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LABORATORIES

OF

THE NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION



# RADIO-FREQUENCY HEATING

OTTAWA

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# RADIO-FREQUENCY HEATING

by

J.A. Hopps



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|---|---|---|
| Introductory pages | - | 3 |
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Ottawa, June, 1949.

ABSTRACT

The basic fundamentals of radio-frequency heating are outlined, and the scope of its application is discussed briefly. Elementary equations for determination of operating parameters, typical oscillator circuits, and photographs of press and electrode systems are given.

## CONTENTS

# RADIO-FREQUENCY HEATING

## I

## INTRODUCTION

During 1948, some experimental work was undertaken by the Radio and Electrical Engineering Division of the National Research Council of Canada to determine the applicability of radio-frequency heating to process work within the laboratories of the Council. Two self-excited oscillators were constructed and operated with various press and electrode arrangements, for such applications as wood-gluing, paint-curing, and drying of freshly developed photographic film, where acceleration of the heating cycle offered obvious advantages. In particular, the experiments in wood-gluing indicated a practical application, and a report on this subject was projected.

While the report was in preparation, an inquiry received by the Division of Information Services, requesting information and recommendations for a proposed industrial application of dielectric heating, was forwarded for comment. The present report is based on a paper submitted to the Division of Information Services to supplement other data dealing with the particular adaptation, and for that reason is expressed in very general terms.

It is not, therefore, the intention of this paper to give a detailed treatise on radio-frequency techniques, but rather to explain briefly its basic principles and to indicate the scope of its application. Fundamental equations are given for the determination of operating parameters for specific applications.

## II

## PRINCIPLES OF RADIO-FREQUENCY HEATING

When a material of high dielectric loss factor is placed in a high-frequency electromagnetic field, energy is dissipated in the form of heat simultaneously throughout the entire mass. It is this internal heating characteristic which constitutes the prime advantage of radio-frequency heating over steam platen, oven, or other conventional heating techniques, wherein the heat is applied externally and must permeate to the centre of the material.

Materials of high conductivity have low dielectric constants, and offer little resistance to the passage of high-frequency current. Such materials are unsuited to dielectric heating, but in the case of inductive metals, induction heating at lower frequencies has wide applications.

The material to be heated by dielectric means acts as the load on the radio-frequency power generator. The power absorbed by this load varies directly with the product of the dielectric constant and the power factor, and this product is the dielectric loss factor mentioned above. The dielectric loss factor of the material being heated must be known for efficient generator and electrode design, to meet the requirements of a specific application.

A radio-frequency heating equipment is comprised of a high-frequency oscillator, power supply and electrode system, with associated matching and coupling circuits. The material to be heated forms the dielectric between electrodes coupled to the plate circuit of the oscillator, acting as a condenser with capacitive-resistive loading effect.

## III

## OSCILLATOR DESIGN

To generate the large amount of power required for dielectric heating, self-excited feed-back oscillators are used. The Hartley circuit is favoured extensively, since conditions of oscillation are not critical. The amplitude of oscillation may be controlled easily by adjustment of the tap on the oscillator coil. The tuned-plate oscillator also provides a stable circuit, but grid coupling is more critical in adjustment. Either circuit may be modified to use two tubes in parallel or in push-pull, the push-pull operation being particularly suited for use at radio-frequency heating frequencies.

Circuits are included in this report for a single-tube, 400-watt, tuned-plate oscillator, and for a two-tube, 1200-watt, push-pull Hartley oscillator. Both oscillators were constructed by the Radio and Electrical Engineering Division of the Laboratories of the National Research Council, and provided satisfactory service for radio-frequency heating.

Where possible, one side of the output of the oscillator should be at ground potential, for convenience of electrode arrangement and to decrease the danger of shock. Output coupling may be direct, using taps on the tank coil, or inductive, with adjustable links. The adjustable inductive coupling system provides convenient panel control.

Temperature variation in the tank circuit components will affect the oscillator frequency stability and cut down the output power. The circulating current portion of the oscillator should provide maximum conductivity, and the coil(s) should be of adequate size to avoid over-heating, and should preferably be silver-plated to increase efficiency. The tank condenser may be of fixed-plate, multi-section design, with various ganging arrangements for capacity variation, or it may be of the vacuum type. Plug-in type coils and interchangeable condensers provide for variation of the oscillator frequency.

Radio-frequency components should be carefully insulated to guard against corona loss. Insulators of high dielectric strength, with corona shields, will improve the design. Interlocks and protective insulation should be provided to eliminate the danger of radio-frequency burns while servicing the oscillator.

Parallel feed to the oscillator is to be preferred, to prevent radio-frequency leakage to the power lines. The plate radio-frequency chokes should be of adequate impedance to block any appreciable radio-frequency passage, and may be supplemented by power line chokes, for added protection.

Power supply design should provide adequate direct-current power for the full, rated, radio-frequency oscillator output, and time-delay protection for the plates of the rectifier tubes. Moderate filtering is warranted by the increased efficiency of the oscillator circuit.

## IV

## ELECTRODE DESIGN

The capacity of the condenser formed by the dielectric load between two electrodes is given by the equation:

$$C = 0.225 \frac{Ka}{d} \mu\mu f \qquad \text{..................(1)}$$

where, K is the dielectric constant,
a is the area, in square inches, and
d is the spacing of the electrodes, in inches.

The value of capacity, thus calculated, is required in determination of the output power and voltage necessary for the heating application.

In general, there are two methods of applying the electrodes to the load. Transverse heating places the load directly between the two electrodes, and utilizes the entire energy of the radio-frequency field. A variation of transverse heating is used in the gluing of plywood sheets, where the "hot" electrode is sandwiched between two identical loads and the press serves as the grounded electrode.

Stray field heating, as the name implies, uses only that portion of the field not directly between the electrodes, which are placed side-by-side on one face of the load. Because of its low efficiency, stray field heating is seldom used in industrial application, except where it is impossible to place the electrodes on opposite faces of the load, or where a surface heat concentration is desired.

For equal concentration of energy over the area of the electrodes, they must be spaced an equal distance apart at all points, assuming the load to be of constant density. If the load does not permit placing of parallel electrodes on its faces, the energy distribution may be equalized either by using flat electrodes and "padding" the space between electrodes and load with material of dielectric constant close to that of the load, or by using electrodes shaped or perforated to offset the irregularities of the load.

Electrodes made of copper screening may be used effectively to reduce the capacity, for applications where low-energy concentrations are required through portions of the load. Returning again to the example of wood-gluing, in many cases it is necessary only to cure a few lines of glue in each joint with high heat concentrations, while the rest of the surface receives only a low concentration, or none at all. The fully cured glue lines maintain pressure, while the balance of the glued surface cures slowly at a lower temperature.

Design of electrodes is perhaps the most critical feature of dielectric heating. As noted above, their shape and form critically control the amount of heat generated in the load. Equally critical in the design is the necessity of avoiding sharp angles or edges on which corona discharge can take place. Electrode shape must minimize dissipation of energy through radiation, which is not only wasteful, but a source of objectionable interference, subject to governmental radio regulations. Finally, care must be taken to eliminate the effect of standing waves along electrodes of excessive length. This condition is discussed further in the section dealing with load coupling and matching.

## V

## DETERMINATION OF HEAT REQUIREMENT

In a specific heating application the final temperature reached in the material may or may not be critical, but it must be established before heat calculations can be made. The difference between initial and final temperature, known as the temperature gradient, governs the amount of heat required during the heating cycle. This heat is given by the equation:

$$H = Sp \times W (t_2 - t_1) \text{ B.T.U.'s} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $Sp$ is the specific heat of the material,
$W$ is the weight of the material, and
$t_2 - t_1$ is the temperature gradient.

The oscillator power required to generate this heat is given by:

$$P = \frac{H}{\text{time} \times 57} \text{ in kw, (r.f.)} \qquad \text{..........(3)}$$

where time is expressed in minutes.

Since radio-frequency oscillators are about 50 per cent efficient in operation, the input power must be approximately double the calculated oscillator output rating.

VI

## SELECTION OF FREQUENCY AND POWER OUTPUT

If the electrodes and dielectric load of a radio-frequency heater are considered as forming a series resistive-capacitive element, the impedance offered to the radio-frequency voltage will be:

$$Z = \sqrt{R^2 + X_c^2} \text{ ohms,} \qquad \text{................. (4)}$$

where R is the resistance, in ohms, and
$X_c$ is the capacitive reactance, in ohms.

The power absorbed by the load will be:

$$P = \frac{E^2}{Z} \cos\theta \text{ (watts)} \qquad \text{.................. (5)}$$

where E is the radio-frequency voltage, and
$\cos\theta$ is the power factor of the dielectric.

Substituting for Z in (5),

$$P = \frac{E^2}{\sqrt{R^2 + X_c^2}} \cos\theta = \frac{E^2}{X_c} \cdot \frac{X_c}{\sqrt{R^2 + X_c^2}} \cdot \cos\theta$$

$$\text{But } \frac{X_c}{\sqrt{R^2 + X_c^2}} = \sin\theta = \sqrt{1 - \cos^2\theta}$$

$$\text{whence, } P = \frac{E^2}{X_c} \sqrt{1 - \cos^2\theta} \cdot \cos\theta \qquad \text{............. (6)}$$

$$X_C = \frac{10^6}{2\pi fC} \text{ (ohms)} = \frac{10^6 \cdot d}{2\pi f \cdot 0.225 \text{ Ka}} \text{ (ohms)}$$

where f is the frequency, in megacycles,
and C is the capacity (from (1)) in micromicrofarads.

Substituting for $X_C$ in (6),

$$P = 10^{-6} E^2 \cdot 2\pi f \cdot 0.225 \frac{Ka}{d} \sqrt{1 - \cos^2 \theta} \cos \theta$$

$$= 1.415 \times 10^{-6} f E^2 \frac{Ka}{d} \sqrt{1 - \cos^2 \theta} \cos \theta \quad \ldots\ldots\ldots(7)$$

When the power factor does not exceed 25 per cent,

$\sqrt{1 - \cos^2\theta}$ approximates 1, giving a further simplification,

$$P = 1.415 \times 10^{-6} f E^2 K \cos \theta \text{ watts/cubic inch} \quad \ldots\ldots\ldots(8)$$

The capacity of the condenser formed by the electrodes and dielectric load is proportional to the dielectric constant of the load, and the power is therefore proportional to the dielectric loss factor.

From (8) it is evident that an increase of frequency lowers the required radio-frequency voltage and lessens the problem of electrode insulation. The optimum frequency of operation will depend in part on the dielectric loss factor of the material, and also on such factors as length of electrodes, and distance from the oscillator unit to the press or electrode system, as discussed below.

## VII

## COUPLING AND MATCHING THE LOAD

A concentric transmission line is used frequently to connect the electrodes to the oscillator unit, with the grounded outer conductor acting as an effective shield. In order to reduce to a minimum the volt-amperes in the line, an inductance may be shunted across the electrodes, bringing the press to parallel resonance. The change of capacity during the heating cycle will, of course, detune the circuit and affect the loading.

If the transmission line is made a quarter-wavelength for the output frequency of the oscillator, the quarter-wave line will act as an impedance-matching transformer, stepping down a large capacitive reactance variation to a small capacitive reactance variation at the oscillator, and hence reducing the loading variation due to change of dielectric loss factor during the heating cycle. The line should be coupled to the oscillator through a large reactance (a reactance of the order of from five to ten times the line impedance is a suggested value) to improve the loading stability. When the distance from the oscillator unit to the electrodes is less than a quarter-wavelength, the concentric line can be extended to a quarter-wavelength by means of a simple T-network.

Variable inductances or variometers are frequently used in the output circuit for matching the load, and provide much better control than fixed coils, despite mechanical difficulties of construction.

In the application of radio-frequency heating to heating operations requiring long electrode systems, care must be taken to prevent standing waves on the electrodes, which may be considered as unterminated transmission lines. An examination of the voltage distribution along transmission lines indicates that where the electrode system is longer than a quarter-wavelength, points of zero voltage exist along the lines commencing at points a quarter-wave from the open ends. When the electrode length is appreciably less than a quarter-wave, the voltage gradient along the electrode is of little importance.

In the case of electrodes of shorter length than a quarter-wave, the ratio of minimum to maximum voltage is given by the equation:

$$E_{min}/E_{max} = \cos(360L/\lambda)$$

where $L$ is the length of the electrodes, in feet, and $\lambda$ is the wavelength, in feet.

Where it is impossible to use electrodes of shorter length than a quarter-wave, multiple-feed arrangements are used to improve the voltage distribution. An improvement over this method is a patented system[1], whereby the electrodes are parallel-tuned by a series of coils dividing the electrodes into sections. By the use of parallel tuning stubs, the voltage over a long electrode can be made almost uniform.

## VIII

## COSTS AND OTHER CONSIDERATIONS

In any proposed application of radio-frequency heating to an industrial process, the capital cost and operating expense will be a prime consideration. The cost of commercial oscillators is high. It has been estimated that, for small generators, the cost is of the order of $1500 per kilowatt output, and for generators of from ten to fifteen kilowatts output, from $800 to $1200 per kilowatt output[2]. Tube replacement cost accounts for most of the operating expense, which may run as low as 35 cents an hour for a one-kilowatt unit, or from 75 to 90 cents an hour for a ten-kilowatt output oscillator.

A comparison of initial costs and operating expenses may well show the economy of using other heating processes in preference to radio-frequency heating. However, other factors should be considered. A high-frequency oscillator is a much more versatile source of heat energy than most other heat sources, and conversion costs from one operation to another are low. Also, the speed of radio-frequency heating - minutes, or even seconds, instead of hours - may effect considerable saving in plant design, by reducing the size of process equipment, and, in some cases, by eliminating warehouse space required for curing or drying in other processes. In applications, such as plastic molding, rubber curing, or wood gluing, where the material is heat-treated under pressure, the press design is simplified and inexpensive as compared with the press requirements of other heating methods.

It should not be assumed that radio-frequency heating is a practical means of applying heat to every dielectric material. In many instances electrode design inevitably will be inefficient, with high heat loss. Also, irregular density variation in the material will prevent uniform heat distribution, sometimes with unsatisfactory results. In the National Research Laboratories, experimental attempts to dry freshly developed survey film showed that with transverse heating there was a danger of puncturing the film electrically at points

(1) Patented by R.A. Bierwirth, RCA Laboratories, U.S.A.
(2) D.G. Miller, Forest Products Laboratory, Ottawa.

where warp in the film put it in close proximity to the electrode. Use of stray field electrodes on either side of the film eliminated this danger, at a sacrifice of efficiency, but the irregular silver deposit on the film made it difficult to apply a uniform heat distribution, and further warping of the film resulted. Careful analysis of technical difficulties in application, and of the quality of the finished product, are necessary to determine the applicability of radio-frequency heating in any specific case.

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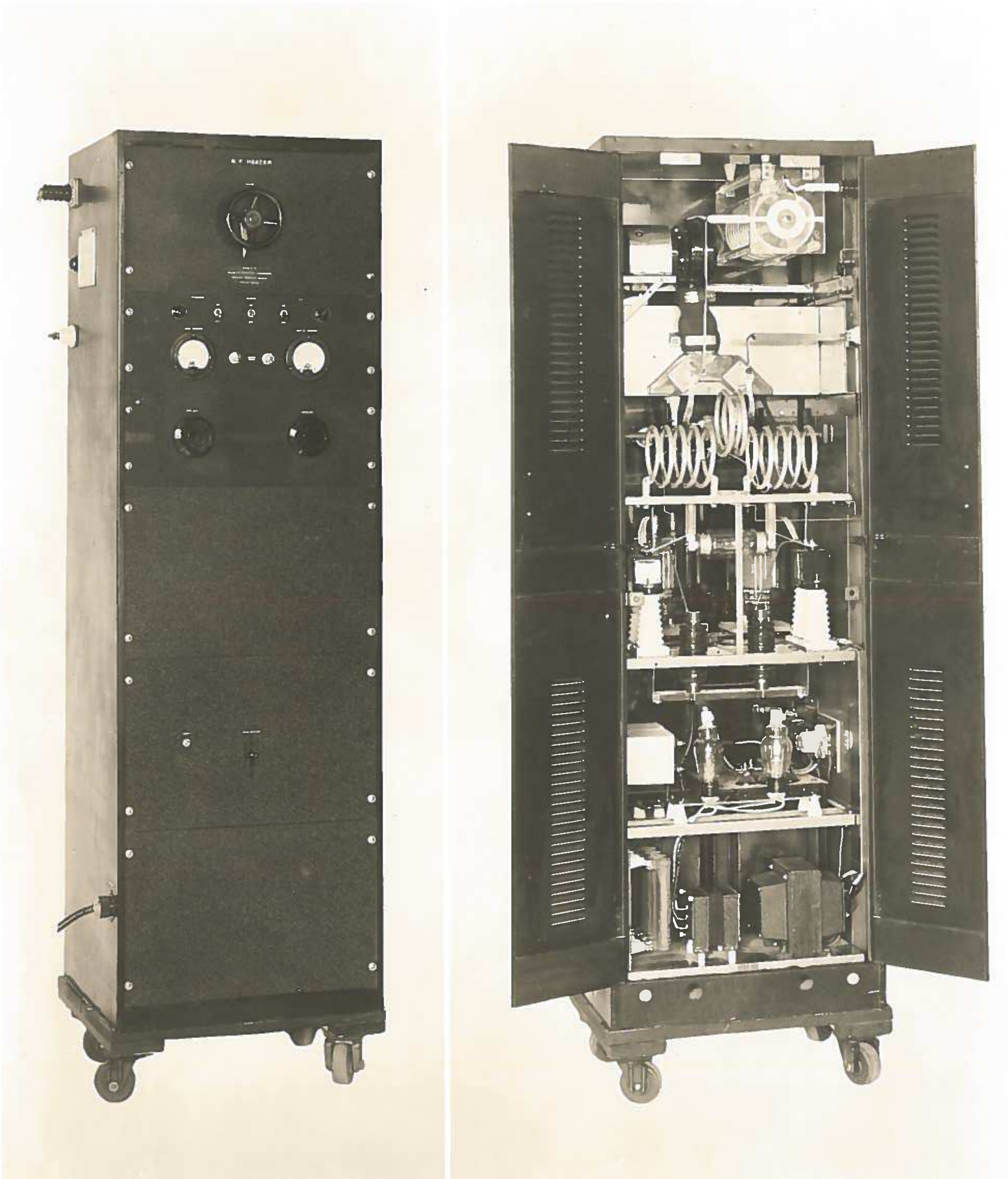


Front View                                                Back View

Photo I

1200 - Watt Radio - Frequency Generator

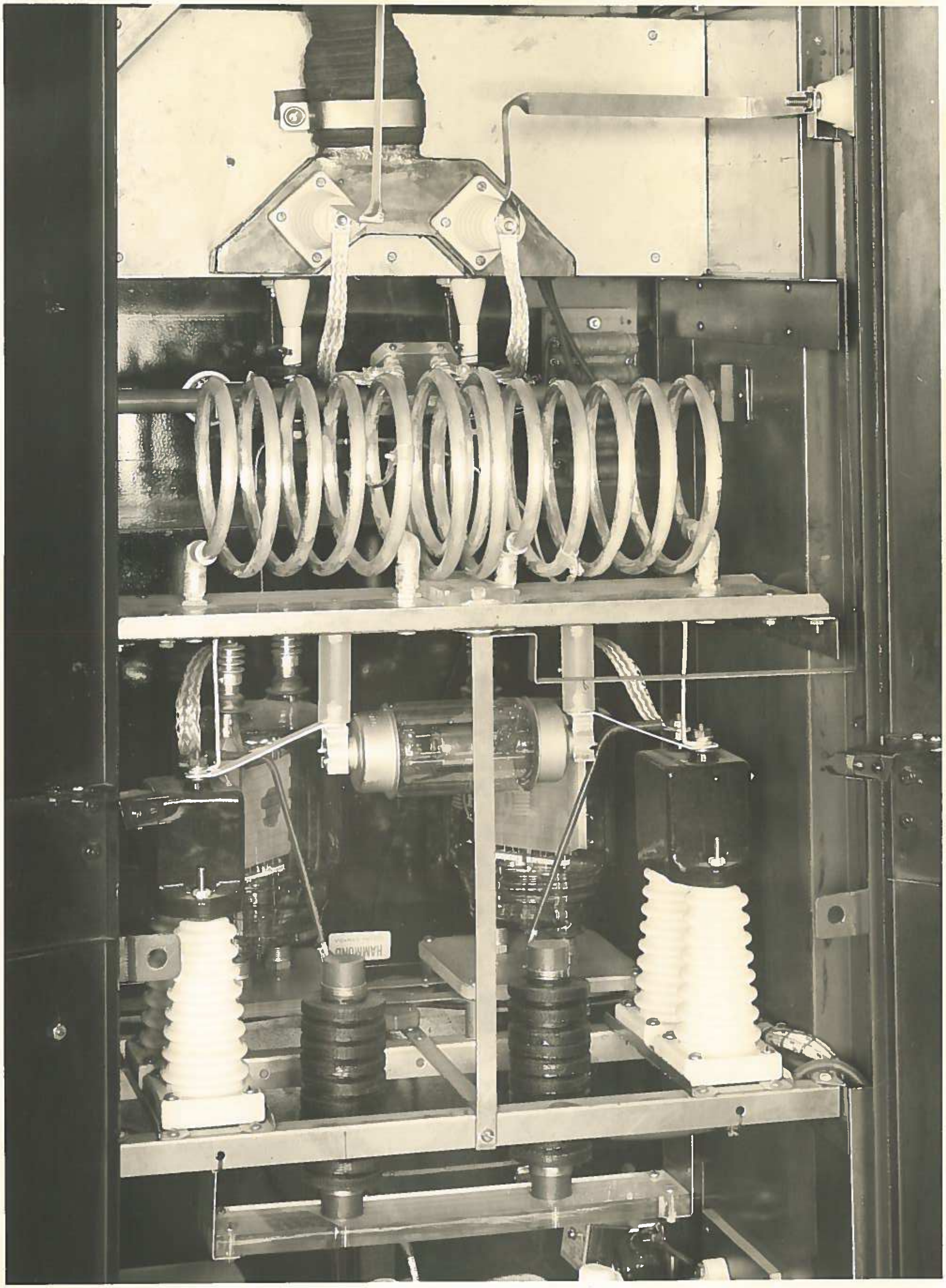


Photo 2
1200 - Watt Radio - Frequency Generator
Details of Oscillator and Tuning Sections

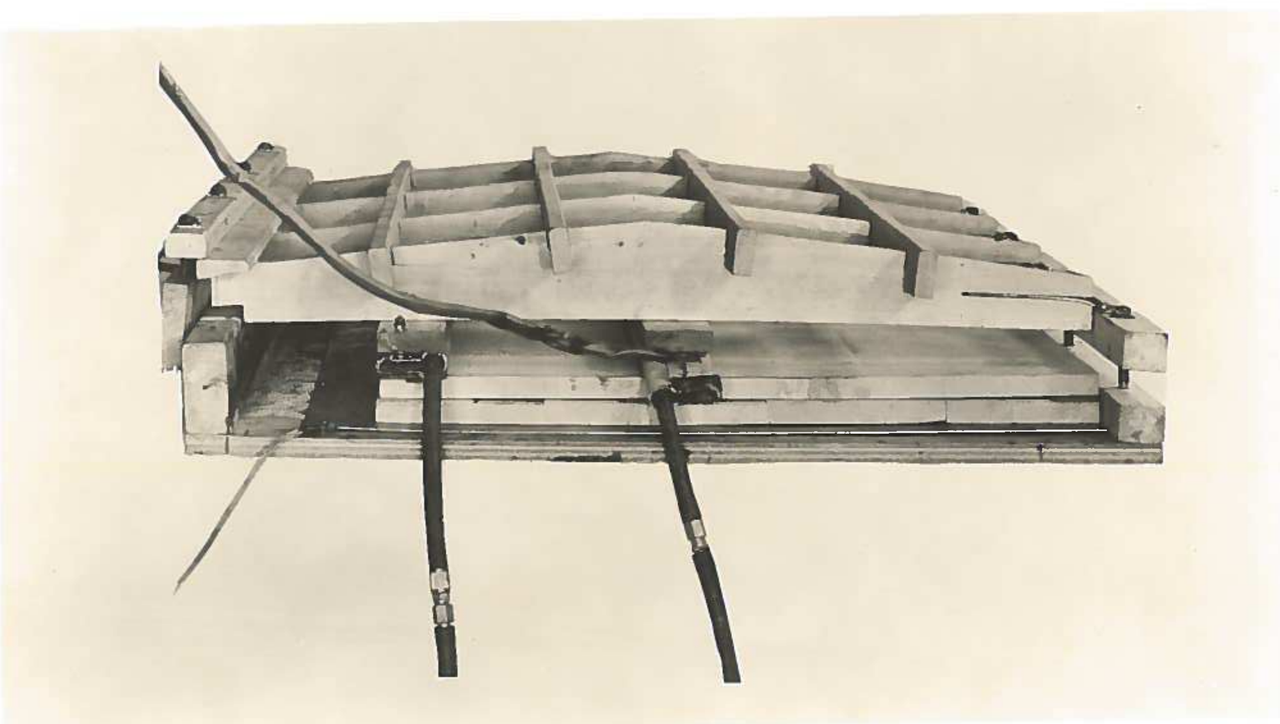
Photo 3

400 - Watt Radio - Frequency Generator

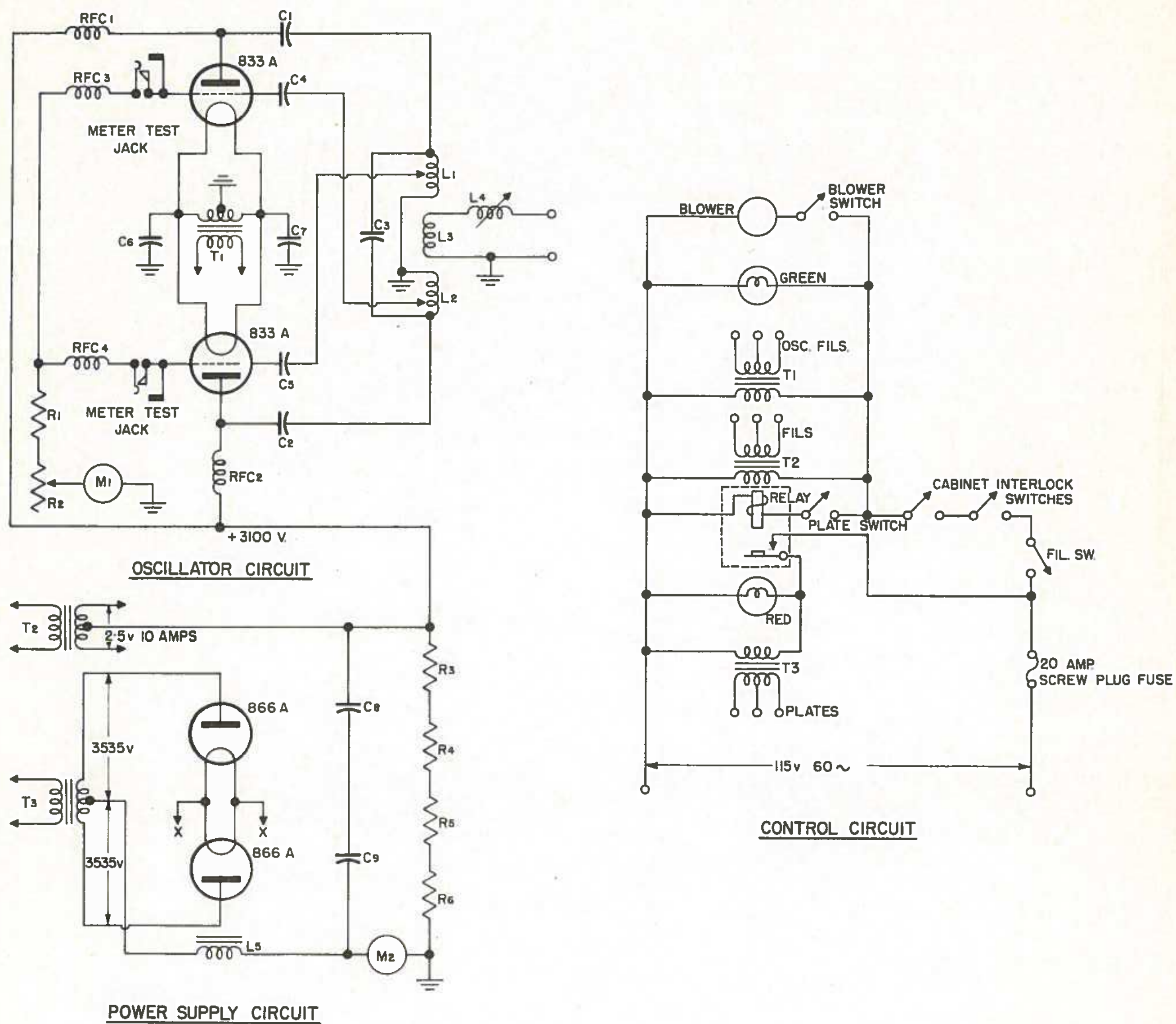
equipped with remote control and heating-cycle timing circuits

front view -- cabinet panels removed

Photo 4
Stray Field Electrode Hand Applicator
for use with 400-watt generator
Unit includes loading coil and neon indicator



Simple Press Assembly
for face-gluing wood surfaces
Compressed air applies pressure
through short lengths of fire hose

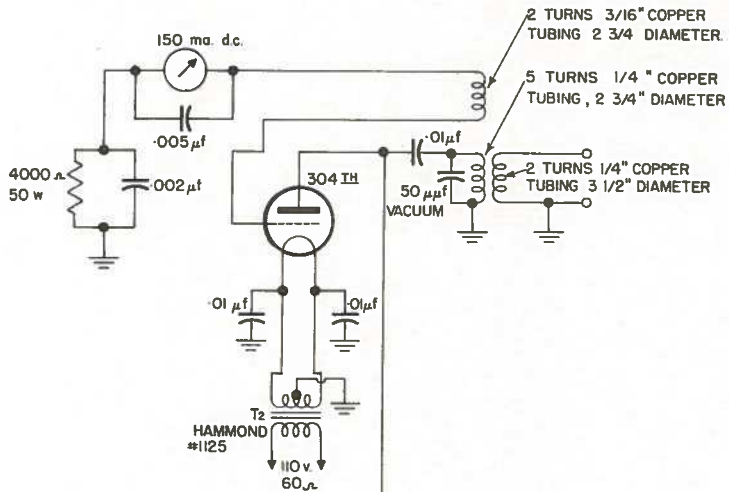



1200 – WATT R–F HEATER

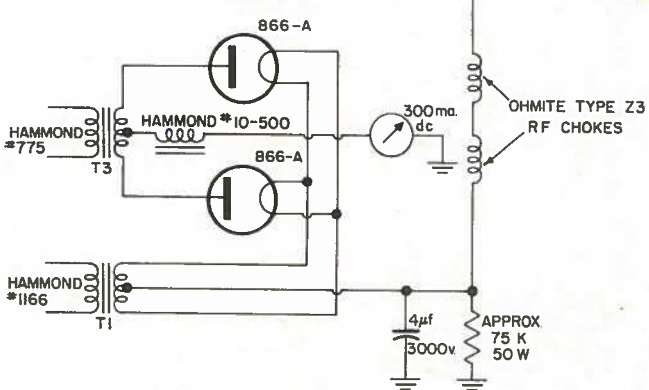
## COMPONENT PARTS LIST

## FOR 1200-WATT R-F HEATER

| Item | |
|---|---|
| $C_1$,$C_2$ | .002 µf, 5000 v. working, 7000 v. test, mica |
| $C_3$ | 50-75-100 or 125 µµf, 7500 v. test, vacuum-type |
| $C_4$,$C_5$ | .002µf, 2500 v. working, 5000 v. test, mica |
| $C_6$,$C_7$ | .002 µf, 2500 v. working, 5000 v. test, mica |
| $C_8$,$C_9$ | 8 µf, 4000 v. working, oil-filled |
| $R_1$ | one 2500 ohms, 40 watts, IRC type-DG resistor, or five 500 ohms, 8 watts, IRC type-DG resistor |
| $R_2$ | 1500 ohms, 25 watts, Ohmite type-K potentiometer |
| $R_3$,$R_4$,$R_5$,$R_6$ | 18,833 ohms, 40 watts, IRC, 5% resistor |
| $L_1$,$L_2$ | 4, 5 or 6 turns 3/8-in. copper tubing, 4-1/2 in dia. |
| $L_3$ | 4 turns 3/8-in. copper tubing, 4 in. mean dia., coupling coil |
| $L_4$ | 12 turns 3/8-in copper tubing, 4-1/2 in. dia., 8-1/4 in. long with tap adjustable over full length |
| $L_5$ | Hammond type 30-500 choke |
| $RFC_1$,$RFC_2$ | 10 pies, 250 mh., 0.4 amp., RF Choke |
| $RFC_3$,$RFC_4$ | Hammond No.1512 RF Choke |
| $M_1$ | 0-300 ma. dc., 3-1/2 in. panel meter |
| $M_2$ | 0-500 ma. dc., 5 in. panel meter. |
| $T_1$ | Hammond No.14683 (Spec.) transformer, 60 cycles |
| $T_2$ | Hammond No.1166-60 transformer, 60 cycles |
| $T_3$ | General Electric Spec. 461100, 3535 v., 2.5 KVA transformer |
| Blower | 115v. 60 cycles, 75 watt motor, 60-75 c.f.m. blower |
| Relay | Gen. Elec. Model 12 HGA 15 FI-DPDT, 115 v. 60 cycles |

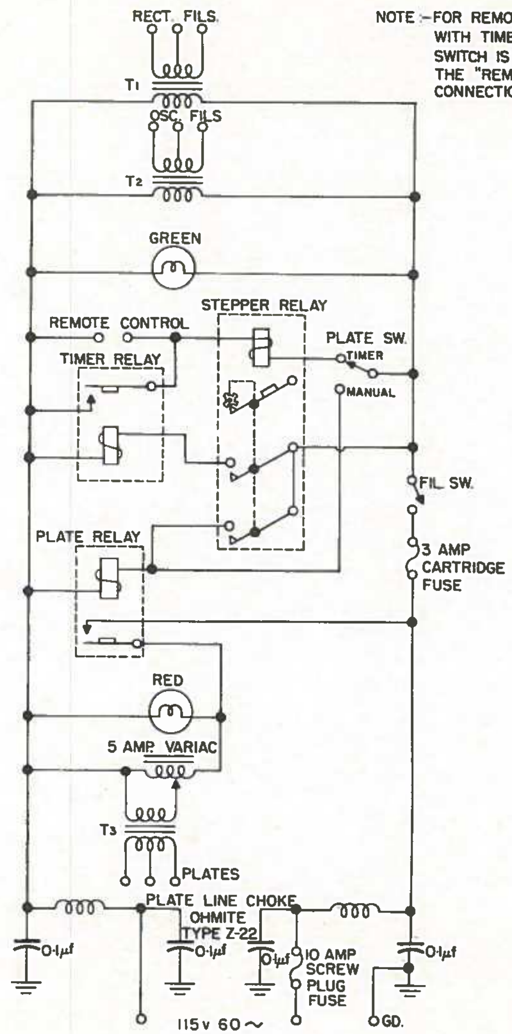



OSCILLATOR CIRCUIT




POWER SUPPLY CIRCUIT

NOTE :- FOR REMOTE OPERATION WITH TIMER, AN EXTERNAL SWITCH IS CONNECTED TO THE "REMOTE CONTROL" CONNECTIONS.




CONTROL CIRCUIT

# 400—WATT R-F HEATER