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A TABULATION OF VOLTAGE-VARIABLE CAPACITORS

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

A tabulation of voltage-variable capacitors is presented. The various types of capacitors available, the frequency ranges in which they will operate, types of circuits in which they can be used, and other pertinent operating characteristics are presented.

In addition, a clarification of the distinction between the ferroelectric capacitor and the back-biased diode with regard to the principle of operation is presented.

It should be noted that the list of manufacturers is not exhaustive but can be considered as representative.

A TABULATION OF VOLTAGE-VARIABLE CAPACITORS

1. INTRODUCTION

Increasing interest in the use of voltage-variable capacitors for electronic frequency control has resulted in a number of queries as to what types are available, frequency ranges in which they will operate, types of circuits in which they can be used, and other pertinent operating characteristics. In many cases several different types could be used, each having somewhat different performance characteristics. The type of voltage-variable capacitor which is most suitable, whether it be ferroelectric or back-biased diode, can be chosen on the basis of a logical evaluation.

The choice will involve simultaneous consideration of several factors for each available type of capacitor in terms of the basic requirements of the circuit in which it is to be used.

2. OPERATING CHARACTERISTICS - FERROELECTRICS AND BACK-BIASED DIODES

A clarification of the distinction between the ferroelectric capacitor and the back-biased diode with regard to the principle of operation appears desirable. The following brief discussion is for this purpose.

In the case of the silicon junction diode, the density of charge carriers at a P-N junction (electrons in the N-region and holes in the P-region) is reduced almost to zero as a voltage is applied in the reverse direction across the junction. This region of zero charge-density, known as the depletion region, is not only swept clear of charge carriers but actually widens as the reverse bias is increased. In effect, the two conducting areas appear to act as two metal plates, which tend to move farther apart as the reverse bias is increased. The plate area and the dielectric constant remain the same, but the distance between the plates varies according to the applied voltage.

When these back-biased diodes are used in a resonant tank-circuit where high RF voltages may be developed across them, the junction must be back-biased far enough so that no part of the signal-voltage swing causes the net voltage applied to the junction to go positive, or clipping will result. This effect can be avoided at the expense of reducing the circuit Q somewhat by placing two back-biased diodes in series opposition across the tank coil.

In the case of ferroelectrics, the method of operation is completely different. Ferroelectricity can be described as a spontaneous polarization. Polarization in dielectric materials may be due to:

(1) Alignment of permanent electric dipoles,

(2) Displacement of the + and - ions relative to one another (e.g., Na^+ and Cl^- in NaCl), or

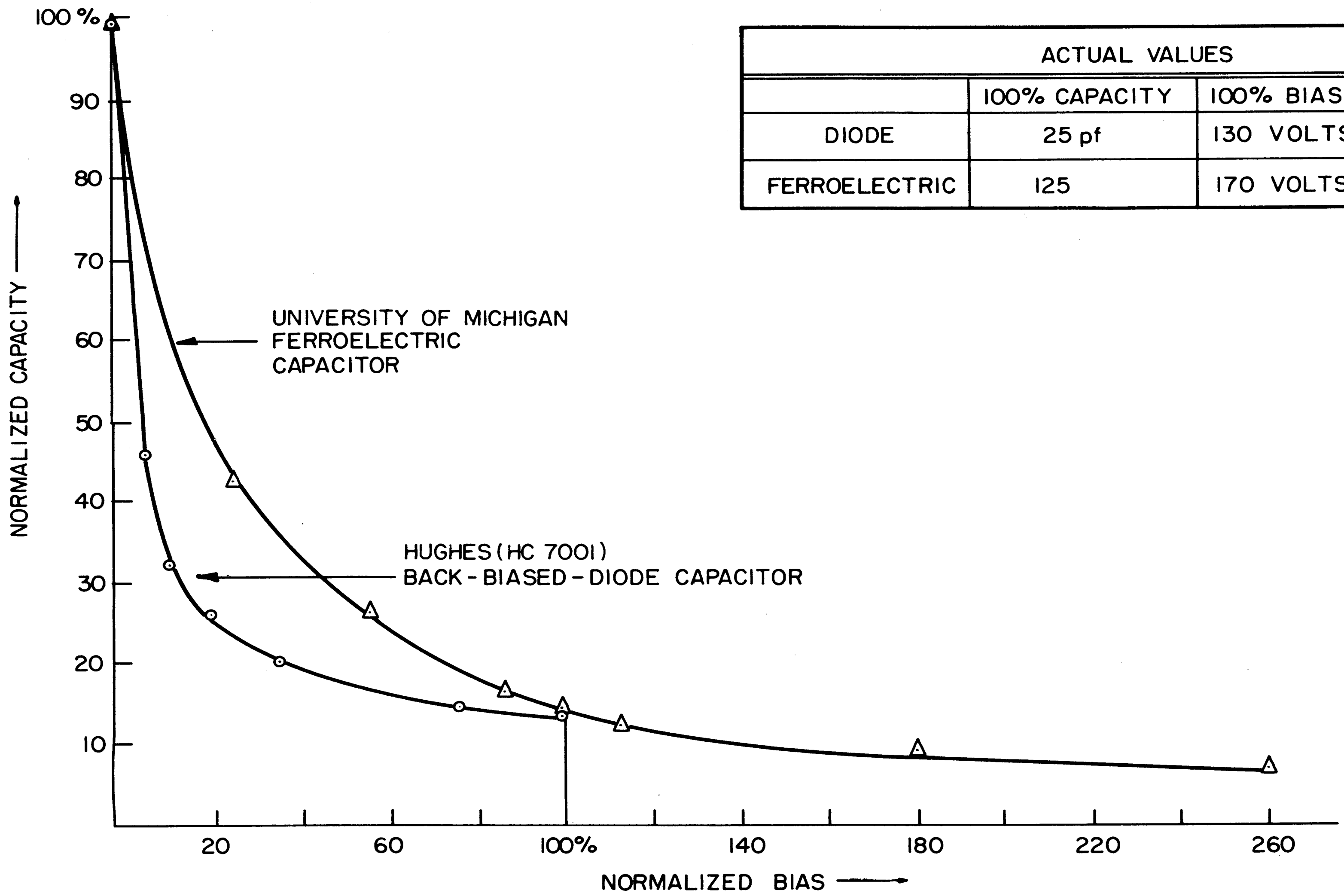
(3) Displacement, relative to the positive nucleus, of the center of gravity of the negative charge of the electrons.

Ferroelectricity will occur if any of these mechanisms, either singly or in combination, occurs spontaneously, i.e., without the application of an external electric field. A number of materials exhibit ferroelectricity, but on the whole the phenomenon is rather rare. Barium titanate ($BaTiO_3$) is, from a practical point of view, the most important ferroelectric and, when mixed with a nonferroelectric buffer material such as strontium titanate, becomes a suitable material for many practical applications.

Although the mechanism of spontaneous polarization which describes ferroelectricity is somewhat complicated, the basic properties may be stated simply. In the ceramic of which practical capacitors are formed, the barium titanate is made up of a multitude of tiny particles whose spontaneous dipoles are randomly oriented. Therefore, the statistical average of the elemental orientations is zero, and there is no net polarization before application of an electric field. When a dc bias is applied to the material, some of the dipoles originally randomly oriented will align themselves with the field; consequently, the dielectric constant decreases. As the biasing field is increased, more and more dipoles are reoriented, and the dielectric constant continues to decrease until saturation is reached, i.e., until a further increase in bias fails to produce a proportionate increase in polarization. This presumably occurs as a result of the exhaustion of the supply of randomly-oriented dipoles.

Unlike the back-biased diodes, the ferroelectric capacitors can be biased in either the positive or negative directions, and clipping will not result when they are used in a resonant circuit.

Figure 1 compares the capacity-vs-voltage curves at 100 mc of an inexpensive commercially-available back-biased diode and the Michigan Ferroelectric Capacitor. These two curves have been normalized to



ACTUAL VALUES			
	100% CAPACITY	100% BIAS	TEMP
DIODE	25 pf	130 VOLTS	27° C
FERROELECTRIC	125	170 VOLTS	27° C

FIG. 1 TYPICAL CAPACITY VS VOLTAGE CURVES AT 100 MC (NORMALIZED)

compare their characteristics. The small table at the top right gives the actual values for the components. The two curves were normalized for the maximum capacitance range of the diode. Other comparisons can readily be made. Figure 2 compares the Q-vs-voltage curves at 100 mc of the same back-biased diode and the Michigan Ferroelectric Capacitor, while Fig. 3 compares the capacity-vs-temperature curves of the same two voltage-variable capacitors. Note that the last two curves are not normalized.

3. TABLE AND RELATED COMMENTS

The list of manufacturers is not exhaustive, but it can be considered as representative (see Fig. 4). Some of the units listed are experimental and not commercially available. In the ferroelectric field almost any manufacturer of high-dielectric-constant ceramic capacitors should be able to provide capacitors with some degree of voltage sensitivity.

Unless otherwise stated, initial capacitance is the small-signal capacitance that exists when the device has zero bias. When bias is the independent variable and other parameters are held fixed, the small-signal capacitance appears to be a maximum at approximately zero bias for both the diode and ferroelectric.

The frequency range of the device is the typical range in which the device may find application.

Minimum capacitance is the small-signal capacitance that occurs when the device has maximum bias applied.

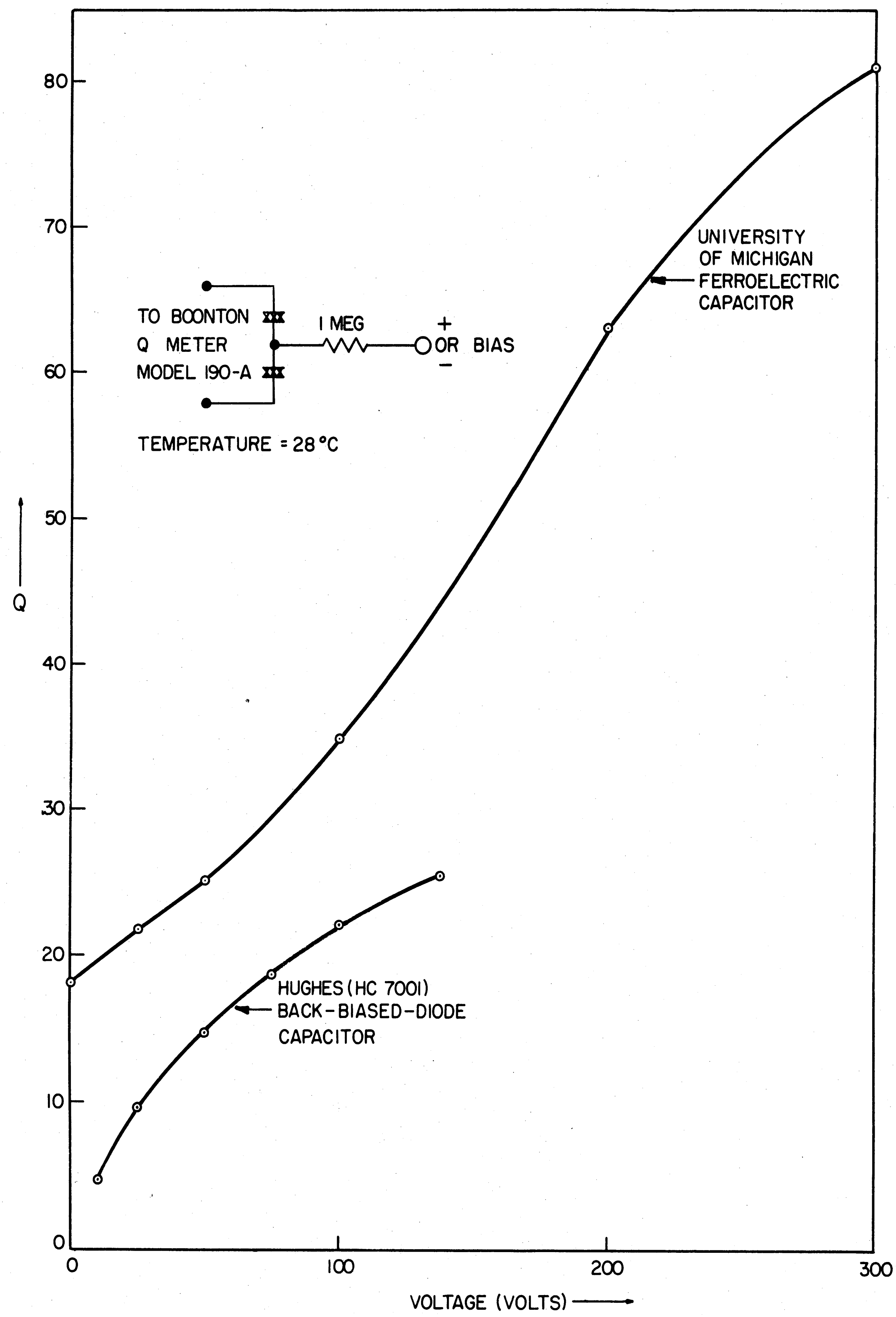


FIG. 2 TYPICAL Q VS VOLTAGE CURVES AT 100 Mc.

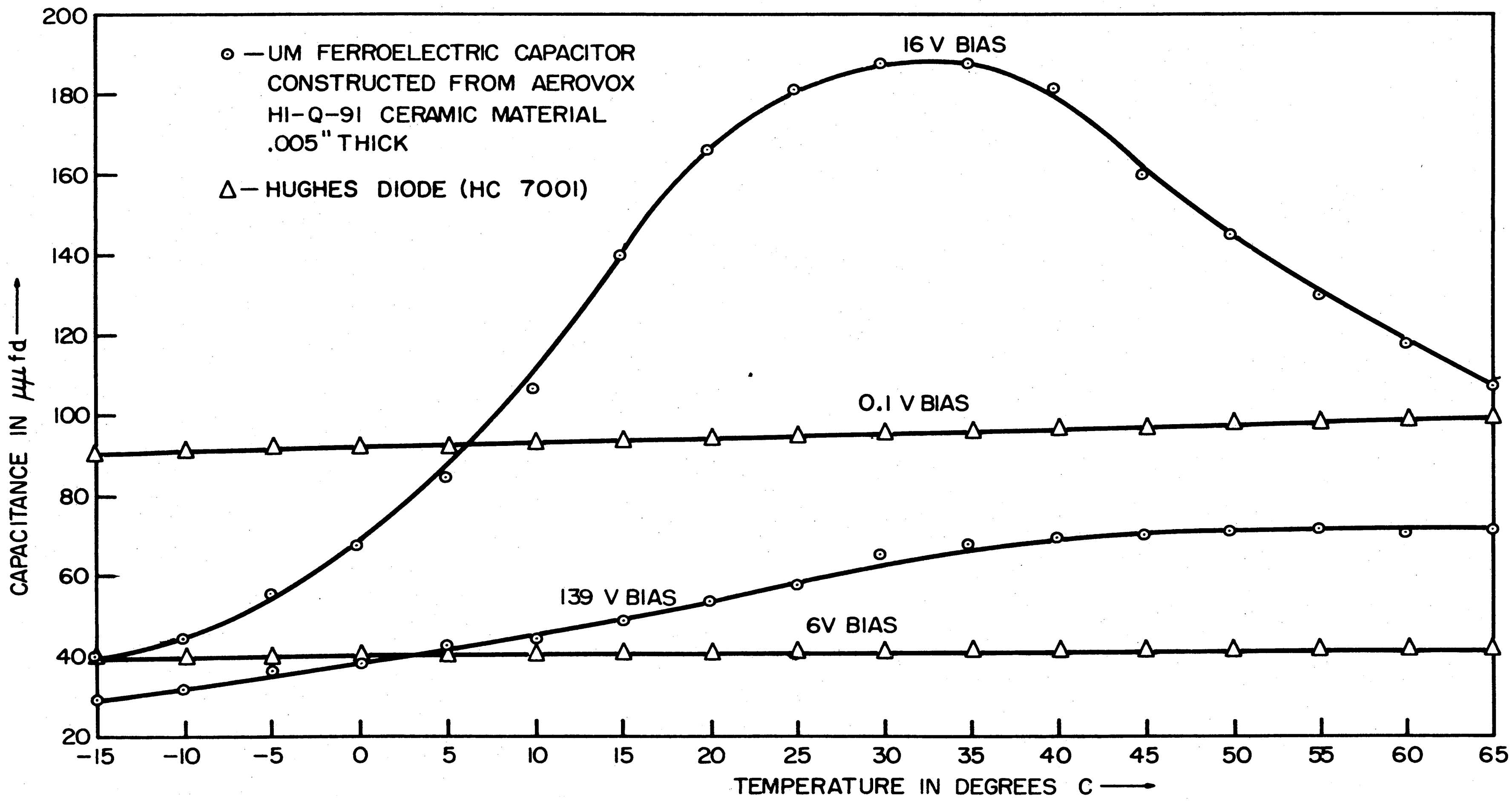


FIG. 3 TYPICAL CAPACITANCE VS TEMPERATURE CURVES

ACA128

BACK BIASED DIODE CAPACITORS

	MANUFAC-TURER	TYPE	INITIAL CAPACITANCE	MINIMUM CAP.	MAX. VOLTAGE	Q	CUTOFF FREQ.	R_{series}	TEMPERATURE SENSITIVITY	COMMENTS
SHF & UHF	BELL LABS	SI 43-7	2.15pf ,0V	1.2pf ,6V	10 V		77KMC	2.3 Ω	ESSENTIALLY T. INSENSITIVE	EXPERIMENTAL UNIT
	MICROWAVE ASSOCIATES	MA-460A MA-460B MA-460C MA-460D MA-460E	4pf 2pf 1.8pf 1.4pf 1.0pf } 0V	1.2pf 1pf 0.4pf 0.2pf 0.2pf	6V	2 3 4 5 6 } AT 10 KMC	20KMC 30KMC 40KMC 50KMC 60KMC		" " "	JUNCTION CAPACITANCE ONLY CASE CAPACITANCE = 0.4pf
	WESTERN ELECTRIC	427 – A SERIAL 7-1026	1.2pf , 0.1V	0.12pf	10 V			15Ω AT 3 KMC	" " "	JUNCTION CAPACITANCE ONLY, CASE CAP. SUBTRACTED – SEE REF. 9
	HUGHES	HPA-2800 HPA-2810	2.5pf , 0V	0.6pf 0.6pf	7V 7V		70 KMC		" " "	CASE CAPACITANCE = .1pf " " = .2pf JUNC. CAP. ONLY
UHF	TRANSITRON	SCH-51 SCH-52	2pf 4pf } 0.1V	0.35pf 0.80pf	10V 7V	100 AT 50 MC 50 AT 100MC } AT 4V	5KMC	85Ω 43Ω	" " "	
VHF	HUGHES	HC 7001 HC 7002 HC 7004 HC 7005 HC 7006 HC 7007 HC 7008	88pf 120pf 170pf 240pf 88pf 120pf 170pf } 0.1V	6pf 12pf 20pf 46pf 14pf 22pf 32pf	130V 80V 60V 25V 25V 25V 25V	360, 330, 270, 200, 175, 175, 175 } 5MC MAX. V 39, 36, 30, 23, 20, 20, 20 } 50MC MAX. V			" " "	
	INTERNATION-AL RECT.	6.8 SC20 100 SC2	35pf 470pf } 0.1V	2.5pf 80pf	200 V 20 V				" " "	
	PACIFIC SEMICONDUC-TOR	V-7 V-10 V-12 V-15 V-20 V-27 V-33 V-39 V-47 V-56 V-68 V-82 V-100 V-7E V-10E V-12E V-15E V-20E V-27E V-33E V-39E V-47E V-56E	18pf 26pf 31pf 39pf 50pf 70pf 85pf 100pf 120pf 145pf 175pf 210pf 260pf 18pf 26pf 31pf 39pf 50pf 70pf 85pf 100pf 120pf 145pf } 0.1V	3pf 4.3pf 5.2pf 6.5pf 10pf 14pf 17pf 20pf 24pf 32pf 39pf 47pf 57pf 1.5pf 2.2pf 2.7pf 3.3pf 5.0pf 7.0pf 9.0pf 11.0pf 14.0pf 20pf	25V 25V 25V 25V 20V 20V 20V 20V 20V 15V 15V 15V 15V 100V 100V 100V 100V 70V 65V 60V 55V 50V 40V	18, 18, 18, 18, 18.7, 15.7, 14.6, 15.1, 15.4, 13.5, 14.0, 13.0, 11.0, 4.5, 5.5, 6.5, 7.5, 18.7, 15.7, 14.7, 15.1, 15.4, 13.5 } 50MC 4V 43, 43, 43, 43, 40.2, 33.8, 31.4, 32.4, 32.4, 24.8, 25.8, 23.9, 20.2, 22.5, 27.5, 32.5, 37.5, 78.5, 63.5, 56.5, 55.8, 53.8, 41.8 } 50MC MAX. V			" " "	
	PHILCO	T-1606	35 ,0.5V	8	30 V	20 AT 50MC & 0.5V			" " "	
	SYLVANIA	D-1156	4pf , 0.1V	0.5pf	20 V				" " "	
	TRANSITRON	SC-1 SC-2 SC-3 SC-5 SC-7 SC-11 SC-15	24pf 48pf 90pf 120pf 165pf 245pf 360pf } 0.1V	4.4pf 8pf 15pf 25pf 55pf 85pf 120pf	22V 22V 18V 11V 9V 6V 6V	350 AT 5MC & 4V , 33 AT 50MC & 4V		9Ω 4.5Ω 3.0Ω 1.8Ω 1.5Ω 0.9Ω 0.6Ω	" " "	

FERROELECTRIC CAPACITORS

UHF TO AUDIO	UNIVERSITY OF MICHIGAN	EDG-HS24F1	ϵ_{max} = 4100 AT 0V & 30°C	ϵ_{min} = 500	200 V/MIL & 30°C	205 AT 50MC & 0V, ABOUT 8 X GREATER AT 200V/MIL			TEMPERATURE SENSITIVE CURIE 30°C	EXPERIMENTAL UNIT
	UNIVERSITY OF MICHIGAN		125pf AT 0V & 25°C	9pf	±400 V & 25°C	18 AT 0V 87 AT ±400 V } 100MC, 25°C			CAPACITY VARIATION 80 TO 132pf FOR A TEMPERATURE RANGE OF −10° TO +50°C, CURIE 12°C AT 0V	EXPERIMENTAL UNIT CAPACITORS CAN BE FABRICATED HAVING VALUES 0.6pf TO 0.1μf
VHF TO AUDIO	MUCON	VSR LVSR }	400pf TO 0.1μf	88pf TO 0.022μf	± 300 V ± 300V				CURIE ≃ 22.5°C 5% ΔC FOR +12°C TO +30°C	
	MUCON	VSE LVSE }	60pf TO 300pf	36pf TO 180pf	±200 V ±200 V				CURIE ≃ 70°C 5% ΔC FOR +67°C TO +75°C	
	GLENCO	MATERIAL 393								STORAGE APPLICATIONS

FERROELECTRIC MATERIALS MAY BE AVAILABLE FROM THESE MANUFACTURERS: AEROVOX, CENTRALAB, MULLENBACH, SPRAGUE, AND OTHERS

FIG. 4 TABULATION OF VOLTAGE-VARIABLE CAPACITORS

Maximum voltage is the highest bias voltage at which the device can be operated. In the case of the diode it is the maximum peak inverse-voltage. The maximum voltage for the ferroelectric is determined by its dielectric strength.

Q is the energy-storage figure of merit. For a capacitor Q may be expressed as $1/\omega R_s C$, where R_s is the equivalent series resistance.

Cutoff frequency, f_c, is defined as $\frac{1}{2\pi R_s C_{min}}$. Specifications of f_c are based on a measurement of R_s and C_{min} at some frequency below f_c, then f_c is calculated. Recent investigations indicate that R_s may not be a constant; in this event, f_c would not be given by the above equation.

R_s is the equivalent series-resistance of the device. For diodes, this is assumed to be a constant. For ferroelectric capacitors, however, no simple relationship for R_s as a function of the frequency is known, although it can be assumed constant at a given frequency.

Temperature sensitivity is used here as a measure of the response of the component to incremental temperature changes. The performance of diode capacitors shows only a slight dependence upon temperature, whereas that of the ferroelectrics is quite sensitive to temperature. Storage-temperature or wiring-temperature of the ferroelectric capacitor is limited by the method of attachment of the leads to the ceramic, which is usually done with ordinary solder.

In general, all of the devices may be used as tuning elements in oscillators and filters. The maximum power-level is a function of the device, the frequency, and the tuning range. Ferroelectrics have been used in oscillators for tuning, with a power output of 0.4 watt at

400 mc with a 20 mc tuning range, showing a negligible shift in capacitor characteristics due to heating of the capacitor by dielectric losses.

Other general applications so described in the references are in parametric amplifiers, modulators, adjustable delay-lines, tunable antennas, thermometers, frequency converters, and distributed-variable devices. Some specific applications are in FM modulation, automatic frequency-control, electric receiver-tuning, panoramic-receiver tuning, tunable audio-oscillators, and tunable filters.

The frequency range of the device is a function of its Q and the range of capacitance values that can be fabricated. That diodes can be made which have high Q's at high frequencies is illustrated by the Bell diode. Ferroelectrics can not now compete in this field. The Q of a good ferroelectric under the best conditions may be 4 at 3000 mc. In the future better ferroelectric materials may be developed.

The maximum capacity of a ferroelectric can be large. For instance, an initial capacitance of 0.1 μfd can be attained with a slab approximately 1.2 x 1.2 x 0.1 cm in size. Fabrication of a diode of this capacitance value would be difficult.

Both diodes and ferroelectrics are physically small components. For instance, a diode with an initial capacitance of 88 μμfd can be packaged in a case 0.25" long x 0.1" in diameter. A ferroelectric capacitor of 100 μμfd can be packaged in a plastic sphere about 0.1" in diameter.

The cost of diodes in small quantities ranges from about one dollar to several hundred dollars. Because of the complexity and non-homogeniety of diodes it is reasonable to expect that their minimum price will remain at about the one-dollar level. The ferroelectrics are inherently easier to fabricate and therefore should have a lower price.

Some applications require tracking of several circuits. The characteristics of diodes will vary significantly from one unit to another and introduce tracking problems unless units are selected. With ferroelectric capacitors it is possible to make all units for a given circuit from the same ceramic wafer, which results in good tracking of the capacitors.

4. COMMENTS CONCERNING MANUFACTURERS' CURVES

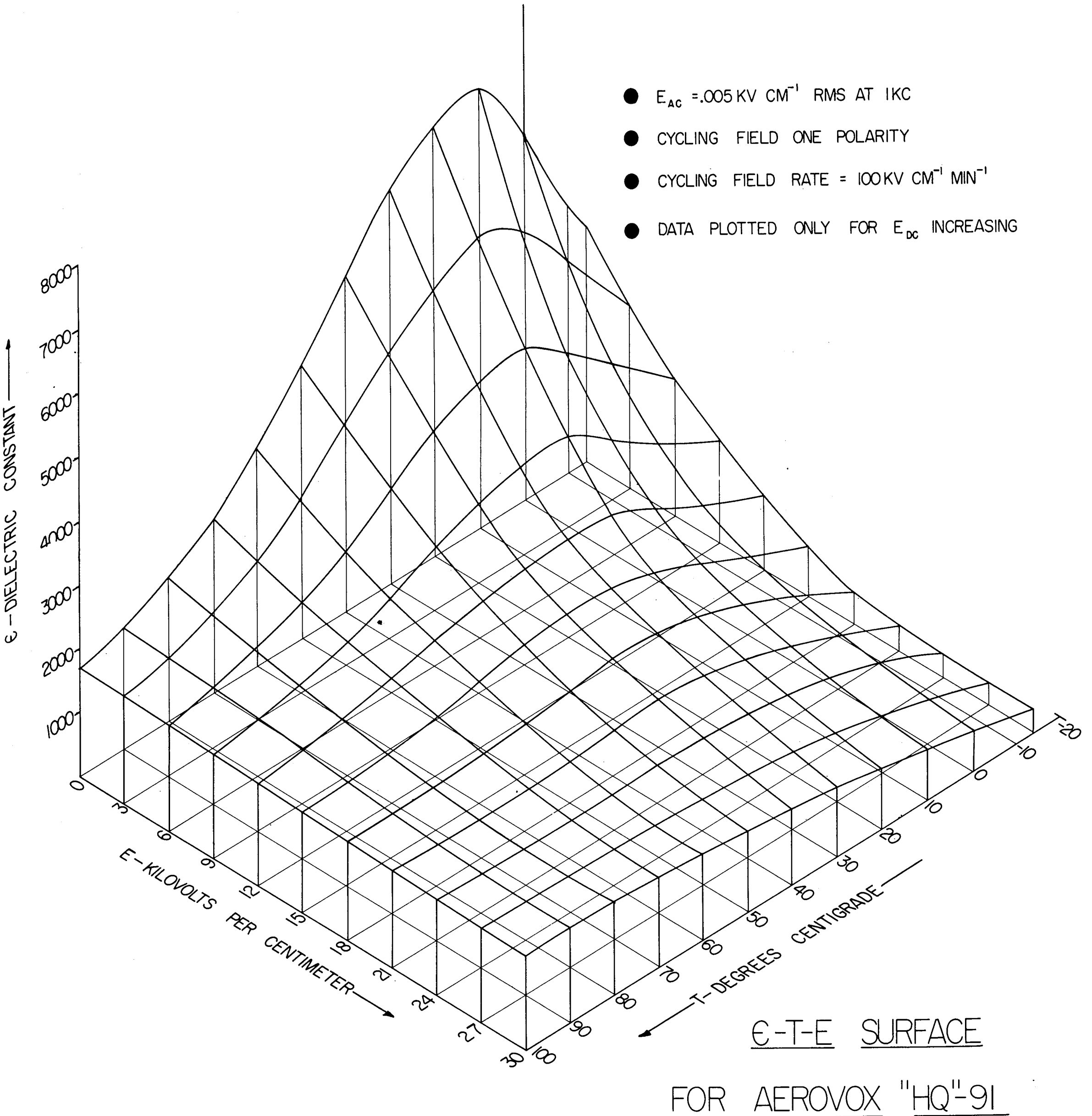
Both diodes and ferroelectrics have complex characteristic-curves. It appears that manufacturers, in an attempt to simplify the data, have left out information that is important. The result is that persons unfamiliar with the device may be misled. In general both diodes and ferroelectrics have capacitance that is a function of bias and temperature, and Q as a function of bias, temperature, and frequency. Some diode manufacturers tabulate Q at a specific frequency at maximum bias and fail to indicate the Q at zero bias or describe the law for Q. Assuming that R_s is independent of bias and that the initial capacitance is 10 times the minimum capacitance, a minimum Q of 1/10 the tabulated value is given. It is also necessary to consider signal level relative to the bias voltage for, if a diode is driven into conduction, the Q will drop and the effective capacitance will change.

In presenting data on ferroelectrics some manufacturers plot percent capacitance change vs bias, with temperature as a parameter and all curves starting at zero bias and 100% capacitance. This tends to give a misleading picture of the temperature characteristics. The ϵ-T-E surface in Fig. 5 is a more descriptive type of presentation.

5. CONCLUSIONS

In conclusion it should be reiterated that the tabulation is not exhaustive but merely representative. It would seem that a complete listing of all the available diodes which might possibly be used in reactance and other voltage-tunable devices would make the tabulation very unwieldy indeed.

In general, recommendation of a particular diode for a specific purpose was avoided, since it was considered likely that the reader might then be biased against using that diode for other applications. It is perhaps more beneficial to require the reader to study the characteristics and make his own choice for a particular application.



ε-T-E SURFACE

FOR AEROVOX "HQ"-91

FIG. 5

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