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RELIABILITY STUDIES ON SOLID TANTALUM ELECTROLYTIC CAPACITORS BY MEANS OF ACCELERATED LIFE TESTS

BY

VENKATA R. GOLTHI

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE
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APPROVAL SHEET

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ABSTRACT

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The purpose of this thesis is to understand the failure mechanisms in Solid Tantalum Capacitors encapsulated in plastic, and to suggest the precautionary measures that prevent the occurance of these failures.

The reliability of Solid Tantalum Capacitors encapsulated in plastic is of considerable interest because in some applications where the mechanical accelerations or shocks are considerable the "better" "hermitically" sealed type are not able to sustain themselves. Poor adherence between the dielectric film and the base metal Tantalum under the conditions of sudden mechanical shocks, causes problems.

Our study was carried out in two different directions, theoretical and experimental. The theoretical part is comprehensive review of the work done on Tantalum Capacitors from 1960 to upto date.

The experimental part of the study is done by means of accelerated life testing under the conditions of high humidity & high temperature as well as various high temperatures with out added humidity.

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My thanks are due to my brother Satya chary, for his valuable time and computer expertise used in bringingout this thesis and also to my mother, my sister Sirisha for their encouragement.

My thanks are also due to the staff of Electrical Engineering department and library for their cooperation. I like to take this oppurtunity to thank fellow graduate students Rajkumar and Ramesh for their valuable time.

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CHAPTER I

INTRODUCTION

CHAPTER I - INTRODUCTION

In certain critical complex electronic instrumentation such as that encountered in Defense, Airborne equipment of civil aviation, Space, Medical malfunctioning of the equipment due to component degradation or catastrophic failures can result in total disaster, loss of precious human life, loss of war or failure of an expensive experiment, which could mean prestige setback at national or international level.

In order to safeguard the electronic equipment or system against such failures and provide the data on the mean time between failures (MTBF) so that preventive maintainence programs can be planned and executed thus preventing expensive shutdowns or breakdowns. Users of electronic components in the above mentioned fields need components of highest reliability.

1.1 RELIABILITY:

Reliability is defined as the probability that the system will operate at a specified level of performance for a specified period of time, operated at specified loading and environental conditions.

It is important that the entire environment should be specified completely, that is the electrical and electromagnetic situation, the temperature and its variations, the climatic conditions such as salt spray, ice formation, dust strom, humidity, and the mechanical conditions such as the frequency and amplitude of vibrations. The electrical environment includes the full range of input signals and the interference, the variation in supply voltage, and the size of any switching transients, together with variation in load if this is relevant. The electromagnetic environment is important if the equipment must operate near other units which generate large electromagnetic fields. For space and nuclear reactor electronics we may also need to specify the level of radiation.

The reliability of specific component depends on design of the component as well as quality of the individual materials used. To produce components of high reliability, the manufacturer shall first make sure that the raw-materials used in production are of correct specifications and are certified for use after standard tests. He must then ensure that the materials are put in production line for processing and check at various stages of manufacturing to monitor the processing as per standards. The control of the environment plays important role to aviod contamination of the component. Defects are either screened out or prevented before they could occur.

1.2 TANTALUM CAPACITORS:

Tantalum electrolytic capacitors replace aluminium electrolytic capacitors in all applications requiring good stability of electrical charactericstics in a wide range of temperature, low leakage currents and long shelf life. Another distinct advantage of tantalum capacitors is the small size. See Table I.

The primary objective of this thesis is to determine and analyze failure mechanisms in plastic encapsulated solid tantalum capacitors, identify the causes and suggest the precautionary measures that can prevent the occurrance of these failures. To achieve this the study was carried out in two directions, theoretical and experimental.

The theoretical part of the work is comprehensive review of the work done on the tantalum capacitors since 1961 upto date. The experimental part of the work is accelerated life tests on plastic encapsulated solid

TABLE I

TYPICAL INTERNATIONAL DIMENTIONS FOR 22 uF / 15V CAPACITOR

TYPE	DIAMETER mm	LENGTH mm
Aluminium Foil	6.35	20.88
Tantalum Foil	5.00	20.00
Wet Tantalum	4.75	11.20
Solid Tantalum Resin Dipped	6.50	10.00
Solid Tantalum Epoxy Molded	4.70	12.80
Solid Tantalum Hermetically Sealed	4.70	15.50

tantalum capacitors under high humidity and high temperature conditions.

The reliability of solid tantalum capacitors is of considerable interest because in some applications where the mechanical accelerations or shocks are high the "better" "hermetically" sealed type are not able sustain themselves. There is a fracture that occurs between the dielectric oxide and the base metal Tantalum under the conditions of sudden mechanicl shocks.

The bibiliography is given extensively, in reverse chronological order, so that upto date list can be available to anyone wishing to do further research on this topic.

CHAPTER II

TANTALUM CAPACITORS

CHAPTER II - TANTALUM CAPACITORS

In march of 1956 the solid tantalum capacitor was introduced by Sprague at the IRE show in New York City. Because of the development of the transistor and interest in the rapid introduction of solid state circuits, these capacitors were an instant success. For the first time a capacitor was available, which offered all the attributes of electrolytics in addition to smaller size, capcitance stability over a wide temperature range, some reverse voltage capability and ability to withstand long life with virtually no change in AC characteristics.

As time went by voltage ratings were extended upward and new case sizes were developed. Before long hermetically sealed types were joined by the capacitors encapsulated in plastic. However hermitically sealed versions remained as the type with most stable electrical characteristics and having the greatest reliability under most circumstances.

In the passage of about thirty years since the introduction of solid tantalum capacitors there has been a host of material and process changes. These refinements resulted in a capacitor which is better in quality and reliability. The improvements have been made despite the fact that the capacitors can now be fabricated with less than 20% of the amount of tantalum used in the original model. This has become possible by increasing the surface area in relation to weight.

In general solid tantalum capcitors manufactured today have a capability of being highly reliable devices. From 1959, when the reliability problem became important, to the present day failure rates have been steadily decreasing. As an example, for the period of 1961 to 1972 the failure rates of premium solid tantalum capacitors decreased from 0.015 to 0.00015% per thousand hours at the 60% upper confidence level (2-85).

2.1 TYPES OF TANTALUM CAPACITORS:

Tantalum capacitors are known for high reliability and high capacitance per unit volume. These capacitors are commercially available from .01 uF to 1000 uF at a rated voltage of upto 450 VDC and in ± 5% to ± 20% tolerances and are widely accepted in millitary, aerospace and digital computer applications. There are three types of tantalum capacitors:

1. Tantalum foil

2. Sintered anode wet electrolyte type
3. Sintered anode solid electrolyte type

All of these types use tantalum oxide of thickness of about 400 to 8000 Angstrom units, as dielectric. This dielectric (Ta_2O_5) has a permitivity of about 25 compared with 7 for typical aluminium electrolytic types (Al_2O_3), therefore high capacitance can be attained in a relatively smaller space.

Tantalum foil capacitors are normally used just for certain high voltage applications only and they are avialable upto 450 volts. The foil is either plain or etched. In the later case, the surface area is considerably increased and therefore more capacitance per unit volume is obtained. The wet tantalum capacitors find their use in typical low leakage applications such as timing circuits. The electrolyte used inside the capacitor is sulphuric acid.

Throughout this thesis, solid tantalum capacitor will be refered to as the tantalum capacitor with sintered anode and solid electrolyte which is usally manganese dioxide. These types of capacitors are very popular as they posses the following excellent features:

1. Great effective surface area
2. High reliability and long proven life
3. Superior dielectric charateristics of Ta_2O_5
4. Larger permissible ripple voltages
5. High volumetric efficiency
6. Stabilized performance over wide temperature range
7. Smaller size
8. Resistance from corrosion of internal parts
9. Small equivalent series resistance, that is low loss
10. Good frequency characteristics
11. Ability to withstand small reverse voltages

2.2 TANTALUM vs. TANTALUM OXIDE:

Tantalum metal lies in the fifth column of the periodic table. This group assumes five valence electrons and very compact atomic size combined with dense, highly symmetrical atomic packing in the crystalline form resulting in high melting temperature. Tantalum atomic weight is 180.95, atomic number is 73, melting point is 2990 degree C, boiling point is 5425 degree C and specific gravity is 16.654.

Tantalum is gray, heavy and very hard metal. When pure, it is ductile and can be drawn into fine wire, which is used as a filament for evaporating metals such as aluminium. Tantalum is almost completly immune to chemical attack at temperatures below 150 C from most materials, however it reacts with hydrofluoric acid, acidic solutions containing the fluoride ions, and free sulfur trioxide. At high temperatures, tantalum becomes much more reactive. The element has a melting point exceeded only by tungsten and rhenium. Tantalum is used to make a variety of alloys with desirable properties such as high melting point, high strength, good ductility, etc.. It is also widely used to fabricate chemical process equipment, nuclear reactors, and aircraft and missile parts. Tantalum is completely immune to body liquids and is a nonirritating metal. It has therefore found wide use in making surgical appliances.

Over the other metals (1-71) that can have coherent oxide layer, tantalum has numerous advantages. With tantalum, we are able to prepare better dielectric by anodization than with aluminium. The result is that the capacitor has a better shelf life than the equivalent aluminium unit.

Tantalum and tantalum oxide (2-62) are much more inert materials than aluminium and its oxide, and for this reason tantalum can be expected to make more stable

TABLE II *

COMPARISION OF SOME PHYSICAL PARAMETERS BETWEEN TANTALUM AND ITS OXIDE

PARAMETER	TANTALUM	TANTALUM OXIDE
Density, g/cm	16.6	8.75
Melting Point, °C	2996	1470
Thermal Conductivity, Cal/ CSeccm	.13	**
Thermal Coeff. of Expansion, °C	6.46 X 10	.55 X 10
Resistivity, ohm-cm	12.5 X 10	**
Dielectric Constant	**	

---

* Handbook of Tables for Applied Engineering and Science
Ray E. Bolz & George L. Tuve
CRC Publications page 264

** Not avialable

and reliable capacitors. The inertness makes it possible to have a much wider choice in electrolytes. Under equal conditions, the leakage current of tantalum electrolytic capacitor is lower than that of aluminium electrolytic capacitor.

The Table II shows some of the physical parameters of tantalum metal and tantalum oxide dielectric. We see in Table II that there is a drastic difference in coefficient of thermal expansion between tantalum oxide and tantalum, which is about 12 times larger for Ta compared to Ta_2O_5. But there has not been a study or research on how this mismatch in the coefficient of thermal expansion affects the reliability of these capacitors.

2.3 MANUFACTURING PROCESS OF SOLID TANTALUM CAPACITORS (3-85):

Before proceeding with reliability studies of any component, it is very important to understand the manufacturing process.

The manufacturing process of solid electrolytic tantalum capacitors begins with mixing tantalum powder with organic binders and pressed into pellets embeded with tantalum wire, to specific densities and sizes depending upon the final capacitance to be achieved. The purpose of the Ta wire is to provide the anode connection. The binder serves three purposes; in the initial stages it temporarily binds the particles of Ta powder together, it serves as a lubricant so that the particles flow freely during compaction to form anodes of uniform density throughout their volume, and it also fills the interstices, thereby helping to prevent overcompaction. Compacting by the use of pressure ensures good electrical contact between the metallic particles.

The next step is removal of binders from the pellets under vacuum and 200°C heat. Then the pellets are sintered at 2000°C under vacuum for about 30 minutes. Vacuum is necessary to prevent contamination and oxidation of tantalum pellets. Sintering results in porous body possesing a large suface area relative to its volume. During the sintering, not only the effective area increases but also the purity of tantalum pellets and ensures electrical continuity between the particles. The problems (1-71) assosiated with the preparation of Ta capacitors using sintered powder are partly concerned with the variation of capacitance with sintering conditions.

The tantalum oxide (Ta_2O_5) dielectric is produced throughout the effective surface area of the pellets by anodization in a conductive solution such as aqueous phosphoric acid at a "Forming" voltage on the basis of capacitance voltage to be achieved.

Thorough washing with very high resistivity pure water of 12 Meg Volt Cm removes all the traces of the conductive solution and, now leaves the anodes completely covered with the dielectric Ta_2O_5. Now the pellets are ready for the next process, the formation of the cathode.

Manganese dioxide, a solid semiconductor, is used as the cathode for these capacitors. It is produced by diffusing the pellets in manganous nitrate solution and converting this into solid manganese dioxide by heat and water vapour at 300°C. Several repetitions of this are done, so that the interstices between the particles coated with the dielectric are filled completely by cathode material.

It is not possible to connect the leads directly to the manganese dioxide cathodes. This problem is overcome by dipping the capacitor in solution of colloidal graphite and baking out. As a result, graphite, a conductive material, coats the surfaces and penetrates into the pores to make sound contact with all the cathode surface. Finally the pellets are dipped in silver paste (in acrylic), to be able to make external connection, after baking out the acrylic.

Now we can imagine the tantalum capacitor as a system composed of $Ta - Ta_2O_5 - MnO_2$ layers, where Ta and MnO as anode and cathode respectively and Ta O as the dielectric.

Now these capacitors have to be encapsulated to be protected from external environment, and to give mechanical strength.

2.4 TYPES OF PACKAGES AND APPLICATIONS:

Solid tantalum capacitors are basically avialable in three different types of packages:

1. "Hermetically sealed" metal case
2. Transfer moulded in epoxy
3. Resin dipped

In "hermetically sealed" type the capacitor assembly is placed in a cylindrical metal case and an anode lead

(Ni welded to the Ta lead) is attached, this comes out through a glass insulated eyelet (glass to metal seal).

In epoxy moulded type, the prepared pellet with anode and cathode leads are transfer moulded with suitable epoxy powder.

In the case of resin dipped type, after attaching the nickel leads, these are dipcoated using fluidized bed technique of encapsulation using epoxy resins.

These three package types have their own merits and demerits depending on the applications. Table III gives some parameters for comparision between these types.

Due to the very nature of encapsulations, "hermetically sealed" are superior in stability of characteristics at low and high temperatures as well as moisture resistance. These are used for high reliabilty equipment. However these cost most but cannot withstand high mechanical shocks and accelerations because of inherent poor adherence between the Ta and Ta O since their coefficient of thermal expansion is drastically mismatched (Ta : Ta_2O_5 = 12 : 1).

TABLE III *

COMPARISON BETWEEN DIFFERENT TYPE OF PACKAGES OF SOLID TANTALUM CAPACITOR

PARAMETER	HERMETICALLY	EPOXY MOLDED	RESIN DIPPED
Temperature	-55 to 85 °C or -55 to 125 °C	-40 to 85°C	-10 to 70°C
Moisture Resistance (Accelerated cycles)	Best	Intermediate	Lowest
Damp heat test (Long term)	56 days	21 days	4 days
Low air pressure	2 kPa (1 kPa = 10 mbar)	2 kPa	**
Useful range of Impedence vs Frequency	upto 2MHz	**	100 KHz
Variation of capacitance at -40°C	4 to 6%	**	6 to 10%
Typical values of DF at -40 °C	6 to 8%	**	8 to 14%

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* Solid Tantalum Capacitors
S. Srinivasan
Electrical & Electronics World
Vol. IV, No. 4, 1976

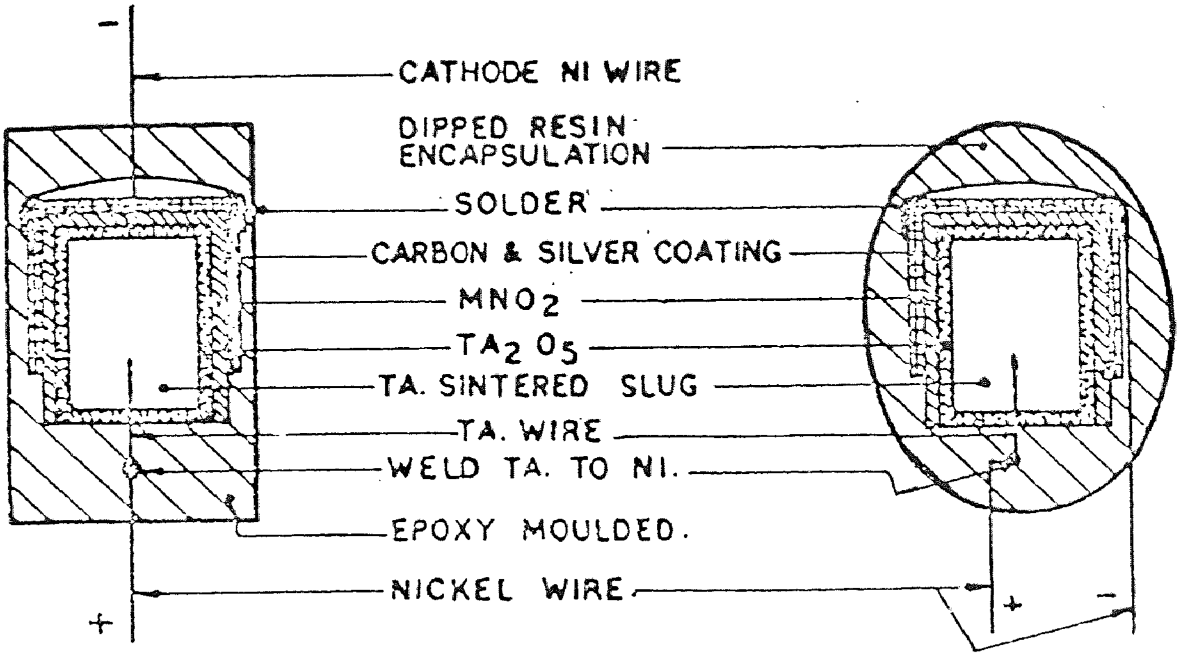
** Not avialable

It may be noticed that in moulded capacitors and dipped capacitors, the encapsulating material surrounds the oxide film and the conducting portions of the cathode completely. The thermal coefficient of expansion of the epoxy will not match with that of tantalum oxide film and the coating combination.

The dipped version is known for its miniature dimentions and low cost, and is less resistant to external ambient conditions than the moulded type. Being low in cost, these are used extensively in consumer products and inexpensive industrial equipment. Of all the tantalum capacitor types these are manufactured in greatest number.

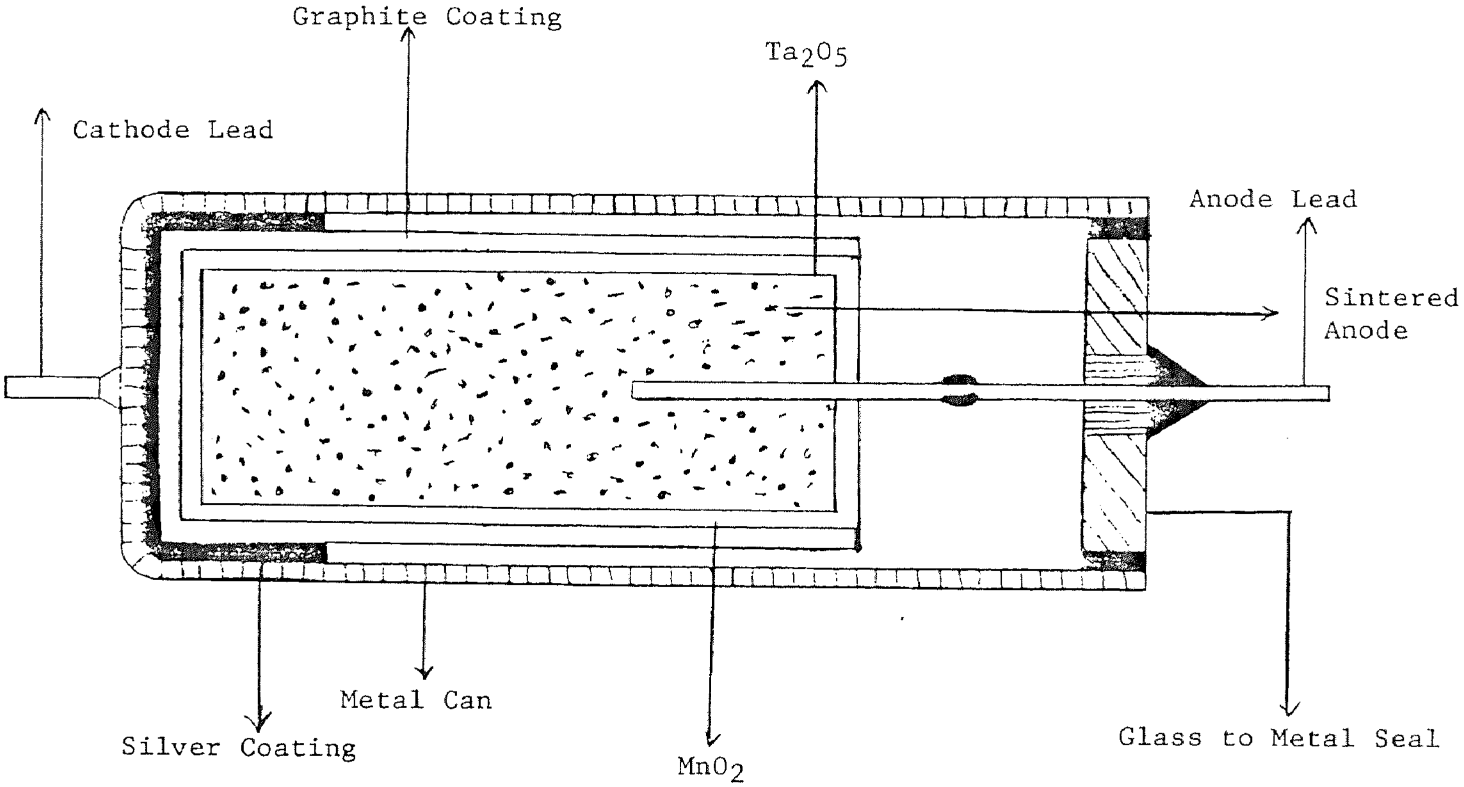
Moulded version posses intermediate characteristics between hermetically sealed type and dipped type. But they have the unique advantage of withstanding high accelerations of the order of 20,000g. These are extensively used in high reliability applications such as aerospace as well as in industrial purposes. For this reason reliabilty of plastic encapsulted solid Ta capacitor are of great interest. This version has an advantage of keeping the capacitor system in compression, which might avoid poor adhesion due to mismatch in thermal coefficient of expansion as discussed earlier.

The cross-sectional diagrams of solid tantalum capacitor in all three differnt package types are shown in Figure 1.



(a) Epoxy Molded

(b) Resin Dipped



(c) Hermetically Sealed

Figure (1) Cross-Sectional Diagrams of Solid Tantalum Capacitors

CHAPTER III

RELIABILITY & FAILURE MODES

OF

SOLID TANTALUM CAPACITORS

CHAPTER III - RELIABILITY AND FAILURE MODES OF SOLID TANTALUM CAPACITORS

It is commonly said that the life of solid tantalum capacitors is 20 years or more and that the failure rate decreases with time.

We can formulate the reliability of capacitors* under the following symbollization for clarity of understanding.

$$R \rightarrow f \begin{cases} \text{ELECTRIC FIELD} \\ \text{MATERIALS} \\ \text{TEMPERATURE} - \text{STORAGE} \\ \qquad\qquad\qquad\quad - \text{OPERATING} \\ \text{PACKAGE} \\ \text{AMBIENT} \\ \text{SPECIAL FACTORS} \end{cases}$$

All these factors are to be considered either in

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* Class notes in EE 641 (Reliability in Electonics Fall 83) course at NJIT, Dr. R.P. Misra.

manufacturing or in design in order to achieve high reliability.

3.1 LOSSES IN SOLID TANTALUM CAPACITORS:

All capacitors (5-60) have some energy losses associated with them. The losses in electrolytic capacitors are mainly due to the equivalent internal resistance. Figure (2) illustrates simplified equivalent circuit of the electrolytic capacitor. Notice that there are two resistances shown. The shunt resistance derived from the dc leakage current. The series resistance is the primary contributor to the energy loss or heating loss within the unit. In the case of solid tantalum capacitors, this resistance is primarily in the electrolyte and cathode system.

The high frequency impedence (6-68) and the maximum allowable ac ripple is determined almost entirely by the equivalent series resistance (ESR) of the capacitor. The stability of the capacitance with variations of frequency and temperature is also determined by the ESR.

The ESR of a capacitor is normally obtained from measurement of dissipation factor and is defined as;

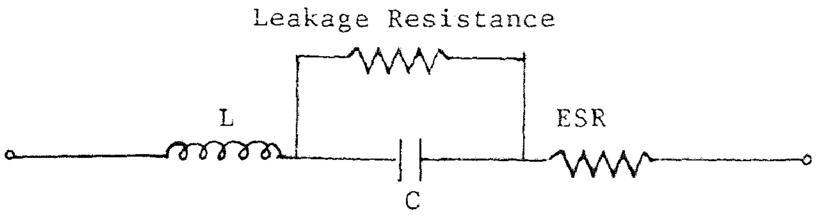


Figure (2) Equivalent Circuit of an Electrolytic Capacitor

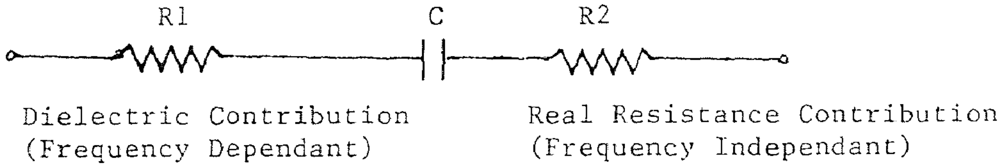


Figure (3) Details of ESR of Solid Tantalum Capacitor

$$ESR = \frac{\text{Dissipation Factor}}{wC}$$

Unfortunately the dissipation factor of these capacitors is not a linear function of frequency and the ESR is not a constant, it increases with increasing frequency. Therefore the total dissipation factor may be expressed as;

$$\begin{aligned} D.F. &= wC\ (R1 + R2) \quad \{6\text{-}68\} \\ &= wCR1 + wCR2 \\ &= \tan\delta + wCR2 \end{aligned}$$

Where C is the capacitance, w is the angular frequency. R2 is the resistance of the elecrolyte (MnO_2), carbon layer and leads tanδ is the dielectric contribution to the dissipation factor. Figure (3) shows the details of equivalent series resistance.

Considering the dielectric loss produced in a hypothetical R1, it is appar~~a~~ent from the Figure (4) that at lower frequencies tanδ is relatively independant of frequency. This is the region where dissipation in the dielectric predominates. Variation of tanδ in this region is extremely small compared to that produced by the true series resistance such as R2 or by a parallel leakage path. Furthermore, the values of tano at the

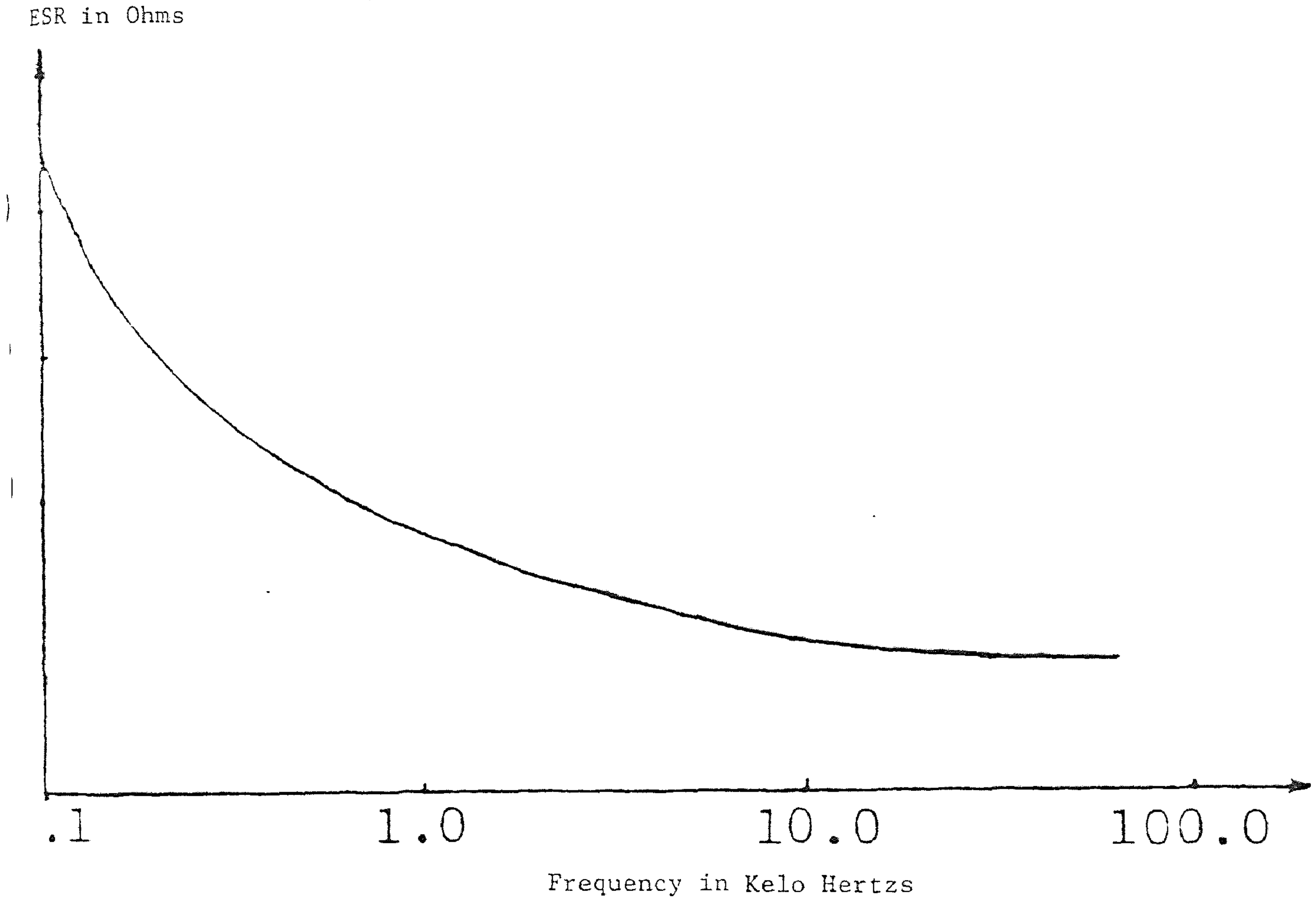


Figure (4) ESR Change with Frequency

lower frequencies are relatively independent of geometry and capacitance, and therefore must be property of the oxide film.

The low frequency values of tano are, somewhat dependent on tantalum purity and the structure and on processing, as might be expected since these are likely to influence the quality of the dielectric. To have tano (=wCR1) independant of frequency, the hypothetical resistance R1, must vary inversly with frequency and can be considered as k/w, where k is a constant.

From these considerations it can be seen that the dissipation factor at low frequency will be a measure of dielectric losses (tan δ) whereas at high frquency it will be a measure of resistive losses (wCR2). Therefore, a frequency of 1 KHz is usally chosen as a basic frequency to measure the ESR of capacitors, and it gives;

$$ESR = \frac{\tan\delta}{wC} = \frac{\tan\delta}{2000\ C}$$

Considering now only the resistive part of the dissipation factor, (since it is the main factor determinig high frequency characteristics), it is convenient to think of this as resistance composed of two parts:

(a) The resistance of the electrolyte which is within the sintered anode of tantalum and is distributed resistance in series with capacitive elements.

(b) The resistance of contact to the electrolyte, leads etc., which is outside of the anode and consequently is a lumped resistance in series with the capacitive element.

Of these two, the electrolytic resistance is normally greater.

Well recognized advantage of solid electrolyte tantalum capacitors over other electrolytic capacitors (6-68) are that the ESR of this type is relatively low and that it remains low over wide range of temperatures. These advantages are utilized where relatively high ac currents are required to pass through the capacitor or where a low capacitor impedence is required at high frequencies and/or at low temperatures.

3.2 FAILURE MODES:

Failures in solid tantalum capacitor may be classified broadly into two types:

(1) Catastrophic

(2) Degradational

Catastrophic failures are characterized by a rapid increase in leakage current, resulting in a short circuit in most of the cases and occationally in an open circuit. Degradatoinal failures exhibit a gradual change in characteristics during the capacitor's life.

Prior to any discussion of reliabilty aspects there should be clear defination of what constitutes a failure.

A solid tantalum capacitor failure (in general for any capacitor) may occur when:

(a) The capacitor becomes effectively short circuited.

(b) The capacitor becomes open circuited.

(c) The dc leakage current increases beyond a given tolerance limit.

(d) The capacitance value drifts outside the specified tolerance.

(e) The dissipation factor rises above the specified limit.

Of these types that occuring due to extremely high leakage current and resulting in a short circuit are most common in the tantalum capacitors. Open circuit type failures are very few and are usually associated with some form of physical damage to the unit. Parametric chagne with time are least in solid tantalum capacitors (3-62).

3.3 FAILURE MECHANISMS:

Collectively, failure mechanisms of solid tantalum capacitors can be one of the following:

(1) Seal failure, which allows moisture and other contaminants to infiltrate and damage the capacitor.

(2) Dielectric failure, which could be either gradual growth of thickness of oxide film leading to reduced capacitance, or field crystallization of amorphous dielectric oxide. It has been found (2-62, 1-77, 5-80) that field crystallization is the basic failure mechanism in solid tantalum capacitor.

(3) Thermal runaway, since the oxides of Manganese are semiconductors with negative temperature coefficient of resistivity (5-80), if temperature in the dielectric zone exceeds a critical value it can

cause loss of control of leakage current.

(4) Chemical change in electrodes or seal.

(5) Mechanical failures in contacts, weld, or seal.

(6) Air gap creation in the interfaces, specially between tantalum and tantalum oxide because of the radical difference of ther coefficients of thermal expansion. Air gap in series with tantalum oxide will have 25 times as much electric field as that in tantalum oxide. But the breakdown voltage for air is much less than that of Ta_2O_5 which means the breakdown or ionization of the air gap is inevitable which in turn leads to an eventual destruction of the capacitor.

This mismatch appears to be most likely cause of failure, there seems to be no research paper published on this item.

The causes of failure in the solid Ta capacitor can be classified into three catogeries:

(a) Contamination

(b) Faulty assembly

(c) Imperfections in the dielectric film

Improved manufacturing techniques and tight process control are capable of almost eliminating first two categeries. However the imperfections in the dielectric film are characteristics of tantalum oxide film grown anodically.

The above discussion indicates that choice of the catastrophic failure is the most logical and useful destination for this reliability study.

3.4 DEFECTS IN TANTALUM OXIDE DIELECTRIC FILM:

The leakage current in solid tantalum capacitors flows through small areas (imperfections) of the dielectric film, not through the film as a whole. There are three (1-77) main type of defects in the tantalum oxide dielectric film;

(1) Bumps
(2) Cracks
(3) Pits

In high voltage capacitors these defects are more as the thickness of the dielectric film is greater. Oxides formed on higher purity tantalum pellets found to have lesser defects. It was found (1-77) that crystalline oxide sites grow at the defective areas in the thin dielectric film.

Impurity elements have concentrations of 1- 2 order of magnitude higher at the surface than in the bulk. Nominally (1-77) 99.99% pure tantalum pellets may have only 99% pure surface layer.

The cracks and bumps (1-77) are found to be of the order of 1 micro meter in dimention.

3.5 FIELD CRYSTALLIZATION:

The basic mechanisms of catastrophic type failures in solid tantalum capacitors are found to be field crystallization. The growth of higher conductivity crystalline oxide within the dielectric film during the operation of the capacitor, causes an increase in leakage current and may result in catastrophic failures. High currents through these crystalline sites can lead to catastrophic thermal breakdown of the capacitor. These crystalline sites are found to be grown at the defect centers in the dielectric film.

3.6 FEATURES OF FIELD CRYSTALLIZATION:

(a) Crystalline form of the oxide (Ta_2O_5-) is more conductive in amorphous state.

(b) The crystalline form grown within the amorphous film may rupture the dielectric.

The effect of field crystallization can be minimized by using high purity tantalum, to reduce number of crystallization nucleation sites.

Since electric field in the capacitor is voltage dependant, voltage (applied) is a primary cause of field crystallization growth. At the same time, high voltage capacitors need thicker dielectric film and thicker the dielectric film the probability of impurities and defects in the film are more. This makes high voltage capacitors more susceptible to field crytallization and hence to failure.

Also if for a long period of time the capacitors are stored without application of any voltage the leakage current seems to increase, probably due to the depletion of the oxide at certain spots. By slow application of voltage with a large series resistance the capacitance may be regenerated.

CHAPTER IV

FACTORS AFFECTING RELIABILITY OF SOLID TANTALUM CAPACITORS

CHAPTER IV - FACTORS AFFECTING RELIABILITY OF SOLID TANTALUM CAPACITORS

4.1 EFFECTS OF TEMPERATURE:

Tantalum capacitors demonstrate an unusual degree of capacitance and dissipation factor stability with temperature.

Although the capacitance is relatively high, it is stable over wide temperature range. The average change in capacitance is of the order of 1500 parts per million (PPM) per degree centigrade. It should also be noted that higher capacitance units have relatively smaller capacitance change with temperature. In case of low voltage, for example for 6 Volts rating capacitors this may be as low as 300 PPM per degree centigrade.

Equivalent series resistance (ESR), which is related to the loss factor of capacitor, remains low over entire range of temperature, which is usually -55 C to +125 C.

The leakage current is found to increase with temperature increase. Compared at the room temperature the leakage current increases by a factor of 10 to 30 when capacitors are at an elevated temperature of +125 degree centigrade.

Temperature is a critical factor since the migrataion rate of impurities to the surface is directly affected by the temperature. This can be seen (5-80) in the Figure 5.

It is belived that a certain proportion of the capacitors have impurities that create defects that are too large to heal, but as a rule these become obvious during the production and are screened out. In others, impurities migrate to surface at a later time.

Oxides of manganese are semiconductors with a negative temperature coefficient of resistivity, therefore excessive temperature in the defect zone can cause loss of control of leakage current. This leads to thermal runaway and eventually catastrophic failure.

Also chemical changes occur as a function of temperature as per the Arrehenious equation which is shown below.

$$R = A \exp[-E / (k T)]$$

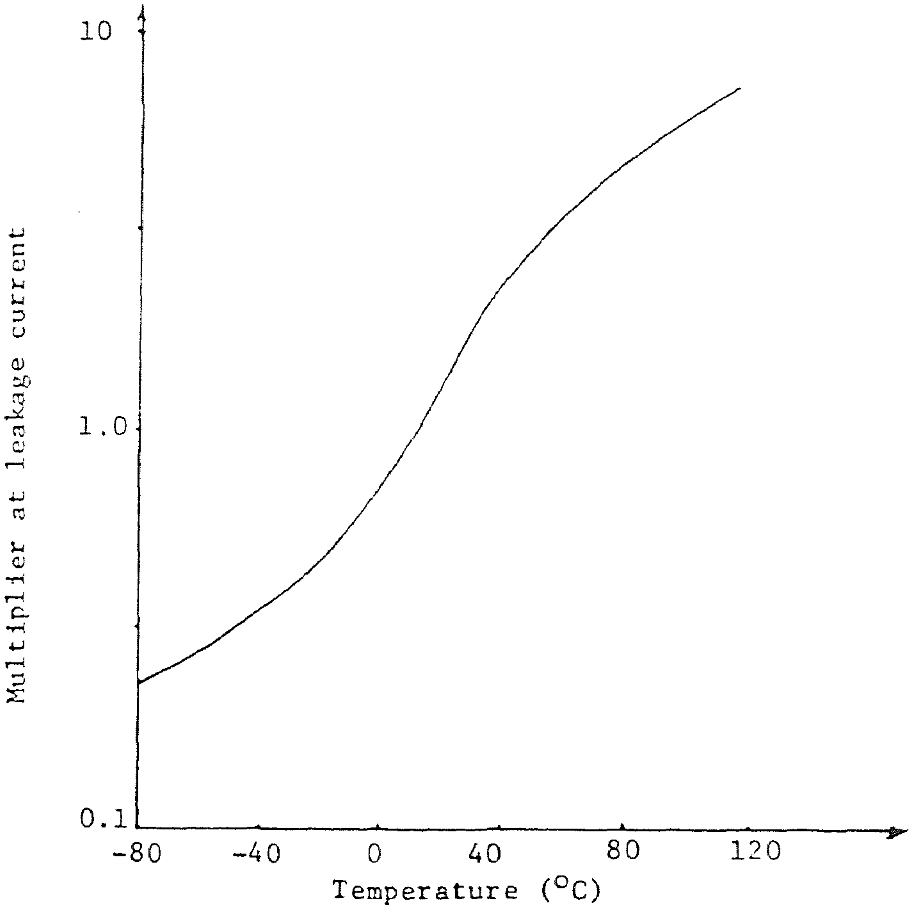


Figure (5) Effect of Temperature on Leakage Current

where R = Reaction rate
A = a constant
E = Activation energy
k = Boltzman's constant
T = Absolute temperature in K

4.2 EFFECTS OF MOISTURE:

Brettle and Jackson (1-77) found that leakage current in solid tantalum capacitors is dependant on environment particularly, the water vapor could affect the degradation mechanism. The effect of water vapor was examined more closely by life testing in capsules attached to a vacuum line so that known pressures of water vapour could be introduced to, or removed from, the capacitor at will during the test. It appeared from the observations two independent processes were occuring. Firstly there was the basic degradation mechanism which caused the leakage current to rise steadily and irreversibly with time, and which was unaffected by water vapour.

Secondly, superimposed on this steady increase in leakage current, short term reversible decreases in leakage current could be made to occur by introducing the water vapour. This effect was in contrast to the effect of liquid water where leakage current rises sharply because water makes contact with damaged areas of oxide previously uncontacted by manganese dioxide.

However water vapour at +125°C found to lower the leakage, it appears water vapour at +125°C enters the manganese dioxide structure and increases its resistivity, thus lowering the leakage current.

Infrequently failures due to increases in capacitance and or dissipation factor are found in solid electrolyte tantalum capacitors. A defective hermetic seal which allows moisture to enter the unit is the most common cause for such failures. Since more of the avilable tantalum oxide is contacted by the moisture than is by manganese dioxide, the capacitance shows an increase. Also the dielectric constant of water greater being 80. The increase in dissipation factor results from an increase in the resistivity of the manganese dioxide due to presense of the moisture.

In a study done by Morimoto of Nippon Ltd. (5-73), solid tantalum capacitors were measured for capacitance and dissipation factor under various conditions of relative humidity. The capacitance increased monotonically with relative humidity while the dissipation factor had a maximum in mid relative humidity.

The cause of change of dissipation factor is the change of dielectric properties of the interface between tantalum oxide dielectric film and manganese dioxide counter electrode by the effect of the amount of absorbed water.

The forming voltage of capacitor plays an important role as to what extent the moisture affects the capacitor. In high forming voltage capacitors, the capacitance and dissipation factor changed mainly with the change of dielectric disspersion caused by the change of conductivity of dielectric surface with water molecules absorbed. In the case of low forming voltage capacitors, the capacitance changed mainly with the change of series capacitance in the interface, while the dissipation factor scarcely changed. These changes were observed to be reversible, because they are apparently due to physical absortion.

4.3 SELF HEALING PROPERTIES:

Tantalum capacitors have ability to heal themselves from a breakdown. Small dielectric breakdowns do not always lead to catastrophic failure (2-64) Figure 6 shows the current flow with time in which dielectric did not undergo catastrophic failure.

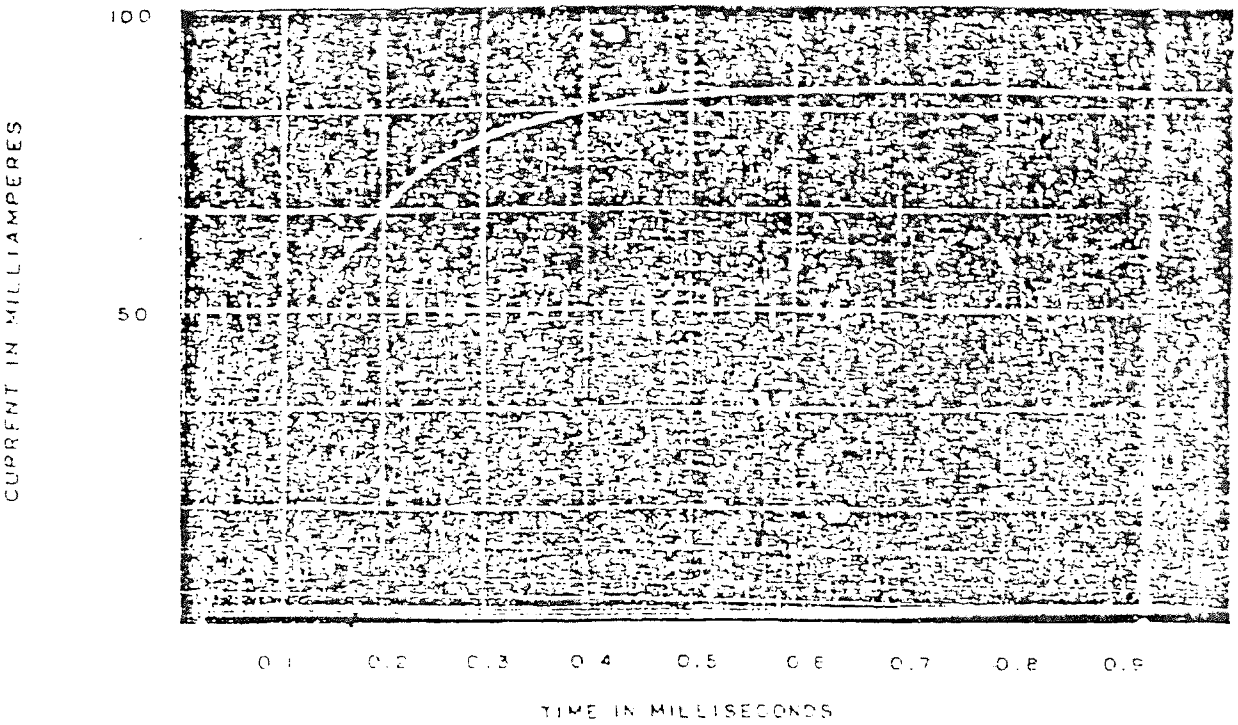
The mechnism for catostrophic failures and leakage current increase can be the result of a phenomenon known as current flickering. The term is used to describe current surges brought about by momentary shorts that sometimes occur within solid electrolytic capacitors. Such bursts of current can behave in different ways, producing a leakage current increase, a decrease, no change at all, or a catastrophic failure.

If the end result of current surge is a catastrophic failure, then the flickering is considered to be of non-healing type, however, if the current surge only affects the leakage current of the capacitor to a minor degree, then the flicker is considered to be of healing type.

The healing mechanism in solid electrolyte tantalum capacitor is not essentially eletrochemical in

OSCILLOSCOPE TRACE OF A SOLID ELECTROLYTE TANTALUM CAPACITOR UNDERGOING CATASTROPHIC FAILURE

TRACE OF DC LEAKAGE VS TIME



DIELECTRIC BREAKDOWN AND HEALING
6.8 MFD/6 VDC

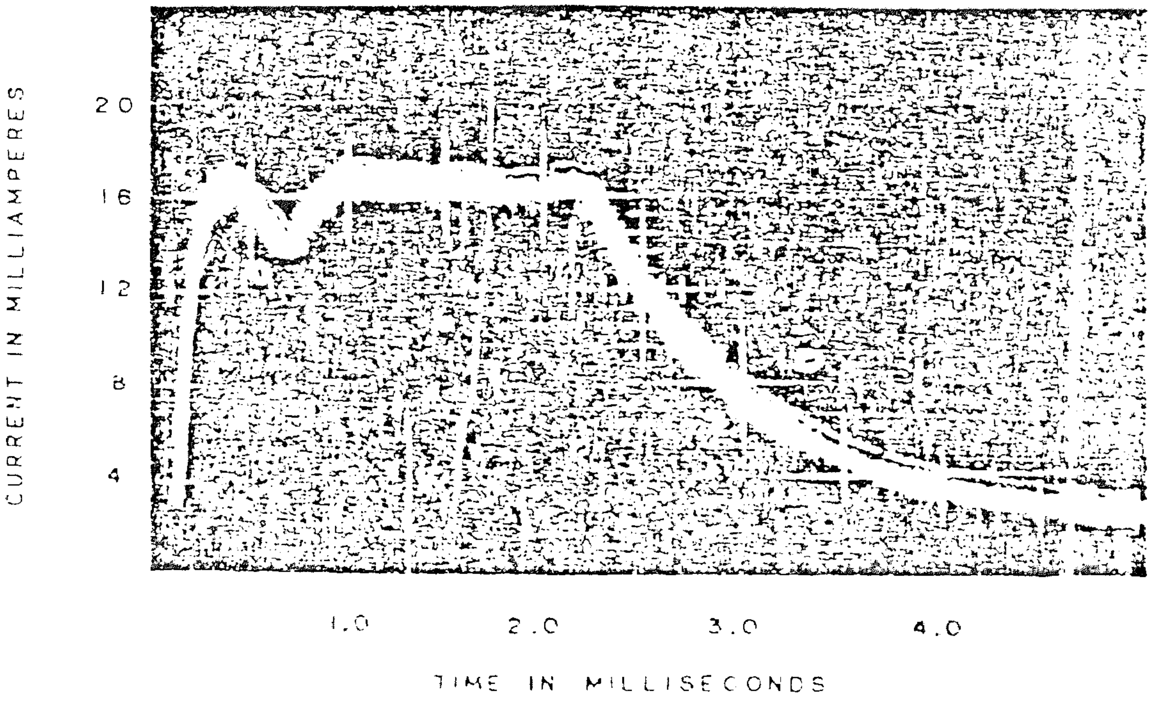


Figure (6)

nature as with the wet electrolytic capacitors. Rather the resulting reaction at an oxide discontinuity is considered to be a thermal breakdown due to passage of large currents for extremely short times through small flaws in the tantalum oxide dielectric film. This results in the liberation of oxygen from the semiconductive manganese dioxide coating and the oxygen probably combines with the exposed tantalum metal to reform a dielectric oxide. Current flow is further inhibited by reduction of manganese dioxide to a lower higher resistivity oxide. Therefore a short burst of current can bring about the healing of the defective sites, and thereby blocking the high leakage current sites.

4.4 CIRCUIT RESISTANCE EFFECTS:

Commercial experience suggests that solid tantalum capacitors are more stable in service if they have an resistance in series with them than when they have applied voltage of low impedence source. Because of their very small size, surge currents through crystallization sites can lead to extremely high temperatures in extremely short times, for example 10000 degree C in 3×10^{-8} seconds (1-77). It is suggested that a circuit resistance should be added which would limit the current passage through the crystallization sites to much less than that of without circuit resistance in case of surge currents.

Jackson and Brittle (1-77) investigated the effects of circuit impedence by the use of life testing. The addition of circuit impedence resulted in a much lower and stable leakage current which increased very slowly over a long period of time. Also, when leakage current is controlled to reasonable limits, the heat generated can reoxidise the crystallized dielectric film.

With high circuit impedence (of the order of 1000 Ohms) the bumps in the dielectric film although increase in number during the life as in the case of low circuit impedence, but donot generally crack in contrast. It appears that an added circuit impedence not only prevents the development of large electrical discharge sites, but also the growth of uncracked bumps into somewhat larger cracked bumps.

4.5 EFFECT OF IMPURITIES IN TANTALUM ANODES:

It is generallybelieved that the DC leakage current of sintered anode tantalum capacitors is effected markedly by chemical purity of the tantalum metal used.

Impurity levels change during sintering (baking below melting point under vaccum) to an extent depending on the sintering conditions i.e., temperature, duration, density of the pellets, level of vaccum etc. The impurities found in tantalum powder include Oxygen, Nitrogen, Copper, Sodium, Iron, Carbon, Nickel, Cromium, Silicon and Titanium. Different impurities behave differently during the period of sintering. Each has a different rate of decrease depending on the sintering conditions. It was found to change appreciably impurities such as oxygen, carbon and sodium, while other contents changed to a lesser extent. However there is no quantitative information avilable.

The surface can be purer than the bulk, if during sintering the rate of the removal of impurities is limited to diffusion in to the metal rather than by vapourization from the surface. The reason for using tantalum wire inserted in the pellet, instead of any other solderable wires is to aviod contamination of the anode pellet.

However leakage current was found to be a direct function of quantity and quality of the contaminants. High leakage due to copper contamination has occasionally been observed. Contaminants such as platinum found to have no effect on the leakage. Field of Ta O crystallization as discussed earlier stem always from these impurity sites in the anode.

CHAPTER V

SOLID TANTALUM FAILURES
VERSUS
PROCESSING PROBLEMS

CHAPTER V - SOLID TANTALUM FAILURES vs. PROCESSING PROBLEMS

5.1 FAILURE TYPES:

All of the solid tantalum failure types worth considering are (2-85) arranged in Table IV. The nature of failures has been defined as follows:

Critical: The function of the capacitor is destroyed.

Important: The capacitor continues to function - but circuit performance may be affected.

Minor: Capacitor parameters somewhat drift - but the circuit is probably unaffected.

Rare: Possible but virtually never hapens under normal conditions.

5.2 FAILURES vs. PROCESS:

...Catastrophic Destruction

...Sudden and Permanent DC Leakage Current Increase

...Upward Drift of DCL with Time

These three failure types are well known to both users and manufacturers of solid tantalum capacitors. To some degree the total impedence of the circuit in

TABLE IV *

CLASSIFICATION OF SOLID TANTALUM FAILURES

	TYPE	DESCRIPTION
CRITICAL	AC/DC	Catastrophic Destruction
	DC	Sudden and Permanent DCL Increase
IMPORTANT	DC	Upward Drift in DCL with Time
	AC	Excessive Capacitance Change with Time
	AC	Excessive Capacitance Change with Temperature
	AC	Poor High Frequency Performance
	AC/DC	Failure Due to Temperature Cycling
	DC	DCL Increase Due to High Humidity Exposure
	AC	Excessive Cap/DF Change Due to High Humidity
MINOR	DC	Very High DCL at Reverse Voltage and Room Temp.
	AC	DF Increase Beyond Limits
RARE	DC	Excessive Drift of DCL on Shelf at Elevated Temp.
	DC	Failing Surge Current Test
	AC/DC	Failing Due to Shock and/or Vibration

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* Relationship of Solid Tantalum Failures to Processing Problems
Richard J. Millard, Retired from Sprague Electric
Proceedings of IEEE and NJIT Reliability Seminar, Sept. 11, 1985

which the capacitor was applied controls the nature of the failure. With total circuit impedence of 3 ohms/volt or greater the failure is not likely to be catastrophic.

These failure types are generally related to the following:

1. Impurities in the Anode

   During the pressing operation tantalum pellets have been contaminated by unclean dies and punches and this should be considered as a critical problem since present-day lower sintering temperatures do not remove impurities as rapidly as the old higher temperatures in the previous processing conditions.

2. Incorrect Anodization Electrolyte

   Use of an electrolyte with the wrong composition can result in incipient oxide crystallization. This might not be immediately apparent either visually or electrically; but, in time, could result in further crystal growth, the consequence of which is increased DC leakage.

3. Physical Contact After Anodization.

Any abrasive contact of the anodized tantalum pellet with foreign object, even tantalum, will damage the thin dielectric film. Since the next step is to deposit MnO_2 there is little hope of healing the damaged site. Such damaged capacitors generally fall out as yield but there is always a possibility of getting through.

4. Over Impregnation with MnO_2

Applying excessive MnO_2 can cause higher DC leakage during life and makes a capcitor failure-prone. When a thin layer of MnO_2 covers the imperfections on the Ta_2O_5 film it readily heats up locally and is converted to a lower (insulating) oxide of the manganese. On the other hand, a thick MnO tends to spread the heat sideways causing rapid local area temperature increase at the tantalum/oxide interface and thus spreading the defect.

5. Inadequte Manganese Dioxide Top Coating

One of the problems of solid tantalum manufacture is the need to apply colloidal graphite between the MnO_2 and the metal counter (cathode) electrode. Any defect in the final MnO_2 layer which allows the graphite to penetrate into the dielectric film will ultimately result in failure.

6. Ta Pellet Oxygen Content Greater than 3000 ppm

Recently it has been found that oxygen levels in the sintered tantalum pellets greater than about 3000 ppm cause defects in the dielectric film. These defects are brought about by an oxide phase which precipitates as surface nodules as you can see from the Figures 7 and 8. To control this problem it is necessary to maintain the oxygen in the powders below about 2000 ppm.

5.3 EXCESSIVE CAPACITANCE CHANGE WITH TIME AND WITH TEMPERATURE:

In the fabrication of solid tantalum capacitors manganese dioxide is deposited by pyrolytically converting manganous solution. This is accomplished at temperatures between 250°C and 400°C and it is necessary to repeat the procedure several times. The anodized tantalum is, therefore, exposed to high temperature for reasonably long time. This produces the undesirable heat cycling effect on the dielectric.

When anodized tantalum is heated above 200°C a permanent increase in capacitance and ESR takes place.

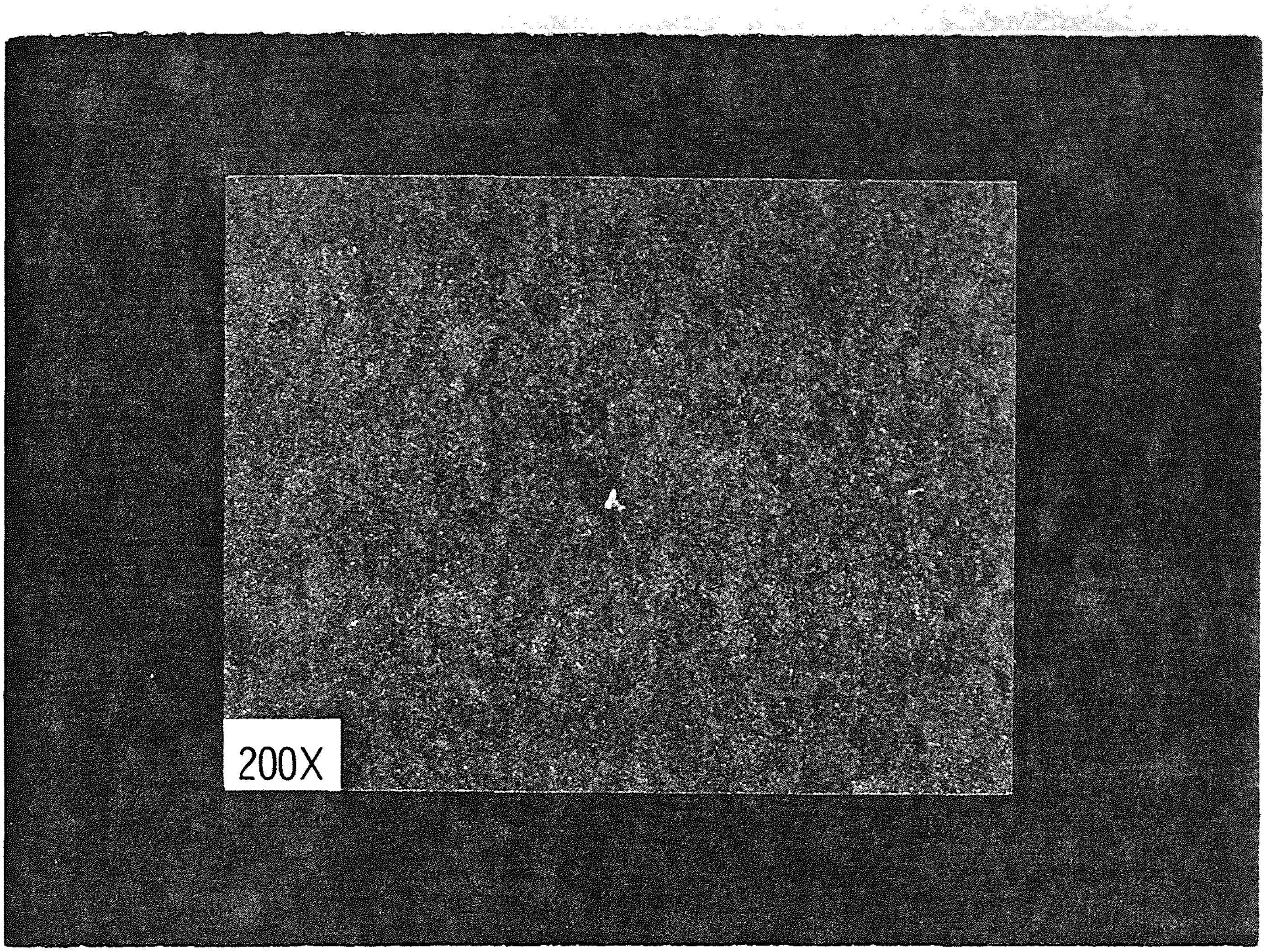


Figure (7) Scanning Electron Microscope View of Pellet with 2000 ppm Oxygen Content

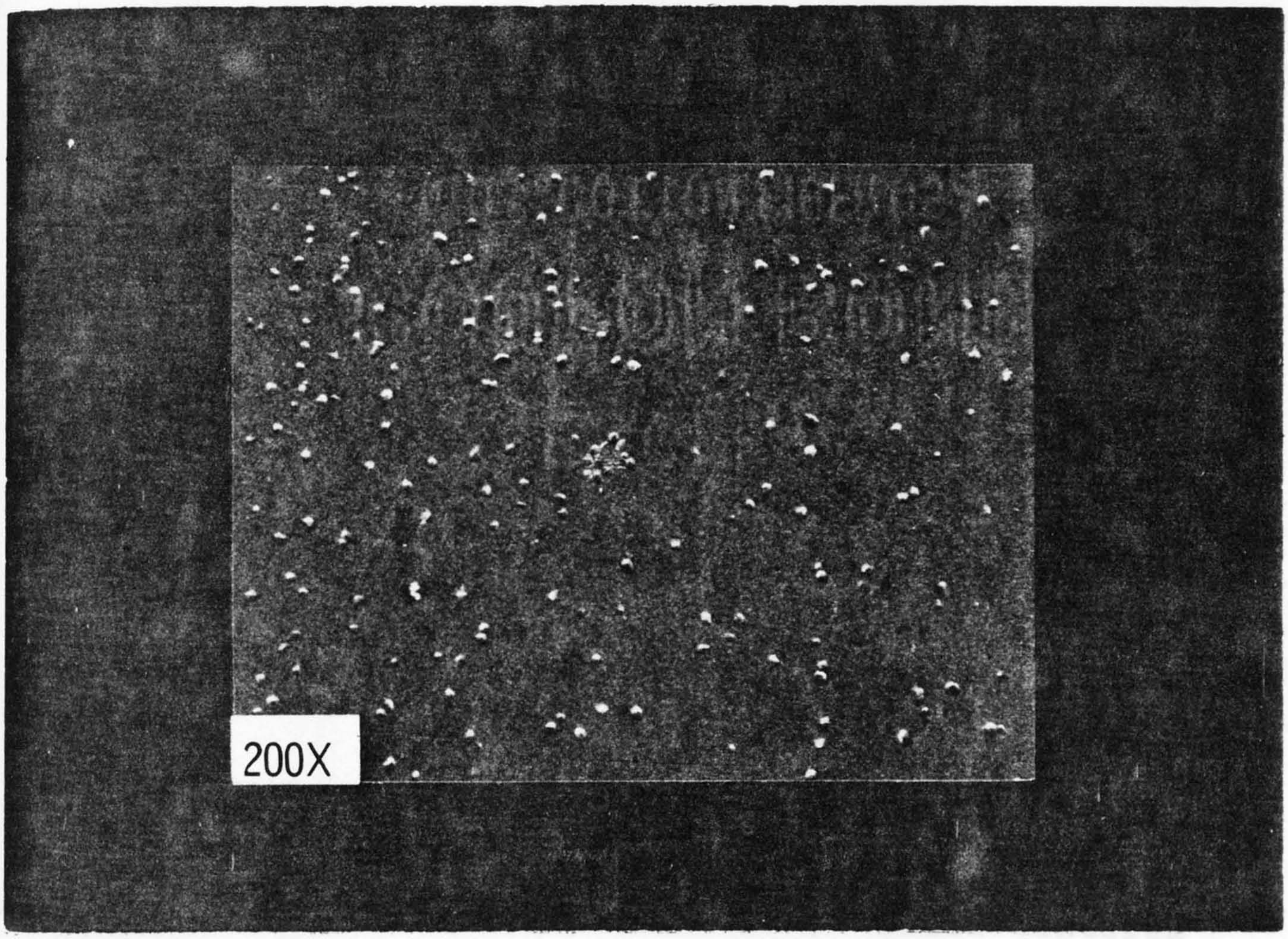


Figure (8) Scanning Electron Microscope View of Pellet with 3700 ppm Oxygen Content

This temperature changes the conductivity profile of the Ta_2O_5 near the tantalum. A gradient of oxygen vacencies is established near the tantalum because of tendency of this metal to oxidize especially at high temperatures. [illegible] The oxygen deficient portions of the Ta_2O_5 will exhibit n-type semi-conductivity. It is this conductivity which causes most of the deleterious effects on the dielectric.

However, inadequate treatment of the dielectric will cause the following:

...Unstable capacitance with time
...Excessive capacitance change with temperature
...Excessive capacitance change with frequency
...Excessive capacitance change with DC bias
...High dissipation factor

5.4 POOR HIGH FREQUENCY (10K to 100KHz) PERFORMANCE:

When properly constructed, solid tantalum capacitors have AC characteristics in the high frquency range of 10K to 100KHz. Poor performance in the high frequency range is generally due to sintered pellet, dielectric or manganese dioxide deposition problems.

1. In order to realize good high frequency charateristics, the resistance from the surface to the center of the porous pellet must be as low as possible. This can be accomplished by several ways: The pellet diameter can be minimized or its shape can be changed completely. The pellet density can be maintained as low as possible; this will increase cross sectional area of the pores.

2. Deposited MnO_2density should be sufficient to make the resistance as low as possible. Inadequate filling of the pores will raise the resistance within the pellet; however over filling can puncture the oxide causing high DC leakage and lowered reliability. It is also necessary to establish a low resistance contact from MnO within the pellet to metal counterelectrode.

3. Improper localized heat during capacitor processing will adversely affect the high frequency characteristics of the tantalum capacitors.

5.5 FAILURES DUE TO TEMPERATURE CYCLING:

During cycling a variety of temperatures are used. Some are more like thermal shock, while others are relatively mild. Failures on this type of test are far more prevalent with non hermetic units. This type of failure is generally caused by stress on the device which is accentuated by the cycling. It is difficult to assign such failures to any processing step but the following are proposed:

1. There is always the possibility of gross mismatch in coefficient of linear expansion between the capacitor and encapsulating material.
2. A short or high DC leakage can be due to the fact that a defective MnO_2 coating has allowed graphite to penetrate and cut through the oxide particularly during the temperature cycling thus shorting the capacitor.

5.6 DC LEAKAGE INCREASE DUE TO HIGH HUMIDITY EXPOSURE:

Solid tantalum capacitor with no encapsulation, although mechanically weak, will withstand high humidity exposure at elevated temperature without significant change in DC leakage (2-85). However, certain encapsulants (non-hermetic) can increase the probabilty of failure due to migration of impurities in the humid environment.

It has been found that the water soluable, ionizable impurity content of cured encapsulating materials has a large effect on generation of this type of failure. It is essential to select encapsulating materials having a low concentration of such impurities.

5.7 EXCESSIVE CAPACITANCE / DISSIPATION FACTOR CHANGES DUE TO HIGH HUMIDITY:

If a solid tantalum capacitor is not hermetically sealed it matters little weather it is bare or plastic coated moisture will eventully diffuse through the entire body. The following procesing problems contribute to this difficulty.

1. Capacitance level of the solid tantalum is a ratio of the amount of anodized surface in contact with MnO in relation to the entire Ta_2O_5 surface. This ratio is generall very slightly lower than unity. When the moist all of the avialable surfaces are contacted. Hence an excessive variation of capacitance with exposure to humidity indicates poor MnO_2 impregnation.
2. As the density of a sintered pellet increases the pores diminish in size. This increases the

difficulty of complete impregnation with MnO_2.

5.8 VERY HIGH LEAKAGE ON DC REVERSE VOLTAGE:

Solid tantalum capcitors will normally withstand small reverse voltage (about 15% of the rated voltage at room temperature). Occasionally capacitors are found to have acceptable forward DC leakage but extremely high current when the potential is reversed. This phenomenon is not adequately understood but, there are certain factors of interest.

1. The presence of certain metallic impurities increase the reverse voltage current.
2. This problem seems to be caused by high heat during the in-processing.
3. Tantalum pellet oxygen content greater than 3000 ppm can greatly increase the reverse voltage current.

5.9 DISSIPATION FACTOR INCREASE BEYOND LIMITS:

Sometimes the dissipation factor increases, sometimes significantly, because of the following processing problems.

Failure to properly apply graphite to MnO_2 surface will result in a gradual increase (2-85) in dissipation factor to veryhigh values.

The graphite and silver coatings do notchemically bond to the MnO_2. Therefore, it is necessary to provide a relatively rough surface onto which they can mechanically lock. Depending upon the degree of smoothness of the MnO surface the DF will increase rapidly or slowly over a period of time.

Because silver dissolves readily in molten tin/lead solder a small percentage of silver is added to minimize this problem. However, application of excessive heat during the assembly operation can cause dissolution of a portion of the silver layer. This increases the series resistance which develops during the operation of the capacitor causing high dissipation factor.

CHAPTER VI

ACCELERATED LIFE TESTING

AND

RESULTS

CHAPTER VI - ACCELERATED LIFE TESTING AND RESULTS

We at NJIT's Reliability Center, did the experimental part of the study on solid tantalum capacitors encapsulated in plastic by means of accelerated life testing under the conditions of severe humidity and high temperature as well as at various high temperatures with out added humidity.

The work was done in two parts. First part is comparative study in which Solid Tantalum Capacitors obtained from five different international manufacturers and life tested to rank the manufacturers. In second part units obtained from the single manufacturers were life tested at high temperature with high humidity as well as at various dry high temperatures to understand the effect of humidity.

6.1 PROCEDURE:

Essentially for each capacitor the following parameters were measured, before, during and after the life tests.

(i) Capacitance

(ii) Leakage Current

(iii) Equivalent Series Resistance

The capacitance was measured using a Digital Capacitance meter (made by Data Precision Model #938). The only precution taken during this measurement was to make sure that the capacitor had no charge before they were measured. This was done by shorting the capacitor for brief period of time.

The equivalent series resistance was measured using a Digital ESR meter (made by Clark Hess model #273A). Again the only precaution taken during this measurement was to make sure that the capacitors had no charge before they were measured. The reason this precaution was taken in both the measurements was to protect the measuring instrument.

The leakage current measurements were done in a very high quality room (manufactured by Shielded ACE Enclosures, and modified by Dr. R. P. Misra for improvement) to aviod stray currents which would have affected the very small leakage current values. The Figure 9 shows the set up used for the leakage current measurements. With this set up, it was possible to measure leakage current for thirty two capacitors in relatively short time after they have been charged at

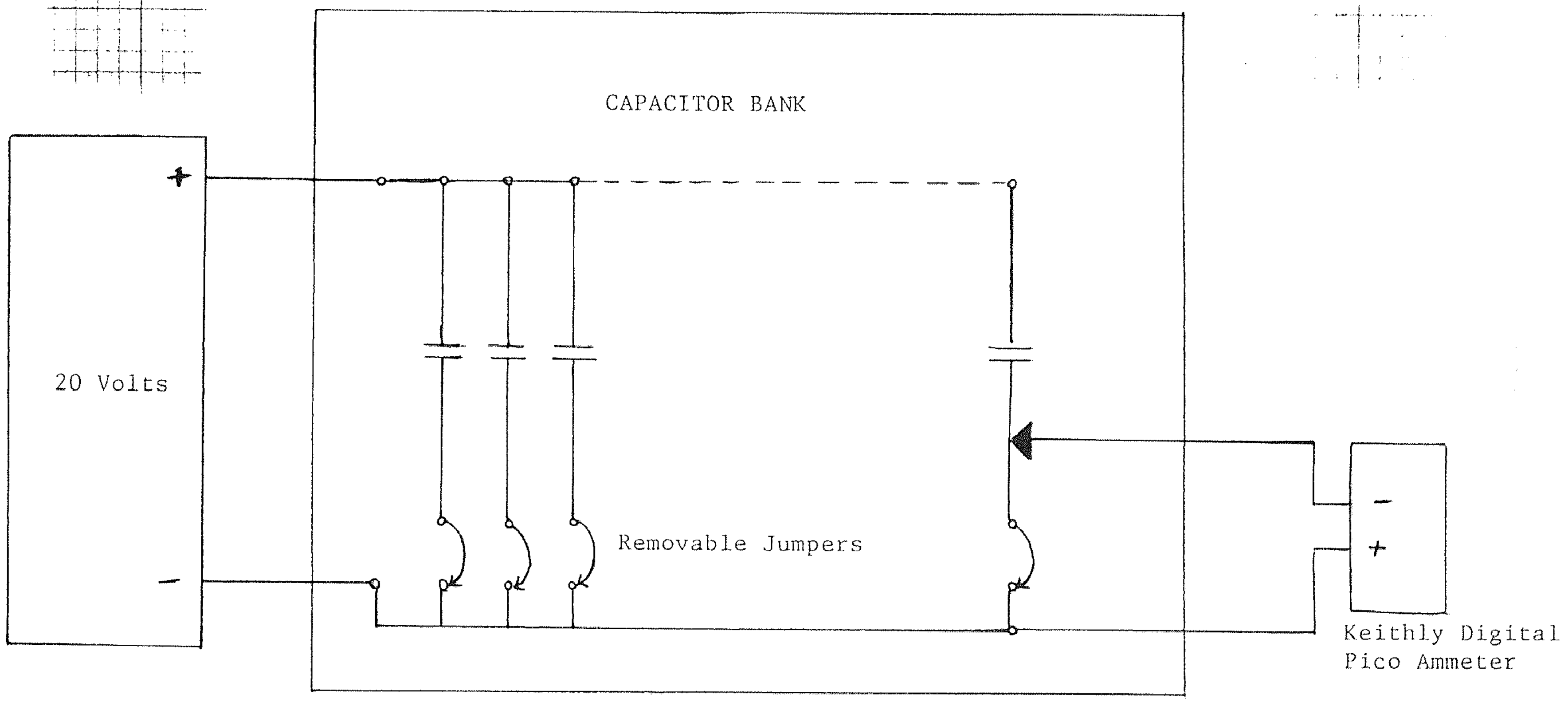


Figure (9) Schematic of Leakage Current Measurements Set Up rated voltage (using Hewlett Packard DC Power supply model Harrison 6290A) and stabilized. The time under bias voltage (charging) varied between one to two hours depending on the stability of the leakage current readings. To determine the stability of the leakage current, readings were taken at various points of time. To aviod interrupting the current, the ammeter is connected first across the detachable jumper in series with the capacitor. Then the jumper is opened and the reading is recorded after allowing about 20 to 60 seconds to stabilize. Kiethly Digital Multimeters Model # 616 and 485 were used to measure the leakage currents.

Each of the capacitor life tested was identified with a Copper tag with its number engraved on the tag. Before putting in the life test chambers all the three parameters mentioned above were measured for each individual capacitor. All these parameters were measured after each 1000 hours of test. The units were then kept at room temperature and room humidity for 48 hours and the three parameters were measured again. The values at the end of each 1000 hours have been noted but not used in the calculations to aviod any misleading instabilities due to abrupt change in the environmental conditions. And the reading taken after stabilizing for 48 hours are designated as the readings after the end of

1000 hours test.

6.2 COMPARISION BETWEEN DIFFERENT MANUFACTURERS:

This part of the experimental work was done by messers Grant, Nakrani and Nasser at our Reliability labs. Solid Tantalum Capacitors were obtained from five different highly reputed manufacturers from both United States and Japan. The suppliers are identified in this study as 1, 2, 3, 4, and 5 according to their standing after the life test. That is the supplier #1 is the company whose capacitors showed least amount of failures and the supplier #5 showed highest amount of failures. Out of the samples gathered, which ranged between 150 & 250 units each, fifty random units of each were introduced to the life test.

It was not possible to obtain capacitors of the same value or even of the same rated voltage. Therefore normalization of the leakage current values was done before any comparison between the suppliers. The leakage current for the each supplier divided by the multiplication of average capacitance and rated voltage using following reasoning.

$C = k\,A/d$, where C is capacitance

A is the area

d is the thickness of the

dielectric.

k is the dielectric constant

But the breakdown voltage is proportional to d and if we assume rated voltage to be some fraction of breakdown voltage for each manufacturer,

C is proportional to A / V rated

For two capacitors C1 and C2,

C1 / C2 = (A1/V rated1) / (A2/V rated2)

i.e. A1/A2 = (C1/C2) X (V rated1 / V rated2)

And also the leakage current IL = V rated /Rp

Where Rp is the equivalent parallel resistance of the dielectric.

Now Rp = d/A

Therefore IL = V rated /(d/A) $\propto$ V rated /(d/A)

$\propto$ V rated . C

Therefore some form of equivalency can be noted between different types.

The life test was carried out for 1000 hours without interruption in a humidity chamber at high temperature. The relative humidity was maintained at 96 ± 3% and the temperature at 98 ± 2°C. The initial and after test statistical data is shown in Tables V and VI respectively.

TABLE V

INITIAL MEASUREMENTS

Capacitor Supplier #	N	Capacitance		Leakage Currentt		ESR	
		$\bar{x}$ uF	σ uF	$\bar{x}$ nA	σ nA	$\bar{x}$ Ohms	σ Ohms
4	50	105.6	.755	18.69	21.64	.16	.023
2	50	22.32	.55	80.24	74.07	.41	.051
5	50	39	2.11	19.56	15.62	.355	.076
1	49	21.67	.4	11.47	26.88	.544	.046
3	50	22.36	.29	66.28	252.87	.47	.061

TABLE VI

MEASUREMENTS AFTER "1000" HOURS @ 96 ± 3% and 98 ± 2°C

Capacitor Supplier #	N	Capacitance		Leakage Curren		ESR	
		$\bar{x}$ uF	σ uF	$\bar{x}$ nA	σ nA	$\bar{x}$ Ohms	σ Ohms
4	16	109.85	.8	5.6	3.58	.859	.552
2	42	22.56	.61	10.7	33.6	.58	.49
5	12	36.24	10.33	15.2	21	.58	.076
1	45	21.87	1.66	18.4	26.1	3.69	1.57
3	27	22.62	.36	18.2	22.8	2.44	2.01

TABLE VII

Capacitor Supplier #	n		Failure Rate	Number of Failures
4	50	p4	.68	34
2	50	p2	.16	8
5	50	p5	.76	38
1	49	p1	.08	4
3	50	p3	.46	23

TABLE VIII

	Δp	σw	$\Delta p/\sigma w$
p1 vs p2	.08	.0649	1.54
p1 vs p3	.38	.088	4.31
p1 vs p4	.6	.097	6.18
p2 vs p5	.68	.106	6.14

Table VII shows consolidated failure data and Table VIII shows the results of Null Hypothesis which indicates that there is not much difference between supplier 1 and supplier 2 but there is no doubt that suppliers 3, 4, and 5 were very much inferior in that order.

Temperature effect in this study is not really profound since most capacitors are designed to operate without change in the range of 30°C to 150°C. The major increase in the leakage current and capcitance occured due to high humidity. However in some cases the capacitance went down and it is felt that this was due to poor adherence of tantalum oxide to tantalum due to tremendus mismatch in thermal coefficient of expansion.

6.3 STUDY AT DIFFERENT ENVIRONMENTAL CONDITIONS:

As seen in the last section the leakage current and equivalent series resistance increased subtantially, in turn failing the solid tantalum capacitors encapsulated in plastic when exposed to high humidity at high temperature.

To make certain high temperatures without added high humidity does not have profound effect on the capacitor parameters (primarily leakage current) and failure rates on these devices, the following experimental work was done. Three hundred (300) solid tantalum capacitors encapsulated in plastic produced by a single manufacturer were obtained. The units were of the capacitance value 22 uF rated at 20 VDC.

These units were subjected to life testing for three thousand (3000) hours under the following four different environmental conditions.

(a) 97 ± 3°C with 98 ± 2% Relative Humidity

(b) 97 ± 3°C without added Humidity (that is at room air circulation)

(c) 85 ± 3°C without added Humidity

(d) 77 ± 3°C without added Humidity

The number of units used in the conditions a,b,c and d are 50, 75, 75 and 100 respectively.

These units were life tested for 3000 hours under the respective conditions given above. As mentioned earlier readings of capacitance value, equivalent series resistance and leakage current are taken at the end of each thousand hours of uninterrupted life test.

Then the units were allowed to stabilize at room temperature for 48 hours and then the readings were taken agian, for all calculation purposes and in the tables these values are used to aviod any misleading transient effects.

The data generated is tabulated in the tables in appendix A and the explaination for the abbrivations used in the tables as follows.

ESR...... Equivalent Series Resistance
CAP...... Capacitance Value
IL....... Leakage Current

CAP0, IL0 and ESR0...... INITIAL MEASUREMENTS
CAP1, IL1 and ESR1...... MEASUREMENTS AFTER "1000" HOURS
CAP2, IL2 and ESR2...... MEASUREMENTS AFTER "2000" HOURS
CAP3, IL3 and ESR3...... MEASUREMENTS AFTER "3000" HOURS

The Table IX-A shows the number of units used in each test condition and number of failures at each stage (that is at 1000, 2000 and 3000 hours) as well as percentage of failures. A unit is said have failed when the DC leakage current exceeds about 200 micro ampheres because at this stage not only the leakage current becomes excessive but one is not able to

TABLE IX

IX-A

TC	N	#FAILED 1 K Hour	#FAILED 2 K Hour	#FAILED 3 K Hour	%FAILED 1 K Hour	%FAILED 2 K Hour	%FAILED 3 K Hour
a	50	15	8+15	13+23	30	46	72
b	75	3	3+3	1+6	4	8	9.33
c	75	0	0	9	0	0	12
d	100	0	2	0+2	0	2	2

IX-B

TC	$\overline{C}$ INITIAL	σ C INITIAL	$\overline{C}$ 1 KH	σ C 1 KH	$\overline{C}$ 2 KH	σ C 2 KH	$\overline{C}$ 3 KH	σ C 3 KH
a	22.098	.218	22.191	.254	22.178	.195	22.271	.202
b	22.176	.22	22.218	.246	22.196	.248	22.212	.244
c	22.107	.231	21.985	.232	22.019	.242	22.135	.26
d	22.117	.224	22.021	.214	22.069	.214	22.018	.226

IX-C

C	$\overline{ESR}$ INITIAL	σ ESR INITIAL	$\overline{ESR}$ 1 KH	σ ESR 1 KH	$\overline{ESR}$ 2 KH	σ ESR 2 KH	$\overline{ESR}$ 3 KH	σ ESR 3 KH
a	.244	.018	5.025	4.087	4.354	3.197	4.847	3.064
b	.248	.013	.498	.306	.61	.509	.607	.444
c	.247	.012	.246	.012	.245	.0115	.382	.206
d	.246	.012	.245	.0116	.243	.0117	.245	.012

IX-D

C	$\overline{IL}$ INITIAL	σ IL INITIAL	$\overline{IL}$ 1 KH	σ IL 1 KH	$\overline{IL}$ 2 KH	σ IL 2 KH	$\overline{IL}$ 3 KH	σ IL 3 KH
a	36.106	28.997	61683	40821	60037	32612	65784	26659
b	34.246	25.81	67.005	105.93	63.39	84.677	86.266	246.6
c	39.695	80.918	27.293	19.497	38.63	80.77	103.38	145.8
d	32.414	24.523	30.023	36.975	41.89	58.523	33.682	36.15

read the value of the capacitance. The two failures occured at 77°C test seems to have associated with mechanical problems as the leakage current readings were very low (few pico amperes) and capacitance readings were zero. Some of the failure noted in other two dry temperature tests were also found to be open circuited as mentioned above.

Table IX-B shows statistcal data for capacitance value. We can see that capacitance values are considerably stable throughout the life test.

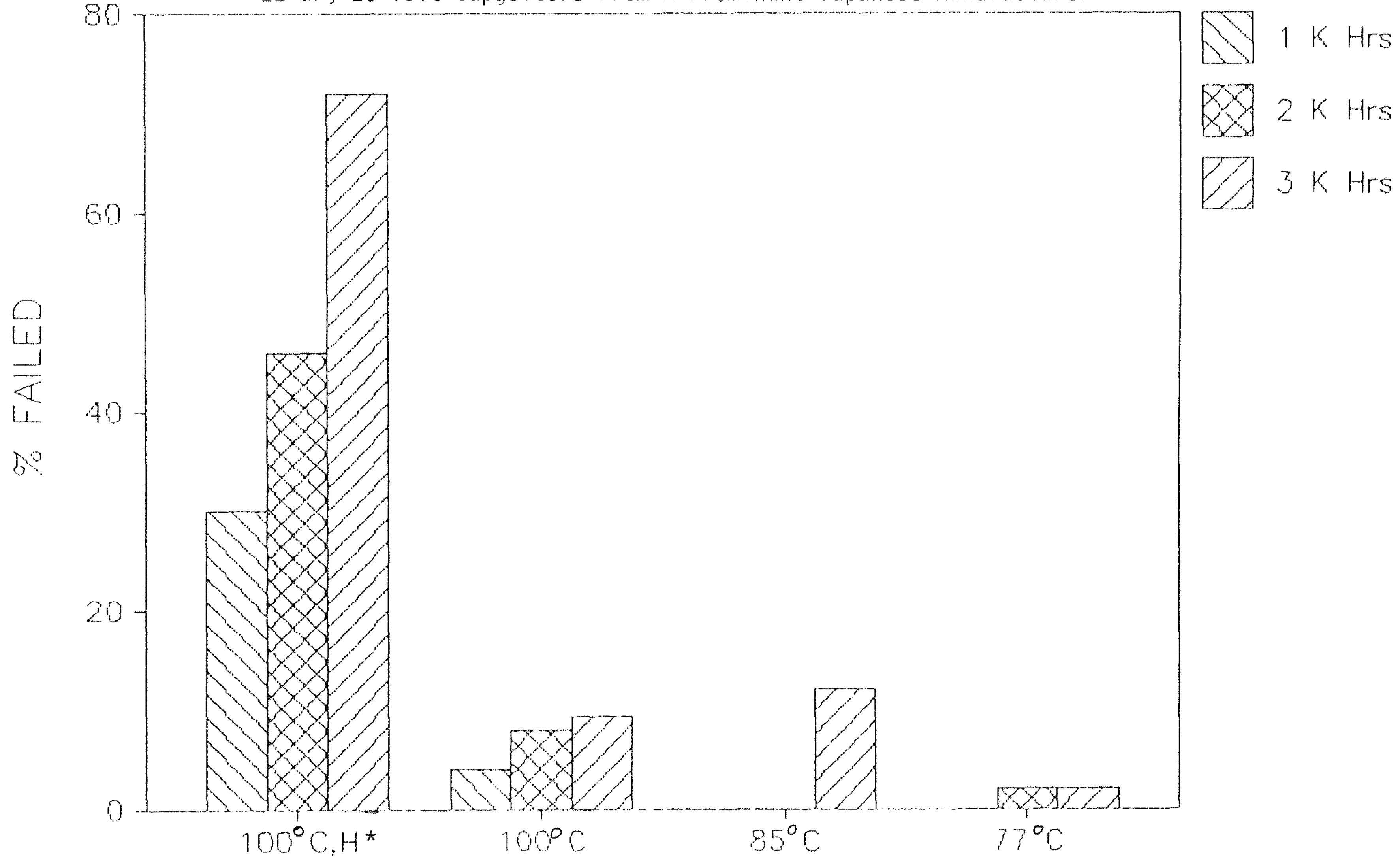
Tables IX-C and IX-D show statistical data for equivalent series resistance (ESR) and leakage current (IL) respectively. In the case of humidity test both the leakage current and equivalent series resistance increased drastically over the life test period.

For better visualization bar charts for leakage current for each and every unit (300) are shown in the Appendix B.

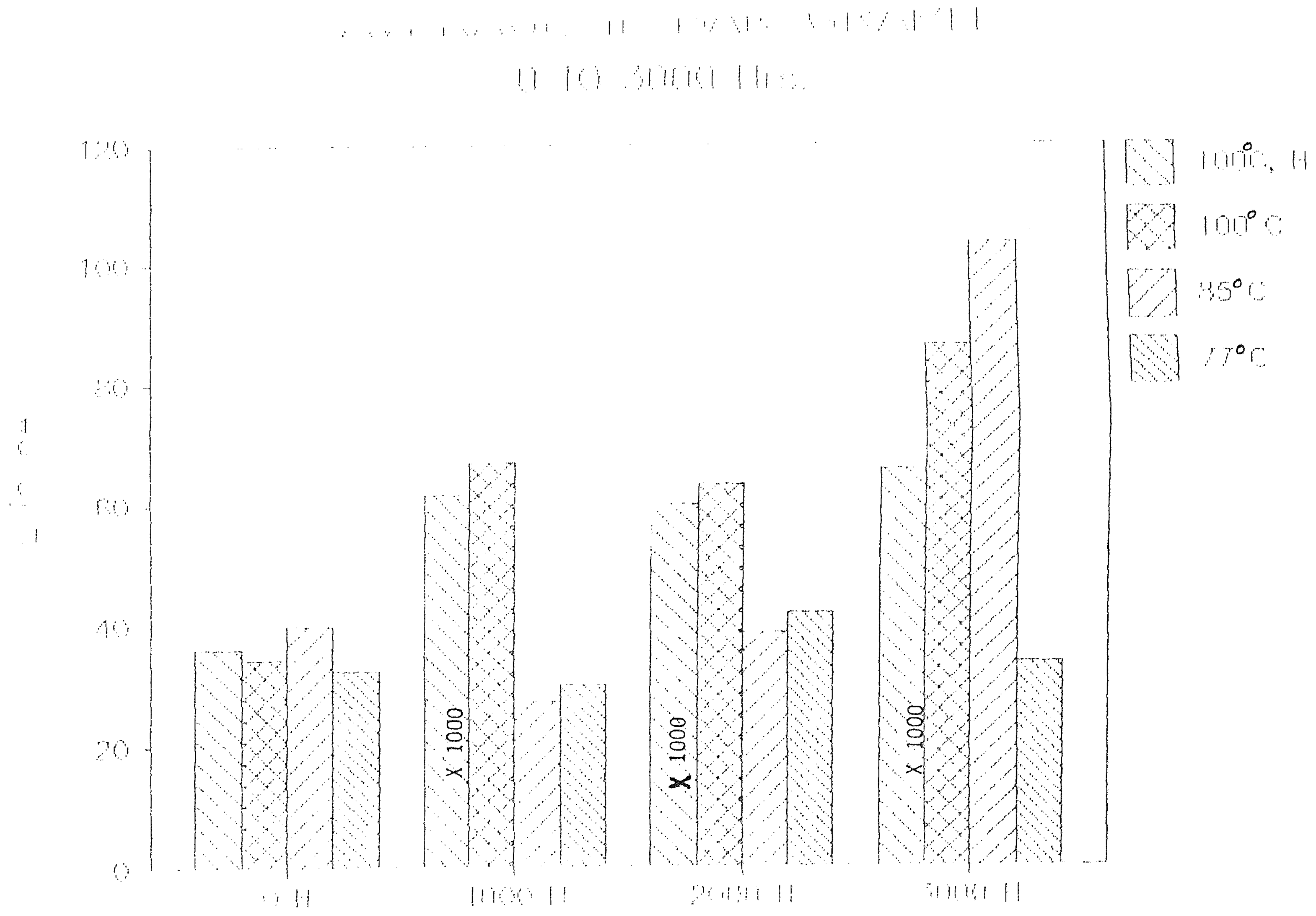
CUMMULATIVE % FAILED

0 TO 3000 Hrs.

22 uF, 20 Volt Capacitors From A Prominant Japanese Manufacturer

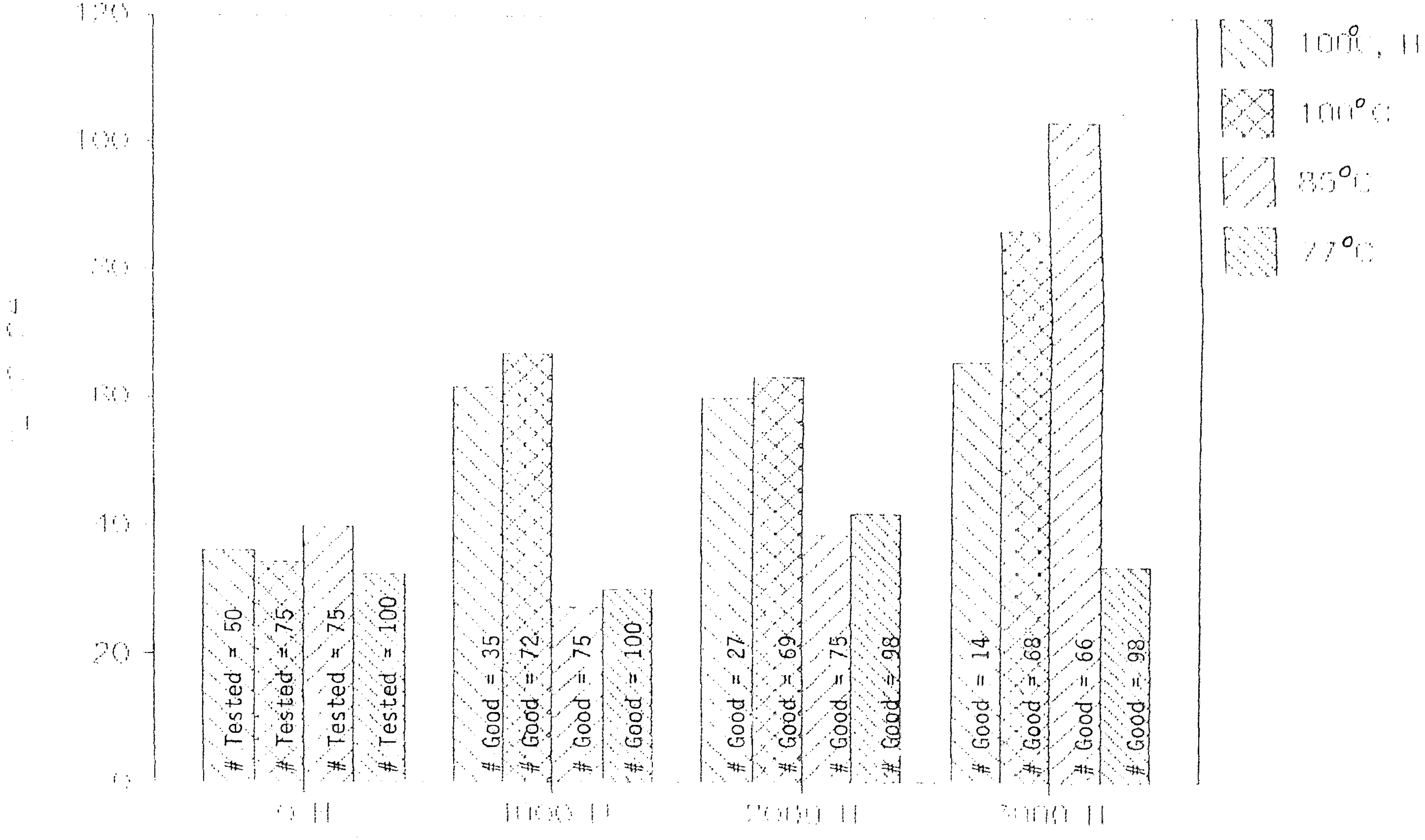


H Refers to 100 % Relative Humidity. The rest of the cases are without added humidity.


[illegible]
0 TO 5000 Hrs.
120
100
80
60
40
20
0
0 H
1000 H
2000 H
5000 H
X 1000
X 1000
X 1000
100°C, H
100°C
85°C
77°C

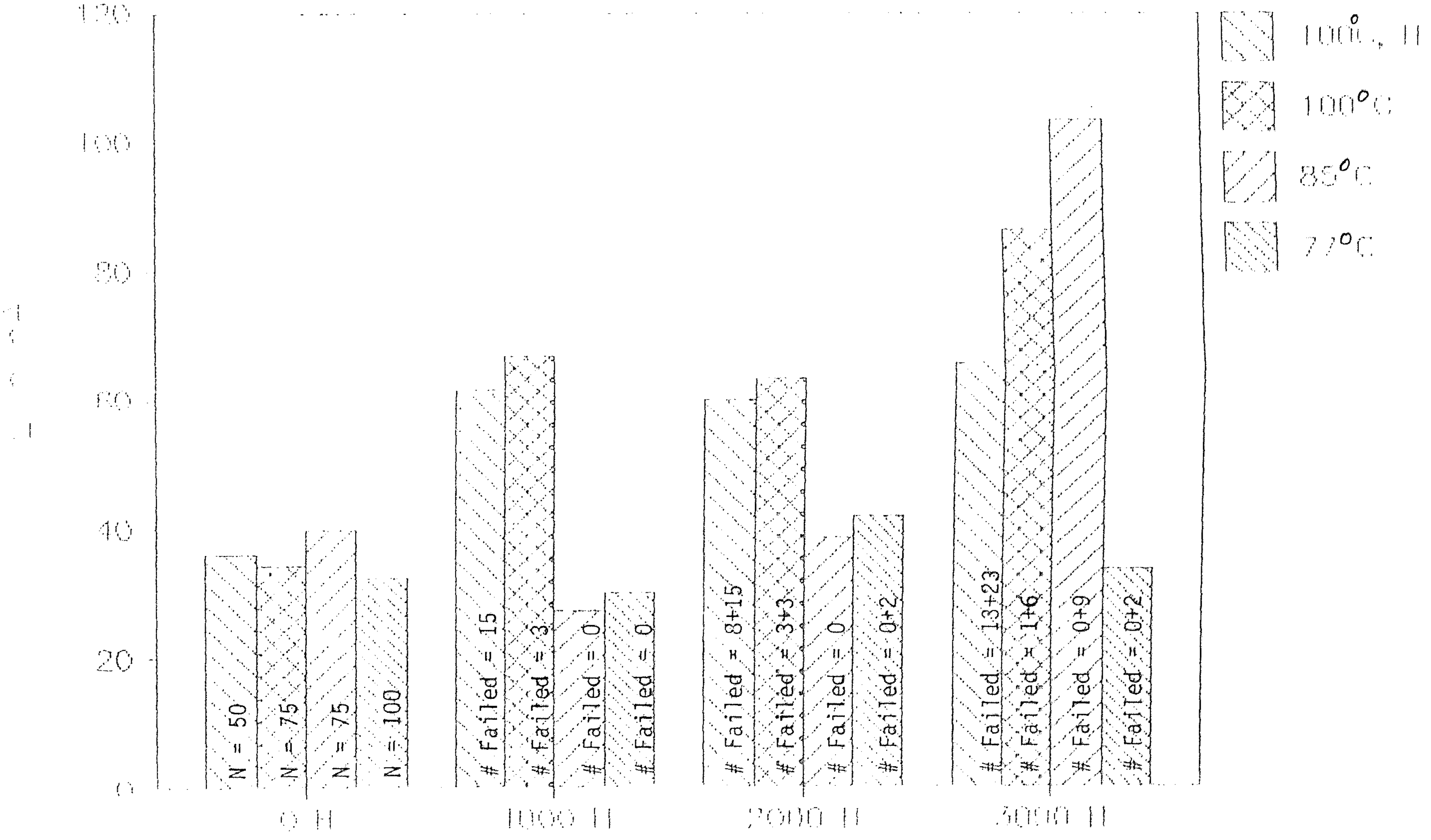
AVERAGE H BAR GRAPH

0 TO 3000 Hrs.

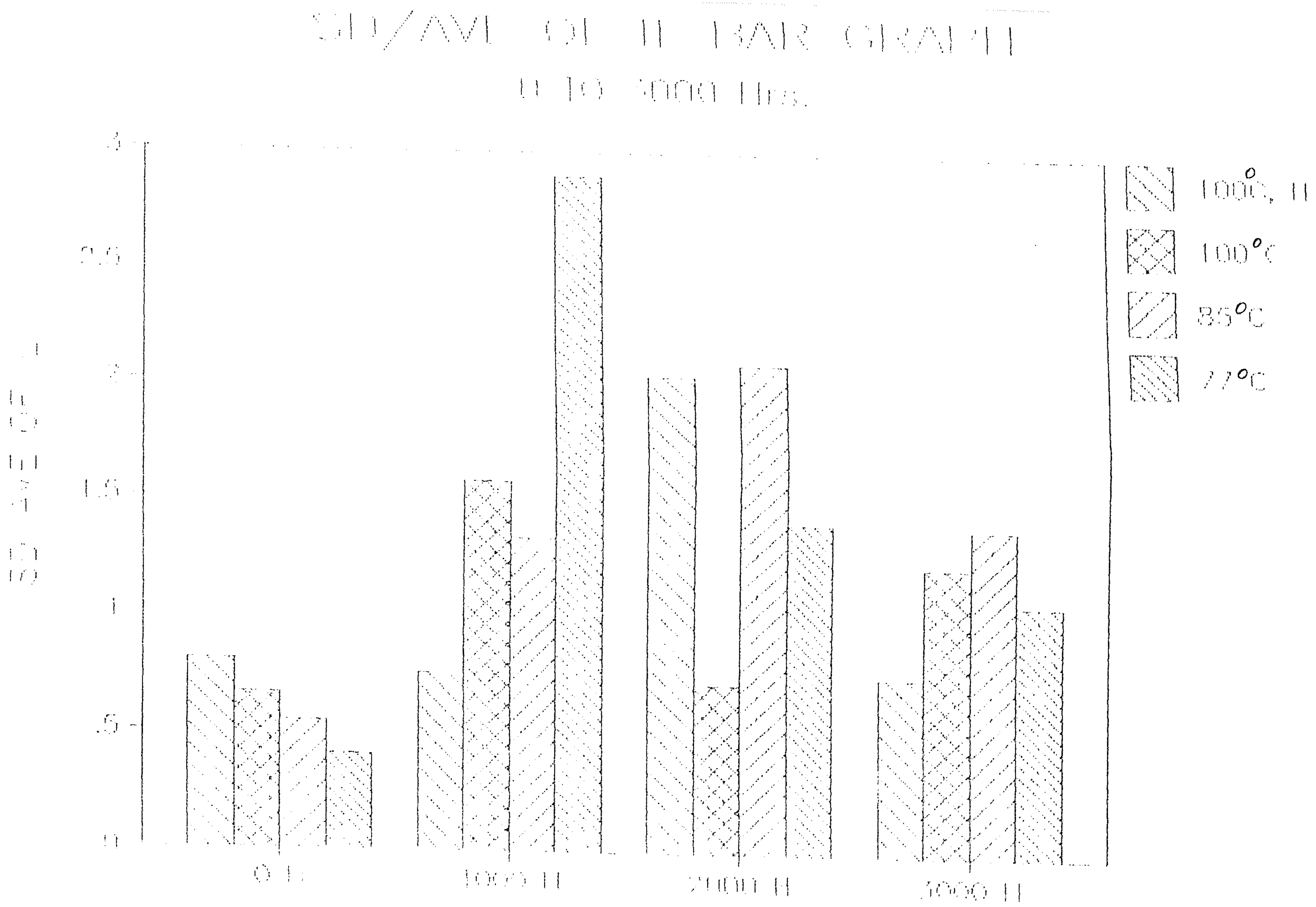


[illegible]

0 TO 3000 Hrs.



0
20
40
60
80
100
120
N = 50
N = 75
N = 75
N = 100
# Failed = 15
# Failed = 3
# Failed = 0
# Failed = 0
# Failed = 8+15
# Failed = 3+3
# Failed = 0
# Failed = 0+2
# Failed = 13+23
# Failed = 1+6
# Failed = 0+9
# Failed = 0+2
0 H
1000 H
2000 H
3000 H
100°C, H
100°C
85°C
77°C


SD/AVE OF IL BAR GRAPH
0 TO 3000 Hrs.
SD AVE OF IL
3
2.5
2
1.5
1
.5
0
0 H
1000 H
2000 H
3000 H
100°C, H
100°C
85°C
77°C

CHAPTER VII

CONCLUSIONS

CHAPTER VII - CONCLUSIONS

Our life tests done at different environmental conditions on 22 uF, 20 Volt solid tantalum capacitors encapsulated in plastic as outlined in previous chapter conclude that high temperature together with high relative humidity causes higher failure rates compared with high temperatures without added humidity. For example at 100°C and 100 % relative humidity the failure percent is 72 % where as at 100 C without added humidity the failure percentage is only 9.33 % by the end of 3000 hours of life test.

The life tests done by messers Grant, Nakrani and Nasser at 100°C with 100 % relative humidity on plastic encapsulated solid tantalum capacitors of five different international manufacturers indicates that there is approximately one order of magnitude difference between one manufcturer to another in failure rates.

There is a drastic difference in co-efficient of thermal expansion between Ta O dielectric and Ta metal which is about 12 times larger for Ta compared to Ta_2O_5 which no doubt gives poor adhession. There should be more research done in this area. Due to this mismatch the tantalum capacitors will not be able to withstand much thermal cycling, mechanical shocks and accelerations if not compressed by plastic moulding.

But unfortunately, the plastic casing does not offer good moisture resistance, one can see this in tremendously increased failure rates as well as the tremendous increase in lekage currents. For example, compare 100°C case of dry versus high humidity and the leakage current ratio at the end of 1000 hours is (62,634 nA/67 nA) = 935 or about three orders of magnitude worse in the case of humidity.

Thus the problem that needs to be solved is to utilize the compression advantages of transfer moulding but develop methods of preventing water vapor to penetrate into the capacitor .

Although the solid tantalum capacitor is in general very reliable yet there are many possible failure types. Problems of materials and processes relating to most failure types are well understood. However there are exceptions.

The basic failure type in the solid tantalum capacitors is found to be increase in leakage current with time leading to catastrophic failure. Basic mechanism of failure has been found to be field crystallization in the dielectric oxide film leading to catastrophic breakdown. It is very important to use high purity tantalum powder in order to produce tantalum oxide films with lesser flaws.

The addition of high series resistance proved to prevent possible hot spots due to transient high currents in turn preventing catastrophic thermal breakdown.

Self healing properties of these devices make major contribution to their high reliability during the operation.

APPENDIX A

MEASURED DATA

APACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 1-50 LIFE TESTED AT

00 DEGREE CENTIGRADE AND 100% RH.

.No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
1	22.0	FAIL	FAIL	FAIL	10.6	FAIL	FAIL	FAIL
2	22.2	22.4	22.3	FAIL	24.0	73400	58900	FAIL
3	21.9	22.0	22.0	21.9	23.8	26900	57200	64900
4	22.3	22.5	22.5	22.6	54.0	50400	29900	45600
5	22.0	22.2	22.2	FAIL	89.0	12600	29700	FAIL
6	22.2	22.1	22.1	FAIL	32.0	26700	24200	FAIL
7	21.9	22.3	FAIL	FAIL	4.8	67300	FAIL	FAIL
8	22.1	22.3	22.2	22.3	9.0	67300	66100	89000
9	22.1	FAIL	FAIL	FAIL	5.3	FAIL	FAIL	FAIL
10	22.1	FAIL	FAIL	FAIL	10.0	FAIL	FAIL	FAIL
11	22.0	FAIL	FAIL	FAIL	43.0	FAIL	FAIL	FAIL
12	22.6	22.4	FAIL	FAIL	13.0	14600	FAIL	FAIL
13	22.2	22.3	22.5	22.6	32.1	14600	12600	27900
14	22.4	FAIL	FAIL	FAIL	25.1	FAIL	FAIL	FAIL
15	21.7	21.9	22.0	FAIL	19.0	88100	69800	FAIL
16	22.1	FAIL	FAIL	FAIL	122.2	FAIL	FAIL	FAIL
17	22.1	22.3	22.3	FAIL	112.0	91500	40300	FAIL
18	21.7	21.8	FAIL	FAIL	4.0	91500	FAIL	FAIL
19	22.1	FAIL	FAIL	FAIL	91.0	FAIL	FAIL	FAIL
20	22.3	22.4	FAIL	FAIL	87.8	12490	FAIL	FAIL

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 1-50 LIFE TESTED AT 100 DEGREE CENTIGRADE AND 100% RH.

S.No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
21	22.2	22.4	FAIL	FAIL	13.0	12490	FAIL	FAIL
22	22.2	FAIL	FAIL	FAIL	14.0	FAIL	FAIL	FAIL
23	22.0	FAIL	FAIL	FAIL	49.2	FAIL	FAIL	FAIL
24	22.0	22.4	22.3	22.4	15.5	30800	33700	62300
25	22.2	FAIL	FAIL	FAIL	74.0	FAIL	FAIL	FAIL
26	22.5	22.7	22.5	FAIL	54.0	33400	78300	FAIL
27	22.1	22.3	22.3	22.5	28.0	33400	37200	59700
28	22.0	FAIL	FAIL	FAIL	9.0	FAIL	FAIL	FAIL
29	22.2	FAIL	FAIL	FAIL	12.0	FAIL	FAIL	FAIL
30	22.0	22.1	22.0	FAIL	31.2	143600	56300	FAIL
31	22.2	22.4	22.2	22.2	34.4	124000	90600	78300
32	21.7	21.7	FAIL	FAIL	25.0	130600	FAIL	FAIL
33	22.3	22.5	FAIL	FAIL	33.0	146700	FAIL	FAIL
34	21.8	21.6	22.0	FAIL	59.0	66200	100800	FAIL
35	22.2	22.4	22.2	22.3	69.0	95200	76800	85400
36	22.6	22.7	22.7	FAIL	3.0	30200	118200	FAIL
37	21.9	22.0	22.0	22.1	35.0	47300	34800	58700
38	22.0	22.1	22.1	22.2	60.0	47300	56800	87300
39	22.6	FAIL	FAIL	FAIL	19.0	FAIL	FAIL	FAIL
40	22.0	22.1	22.0	22.3	15.0	37800	50500	112500

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 1-50 LIFE TESTED AT 100 DEGREE CENTIGRADE AND 100% RH.

S.No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
41	22.3	FAIL	FAIL	FAIL	17.1	FAIL	FAIL	FAIL
42	22.2	22.3	22.2	FAIL	68.0	20800	65400	FAIL
43	22.2	22.2	22.1	22.3	13.0	20800	25700	52700
44	22.1	FAIL	FAIL	FAIL	56.0	FAIL	FAIL	FAIL
45	21.7	21.8	21.9	22.0	72.0	21100	25300	63200
46	22.0	22.1	FAIL	FAIL	27.0	58600	FAIL	FAIL
47	22.0	22.1	22.2	FAIL	29.0	88000	101100	FAIL
48	22.0	22.1	22.0	22.1	28.0	31200	26600	53100
49	21.9	22.1	22.0	FAIL	7.0	121300	122200	FAIL
50	21.8	21.9	22.0	FAIL	24.2	133600	132000	FAIL

CAPACTANCE AND LEAKAGE CURRENT DATA FOR S.NOs 51-125 LIFE TESTED AT 100 DEGREE CENTIGRADE.

S No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL3 nA	IL4 nA
51	22.1	22.4	22.3	22.4	15.0	45.1	62.2	28.7
52	22.1	22.3	22.2	22.2	27.0	518.3	521.8	530.0
53	22.2	22.2	22.1	22.2	29.6	13.1	24.7	26.7
54	22.3	22.0	22.2	22.2	30.0	40.6	44.2	44.6
55	22.2	22.3	22.1	22.2	10.0	44.2	38.8	62.3
56	22.1	22.3	22.0	22.3	6.0	16.9	18.3	32.7
57	22.2	22.3	22.1	22.2	14.0	186.0	175.6	110.5
58	22.3	22.5	22.4	22.4	35.0	36.7	38.2	81.3
59	22.0	22.0	22.1	22.0	13.0	36.4	34.3	18.7
60	21.8	21.8	FAIL	FAIL	33.0	253.2	FAIL	FAIL
61	22.3	22.3	22.4	22.3	30.2	60.8	68.3	1980.0
62	21.8	21.8	21.9	22.8	77.0	72.1	75.6	65.6
63	22.1	22.2	22.0	22.1	22.0	26.8	29.2	38.9
64	22.1	22.2	22.1	22.1	34.2	11.6	18.3	60.7
65	22.7	22.6	22.5	22.5	103.0	55.8	73.1	32.3
66	22.5	22.6	22.6	22.6	32.0	35.7	39.7	48.7
67	22.3	22.3	22.3	22.2	34.0	36.5	42.3	46.7
68	22.5	22.7	22.6	22.7	18.0	13.2	16.7	17.8
69	22.1	22.0	22.0	22.0	68.0	39.5	48.3	49.7
70	22.4	22.5	FAIL	FAIL	23.0	324.7	FAIL	FAIL

CAPACTANCE AND LEAKAGE CURRENT DATA FOR S.NOs 51-125 LIFE TESTED AT 100 DEGREE CENTIGRADE.

S No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL3 nA	IL4 nA
71	22.0	22.1	22.1	22.1	15.4	12.9	17.3	56.7
72	22.4	22.4	22.3	22.3	31.0	32.1	35.1	33.1
73	22.4	22.6	22.6	22.5	90.0	24.6	67.5	25.2
74	22.4	22.4	22.3	22.4	12.0	39.2	45.8	61.8
75	21.9	21.9	21.9	21.9	10.0	11.8	13.7	17.3
76	22.0	21.9	21.9	21.9	40.0	51.6	65.4	24.3
77	22.2	22.2	22.2	FAIL	35.0	25.3	33.2	FAIL
78	22.3	22.2	22.2	22.2	16.0	46.5	62.3	63.8
79	22.0	21.9	21.8	21.9	102.0	87.2	92.1	36.4
80	22.1	22.1	22.0	22.0	40.0	31.1	35.6	121.0
81	21.9	22.0	22.1	21.9	27.1	50.3	63.1	16.3
82	22.2	22.2	22.1	22.2	44.1	38.8	45.3	53.6
83	22.2	22.1	22.2	22.1	42.0	51.1	60.9	44.5
84	22.1	22.1	22.0	22.1	28.0	32.2	35.4	52.6
85	22.2	FAIL	FAIL	FAIL	11.0	FAIL	FAIL	FAIL
86	22.0	FAIL	FAIL	FAIL	15.0	FAIL	FAIL	FAIL
87	22.6	22.6	22.5	22.5	25.0	41.2	51.3	8.9
88	22.3	22.3	22.2	22.3	57.9	38.3	41.3	FAIL
89	22.3	22.3	22.3	22.2	28.0	39.8	41.7	68.1
90	22.5	22.4	22.4	22.4	30.0	46.2	98.2	29.7

CAPACTANCE AND LEAKAGE CURRENT DATA FOR S.NOs 51-125 LIFE TESTED AT 100 DEGREE CENTIGRADE.

S No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL3 nA	IL4 nA
91	21.9	21.9	21.8	21.9	12.0	33.8	37.7	46.6
92	22.0	21.8	21.7	21.9	64.7	44.0	56.3	66.7
93	21.9	22.0	22.1	21.8	26.0	40.1	46.7	21.3
94	22.1	22.0	22.0	22.0	14.0	4.3	8.2	13.2
95	22.1	22.0	22.0	22.0	10.0	28.1	33.7	93.8
96	22.1	22.1	22.0	22.0	83.0	47.1	66.3	70.8
97	21.8	21.7	21.7	21.8	16.0	45.3	54.2	16.7
98	22.2	22.2	22.1	22.2	29.0	47.8	45.3	11.7
99	22.3	22.2	22.2	22.2	18.2	46.3	61.9	63.8
100	22.2	22.1	22.1	22.1	15.2	25.2	44.7	9.2
101	21.8	21.9	22.0	21.9	9.0	342.1	287.3	181.9
102	22.1	FAIL	FAIL	FAIL	42.0	FAIL	FAIL	FAIL
103	21.6	21.8	21.8	21.7	20.0	5.7	15.4	11.2
104	22.5	22.6	22.6	22.6	29.0	4.8	10.9	11.9
105	22.2	22.3	FAIL	22.3	35.8	396.2	FAIL	340.0
106	21.9	22.0	22.0	22.0	37.0	21.0	32.3	33.8
107	22.6	22.6	22.5	22.6	10.0	10.8	12.6	21.9
108	22.0	22.0	21.9	22.0	42.0	29.3	34.4	43.2
109	22.4	22.5	22.6	22.4	25.0	9.9	14.8	18.7
110	22.1	22.2	22.4	22.1	29.0	7.3	18.7	14.7

PACTANCE AND LEAKAGE CURRENT DATA FOR S.NOs 51-125 LIFE TESTED AT 100 DEGREE CENTIGRADE.

S No	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL3 nA	IL4 nA
111	21.8	21.8	21.7	21.8	74.0	19.1	33.8	19.7
112	22.5	22.5	22.4	22.6	6.8	13.2	21.7	11.9
113	22.2	22.4	22.4	22.3	24.0	9.3	22.3	13.2
114	22.2	22.2	22.1	22.2	14.0	12.7	18.6	11.8
115	22.2	22.3	22.3	22.3	39.0	17.8	25.7	12.6
116	22.2	22.3	22.4	22.3	71.8	243.2	236.9	262.0
117	22.5	22.5	22.6	22.5	79.0	22.2	45.7	28.7
118	22.6	22.7	22.7	22.7	12.0	12.6	18.5	12.4
119	22.1	22.3	22.4	22.2	122.0	104.1	164.3	32.6
120	21.9	22.0	22.0	22.1	81.0	26.9	51.7	26.7
121	22.3	22.5	22.5	22.5	79.0	38.3	57.6	31.8
122	22.2	22.3	22.4	22.3	53.0	20.4	45.5	21.6
123	22.2	22.2	22.3	22.2	17.1	14.3	24.7	15.3
124	22.2	22.3	22.3	22.4	32.0	484.2	396.7	560.0
125	22.2	22.5	22.5	22.5	7.1	29.6	54.3	25.7

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 126-200, LIFE TESTED AT 85 DEGREE CENTIGRADE.

S No.	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
126	22.4	21.8	21.9	22.0	50.0	35.6	44.2	68.5
127	22.0	21.9	22.0	FAIL	6.0	8.8	11.6	FAIL
128	22.3	22.2	22.2	22.3	42.0	37.4	41.4	85.3
129	22.8	22.6	22.7	22.8	8.6	13.5	17.4	24.8
130	22.1	22.0	22.0	22.2	37.0	26.5	33.8	68.7
131	21.9	21.7	21.8	21.9	20.2	13.4	20.6	34.4
132	22.1	22.0	22.0	22.2	61.2	14.9	54.2	FAIL
133	21.9	21.9	21.9	22.1	31.9	12.6	20.4	46.7
134	22.2	22.1	22.1	22.1	100.0	81.2	102.2	52.7
135	21.6	21.5	21.6	21.8	17.0	75.1	18.2	40.5
136	22.3	22.2	22.3	22.4	15.6	9.9	16.3	23.4
137	22.0	21.9	21.9	22.0	14.0	19.3	10.1	26.4
138	22.3	22.2	22.2	22.2	13.9	9.7	16.7	72.9
139	22.4	22.3	22.4	22.3	41.0	33.9	38.2	38.3
140	22.1	22.4	22.0	22.1	72.7	74.2	82.2	92.7
141	22.0	21.9	21.9	22.2	68.4	67.1	62.7	62.8
142	22.1	22.0	22.0	FAIL	7.0	12.4	13.9	FAIL
143	22.2	22.0	22.1	22.1	22.0	12.8	18.3	61.5
144	22.1	21.9	22.0	22.2	59.1	21.8	12.7	69.1
145	21.8	21.6	21.7	21.9	17.7	91.2	92.3	71.8

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 126-200, LIFE TESTED AT 85 DEGREE CENTIGRADE.

S No.	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
146	22.4	22.2	22.3	22.5	51.0	51.4	58.2	64.3
147	22.3	22.2	22.3	22.3	35.0	19.0	26.2	41.7
148	22.3	22.2	21.3	22.3	8.0	21.5	8.3	97.4
149	22.5	22.4	22.4	22.4	18.0	15.1	11.2	27.2
150	22.6	22.5	22.6	22.7	59.0	59.6	57.5	102.3
151	22.2	22.0	22.0	22.1	29.8	26.4	30.8	59.3
152	22.0	21.9	22.0	22.0	29.1	17.9	23.6	19.7
153	22.1	21.9	22.0	21.9	114.4	78.2	80.7	53.7
154	21.8	21.7	21.8	21.7	20.0	38.2	20.8	33.5
155	22.0	21.9	21.9	22.0	23.0	16.7	25.4	21.7
156	22.3	22.2	22.3	22.5	49.0	33.4	30.0	91.7
157	21.9	22.1	21.7	21.7	5.0	15.4	27.9	26.7
158	22.1	22.0	22.0	22.0	74.0	19.6	30.0	649.0
159	22.0	21.9	21.9	21.9	23.0	24.4	32.7	29.3
160	22.3	22.3	22.3	22.3	58.0	47.2	49.5	130.2
161	22.2	22.0	22.1	22.4	10.0	16.8	13.6	48.3
162	22.2	22.0	22.1	22.1	39.0	32.8	37.6	32.4
163	21.9	21.8	21.9	21.8	23.0	24.9	17.6	58.2
164	22.1	22.0	22.0	22.2	27.0	13.1	16.2	6.9
165	22.4	22.3	22.4	22.6	47.0	29.3	33.4	879.0

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 126-200, LIFE TESTED AT 85 DEGREE CENTIGRADE.

S No.	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
166	21.9	21.8	21.9	21.9	23.4	24.7	18.4	634.0
167	22.1	22.0	22.0	22.5	44.0	33.9	34.3	32.3
168	22.0	21.9	22.0	22.0	17.2	18.5	20.5	36.8
169	22.1	22.1	22.1	22.2	8.0	7.8	19.2	15.9
170	21.9	21.9	21.8	22.0	27.0	15.6	16.8	212.3
171	22.0	22.0	22.0	22.1	47.1	40.9	40.9	92.7
172	22.2	22.2	22.1	22.4	14.0	20.4	15.3	224.2
173	22.2	22.1	22.1	22.1	42.0	26.1	27.4	23.6
174	22.0	21.8	21.9	22.0	22.0	16.6	21.3	40.2
175	21.8	21.7	21.8	FAIL	43.0	50.1	48.7	FAIL
176	22.6	22.1	22.2	FAIL	24.9	17.3	18.0	FAIL
177	22.2	22.1	22.1	22.5	31.4	24.8	54.1	98.3
178	22.2	22.0	22.1	FAIL	17.0	11.9	40.0	FAIL
179	22.1	22.0	22.0	22.2	11.0	11.2	11.8	97.1
180	22.0	21.8	21.9	21.9	15.0	14.2	23.7	54.3
181	21.8	21.7	21.9	21.8	21.0	20.6	25.3	190.1
182	22.0	21.8	21.9	22.1	710.0	21.7	19.2	143.2
183	22.0	22.1	22.2	22.4	15.0	13.5	12.4	188.1
184	21.9	21.7	21.7	21.8	10.7	10.8	12.2	210.0
185	22.1	21.9	22.0	22.2	28.0	17.6	21.1	173.0

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 126-200, LIFE TESTED AT 85 DEGREE CENTIGRADE.

S No.	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL 2 nA	IL 3 nA	IL 4 nA
186	22.5	22.4	22.4	22.6	39.0	23.7	18.6	FAIL
187	21.8	21.7	21.8	FAIL	53.0	39.3	43.4	FAIL
188	22.0	21.8	21.9	22.2	10.8	46.4	26.3	112.3
189	21.8	21.7	21.8	21.9	15.7	5.2	8.7	7.7
190	22.0	21.8	21.7	22.1	12.2	16.7	15.8	82.3
191	22.2	22.1	22.2	22.2	18.0	13.2	13.8	123.0
192	22.5	22.3	22.4	22.5	12.9	13.8	14.2	130.0
193	22.3	22.2	22.3	22.4	20.0	38.7	14.5	91.7
194	21.5	21.4	21.4	21.5	20.9	8.5	11.6	57.2
195	21.7	21.5	21.6	21.5	55.0	41.7	48.9	48.2
196	22.0	21.9	22.0	22.1	17.0	17.5	20.2	62.9
197	22.2	22.1	22.1	22.3	58.0	60.8	67.4	102.6
198	22.1	21.9	22.1	FAIL	2.1	6.7	7.9	FAIL
199	22.1	22.0	22.1	22.1	12.0	10.1	711.6	52.6
200	22.0	21.8	21.9	22.0	11.2	14.3	15.4	73.2

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 201-300, LIFE TESTED AT 77 DEGREE CENTIGRADE.

S.NO	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL2 nA	IL3 nA	IL4 nA
201	22.1	22.1	22.2	22.1	9.3	6.9	10.8	14.8
202	22.3	22.2	22.3	22.3	16.0	11.5	16.4	18.7
203	22.0	21.9	21.9	21.9	11.0	9.6	11.5	62.3
204	21.9	21.8	22.3	21.8	40.0	35.4	90.1	38.0
205	22.1	22.0	22.0	22.0	30.0	20.7	23.4	26.7
206	22.4	22.2	22.4	22.3	66.4	51.1	51.2	86.9
207	22.3	22.2	22.3	22.3	14.0	11.2	31.2	14.5
208	22.0	21.9	22.0	22.4	21.0	21.7	26.5	26.7
209	22.1	21.9	22.0	21.9	48.0	28.2	26.1	36.4
210	21.8	21.7	21.8	21.8	21.0	20.6	16.8	20.8
211	22.2	22.2	22.2	22.2	30.0	27.2	31.6	24.9
212	22.2	22.1	22.2	22.1	11.0	14.9	16.5	15.7
213	21.9	21.8	21.9	22.6	42.6	29.3	35.3	35.3
214	22.1	21.9	22.0	22.0	14.0	7.4	8.7	10.6
215	21.8	21.6	21.7	21.6	18.6	20.7	21.3	29.6
216	22.1	22.0	22.0	22.0	70.0	52.4	60.2	58.3
217	22.3	22.1	22.2	22.7	28.9	23.5	29.7	28.3
218	22.2	22.1	22.2	22.1	28.0	24.9	18.9	24.6
219	22.1	21.9	21.9	21.9	9.1	37.3	40.8	37.2
220	22.0	21.9	22.0	21.9	4.4	5.3	21.3	12.6

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 201-300, LIFE TESTED AT 77 DEGREE CENTIGRADE.

S.NO	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL2 nA	IL3 nA	IL4 nA
221	22.1	21.9	22.0	22.0	61.7	48.2	58.1	50.2
222	22.0	21.9	21.9	21.9	26.0	13.8	20.9	23.7
223	21.9	22.3	21.8	21.8	10.3	7.8	9.7	14.8
224	22.2	22.1	22.2	22.1	28.0	26.7	33.2	28.3
225	22.1	21.9	22.0	22.0	21.2	10.8	15.6	10.6
226	22.6	22.5	22.6	22.4	14.3	17.3	28.2	72.6
227	22.2	21.7	21.7	21.6	9.0	8.8	12.3	17.7
228	22.2	22.2	22.2	22.2	24.0	39.8	17.7	14.4
229	22.2	22.1	22.1	22.0	19.0	19.7	23.2	18.9
230	22.2	22.1	22.2	22.1	37.1	32.6	22.7	33.7
231	22.3	22.2	22.2	22.2	29.0	22.0	29.1	22.9
232	22.6	22.5	22.5	22.5	21.0	27.8	31.7	21.6
233	22.2	22.5	22.1	22.0	41.0	26.0	18.3	17.8
234	22.7	22.6	22.7	22.6	22.0	15.2	35.1	16.4
235	21.8	21.7	21.8	21.7	99.0	40.2	42.7	25.8
236	21.9	21.8	21.8	21.8	55.0	32.8	41.1	27.3
237	22.1	22.0	22.1	22.0	39.2	46.1	101.7	47.6
238	22.2	22.1	22.2	22.1	14.0	7.2	8.5	47.1
239	21.7	21.6	21.6	21.5	44.0	27.9	30.3	18.7
240	22.1	22.0	22.0	22.0	48.0	17.3	24.6	16.8

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 201-300, LIFE TESTED AT 77 DEGREE CENTIGRADE.

S.NO	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL2 nA	IL3 nA	IL4 nA
241	22.4	22.3	22.4	22.3	4.6	8.1	10.2	8.2
242	22.0	21.9	22.0	21.9	23.0	14.1	40.1	12.9
243	22.1	22.0	22.1	22.0	17.0	14.7	19.1	15.3
244	22.1	22.1	22.1	22.1	6.9	7.7	7.7	15.4
245	22.0	21.9	21.9	21.9	23.8	22.5	29.7	26.5
246	22.3	22.2	22.2	22.1	73.2	276.0	510.0	269.7
247	21.9	21.7	21.8	21.7	29.0	25.6	54.1	27.9
248	22.0	21.8	21.9	21.8	14.0	13.1	17.2	14.3
249	22.2	22.1	22.2	22.1	72.0	50.4	28.7	43.7
250	22.0	22.1	22.1	22.1	11.0	10.5	25.4	7.8
251	21.9	21.7	21.8	21.7	8.1	11.6	16.2	14.0
252	22.0	21.9	21.9	21.9	46.2	36.8	52.6	36.7
253	22.5	22.4	FAIL	22.4	94.0	107.5	FAIL	115.4
254	22.3	22.2	22.2	22.2	15.0	15.2	8.8	14.6
255	21.8	21.7	21.8	21.7	90.1	80.7	96.8	86.5
256	22.2	22.1	22.1	22.0	6.0	6.8	23.2	11.3
257	21.1	22.0	22.1	22.0	21.0	26.3	24.6	22.9
258	22.3	22.1	22.2	22.1	27.1	25.7	34.3	29.8
259	21.9	21.8	21.8	21.8	19.2	9.7	7.2	8.0
260	22.1	22.0	22.0	22.0	10.2	10.1	16.1	16.0

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 201-300, LIFE TESTED AT 77 DEGREE CENTIGRADE.

S.NO	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL2 nA	IL3 nA	IL4 nA
261	22.2	22.0	22.1	22.0	20.2	18.1	18.3	13.1
262	22.1	22.0	22.0	21.9	11.0	18.6	14.2	18.7
263	22.1	22.0	22.0	21.9	22.0	10.5	87.1	18.3
264	22.5	22.3	22.3	22.3	8.0	3.9	5.6	8.7
265	22.5	22.3	22.4	22.3	28.0	18.2	23.4	23.9
266	22.5	22.5	22.5	22.4	48.0	36.0	42.3	33.4
267	21.9	21.9	21.9	21.9	28.2	10.3	40.9	12.6
268	22.2	22.1	22.1	22.1	36.0	28.4	32.1	28.7
269	22.1	22.0	22.1	22.0	7.0	15.2	36.3	14.6
270	22.1	22.0	22.0	22.0	85.0	57.2	69.3	51.7
271	22.0	21.9	22.0	21.9	40.4	29.6	76.0	36.4
272	22.0	21.9	21.9	21.8	35.1	16.3	26.3	118.0
273	22.4	22.3	FAIL	22.3	20.0	9.7	FAIL	27.6
274	21.8	21.7	21.8	21.7	14.7	9.8	8.2	11.9
275	22.1	22.0	22.1	22.0	25.0	20.1	18.4	15.6
276	22.0	21.9	22.7	21.9	130.0	25.3	161.2	126.7
277	21.9	21.8	21.9	21.8	9.0	18.8	14.3	13.2
278	22.0	21.9	21.9	21.9	20.0	12.3	17.3	7.8
279	22.3	22.3	22.3	22.3	24.0	20.4	24.1	9.3
280	22.1	22.0	22.0	22.0	54.0	45.8	62.1	52.8

CAPACITANCE AND LEAKAGE CURRENT DATA FOR S.NOs 201-300, LIFE TESTED AT 77 DEGREE CENTIGRADE.

S.NO	CAP1 uF	CAP2 uF	CAP3 uF	CAP4 uF	IL 1 nA	IL2 nA	IL3 nA	IL4 nA
281	22.4	22.3	22.3	22.3	9.0	11.7	19.4	15.3
282	22.2	22.1	22.1	22.1	20.4	35.2	23.5	14.7
283	22.4	22.3	22.3	22.3	36.1	26.7	80.9	17.6
284	22.1	21.9	22.0	21.9	27.0	27.9	36.3	95.5
285	22.2	22.0	22.1	22.0	34.7	26.1	41.6	31.3
286	22.0	21.8	21.9	21.8	42.1	16.5	48.2	11.7
287	22.0	21.8	21.8	21.8	62.3	41.7	75.9	3.9
288	22.1	22.0	22.0	22.0	FAIL	22.6	17.6	FAIL
289	22.1	22.0	22.1	22.0	31.2	23.1	26.3	9.1
290	22.1	22.0	22.0	22.0	14.4	236.0	256.1	164.6
291	21.7	21.6	21.7	21.6	12.8	16.6	19.6	14.1
292	22.2	22.1	22.1	22.1	70.0	64.1	72.9	51.2
293	22.2	22.2	22.2	22.1	91.0	78.6	102.1	76.5
294	22.0	21.9	21.9	21.9	46.3	46.6	52.2	30.9
295	22.1	22.0	22.0	22.0	85.0	77.9	86.7	79.6
296	22.1	21.9	22.0	21.9	25.7	28.9	26.3	26.7
297	22.0	21.9	22.0	21.9	27.0	30.3	43.2	21.7
298	21.9	21.8	21.9	21.8	2.0	12.4	16.5	10.8
299	22.6	22.4	22.5	22.4	61.9	17.8	32.3	54.3
300	22.2	22.1	22.1	22.0	26.2	16.2	34.8	48.5

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 1-50, LIFE TESTED AT 100 DEGREE CENTIGRADE AND 100% RH.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
1	258	FAIL	FAIL	FAIL
2	245	5.23	4.88	FAIL
3	248	2.94	2.87	3.1
4	235	1.93	2	2.18
5	244	13.18	11.6	FAIL
6	253	5.41	1.7	FAIL
7	268	1.7	FAIL	FAIL
8	234	7.8	8.1	8.5
9	259	FAIL	FAIL	FAIL
10	233	FAIL	FAIL	FAIL
11	241	FAIL	FAIL	FAIL
12	250	FAIL	FAIL	FAIL
13	248	4.28	5.14	6.32
14	238	FAIL	FAIL	FAIL
15	216	.68	.78	FAIL
16	247	FAIL	FAIL	FAIL
17	239	4.08	3.84	FAIL
18	256	1.56	FAIL	FAIL
19	234	FAIL	FAIL	FAIL
20	236	15.3	FAIL	FAIL

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 1-50, LIFE TESTED AT 100 DEGREE CENTIGRADE AND 100% RH.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
21	231	1.38	FAIL	FAIL
22	225	FAIL	FAIL	FAIL
23	261	FAIL	FAIL	FAIL
24	233	4.28	4.45	4.81
25	249	FAIL	FAIL	FAIL
26	238	8.52	7.79	FAIL
27	242	5.07	4.79	4.32
28	245	FAIL	FAIL	FAIL
29	249	FAIL	FAIL	FAIL
30	240	3.78	3.55	FAIL
31	248	1.75	1.72	2.11
32	219	6.12	FAIL	FAIL
33	234	4.7	FAIL	FAIL
34	259	4.22	4.54	FAIL
35	246	1.97	1.98	4.51
36	230	2.96	2.79	FAIL
37	243	10.82	9.86	8.76
38	237	1.15	1.22	1.83
39	255	FAIL	FAIL	FAIL
40	245	.95	1.06	1.51

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 1-50, LIFE TESTED AT 100 DEGREE CENTIGRADE AND 100% RH.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
41	247	FAIL	FAIL	FAIL
42	231	3.96	3.96	FAIL
43	245	1.38	1.44	1.73
44	236	FAIL	FAIL	FAIL
45	243	13.82	12.2	11.97
46	275	13.92	FAIL	FAIL
47	247	1.66	1.67	FAIL
48	247	4.33	4.22	6.21
49	243	1.21	1.22	FAIL
50	268	8.82	8.2	FAIL

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 51-125, LIFE TESTED AT 100 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
51	263	1015	2150	1070
52	245	291	302	324
53	249	376	470	489
54	265	380	407	404
55	241	241	250	252
56	246	1712	209	1980
57	247	637	875	1340
58	239	515	632	632
59	250	716	996	716
60	289	759	FAIL	878
61	233	239	240	248
62	257	281	274	289
63	273	531	274	577
64	260	631	633	691
65	233	512	866	1040
66	245	429	782	557
67	234	480	502	657
68	215	765	1556	1370
69	255	391	436	526
70	245	966	FAIL	1500

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 51-125, LIFE TESTED AT 100 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
71	252	934	1666	1130
72	237	251	246	253
73	248	658	1708	1470
74	246	1149	2330	1400
75	227	476	873	1700
76	250	330	349	338
77	236	235	240	243
78	241	418	491	478
79	243	301	309	318
80	260	258	262	264
81	247	253	258	260
82	243	255	249	257
83	237	352	378	371
84	235	242	243	264
85	258	FAIL	FAIL	FAIL
86	253	FAIL	FAIL	FAIL
87	229	227	230	235
88	244	250	248	257
89	243	247	241	252
90	252	261	261	266

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 51-125, LIFE TESTED AT 100 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
91	237	383	455	556
92	233	338	357	342
93	246	322	348	357
94	260	468	512	433
95	255	269	265	274
96	254	427	492	542
97	254	258	252	258
98	250	245	247	252
99	241	337	358	379
100	253	258	258	258
101	237	1162	1160	894
102	292	FAIL	FAIL	FAIL
103	260	278	275	274
104	246	359	456	572
105	257	985	FAIL	FAIL
106	241	561	670	695
107	241	272	267	276
108	249	522	908	1000
109	236	795	1450	712
110	247	734	1080	713

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 51-125, LIFE TESTED AT 100 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
111	233	292	285	291
112	235	313	338	362
113	260	632	792	669
114	247	368	382	385
115	274	1188	1650	2050
116	237	367	434	490
117	235	599	775	512
118	255	263	266	272
119	263	693	733	708
120	272	1428	2130	1550
121	250	258	255	258
122	243	439	469	477
123	249	272	274	276
124	237	258	258	264
125	239	539	787	1240

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 126-200, LIF TESTED AT 85 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
126	251	256	253	273
127	241	238	237	268
128	237	243	244	498
129	237	235	233	245
130	245	245	243	942
131	277	269	274	279
132	247	252	254	FAIL
133	238	232	229	246
134	252	251	256	257
135	229	226	228	258
136	262	255	255	268
137	257	256	259	271
138	246	235	240	237
139	249	247	248	268
140	255	253	250	298
141	243	244	243	491
142	226	229	229	FAIL
143	244	238	237	256
144	258	262	254	253
145	257	256	256	758

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 126-200, LIF TESTED AT 85 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
146	248	250	249	258
147	242	233	235	247
148	258	258	254	305
149	253	248	245	279
150	243	246	245	286
151	245	244	244	316
152	224	224	225	233
153	233	232	235	237
154	255	259	253	247
155	250	251	253	483
156	251	251	250	961
157	252	247	246	322
158	235	237	233	245
159	248	242	235	229
160	229	232	234	436
161	236	228	223	776
162	238	254	242	253
163	236	242	242	245
164	233	234	236	285
165	231	240	233	509

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 126-200, LIF TESTED AT 85 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
166	252	250	250	338
167	263	265	268	640
168	268	272	267	273
169	253	249	242	250
170	233	235	232	238
171	242	234	239	621
172	231	228	232	387
173	242	245	245	240
174	245	235	235	424
175	275	283	272	311
176	241	244	245	FAIL
177	237	239	234	320
178	255	254	251	FAIL
179	230	223	224	226
180	254	248	256	287
181	244	236	237	468
182	260	263	257	264
183	237	239	244	288
184	236	239	238	319
185	257	259	257	867

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 126-200, LIF TESTED AT 85 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
186	254	249	253	FAIL
187	250	244	246	FAIL
188	242	249	244	887
189	279	275	274	921
190	239	238	239	461
191	264	268	261	643
192	237	239	235	264
193	245	242	238	232
194	249	241	237	253
195	252	246	249	275
196	239	235	236	694
197	242	246	246	257
198	248	240	241	452
199	256	256	253	291
200	266	270	262	361

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 201-300, LIF TESTED AT 77 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
221	247	246	246	249
222	246	245	241	249
223	252	250	252	257
224	233	230	231	230
225	249	250	252	252
226	243	239	242	243
227	250	243	244	250
228	228	229	224	222
229	264	259	263	262
230	258	254	253	256
231	244	246	239	238
232	259	258	252	246
233	255	254	253	258
234	238	235	228	240
235	251	250	247	246
236	244	245	243	244
237	232	238	231	235
238	239	242	234	237
239	256	252	250	252
240	248	250	246	252

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 201-300, LIF TESTED AT 77 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
201	251	244	247	244
202	250	245	245	244
203	237	231	225	227
204	238	238	234	231
205	232	228	224	227
206	242	239	241	238
207	248	251	249	251
208	254	251	246	249
209	233	227	241	242
210	272	271	272	269
211	271	268	271	271
212	257	257	248	256
213	227	229	226	226
214	240	248	255	260
215	249	245	245	249
216	238	239	232	238
217	236	235	233	235
218	294	295	287	293
219	237	245	245	248
220	222	227	229	230

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 201-300, LIF TESTED AT 77 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
241	245	246	244	248
242	247	241	243	237
243	246	242	232	232
244	245	250	242	246
245	239	236	234	232
246	230	237	234	238
247	244	235	239	237
248	239	236	227	230
249	261	263	261	265
250	257	256	251	255
251	244	239	254	245
252	252	250	251	256
253	255	250	FAIL	FAIL
254	251	251	247	251
255	258	256	253	255
256	248	245	234	243
257	247	243	243	245
258	244	247	240	243
259	251	243	238	247
260	247	256	251	254

EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 201-300, LIF TESTED AT 77 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
261	238	240	230	233
262	247	242	246	248
263	250	249	239	250
264	242	230	233	235
265	255	252	249	250
266	250	245	247	247
267	239	233	232	239
268	249	251	245	253
269	235	229	227	230
270	231	239	237	234
271	236	233	227	231
272	226	223	232	232
273	240	239	FAIL	239
274	242	248	244	254
275	237	239	234	231
276	273	268	268	270
277	250	252	253	254
278	240	232	237	236
279	229	229	235	236
280	252	255	257	257

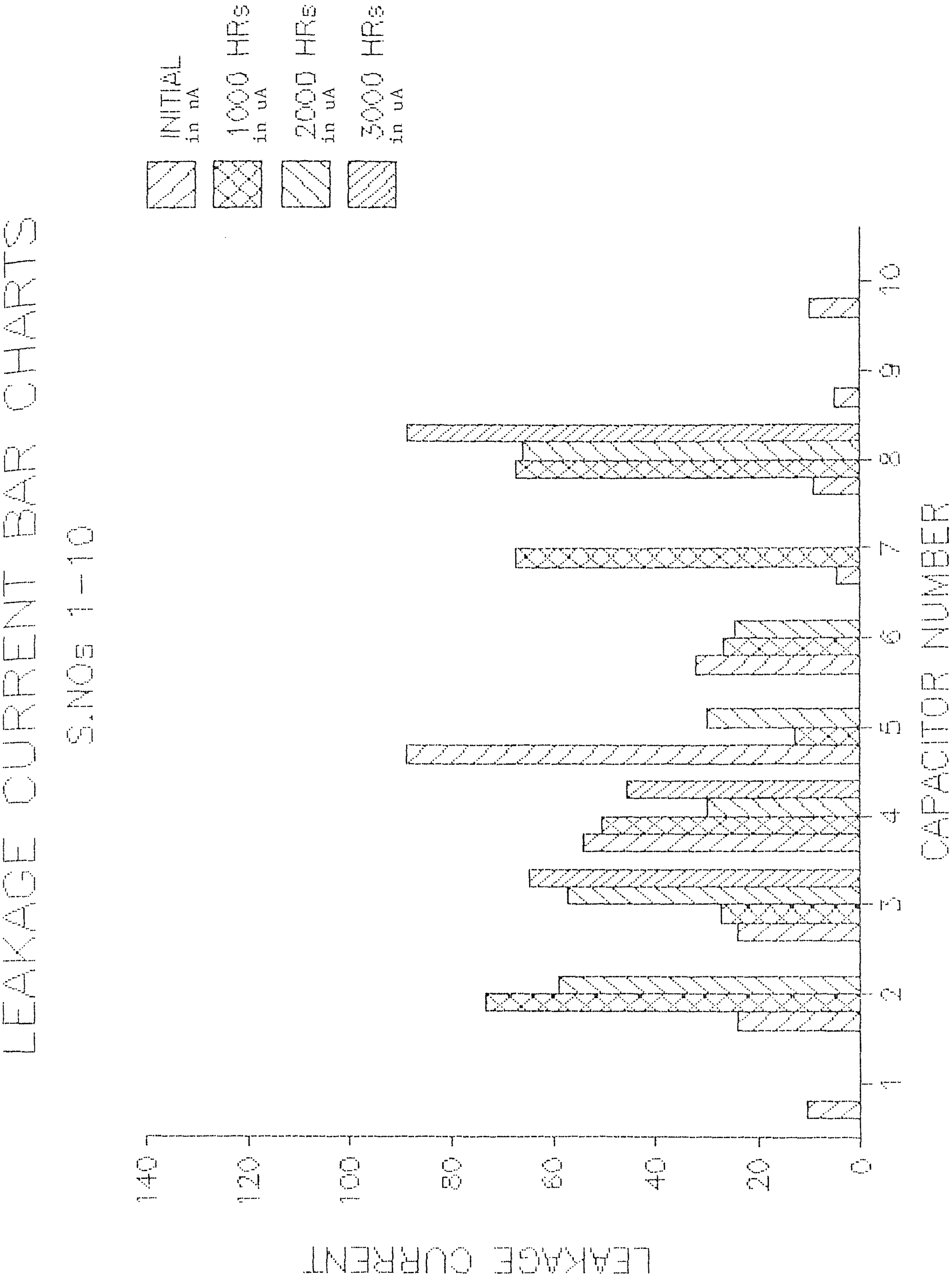
EQUIVALENT SERIES RESISTANCE DATA FOR S.NOs 201-300, LIF TESTED AT 77 DEGREE CENTIGRADE.

S.NO	ESR1 m.Ohms	ESR2 m.Ohms	ESR3 m.Ohms	ESR4 m.Ohms
281	249	247	243	235
282	236	231	229	232
283	266	261	263	261
284	261	255	259	253
285	252	249	252	253
286	234	232	236	243
287	229	237	238	241
288	260	268	261	271
289	249	248	240	239
290	253	247	246	255
291	230	224	221	226
292	231	229	233	232
293	232	233	236	238
294	244	246	241	246
295	254	255	253	255
296	268	261	261	261
297	249	247	243	244
298	232	232	233	232
299	245	249	248	249
300	236	233	234	238

APPENDIX B

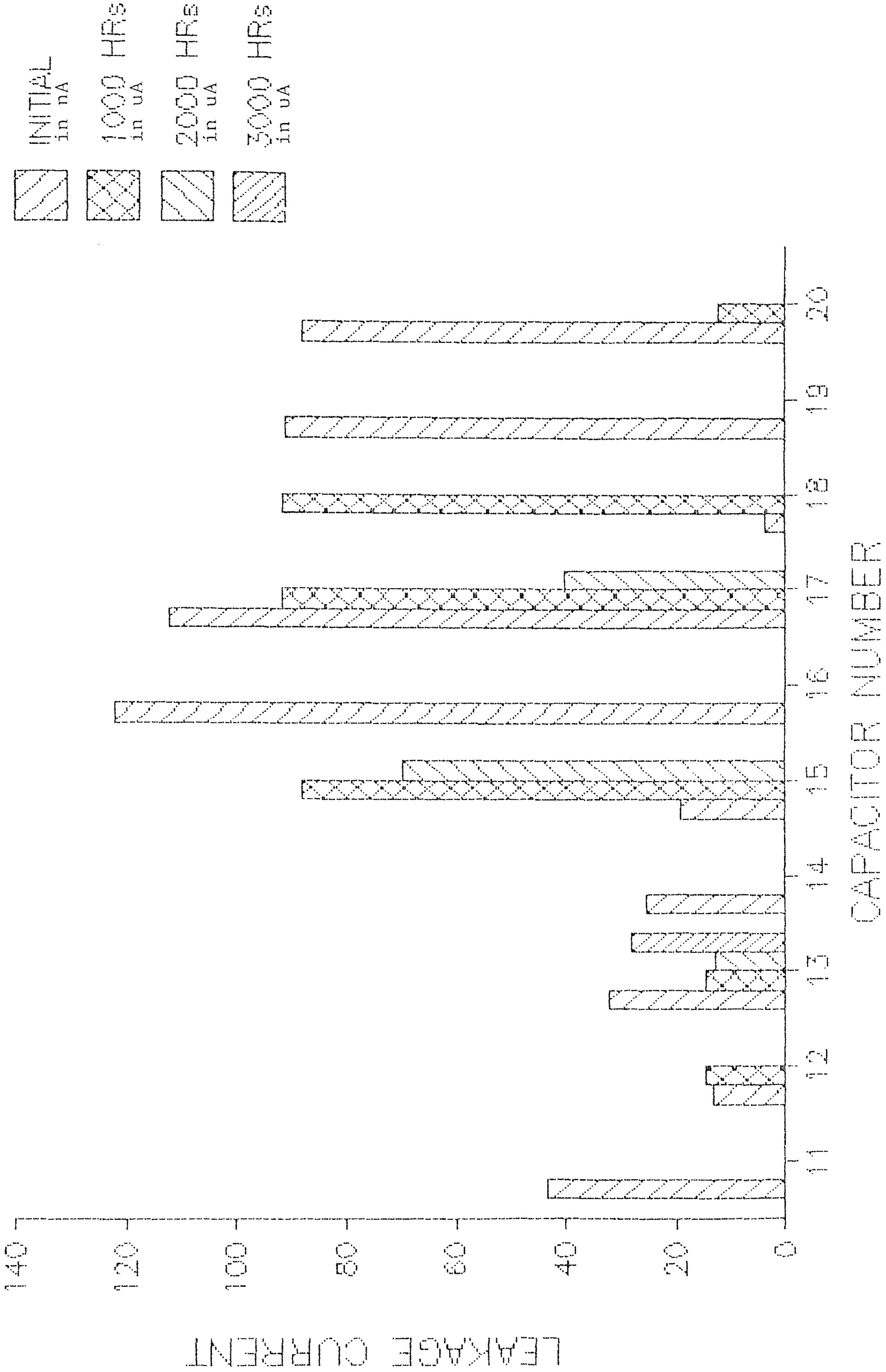
LEKEAGE CURRENT

BAR CHARTS

LEAKAGE CURRENT BAR CHARTS
S.NOs 1—10
INITIAL in nA
1000 HRs in uA
2000 HRs in uA
3000 HRs in uA
LEAKAGE CURRENT
0
20
40
60
80
100
120
140
CAPACITOR NUMBER
1
2
3
4
5
6
7
8
9
10

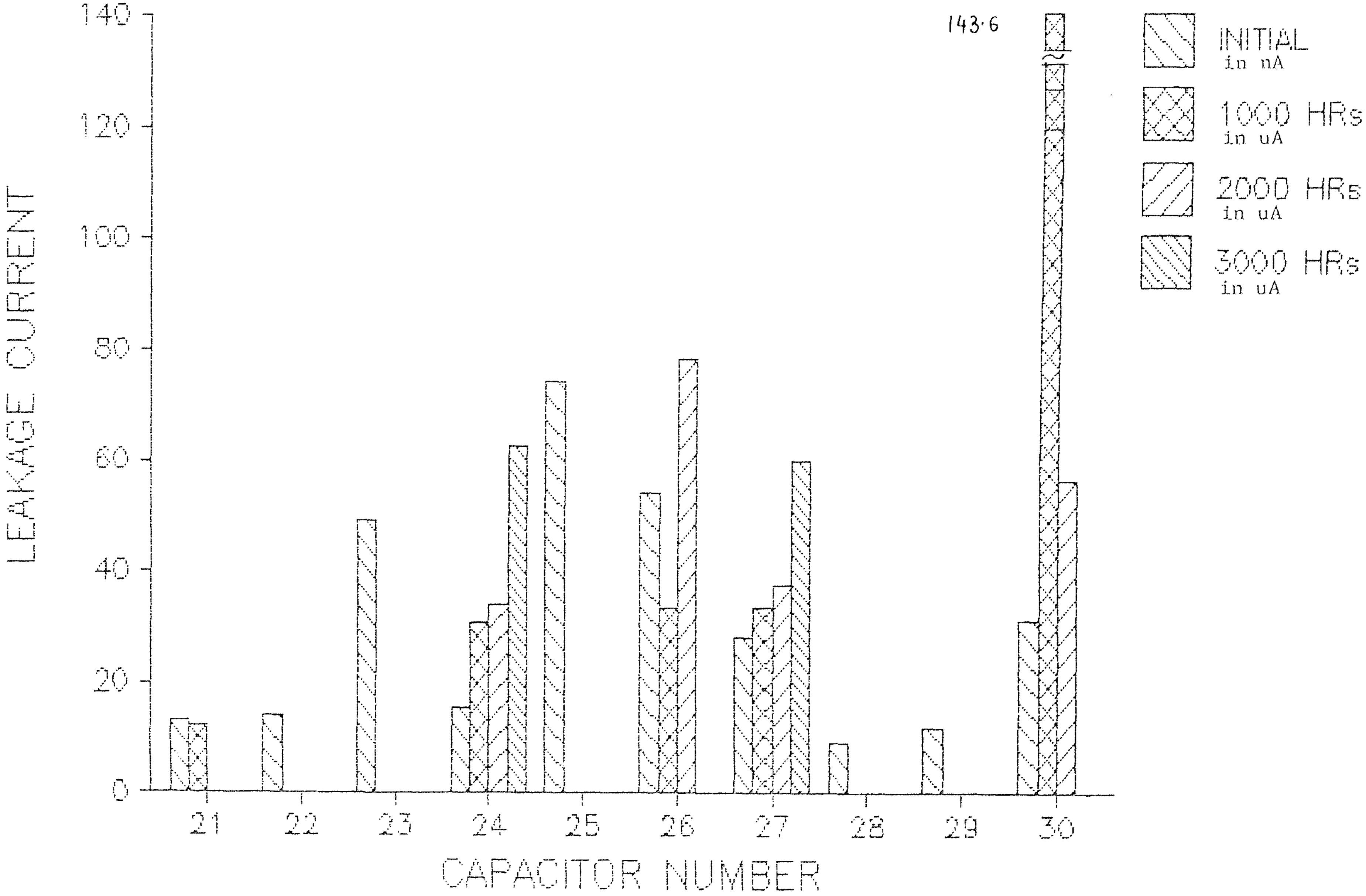
LEAKAGE CURRENT BAR CHARTS

S.NOs 11 – 20



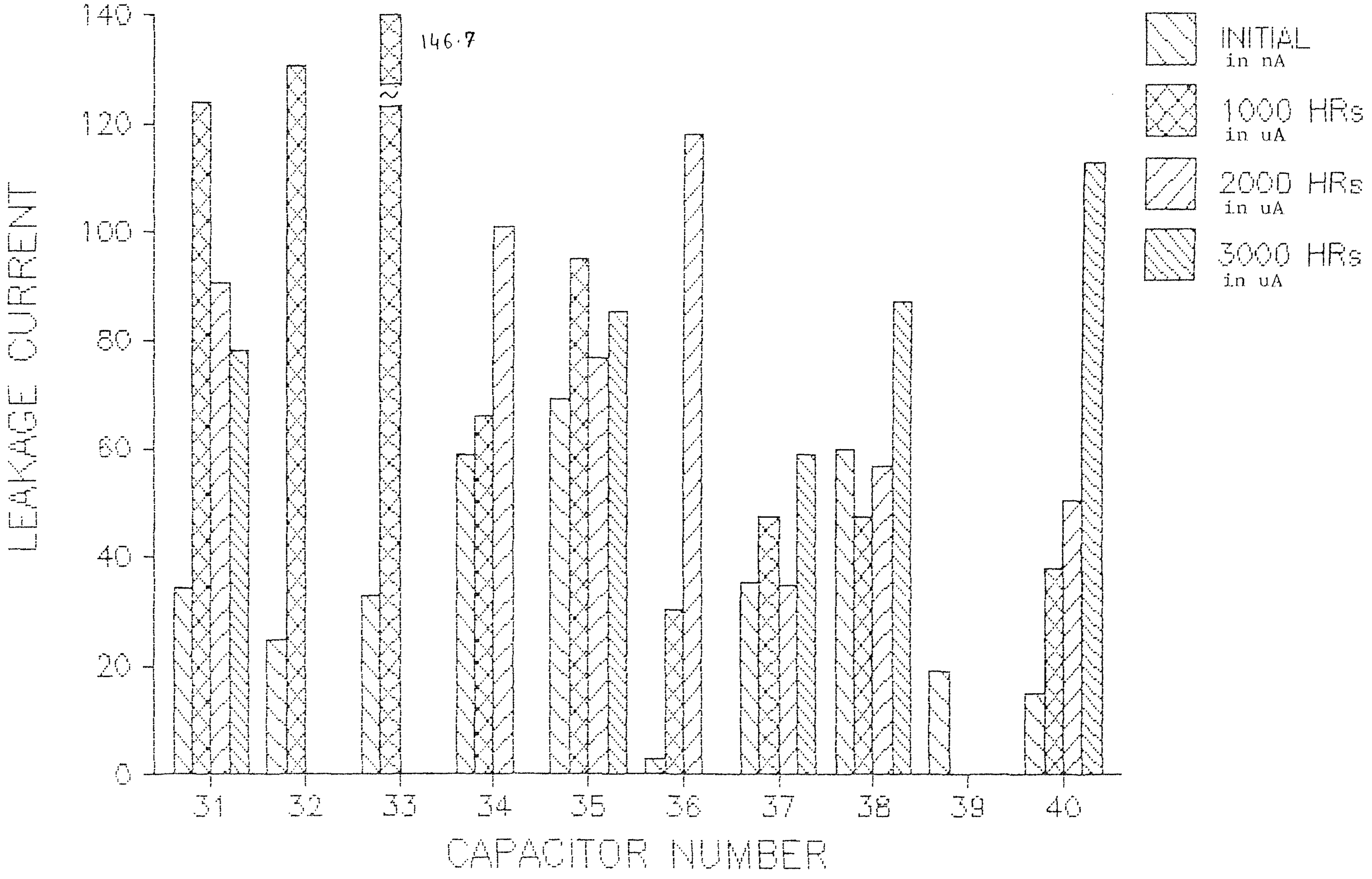
LEAKAGE CURRENT BAR CHARTS

S.NOs 21–30



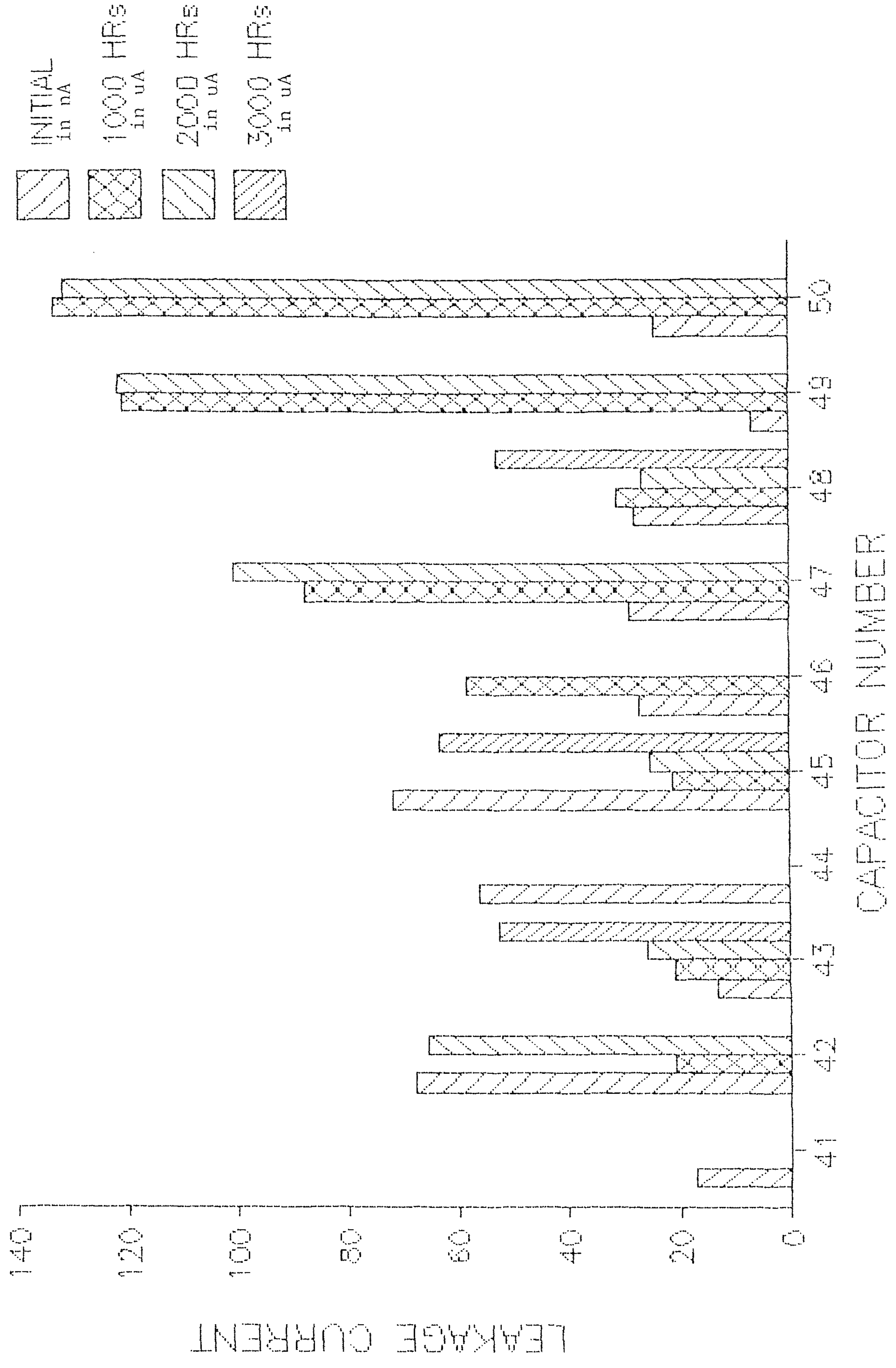
LEAKAGE CURRENT BAR CHARTS

S.NOs 31–40



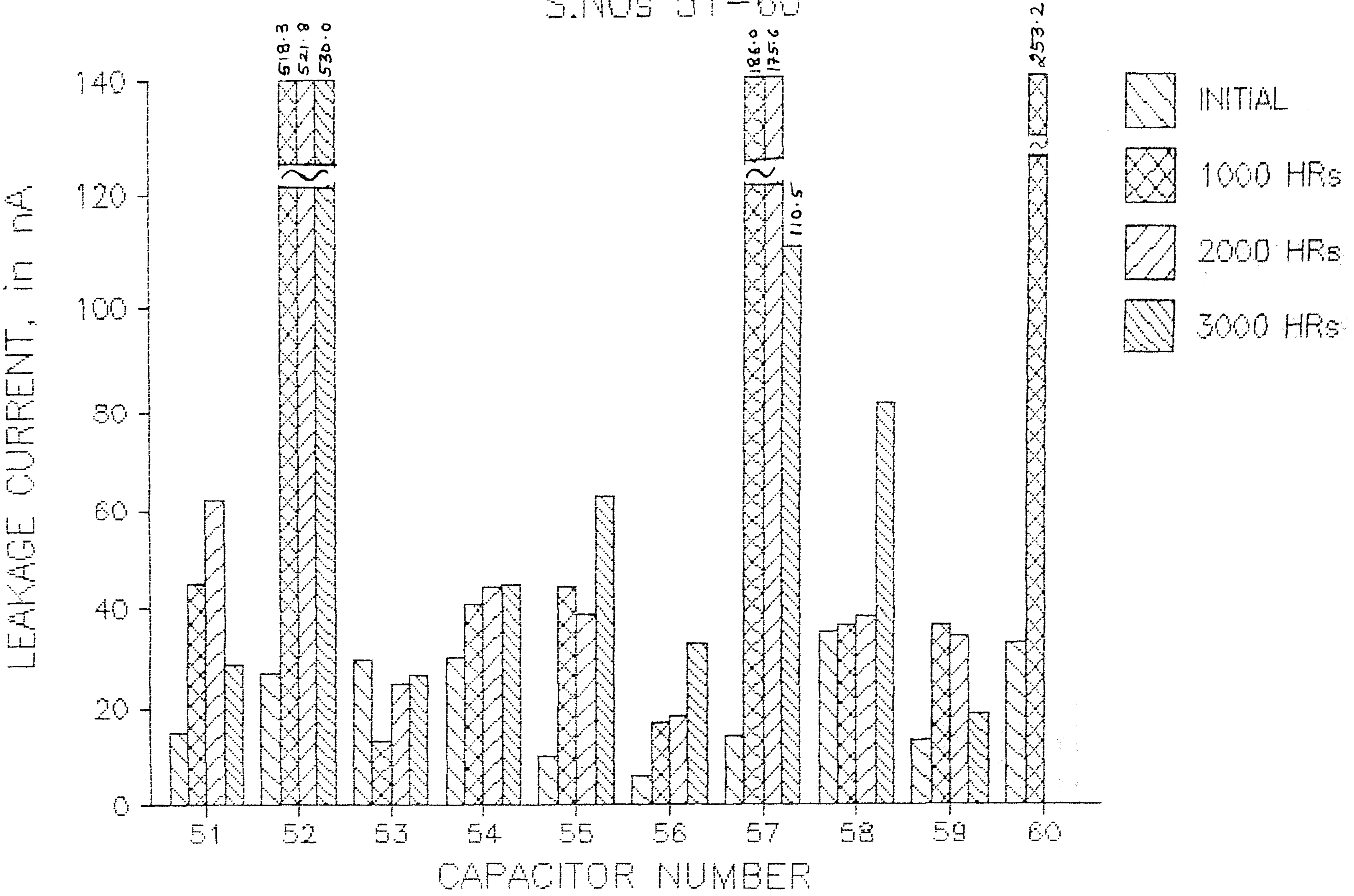
LEAKAGE CURRENT BAR CHARTS

S.NOs 41 — 50



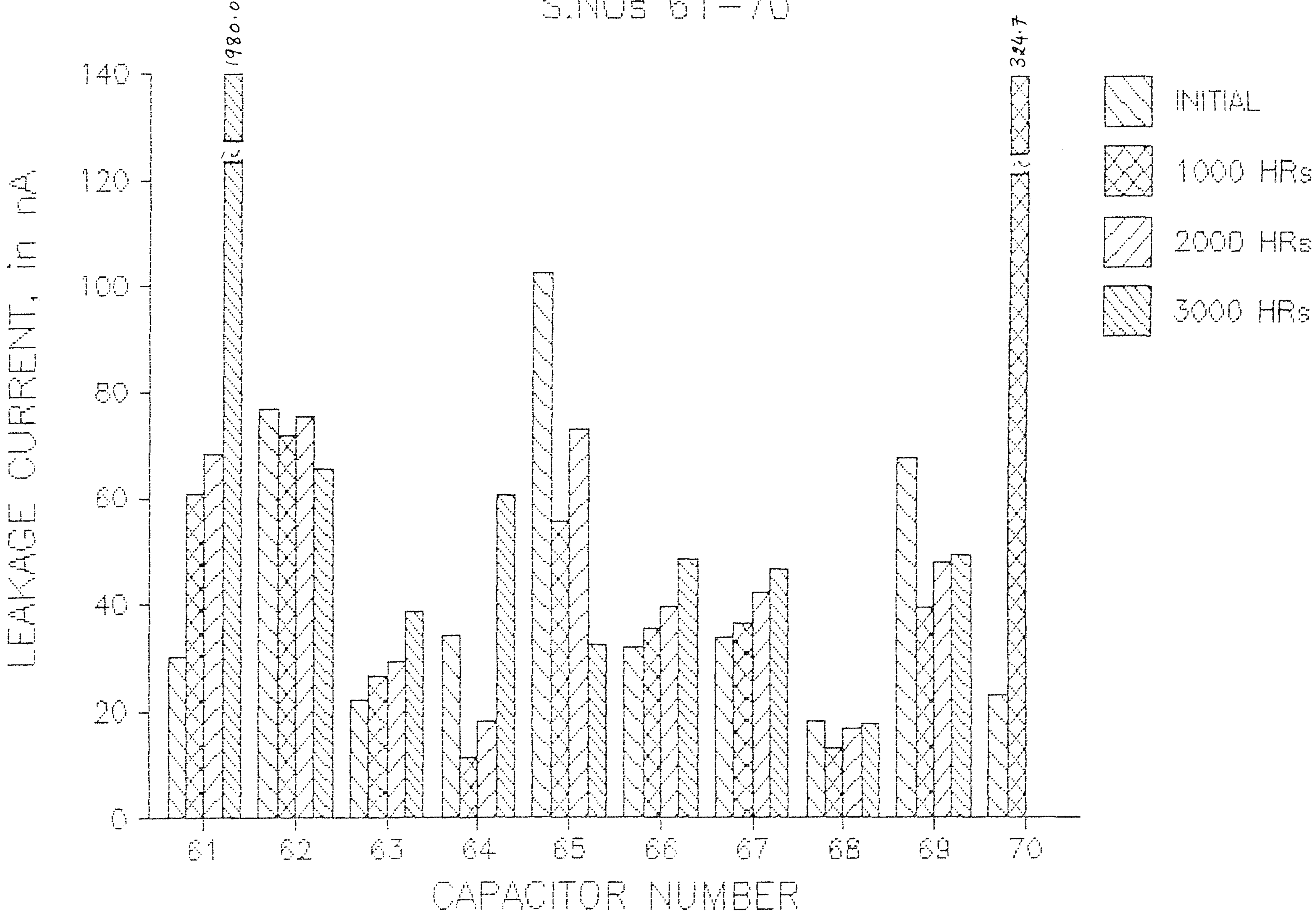
LEAKAGE CURRENT BAR CHARTS

S.NOs 51–60



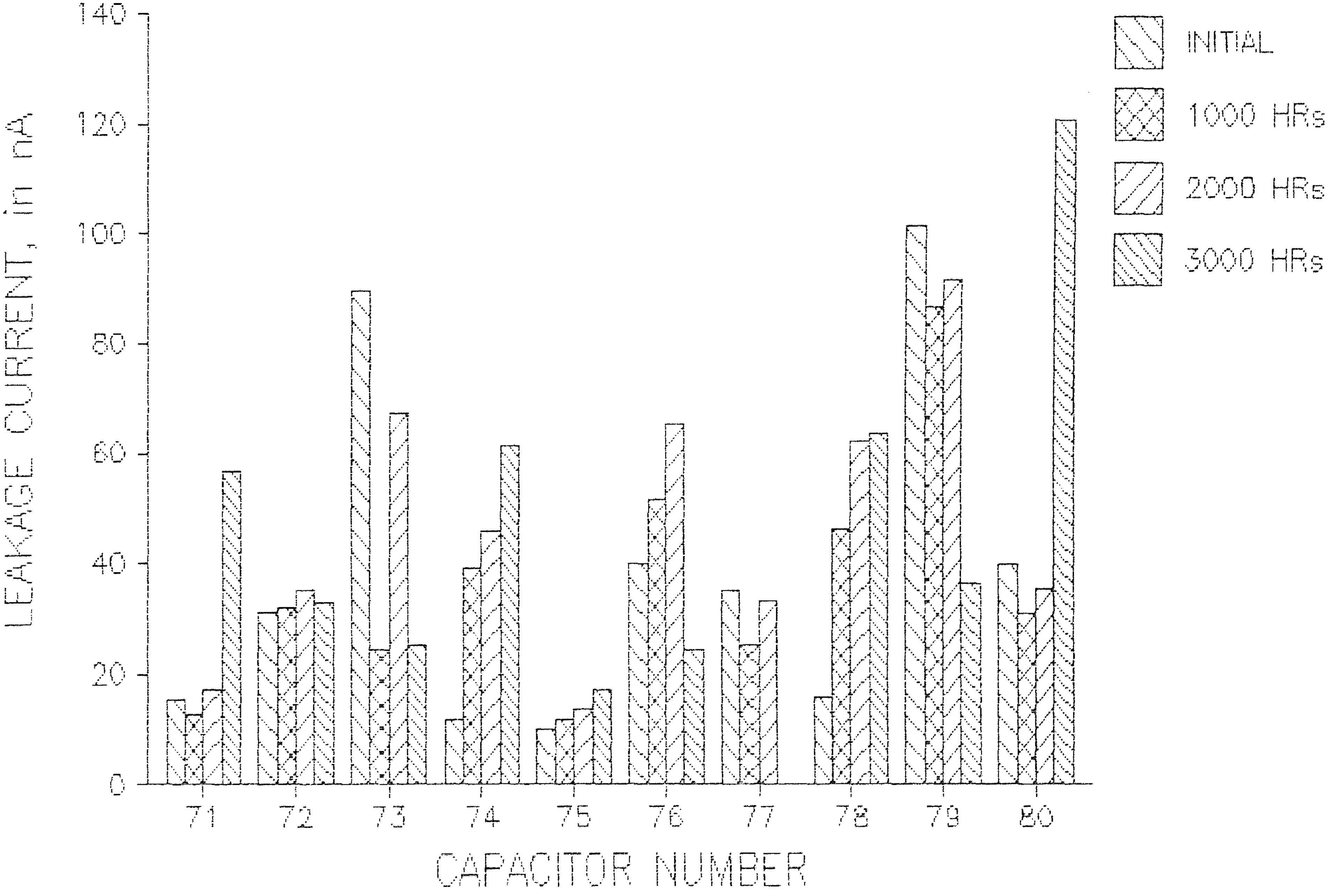
LEAKAGE CURRENT BAR CHARTS

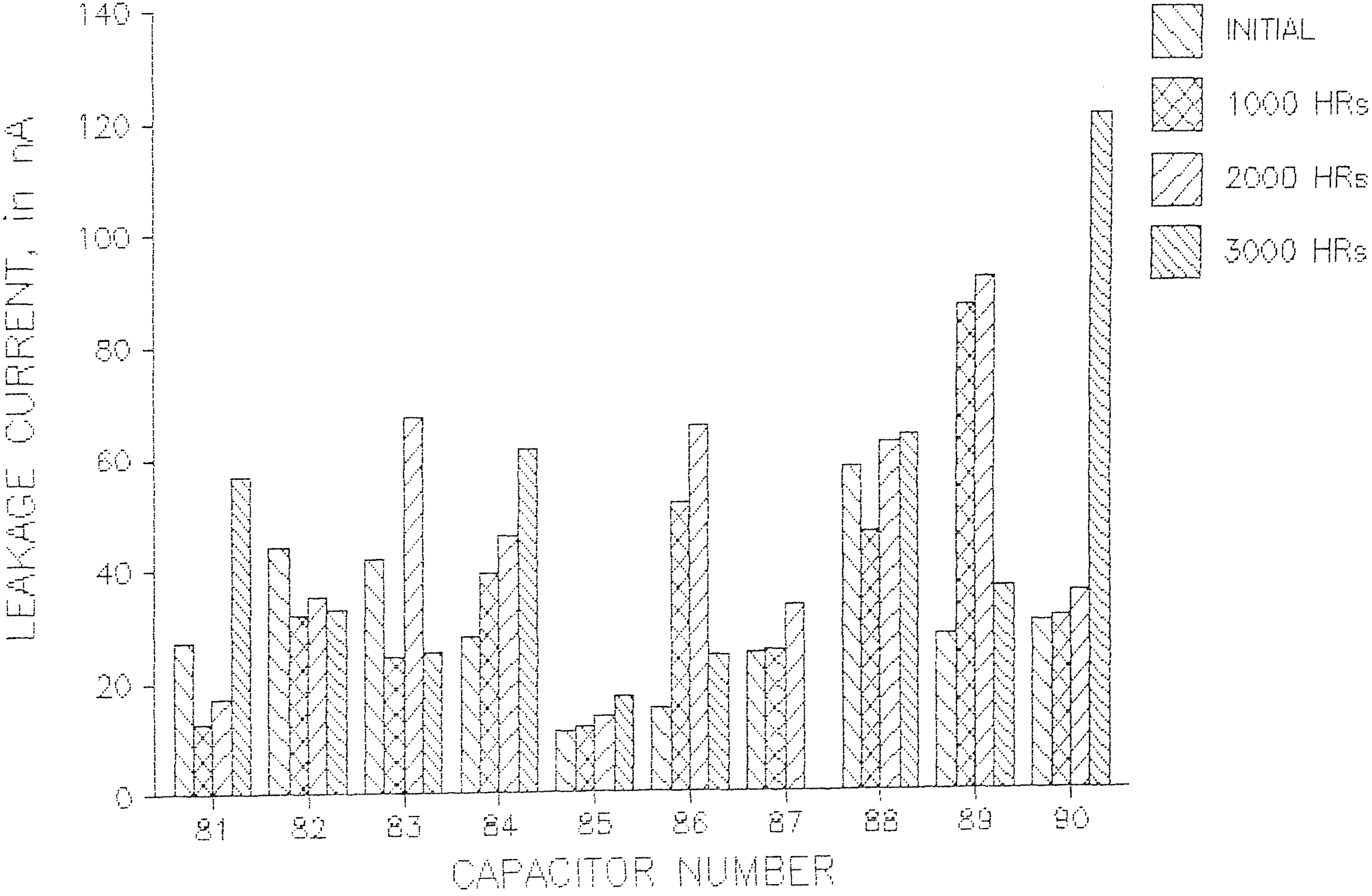
S.NOs 61–70



LEAKAGE CURRENT BAR CHARTS

S.NOs 71–80



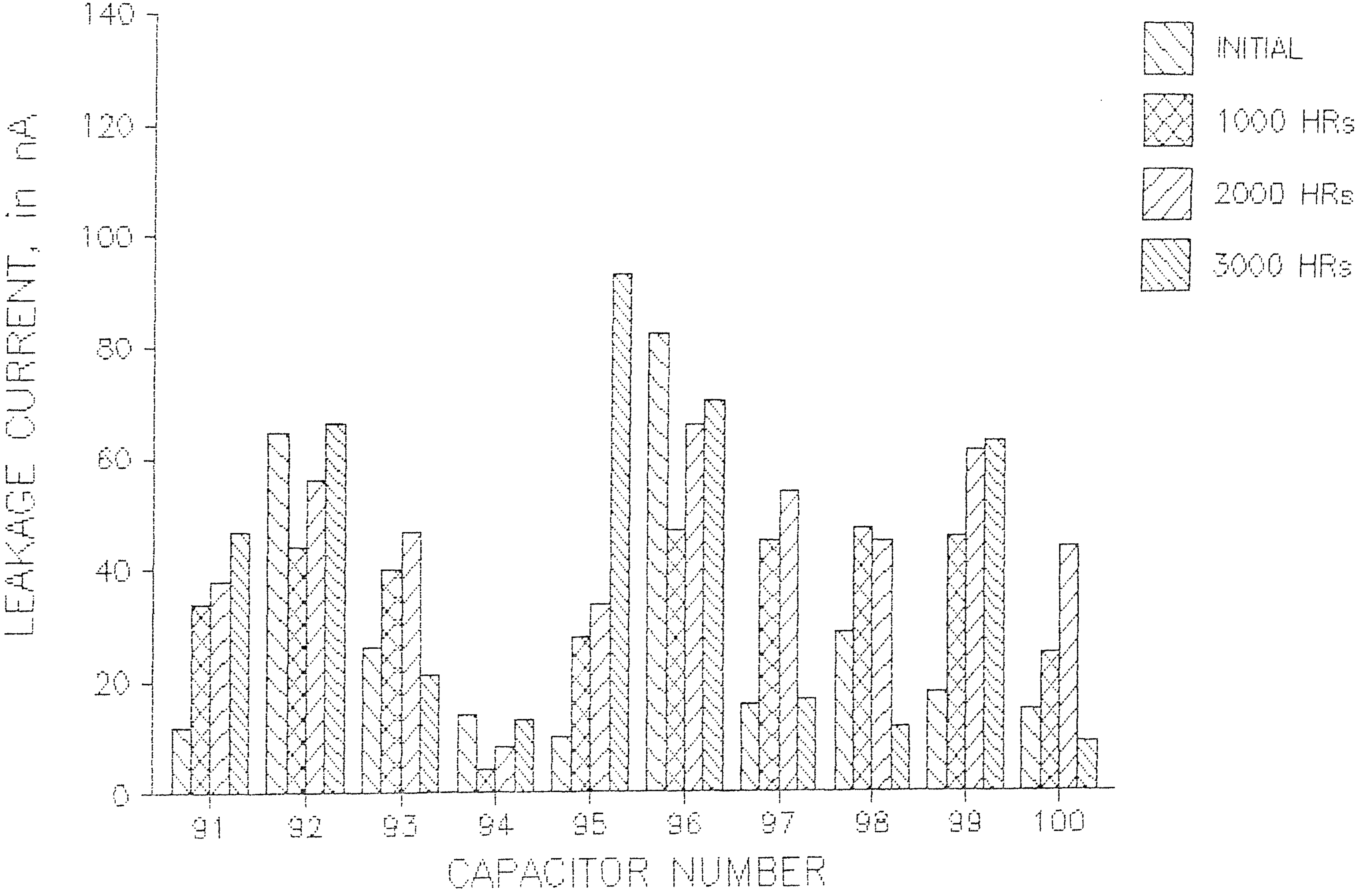


LEAKAGE CURRENT BAR CHARTS

S.NOs 81–90

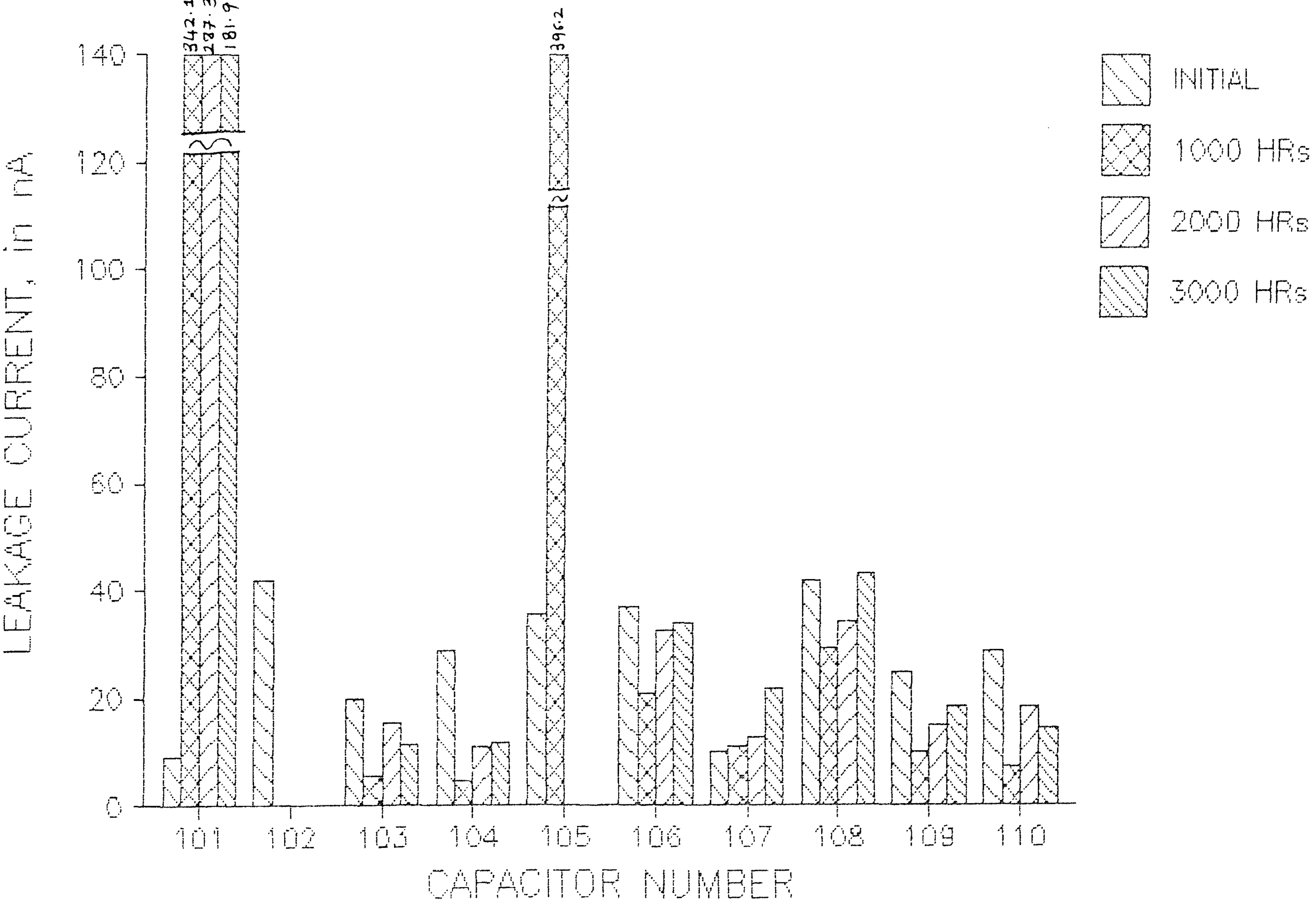
LEAKAGE CURRENT BAR CHARTS

S.NOs 91–100



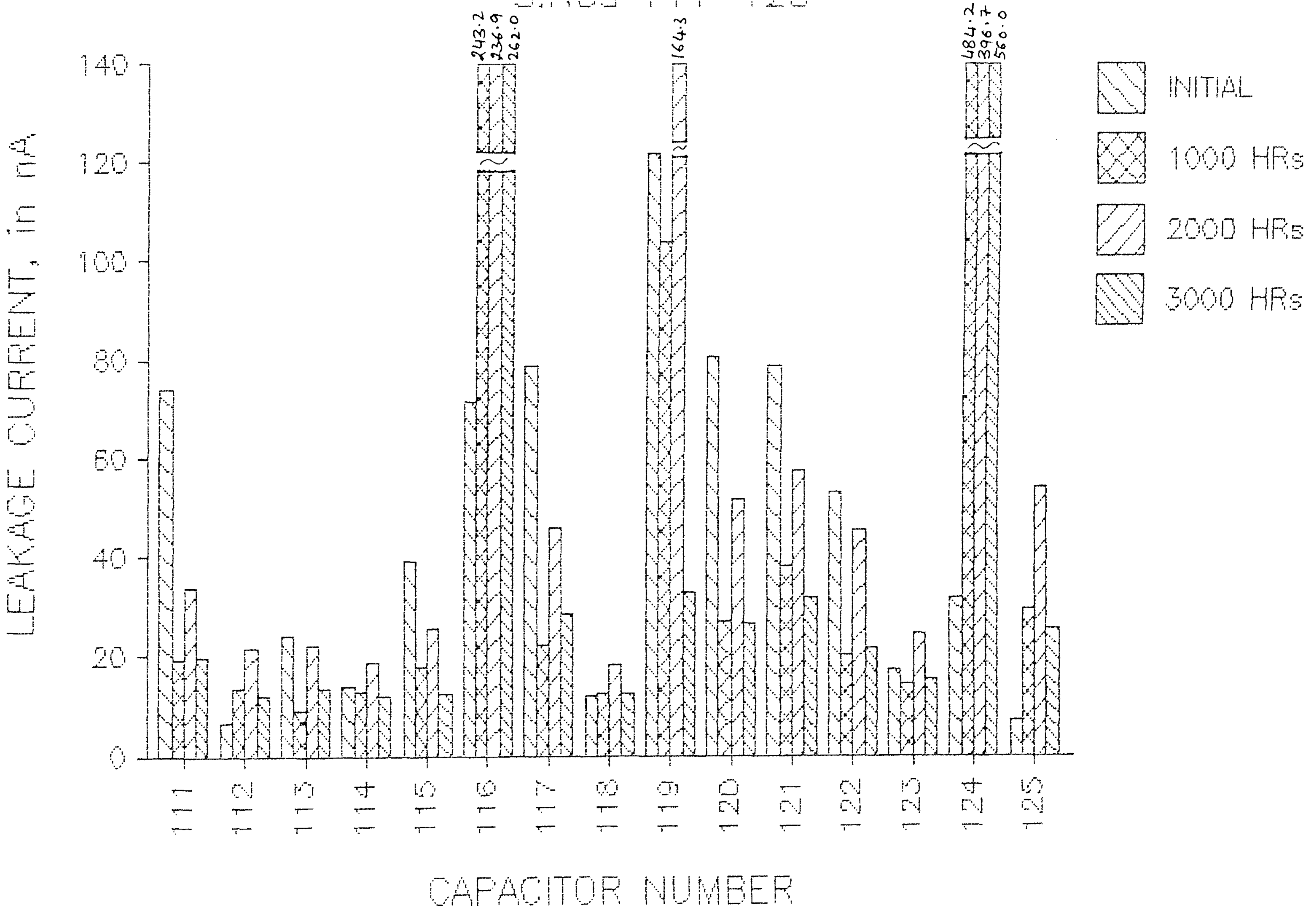
LEAKAGE CURRENT BAR CHARTS

S.NOs 101–110



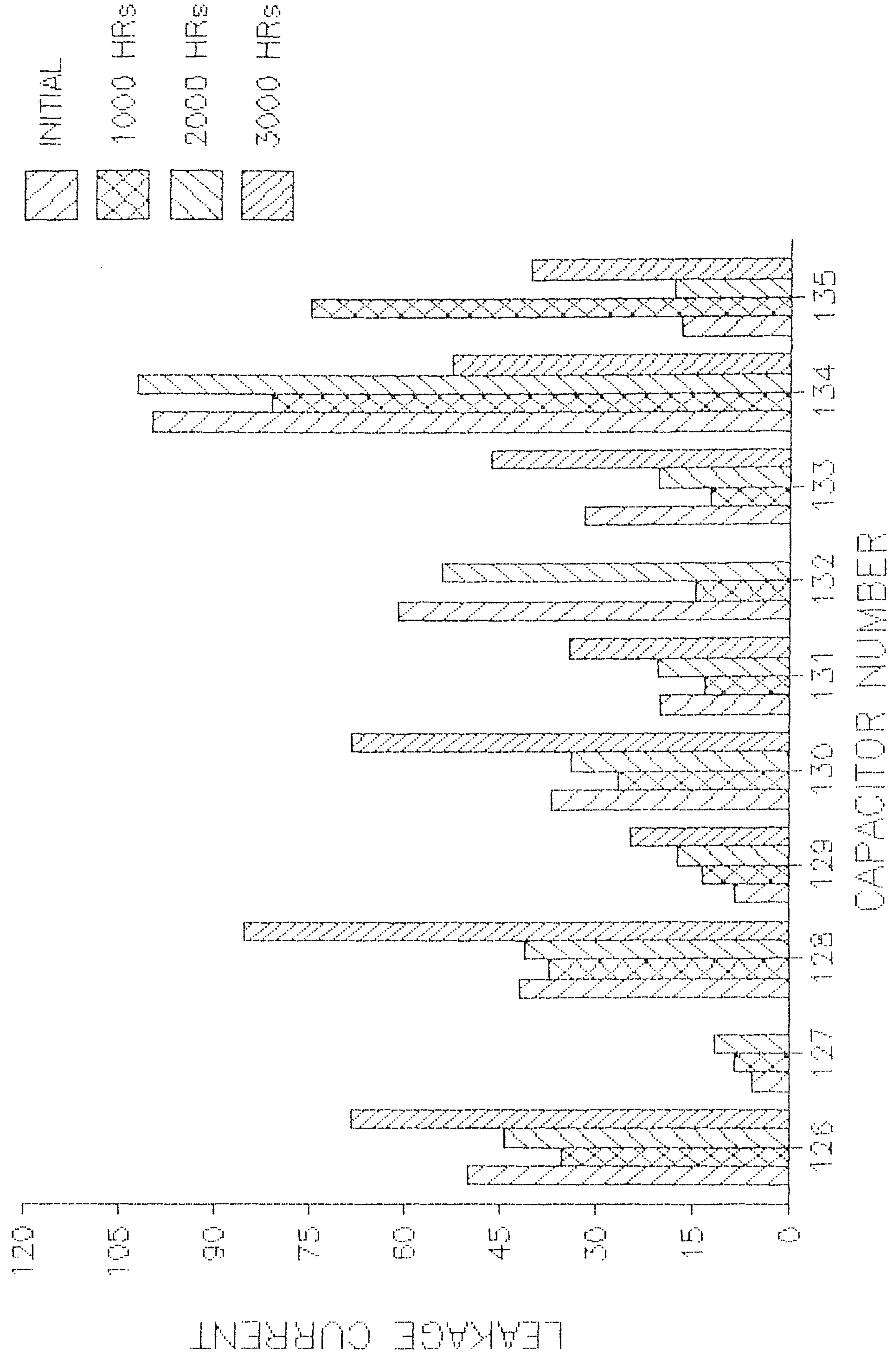
LEAKAGE CURRENT BAR CHARTS

S.NOs 111-125



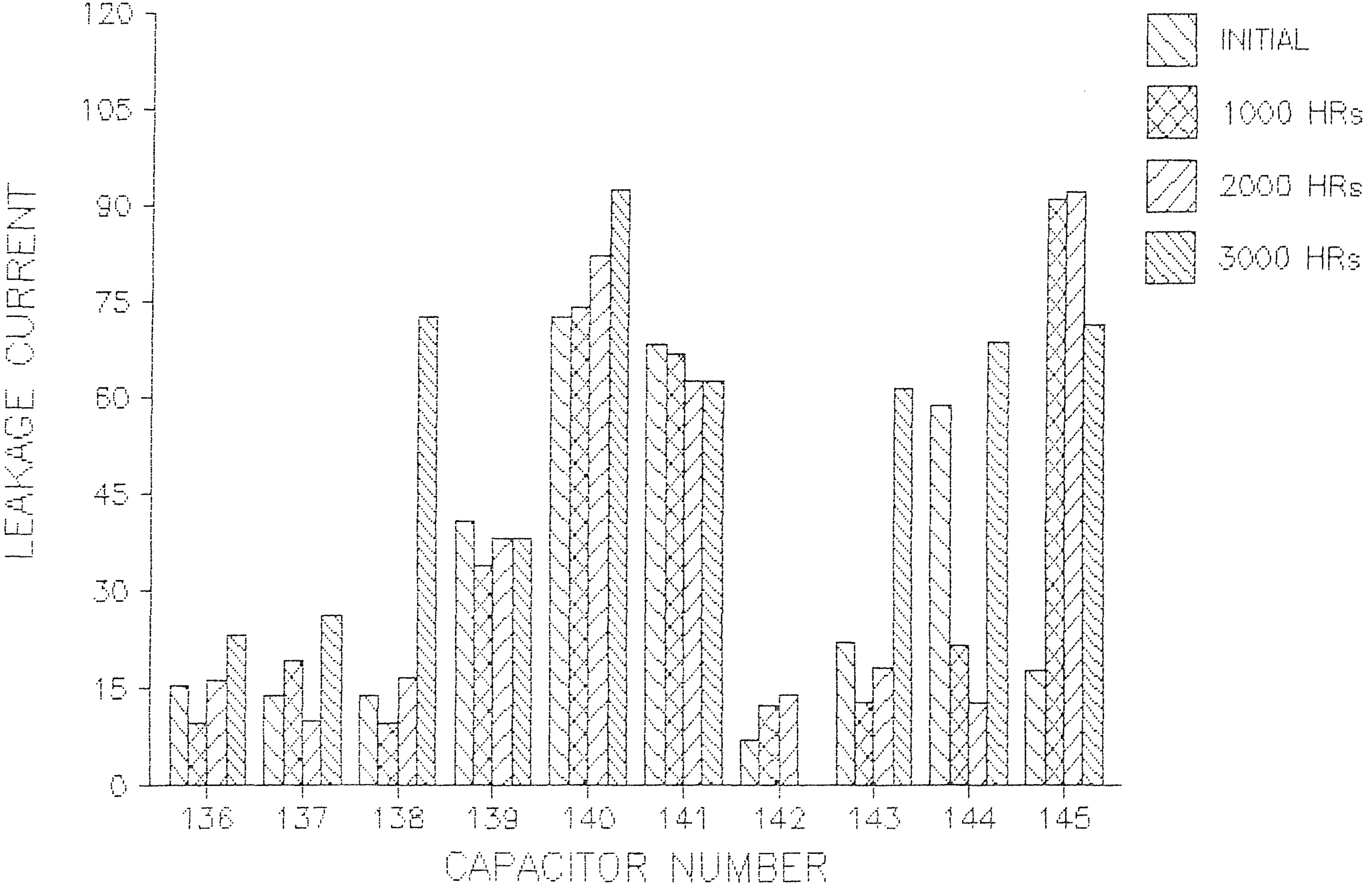
LEAKAGE CURRENT BAR CHARTS

S.NOs 126 – 135



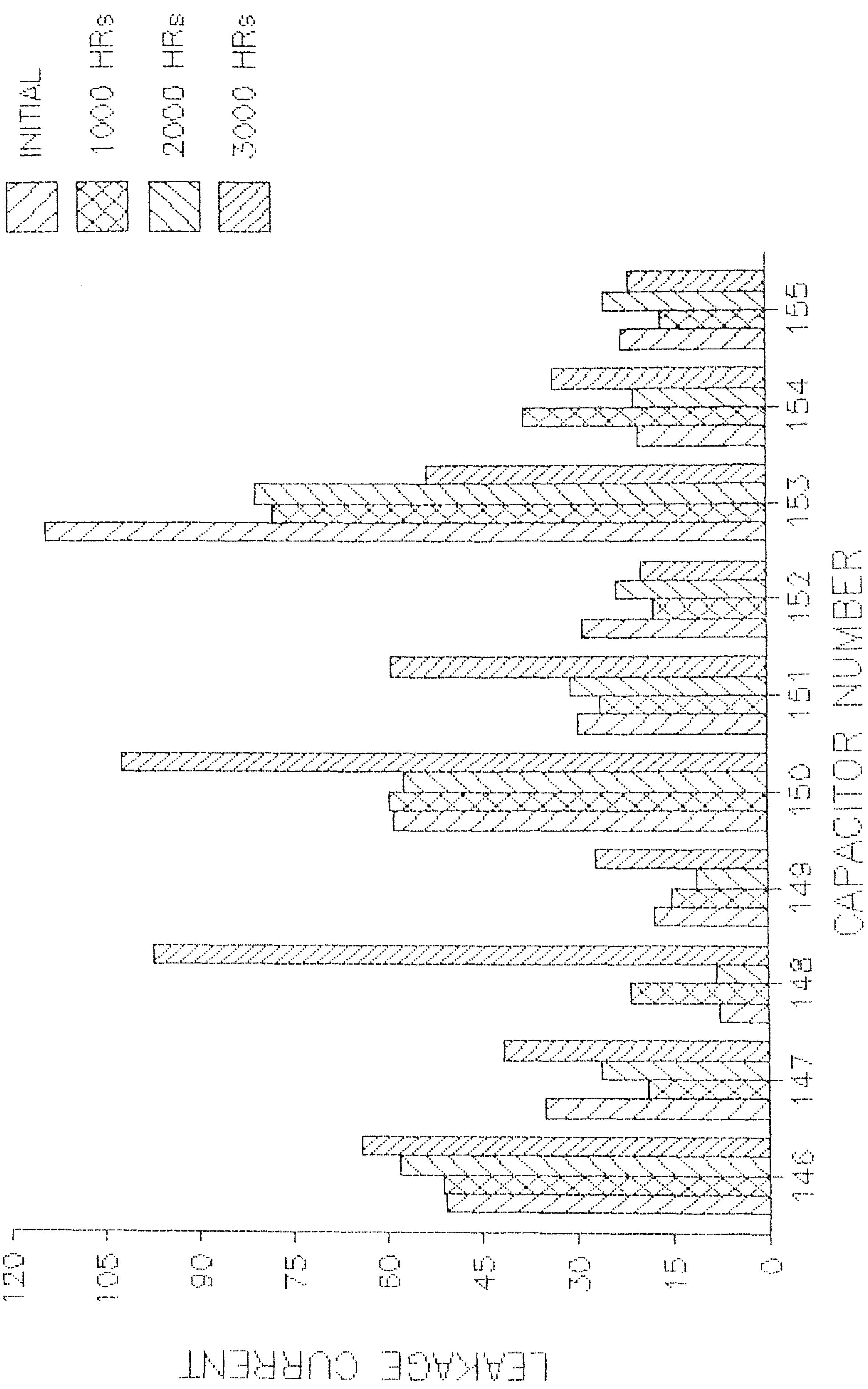
LEAKAGE CURRENT BAR CHARTS

S.NOs 136–145



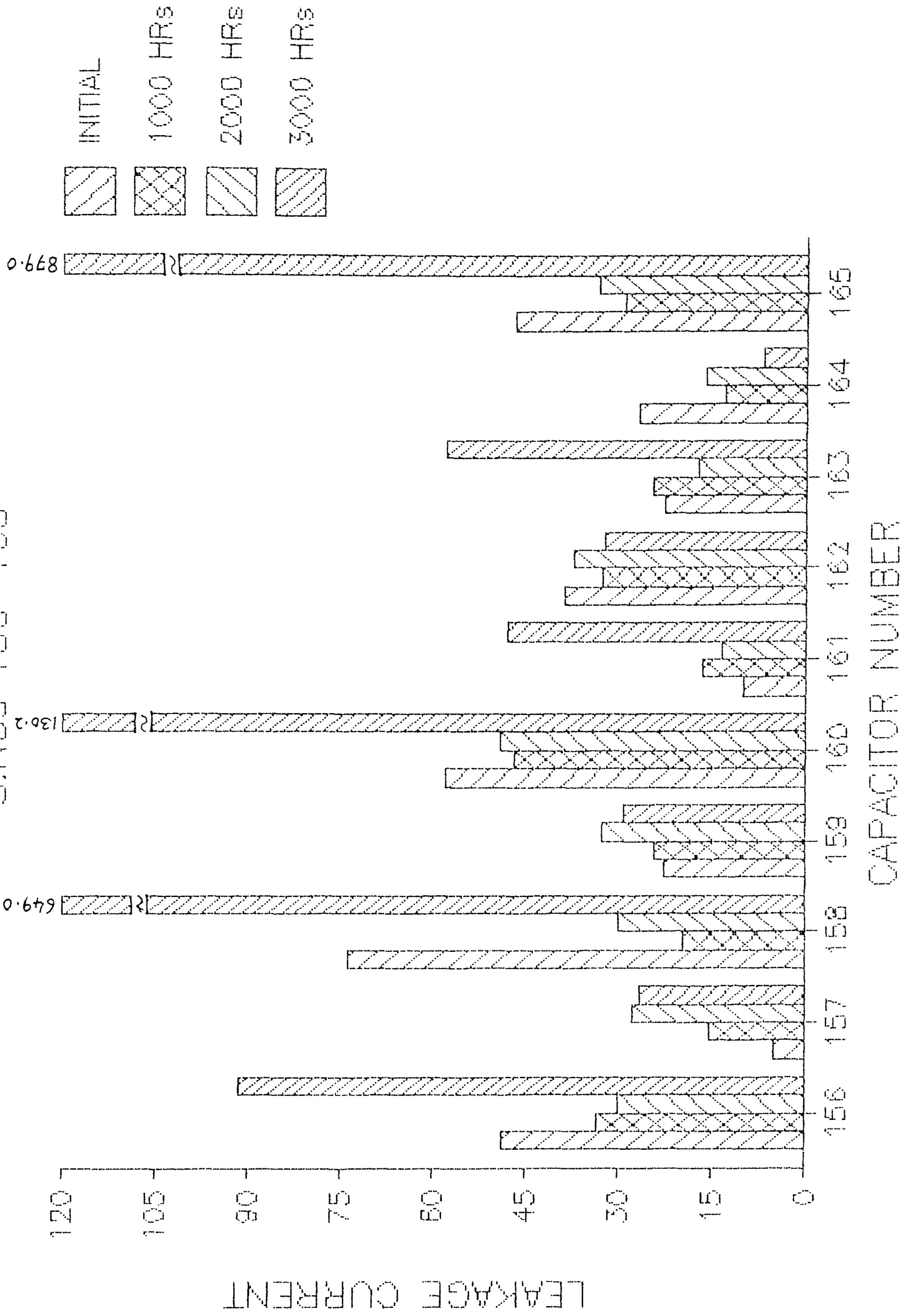
LEAKAGE CURRENT BAR CHARTS

S.NOs 146—155



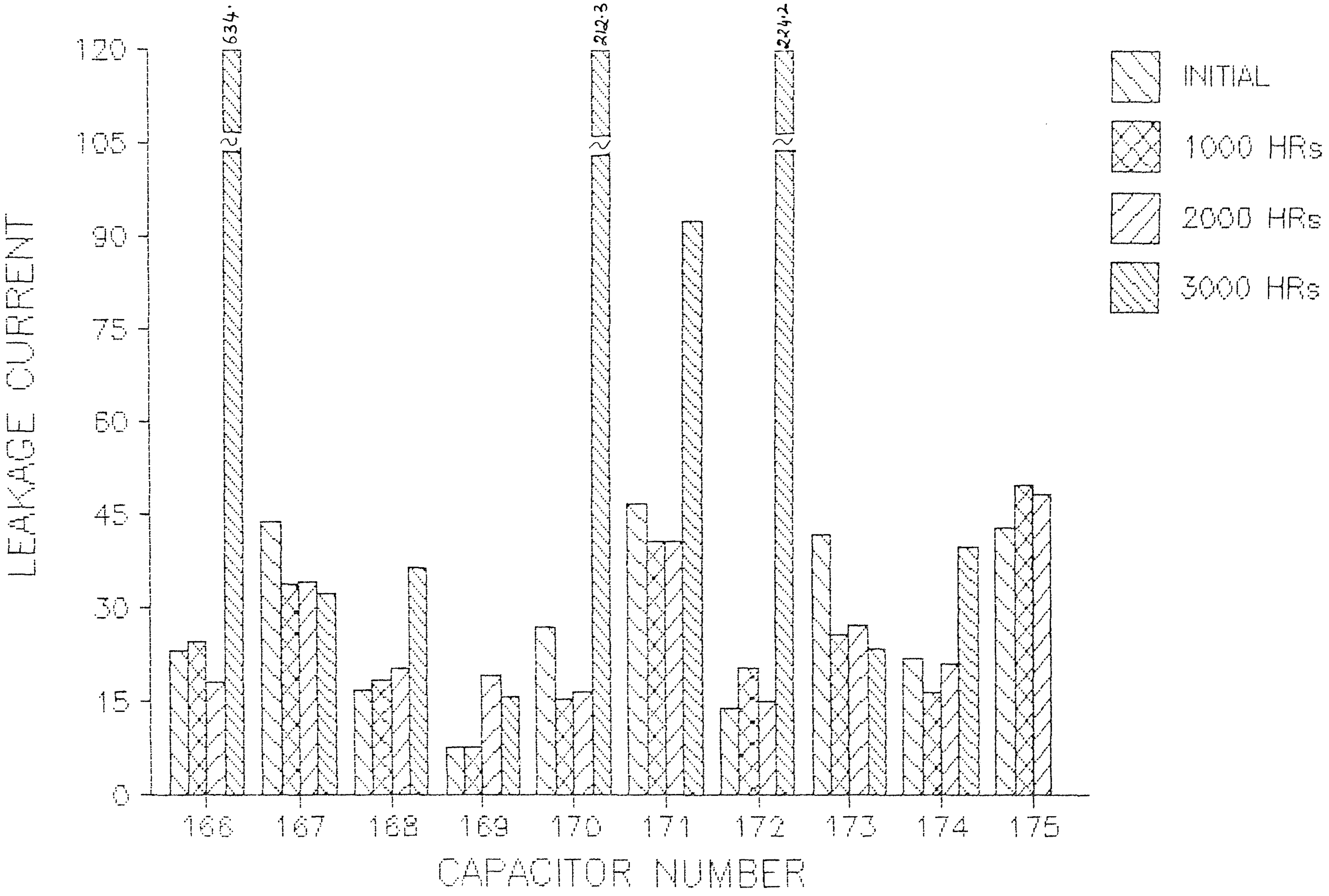
LEAKAGE CURRENT BAR CHARTS

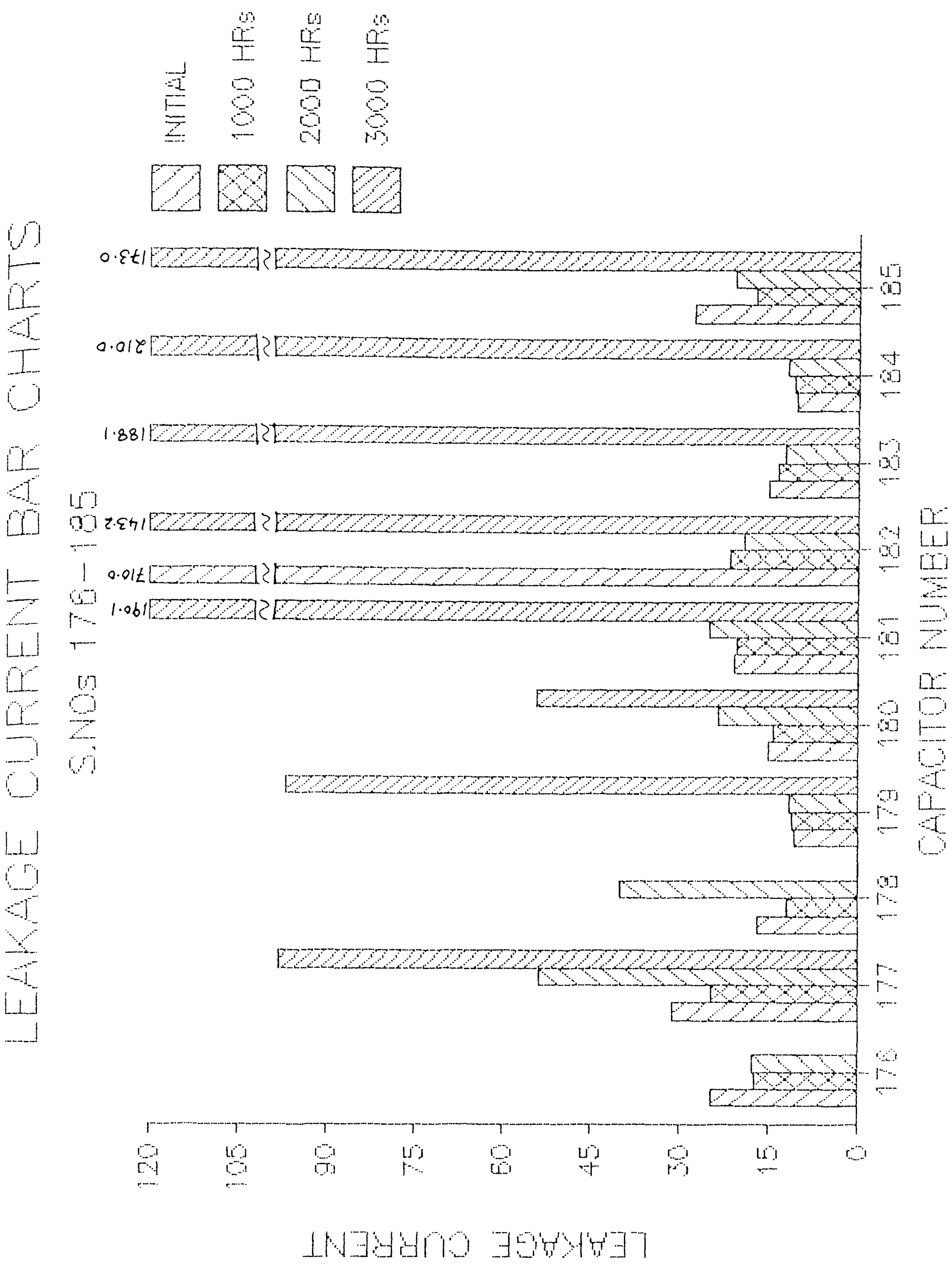
S.NOs 156–165



LEAKAGE CURRENT BAR CHARTS

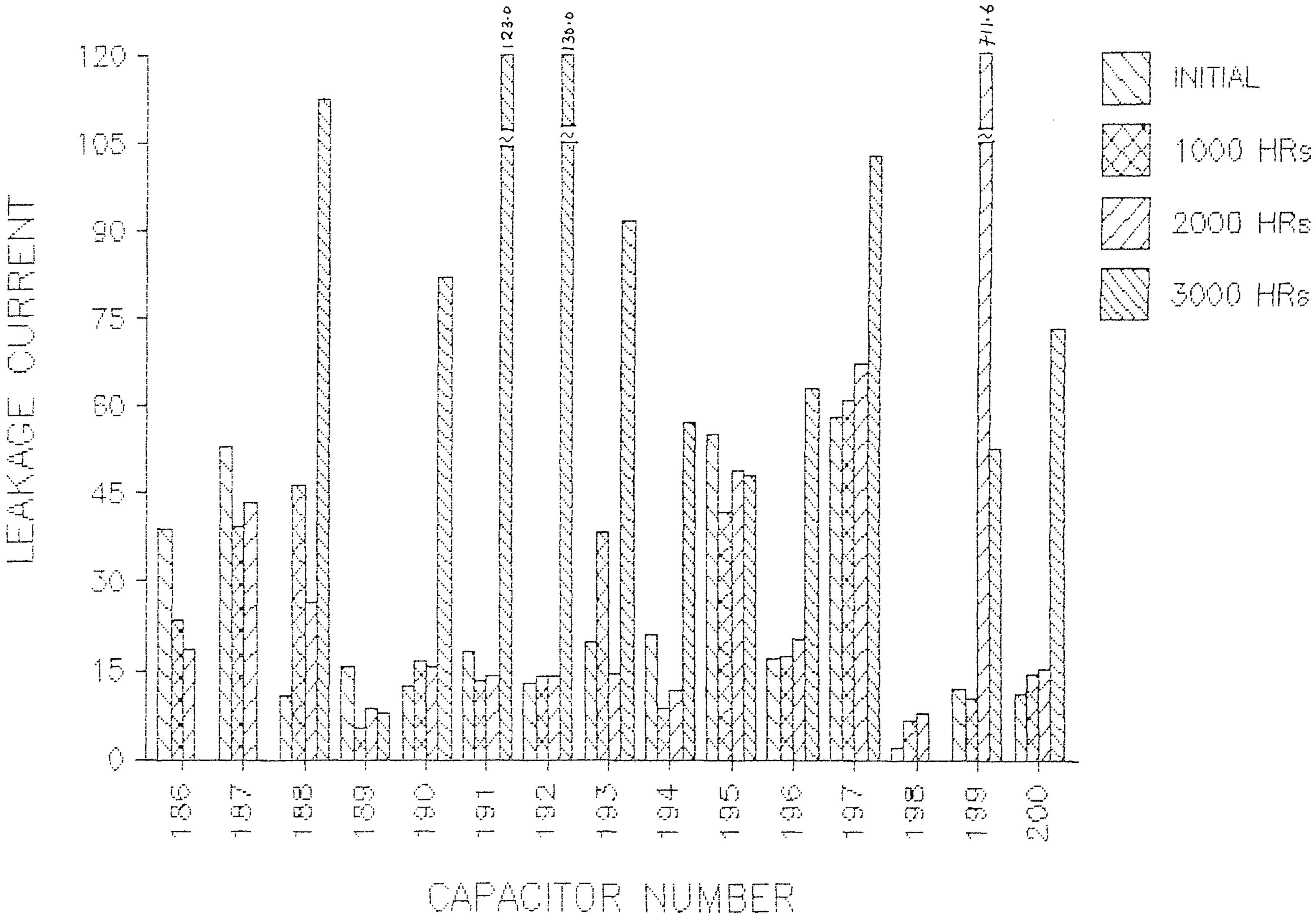
S.NOs 166–175




LEAKAGE CURRENT BAR CHARTS
S.NOs 176–185
INITIAL
1000 HRs
2000 HRs
3000 HRs
173.0
210.0
188.1
143.2
710.0
190.1
0
15
30
45
60
75
90
105
120
LEAKAGE CURRENT
176
177
178
179
180
181
182
183
184
185
CAPACITOR NUMBER

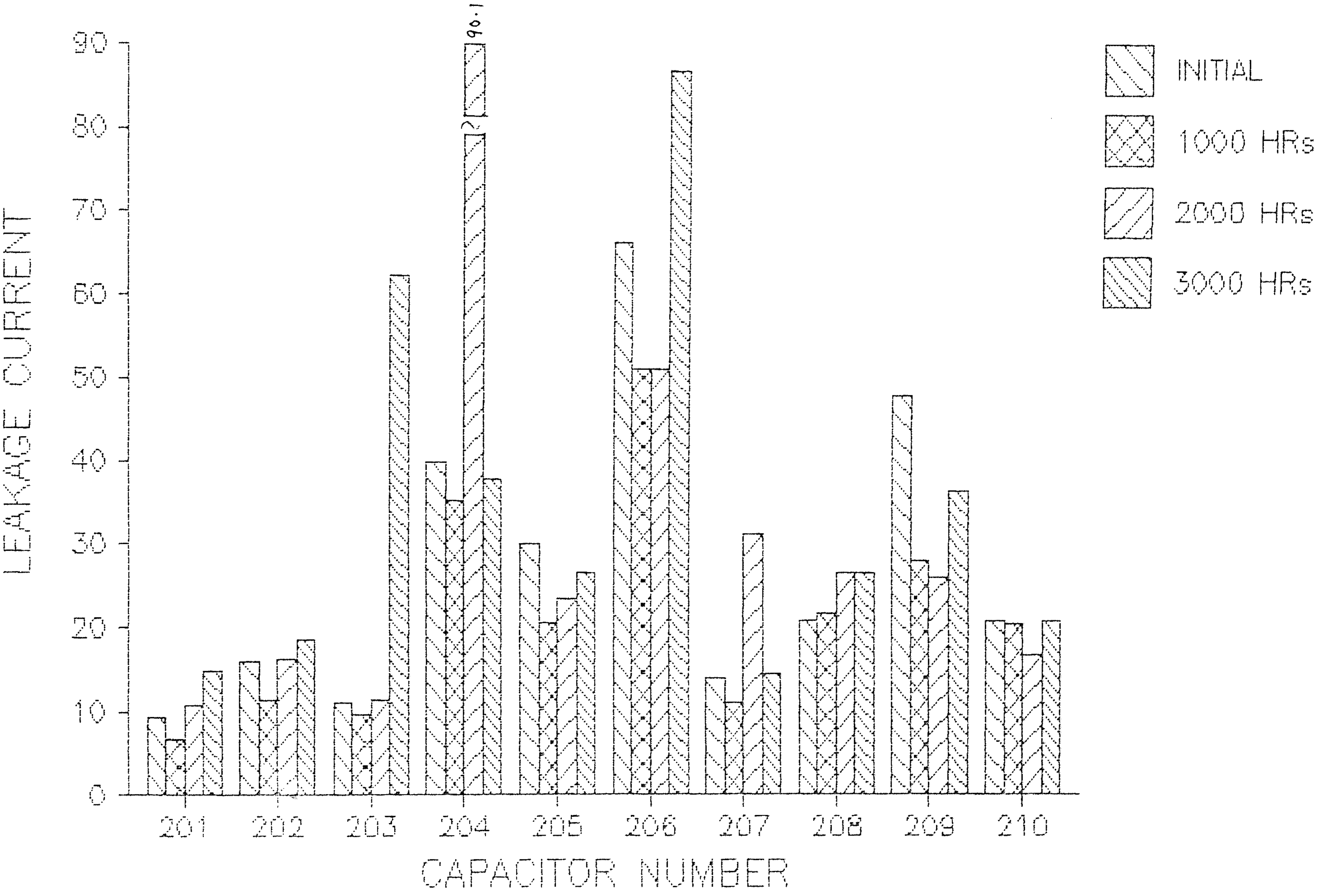
LEAKAGE CURRENT BAR CHARTS

S.NOs 186–200



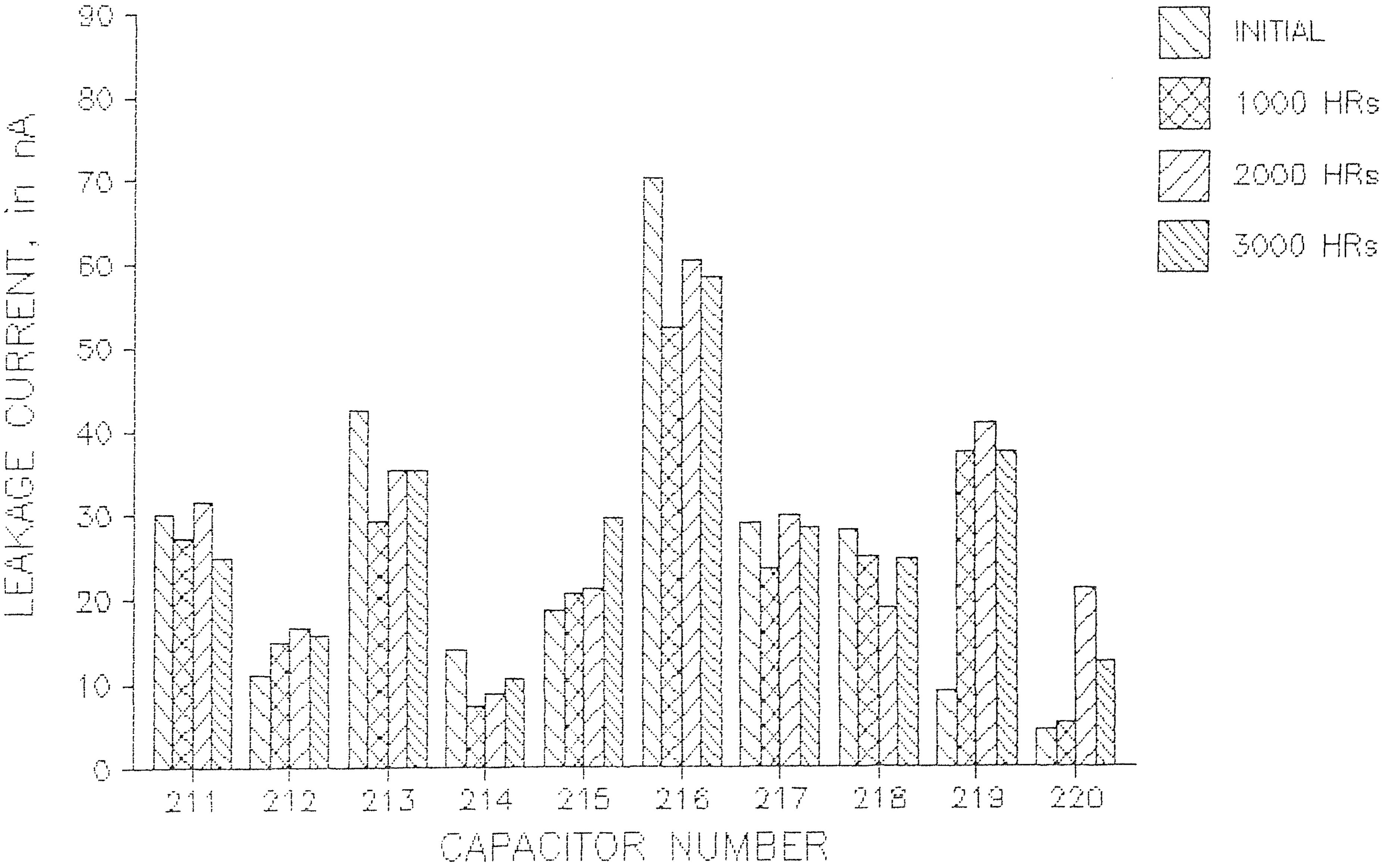
LEAKAGE CURRENT BAR CHARTS

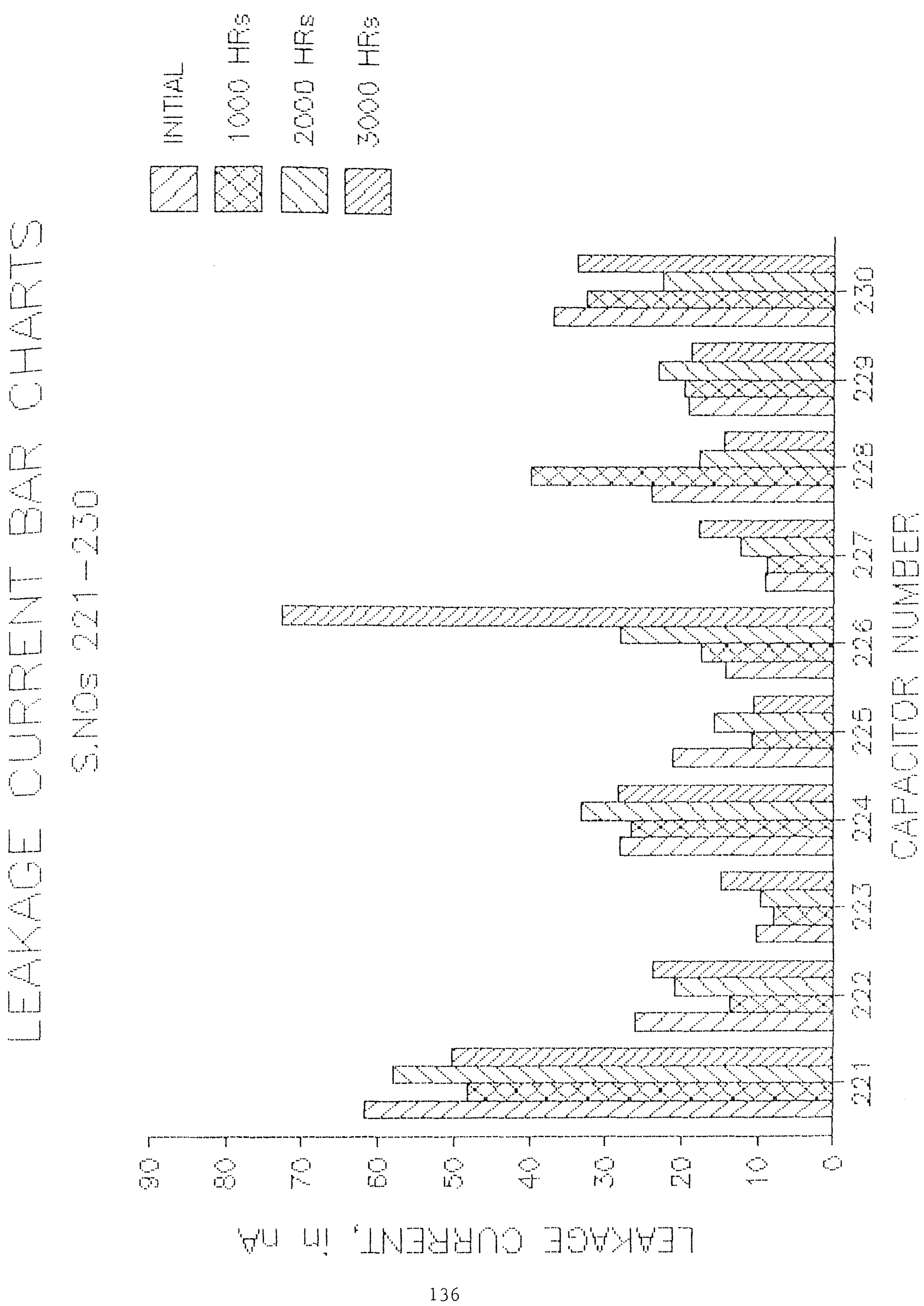
S.NOs 201–210



LEAKAGE CURRENT BAR CHARTS

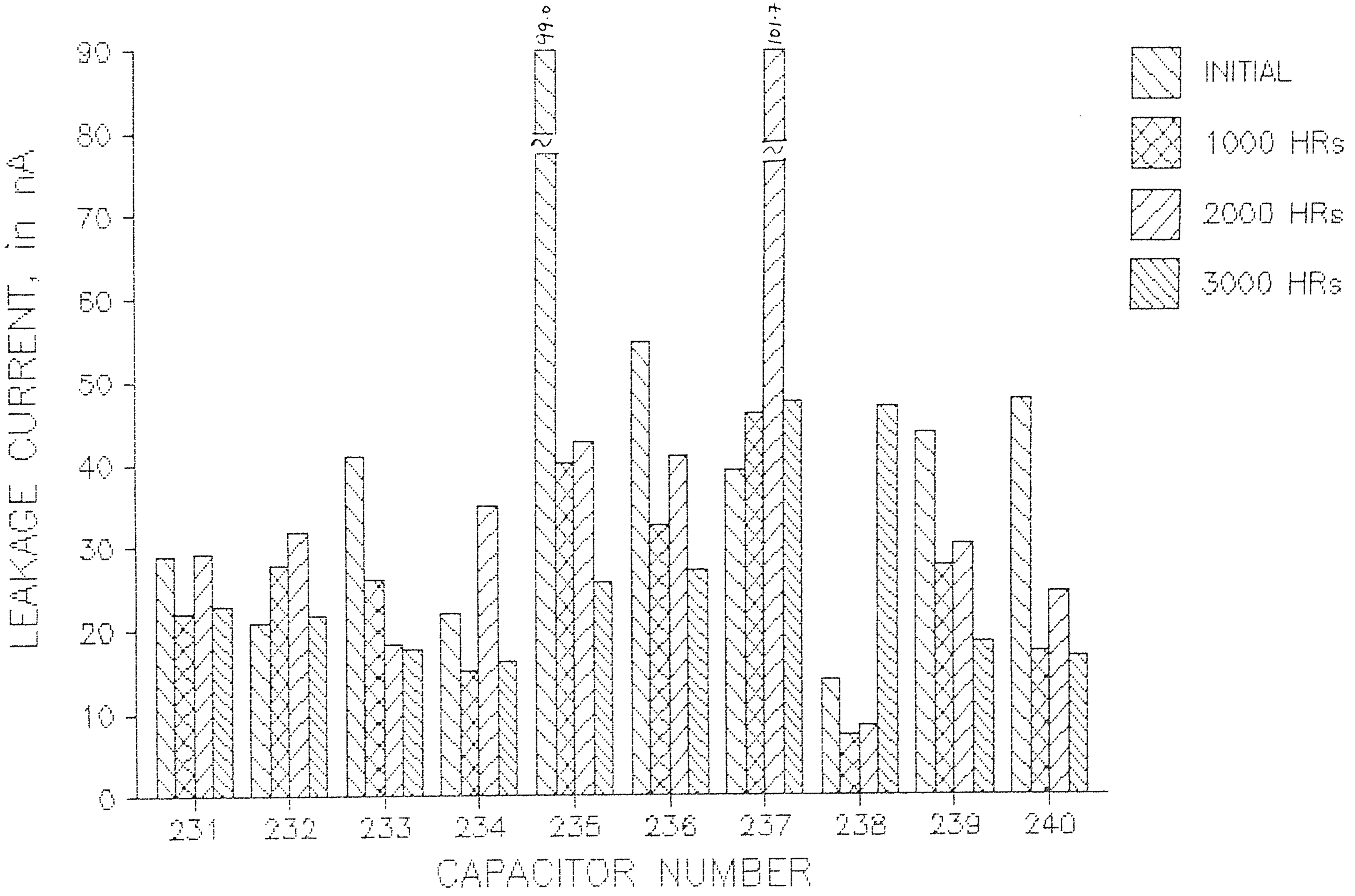
S.NOs 211-220




LEAKAGE CURRENT BAR CHARTS
S.NOs 221 - 230
INITIAL
1000 HRs
2000 HRs
3000 HRs
LEAKAGE CURRENT, in nA
0
10
20
30
40
50
60
70
80
90
CAPACITOR NUMBER
221
222
223
224
225
226
227
228
229
230

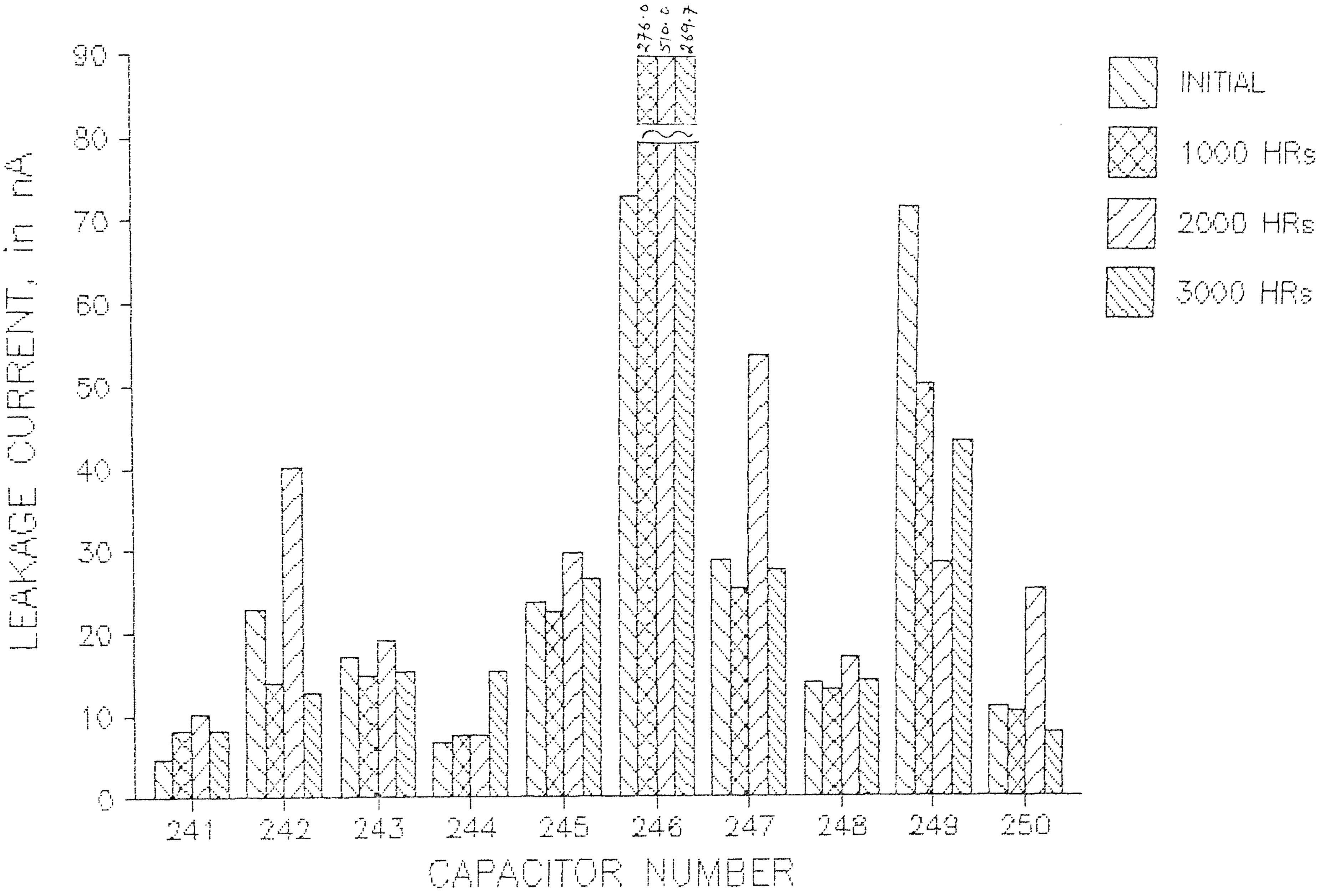
LEAKAGE CURRENT BAR CHARTS

S.NOs 231–240



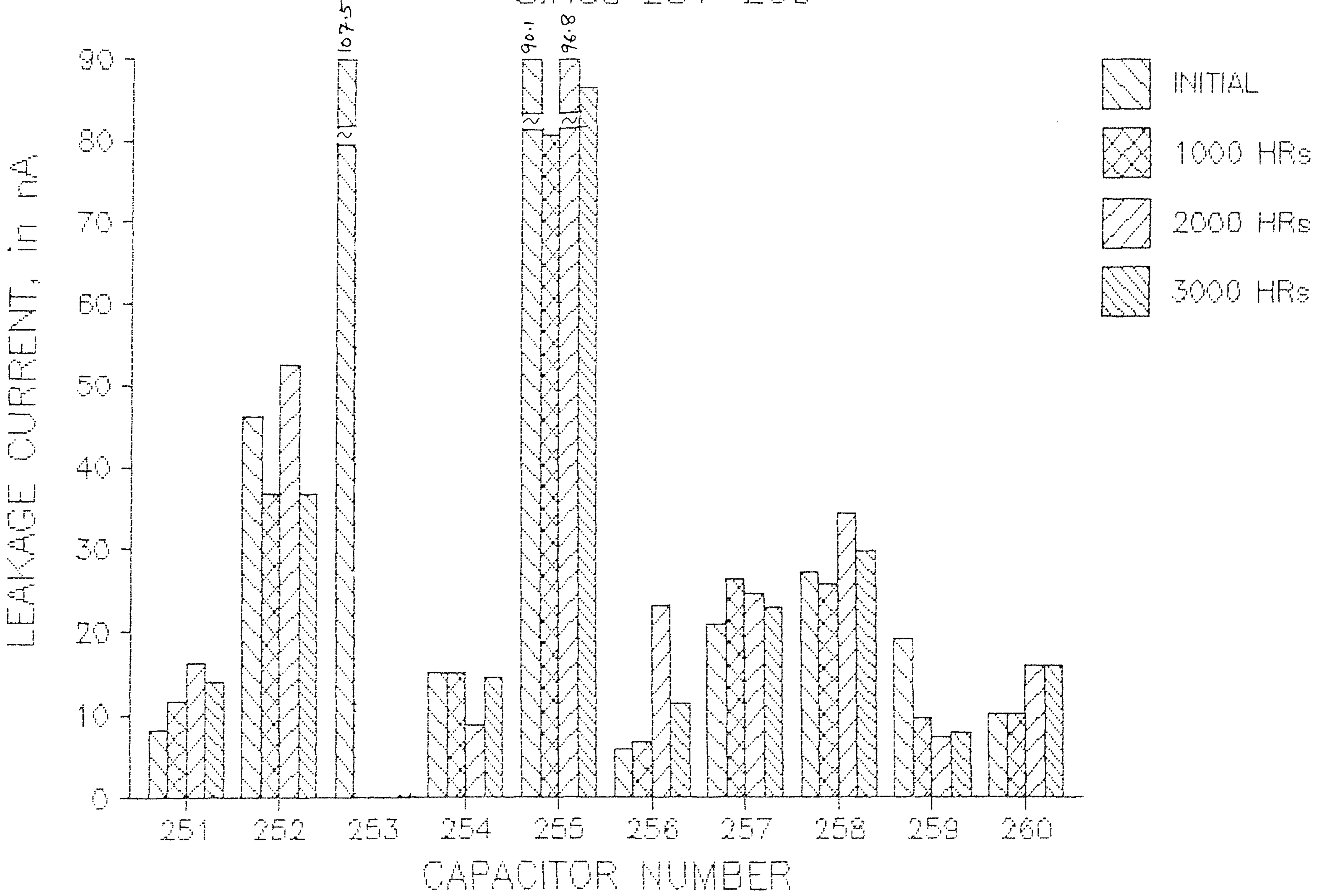
LEAKAGE CURRENT BAR CHARTS

S.NOs 241–250



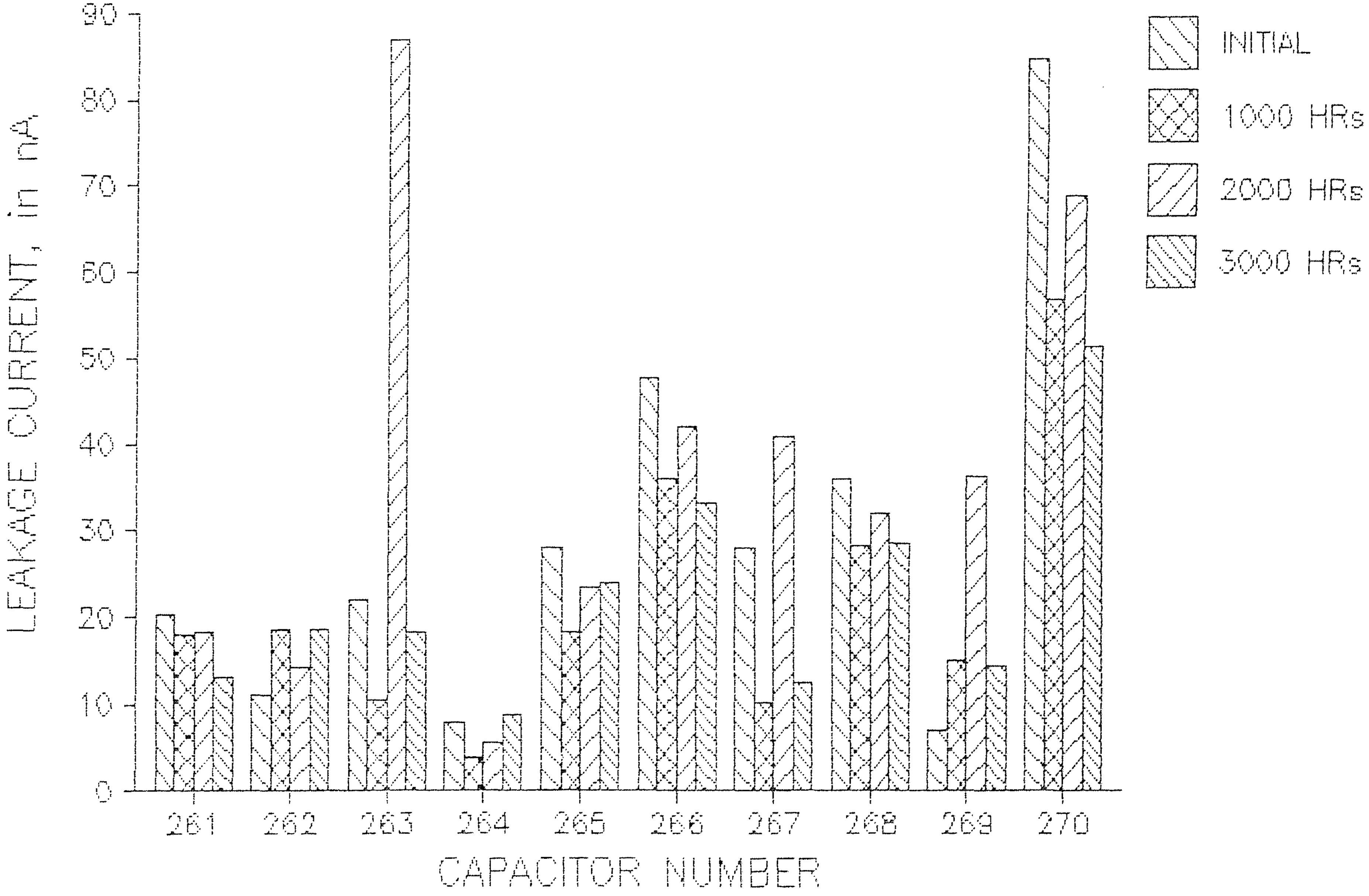
LEAKAGE CURRENT BAR CHARTS

S.NOs 251-260



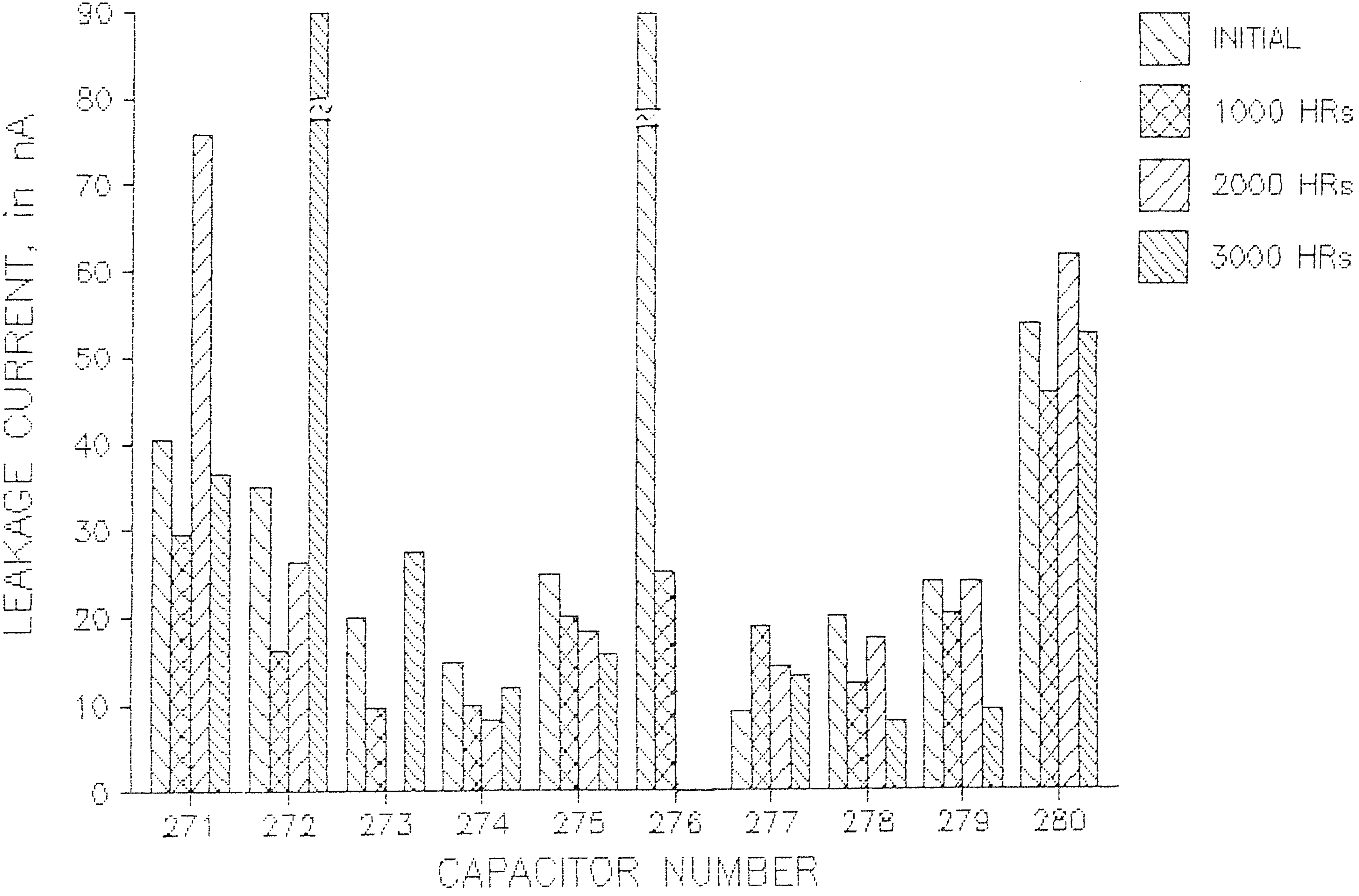
LEAKAGE CURRENT BAR CHARTS

S.NOs 261-270



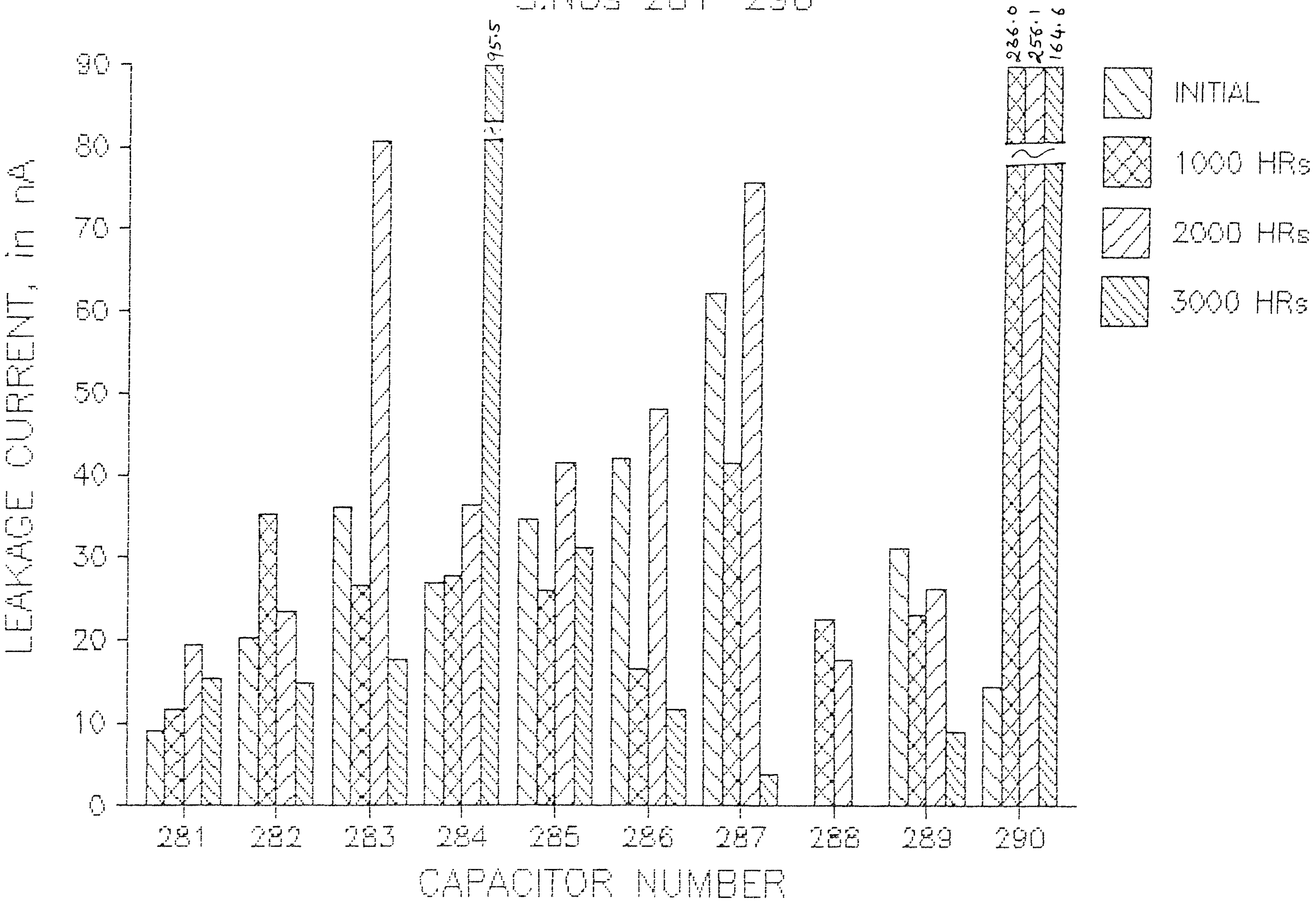
LEAKAGE CURRENT BAR CHARTS

S.NOs 271-280



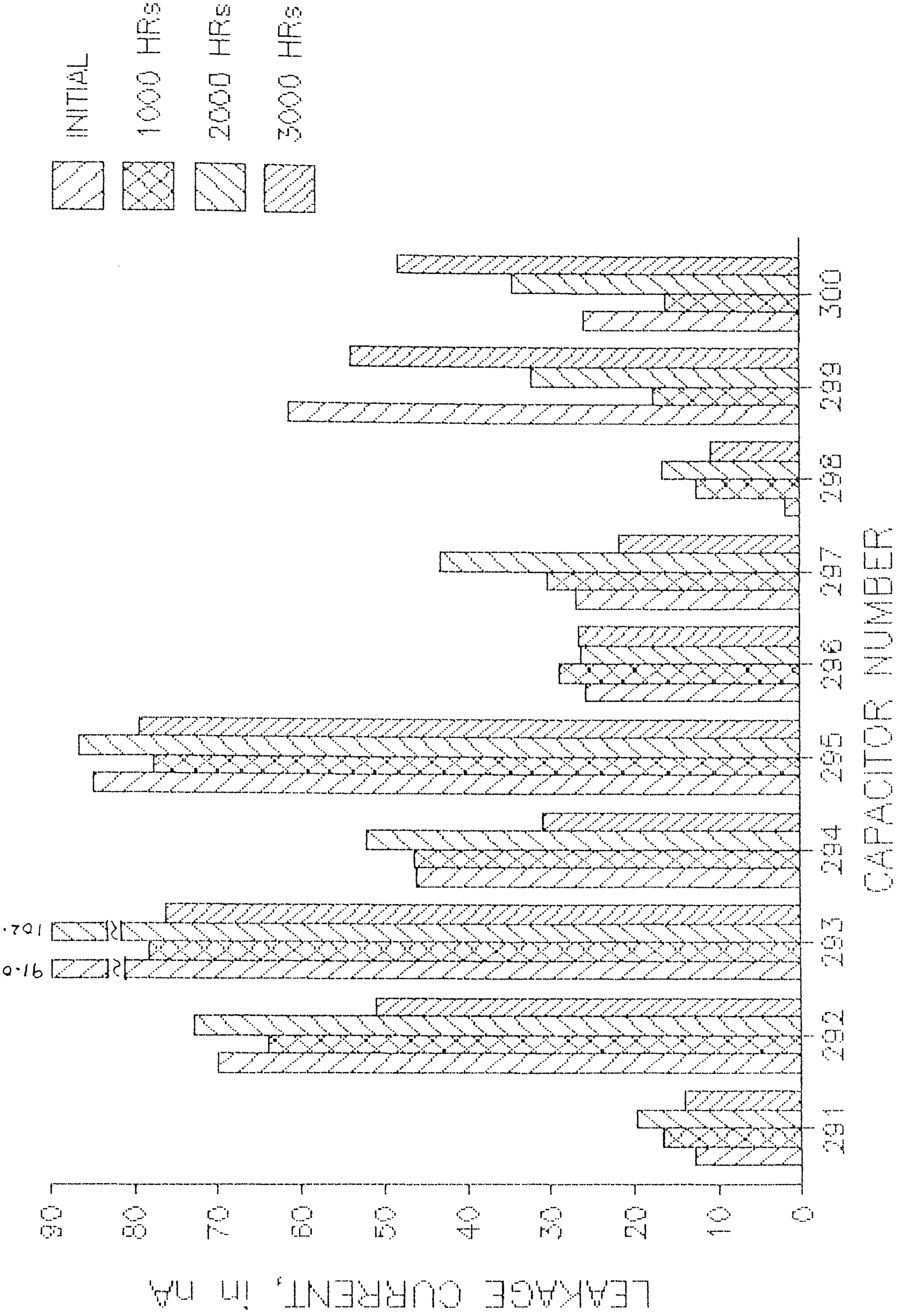
LEAKAGE CURRENT BAR CHARTS

S.NOs 281–290



LEAKAGE CURRENT BAR CHARTS

S.NOs 291 – 300



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*   B I B I L I O G R A P H Y  *
*                              *
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