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PIEZO-ELECTRIC CRYSTAL-CONTROL FOR TUBE TRANSMITTERS

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PIEZO-ELECTRIC CRYSTAL CONTROL FOR TUBE TRANSMITTERS

Introduction

The importance of producing vacuum tube transmitters which generate a constant frequency has never been seriously considered until recently, when the advent of broadcasting stations and the increasing number of ship and shore radio stations has demanded that such transmitters be made available.

The Naval Radio Service has been faced with this problem for a number of years particularly in the operation of the United States Fleet. Such a fleet generally consists of a group of vessels, numbering from 150 to 200 ships, which move as one unit and, for the greater part, their movements are controlled by radio. These vessels have one or more transmitters on board and are required to be in constant touch with each other and also with a group of shore stations. When we consider such a large number of stations, as represented by this Naval force, it is very easy to imagine the confusion that may result if no means are employed to maintain a constant frequency for each station's transmitter.

Various means have been employed to hold constant the frequency of transmitters, but no absolutely satisfactory means has been devised which will maintain a constant frequency in vacuum tube transmitters which employ self-oscillating circuits. This statement has special reference to transmitters which are required to operate over a band of frequencies and are dependent for plate and filament supply power upon the usual ship's dynamo or shore station power sources.

When we consider that the beat note of a continuous wave transmitter has to remain within a certain range, say 350 cycles, it can be realized that the constant frequency condition becomes harder to meet as the frequency of the transmitter is increased. This can be readily seen when we consider that the frequency of a 4000-Kc. transmitter cannot be changed more than 1/100 of one per cent. before it has exceeded the specified frequency range.

Realizing, after years of experimentation, that we could not meet the demands made on us by the Fleet with vacuum tube circuits employing the self-oscillating principle, it was necessary to turn to some other means for meeting this demand. One means which has proved successful is the piezo-electric crystal-controlled transmitter. Such a transmitter has been found to meet all our requirements if suitable means are provided to keep the temperature of the crystal constant.

THE PIEZO-ELECTRICAL CRYSTAL

There are a number of crystalline substances such as quartz, tourmaline and Rochelle salts which have excellent piezo-electric and pyro-electric properties. All these are from an optical standpoint doubly refracting and of unsymmetrical atomic structure. Bragg and Gibbs show that alpha quartz which is piezo-electrically active has an unsymmetrical hexagonal atomic structure, while beta quartz which has no piezo-electric properties is of a regular hexagonal atomic structure.

It is only natural to assume that any crystalline body which has double refracting properties and whose atomic structure is unsymmetrical should be piezo-electrically active. F. Pockels states that 20 out of 32 crystalline substances show some piezo-electric properties.

Considering the three commonly known piezo-electric crystals, i. e., quartz, tourmaline and Rochelle salts, we find that quartz is to be preferred. Rochelle salts although it has ten times the piezo-electric properties of quartz is not reliable. It is fragile, extremely hard to manufacture and its physical dimensions can be easily changed by handling, especially when subjected to contact with water. It also will not stand any electrical load; for instance, if used as a resonator in connection with the output of an oscillator of a few watts capacity it will break down. This breakdown will either be in the form of a series of mosaic cracks throughout the crystal or it will consist of a melting process wherein the crystal suddenly flattens out and assumes an isotropic state. If the power is increased the salts will return to a liquid state.

Repeated attempts have been made to make Rochelle salt crystals function as well as quartz, for controlling the frequency of a vacuum tube transmitter, but no success has been obtained in this endeavor. The Rochelle salt crystal is not mechanically strong enough to withstand the vigorous vibration which is met with in the quartz crystal when controlling the frequency of a vacuum tube transmitter. It is also possible that the hysteresis losses in the Rochelle salt crystal are such that they tend to damp out any properties of the crystal for generating a return piezo-electric voltage required for maintaining a vacuum tube circuit in an oscillating condition.

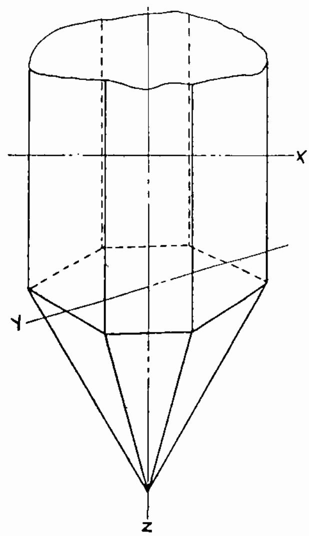

Fig. 1

There is no literature available which shows the application of Rochelle salt crystals as a means for controlling the frequency of a vacuum tube circuit.

Tourmaline is too expensive to be considered as a commercial product and therefore result has to be made to the use of quartz.

Quartz can be obtained in reasonable quantities in Brazil, Madagascar, Japan and the United States. Any quartz which has no flaws, intergrowths or optical twining can be so manufactured that it has excellent piezo-electrical oscillating properties. By this we mean that such a crystal can be used to control the output of a vacuum tube oscillating circuit at one definite frequency and with maximum output.

Quartz will retain its physical dimensions if kept at a definite temperature. It will also stand considerable abuse, which accompanies its use in oscillation test circuits, where the crystal is heated momentarily to temperatures in excess of 45 deg. cent. and is subjected to frequent washing. Experience has demonstrated that crystals will hold the original oscillation frequency for periods in excess of ten months, when operated continuously in a high-frequency transmitter system. Other exacting tests have proved that quartz is the only material known which is satisfactory for use in crystal-controlled vacuum tube circuits.

The quartz crystal is hexagonal in shape and when in its true form has an apex at each end. The methods of mining and also the process of growing are such that the two apexes are rarely found on crystals which are purchased from the importers. In the majority of cases, it is rare to obtain crystals having sides and one apex which are not chipped or cracked due to rough handling or poor mining methods.

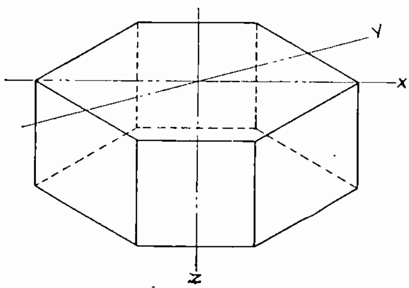

Fig. 2

The usual crystal when received is similar in shape to that shown in Fig. 1. In this crystal the optical axis is parallel to an imaginary line *Z* which is drawn between two apexes. The electrical axes are of two types, one which is parallel to a line *X* drawn between the corners of the hexagonal sides and the other which is parallel to the line *Y* which is drawn between the opposite flat faces of the hexagonal sides. From this we note that there are three *X* electrical axes and three *Y* electrical axes and one optical axis. The optical axis is always at right angles or perpendicular to any of the electrical axes.

Now cut a slab of quartz from the crystal as shown in Fig. 2 making this cut at right angle to the optical axis *Z*. Then in order to obtain a workable crystal, we cut a slice from this slab as shown in Fig. 3. This slice is so cut from the slab that the slicing produces a crystal whose sides are parallel to one of the *Y* electrical axes and at right angles to one of the *X* electrical axes. We now have a crystal whose thickness represents an *X* axis, whose length a *Y* axis and the depth an optical axis.

Methods of manufacturing the crystal from this point on to the perfect oscillating condition is a specialty in itself.

Having completed the cutting of the crystal which we will term the "Curie 3" or "zero angle cut" we find that there are three frequencies to which the crystal will resonate. One frequency corresponds to the *X* dimension, one to the *Y* dimension and the other to a frequency which is between *X* and *Y* axis frequency and is termed the coupling frequency. This coupling frequency depends on the dimensions of the *X* and *Y* axes. In round crystals as shown by Dr. Hund, the *X* dimension will produce 104.6 meters per mm., the *Y* dimension 110.5 meters per mm. and the coupling frequency is equal to 0.71 of the *Y* dimension wave-length. In rectangular crystals the meters per mm. for the *X* dimension vary from 103.5 to 105.0 while for the *Y* dimension it varies from 110 to 117 meters per mm. The meters per mm. obtained for the coupling frequency cannot be stated because this depends on the dimensions of the rectangular form which may be square or any shape which the requirements demand. These figures are based on the true Curie cut and on crystals whose *Y* dimension is between 20 and 28 mm. If any cut is made which is at an angle from the Curie cut the meters per mm. will be greater, especially for the *X* dimension oscillation.

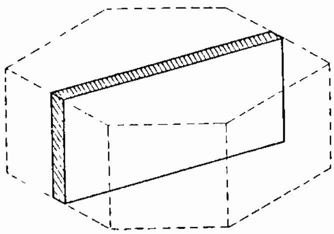

Fig. 3

Rectangular crystals are to be preferred to round crystals, first because they are cheaper to make and second because they will control a greater radio-frequency output without cracking or chipping. The latter condition is probably explained by the uneven stress conditions present in round crystals when they are oscillating under influence of radio-frequency currents.

HISTORY

P. and J. Curie first investigated quantitatively the piezo-electric properties of quartz and derived equations showing the relation between the applied pressure and the piezo-electric charge on the faces of the crystal. They also showed the converse effect where an electric charge on the crystal would produce a change in crystal dimensions.

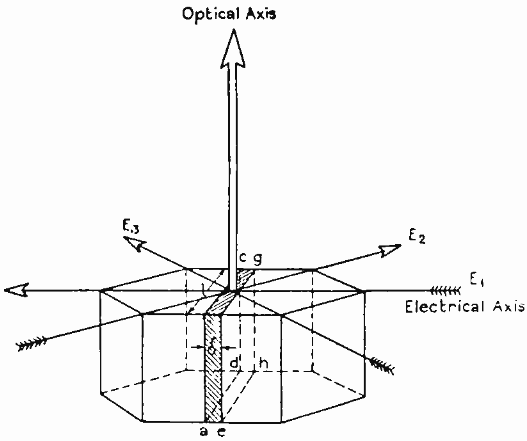

Fig. 3-A Illustrates More in Detail the Different Axes for the Crystal and Shows How the Crystal is Cut from the Rough Quartz.

Since this disclosure, various uses have been made of piezo-electric crystals, namely, as pressure gauges, loud-speakers and sound transmitters for underwater signalling.

Cady first discovered that quartz could be employed as resonators and as such to be used as standards for precision frequency determinations. Cady later discovered that crystals could be used to hold the frequency of self-oscillating circuits constant and also that crystals could be made to control the frequency of a vacuum tube circuit. It is this feature of crystal control that we are most interested in and in order to present this subject we will consider each step made by various investigators in producing vacuum tube circuits which would be capable of obtaining maximum radio-frequency output from a quartz crystal.

Cady's work may be summarized by reference to Figures 4, 5, and 6. The circuit shown in Figure 4 is essentially a self-oscillating vacuum tube circuit with a crystal placed across the grid tuning condenser. When the circuit is adjusted to

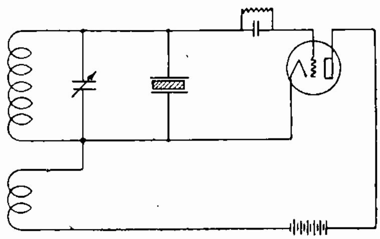

Fig. 4

the resonant frequency of the crystal, there is a tendency in the crystal to keep the frequency of the circuit equal to that of the crystal. If the plate voltage, filament voltage and load remain the same, the crystal will hold constant the frequency of the circuit, but if one or more of the above conditions are changed the circuit will oscillate at any frequency which the circuit conditions permit.

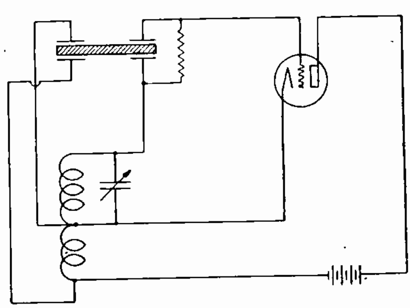

Fig. 5

Figure 5 is an elaboration of Figure 4 and is employed to obtain a greater piezo-electric voltage for controlling the frequency of the circuit. The greater piezo-electric voltage is obtained by the use of the plate feed-back principle represented by the extra set of plates on the crystal. The operation of this circuit is limited by the same conditions which are cited for the circuit shown in Figure 4.

It has been our experience that any method which depends on any self-oscillating conditions in a vacuum tube circuit in addition to piezo-electric control is dangerous for two reasons: i. e., first, because of the danger of frequency shifting and second it is very easy to crack or chip crystals in such circuits. This latter case is exaggerated when we

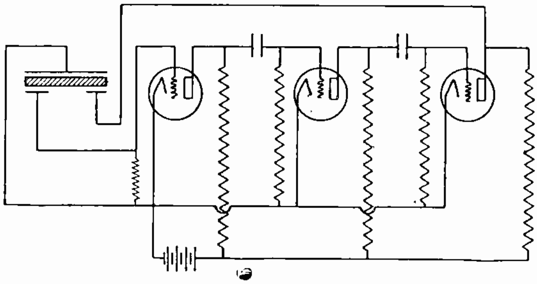

Fig. 6

tie in the crystal oscillating circuit with an unbalanced amplifying system where the radio-frequency current feed-back from the amplifying circuit is sufficient to supply enough additional current through the crystal to cause it to heat up and crack.

Figure 6 is the first circuit known to the art wherein the crystal with the associated amplifying circuits comprise a

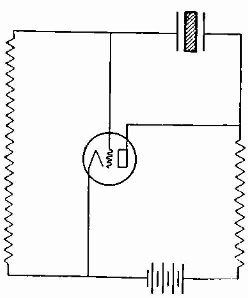

Fig. 7

system in which the crystal is the only control for the generator frequency. In this circuit the initial piezo-electric charge on the grid is amplified through three stages of resistance-coupled amplification, and by the means of a third contact plate on the crystal this amplified charge is applied to the crystal in the right phase relationship to reinforce the initial charge and by this process assist the circuit in generating radio-frequency currents.

Pierce later developed a circuit shown in Figure 7 which is capable of generating, by the use of crystal control, a source of constant frequency. In this figure the crystal is placed between grid and plate of a vacuum tube and a resistance load is inserted in the plate circuit. A grid leak is employed to hold the grid at a certain voltage with respect to the filament.

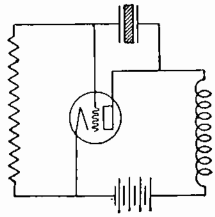

Fig. 8

Figure 8 is a modification of Figure 7, wherein an inductance is substituted for the plate resistance. Both of the Pierce circuits function in the same manner as the old De Forest Ultraudion circuit. In the Ultraudion circuit, a tuned circuit was interposed between grid and plate as shown in Fig. 9 and a choke coil was employed as a load in the plate circuit. This choke coil was so constructed that it acted as a capacitive load for all frequencies to which the tuned circuit was resonant.

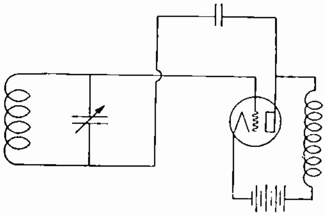

Fig. 9

In the Pierce circuits the crystal functions as a tuned circuit having a preponderance of inductance, while the plate load for the condition of oscillation has to be capacitive. To accomplish this end, Pierce uses a very large inductance coil in the plate circuit. The true inductance and the distributed capacity of the coil system used in this circuit has to be such that it will resonate to a lower frequency than that of the crystal before the circuit will oscillate. In the case where resistance is used, as in the plate circuit of Fig. 7, it is the distributed capacity of the resistance together with plate-filament capacity that affords the capacitive reactance required for the oscillation condition.

If the proper precautions are observed with the Pierce circuit with respect to the capacitive plate load condition, any crystal can be made to trigger off this circuit into the oscillating condition. In view of the fact that a grid leak is employed and the plate load is a resistance or a large inductance, it is not possible to obtain the rated power output from a given tube with this circuit. This statement is based on the fact that the I^2R losses in the resistance and inductance are considerable and the grid leak method of biasing is inefficient for reasons which will be explained later in this book. There is another objection to the Pierce circuit and that is the broad impedance curve of the plate circuit, which

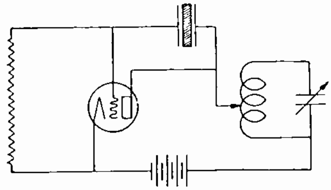

Fig. 10

permits the generation of a number of oscillations at one time should the crystal be so constructed that there are two possible oscillations, for the *X* dimension or the *Y* dimension frequency may be very close to the coupling frequency with the result that both frequencies will be heard.

PIEZO-ELECTRIC CRYSTAL RESEARCH WORK AT THE NAVAL RESEARCH LABORATORY

Realizing the limitations of piezo-electric crystal circuits then known to the art, further development work was carried on at the Naval Research Laboratory to determine whether piezo-electric crystals could be employed to control any system which could permit a reasonable radio-frequency output.

J. M. Miller, formerly of this Laboratory, developed the circuit shown in Fig. 10. This circuit is similar to Pierce's circuit with the exception that Miller employed a tuned plate circuit and a variable tap on the inductance. The tuned circuit permitted tuning to any desired frequency, thus excluding undesired frequency oscillations. The variable plate tap permitted matching of tube impedance to circuit impedance whereby maximum power transfer was possible. Low loss inductance and condensers were employed thus reducing I^2R losses in the tuned circuit to a minimum.

Miller also developed the circuit shown in Fig. 11, which circuit is the fundamental Navy circuit. In this circuit the crystal is placed between grid and filament instead of between grid and plate as in Fig. 10. With this circuit the load for the plate circuit should be inductive in order that a condition for oscillation be obtained. The action of this circuit with reference to the oscillating condition is similar to the well known Hartley self-oscillating circuit. This may be better understood by stating that the crystal, being equivalent to an inductance, is similar to the grid coil of the Hartley circuit, while the inductive load in the plate circuit of the crystal oscillator is identical to the plate coil of the Hartley system.

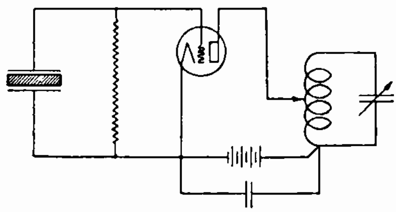

Fig. 11

Miller demonstrated that he could make both circuits oscillate with crystals of different frequency ratings. Preference was given to the use of the circuit shown in Fig. 11 because in such a circuit there is no tendency for short-circuiting the high-voltage plate circuit should the crystal crack or slide out from between the contact plates, thus causing the plates to come in contact with each other. Experiments with high-frequency crystals show that good output is obtained with high as well as low-frequency crystals when employed in the circuit shown in Fig. 11.

The problem of obtaining greater output from the crystal oscillating circuit and the amplification of this output on low frequencies was assigned to A. Crossley. The Miller circuit Fig. 11 was used as a foundation and efforts were made to increase its radio-frequency output.

A study of this circuit showed that the crystal-controlling voltage was reduced materially by the fact that a grid leak was shunted across it. This grid leak provided a shunt path for the radio-frequency piezo-electric control voltage and at the same time carried the rectified grid current required for obtaining the negative voltage for biasing the grid. Miller suggested the use of a choke coil in series with the grid leak to eliminate that part of the radio-frequency voltage loss that is due to the direct flow of current through the grid leak resistance. This materially increased the output of the crystal oscillating system.

Crossley eliminated the second load on the crystal by substituting a battery for the grid leak, connecting the negative terminal of the battery to the low radio-frequency potential side of the choke coil shown in Fig. 12.

The object of the use of the battery was to keep the swing of the crystal-controlling voltage over on the negative side of the grid voltage plate current characteristic curve, thus eliminating the load in the grid-filament path which is obtained when the grid swings positive past the zero grid voltage point on this curve. The act of swinging over the positive side of grid voltage plate current characteristic curve causes a current flow between grid and filament which represents an I^2R loss. Any method for eliminating this grid current flow or rendering it of negligible value will also permit the crystal controlling voltage to be kept at a maximum and therefore permit a maximum output to be obtained from the circuit.

In actual practice, there is a small amount of grid current flowing, but the grid voltage swing is for the greater part over on the negative side of the grid voltage plate current characteristic curve. This grid current flow is due principally to the fact that the grid battery employed does not block the plate current to zero, because a small amount of plate current is necessary before the crystal circuit will start oscillating.

The use of the battery increased the output of the circuit tremendously. Using a 600-Kc. crystal, it was possible to obtain one watt output with the original circuit employing the grid leak while with the choke and battery, an output of 21 watts was obtained. The tube used in this experiment was the UV-210 type rated at 7½ watt allowable plate dissipation. The efficiency of this circuit was 65 per cent. figuring plate input watts against radio-frequency output. The plate voltage for this test was 650 volts, while the grid battery was 80 volts.

Further experiments with 50 Watt tubes and also special tubes have shown that as high as 100 watts output can be obtained when employing high-frequency crystals in the 3000 to 4000-Kc. band. It is not possible to obtain such outputs when employing higher or lower frequency crystals. With the lower frequency crystals, the feed-back afforded by the grid plate capacity is proportional to the frequency, while the capacity between crystal plates is reduced as the frequency of the crystal is decreased. In other words, the charge on the crystal is reduced as the frequency of the crystal is decreased and correspondingly the piezo-electric controlling voltage from the crystal is likewise reduced. To make up for the reduced charge on the crystal, it is customary when using lower frequency crystals to increase the plate and grid battery voltage.

There is, however, as stated before, a certain high frequency where maximum output is obtainable and on either

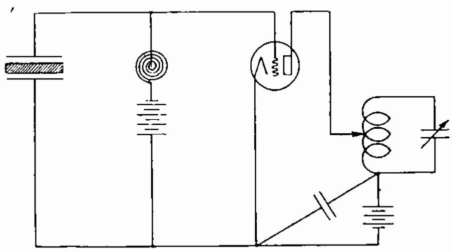

Fig. 12

side of this frequency there is a slow decrease in output. Around 3500 Kc. is approximately the peak output frequency point, while 12,000 and at 100 Kc. are the frequencies where minimum output is obtained. These output ratings are based on safe crystal current-carrying ratings, which was first shown by A. Hoyt Taylor. Taylor shows that for the different frequency crystals, there is a safe working current at which the crystal can be operated and if this point is exceeded the crystal will heat up and crack.

This condition can also be tied down to a safe wattage dissipation in the crystal, but not knowing the resistance of the crystal, we can only consider it from a current standpoint. In the 3000 to 4000 Kc. band, electrostatic voltmeter and thermal ammeter readings in the crystal circuit show approximately five watts loss in the crystal. It is only at this and higher frequencies that an electrostatic voltmeter can be used to measure the voltage across the crystal, because the shunting effect of the capacity of the meter at the lower frequencies is such that it seriously reduces the output. When measurements were made with a 500-Kc. crystal, the placing of an electrostatic voltmeter across the terminals of crystal holder was such as to reduce the output to less than one-half of the original output. This reduction in crystal piezo-electric controlling voltage is due to the fact that the plate grid feed-back voltage is divided between the two capacities, i. e., the voltmeter capacity and the crystal capacity, while at the lower frequencies the crystal capacity is nearly equal to the voltmeter capacity.

This can be shown further by reference to Fig. 13 where *Cr* is the capacity equivalent to the crystal, capacity *Cv* represents the voltmeter capacity and *Cf* the grid-plate feed-back capacity.

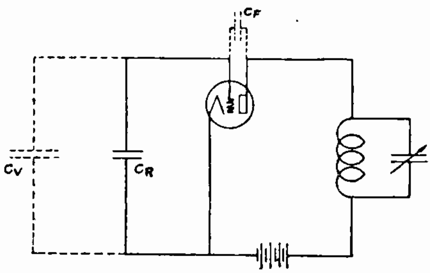

Fig. 13

From the above figure, we can note that it is not possible to obtain true voltmeter readings due to the presence of the shunt capacity *Cv* which divides the feed-back charging voltage into two paths, thus robbing the crystal of the maximum charging voltage from the plate circuit. Although we have cited the case of the shunt capacity afforded by the voltmeter, it is also true that any extraneous capacities, such as long leads from crystal to grid, poor design of crystal holder which permits additional capacity other than that of the crystal contact plates, and choke coils which have high distributed capacities, will also produce the same effect.

The capacity between contact plates of crystals in the range between 100 and 12,000 Kc., respectively, varies from 12 to 125 micro-microfarads. When we consider the capacity of the crystal and the fact that the grid plate feed-back capacity is constant, it can be readily seen, when using the same plate voltage, that the charge delivered to the crystal is reduced with the decrease of frequency. An example of this case is cited by comparing charges delivered to two crystals, i. e., a 500 and a 4,000 Kc. crystal when employed in a 7½ watt UV-210 tube circuit. With the 4,000 Kc. crystal, the charge is 64 times as great as that delivered to the 500-Kc. crystal. This increased charge on the crystal with the increase of frequency explains why it is possible to obtain greater radio-frequency output at high frequencies and why we have to be so particular about low-frequency crystals and their associated circuits. With the low-frequency crystals, it is imperative that we employ the right amount of grid biasing voltage for the condition of maximum output, while with the high-frequency crystals, it is possible to eliminate the biasing voltage and still obtain good output. It is, of course, understood that the elimination of the biasing battery means a reduction in the efficiency of the circuit and sluggish oscillating action of the crystal, especially when we use the crystal as a master oscillator.

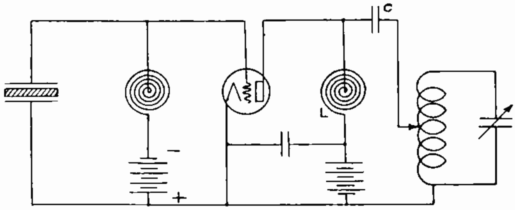

Fig. 14

An improvement on the Miller circuit was made by Crossley and is shown in Fig. 14. This improvement provides for the isolation of the radio-frequency output circuit from the high voltage direct current circuit, thus preventing the operator from accidentally coming in contact with the high voltage direct current supply. The insertion of the choke coil *L* and the condenser *C* in the circuit permits the segregation of the radio-frequency and direct current circuits. It is good practice to make the resonant period of the plate choke coil *L* equal to a frequency which is lower than that of the crystal, thus making the choke coil a capacitive reactance at the crystal frequency.

CRYSTAL HOLDERS

The subject of crystal holders is very important. Experiments conducted by Crossley, particularly in the low-frequency range, show that the crystal will become inoperative if any dirt or moisture comes in contact with the crystal. If a crystal is placed in a circuit and started oscillating and a minute drop of water or oil is placed on the crystal, it will immediately stop oscillating. The stopping of oscillations may be explained when we consider that for best operation, the top crystal contact plate is separated by a minute air cushion from the surface of the crystal when the crystal is oscillating and the introduction of moisture in place of the air causes a load to be placed on the crystal. This latter condition is similar to the use of mercury as a contact surface for the crystal, which type of contact adheres so closely to the crystal that it damps out any oscillation that tries to start up.

From the above facts it is imperative that the crystal be placed in a hermetically sealed container where no moisture or dirt can come into contact with it.

It is necessary that capacities other than that between the crystal contact plates be kept as small as possible, thus eliminating the charging losses occasioned by extraneous shunt capacities. For reliable operation and maximum output, the crystal contact plates should be intimately touching the surface of the crystal. Lapped surfaces on these plates are to be preferred, while the weight of the upper plate should be kept to a minimum. No restriction of up and down movement of the upper plate should be tolerated. Light spring pressure can be applied to this plate but for best results no pressure other than the weight of the plate is necessary.

Retaining rings of bakelite or other insulating material or brass retaining pegs can be employed to hold the crystal in one fixed position with respect to the sides of the container. A holder having all these features together with means for restricting the tendency for the crystal to jump clear of the retaining pegs when being transported is shown in Figure 15.

Experience has shown that any air-gap between upper surface of crystal and the contact plate means a great reduction in output and when used in a regular power circuit, the air-gap causes brushing between the surface of the crystal and the plate which, in turn, causes the crystal to heat and crack. Crystals which have been subjected to the brushing effect show a discoloration on the surface of the crystal at the place where the brushing occurred.

The frequency of any crystal changes with temperature and for absolute constancy of frequency it is necessary that some type of temperature control be applied either directly or indirectly to the crystal. One method is to place the crystal in a hermetically sealed container and by use of a thermostat and heating unit in this container maintain the crystal at a predetermined temperature. The second method is to place the crystal in a crystal holder of a similar type as that shown in Fig. 15 and to secure this holder on a metal plate which can be maintained at a constant temperature. The heat from the plate will be conducted through the lower crystal contact plate direct to the crystal.

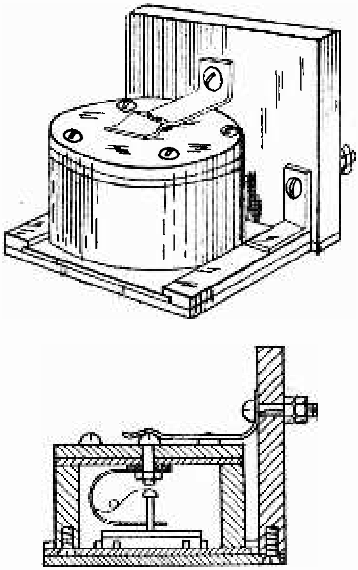

Fig. 15—Typical Crystal Holder.

The metal heating plate can be kept at a constant temperature by circulating water through it, or a sub-compartment with suitable heating unit and thermostat can be attached to this plate. A thermostat can be employed with the water circulating system to turn on or off the current in a heating coil which is placed in the water intake line to the plate. This latter water-cooling method was developed by Taylor and applied by E. L. White to the high-power high-frequency transmitters at this Laboratory.

The importance of constant temperature control is appreciated when operating high-frequency crystals, as a change of 10 deg. cent. will change the frequency as much as one kilocycle in the 4,000-Kc. range. Extreme changes in temperature met with on board Naval vessels when cruising can change the crystal frequency as much as three kilocycles, which change is very detrimental to perfect communication conditions. A remedy for this is to provide a thermostatic control which will maintain the crystal temperature above that which is ever encountered, throughout the year. This is identical with the practice now in force with reference to our Navy Standard 25 Kc. crystal calibrator, which is used as a standard of frequency for the Navy.

Recent data on temperature co-efficient in quartz crystals obtained by the Naval Research Laboratory show for the *X* axis there is a frequency change of 25 parts in a million per degree centigrade, while with the *Y* axis a change of 50 parts in a million is noted. These data on electrical characteristics appear to show that the temperature co-efficient of the elastic constant along the *Y* axis is approximately double that of the *X* axis, as we can assume that the frequency change must tie in with the mechanical change. This statement is based on our previous experiments on the resonant condition, in crystals, namely, the relation of meters per millimeter for respective electrical axes.

Several types of multiple crystal holders have been developed. One type employs the holder shown in Fig. 15 which was placed on a circular disk with a knob and pointer on the front of a panel for rotating the disk. Two contactors were placed behind the panel for making contact with each crystal holder as it was rotated past the indicated point.

CRYSTAL CONTROLLED POWER AMPLIFIERS

Having obtained reliable operating conditions with the crystal controlled oscillator, our next and most important problem was to amplify this output.

The first attempt to amplify the crystal oscillator output was made by resorting to two stages of amplification. The first stage consisted of a 7½-Watt tube, while in the second stage two 50-Watt tubes were employed. Grid leaks were used to bias the grids of the amplifier tubes. An output of 96 watts was obtained with this power amplifier at a frequency of 600 Kc. Another stage of amplification consisting of three 250-Watt tubes was added to this amplifier and the maximum output obtained was approximately 700 watts.

About this time Dr. Taylor and L. C. Young demonstrated that amplification of power from a 3,000-Kc. crystal oscillator was possible.

Considerable trouble was experienced from self-oscillations in the amplifier system. Various methods were employed to eliminate these undesired frequencies with no satisfactory result. Crossley discovered that these oscillations were in general of a high-frequency nature and that the only method of eliminating them was to place a resistance of a certain value in the plate lead, preferably as close to the plate as possible. The location of this resistance in the plate lead placed a load on the high-frequency circuit, and if sufficient resistance was inserted the load would be too great to permit the grid-plate feed-back to cause a condition of self-oscillation. The maximum value of the resistance should not exceed 300 ohms at 300 Kc. and can be very low on sets of very high frequency; that is, small enough to have a negligible effect

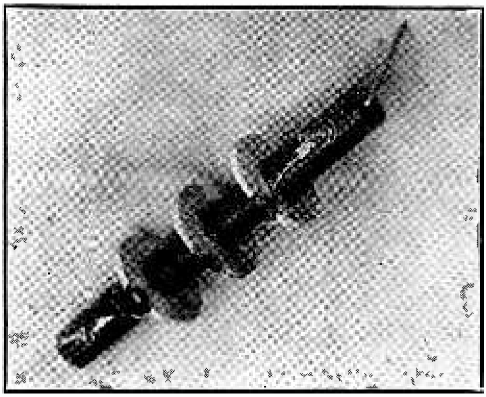

Fig. 16—Choke Coil.

on the output of the amplifier circuit at the amplified frequency. This can be better understood when we consider that the plate circuit impedance at the desired frequency is at least 5,000 ohms at medium frequencies for all types of tubes other than the one-Kw. type, and the additional resistance placed in this circuit for purpose of stopping self-oscillations never is greater than 6 per cent. of the total circuit impedance. The impedance of the plate circuit which is resonant to the self-oscillation frequency is low, and the resistance referred to above is so located that it is in series with this resonant circuit.

The importance of shielding each stage of amplification was soon apparent and this was accomplished by providing metal containers for each stage. It was noted that there was sufficient feed-back through the grid plate capacity of the amplifier tubes to prevent maximum power amplification per stage. L. A. Gebhard and Miller suggested and demonstrated the power amplification gain which is possible when neutralizing the feed-back and also applying a high value of biasing voltage to the grid of the amplifying tubes.

The neutralizing of the feed-back in the amplifier tubes permitted maximum grid excitation while the use of the high value of grid biasing voltage reduced grid filament circuit losses to a minimum. A power amplification of 80 is obtainable by the method proposed above. A concrete case of this condition was cited when we amplified the output of a 7½-Watt tube circuit by use of a UV-851 one-Kw. tube and obtained 600 watts. From the above it can be noted that it is possible to reduce the number of stages of amplification very materially, thus eliminating troubles experienced with the excessive number of stages which are required when employing the old method of cascade amplification.

One more source of trouble was experienced in the development of the amplification system, and that was in the choke coils. It was found during numerous incidences that the choke coils would burn up, particularly the plate choke coils. These choke coils were of the single-layer and the pancake universal wound type. An investigation of the reason for this burning effect showed that the burning occurred at frequencies which were close to the second, fourth, sixth, and other even harmonic frequencies of the fundamental of the choke coil. It then became necessary to make our choke coils such that the danger or burning frequencies would be other than that of the operating frequency of the transmitter.

If the transmitter is required to cover a broad band of frequencies, a radical change has to be made in the choke coils. This change consists of using at least three choke coils, preferably of the universal wound type, in a series connection. Each coil should have the same number of turns and the same shape and arranged on a bakelite or pyrex rod or form in such a way that the magnetic fields add. This multiple choke arrangement provides a method of obtaining in a concentrated form a choke coil which has nearly twice the inductance and two-thirds the distributed capacity of the best type single-layer choke coil. It also has, by virtue of the addition of impedance of the respective coils, a high value of impedance at the dangerous harmonic frequencies. This latter characteristic makes this type of choke well suited for use in transmitters which employ the principle of frequency doubling or tripling to obtain super high-frequency oscillations. A choke coil similar to the type referred to above is shown in Figure 16.

Having solved the major problems involved in the crystal controlled transmitter with reference to output, the next problem was that of keying the system. Various methods were tried and abandoned due partly to sluggishness of action or the fact that too large a load was taken from supply source which furnished the necessary negative voltage for blocking the grid of the control tube. A satisfactory system was finally obtained and may be explained by reference to Figure 17.

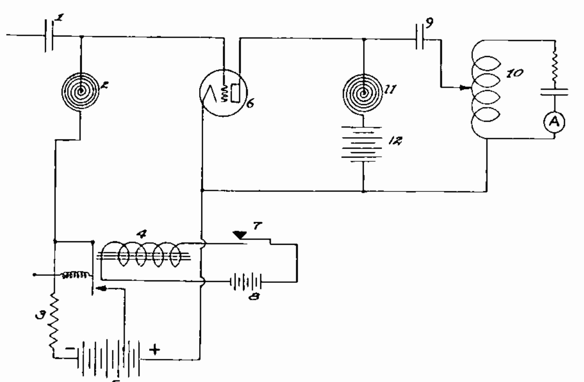

Fig. 17

In this figure there is shown one of the stages of amplification which it is intended to key. The grid circuit consists of the blocking condenser 1, choke coil 2, relay 4, high resistance 3 and the battery 5. Associated with the relay 4 is the key 7 and relay battery 8. The plate circuit is of the conventional type and consists of blocking condenser 9, antenna or dummy circuit 10 with the usual plate choke 11 and plate potential source 12.

The keying is accomplished by changing the grid biasing voltage from an operating voltage to a high blocking voltage through the agency of the relay 4 and the associated circuits. With the key 7 closed, current flows through the relay 4 and closes the contacts, thus permitting the grid lead to be connected to the low-voltage tap on the battery 5. The high-resistance 3 is then placed across the remainder of the battery and, due to its high value, it takes no appreciable load from the battery 5. When the key is up or in the open position, the contacts on relay 4 spring back and disconnect the low voltage tap on the battery 5, thus through the resistance 3, making a path for the high blocking voltage to be impressed on the grid. The fact that there is no current flow through the grid circuit also indicates that there is no *I R* drop over the resistance 3, thus we can, by means of the relay, change the grid voltage from an optimum operating value to an absolute blocking value. The use of the high-resistance also cuts down to a minimum the sparking and sticking of the contacts on the relay. With this method of keying it is possible to key at speeds in excess of 100 words per minute.

COMPLETE TRANSMITTER

Further work on this problem of amplification at frequencies from 150 to 600 Kc. proved that it was possible to obtain an output of 13 Kw. into a dummy antenna system. The complete details of the system which is capable of delivering this radio-frequency power output may be explained by reference to Fig. 18.

In this figure three stages of amplification are shown. The first stage consists of a 50 Watt impedance coupled amplifier which feeds into a 1-Kw. tuned amplifier stage and from this stage to a 20-Kw. amplifier circuit.

The crystal controlled oscillator consists of a multiple crystal holder with the associated grid circuit which comprises the grid radio-frequency choke and the source of biasing voltage. The plate circuit of this oscillator employs the parallel feeds through agency of the multiple choke coil, a source of high direct voltage, a 0.001 mfd. radio-frequency bypass condenser and a resonant circuit consisting of an inductance and two condensers with a suitable radio-frequency ammeter. Two condensers, one of which is variable, are employed to permit tuning to resonance with the inductance over a given range of frequencies.

Voltage required for exciting the grid of the first amplifier tube is obtained from a tap on the inductance of the resonant circuit. Proper biasing voltage for the grid of the amplifier tube is obtained from a potentiometer and flows through the inductance of the resonant circuit direct to the grid. This method of biasing the grid of the amplifier tube eliminates the usual grid condenser and choke coil system.

The plate circuit of the first amplifier tube comprises a multiple radio-frequency choke coil with the usual high voltage direct current source and a resistance load circuit. The radio-frequency output of the choke coil is delivered to the resistance load through the two by-pass condensers shown in the diagram.

The choke coil system is so constructed that it is resonant to a lower frequency than that of the range of the transmitter and therefore provides a capacitive load. This capacitive load prevents any tendency for feed-back in the amplifier, thus saving the crystal circuit from any surge effects which tend to overload and break the crystal.

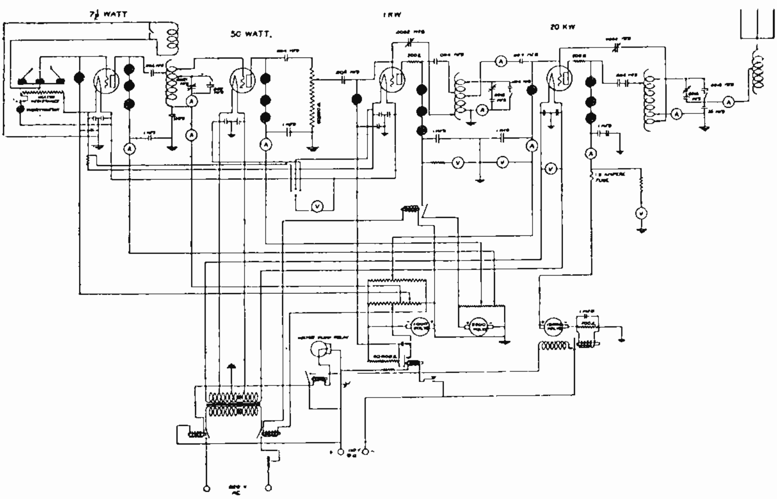

Fig. 18

A variable contactor is used on the load resistance for obtaining optimum controlling voltage for the grid of the second amplifier tube. A 0.001 mfd. by-pass condenser segregated the radio-frequency resistance load circuit from the grid biasing system. It will be noted that the grid biasing system of this tube includes the keying system referred to previously in this text.

The plate circuit of the second amplifier has the usual parallel radio-frequency feed circuit and in addition there is the balance or neutralizing circuit which comprises the counter-inductance and a .0002 mfd. variable air condenser.

This balance or neutralizing system is found to be very reliable and easy to adjust.

The third amplifier stage is identical to the second stage with the exception of the addition of the antenna load system. As will be noticed, the voltage for feeding the antenna is obtained from the drop across a condenser which is placed in series with the plate resonant circuit. This condenser was a 0.25 mfd. mica condenser with five taps of 0.05 mfd. each. This condenser in addition to supplying required voltage for the antenna system also functions by virtue of its low impedance in reducing harmonic frequencies to a low value.

PROTECTIVE DEVICES

Various kinds of protective devices were employed in this transmitter. The first and most important protective device was tied in with the biasing battery circuit and functioned in opening the filament and 2,500 Volt supply when no current was being supplied from the biasing battery.

The second device consisted of a water flow protective relay circuit. When there was no flow of water through the water-cooled tubes, the device opened the filament supply circuit and also the field of the high-voltage generator.

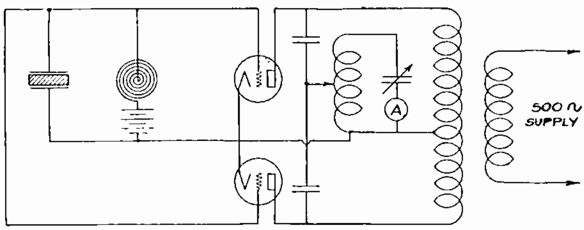

Fig. 19

A circuit breaker was placed in series with the negative terminal of the high voltage generator and when an overload was placed on the generator it opened the generator field circuit.

As a safety-first precaution, a condenser and a resistance was placed across the coil of the circuit breaker. These units maintained the negative side of the generator at ground potential should the breaker coil accidentally open. They also had a tendency to reduce line surges to a great extent by acting as a damping means.

MISCELLANEOUS

Very small output is obtainable from a crystal on the lower frequencies required of the transmitter and for this reason a small amount of regeneration was employed in the crystal circuit. The regenerative feature is shown in Fig. 18, by the grid feed-back coil in the crystal oscillator circuit. On the higher frequencies this coil was short-circuited, for as previously stated, regeneration, especially at higher frequencies than 400 Kc., is liable to crack the crystal.

The 50 Watt stage of amplification was required for the low-frequency amplification, but can be dispensed with at the high frequencies. With well made crystals and proper circuits, it is possible to use only two stages of amplification

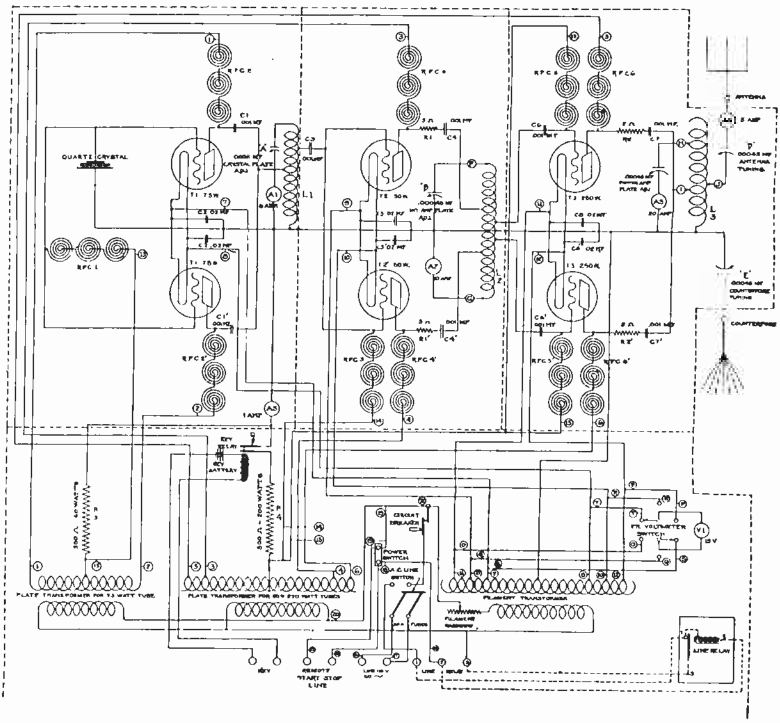

Fig. 20—Schematic Circuit of Crystal-Controlled Transmitter.

and obtain outputs in excess of 10 Kw. when operating the transmitter over the range from 400 to 600 Kc.

There was no need for frequency doubling in this transmitter and consequently no mention was made of it. Frequency doubling and tripling circuits were developed by Taylor and have been used very extensively in our numerous high-frequency transmitters which are in operation at N. K. F. This principle is also used in transmitters furnished by the Naval Research Laboratory to the Coast Guard, Army, Naval ships and stations.

The work covered in the construction of the low frequency transmitter was undertaken by A. Crossley with the assistance of W. F. McBride. Messrs. Gebhard, Young, White and Taylor were responsible for the development of the high power high-frequency transmitters.

The development of the low power high-frequency transmitter which derives its source of plate potential from alternating current circuits was undertaken by R. B. Meyer. Meyer developed the crystal oscillator circuit which employs one crystal and two tubes with the split transformer plate supply circuit. Best results are obtained with such a circuit when the frequency of the supply source is 500 or more cycles. The Meyer circuit is shown in Fig. 19. This circuit is used in transmitters designed and built for the Army and the Marine Corps. A schematic wiring diagram of this transmitter is shown in Fig. 20. An inspection of this diagram will show the automatic balance which is obtainable in the amplifier circuits when one resorts to the use of an alternating plate current supply. This balance is obtained by using approximately the same number of plate turns in each amplifier tube circuit.

This transmitter is designed for frequency doubling and is capable of covering a frequency range from 3,500 to 9,000 Kc. The rated output of the transmitter is 500 watts.

Figures 21 and 22 are photographs of this transmitter showing front and side views.

A method for obtaining more piezo-electric controlling voltage was developed by Taylor. This is accomplished by employing two crystals which have identical frequency characteristics and connecting these crystals in parallel with each other in the conventional circuit. Series stabilizing choke coils are placed in each crystal circuit for the purpose of holding both crystals in synchronism should temperature effects tend to change the natural frequency of the respective crystals.

Taylor also developed a method for obtaining three-phase source of radio-frequency by employing three synchronized crystal circuits which feed into a *Y*-connected output circuit.

Among other developments of the Naval Research Laboratory is a means for obtaining a crystal-controlled oscillating circuit which by use of stacked crystals and retuning of plate circuit can be made to generate currents of a frequency which corresponds to that of any crystal employed in the stack. The Western Electric type 211D tube is well adapted to crystal control.

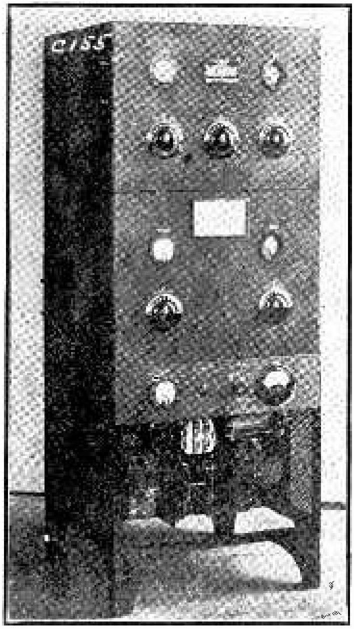

Fig. 21

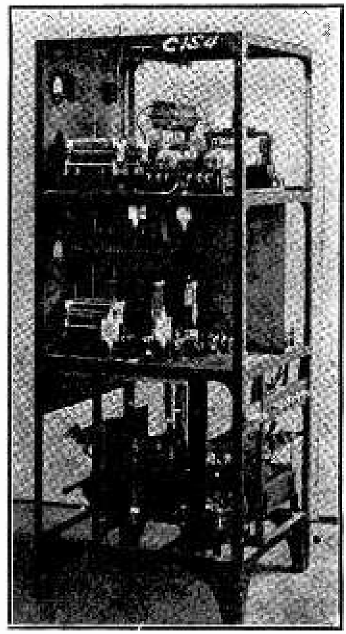

Fig. 22

CRYSTAL CONTROLLED BROADCAST AMPLIFIER

A schematic diagram of a 1-Kw. crystal-controlled amplifier which is used in some of the General Electric broadcast stations is shown in Fig. 23. The crystal-controlled tube, type UX-210, operates with the crystal connected between its grid and filament circuits. The plate circuit of the tube is tuned by means of a variable condenser which is designed to cover the broadcast frequency band. The crystals themselves are mounted on a temperature-controlled compartment and a thermostat is supplied in order to maintain the temperature constant at 45 degrees C. Provision is made for mounting four crystals, any one of which may readily be selected by means of a switch on the panel.

A second UX-210 tube is used to amplify the output from the crystal-controlled tube and this in turn is followed by a

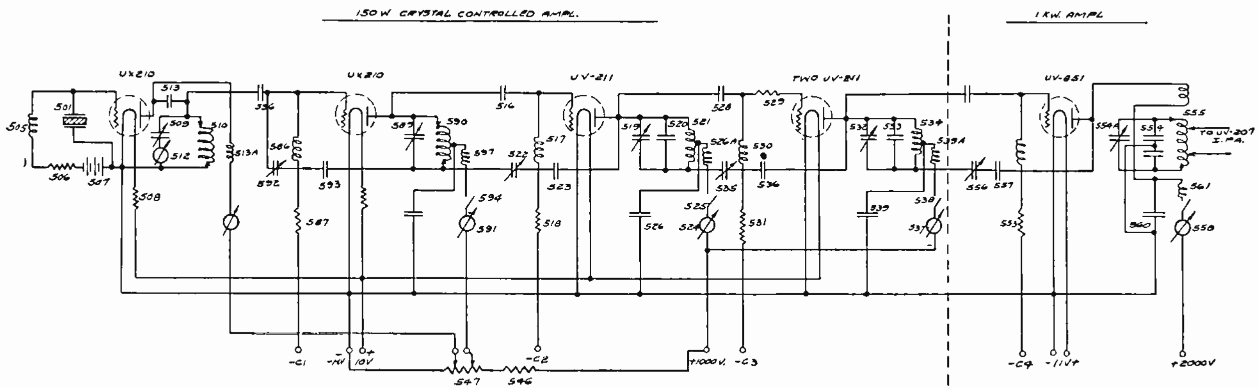

Fig. 23—Schematic Diagram Illustrating Various Circuits Employed in Crystal-Controlled Unit.

UV-211, 50 watt tube. Two additional UV-211 tubes connected in parallel amplify the output from the first UV-211 tube and these are followed by a 1-Kw. tube type UV-851. Straight amplification is employed throughout this unit, the crystal being ground for the final output frequency that is desired. Sufficient energy is available from the UV-851 stage to excite one or two water-cooled radio amplifier tubes.

TEST QUESTIONS

Number Your Answers 41 and add Your **Student Number**

1. State the material used and show, by a figure, how the crystal is cut from it.

2. Name several persons who contributed largely in the development of the piezo-electric crystal-control systems.

3. Draw a diagram of the fundamental Navy circuit crystal oscillator.

4. When employing a high-frequency crystal oscillator in the 3,000 Kc. band, how many watts output may be obtained?

5. What may stop a crystal from oscillating?

6. Will a change in temperature change the frequency of an oscillating crystal?

7. Can the power from a 3,000 Kc. crystal oscillator be amplified?

8. What is the chief trouble in the amplifier system of a crystal oscillator?

9. Draw a diagram showing how keying may be accomplished in a crystal oscillator.

10. What kind of tubes are mentioned in this lesson as being suitable for use in a crystal oscillator?

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