitors can withstand high peak currents. Systems with 80 to 300 amps peak currents lack suitable capacitors.

### 3.2.4 Temperature Limits

The ambient temperature limits should always be quoted, as capacitance change with temperature can be very pronounced with certain types of capacitor. Fig. 3 shows the percentage change in capacitance with temperature for three types of capacitor. The graph clearly indicates the benefit of using polycarbonate types where wide temperature variations are expected.

Commutation capacitors should be capable of operating satisfactorily from  $-55$  to  $+135^{\circ}\text{C}$ .

### 3.2.5 Power Factor

Section 3.2.2 has mentioned that Series L and R should be kept low. This fact is doubly important as short discharge times are necessary during commutation, when low power factor is essential.

## 3.3 Types of Commutation Capacitors

3.3.1 The types of capacitor most generally used for commutation are foil and paper (or metallised paper) or perhaps metallised

polyester. Because of their technical advantages it is hoped that in the near future polycarbonate capacitors will be more economic.

3.3.2 Polycarbonate capacitors are preferred for several reasons:

- (i) Their reliability is very good and is described further in Section 9.
- (ii) They can operate between wide temperature limits.
- (iii) The units are of smaller size and better performance than comparable capacitors, although at present the capacitance and voltage ratings need to be improved.
- (iv) Polycarbonates employ lower power factor materials which enable high commutating currents to flow without thermal runaway.
- (v) A graph of insulation (ohms-farads) against temperature, Fig. 4, shows a further advantage of polycarbonate dielectric and its temperature capability.

3.3.3 It is likely that either solid tantalum or tantalum gel capacitors would be suitable for commutation, however capacitance and voltage ratings would need to be improved and price considerably reduced.

3.3.4 Solid aluminium capacitors are attractive as they are more reliable than tantalum capacitors and have longer life expectancy at higher temperatures.

They have limited capacitance and voltage ratings but their price is approximately one third of the solid tantalum equivalent.

## 4. FILTER CAPACITORS

### 4.1 Introduction

In power conversion equipments the largest components are the energy storage capacitors. As the trend is towards light-weight and high efficiency, it is vital that smaller and more reliable capacitors be made available.

Several types of filters are built into conversion equipment.

- (i) Ripple suppression filters for d. c. outputs
- (ii) Harmonic suppression filters for a. c. outputs
- (iii) Radio interference suppression filters.

These filters are often designed to cope also with transients that occur in power systems and which would otherwise cause damage. All these types are covered by this report and it will be seen that ripple filters present the biggest problem. High energy storage is coupled with output filter arrangements, and for this reason very high values of capacitance are necessary.

## 5. RIPPLE SUPPRESSION FILTER CAPACITORS

### 5.1 Electrical conditions

#### 5.1.1 Capacitance and Voltage Ratings

The requirements for capacitors for this application vary quite considerably. The graph of d. c. voltage against capacitance Fig. 5 shows the area in which capacitors are required, and also shows the specific requests.

Generally capacitors of up to 10,000  $\mu\text{F}$  were requested, although up to 500,000  $\mu\text{F}$  was quoted.

#### 5.1.2 Current capability

The ripple current capability of most high valued capacitors is usually too restricted, and it appears that considerable improvement is necessary in this parameter. It is hoped that the ripple current capability can be improved by four or even ten times the presently available figures.

It is anticipated that ripple currents up to 50 amps will be normal, however specific requirements are:-

- (1) 75 Amps (2,000  $\mu\text{F}$  450V d. c.)
- (2) 26 Amps (500,000  $\mu\text{F}$  5V d. c.)

It is also apparent that ripple currents should be quoted as a function of frequency in data sheets.

#### 5.1.3 Impedance Values

In order that fast response times can be obtained with filter capacitors, the series L and R values should be low. The inductance value should be such that at 50 Kc/s the capacitor is still capacitive. Alternatively, the inductance should be that of a copper bar of dimensions equivalent to the capacitor.



Lower valued capacitors could be employed for certain high frequency operations if the series resistance could be reduced, e. g. if the series R could be reduced to typically 10 milliohms for a capacitor size of  $2\frac{1}{2}$ " diameter by  $4\frac{1}{2}$ ", the circuit capacitance value could be reduced with a consequent reduction in size for certain applications.

#### 5.1.4 Frequency

It is necessary for the upper frequency limit to be as high as 50 Kc/s (para. 5. 1. 3). At this frequency the capacitance value should not start to fall off sharply.

#### 5.1.5 Temperature Limits

It is likely that filter capacitors will be exposed to temperature variations between -55 and +135°C.

### 5.2 Types of Ripple Filter Capacitors

In almost all applications where high capacity is required aluminium electrolytics are employed, however it is becoming more certain that other types of capacitor would, after development, be more suitable for filter purposes.

These types are:-

- (i) Tantalum electrolytics
- (ii) Polycarbonate dielectric
- (iii) Solid Aluminium.

For all these types of capacitors the following parameters need considerable improvement.

- (a) d. c. voltage ratings.
- (b) Capacitance value - so that unreliable series and paralleling techniques could be eliminated.
- (c) Surge current capability.
- (d) The prices should be competitive.

Both tantalum and polycarbonate types can offer better capacitance to size ratio and have better reliability than aluminium types.

Dry electrolyte aluminium capacitors have the advantage of low leakage and excellent temperature capability (-55 to +135°C).

They are also cheaper than comparable tantalums and do not require reforming, a very important advantage.

## 6. HARMONIC SUPPRESSION FILTER CAPACITORS

There is a requirement for harmonic suppression filter capacitors of up to 40  $\mu\text{F}$  value which are rated at a voltage of 115 volts (r. m. s.). They should be capable of handling high peak voltages of up to 600 volts which exist for less than 10 milliseconds.

These capacitors should have series inductance values such that the capacitor is still capacitive at 10 Kc/s.

## 7. RADIO INTERFERENCE SUPPRESSION FILTER CAPACITORS

Conversion equipment is likely to experience voltage transients of considerable magnitude, and filters must be provided to prevent these surges from damaging the equipment.

For this purpose capacitors are required with the following parameters.

### 7.1 Capacitance and Voltage Ratings

Capacitors should have a value up to 100  $\mu\text{F}$  and be rated at 400 volts r. m. s. (continuous), and be capable of handling high peak voltages (600 volts) which exist for less than 10 milliseconds.

### 7.2 Other Electrical Characteristics

The series inductance should be low, as high frequencies will be present in the spikes, and the unit must be capacitive. The lead-through type of capacitor could be employed for this application, but usually the paper and foil type is used.

## 8. PHYSICAL REQUIREMENTS FOR CAPACITORS

This section covers all the applications included in the report, and where specific requirements are discussed mention is made of the fact.

### 8.1 Capacitor Terminals

It is agreed by most equipment manufacturers that the terminations on all capacitors are poor. The terminals should be capable of accepting welded, wrapped, crimped or soldered joints. There appears to be no metallurgical reason why all these types of connections could not be made.

The terminals should also be capable of handling the rated current.

## 8.2 Heat Transfer

Good heat transfer is very necessary for all types of capacitor as excessive temperature can reduce capacitor life. Ideally, cooling should be by conduction through the fixing bolts to the chassis or heatsink. This process enables more precise loss calculations to be made, also sealed packaging of the equipment can be more easily arranged if cooling interfaces are adequately designed.

Capacitors of foil construction should have the foil extended and connected to substantial terminals or to one side of the can.

The polycarbonate capacitors required by many manufacturers appear to offer reduced heat problems because of their higher operating temperatures. At temperatures lower than the maximum a low power factor will mean that less heat will be generated.

A further recommendation is that capacitors should be painted a matt black finish for improved heat dissipation.

## 8.3 Life expectancy

Capacitors are required to be used in equipments designed for an overall life of 10 years with a utilisation rate of 1,000 hours/year. Thus a capacitor life of 10,000 operating hours with a reliability of at least 99.9% (implying a M. T. B. F. of 10 million hours) is needed.

It is also hoped that the shelf life of large aluminium capacitors can be improved.

## 8.4 Physical Size and Shape

Physically smaller capacitors are very desirable. Most equipment manufacturers agree that a cubic or rectangular shape is preferred for better space utilization and also for better heat dissipation.

In order to obtain small size the polycarbonate, polyester or metallised paper capacitors are the most promising for commutation purposes; and the tantalum and solid aluminium for smoothing purposes.

## 8.5 Environmental Conditions

Every effort must be made to ensure that capacitors will withstand vibration, humidity and shock. To obtain these parameters good sealing and improved fixing terminals (Para. 8.1) are necessary.

The problem of temperature capability has already been discussed (Para. 3. 2. 4 and 5. 1. 5).

#### 8. 6 General Comments

The following comments are included to indicate further necessary improvements.

- (a) Information sheets on capacitors should be improved by showing:
  - (i) Ripple current ratings (especially at higher frequencies)
  - (ii) Power handling capability.
  - (iii) More clearly defined de-rating characteristics.
- (b) Consideration should be given to the eventual operating conditions of capacitors when they are designed, especially in respect of peak current and voltages.

#### 9. RELIABILITY

9. 1 The reliability of capacitors is extremely important to equipment designers. For the life expectancy mentioned (Para. 8. 3) the failure rates must be extremely low.

The table, Fig. 6, shows the failure rates for most types of capacitor in conversion equipments.

The figures verify that the polyester and polycarbonate capacitors are more reliable than all other types, and that the tantalum types are more reliable than the aluminium electrolytics which are extensively used for filter purposes.

9. 2 Fixed capacitors tend to fail due to a fall in insulation resistance as the moisture content increases through bad sealing, however complete sealing is a difficult and costly process.
9. 3 Paper capacitors tend to fail as the impregnant deteriorates causing excessive leakage currents. Also, the paper tends to dehydrate above 70°C.
9. 4 All dry aluminium electrolytics tend to exhibit catastrophic failure - the aluminium tends to bulge in and out with high voltages. They also have their own problems of storage and the reforming process, necessary because the electrolyte depolarizes, is time consuming and costly. At the higher temperatures wet aluminium types tend to dry out, with the consequent high power factor and falling off in capacitance.
9. 5 Wet tantalum capacitors were not recommended by one firm because they tend to cause severe and costly damage due to

leaking electrolyte. Sealing of this type is difficult because of the risk of explosion.

Dry tantalum types have been quite reliable, as also have tantalum gel. The tantalum gel capacitors have been used on a space project and have the advantages of being compact, shock resistant and almost leakproof.

- 9.6 P. T. F. E. capacitors appear fairly promising as their temperature capabilities are good, and they are reliable, however the dielectric is poor and consequently they have unsatisfactory volume to capacitance values.

## 10. CONCLUSIONS

The assessment of capacitor requirements for conversion equipments has enabled a selection of the equipment manufacturers to discuss their particular difficulties in design and development. It has been found that capacitors, and also semiconductors, have not kept up with modern developments and considerable improvements are necessary.

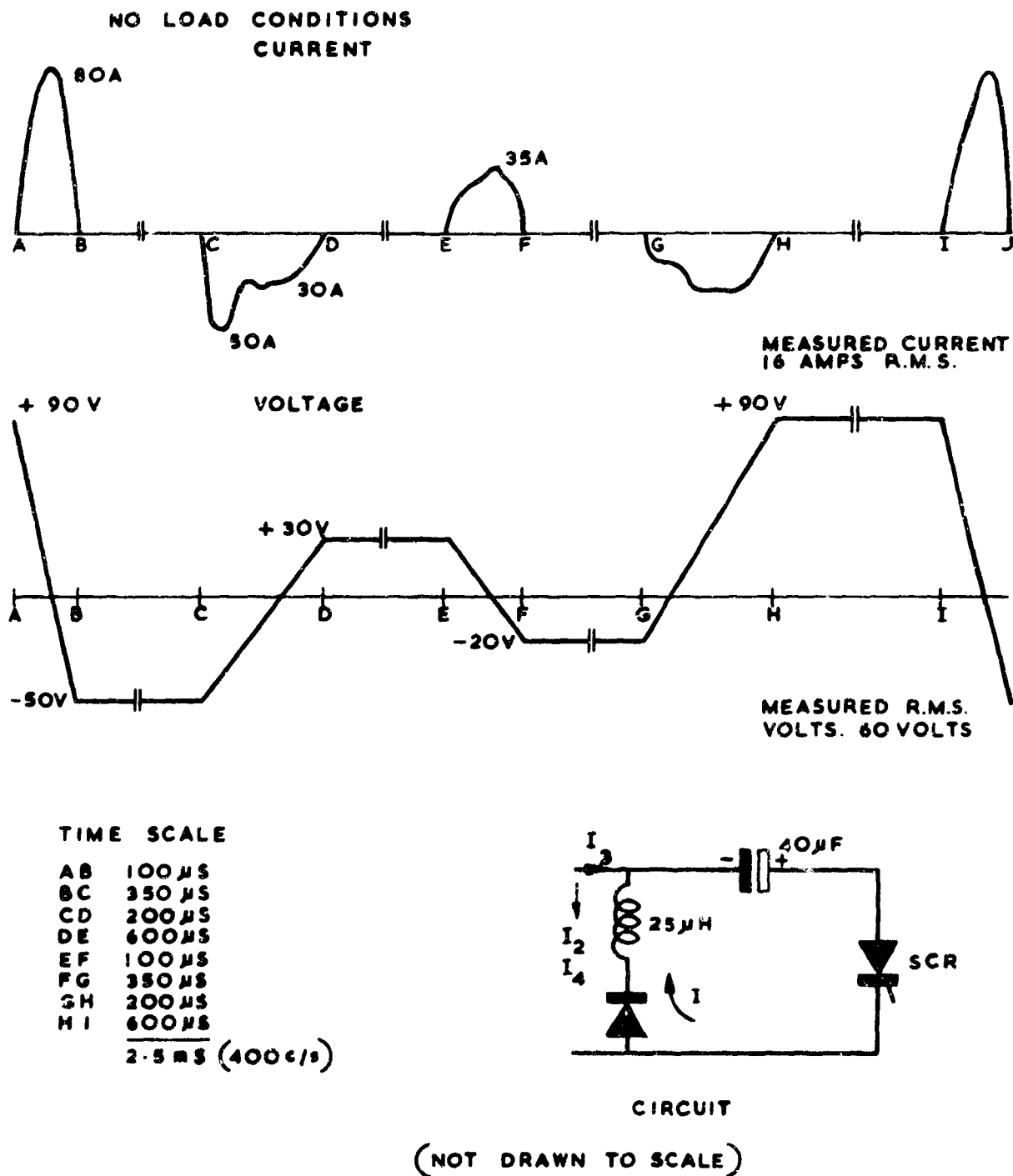
This report has shown that the use of polycarbonate, solid aluminium and certain tantalum types is very desirable, nevertheless, large improvements in working voltage and capacitance together with ripple current values are required to enable them to compete with types used at present. The paper and aluminium types used extensively today have been shown to be more bulky and less reliable.

It is hoped that this report indicates to the capacitor manufacturers the electrical and environmental conditions that capacitors experience in conversion circuits and that it has shown how important the physical requirements such as size, shape and terminals are to the designer.

Although the production requirements of the power conversion manufacturers appear relatively small at present, it is anticipated that during the next decade extensive requirements by commercial and also military sources will reward the necessary and overdue research and development.

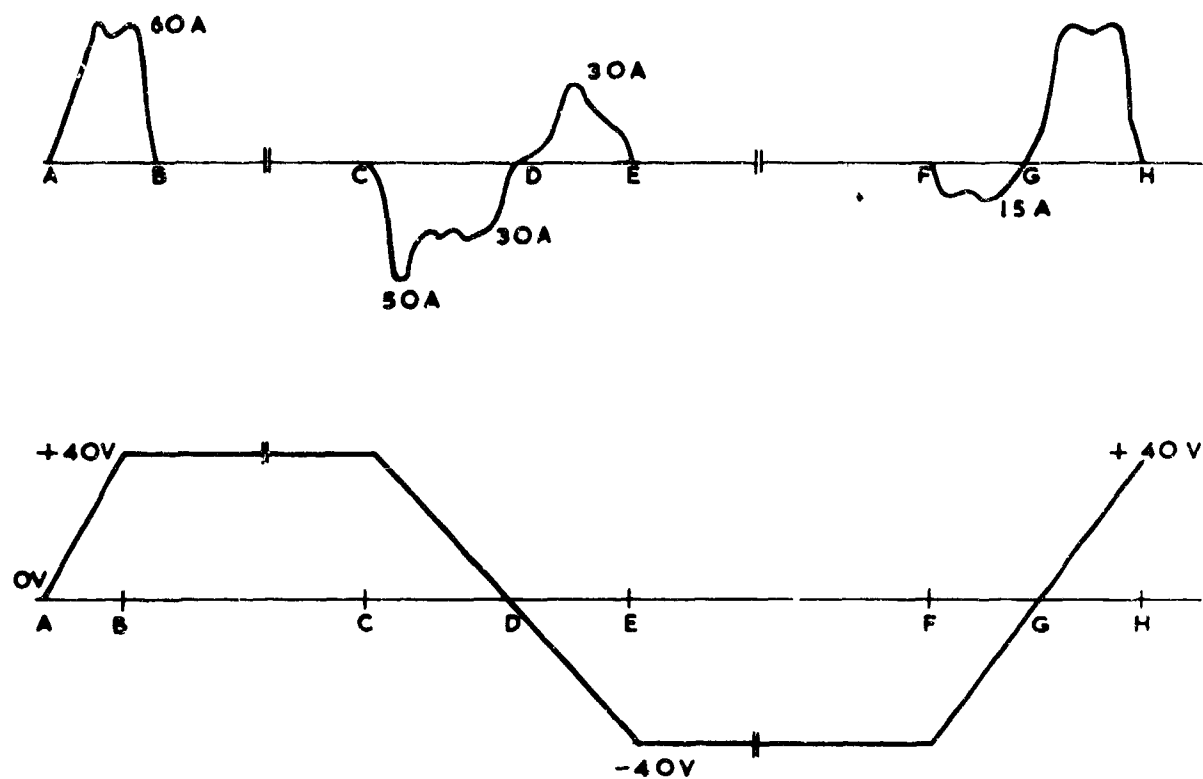
## 11. ACKNOWLEDGEMENT

S. R. D. E. acknowledges with thanks the information and help given by Industry during the preparation of this report.



**FIG. 1A CURRENT AND VOLTAGE WAVEFORMS MEASURED FOR A  
40  $\mu$ F CAPACITOR DURING COMMUTATION**

FULL LOAD CONDITIONS  
 INPUT 29 VOLTS  
 CURRENT



TIME SCALE :-

AB 100  $\mu$ S  
 BC 960  $\mu$ S  
 CD 190  $\mu$ S  
 DE 100  $\mu$ S  
 EF 960  $\mu$ S  
 FG 190  $\mu$ S

2.5 MS (400 c/s)

(CIRCUIT AS SHOWN FIG. 1A)

(NOT DRAWN TO SCALE)

FIG. 1B CURRENT AND VOLTAGE WAVEFORMS MEASURED FOR A  
 40  $\mu$ F CAPACITOR DURING COMMUTATION

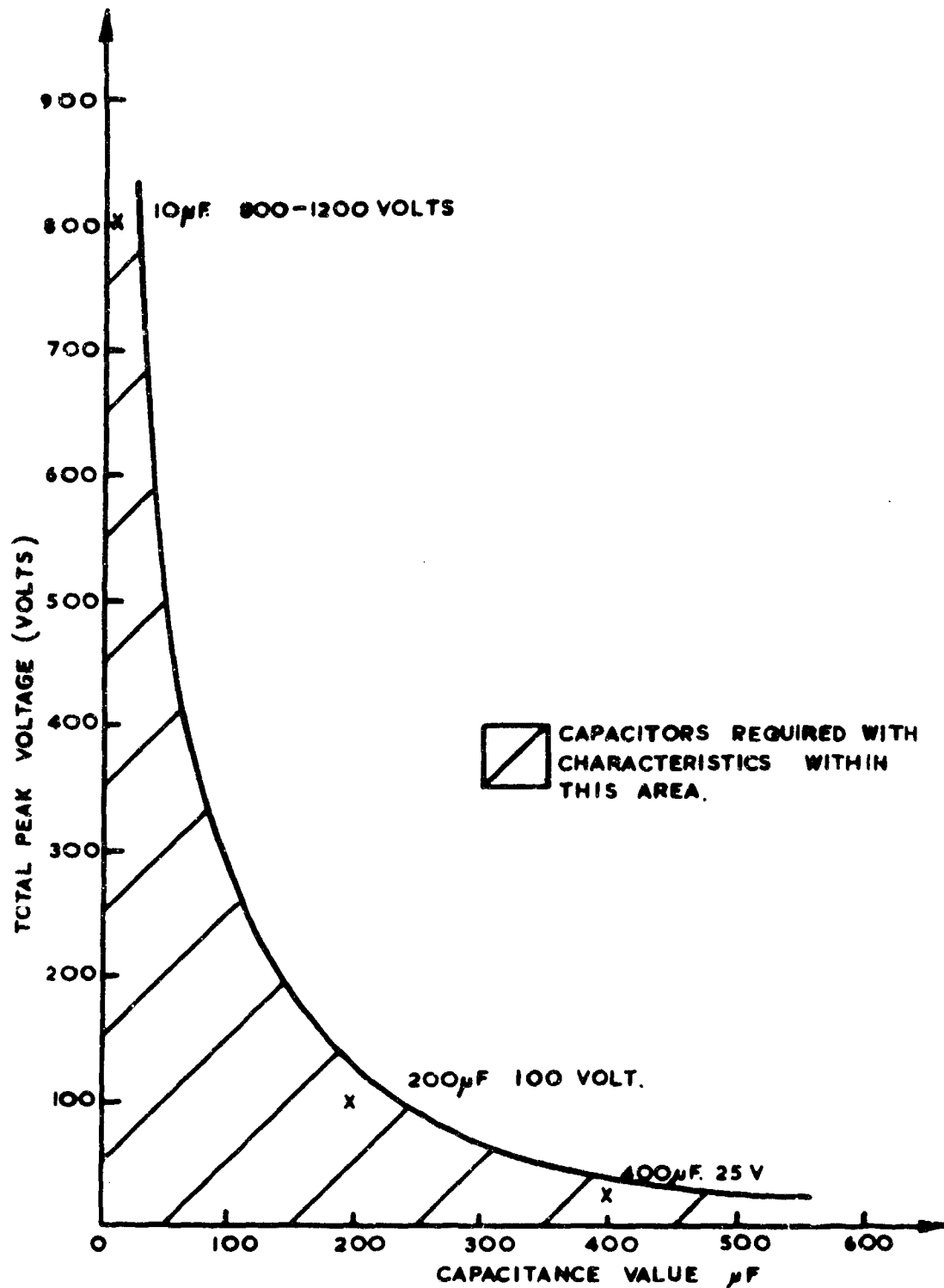


FIG. 2 GRAPH SHOWING TOTAL PEAK VOLTAGE V CAPACITANCE FOR COMMUTATION CAPACITORS.



(S.T.C. DATA AUG. 1965)

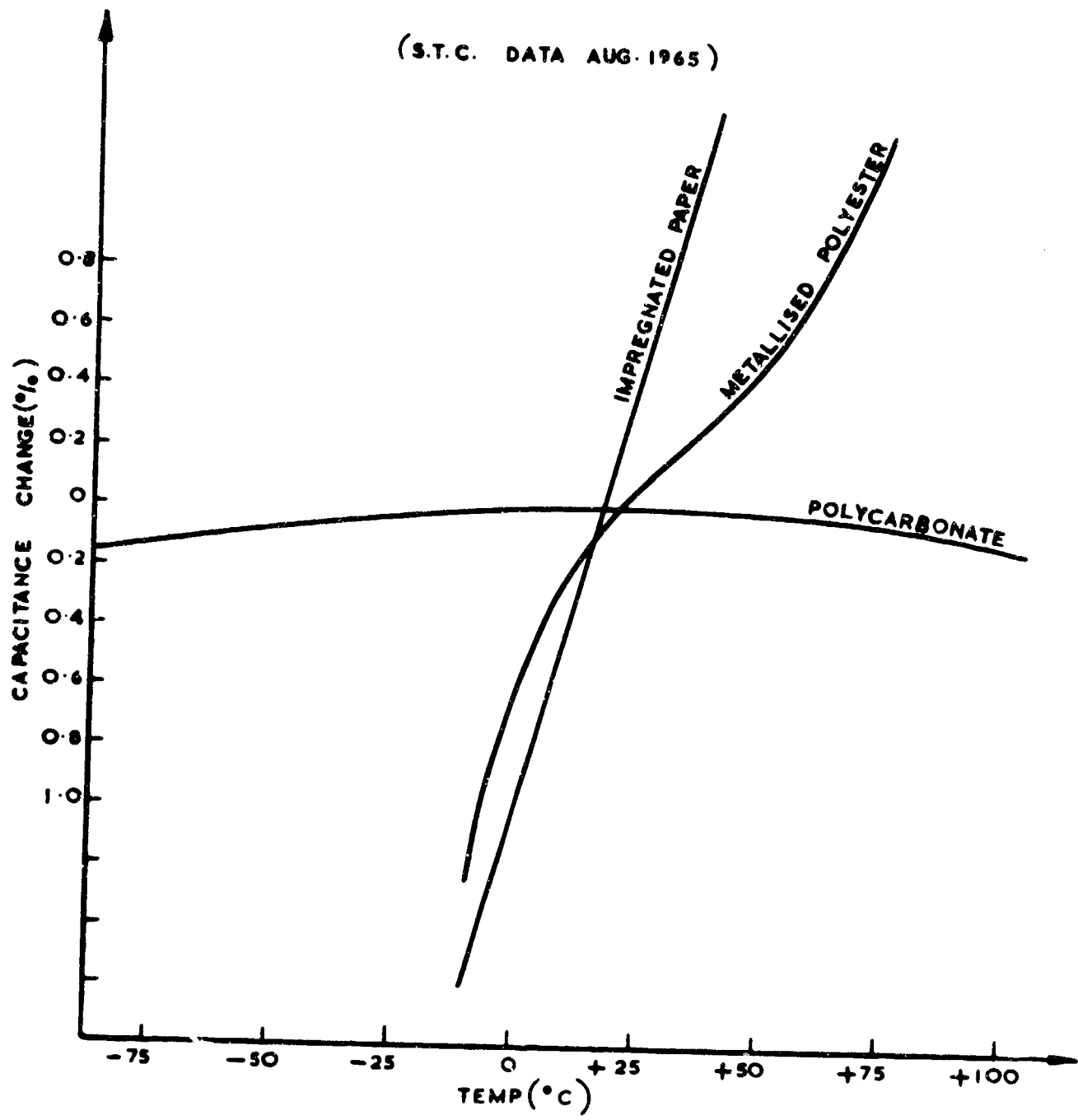


FIG 3 PERCENTAGE CHANGE IN CAPACITANCE WITH TEMPERATURE.

(S.T.C. DATA AUGUST 1965)

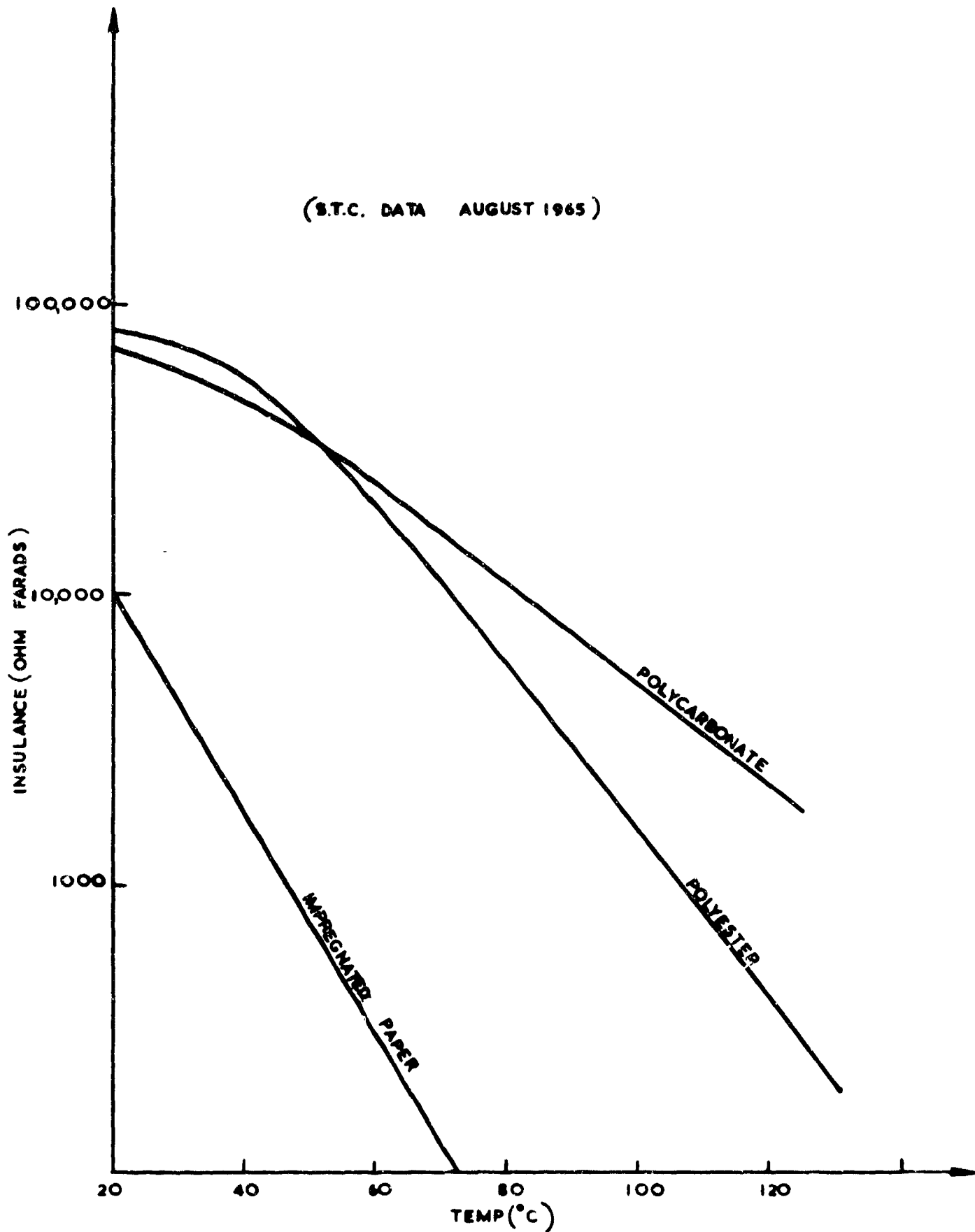


FIG. 4 INSULANCE CHANGE WITH TEMPERATURE

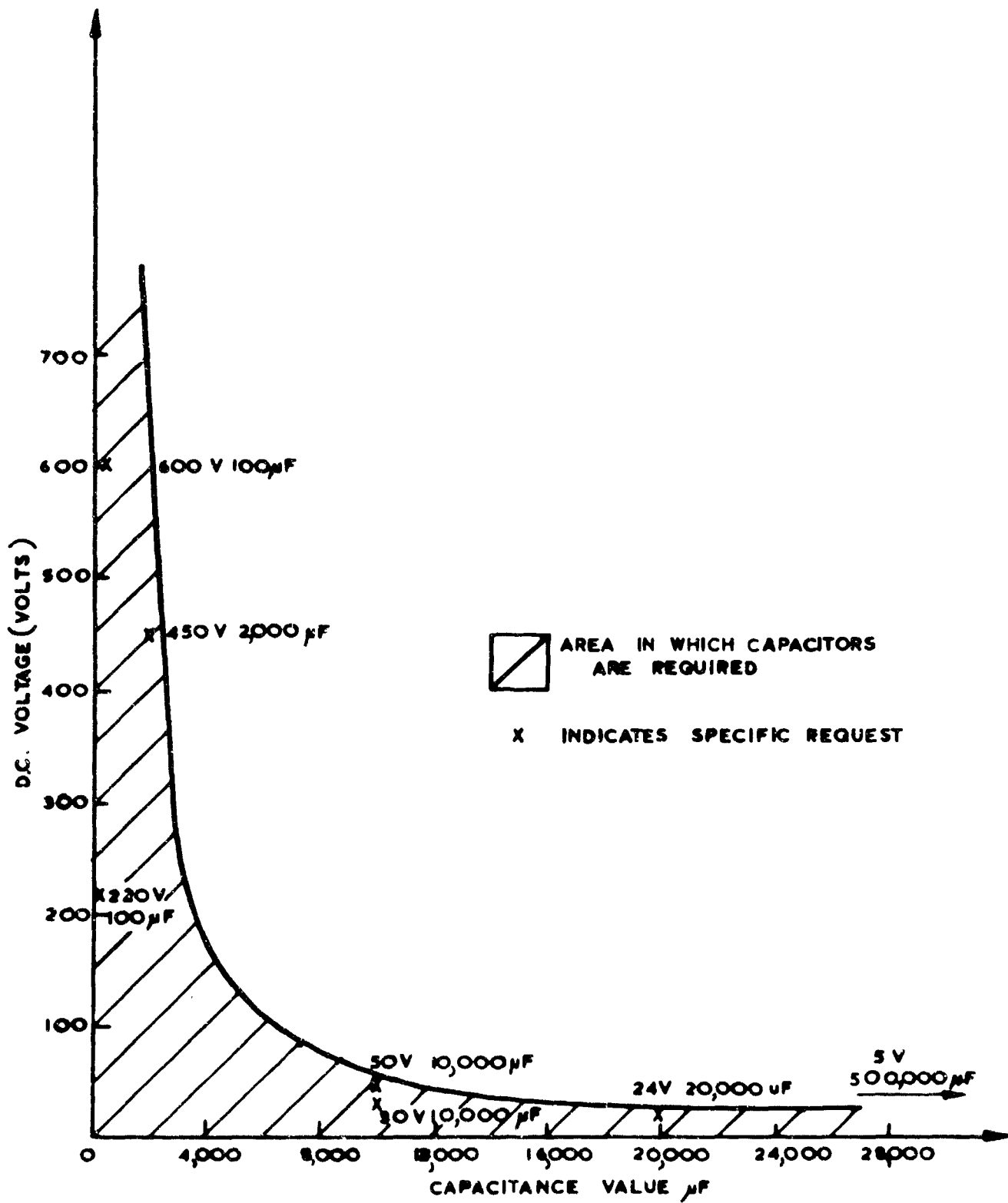


FIG. 5 GRAPH SHOWING VOLTAGE/CAPACITANCE REQUIREMENTS FOR FILTERS. (RIPPLE SUPPRESSION)

Fig. 6

RELIABILITY OF CAPACITORS

TYPE OF CAPACITOR	FAILURE RATE % per 1000 hours
Paper Foil	0.1
Metallised Paper	0.05
Polyester, Polycarbonate	0.025
Dry Aluminium Electrolytics	0.1
Tantalum Foil	0.1
Tantalum Wet	0.1
Tantalum Solid	0.05

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<p><u>SDS</u> <u>REPORT NO. 68007</u></p> <p>U.D.C. No. 621.319.4</p> <p><u>AN ASSESSMENT OF THE LONG TERM CAPACITOR REQUIREMENTS FOR STATIC POWER CONVERSION EQUIPMENTS</u> by C. E. Muford</p> <p>The recent trends in conversion equipments towards higher powers and smaller sizes highlights the need for more advanced components. This paper discusses the equipment designer's requirements for capacitors in the next decade.</p> <p>The paper consists of three main sections dealing with commutation, filters and the environmental conditions of capacitors.</p> <p>MAY 1968</p>	<p><u>SDS</u> <u>REPORT NO. 68007</u></p> <p>U.D.C. No. 621.319.4</p> <p><u>AN ASSESSMENT OF THE LONG TERM CAPACITOR REQUIREMENTS FOR STATIC POWER CONVERSION EQUIPMENTS</u> by C. E. Muford</p> <p>The recent trends in conversion equipments towards higher powers and smaller sizes highlights the need for more advanced components. This paper discusses the equipment designer's requirements for capacitors in the next decade.</p> <p>The paper consists of three main sections dealing with commutation, filters and the environmental conditions of capacitors.</p> <p>MAY 1968</p>
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