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C. R. TUBE ENGINEERING - 2

Investigation of R. F. Heating

The factory uses G. E. type 4 H.L. 4A oscillators, the essential circuit part of which is given in Figure 1.

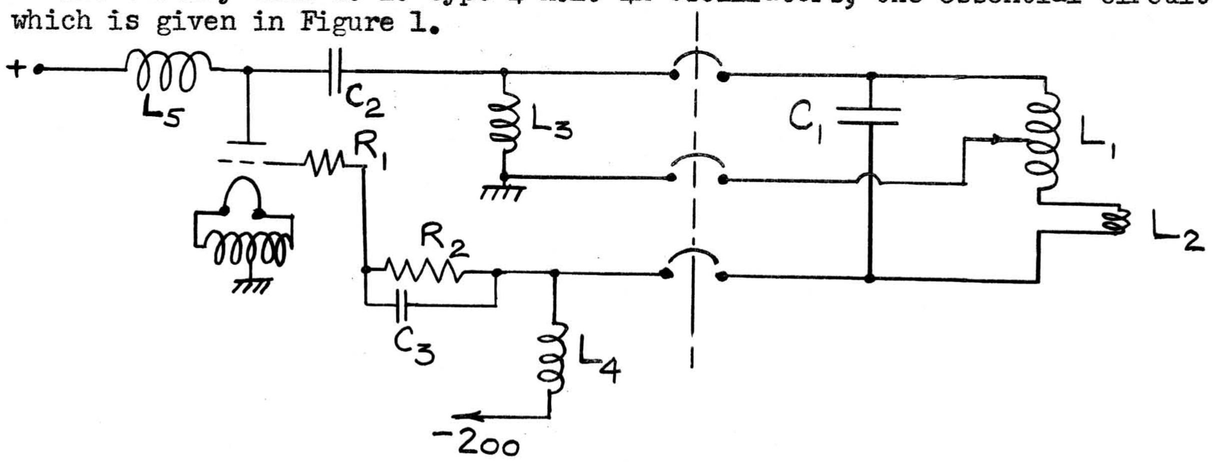

Figure 1

L_1 = tank coil
L_2 = work coil
C_1 = tank capacitor
L_3 = drainage choke
L_4 = R. F. choke

L_5 = R. F. choke
C_2 = blocking capacitor
C_3 = grid capacitor
R_1 = antiparasitic resistor
R_2 = grid leak resistor

The parts to the left of the dotted line, together with a power supply capable of giving a variable high voltage up to 2650 volts by means of a variac with a mechanical stop and a full wave rectifier using 2 - 866A rectifiers are mounted in a cabinet. The transmitting tube is a 833A type.

The frequency determining parts, namely L_1 + L_2 and C_1 are mounted on the buggies. The allowable frequencies are from 510 - 540 KC.

1. General Oscillator Considerations

The circuit is essentially a Hartley circuit, the necessary 180° between grid and plate R.F. voltages being obtained by grounding (that is connecting to the midpoint of the filament) a point on the inductance.

It should be realized that the following variables come into play (see figure 2)

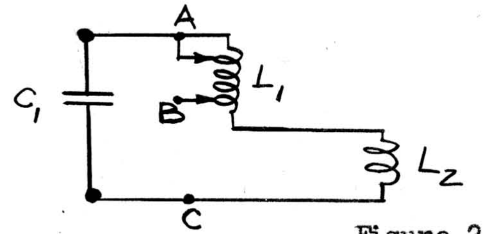

Figure 2

(a) The frequency is given by $L_1 + L_2$, C as follows: $w^2LC = 1$ in which $w = 2\pi n$ with n = frequency in cycles with L in Henrys and C in farads.

With the inductance values in microhenrys and C in microfarads to get the frequency in Kilocycles, the formula becomes

$$w_{k.c.} = \frac{10^3}{2\pi\sqrt{L_{\mu H}\, C_{\mu F}}} \qquad (1)$$

The frequency can then be varied, with a given fixed capacitor value (as mounted in the buggies) only by varying L, as for instance with a tap as indicated in figure 2.

(b) The tap connected to ground varies the feed-back voltage, that is for a given amount of R.F. circulating tank current (which for a given configuration sets the amount of heat), the total R.F. voltage between plate and grid (voltage A-C in figure 2 is given. The tap now only varies the ratio AB/BC, and therefore influences the efficiency more than anything.

(c) The output (and input) should be varied only by varying the D.C. plate voltage (variac adjustment) and once a good operating efficiency has been obtained this should be the main and only power control.

2. Calculations

2.1 Unloaded / Loaded

Ideal / Practical / Ideal / Practical

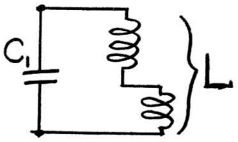

Fig 3a

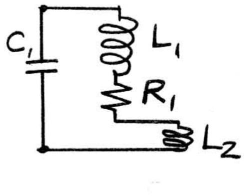

Fig 3b

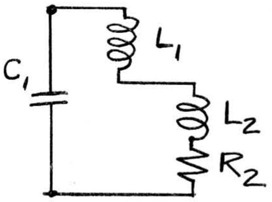

Fig 3c

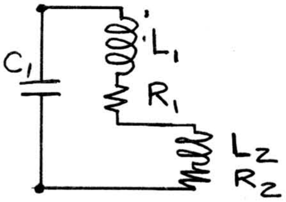

Fig 3d

Figure 3a shows the ideal circuit with loss - less components LC_1 under unloaded circumstances.

Note: Any disturbance set up in this circuit would maintain oscillations forever.

Figure 3b shows the practical unloaded circuit with a series resistance R_1 representing the losses. At the frequencies covered in this report the losses can be thought of as being caused by the inductance, the capacitor loss being negligible.

Figure 3c represents the ideal loaded circuit R_2 being the useful equivalent resistance which dissipates the useful power.

Finally, Figure 3d represents the practical circuit whereby R_2 has been added to R_1.

The power in all the above circuits is: I^2 (R_{total}), wherein $R_{total} = R_1$; R_2 or $R_2 + R_1$ and I is the circulating tank current. It is obvious that for good efficiency R_1 should be small.

2.2 Figure 4 shows A.C. and D.C. voltages and currents in the tube during a R.F. cycle. Although a close analysis can be made by simple considerations of load, power, etc., figure 4 which essentially depicts a graphical analysis or point by point method, is included only for a better understanding of the determining factors, which come into play.

The starting points are the static plate voltage versus plate current and plate voltage versus grid current curves published in the tube handbook (see for instance in the GE Transmitting Tube Handbook, sheets ETX 162A, which refer to the 833A type). The tank current produces an a.c. voltage (amplitude E_p AC in figure 4) which is superimposed upon the D.C. plate voltage E_pDC. When sufficient circulating tank current is assumed (and certainly in the factory R.F. equipment this is the case) the A.C. voltage is a sine wave at fundamental frequency as indicated. One can generally assume for good efficiency that the amplitude of this A.C. voltage should be 80% of the D.C. voltage, in other words the momentaneous plate-filament (e_p mom in figure 4) varies between 1.8 and 0.2 $E_{P\ DC}$, also $E_{P\ MIN}$ and E_{PMAX}. Now assume a grid-drive voltage, 180° out of phase with the A.C. plate voltage on the same vertical voltage scale (note that figure 4 is not to scale). Good values are generally those given in the handbook; for instance on page 3 of the handbook for C.C.S. (continuous commercial service), D.C. grid voltage -200, and Peak R.F. grid voltage 360. These are $E_{G\ DC}$ and $E_{G\ AC}$ in figure 4. Note that the grid in this example swings 160 volts positive. We now know the momentaneous plate and grid voltages ($E_{p\ mom}$ and $E_{G\ MOM}$) and from the static curves in the handbook can construct the plate and grid current curves $i_{p\ ac}$ and $i_{g\ ac}$. Note that a very high peak plate current pulse is produced. If we integrate the surface under $i_{p\ ac}$ and divide by one cycle on the time axis, we can construct a rectangle of equal surface the height of which is $i_{p\ dc}$, and this is what a plate current D.C. meter will show, similarly for grid current.

The plate dissipation is again the average over one cycle of multiplying momentaneous plate voltage by momentaneous plate current. Note here that when plate current is maximum, momentaneous plate voltage is minimum ($E_{p\ min}$) and that when plate voltage is maximum ($E_{P\ MAX}$) plate current is zero, thus making average plate dissipation low.

Input in D.C. plate voltage X DC plate current ($E_{P\ DC}$ X $L_{P\ DC}$) and therefore output has to be the difference between input and plate dissipation. Another way of visualizing output is to notice that the first harmonic or fundamental of the plate current pulse multiplied by the A.C. plate voltage represents the output.

From this brief description it now becomes obvious that to get high output, we need sufficient grid drive so that the plate current pulse is high and therefore this pulse impressed on the load (tuned circuit) produces a high A.C. plate voltage, making $E_{P\,MIN}$ low and therefore dissipation (loss) low. The necessary negative grid voltage can be obtained by sending the grid current ($I_{g\,DC}$) through a resistor of such value to give $E_{G\,DC}$ as assumed for the operating condition. The voltage can also be obtained by a power supply of good regulation, or a combination of both. The above operation whereby maximum efficiency is obtained by having the plate current flow during essentially less than half a R.F. cycle is class C operation.

2.3 The only reference made to the load circuit under 2.2 was when it was mentioned that the load should produce the assumed and desired A.C. voltage. Now therefore,

$$I\,Z = E \qquad (2)$$

If we take E as $E_{peak\,AC}$ we should also take the peak current of the fundamental to find Z. (This is not the peak plate current of figure 4). Z has one of the 4 configurations of figure 3 and will be figure 3b for the unloaded and figure 3d for the loaded condition. Keeping in mind that the A.C. voltage is essentially produced by the tank current flowing either through the capacitor or the inductor we can calculate this voltage as follows:

frequency range 510 - 540 K.C.
capacitor value recommended by instruction book 0.006 µfd

then impedance = $1/WC = 10^6/2\pi\ 520000\ \ 0.006 = \pm 50$ ohms

If the tank current is 40 amps the R.M.S. voltage is 50 x 40 = 2000 volts or 2820 volts peak. This (see figure 2) is the voltage between grid and plate. To get the plate A.C. voltage ($E_{P\,AC}$ in figure 4) substract the grid A.C. voltage.

If we take the values recommended in the equipment instruction book the grid drive is given as 210 volts RMS = 292 volts peak, say 300. We then get A.C. plate voltage = 2820 - 300 = ± 2500 volts peak. Compare this to the DC voltage of 2650 as recommended giving minimum plate voltage 150 volts which should give good efficiency. As a matter of fact the minimum plate voltage seems too low.

Now, as far as the circuit goes, the tube is just a device to send current through the circuit and produce the above 2500 volts peak = 1750 volts RMS. We then have:

$$E^2/Z = \text{power and } Z = E^2/\text{power} \qquad (3)$$

In our example to get 500 watts

$$Z = 1750^2/500 = 6125 \text{ ohms} \qquad (4)$$

This impedance should be presented between plate and filament that is it should be the plate load (AB in figure 2). The total circuit impedance from plate to grid is then increased by the grid filament portion. Assuming unity coupling between all the windings (not necessarily true but close enough for calculations) the impendance goes with the square of the number of turns. In our case

$$\frac{300}{2500} \quad \begin{matrix}\text{grid a.c. voltage}\\ \text{plate a.c. voltage}\end{matrix}$$

then:

$$(\,(3/25)^2 \times 6125) + 6125 = 7213 \text{ ohms}$$ is the total circuit impedance from plate to grid. This equals L/RC in which

L in henries
C in farads
R in ohms

L is the inductance needed to resonate with C (0.006 ufd) at 510 - 540 K.C. which is the operating frequency range. Taking 525 K.C. as an average frequency, we get from (1)

$$525 = \frac{10^3}{2\pi\sqrt{L_{\mu H} \times 0.006}}$$

which gives L = ± 15.1 μH.

Substituting this value in Z = L/RC we get

$$R = \frac{L}{ZC} = \frac{15.1 \times 10^{-6}}{7213 \times 0.006 \times 10^{-6}} = 0.35 \text{ ohms} \qquad (5)$$

The above analysis seems somewhat tedious and is only shown to give a fuller understanding of the impedance orders to be expencted.

A simpler way to get at the aequivalent series resistance R is to realize that the 40 amps tank current flowing through R should give 500 watts. Thus $I^2R = 500$

$$R = 500/I^2 = 500/1600 = 0.33 \text{ ohms} \qquad (6)$$

Inspection of the values obtained between (5) and (6) shows that we are really dealing with very low R values, and that extra circuit losses such as shown in figures 3b and 3d should be kept extremely low.

For instance a 0.1 ohm loss resistance would absorb 160 watts with the above circulating current values and increase the necessary input by ± 300 watts. In general R.F. oscillators for heating are designed for high tank current because the ampere turns produce heat in the work piece. But this implies the best known techniques to keep other losses down.

3. Practical Considerations and Measurements Made on Equipment

3.1 Useful inductance formula. For the configuration of figure 5 a good formula to use is:

$$L_{\mu H} = \frac{0.2\, a^2 n^2}{3a + 9b + 10c}$$

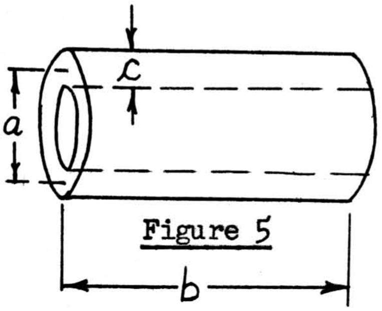

Figure 5

in which
n = number of turns
a = mean diameter in inches
b = length in inches
c = depth in inches

c is in general the wire or tube diameter

For flat wound coils use C as would result from the same material surface using a square instead of a reactangular cross section.

3.2 The Q concept.

Losses are generally in the coils. Capacitor losses can be neglected. Q is defined as:

$$\frac{\text{impedance at working frequency}}{\text{resistance}}$$

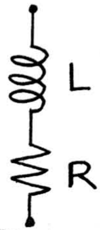

Figure 6

For figure 6 $Q = WL/R$ or $R = WL/Q$

In general so called Q meters make use of the following circuit:

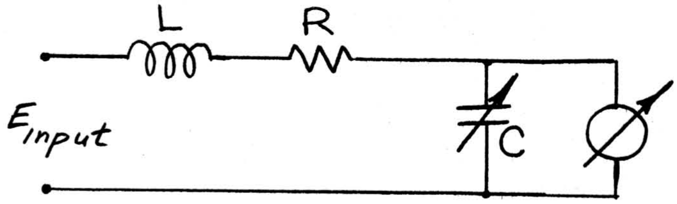

Figure 7

At resonance $WL = 1/WC$ and by introducing a standard voltage (generally around 1 volt) at E input, we have:

$$I = \frac{E}{R}$$

The circuit is tuned to series resonance by a variable capacitor C in figure 7. A voltage across C is now measured. This voltage is:

$$\frac{I}{WC} = \frac{E}{RWC} = \frac{E\,WL}{R} = E\,Q \qquad (7)$$

The meter showing this voltage can then be calibrated at once in Q for a given constant input voltage. The instrument we used was a Boonton Q meter which operates on the above principle.

If we know Q and we know the frequency, and the inductance value, we know R. By measuring various coil configurations and positions relative to the iron parts encountered in the buggies, some very interesting improvements in positioning of the elements could be demonstrated.

Note: The capacitance values used in the Q meters are generally lower than those in the tank circuits to be measured (± 500 µµ fd) to bring the instrument in range for the components used, connect fixed capacitors of good quality (mica!!!) in parallel with the variable capacitor C in figure 7. Terminals are provided for this purpose on the Q meter.

3.3 Measurements

Before proceeding with the measurements, calculate the aequivalent Q of the final loaded tank circuit in which previous calculations R = 0.35 Ω (equals 5) and L ; 15.1 µH.

$$\text{Then } Q = \frac{2\pi \times 525000 \times 15.1 \times 10^{-6}}{0.35} = \pm\ \underline{\underline{156}} \qquad (8)$$

Q of the unloaded circuit should be at least two or three times higher than this.

It is not thought necessary to give here all the detailed measurements made in the circuit and its components. It should be mentioned here however, that the unloaded circuit as mounted in the buggy from which experiments started had a Q of 70 - 75 !!! and therefore excessive heating and low efficiency was to be expected.

The worst offender was the tank coil as used and another tank coil with better geometry and silver plated windings (± 4 mils for this frequency) was built and measured.

A "Johnson" inductance was also measured and found to be slightly lower in Q than our new coil. The inductance of the Johnson coil was also too low, and the desired frequency could only be obtained by incorporating long leads(that is making big loops) between the tank and work coil).

Another important factor are the interconnections between coils and capacitor. As used in the buggies they are plain copper tubing. As long as a flat thin conductor (or a multiplicity of parallel conductors of this form) has minimum R.F. resistance it was shown that replacing the copper tubing by flat copper strips (used in the factory for ground strips) reduced the R.F. resistance by ± 0.07 ohms. With full load (± 40 amps tank current) we reduced therefore the losses by 1600 x 0.07 =112 watts!! It is recommended that excellent contact and silver plating of at least the connecting ends of these strips to the coils be maintained. The silvered springs and screws (brass!!) as made for our recommended coil are satisfactory if tightened.

The work coil could be improved. Granted that some support is needed for this coil, it is nevertheless interesting to note that the stripped coil alone showd 0.02 ohms improvement over the structure as used.

Wiring and Placement of Parts

Not much can be done about the placement of the work coil and therefore long leads result from the connections between the tank coil and the work coil. The following observations seem to be in order.

(a) The tank coil will have a (unwanted) field to ground and losses in this field are dependent upon voltage as the a.c. grid voltage is lower than the a.c. plate voltage we will then gain by

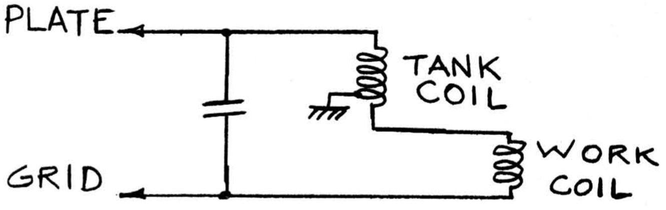

Figure 8a

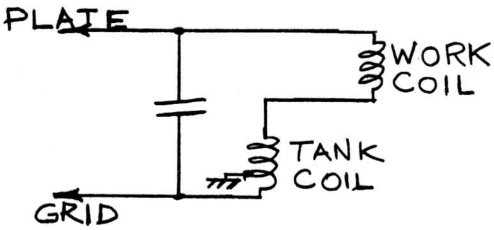

Figure 8b

connecting the work coil at the grid end as indicated in figure 8a, rather than as used now (figure 8b).

(b)

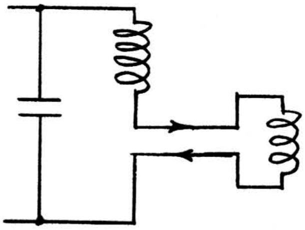

Figure 9a

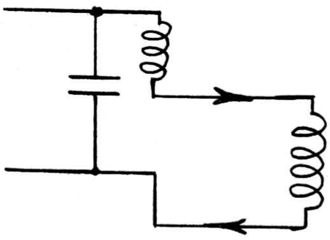

Figure 9b

If long leads must be used a situation as per figure 9a is to be preferred over figure 9b. The loop current in figure 9a cannot give much external field and therefore there will be less losses due to the induction in neighboring metal conductors, mounting strips, switch boxes, etc. Compare with figure 9b.

c. The tank coil can have a better position than the present one in use. This was demonstrated with a Q meter. It is recommended that this new position be adopted.

d. The tank current is a main measure of heating power for a given configuration and should be considered. R.F. ammeters for these ranges are available, but their use involves opening the tank circuit at some convenient point. As this is rather cumbersome a peak-volt meter was constructed and its use demonstrated. The device is based on the fact that a certain current flowing through an impedance produces a voltage. In figure 10 this voltage across one or two turns (from the ground tap is measured. The scale of the instrument is linear which is a big advantage. The load resistor is several megohms and therefore the circuit does not alter the load imposed on the generator. The leads between the voltmeter and the tank coil should be kept short and close together, concentric cable can be used. The instrument is available.

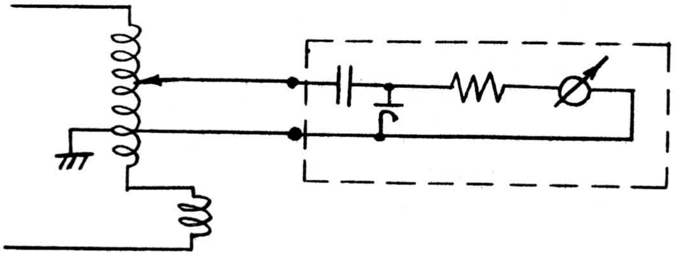

Figure 10

Adjustment of Individual Buggies

Individual buggies passing a certain position should produce the same heat or reasonably close so.

The variac adjustment can be set only once for a general adjustment of high voltage.

It should be pointed out here that although variations from buggy to buggy are to be expected, these variations in present factory practice are probably bigger than should be obtained and could be considerably reduced by careful and uniform parts placement and inter-parts wiring.

It is highly probable that the big open loops as now used and the rather strong fields set up by these (see figure 9b as opposed to 9a) are important, if not the main offenders to cause non-uniformity. Reduction of those fields should prove beneficial to obtain uniformity from buggy to buggy. If it must be, further adjustment can be made by the ground tap position.

Heat Measurement

A R.F. meter or the peak voltmeter just described should be the indicator for tank current. Heat should then be close to a uniform value for each buggy.

The present system of heat measurement can give errors (oxide on the metal, drafts in the room, exact placement of the part, etc.).

It is suggested that a small tungsten disc together with a carbon anode disc be built in a small vacuum tube. If this device is placed in the field the tungsten will be heated and constitute a temperature limited emitter. The diode current to the anode can now be measured and gives the temperature of the tungsten emitter, that is the heat produced.

No such device has been built yet but it should be entirely feasible.

/fmd A. C. Nonnekens