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Health Physics Division

DETECTION AND TELEMETERING OF IONIZING RADIATION BY FREQUENCY VARIATION

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I. INTRODUCTION

The project described has two major objectives: (1) the detection of ionizing radiation and (2) the transmission of the information by radio frequency to the monitoring station. These requirements shall be satisfied by the same operation and equipment.

The first requirement can be fulfilled in many ways: With an electrometer, ion chamber or extrapolation chamber, Geiger counter, or crystal detector. These instruments may be connected with the proper electronic, optical or acoustical instrumentation.

Ordinarily, the transmission of the intelligence requires an elaborate system to impress the information on the transmitting equipment, as reactance tubes, pulse generators, amplifiers, depending whether F.M., A.M., or pulse modulation shall be applied.

All the methods described below make use of the frequency variation of a R.F. generator. This variation was effected by changing the value of a reactance component incorporated in the frequency determining network. This reactance change can be produced by the ionization current of an ion chamber or by the pulse current of a counter. The transmitted radio signal could be received at any distance, depending only on the power of the transmitter. At the receiver side a quartz crystal standard produces a constant frequency, close to that of the received signal. The difference or beat frequency of the standard and transmitted signals was usually in the audio range and could be observed on an oscilloscope by means of an interpolation oscillator when the interpolation oscillator output was applied to one pair of deflecting plates and the beat frequency to the other one. However, any other way of audio

frequency detection can be applied, as will be discussed later.

The variation of the R.F. generator frequency due to ionizing radiation can be observed and this frequency variation can be plotted against the dose rate.

Any detection and telemetering of ionizing radiation has to satisfy certain conditions: (1) the transmitter frequency has to remain constant in the absence of ionizing radiation, and (2) the radiation shall produce a signal large enough to be easily observable.

The first condition is the most difficult one to fulfill. Further desirable features are: low power consumption, stability against mechanical vibrations, and no frequency drift due to temperature variation.

The first method to be discussed requires a vibration and shock-free position. The other methods discussed do not have this limitation.

II. RADIATION DETECTION BY REACTANCE VARIATION OF AN ELECTROMETER WITH A MOVABLE VANE

A. Design

An ionization chamber (Fig. 1) included an electrometer section with a movable vane. The movable vane is suspended by means of a silverplated quartz fiber as shown in Fig. 1. The capacitance between the electrode pairs has a maximum when the vane position is in the direction of the electrode pairs. The frequency is determined by the inductance L_1 the capacitances C_1 and C_2 and the capacitance of the electrometer system. When the vane is charged electrically and ionizing radiation enters the chamber, the vane loses its charge and turns out of the space between the two electrode pairs. This change of position decreases the effective capacitance and increases the frequency of the oscillator. When the ionization chamber is connected

as shown in Fig. 2a the capacitances - first electrode pair - vane - second electrode pair are in series for the R.F. circuit, (Fig. 2b - "R.F. Equivalent Circuit.") Electrostatically, however, the two capacitances are in parallel since both electrodes are on D.C. ground potential. The resultant R.F. capacitance is about $1 \mu\text{F}$, the electrostatic one about 4-5 μF .

If the vane is just outside of the space between the electrode pairs and an electrical voltage is applied to the electrode 1, while the two electrode pairs are electrostatically grounded, the vane will turn against the torsion force of the quartz fiber into the space between the two electrode pairs, and, therefore, increase the capacitance of the system. The maximum capacitances between the vane and each electrode pair amounted to about 2 μF .

The R.F. circuit in Fig. 2a provides a high stability, since the parallel capacitance between grid and cathode is approximately 1000 μF and eliminates the effect of grid-cathode capacitance fluctuations.

The increase of R.F. capacitance A.C. produces a frequency increase $\Delta F = \frac{\Delta C}{2C_T} F_0$, where F_0 is the operating frequency and C_T the total frequency controlling capacitance. For an optimum condition, C_T should remain as small as possible.

The total range of frequency variation at a center frequency of 2.3 MC amounted to about 10,000 - 20,000 cycles. By measuring at the 3rd harmonic this range can be tripled but the mechanical conditions impose a practical limit to the sensitivity.

B. Experimental Results

An aluminum ion chamber contained a volume of about 100 cm^3 air under normal pressure. A window of 25 cm^2 of .001 inch copper foil permitted practically all gamma radiation and hard beta particles to enter the chamber. The electrode 1 was charged to about 300 V. 1.58 mr/hr Ra gamma produced a frequency variation of 35 cycles/sec during an exposure of one minute. The saturation current is about 1.75×10^{-14} Amp for 100 cm^3 at this dose rate.

When the copper window was replaced by polyethelene, fast neutrons could be measured by means of recoil protons, taking into account the gamma and X-ray radiation by a preceding measurement with the copper window in place. 1.57×10^6 fast neutrons from a Polonium-Beryllium source entering the polyethelene gave a frequency variation of 15 cycles/sec when exposed one minute.

The operation requires a minimum leakage of the charge when not exposed to radiation. The use of polyethelene or teflon for suspension of the quartz fiber and moving vane reduces the leakage so that the frequency drift amounts to only a few cycles/hour.

In a later model or modification a quartz, crystal-controlled oscillator was used for better frequency stabilization. The fundamental frequency was 5 MC (Fig. 3a), but the frequency was multiplied to 15 MC in the plate circuit of the second tube 12-AT-7. The frequency can be varied within a range determined by the ratio of the electro-mechanical equivalent capacitance C to the parallel capacitance C_0 , both shown in the equivalent quartz crystal circuit, Fig. 3b. By adding an inductance in series to the quartz crystal, this range can be extended, but some of the control is sacrificed.

Quartz crystal control was applied in all subsequent designs.

The method described has a relative high sensitivity, but suffers from the necessity of eliminating all vibrations. Better design might overcome this disadvantage. A still higher degree of charge leakage reduction would also be desirable.

III. DETECTION OF IONIZING RADIATION BY FREQUENCY VARIATION USING THE FERROELECTRIC EFFECT

A. Ionization Chamber

a. Apparatus: The elimination of movable parts can be effected by the replacement of the electrometer section with a non-linear capacitance. Non-linear capacitances can be constructed by the use of ferroelectric materials. These materials, particularly bariumtitanate, have very high dielectric constants that are functions of the applied electrical field.¹ Bariumtitanate was used in all the designs described below. This material has a dielectric constant of about 6000 at 25° C. A major disadvantage is the dependance of the dielectric constant on the temperature. Therefore, a thermostatic control is required if the ambient temperature varies. Later developments have produced combinations of bariumtitanate with calciumtitanate and other compounds that give nearly a zero temperature coefficient over certain temperature ranges. A compensation method to overcome the temperature variation of the material will be discussed below.

The material for the bariumtitanate capacitances was generously supplied by the American Lava Company in Chattanooga. A disc of about 1.2 cm diameter and 1/2 mm thickness was silverplated on both sides by evaporation in vacuum. The disc was afterwards broken into small pieces.

Only pieces with freshly broken sides were used as ferroelectric capacitances. These pieces were first tested for their leakage resistance by applying a voltage between 300 and 600 volts between the two silver-plated electrodes. After removal of the voltage source, the decay of the voltage was observed with a low capacitance electroscope. For capacitances of 15 - 20 μF , the voltage decay e - folding time was several hours. The leakage resistance is of major importance since it determines the minimum dose rate that can be measured. The capacitances were mounted between metal springs and covered with ceresin wax, (Fig. 4).

The dielectric characteristic of the material was measured by applying voltages from zero to 900 volts. As shown in Fig. 5, there is a large section of the curve from 300 volts to 600 volts with an approximate linear voltage - capacitance characteristic.

The ferroelectric capacitance was placed in an ionization chamber as shown in Fig. 6. C_1 is the ferroelectric capacitance, C_2 either a common capacitance of the same magnitude as C_1 or another ferroelectric capacitance. C_1 and C_2 had capacitances of 15 to 20 μF and the resultant R.F. capacitance is therefore 7.5 to 10 μF .

One electrode of each capacitance was connected to the central electrode of the ion chamber, while the other electrode of the one capacitance was grounded and that of the other capacitance was connected to an element of the oscillator circuit.

As Fig. 6b shows, C_1 and C_2 are electrostatically connected in parallel, since (Fig. 7) the side connected to the R.F. circuit is

grounded over a 10 Megohm resistance. The control electrode was charged during the operation usually to 300 volts positive above ground. This resulted in a capacitance reduction by about 8%.

Figure 7 shows the modified Clapp circuit with the quartz crystal frequency control operated somewhat below series resonance on the left side of the center line. The tubes used are subminiature tubes.

Since C_3 and C_4 are about 100 μF each, while the series capacitance of C_1 and C_2 amounts to about 8-10 μF , the frequency will be determined essentially by C_1 and C_2 as far as the crystal control permits. C is in parallel with the resultant control capacitance and serves for the exact adjustment of the frequency. C could be varied from about 3 - 20 μF .

A voltage applied to the center electrode of the ion chamber reduced the controlling capacitance and therefore increased the frequency.

The quartz crystal frequency was about 2 MC. The resonance plate circuit was tuned to the 3rd harmonic, i.e., 6 MC.

As shown in Fig. 8, the frequency variation of oscillator I at 6 MC was plotted against the voltage applied to the central electrode of the ion chamber and ferroelectric capacitances.

As can be seen, the characteristic with increasing voltage differs from that with decreasing voltage, showing a hysteresis loop similar to that of electromagnetic material.

If the operation point is selected at the decreasing characteristic, the straight portion extends down to 200 volts. The operating point generally used was 300 volts.

Another effect observed with the bariumtitanate capacitances consists of a time delay between the applied charge and the change of capacitance. It takes the capacitance several minutes to reach its final value. Therefore, the ion chamber should be charged about 5 minutes before exposure. Once charged, there will be an immediate response to radiation. For correct readings it is advisable to wait for some seconds after the end of the exposure. The slow discharge due to leakage, as mentioned above, is negligible for dose rates above 50 mr/hr during the measurement.

In order to eliminate or to reduce the effect of temperature variation on the ferroelectric material as well as the capacitance variation due to charge leakage, a second oscillator of the same design was added, as shown in Fig. 7, on the right side of the center line. The two oscillators have approximately the same drift due to charge leakage or temperature variation and this drift rate could be made practically identical by suitable adjustment of the capacitance C. Since the second oscillator is not connected to any ionization chamber, its frequency is not affected by radiation.

Each oscillator transmits a frequency of approximately 2 MC or 6 MC. These two frequencies differ by some few hundred or thousand cycles/sec. The frequency of the second oscillator serves as the reference. As long as no radiation enters the chamber, the difference of the frequency appears after detection on the receiver side as a constant audio-tone or an ellipse on the screen of an oscilloscope against an interpolation oscillator frequency. If ionizing radiation discharges the ferroelectric capacitances

connected to the center electrode of the ionization chamber, the two oscillator frequencies will drift apart proportional to the dose rate of the radiation. This method eliminates the use of a secondary standard on the receiver side due to the action of the second oscillator.

b. Experimental Results: Measurements with low dose rates are shown in Fig. 9. The R.F. frequencies were close to 6 mc. The ionizing radiation was radium gamma, with the dose rate varying from 5 mr/hr to 20 mr/hr. The time of measurement varied from 5 to 10 minutes and the frequency variation per minute is shown on the graph.

Since the frequency over hours varied only some few cycles, an observation during 5 to 10 minutes gives approximate values down to low values.

c. Discussion of Applications and Improvements: At the present time the instrument with compensation can transmit dependable information above 20 mr/hr and preferably above 50 mr/hr with the compensation method. At higher dose rates the effect of self discharge becomes negligible even without the compensation circuit.

Temperature variations could be eliminated by thermostatic control of the ferroelectric material. Due to the small volume of this material very little power and space are needed. A further improvement could be obtained by reduction of the ferroelectric capacitances. The sensitivity can be greatly increased by using a larger chamber volume or a pressure chamber.

As pointed out, the chamber has to be recharged after some few hours. This can be done automatically by a relay controlled by a clock.

On the detector side, the interpolation oscillator and oscilloscope can be replaced by any frequency detector that converts frequency variation into an amplitude variation. This detector will be effective only at high dose rates or improved sensitivity.

The disadvantage of the methods so far discussed is the dependence on the electrostatic leakage that required high grade insulation. It should be emphasized, however, that at large dose rates, one r/hr and higher, this disadvantage disappears and an improvement of insulation will extend the usefulness to low dose rates.

B. Geiger Counter

a. Apparatus: The disadvantage of electrostatic leakage disappears completely by replacement of the ionization chamber by a Geiger counter. Insulation problems are eliminated even for ferroelectric materials with a resistance of 1000 M and less. This improvement is due to the fact that the counter discharge produces a dynamic characteristic and the electrostatic charges required for the polarization of the ferroelectric capacitances become negligible quantities. It should be noted, however, that the Geiger counter serves as a detector of radiation only, and does not measure dose.

The design, shown in Figure 10, can be divided into a counter circuit and an oscillator circuit. These circuits are coupled electrostatically, but are separated for R.F.

A counter operated at about 900 volts is connected by $R_1 = 100 \text{ M}$ to the supply battery. $R_2 = 10 - 20 \text{ M}$ decouples the counter from the R.F. circuit. $R_3 \sim 10 - 20 \text{ M}$ is in series with R_1 and might be connected to $C_3 \sim 0.1/\mu\text{F}$. C_F is the ferroelectric capacitance, about $30 - 60 \mu\text{F}$.

The rest of the oscillator circuit is the modified Clapp circuit as described previously. As seen, C_F is connected to C_2 and grounded for R.F. by $C_2 \sim 0.1 \mu F$. When no counter discharge occurs, the polarization voltage applied to C_F is 300 volts.

Any discharge through the counter and R_1 will lower the voltage at C_F . With C_3 disconnected, each current pulse will vary the capacitance of C_F and therefore vary the frequency.

On the screen of an oscilloscope the ellipse will disappear with every pulse due to the frequency change. This information is automatically transmitted by an antenna connected to the output circuit.

The time constant of the pulse circuit depends primarily on the resistance R_1 and the capacitance of C_F together with those in parallel to C_F . This total capacitance is in the order of $100 \mu F$. $C_1 R_1$ is therefore about 10^{-2} seconds.

For high intensities the observation of single counts can be replaced by integration. A capacitance C_1 is connected in parallel to R_1 . C_1 is $0.1 - 0.4 \mu F$ and any frequency change represents the average of many counts. An improved circuit is given in Fig. 10b, where $R_2 \sim 1 - 2 M$ acts as the quenching resistance and the time constant for discharge depends primarily on C_F and R_2 .

The integrating network $R_1 C_1$ determines the average decrease of voltage due to many pulses over a period of seconds, depending on R_1 and C_1 .

Figure 10c shows the application of an intermediate amplifier stage between the counter and transmitter circuit. The low coupling capacitance C_1 reduces the time constant for the single counts and the amplified pulses

may be integrated by the network R_4 and C_2 . The polarization voltage for C_F is the difference between the 300 volt battery B_1 and the B-Battery B and the voltage through R_4 . The voltage through R_4 will vary in accordance with the amplified pulses. R_5 separates the R.F. transmitter from the amplifier circuit.

The transmitter circuit is identical with those described previously. Figure 11 shows the transmitter with the drift compensation that serves also to establish the reference frequency. An antenna is coupled with the 3rd harmonic circuit as seen in Fig. 11. It is evident that many modifications in the Geiger circuit and the transmitter circuit are possible.

b. Results of Measurements: The first measurements were made with the circuit of Fig. 10a, with a secondary standard. The nominal quartz crystal frequency was 2 mc, and the output frequency was the 3rd harmonic, 6 mc. A calibrated standard of .11 mc Ra-γ was used. The counter was in a field of 1/2 mr/hr to 10 mr/hr. When no capacitances were used parallel to the resistances, the background radiation could be easily observed by sudden disappearance of the circle at the oscilloscope screen for every pulse in the counter. Since the frequency drifted slightly after some time, the interpolation oscillator had to be retuned.

By adding a capacitance as described before, the single pulses became less pronounced and the frequency variation could be observed when gamma radiation entered the counter. The sensitivity depended, as before, on the operating position of the tuning condenser C_5 in Fig. 10a. This capacitance permitted to "pull" the oscillator frequency somewhat to the low side of the nominal quartz crystal resonance frequency. At this

position the frequency changed by 7000 - 10,000 cycles/sec when the capacitance C_F was polarized by 300 volts. This is the range available for the frequency variation. It takes about 20 minutes to one hour before the full polarization of C_F is reached but there is no need to disconnect the polarization battery at the end of the experiment, since no current flows except for a very minor leakage. Figure 12 shows the results of the measurements. As it is seen, the field of dose rates from 0.5 mr/hr to 7 mr/hr corresponded to a nearly straight line. However, the shape of the dose rate frequency characteristic can be varied by using the relation between the polarization voltage and the capacitance variation as seen in Fig. 5. At high dose rates, depending on the operating point, the polarization voltage decreases so far that the capacitance approaches its non-polarized condition. This results in an approximately logarithmic characteristic. Another control is the tuning of C_5 as pointed out previously. At a higher frequency setting the circuit becomes less sensitive, but more stable. The Geiger counter determines the overall sensitivity. The counter was operated at about 900 volts at the plateau. Figure 13 shows the results of measurements with the compensated circuit. The frequencies of the two oscillators had a difference from 800 to 1600 cycles/sec. A zero difference setting would be advantageous, but the circuits jump into the same frequency due to coupling at 200 - 400 cycles/sec if not carefully shielded.

As explained previously, the two frequencies produce an audio tone in any common R.F. receiver. The audio frequency can be detected, in addition to the oscilloscope method, by any frequency discriminating network. Figure 14 shows such a circuit consisting of an inductance and capacitance in parallel and connected to a diode rectifier with a

microammeter in series. A capacitance of about $0.01 \mu\text{F}$ and an inductance of approximately 2.5 H have an anti-resonance frequency of about 1000 c/sec . The circuit impedance has a maximum at this frequency. With a constant voltage input, the meter has a minimum current reading at 1000 c/sec and increases its reading for higher and lower frequencies. The inductance should have a comparatively high "Q". Deviations of 40 to 80 c/sec change the current by 100% and correspond to about $1/2$ to 1 mr/hr , as was shown in Figs. 11 and 12. The current approaches a maximum asymptotically. This gives an approximately logarithmic response. A limiter circuit precedes the discriminating network to provide a constant voltage input. The microammeter can be calibrated in mr/hr . The "width" of the resonance curve depends on the "Q" of the inductance. For higher dose rates the scale can be enlarged by reducing the "Q" of the inductance.

The audio frequency discriminator circuit and the limiter stage can be connected to the audio output of any ordinary R.F. receiver. For the reading of dose rates at the transmitter only a frequency discriminating network will be necessary.

At the time of this report, halogen counter tubes are becoming available at a higher price to replace the ordinary Geiger counter tubes. Experiments have shown that at the transmitter circuit the resistance R_1 should be reduced for halogen tubes to about 2 M . It has been found also that at the transmitter the dose rate can be read directly with a microammeter inserted in the counter circuit.

C. Applications and Improvements

For detection of radiation in the immediate vicinity of the source, the frequency variation method has no general advantage. However, the detection with a Geiger counter permits a very precise way of measurement, since the use of an interpolation oscillator makes it possible to measure every cycle per second over a range of many hundreds or thousands of cycles. Within the laboratory the random frequency drift of the equipment can be held within very narrow limits, three or four cycles per second during ten to twenty minutes. The advantages for telemetering consist in the very simple circuitry that can be built with standard equipment. With a counter, integrated dose rates as well as single pulses can be transmitted. Very many variations, not discussed in this paper, can be applied to this method. Two subminiature tubes represent the minimum requirements for drift compensation and reference frequency. With subminiature tubes and dry cells the transmitter can operate for many hours.

In order to make the drift compensation as effective as possible, the ferroelectric capacitances should be as close as possible in size and be broken from the same disc of the raw material.

All the other parts of the two oscillators should be identical and arranged symmetrically. The development of better ferroelectric material with zero temperature gradient will be desirable. For the present time, the resistivity limits the use of the ion chamber to high dose rates.

With a dependable drift compensation many transmitters can be operated simultaneously at frequencies separated by 5 - 10 KC or less and be observed from a central station. In order to check the zero point

frequency, i.e., without radiation, the counter circuit should be blocked periodically by a clockwork or electronically.

The existence of a leakage current due to a finite conductivity limits this method to higher intensities. A compensation circuit consisting of a twin transmitter of identical design, but without an ion chamber, eliminates to a certain extent the effect of the leakage. It also provides a reference frequency that permits detection of the radiation effect with any ordinary receiver. The third method replaces the ion chamber by a counter. This method represents at the present time the most satisfactory solution. Single pulses as well as integrated pulse rates can be detected. This design permits very many variations and applications. Charge leakages that reduce the effectiveness of the ion chamber application, are of no consequence for the counter. By using the compensation method, a high degree of stability can be accomplished. Quartz crystal control was generally used, but is not required, when very large frequency variations should be desirable. The quartz crystal characteristic together with that of the ferroelectric material permits a large selection of the overall characteristics for the instrument.

IV. CONCLUSIONS

Three methods ^{are} ~~have been~~ discussed ^{for} ~~to~~ detect ^{ing} ionizing radiation and ^{to} ~~transmit~~ the intelligence. All three methods make use of the reactance variation of a frequency determining network, to vary the frequency of an R.F. transmitter as a function of ionizing radiation entering an ion chamber or counter. ^{The} ~~This~~ first method is based on the capacitance and

subsequent frequency variation of an electrometer incorporated in an ion chamber. The variation is achieved by a moving vane electrometer, where the position of the vane changes as a function of the leakage of an electrostatic charge when exposed to radiation and thus varies the electrometer capacitance. Gamma, beta particles, and fast neutrons were measured during these experiments. The second method replaces the moving vane electrometer by ferroelectric capacitances. This reduces the sensitivity, but permits movement of the instrument during exposure. These ferroelectric capacitances are physically very small and can be enclosed inside of an ion chamber. The variation of the capacitance with charge or voltage permits measurement of the ionization current as a function of capacitance and frequency. The third and most successful method replaces the ion chamber by a Geiger counter, single pulses and integrated pulse rates can be measured and transmitted. (auth)

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FIG. 1 ION CHAMBER WITH MOVABLE VANE
ELECTROMETER

OSCILLATOR CIRCUIT

R.F. EQUIVALENT CIRCUIT

ELECTROSTATIC EQUIVALENT CIRCUIT

FIG. 2 R.F. OSCILLATOR WITH ELECTROMETER OF VARIABLE CAPACITANCE

FIG. 3a QUARTZ CRYSTAL CONTROLLED OSCILLATOR 12-AT-7

FIG. 3b QUARTZ CRYSTAL EQUIVALENT CIRCUITS

FIG. 4 FERROELECTRIC CAPACITANCES IN SERIES

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FIG.5- VARIATION OF A FERROELECTRIC CAPACITANCE WITH APPLIED VOLTAGE $C_0=8\mu\mu\text{F}$

FIG. 6a ION CHAMBER CONSTRUCTION

FIG. 6b R.F. AND ELECTROSTATIC EQUIVALENT CIRCUITS FOR THE CHAMBER

FIG. 7 - OSCILLATORS WITH IONIZATION CHAMBER AND DRIFT COMPENSATION

FIG. 8-FREQUENCY VARIATION AS A FUNCTION OF APPLIED VOLTAGE

CYCLES
MIN.

FIG. 9 - IONIZING RADIATION MEASURED BY FREQUENCY VARIATION WITH IONCHAMBER

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FIG. 10a. DETECTION OF IONIZING RADIATION BY FREQUENCY VARIATION WITH A FERROELECTRIC CAPACITANCE, GEIGER COUNTER AND INTEGRATING CIRCUIT

FIG. 10b. COUNTER AND INTEGRATING CIRCUIT BY J.M. GARNER

FIG. 10c. AMPLIFIER STAGE BETWEEN COUNTER AND FERROELECTRIC CAPACITANCE

FIG. II DETECTION AND TRANSMITTING OF IONIZING RADIATION
USING FERROELECTRIC MATERIAL AND DRIFT COMPENSATION.

FIG. 12 FREQUENCY VARIATION BY IONIZING RADIATION WITH FERROELECTRIC CAPACITANCE AND GEIGER COUNTER. NO DRIFT COMPENSATION.

FIG. 13 GEIGER COUNTER CIRCUIT WITH DRIFT COMPENSATION AND REFERENCE FREQUENCY GENERATOR MEASURED AT $F_0 = 6\text{-MC}$

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FIG. 14, AUDIO FREQUENCY DISCRIMINATOR

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