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FERROMAGNETIC AND FERROELECTRIC TUNING

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

Ferromagnetic and ferroelectric tuning are compared on the basis of presently known materials and techniques. Conclusions are based on present knowledge in two rapidly growing fields. In general, magnetic tuning appears more satisfactory on most counts below 50 mc, but at higher frequencies electric tuning has certain advantages. Such aspects as frequency stability, manufacturing problems and cost are considered in detail.

FERROMAGNETIC AND FERROELECTRIC TUNING

Foreword

This report attempts to make a critical comparison between methods of ferromagnetic and ferroelectric tuning. The comparison is based on present knowledge in two rapidly developing fields, and because it is impossible to predict properties of materials now in development, the conclusions drawn here must be regarded as subject to modification as new materials are developed.

At the present time, magnetic tuning appears generally more promising than ferroelectric tuning, except for certain features which are discussed in detail, but it must be recalled that magnetic tuning has been in development for five years or more and is consequently more advanced.

The ideal tuning element may be thought of as having such low loss that this may be neglected. Its tuning capabilities should extend to 1000 megacycles or better with little change in Q. It should have a zero temperature coeffecient of frequency from -50° C to 100° C. It should be small, compact and capable of large scale manufacture with only a small fraction of rejects. It should scan a frequency ratio of 10:1 or better with relatively small control power, and this requency ratio should not be reduced at the higher frequencies. The control power for rapid scan (up to 50 megacycles per microsecond) should not become excessive.

As usual the ideal does not exist, and it is highly unlikely that it will be developed within the next few years. Therefore the present choice for a particular tuning method and tuning material must be a compromise to obtain a close approach to the ideal in those properties most important for a specific application.

For the purpose of this report "ferromagnetic tuning" will be abbreviated to "magnetic tuning," and "ferroelectric tuning" to "electric tuning."

1. GENERAL REMARKS

1.1 Electronic Tuning

To add versatility and avoid mechanical difficulties, electronic control of the tuning of resonant circuits is desired for search receivers and other allied applications. Magnetic tuning uses the principle that the inductance in the resonant circuit can be varied by means of a magnetic bias field usually furnished by a variable current in a solenoid. Electric tuning uses the principle that the capacitance of the resonant circuit can be varied by an electric bias field usually furnished by a variable voltage. Both of these principles adapt themselves readily to electronic control.

1.2 Magnetic Tuning

In magnetic tuning, a special magnetic core material is used which has a wide variation of permeability with applied field. It is the selection of a suitable core material which determines the success of the device. A class of magnetic ferrospinels or ferrites have enjoyed prominence in this field because of their high resistivity and freedom from eddy current losses at high frequencies.

1.3 Electric Tuning

In electric tuning, advantage is taken of the ferroelectric property of certain dielectrics -- the dielectric constant changes as an electric field is applied. There is a variety of ceramics falling in this category, but most of the commercial capacitors available are in the barium-stronium titanate class. The choice of a particular dielectric material for electric tuning is generally a compromise, since very high dielectric constant, low temperature coefficient and low losses are very often mutually exclusive, as will be shown.

2. MATERIAL PROPERTIES

2.1 Properties of Ferrites

In comparing magnetic and electric tuning, we must first compare the corresponding properties of existing magnetic and ferroelectric materials. In considering the most important properties pertinent to magnetic tuning, we will confine our attention to the magnetic ferrites (ferrospinels). These materials have such high resistivities (10^3 to 10^9 ohm-cm.) that they have negligible eddy-current loss at all rf frequencies.

For the maximum tuning range, the largest possible change in permeability is desired. Regardless of the initial permeability, it is theoretically possible to obtain a permeability approaching unity by driving the specimen hard into magnetic saturation. Therefore one should first look for materials having a large initial permeability, μ_0.

The quantity actually concerned in magnetic tuning is the incremental permeability, μ_Δ. This is the permeability observed when the specimen is subject to combined ac and dc magnetic fields applied in the same direction. This is illustrated in Fig. 1. μ_Δ changes with both bias field H_o and ac field ΔH. A convenient way of presenting these variations is by means of a three dimension

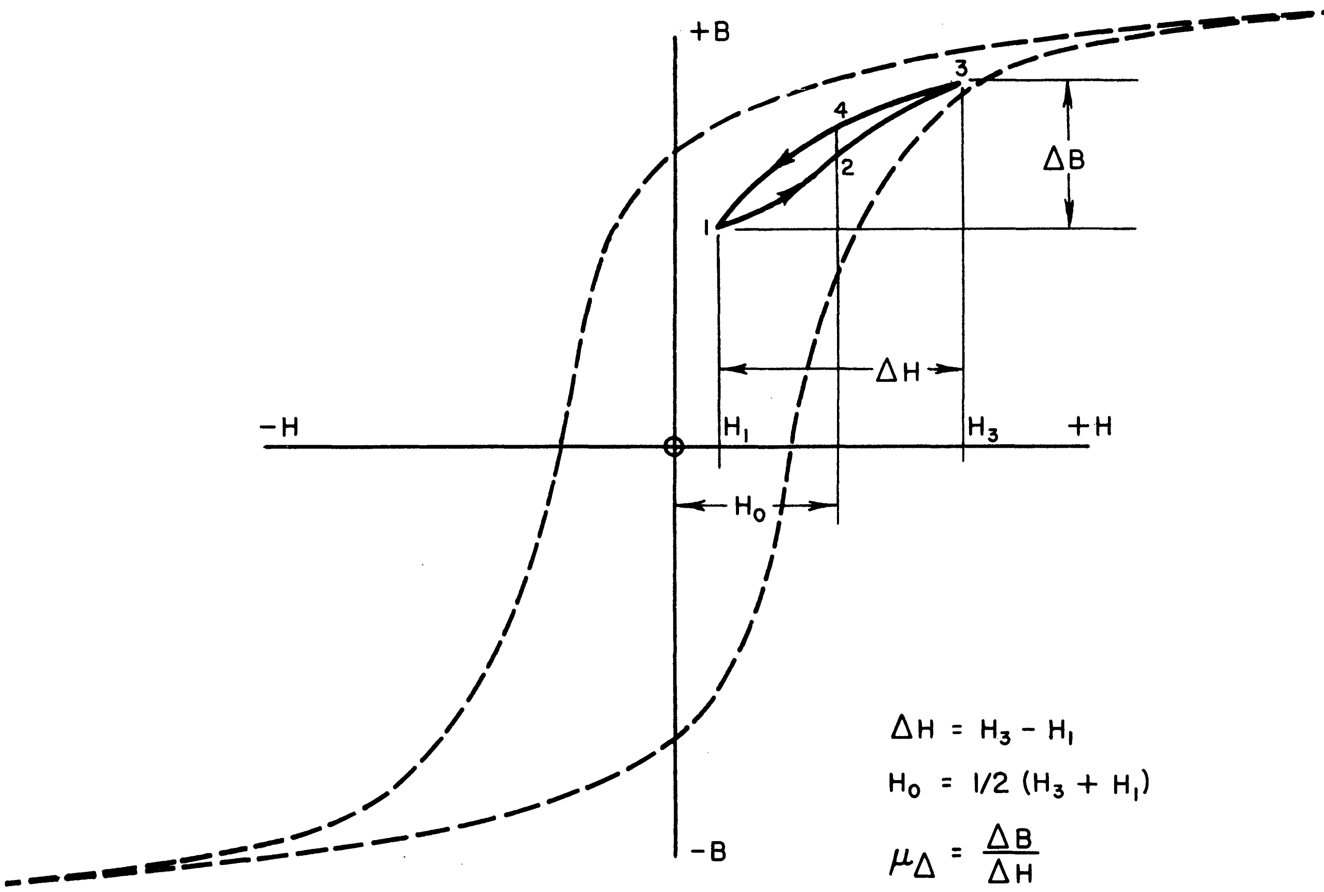

FIG. 1
DEFINITIONS OF MAGNETIC PARAMETERS

plot called a mu surface[1]. The mu surface for a typical ferrite is shown in Fig. 2.

The mu surfaces are very useful in comparing the properties of two ferrites in a particular application, such as a swept oscillator where both H_o and ΔH are expected to vary.

The permeability is also affected by a number of other, parameters such as temperature, frequency and magnetic history as previously reported[1].

2.2 Properties of Titanate Ceramics

The titanate ceramics may be considered as representative of materials suitable for electric tuning. Because of this and the fact that most of the available data is concerned with them, our attention will be confined to the titanate ceramics in the present report.

The important parameter in electric tuning is the dielectric constant, ϵ. This is the parameter corresponding to permeability in magnetic tuning. For the maximum tuning range, materials showing the largest change in ϵ with applied electric field E, are desired.

When a very large electric field is applied to a ferroelectric material it is driven into saturation or maximum polarization, but the theoretical limit of ϵ is not unity. This is because the dipole moment at saturation may still be increased by further increasing the electric field. In a practical situation however, the limit of E is generally determined by the electric breakdown field of the specimen. In addition, when both ac and dc electric fields are applied, thermal failure may occur at dc fields much lower than the ordinary dc electric breakdown field[2].

Corresponding to the mu-surface, a surface representation of ϵ

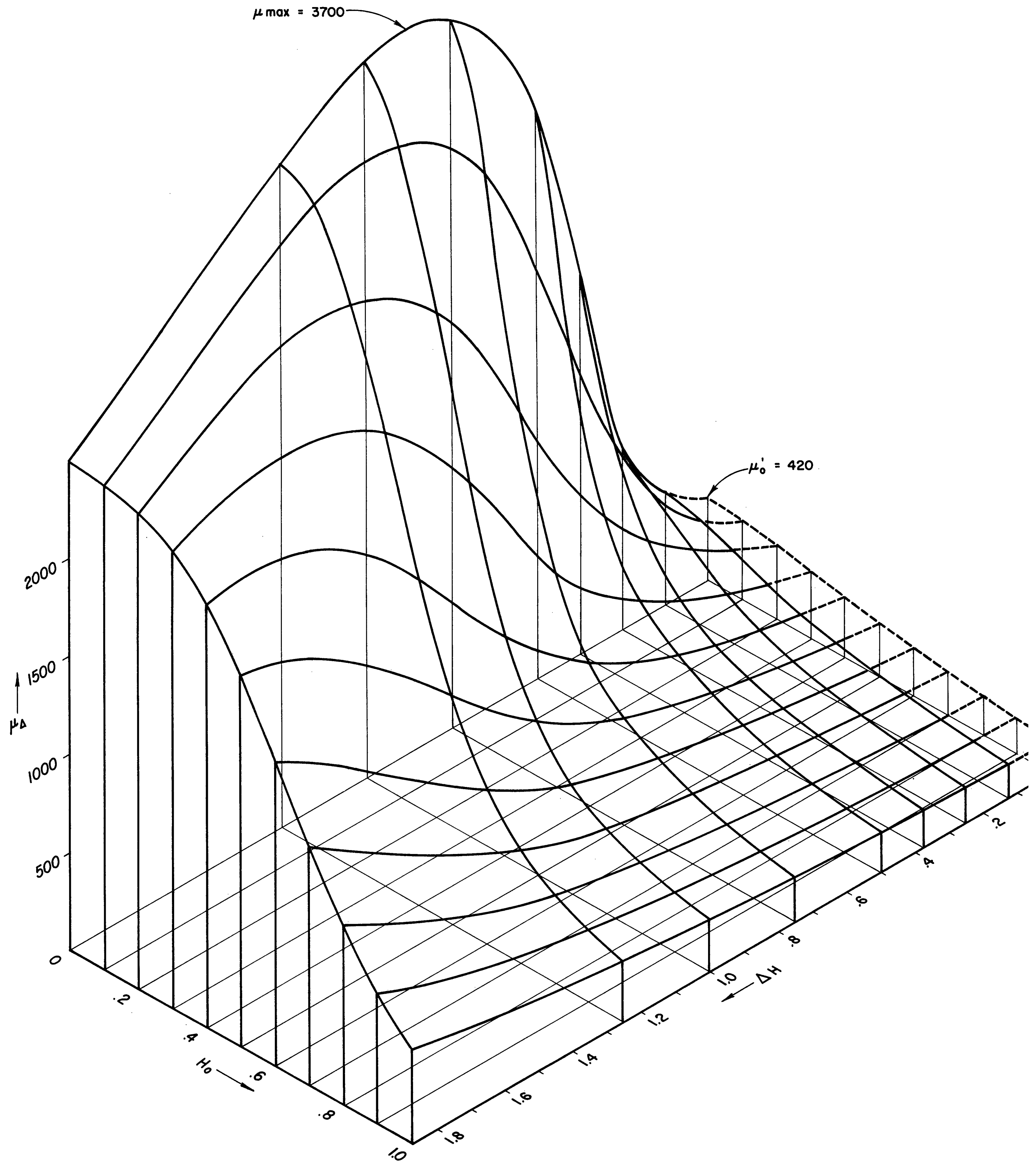

FIG. 2

MU SURFACE FOR FERRAMIC H.

may be used to show the variation with dc field E_o and ac field Δ E. A typical Epsilon surface is shown in Fig. 3. It is noted that the variation in ϵ with ΔE is not nearly as great as for the corresponding variation of μ_Δ with ΔH.

Although it is possible to design ceramic materials with very small or even zero temperature coefficient of ϵ over a wide temperature range[3], such materials are not particularly field-sensitive, and hence not suitable for electric tuning. Titanate ceramics in general exhibit a wide variation of ϵ with temperature and dc field. This variation is conveniently presented by a three dimensional Epsilon-Temperature surface[4]. A representative surface of this type is shown in Fig. 4. The point of maximum capacitance at each value of field is indicated by a small circle on the figure. These points show that as the dc field is increased, the point of maximum capacitance (i.e. zero temperature coefficient) shifts to a higher temperature. This Curie shift[5,6] is an important factor to consider in the design of electric tuning units.

2.3 Comparison of Properties

A graphic comparison of the properties of ferrites and titanates is given in Fig. 5. Fig. 5A indicates the typical properties of a high-mu ferrite. Note that there is the desired large change in μ with a relatively small change in magnetic field H, but that this is offset usually by a large temperature coefficent of μ_o and some variation of μ_o with frequency up to the useful limit f_c where the losses become excessive. A great improvement in temperature coefficient of μ_o may be made by special composition low-mu ferrites[7,8] as in B. However it is found that a much smaller tuning range is possible because of the low sensitivity of μ to bias field H. Although the useful frequency limit f_c may be larger than in A, the losses are usually larger at all frequencies below f_c which is undesirable. Because of longer and more extensive research in ferrite

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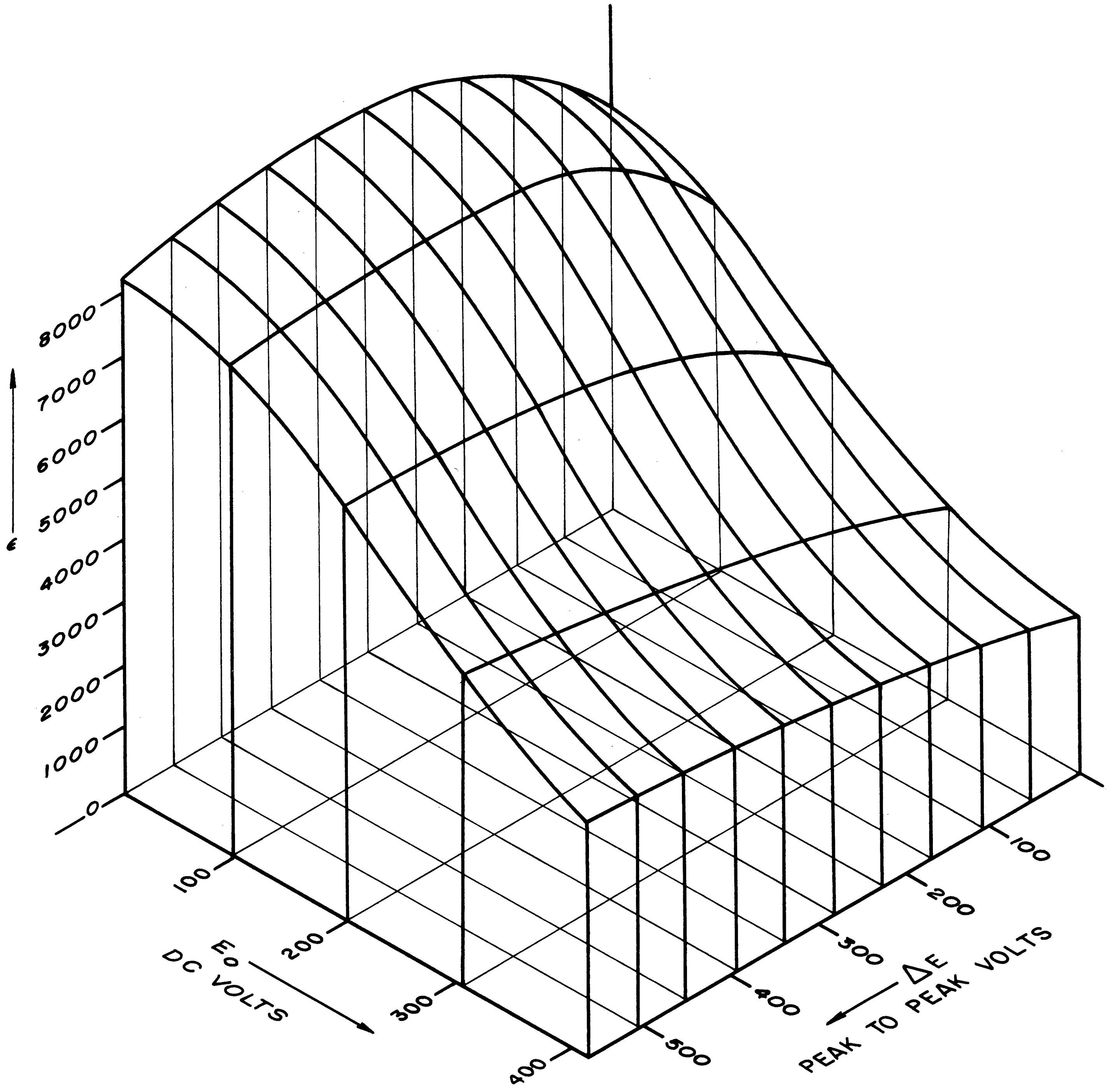

FIG. 3

EPSILON SURFACE FOR AEROVOX "HI-Q"
BODY 40 AT 26°C.

SPECIMEN THICKNESS = 0.02 INCH .

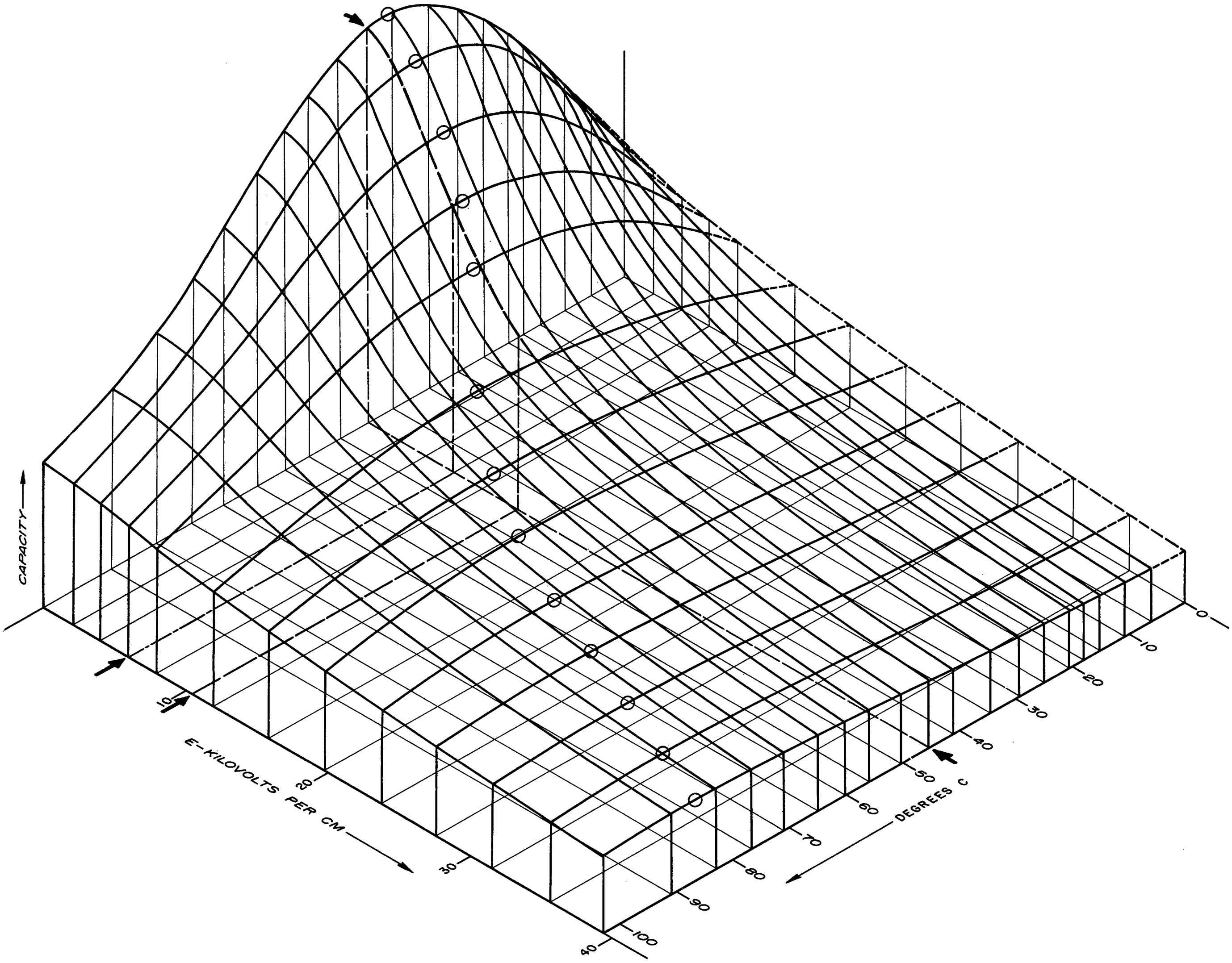

FIG. 4

EPSILON-TEMPERATURE SURFACE
FOR AEROVOX HI-Q 41.

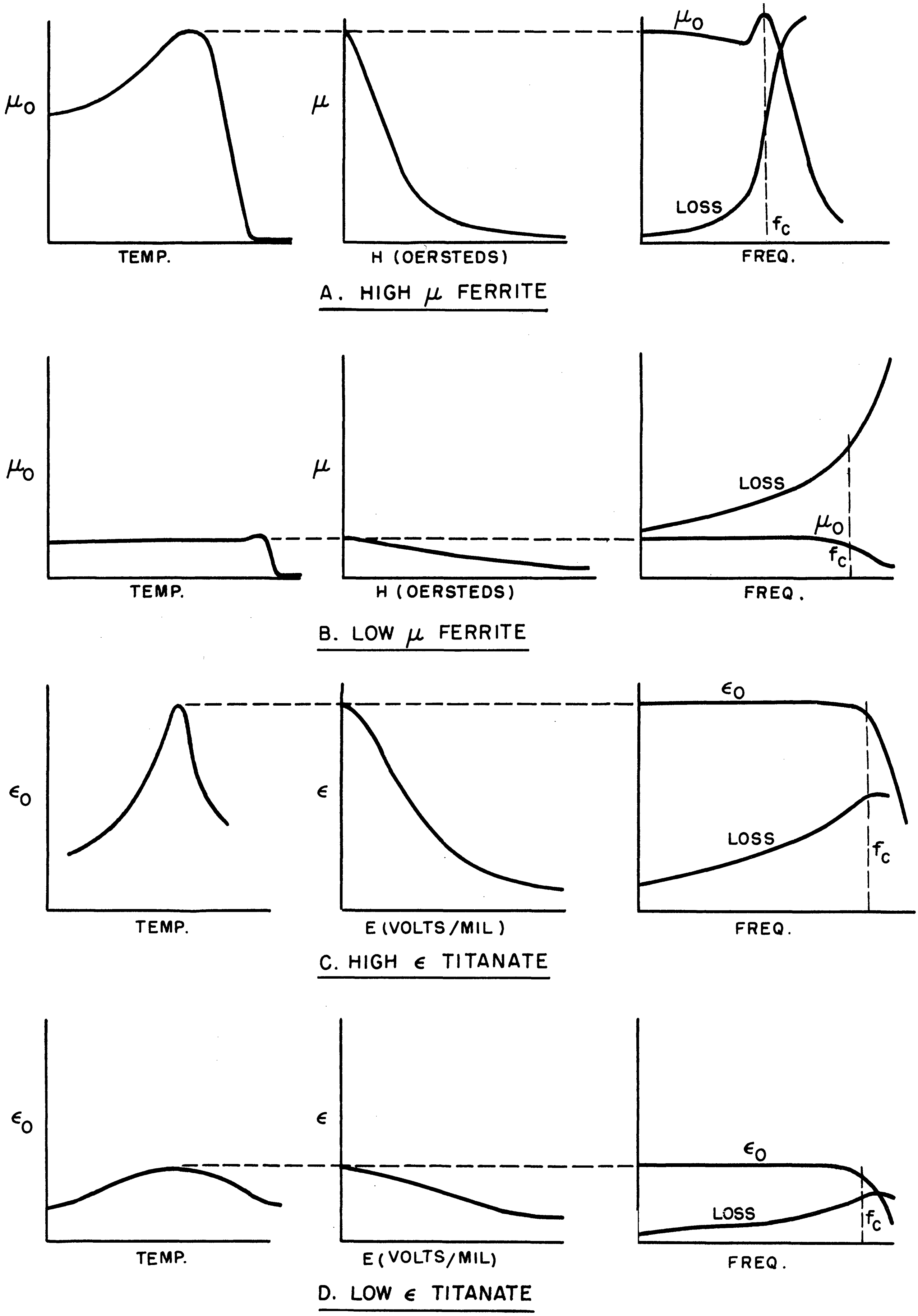

FIG. 5. COMPARISON OF PROPERTIES.

tuning units, it has been possible to make a fairly good compromise between temperature sensitivity, and tuning ratio (See Section 3.3 below).

The corresponding curves for a titanate ceramic are shown in C and D. The high-ϵ titanate in C has a large field sensitivity but the temperature variation is even worse than in A. However ϵ_o stays reasonably constant with frequency up to the useful limit f_c which is generally a few hundred megacycles for both C and D. The temperature sensitivity is improved in D but at a cost of smaller field sensitivity. However in this case the losses are lowered from C to D instead of increased as was the case from A to B.

Fig. 5 illustrates the situation in a general way, and indicates the sort of compromises which must be made. However this does not demonstrate certain other considerations which must be dealt with in detail. It also does not bring out the important point that the specialized materials now being developed may greatly alleviate the situation.

Because the demands of magnetic tuning have been felt over a period of several years, there has been considerable attention to the development of ferrite materials having <u>large</u> field sensitivities in conjunction with other desirable properties. On the other hand, the main trend in titanate ceramic development over the past few years has been to <u>reduce</u> the field sensitivity. This is highly desirable for the producer of linear capacitors, since it permits him to assign larger dc voltage ratings without reducing the GMV* capacitance, but not at all helpful to the designer of electric tuning units.

However it is safe to say that at present there is no ideal material for either electric or magnetic tuning. There is also no one material which represents the best compromise for all frequency ranges.

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*GMV = Guaranteed minimum value

3. COMPARISON OF MAGNETIC AND ELECTRIC TUNING

3.1 Manufacturing Problems

A major problem in tuning unit manufacture is that of obtaining a supply of ferrite cores or titanate capacitors with uniform and consistant properties. Because magnetic tuning is farther advanced, ferrite property tolerences for a particular application have become quite rigid, and more is known about the sort of difficulties which arise.

In particular, a ferrite core material chosen for a specific application in magnetic tuning tends to vary from batch to batch and from month to month. The ferrite manufacturer in turn has a difficult problem in control of raw materials -- even small differences in the purity of the raw oxides have a profound effect in the variations of product properties. These also vary between individual cores of the same batch unless core production is in unusually good control. A consequence of this second variation is that the tuning unit assembly plant has a difficult core-pair matching problem, and a large wastage or shrinkage due to unusable cores.

No such severe problem is encountered in the production of titanate capacitors because of two facts. The first fact is that present-day quality control of titanate ceramic production is quite good. The second is that titanate property tolerances for electric tuning are not as severe as for magnetic tuning. There is nothing corresponding to the core-pair matching problem in the construction of electric tuning units, since an exact capacitor-pair match is not essential to the electric tuning unit.

For search receivers, the required tracking of the various tuned circuits creates a tracking problem which imposes further tolerance requirements on tuning units. For a particular search receiver, the wastage of magnetic tuning units which fall outside tolerance is serious because of the limited market for such specialized units. In the case of electric tuning, however, ferroelectric capacitors which fall outside tolerance for tracking requirements can be diverted to a large number of other uses, and thus do not represent a loss to the manufacturer.

Unique to electric tuning is the problem encountered when the dielectric is made very thin. (A thin dielectric is desirable for electric tuning as discussed in Section 3.6 below.) It is more difficult to produce thin sheets of titanate dielectric having apparent homogenious properties. This is because the effect of small, local impurities in thin specimens is very noticeable -- even tending to produce electric breakdown in some cases. In thicker specimens, the effect of small, local impurities is masked by the larger volume of surrounding homogenious material.

3.2 Cost

A magnetic tuned resonant circuit consists of a variable inductance element and a fixed capacitance element. The major expense is in the former. First the ferrite cores must be manufactured, sorted and selected. The tuning unit may consist either of two matched cores, or of a single core with special machining. There is therefore the cost of machining, which is large for ferrite materials, or of core matching, which involves semi-skilled labor plus the resulting shrinkage mentioned above. To this must be added the cost of winding, handling, assembling, and final testing. It is clear that the final cost of the resonant circuit is considerable.

An electric tuned resonant circuit consists of a fixed inductance and two variable capacity elements, plus an inexpensive isolating element such as a resistor or rf choke. Here the cost is approximately equally divided between the inductance and the capacitors. In the manufacture of the capacitors, large sheets of the dielectric may be made at a time and sliced down to size. Electrodes are plated on and electrode wires attached. The capacitors are then coated with a resin covering by dipping. Finally, the finished capacitors are usually sorted on semi-automatic testing bridges, so that the final product for use in tuning units may be held within tolerance. In addition, the rejects may be sold as by-pass capacitors not requiring the tight tolerance. The total cost of a finished electric tuned resonant circuit is therefore considerably less than the corresponding magnetic tuned circuit. Although actual manufacturing costs are not available at present, it is estimated that the cost of an electric tuned resonant circuit is from 3 to 8 per cent of the cost of a corresponding magnetic tuned resonant circuit.

3.3 Temperature Stability

Magnetic tuning units are now being produced with very good temperature stability[9]. Fig. 6, reproduced from the reference article, shows the tuning temperature curves for an Increductor in a resonant circuit operating between 28 and 55 megacycles. When the control current is 10 ma, the temperature coefficient of frequency is approximately zero over a wide temperature range (-40°C to +80°C).

Electric tuning, to give the same frequency ratio, must employ ferroelectric capacitors capable of at least 4:1 capacity variation. Presently available titanate capacitors in this class have relatively poor temperature stability. For comparison with Fig. 6, the predicted Tuning Temperature curves for

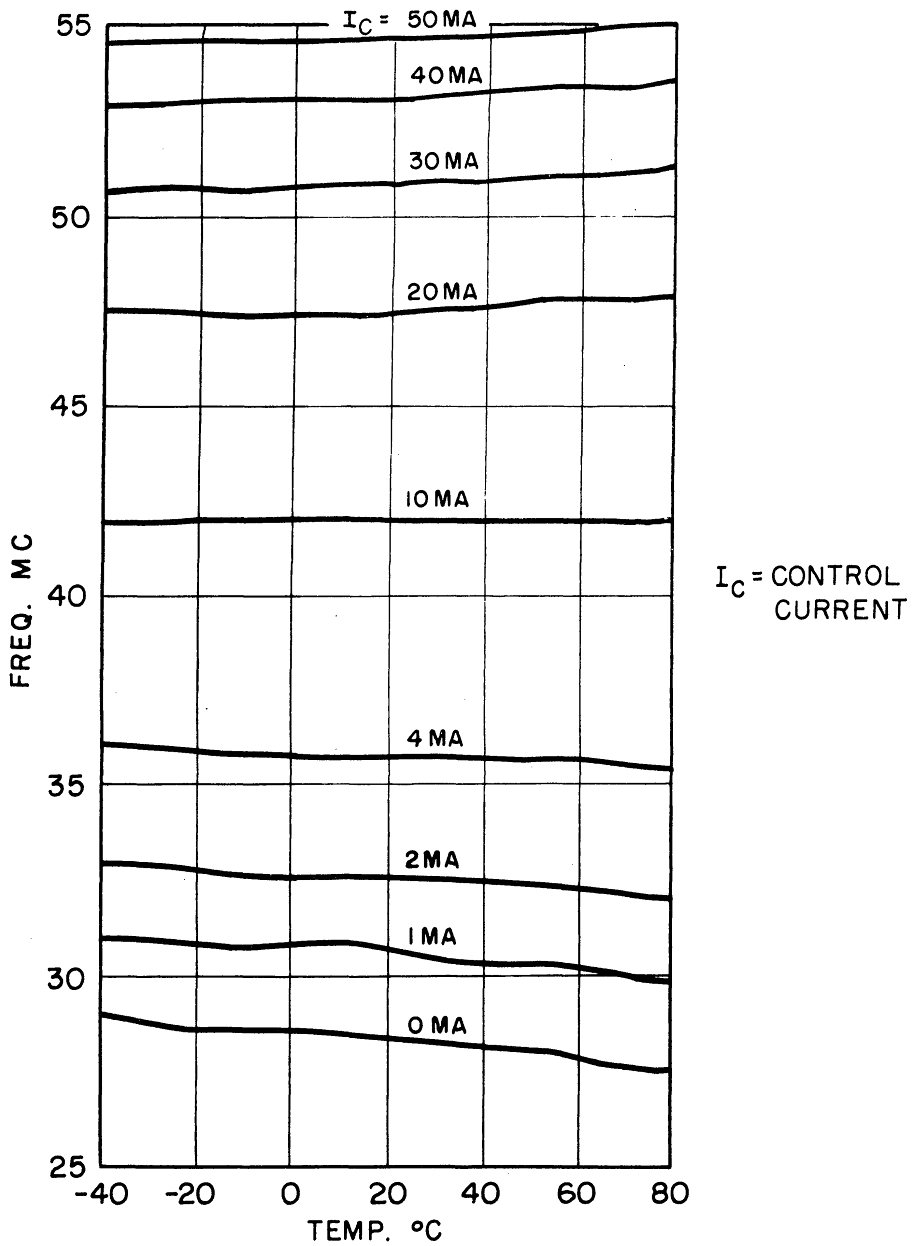

FIG. 6

INCREDUCTOR TUNING TEMPERATURE CURVES.

an oscillator using Aerovox Hi-Q 41 20 mil Capacitors as the variable elements are shown in Fig. 7. These curves are plots of the ratio $(\epsilon_{max}/\epsilon)^{1/2}$, which is proportional to oscillator frequency, using the same data as for Fig. 4 ϵ_{max} occurs at 41° C and zero electric field.

It should be mentioned that Aerovox Hi-Q 41 does not necessarily represent the "best" material available, but as the curves show, a frequency ratio of 2.4 is possible with the temperature stabilized at 40° C, and a control voltage varying from zero to 2000 volts.

It is clear from the curves that there is no value of control voltage that gives a zero temperature coefficient over a wide temperature range as was observed in Fig. 6. The design of an oscillator using electric tuning which must operate over a wide range of ambient temperatures must therefore include temperature control of the capacitors. This is not a serious problem however, because of the very small volume occupied by the capacitors. It is not difficult to build a capacitor tuning unit and a low-watt thermostat-controlled heater in a miniature oven having a volume of 0.1 cubic inch.

3.4 Time Relaxation Phenomena

Time relaxation effects are exhibited by both ferrites and titanate ceramics. In the case of ferrites a time decrease of permeability is observed after a ferrite core is subject to a degaussing treatment. When used as a tuning element in a low power oscillator, this effect can cause up to 3.8 per cent increase in frequency in Ferramic G over a period of several hours[1]. This effect was reported by Snoek[10] in 1947, and is variable from one material to another. In general, those materials showing a large change in μ_Δ with applied H, have also a relatively large relaxation effect.

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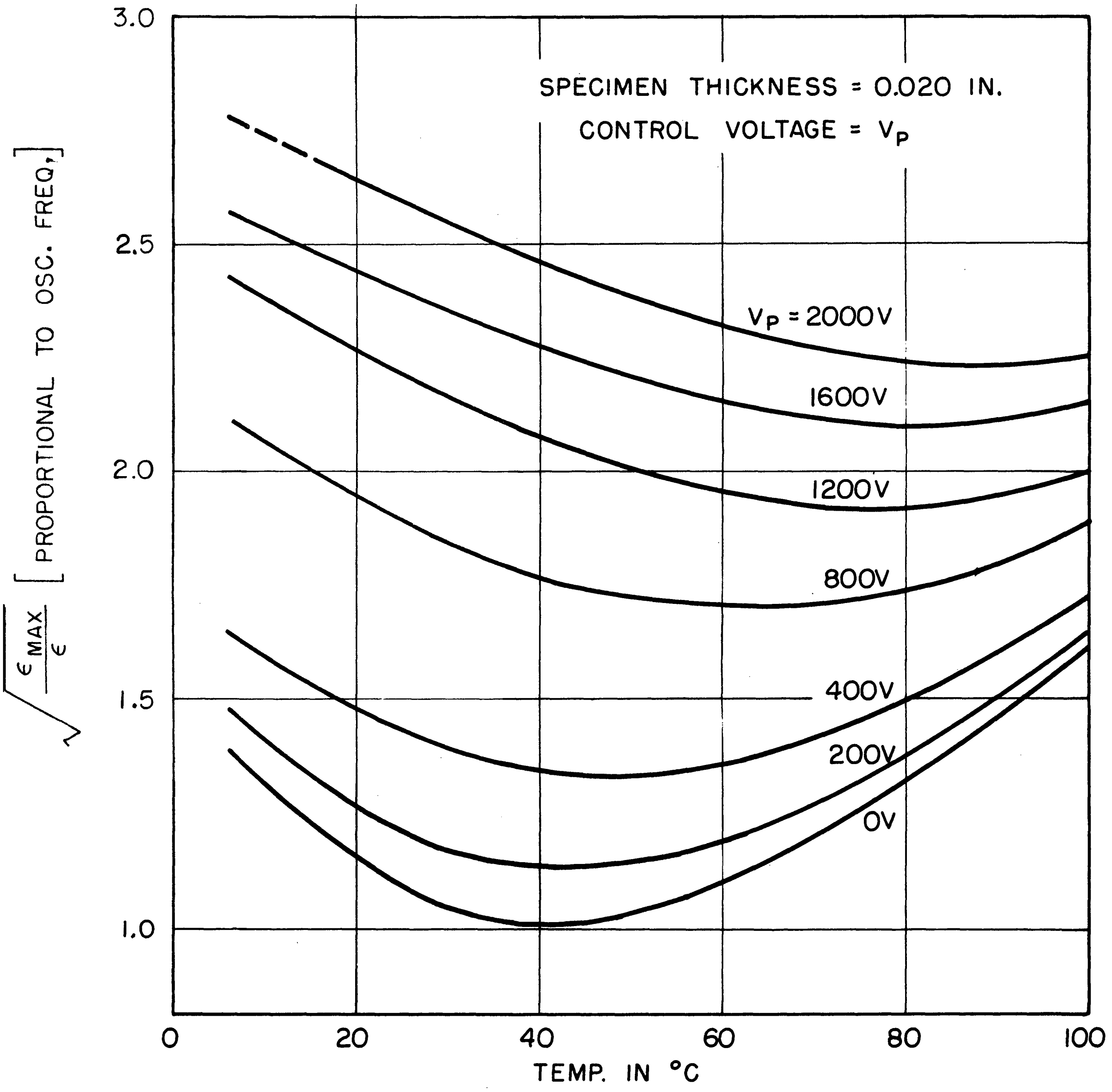


FIG. 7

AEROVOX HI-Q 41 TEMPERATURE CURVES.

A similar relaxation effect is noted in titanate ceramics, although this doe not correspond exactly to the effect just described. If an electric field is applied to a specimen of titanate ceramic for a period of several minutes and then suddenly removed, the dielectric constant increases first abruptly and then slowly with time. When such a ceramic is used as a tuning element in a low power-oscillator, the frequency drops abruptly at the time the field is removed. This is followed by a relatively slow decrease in frequency[11]. The frequency drift substantially ceases after a period of 5 to 30 minutes, depending on the material In this respect the effect is shorter-lived than the corresponding magnetic relax ation. In general, the longer period is associated with materials which show a large change in ϵ_Δ with applied electric field, such as Centralab K 7000[6].

In a swept receiver applications, the consequences of these effects are as follows:

A. Reduction of Tuning Range. When swept at 60 cycles or faster, the tuning range will be smaller by several per cent than it is with manual, arbitrarily slow tuning.

B. Frequency drift. If the amplitude of frequency sweep is reduced, or stopped altogether, there will be a slow frequency drift. The drift will probabl be small in both magnetic and electric tuning, but is shorter-lived in the case of electric tuning.

C. Sweep waveform. If a sawtooth sweep is employed, it is more satisfactory for electric tuning to use a jump-rise, slow decay wave than a jump-drop, slow-rise waveform. The reason for this is that the ferroelectric ceramic responds more quickly to a jump-rise step-function of voltage than to a jump-drop step-function[11]. A consequence of this is that the ferroelectric-tuned unit is best used to sweep downward in frequency, starting at the highest frequency and sweeping to the lowest.

In magnetic tuning, the frequency may be swept in either direction but there is some slight preference for sweeping upwards in frequency because of circuit considerations. This mode of sweeping requires a slow rise and abrupt drop in control current. Because the control tube may be rapidly cut off, permitting a high inductive kick from the control winding, the flyback time may be made somewhat shorter than in the other mode.

3.5 Frequency Range and Tuning Ratio

The frequency ratio is the ratio of upper to lower frequency of a swept oscillator or amplifier. It is desired that this be as large as possible so a relatively small number of receiver units may cover the entire communications rf spectrum. In both magnetic and electric tuning it is increasingly difficult to obtain large frequency ratios as the starting frequency becomes higher. Tables 1 and 2 indicate representative frequency ranges and ratios for increductor-tuned and ferroelectric-tuned oscillators.

In the frequency ranges below 10 mc, magnetic tuning gives much larger tuning ratios than are possible with electric tuning. Magnetic tuning offers ratios of 10:1 or better up to 30 mc. For starting frequencies in excess of 30 mc, magnetic tuning gives ratios of 2:1 or less, and electric tuning can compete in this frequency range. At a starting frequency of 50 mc electric tuning gives a tuning ratio of 2:1 which is superior to that available with magnetic tuning.

The theoretical limit for magnetic tuning is set by the ferromagnetic resonance phenomenon. This phenomenon occurs in ferrites at some frequency between 500 and 3500 mc. Because of the fact that materials having adequately low losses at very high frequencies have a rather small field sensitivity, the

TABLE 1

MAGNETIC TUNED OSCILLATORS[12]

Maximum Frequency Range	Frequency Ratio	Oscillator Type
15 kc -- 2 mc	130	Wien Bridge
0.2 mc -- 2 mc	10	Tuned L C Type
3 mc -- 30 mc	10	"
20 mc -- 60 mc	3	"
75 mc -- 95 mc	1.27	"
100 mc	1.1 to 1.3	"
200 mc -- 210 mc	1.05	"

Table 2

ELECTRIC TUNED HF OSCILLATORS[5,6]

*Observed Frequency Range mc	Frequency Ratio	Oscillator Type	Applied control field volts/mil
50 -- 100	2.0	Hartley	0 -- 100
95 -- 115	1.21	Push-pull	0 -- 60
110 -- 140	1.27	Colpitts	0 -- 60
135 -- 160	1.18	Push-pull	10 -- 60
365 -- 375	1.03	Ultra-audion	0 -- 60

*These figures do not necessarily represent the maximum range, but represent behavior of oscillators which have been constructed in the laboratory.

tuning ratio is considerably reduced as the top frequency is raised, as indicated in Table 1. Increductor-tuned oscillator units[9] have been operated at frequencies in excess of 300 mc.

The top frequency for dielectric tuning is limited by piezoelectric resonance phenomena and increased losses at high frequencies, but the ultimate theoretical limit is determined by a ferroelectric resonance which appears somewhat above 1000 mc. A major problem in the design of very-high-frequency power oscillators using electric tuning is that of heat removal from the dielectric.

Development work is now in progress on high frequency electric tuned oscillators at the University of Michigan, and results on bread board models are shown in Table 2. Satisfactory operation up to 375 mc has been achieved in one experimental model using the Ultra-audion circuit[5,6].

Because of the increase in losses with frequency, the Swept Oscillator has a higher frequency limit than the Swept rf Amplifier. This is due to the fact that a low impedance tube may be used to furnish tank losses in the Oscillator, whereas such losses would be excessive for satisfactory rf amplifier operation. This consideration applies to both magnetic and electric tuning. The present practical limit of frequency for magnetic tuning is of the order of 100 mc for amplifiers, and 300 mc for oscillators.

An interesting development in wide band swept oscillators has recently been released by the Kollsman Instrument Company, Elmhurst, New York. Their Type 2144 Wide range Sweep Generator will presently be available in three ranges: (a) 225 to 420 mc, (b) 470 to 890 mc, and (c) 850 to 1275 mc. The output is 10 mw from a 50 ohm source impedance, and the full range is swept at a 60 cycle rate with ± 1 db variation in output. The actual circuit has not been released.

3.6 Scanning Rates

Magnetic tuning is accomplished by varying the dc magnetic control field in a magnetic tuning unit, Fig. 8A. This is done by varying the current in a control winding, and electronic means must be provided to furnish the required variable current i. To obtain sufficient maximum magnetic field at a reasonable control current, a large number of turns is required on the control winding. This generally results in a control inductance of several henries. If L is the inductance of the control winding, the electronic means must furnish a voltage L di/dt to produce the desired rate of change of current.

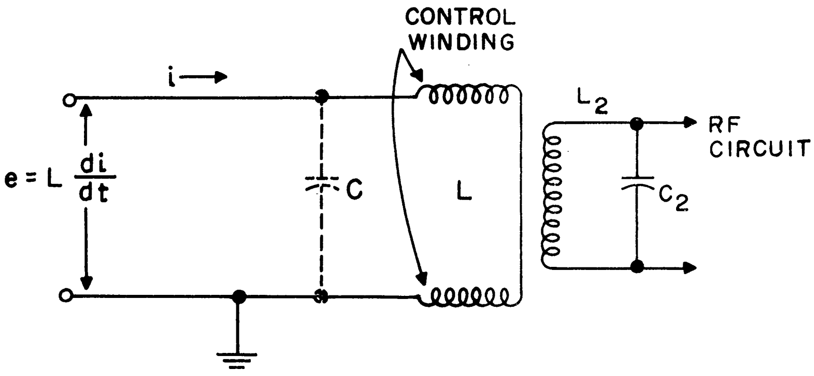
Electric tuning is accomplished by varying the dc electric field in the titanate tuning capacitors, Fig. 8B. Electronic means must be furnished to do this by changing the voltage e. To obtain sufficient maximum electric field at a reasonable voltage the dielectric in the tuning capacitors is made thin. If C is the effective capacity in the control circuit (generally four times the rf resonating capacity), the electronic means must furnish a charging current of C de/dt to produce the desired rate of change of electric field.

With relatively low scanning rates (i.e. 60 cycles) there is no serious problem in furnishing the electronic means for either magnetic or electric tuning. When the scanning rate is increased, the control circuit design problems become more difficult. For high scanning rates a short "flyback" or return time, say on the order of one microsecond, is desired. This presents a rather severe problem in magnetic tuning as illustrated by the following example:

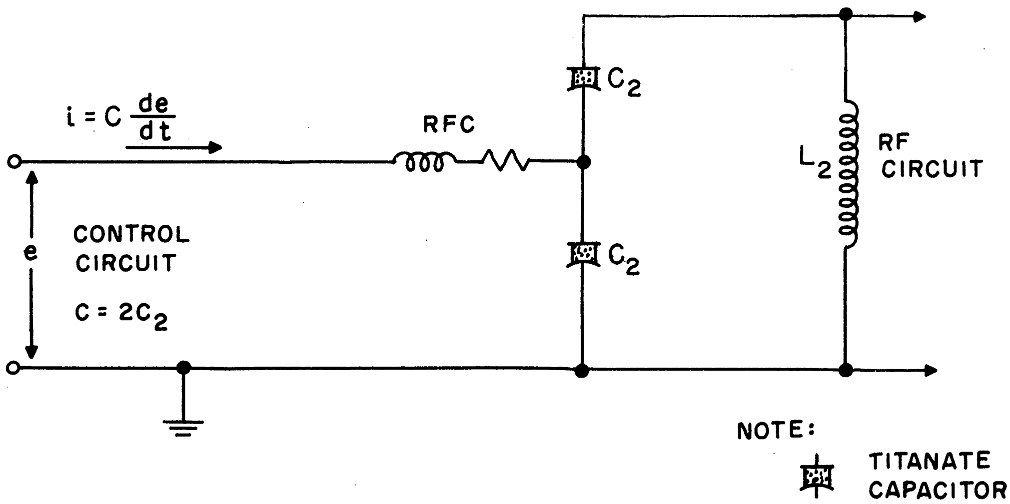
A rapid scan magnetic tuning unit tunes from 50 to 100 mc signal frequency and has the following properties:

Control Inductance = 2.0 henries

Control Current = 50 ma (max.)



A. MAGNETIC TUNING UNIT



B. ELECTRIC TUNING UNIT

FIG. 8

TUNING UNITS.

For a flyback time of 1.0 microsecond, the flyback voltage is found to be

$$L \frac{di}{dt} = 2.0 \times .05 \times 10^6 = 100{,}000 \text{ volts.}$$

This serves to illustrate the seriousness of the problem not only in control circuit design, but also in voltage insulation in the design of the control winding itself.

In order to improve the situation, we first note that the magnetic field is proportional to the number of ampere turns NI. The inductance of the control winding is proportional to N^2, so the flyback voltage may be reduced at the expense of a larger control current i.

Let us re-examine the calculation just made if N is reduced by a factor of 10. We then have a unit which has the following control constants:

Control Inductance = 0.02 henries

Control Current = 500 ma (max.) (For same NI max)

For a flyback time of 1.0 microsecond the flyback voltage is found to be

$$L \frac{di}{dt} = 0.02 \times .5 \times 10^6 = 10{,}000 \text{ volts.}$$

Thus an improvement is acheived in flyback voltage, but at a price of increased control current maximum, which imposes a difficult control circuit design problem

There is another serious effect in flyback with magnetic tuning. The control inductance resonates with its self capacity C in Fig. 8A, and generates a serious flyback transient if not properly damped. Since it is highly desirabl to use pentodes for the control circuit because of their constant current property, an additional damping circuit is generally required for rapid flyback to suppress the flyback transient.

A corresponding example of rapid scan electric tuning is a unit tuning from 50 to 100 mc signal frequency with the following properties:

Capacitance in control circuit = 200 uuf.

Control Voltage Swing = 500 volts (max.)

For a 1.0 microsecond flyback time, the flyback current is found to be

$$C \frac{de}{dt} = 200 \times 10^{-12} \times 500 \times 10^{6} = 0.1 \text{ ampere.}$$

This flyback current may be easily obtained from a conventional vacuum tube, so the design problem is reasonably simple. Even faster flyback times are possible by using thyratrons.

There is also no problem of flyback transients with electric tuning. It is true that the stray circuit inductance might tend to resonate with the control circuit capacity, however this is easily damped. A series resistor is generally present for isolation puropses, so that no additional damping is required.

There are thus a number of definite advantages in electric tuning for rapid scan applications. It may also be noted that as the signal frequency is increased, the control capacity C generally decreases. In this case it is seen that faster flyback times are possible at higher signal frequencies without increasing the flyback current pulse. This is not the case in magnetic tuning where the control inductance does not decrease as the signal frequency is increased.

3.7 Very Rapid Scan Systems

Scanning search receivers at very rapid rates, such as 50 megacycles per microsecond, has been shown to have certain unique properties[13] which may be desirable for particular services. At present it is not known how valuable such systems will be, but their investigation is important.

Scanning at 50 megacycles per microsecond may be performed if it is possible to scan continuously the units given as examples in Section 3.6 at their flyback rates. In this case a triangular wave of 500 kc and the proper amplitude might be used.

From the preceeding discussion it is clear that electric tuning might be used at these rates, but that magnetic tuning is unsuitable.

4. CONCLUSIONS

In performance, magnetic tuning is generally more advanced and therefore more satisfactory than electric tuning in a large number of categories. The category in which electric tuning is definitely superior is that of rapid scan. Here magnetic tuning is restricted to scanning rates which are low compared to those possible with electric tuning.

In cost, electric tuning is extremely attractive, and as a rough estimate is between 3 and 8 per cent of the corresponding cost of magnetic tuning. The cost of electric tuning may be decreased even further if production methods and printed circuits are employed.

The chief difficulty with electric tuning at present is that of obtaining a large tuning ratio together with low temperature sensitivity. But it is possible that a combination of new materials and techniques may solve this difficulty as electric tuning becomes further advanced.

These conclusions are based on presently known materials and techniques in two rapidly growing fields, and therefore represent the situation only as it appears at the present time.

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