SECTION IV—CRYSTAL OVENS

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SECTION IV—CRYSTAL OVENS

INTRODUCTION

4-1. Section IV is divided into two main parts. Part I is a discussion of the design of crystal ovens. Part II consists of a series of technical data sheets describing currently available crystal ovens that are suitable for use with the recommended Military Standard crystal units listed in Section II.

4-2. Part I, *Design of Crystal Ovens,* begins with a brief discussion of the development of crystal ovens leading to the present state of the art. Included is a reprint of a Signal Corps Technical Requirements report that outlines the operational and test specifications to be met in the development of new crystal ovens for use by the Armed Services. Following this is a general discussion of the construction features of a representative crystal oven. Next, various types of thermostats and temperature-control circuits are described briefly and illustrated. Finally, the thermal factors involved in maintaining a crystal at a constant operating temperature are analyzed qualitatively in some detail. As an aid to the radio engineer, the thermal parameters are interpreted in terms of their electrical analogues. Because of the complexity of the many distributed variables, a non-approximating rigorous approach is not practical at the present state of the art. What is attempted is to aid the developmental engineer by making explicit the basic physical problems involved.

4-3. Part II, *Technical Descriptions of Crystal Ovens,* includes descriptions only of crystal ovens meeting military specifications, which have been designed to accommodate Military Standard crystal holders of Group I, Section III. All such ovens, where the information has been available, have been included; but because of unavoidable omissions, the list should be considered representative rather than inclusive. A listing by type and number of crystal holders each oven will accommodate is provided by a technical data chart at the beginning of Part II.

PART I

DESIGN OF CRYSTAL OVENS

DEVELOPMENT OF TEMPERATURE-CONTROLLED CRYSTAL OVENS

Trends in the Demands of Crystal-Oven Performance

4-4. During the early years of crystal oscillators, when the large frequency-temperature-coefficient X and Y cuts were the principal quartz elements, good frequency stability required very accurate control of the crystal temperature. For example, an X-cut element having a temperature coefficient of 20 parts per million per degree C would need to be maintained within $\pm 1/4$°C of its mean temperature if the frequency were not to deviate more than 0.0005 per cent. A Y-cut element having a temperature coefficient four times as great would need to be limited to an operating temperature range of $\pm 1/16$°C for the same permissible frequency deviation. To control the temperature of relatively large crystal units within such narrow limits required the use of carefully designed, but rather bulky and expensive ovens.

4-5. With the arrival of the zero-temperature-coefficient quartz elements, the demand for precise temperature control greatly decreased. Where an oven formerly was required to maintain an operating temperature within ± 0.1°C, its subsequent functional equivalent was permitted temperature cycles of ± 1°C and greater. As a result, smaller and cheaper ovens soon became conventional.

These consumed less power and employed less sensitive but more rugged thermostats than was originally feasible.

4-6. It has only been in recent years that a strong demand has again arisen for greater care in oven design. This demand has a threefold nature:

a. Better ovens are needed to maintain even the conventional tolerances in operating temperature for the wide variations in ambient temperature now required of military equipment.

b. To relieve the overcrowding of the radio-frequency spectrum, very small percentage deviations in crystal frequency, and hence in oven temperature, are needed to make full use of the v-h-f range.

c. It is important that improved performance be obtained without increasing the size of ovens; indeed, it is highly desirable that the size be further reduced. For the above reasons more than routine attention is now being given to possible improvements in the design of crystal ovens, especially small ovens.

Types of Crystal Ovens

4-7. Ovens used for housing crystal units can be broadly classified into three types: a. Large transmitter ovens. b. Precision laboratory ovens. c. Small ovens.

a. *Large temperature-controlled compartments employed in fixed-plant radio transmitters.* It is not uncommon for these ovens to house the entire oscillator circuit; in which case the crystal unit may be additionally protected from temperature changes by being mounted in a separately-controlled inner chamber. These ovens are normally equipped with thermometers for indicating the compartment temperature on the front panel or through a window. The transmitter, of which the oven is an integral part, is often intended to operate in buildings where the room temperature is not expected to vary by more than ±15°C. Under such an ambient range, the large transmitter oven can be expected to maintain the crystal temperature within ±1°C to ±0.1°C, depending upon the type of thermostat, the compartment design, and the mounting arrangement of the components within the oven. Monitoring, alarm, and automatic standby thermostatic circuits in case of thermostat failure are occasionally to be found.

b. *Large temperature-controlled boxes for housing crystal units employed in frequency and time standards requiring laboratory precision.* This type of oven most often uses a mercury thermostat. Where extreme precision is required, electronic amplification of a thermistor-bridge thermostat may be employed. The boxes are constructed with thick walls consisting of heat-distributing and heat-insulating layers interleaved with heater windings. For ambient temperature variations of ±15°C, temperature-controlled boxes can maintain the temperature at tolerances of ±0.1°C to ±0.001°C. The latter tolerance is sufficient to limit the frequency deviation of an average zero-coefficient quartz element to one part in ten billion, if the operating interval is not too long.

c. *Small crystal ovens equipped with plug-in bases for mounting in standard sockets, or with bases designed for fastening directly to a chassis.* This is the type of crystal oven most commonly encountered and of greatest importance to the design engineer of military radio equipment. It is the only oven type to consider for use in small- and medium-sized equipments. The data sheets in Part II of this section describe several small ovens of this class which are currently available and which have been designed for use with Military Standard crystal units. The average performance of these ovens, although generally satisfactory for normal ranges of room temperature, cannot be said to be entirely satisfactory when subjected to the subfreezing temperatures often required of military equipment. Because of the increased attention being given to the design and development of better small ovens, the radio engineer can reasonably expect a continuous improvement in available models for the next few years. A landmark in the recent trend toward improved oven design was established when Messrs. H. Keen, N. Tetrault, and J. Gilbert of Lavoie Laboratories developed a small oven capable of ±0.15°C stability over the ambient range of −40° to +70°C. Such a temperature stability is more than adequate for the great majority of purposes. For airborne equipment, until such time that crystal units and/or crystal circuits can be designed to be inherently temperature-compensating, the demand will continue for ever smaller sizes, lighter weights, less power consumptions, as well as greater temperature stabilities, particularly in the case of the multiple-position ovens mounting several crystal units.

Armed Services Technical Requirements for Crystal Ovens of New Design

4-8. The following digest is a reprint of the detailed requirements for the development of crystal ovens to be used by the Armed Services, as established by the Frequency Control Branch, Squier Signal Laboratory, Fort Monmouth, New Jersey, October 21, 1952, in *Technical Requirements for PR&C 53-ELS/R-3610:*

a. Temperature, Operating: 75°C and 85°C.
b. Temperature Setting Tolerance: ±3°C.
c. Temperature Cycling Tolerance: ±1°C over the entire operable temperature range.
d. Operable Temperature Range: —40 to +60°C (75° oven), —40 to +70°C (85° oven).
e. Storage, Vibration and Shock: After undergoing the following tests, outlined in Specification MIL-T-945A, there shall be no degradation of performance and the oven shall continue to meet all other requirements of the Technical Requirements. The expression "crystal oven" shall be substituted wherever the expression "test set" appears in the referenced specification:
   Par. 4.4.2—Humidity Test
   Par. 4.4.4—Temperature and Altitude Test
   Par. 4.4.5—Vibration Test (omit Test 2)
   Par. 4.4.6—Shock Test
f. Aging: Total shift shall not exceed 1°C per month, oven operating, except temperature setting tolerance of sub-panel b shall not be exceeded.
g. Temperature Retrace: The unit shall be capable of returning to its operating temperature ±1°C during the following temperature-cycling test: unit on 8 hours, off for 16 hours, for a period of 10 cycles.
h. Stabilizing: Unit should reach thermal equilibrium within 15 minutes at any temperature within the operable range.
i. Operating Voltage: A-C—6.3 and 12.6 volts ±10% obtained by center-tapping the heater winding; also 26.5 volts ±10%.
j. Temperature Measurement: Method will employ a high drift crystal.
k. Mounting: Octal base with clamping fixture.
l. Shape: No factor.
m. Interchangeability of Components: Desirable for replacement purposes.
n. Size: Maximum limits: 4 in. high x 1½ in. diameter, or, if rectangular, 1½ in. on a side.
o. Pin-to-Pin Capacitance: Shunt capacitance across crystal pins (crystal removed) shall not exceed 5 $\mu\mu$f.
p. Thermostats: If thermostats are employed they shall be hermetically sealed.
q. Cavity Size: Shall be capable of housing Crystal Holder HC-6/U. It is desirable, but not essential, that it shall also accommodate Crystal Holder HC-13/U. Temperature tests which may be conducted employing the latter type of holder will permit a greater tolerance in temperature limits.
r. Workmanship: Components, subassemblies and parts shall be manufactured and assembled in a thoroughly workmanlike manner.
s. Materials: All materials shall be entirely suitable for the purpose for which intended.

GENERAL CONSTRUCTION FEATURES OF CRYSTAL OVENS

Provisions for Temperature Control

4-9. Figure 4-1 illustrates by diagram the principal elements to be considered in the construction of a crystal oven. The thermostat contains a temperature-sensitive element, usually one that operates by expanding and contracting as the temperature rises and falls. By one means or an-

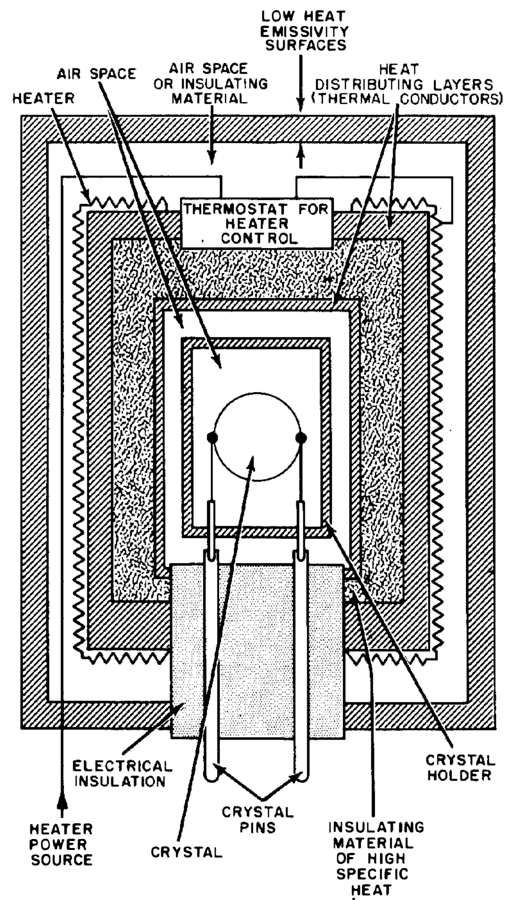


Figure 4-1. General construction features of typical crystal oven

other, the temperature-varying property of the sensing element is used to control the power to an electrical heater, so that the power increases, or starts, when the temperature of the thermostat falls below the operating level, and decreases, or stops, when the temperature rises above the operating level. The heater power-control mechanism may, or may not, be mounted within the oven proper.

4-10. For minimum temperature deviation at the crystal, the thermostat should be thermally insulated from the crystal chamber but in close thermal contact with the heat-distributing layer adjacent to the heater. This arrangement permits the crystal to be insulated from the temperature variations that must occur at the location of the thermostat in order for the thermostat to operate. The greater the heat capacity and the greater the heat resistance of the intervening layers, the more constant will be the crystal temperature. The inside walls of the crystal chamber should be metallic, that is, should have high thermal conductivity to distribute the heat uniformly around the crystal unit and minimize the temperature gradients within the crystal chamber.

Provisions for Minimizing Power Requirements

4-11. For conservation of operating power, the heater should be as well insulated as is practical against loss of heat to the outside. Ideally, maximum insulation is to be obtained by enclosing the heater and inner compartment within an evacuated container having highly reflective walls—utilizing the same principle as in the Dewar flask and thermos bottle. Practically, the best insulation has been achieved by allowing an air space to separate the heater from the outer walls of the oven. Air, or other gas, is superior as a heat insulator compared with the best of the solid insulators; but this is true only if there is little or no transport of heat by mass movements of the gas from regions of higher to regions of lower temperature. Thus, if the dimensions and temperature gradient of the insulating air space are sufficient for convection currents to circulate around the heater, the space should either be subdivided by horizontal insulating sheets or filled with porous insulating material such as glass wool, Celotex, cotton, hair felt, or balsa wood. Care should also be taken to prevent, or at least retard, convection currents at the outer surface of the oven.

4-12. To reduce to a minimum the heat lost by radiation, the outer case of the oven should be a smooth-surfaced unpainted metal of low emissivity —aluminum, for example. If a plastic case is used, lining the inner and outer surfaces with metal foil will equally retard heat loss by radiation. Coating a plastic surface with metallic paint can reduce the surface emissivity, and hence the radiation losses, to almost one-half that of the unpainted plastic, but these losses will be ten or more times greater than that of a pure metal surface. Markings on a metallic case should be kept to a minimum. A serial number alone can more than quadruple the radiation losses from that side of the oven. However, these precautions lose much of their importance if it is not practicable to prevent air currents from circulating around the outside of the oven; in which case the heat loss by radiation becomes relatively negligible compared with that by convection and need not be considered a major design consideration.

4-13. The electrical leads from the crystal chamber to the outside should be kept as small in cross-sectional area as possible, since these leads tend to "short-circuit" the crystal chamber thermally to the outside. From the point of view of small temperature tolerances, it would be desirable for these leads to be extended in length and close in thermal contact with the heat-distributing layers of the oven. Unfortunately, the leads must be kept short, well-spaced, and insulated electrically (which is equivalent to being insulated thermally) from metallic parts of the oven. These requirements are necessary in order to minimize the shunt capacitance that the oven adds across the crystal unit, and to a lesser extent, to minimize the distributed resistance and inductance added to the crystal circuit. As a general rule, the major factor limiting the performance of small crystal ovens over wide ambient temperature ranges is the heat leakage through the base; particularly is this true for multiple-position ovens, where a leakage path exists for each individual terminal leading from a crystal socket.

Construction of Typical Small Oven

4-14. Figure 4-2 shows the principal parts of a small commercial crystal oven equivalent to the Military type HD-54/U. The oven is not designed for precision control of the temperature. Because of the heat leakage through the base, it is questionable whether the temperature tolerance is less than $\pm 5°C$ over an ambient range of 100°C. The advantage of this type of oven is its small size, light weight, and inexpensive design, which make it particularly suitable for general-purpose use in airborne installations. The thermal key, which is shown as part of the base assembly, is a metallic heat-distributing layer that makes close thermal contact with the base of the distributing shell around which the heaters are wound. The purpose

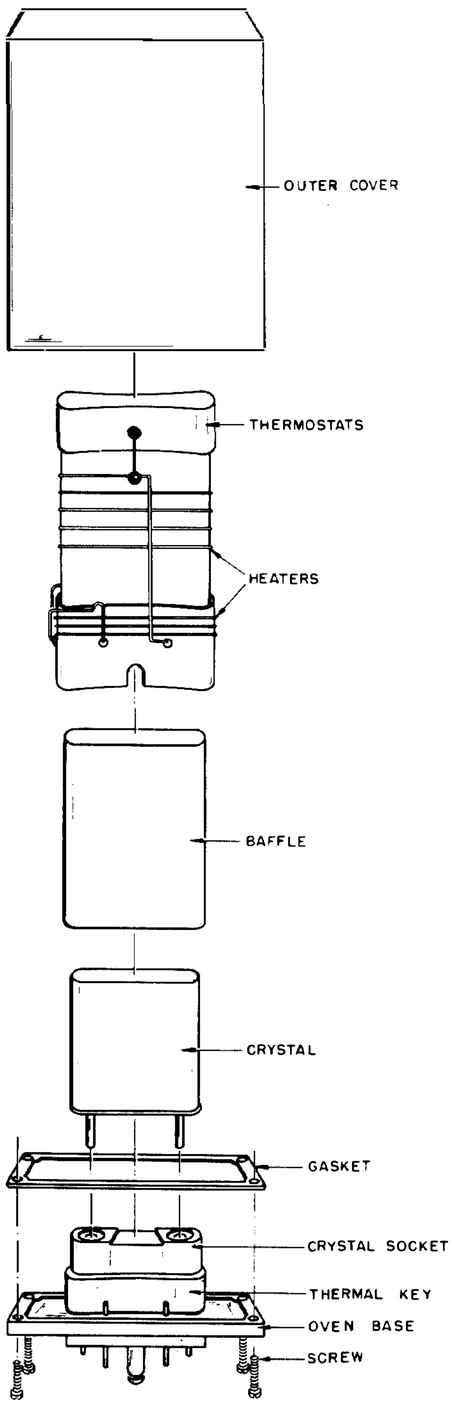


Figure 4-2. Small crystal oven equivalent to Military Type HD-54/U

of the thermal key is to conduct as much heat as possible around the crystal leads before they enter the crystal chamber. The baffle is a plastic cover that forms the walls of the crystal chamber. Its purpose is to provide a heat-storing, as well as a heat-insulating layer between the heater distributing shell and the crystal unit. The metallic case of the crystal holder (type HC-6/U) provides sufficiently uniform heat distribution within the crystal chamber, for the purposes of the oven, so that an additional inner distributing layer is not provided. Two thermostats and two heaters are provided. One thermostat-heater combination is for quick oven warm-up when the oven is first turned on. This thermostat is adjusted to open its associated heater circuit at a temperature slightly below the desired operating temperature. The second thermostat-heater combination determines the actual operating characteristics. The outer cover is plastic and is of sufficient size to provide a small air space around the crystal compartment. The radiation losses are not considered significant compared with the conduction losses through the base and with the expected convection losses around the sides, so that a low-emissivity surface is not provided.

METHODS OF THERMOSTATIC HEATER CONTROL

4-15. There are two general methods of thermostatic heater control: the *on-off* method and the *continuously-variable* method. The latter permits the heater current to be varied gradually with the aid, usually, of vacuum-tube amplifiers until an equilibrium is reached between the heat being supplied and that being lost. This method is used so rarely that it will not be further considered. However, the thermistor-bridge thermostat, which is discussed below as the control element of an on-off vacuum-tube heater circuit, is equally applicable as the control element of a continuously-variable vacuum-tube heater circuit. In the on-off method, the heater circuit is opened and closed periodically. The action of the thermostat varies the ratio of the *on* period to the *off* period until equilibrium is reached at the predetermined operating temperature between the periodic supply of heat and the continuous heat leakage. The on-off thermostat of small ovens is usually connected in series with the heater windings. Where more sensitive thermostats are used, the heater current is controlled indirectly by relay—the thermostat contacts not being required to pass more than a small current sufficient to operate the relay.

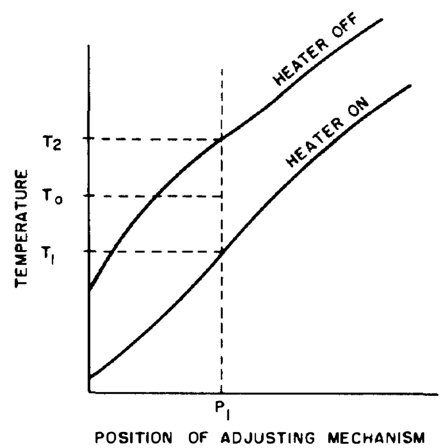


Figure 4-3. Typical differential curves of adjustable thermostat

Temperature Differentials of Thermostats

4-16. Figure 4-3 shows typical on-off curves of an adjustable thermostat. For any given thermostat adjustment, P_1, the thermostat operating temperature is the temperature, T_0, midway between the *on* and *off* temperatures, T_1 and T_2, respectively. The total width of the temperature gap, T_2-T_1, is called the *backlash,* and plus or minus one-half the backlash is called the *differential* of the thermostat. In general, the larger the differential, the longer is the operating life of the thermostat, although, of course, the less precise is its temperature-controlling ability.

Thermostats Used for On-Off Heater Control

4-17. Any device that can be used as a thermometer can be modified for use as a thermostat. In practice, the bimetallic thermostat is the type most commonly encountered in crystal ovens, but any corrosion-resistant metal having a large temperature coefficient of expansion can be used as the sensing element without the bimetallic construction, as long as the associated mechanism provides sufficient sensitivity for opening and closing the thermostat contacts. Where above-average precision is required, a mercury thermometer is usually employed. Thermistors are also occasionally used as the temperature-sensing element, maximum sensitivity being obtained by connecting the thermistor as one arm of a resistance-bridge circuit.

BIMETALLIC THERMOSTATS

4-18. Bimetallic sensing elements are constructed by welding together two thin metallic strips which have widely different temperature coefficients of expansion. Since one of the metals expands and contracts with changes in temperature at a greater rate than the other, the effect of a change in temperature is to cause a straight bimetallic strip to bend. Figure 4-4 illustrates a number of the more common types of bimetallic sensing elements. The deflection of these elements is denoted by the symbol d for linear displacements and by the symbol ϕ for angular displacements. An angular expression of the deflection is more convenient for the helix and spiral elements since the exact linear deflection of a contact will depend upon the length of a contact arm fastened to the moving end of the bimetallic coil. Equations for the deflections indicated in figure 4-4 are given in the table below.

d = linear displacement in same dimensions as l, t and D
ϕ = angular displacement in radians
l = length of strip
t = overall thickness of strip
D = diameter of double-helix coil
ΔT = degrees centigrade change in temperature
k = k_a, k_b, or k_c = temperature coefficient of deflection in parts per degree centigrade

Bimetallic Strip	*Deflection Equation*	*Representative Values of k*
(A) Cantilever	$d = k_a l^2 \Delta T/t$	12 to 20 $\times 10^{-6}$
(B) U-Cantilever	$d = k_a l^2 \Delta T/2t$	12 to 20 $\times 10^{-6}$
(C) End-Supported	$d = k_a l^2 \Delta T/4t$	12 to 20 $\times 10^{-6}$
(D) Double-Helix	$d = k_b l D \Delta T/t$	10.5 to 18.5 $\times 10^{-6}$
(E) Helix	$\phi = k_c l \Delta T/t$	1600 to 2500 $\times 10^{-6}$
(F) Spiral	$\phi = k_c l \Delta T/t$	1600 to 2500 $\times 10^{-6}$

Electrical Resistance of Bimetals

4-19. Since the thermostat deflection is used to open and close an electrical circuit, the bimetallic strip, itself, often forms part of the circuit. In this case, with proper design, the additional heat supplied the bimetal due to its electrical resistance can be used to boost the thermostat's temperature response, making it more sensitive, and effectively reducing the operating differential of the surrounding area. In general, the bimetals having the higher deflection coefficients also have the higher electrical resistivities. Per circular mil foot, bimetal resistances range approximately from 20 to 700 ohms.

Adjustment of Bimetallic Thermostat

4-20. Within limits, the operating temperature of a bimetallic thermostat can be adjusted by varying the position of the fixed contact relative to the room-temperature position of the moving contact. The greater the deflection that is required of the moving contact relative to its initial position, the higher will be the operating temperature.

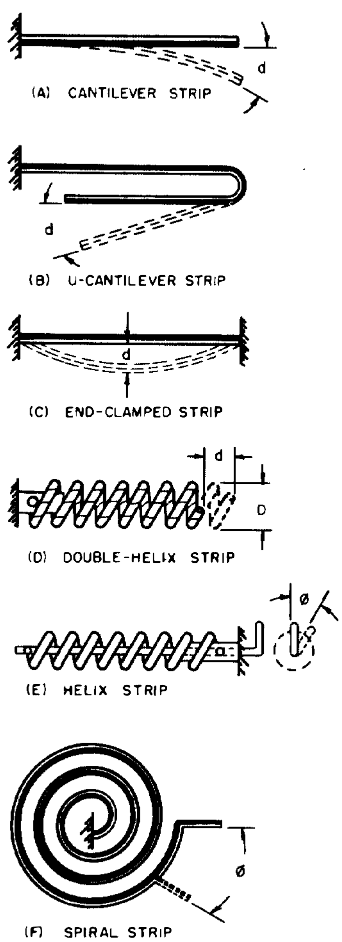


Figure 4-4. Basic types of bimetallic strips

Creep- and Snap-Action Bimetallic Thermostats

4-21. The deflection of a bimetallic strip can be used to open and close an electrical circuit either slowly, *creep action*, or abruptly, *snap action*. Creep thermostats are the more sensitive, requiring smaller differentials, and are less likely to fail because of fatigue since the bimetallic element is not subjected to vibration or shock. But the contact life is short compared with that of the snap thermostat. This is because of the increased exposure to heating and sparking due to the prolonged periods when the contacts are only barely touching or barely separated. Other limitations of the creep thermostat are its tendency to chatter and the fact that it cannot be used in equipment subjected to vibration. These disadvantages are avoided by the use of a snap thermostat. In fact, the response of the abrupt, positive contact action of the snap thermostat is actually aided by a moderate amount of vibration, requiring slightly smaller temperature differentials than would otherwise be the case. A creep thermostat can be readily converted into a snap type by fastening permanent magnets to the contacts. The contact life of either type is increased by mounting in vacuum, or at least, in a hermetically sealed holder, and by using low a-c voltages in noninductive circuits. Where necessary, additional protection against sparking at the contacts is to be had by shunting the contacts, or inductive parts of the circuit, with a suitable resistance and capacitance in series. This is particularly necessary if the thermostat is used to control the current of an inductive relay, or if voltages higher than 30 volts are employed. The average life of a snap thermostat is on the order of 100,000 actions, although there are a number of significant exceptions to the average. For example, the E-shaped, bimetallic cantilever element, see figure 4-5, is claimed to have a life of a million actions. These elements are available in a number of small sizes that should be sufficiently sensitive for use in crystal heater circuits where the thermostat contacts must pass the entire heater current.

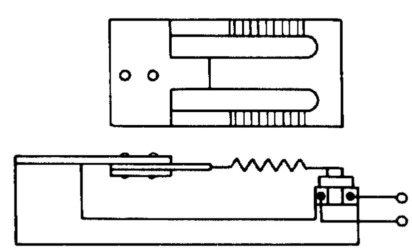


Figure 4-5. E-shaped, bimetallic, snap thermostat

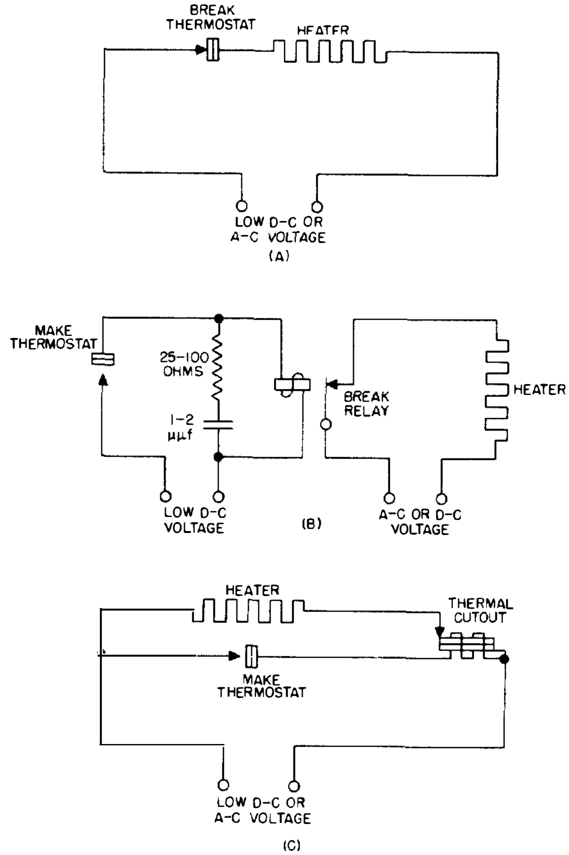


Figure 4-6. Bimetallic thermostat circuits

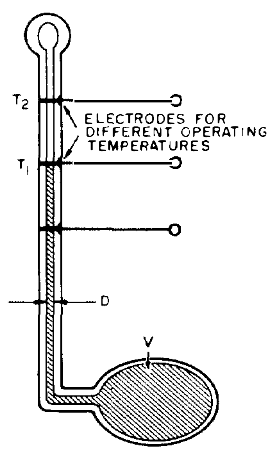


Figure 4-7. Diagram of typical mercury thermostat

Heater Control Circuits Using Bimetallic Thermostats

4-22. Figure 4-6 shows several temperature-controlled heater circuits suitable for use with bimetallic thermostats. Generally, voltages over 30 volts are avoided in the thermostat circuit, 6-volt sources being those most often employed. In circuit 4-6(A), the thermostat contacts must be of sufficient size to pass the full heater current. Differentials as low as ±0.5°C are possible here, but values two and three times this are more common in the average oven. Short cantilever strips mounted in evacuated glass envelopes are the most sensitive per unit length and have comparatively long lifetimes. This type of thermostat is tamper-proof and is the most economical in space and in cost. Its chief disadvantage is that the sealed unit, although permitting a long contact life, prevents the thermostat from being adjustable. Thus, relatively high tolerances in the nominal operating temperature must be allowed the manufacturer.

4-23. Figure 4-6(B) shows a circuit in which a sensitive helix-type bimetallic thermostat can be used to control an electromagnetic relay. The resistance of the relay must be sufficient to limit the current to a value not exceeding the maximum current permissible for the thermostat contacts. In this type of circuit the thermostat current need not exceed 5 or 10 ma, and operating differentials less than ±0.1°C are possible. The resistor- capacitor combination protects the thermostat from high induced voltages when the circuit is opened.

4-24. Figure 4-6(C) is a hot-wire-relay circuit that permits the use of the more sensitive bimetallic thermostats without the disadvantages of highly inductive loads introduced by electromagnetic relays. The hot-wire relay permits thermostat currents as low as 50 ma, and operating differentials as low as ±0.1°C.

MERCURY THERMOSTATS

4-25. Mercury thermostats, see figure 4-7, are mercury thermometers constructed with bulb and capillary electrodes which enable the mercury column to close an electrical circuit at a preset temperature. The sensitivity of the average mercury thermostat is on the order of 0.2 in./°C; but sensitivities 5 times as great are feasible. The sensitivity is directly proportional to the ratio, V/D^2, where V is the volume of the bulb and D is the diameter of the capillary. Theoretically the sensitivity can be increased indefinitely by increasing the volume of the bulb. Practically this is not possible, because when large bulbs are used ambient effects other than temperature, pressure for example, also become significant factors in determining the exact height of the mercury column. In addition, the larger the bulb, the greater its thermal inertia, so the slower becomes the response to changes in the temperature of the surroundings. Average operating differentials range from ±0.02°C to ±0.05°C. The operating temperature can be adjusted by having separate electrodes in the capillary for each desired temperature, as is indicated in figure 4-7. For a continuous range of operating temperatures, mercury thermostats have been designed with a movable platinum-wire electrode that makes sliding contact with a fixed terminal. The movable electrode is fastened to a small iron rod so that adjustments can be made with the aid of a small permanent magnet. The height of the electrode is varied simply by sliding the magnet up and down the outside of the capillary tube. This type of laboratory thermostat permits excellent frequency precision since the operating temperature of the oven can be adjusted to match exactly the zero-temperature-coefficient point of a crystal.

4-26. Figure 4-8 shows a typical temperature-control circuit employing a mercury thermostat. Note the high resistance in the thermostat circuit. This resistance should be sufficient to limit the current to 1 or 2 microamps or less. At the most, the current should not exceed 5 microamps, otherwise the mercury may become fouled. With negligible currents, the operating life of the thermostat can be quite long. When inoperation does occur it is usually due to capillarity effects. The mercury thermostat, because of its fragility and the size and expense of the associated circuit components is suitable for use only in those large fixed-plant or laboratory crystal ovens that require above-average temperature stability.

Thermistor-Bridge Thermostats

4-27. Thermistor-bridge thermostats have the advantage of requiring no moving parts. Their sensing of temperature changes takes the form of a continuously variable voltage subject to unlimited vacuum-tube amplification, so that theoretically no minimum limit exists for the operating differential. In practice, with the use of high-gain vacuum-tube circuits, the thermistor bridge can be made to respond to temperature differentials as small as ±0.001°C. Because of its elaborate circuit requirements the thermistor bridge is not generally practical for temperature control of crystals except when the utmost temperature stability is necessary.

4-28. Figure 4-9(A) is the schematic diagram of a moderately sensitive thermistor circuit which

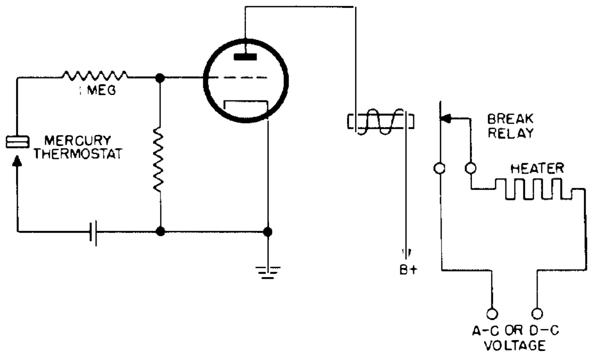
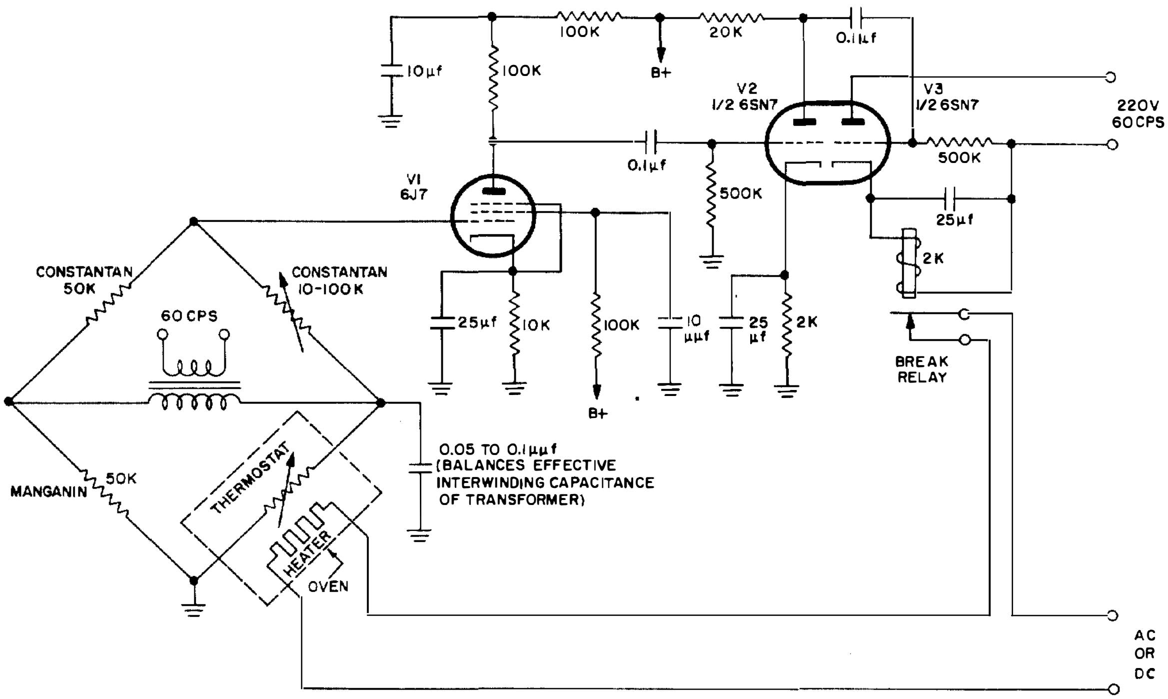


Figure 4-8. Heater control circuit using mercury thermostat

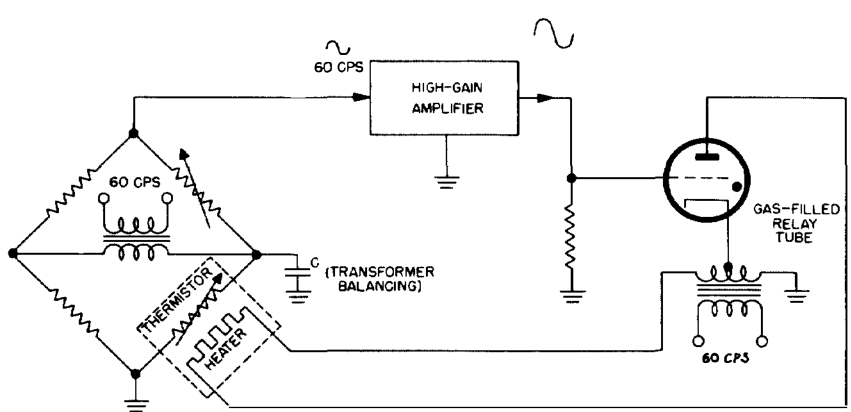
employs a vacuum-tube-operated electromagnetic relay to control the heater current. It can be seen that the input of V_1 is connected across the resistance bridge, which is driven by a 60-cycle signal introduced from the bridge transformer. When the temperature rises to a point where the thermistor resistance balances the bridge, the input signal to V_1 becomes zero. As the temperature continues to rise, the signal again begins to build up, but opposite in phase to its polarity when the temperature was below the balance point. The polarity of the "above-balance" signal is such that the amplified input to V_3 is in phase with the 60-cycle voltage applied to the V_3 plate. Note that V_3 is operated primarily as a half-wave rectifier. The heater relay coil serves as the inductance of the LC filter of the rectified plate voltage, but also as a 2-K cathode-biasing resistance. When the polarities of the V_3 input and plate voltages are in phase, the plate current is sufficient to operate the relay and open the heater circuit. The thermostat circuit that is shown is not sufficiently sensitive to justify its operation for crystal ovens without the addition of at least one more amplifier stage. To be preferred, is a high-gain voltage amplifier used in conjunction with a gas-filled relay tube as shown in figure 4-9(B). If desired, the thermistor can be simply a copper winding. Copper, with a temperature coefficient of resistance of 0.0043/°C, will have a resistance variation with temperature 100 or more times that of the manganin bridge arm of equal nominal resistance. Among the metals, the highest temperature coefficients of resistance at normal oven temperatures are those of iron and of nickel, which range between 0.006 and 0.007 parts per °C. The temperature coefficient of tungsten is between 0.0045 and 0.005 part per °C at oven temperatures.

Thermostat Monitoring

4-29. Where a constant check on the crystal tem-



(A)



(B)

Figure 4-9. On-off heater control circuits

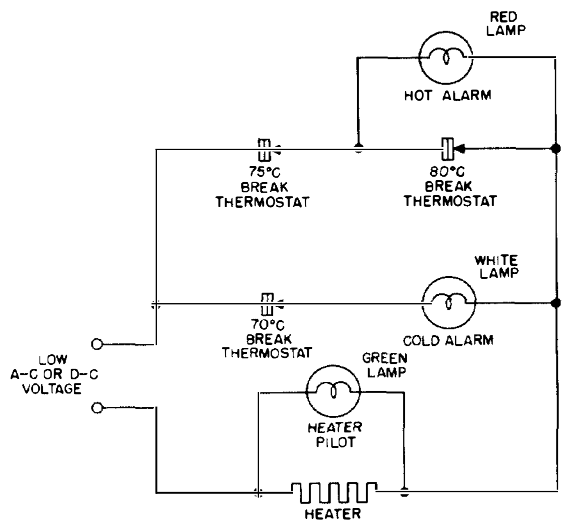


Figure 4-10. Thermostat monitoring and alarm circuit

perature is necessary, additional thermostat circuits can be provided for automatic monitoring. In the event the temperature should fall below or rise above the desired differential range, the thermostat monitoring circuits can be designed to operate alarms or to switch the heater control to a standby thermostat. The possible modifications are quite varied, but relatively easy to design once the basic monitoring requirements of the circuit are agreed upon. Figure 4-10 shows a typical alarm circuit. For simple monitoring, a pilot lamp connected across the heater is sufficient to indicate the on-off operating cycle, and a mercury thermometer is sufficient to indicate the operating temperature.

THERMAL ANALOGUES OF ELECTRICAL PARAMETERS

4-30. The electrical concepts of voltage, current, conductance, and capacitance have their analogues in the thermodynamic laws of heat conduction and storage, where the laws that govern the flow of heat are mathematically equivalent to the laws that govern the flow of electricity. If *difference of temperature* replaces the term *difference of potential,* and *current* is interpreted to mean a net flow of thermal energy past a point per unit time, instead of a net flow of electric charge, then the terms, *thermal conductivity* and *thermal conductance,* and the reciprocals, *thermal resistivity* and *thermal resistance,* are defined by the same relations that define their electrical counterparts.

Thermal Current

4-31. Thermal current, heat/unit time, has the same physical dimensions as power, and, if desired, can be expressed in watts. For example, if a metal rod, well insulated along its length, is heated continuously at one end by an electrical heater imbedded in the rod at that end, the heat will be conducted down the rod at the same rate at which it is produced; so that a proper measure of the thermal current would be the wattage of the heater. Where units of heat capacity are involved, it is common to express heat in units of the gram-, or kilogram-calorie. One gram-calorie is the quantity of heat required to raise the temperature of one gram of water one degree centigrade. One gram-calorie per second equals 4.186 watts. A 1-watt flow of heat is thus equal to a thermal current of approximately 0.25 gram-calories per second.

Thermal Conductivity

4-32. The thermal conductivity, K, of a well-insulated conducting segment of cross-sectional area A and length L is given by the equation

$$K = \frac{I_H L}{\Delta T A} \qquad 4\text{—}32\ (1)$$

where ΔT is the difference in temperature between the two ends of the segment when a steady thermal current, I_H, is caused to flow along the length. If I_H is measured in gram-calories/second, A and L in centimeter units, and ΔT in centigrade degrees, K is expressed in units of gm-cal/sec cm deg C. Approximate values of representative conductivities are given in the following table.

Thermal Conductivity, K (gm-cal/sec cm deg C)	*Material*
1.0 0.5	Copper, Silver Aluminum
0.19	Mercury
0.03	Quartz (parallel to Z axis)
0.016	Quartz (perpendicular to Z axis)
0.012	Carbon (graphite)
0.0025	Glass, Porcelain
0.0018	Mica
0.0006	Asbestos paper
0.0004	Rubber, Average Plastic
0.0001	Cork, Glass wool in air
0.00008	Hair felt in air, Rock wool in air
0.000057	Air
0.000052	Nitrogen

Thermal Resistance

4-33. The thermal resistance of a conductor of length L, cross sectional area A, and thermal conductivity, K, is defined by the equation

$$R_H = \frac{L}{KA} \qquad 4\text{—}33\ (1)$$

We shall arbitrarily define the unit of thermal resistance to be the resistance of a thermal conductor that requires a difference of temperature of 1°C between the ends of the conductor in order for one calorie per second to flow through it. This unit we shall call a "thermohm."

Thermal Ohm's Law

4-34. When equations 4—32(1) and 4—33 (1) are combined to cancel the term, L/KA, the following "Ohm's law" for thermal circuits is derived:

$$\Delta T = I_H R_H \qquad 4\text{—}34\ (1)$$

Note that ΔT, the "temperature drop" across the resistance, R_H, of a thermal circuit, is similar to ΔV, the voltage drop across the resistance of an electrical circuit. Where ΔV is a measure of the difference of potential energy per unit charge, ΔT can be shown to be a measure of the difference of kinetic (thermal) energy per unit matter (i.e., per unit particle).

Stefan-Boltzmann Law

4-35. The heat radiation from a surface is not a linear function of the temperature, but obeys a fourth power equation that is known as the Stefan-Boltzmann law:

$$I_R = Ae\sigma T^4 \qquad 4\text{—}35\ (1)$$

where I_R is the total heat radiated per second, A is the area of the radiating surface, e is the *emissivity* of the surface, σ is the Stefan-Boltzmann constant, and T is the temperature in Kelvin (absolute) degrees.

Radiancy

4-36. The radiant energy emitted per second per unit area is called the *radiancy* of a body. Thus,

$$\text{Radiancy} = \frac{I_R}{A} = e\sigma T^4 \qquad 4\text{—}36\ (1)$$

Absorptivity and Emissivity

4-37. An isolated body in thermal equilibrium with its surroundings will necessarily be absorbing and emitting thermal energy at the same rate. A body that absorbs all of the radiation incident to its surface, reflecting none, is called an *ideal black body*. The fraction of the incident radiation absorbed is called the *absorptivity* of the body, which in the case of an ideal black body is equal to 1. Now, since at thermal equilibrium, the radiancy must equal the rate of absorption per unit area, the radiancy of an ideal black body must equal the radiancy of the empty space surrounding the body. For the same reason, if the absorptivity of a body is small, its radiancy, relative to black body radiancy, must also be small in exactly the same proportion when at thermal equilibrium with its surroundings. The ratio of the radiancy of a body to that of an ideal black body is the *emissivity*, e, of the body. Note that e is also equal numerically to the absorptivity.

Stefan-Boltzmann Constant

4-38. Since e is equal to 1 for an ideal black body, the radiancy of an ideal black body is equal to σT^4. The constant σ, which equals the radiancy of an ideal black body per $(\text{degree})^4$, has been found experimentally to be

$$\sigma = 5.73 \times 10^{-9} \text{ milliwatts/cm}^2 \text{ deg}^4 \text{ K}$$

Expressed in calories,

$$\sigma = 1.37 \times 10^{-12} \text{ cal/sec cm}^2 \text{ deg}^4 \text{ K}$$

Emissivities of Various Substances

4-39. The emissivities of bodies for radiations in the visual range can be judged by the amount of reflection when the body is exposed to white light. Thus, in the case of diffuse reflections, bright white surfaces have low absorptivities, and hence, low emissiviities, and dull black surfaces have high emissivities. However, the emissivities of most substances vary considerably with the frequency. A green object, for example, indicates a lower emissivity for the green band of the light spectrum than for the other bands. Asbestos, which is white, has a total emissivity at low temperatures equal to that of lamp black, which is 0.95. Wet ice at 0°C has an emissivity of 0.97, and white hoar frost has an emissivity of 0.985, which is the nearest to ideal black body conditions so far discovered in solids or liquids. The lowest emissivities are to be obtained with polished silver and gold, where at low temperatures values of 0.02 can be realized. Values for the total emissivity of aluminum vary somewhat, ranging from 0.022 to 0.08 at relatively low temperatures. Emissivities of 0.022 and 0.028 appear to be approximately correct for pure aluminum at temperatures of 25°C and 100°C, respectively, whereas the higher emissivities are due to various degrees of oxidation or moisture adsorption at the surface. A completely oxidized aluminum surface, for instance, has an e of 0.11 at 200°C. Surface oxidation usually raises the emissivity of a metal several fold. On oxidation, the emissivity increases from 0.02 to 0.6 for copper, 0.05 to 0.35 for nickel, 0.09 to 0.43 for monel metal, 0.05 to 0.6 for lead, 0.08 to 0.8 for steel, and 0.035 to 0.6 for brass. Quartz, itself, has a relatively high emissivity (approximately 0.9) at low temperatures, so that even if the unplated surface area of a metal-plated crystal is only as much as 1/10 the total area, the total effective emissivity will be several times that of the plated area alone.

Radiant Heat Flow

4-40. Since the absorptivity is equal to the emissivity, the radiant energy being absorbed by a substance is given by the same equation that defines the energy being radiated—that is, by equation 4—35 (1), except that T represents the absolute temperature of the surroundings, rather than of the substance, itself. Thus, the net flow of radiant heat away from a surface, equal to the radiated minus the absorbed energy per second, is given by the equation

$$I_H = I_R - I_A = Ae\sigma\,(T_o^4 - T_s^4) \qquad 4\text{—}40\ (1)$$

where I_A is the rate of radiant heat being absorbed, T_o is the temperature in Kelvin degrees of the surface, and T_s is the temperature of the surroundings. Now

$$\begin{aligned} T_o^4 - T_s^4 &= (T_o - T_s)(T_o + T_s)(T_o^2 + T_s^2) \\ &= \Delta T(2T_o - \Delta T)(2T_o^2 - 2T_o\Delta T + \Delta T^2) \\ &= \Delta T(4T_o^3 - 6T_o^2\Delta T + 4T_o\Delta T^2 - \Delta T^3) \end{aligned}$$

where $\Delta T = T_o - T_s$. If the difference in the two temperatures is small in comparison with their magnitudes, the percentage error will be negligible for most practical purposes if the higher-power ΔT terms are dropped. Thus, equation (1) can be written approximately

$$I_H \approx 4Ae\sigma T_o^2(T_o - 1.5\,\Delta T)\Delta T \qquad 4\text{—}40\ (2)$$

Equivalent Thermal Radiation Resistance

4-41. Technically, thermal conductance and its reciprocal, thermal resistance, are measures of the ability of a substance to transport heat by virtue of molecular impacts alone; but to facilitate the illustration of thermal circuits schematically, we shall represent heat radiation by assuming equivalent conducting paths having appropriate thermal resistances. (Heat transport by air convection shall be treated merely as an increase in air conductance, and not as being due to a separate conducting path.)

4-42. The equivalent radiation resistance indicated by equation 4—40 (2) is

$$R_H = \frac{\Delta T}{I_H} = \frac{1}{4Ae\sigma T_o^2\,(T_o - 1.5\,\Delta T)} \qquad 4\text{—}42\ (1)$$

Equation (1) indicates that for oven surface temperatures between 50° and 85°C (323° and 358°K), the effective radiation resistance approximately doubles as ΔT is varied from 0° to 100°. For example, assuming a T_o of 350°K and an e of 0.08, the effective radiation resistance of 1 sq cm of a partially oxidized aluminum surface will vary approximately from 50,000 to 100,000 thermohms as the ambient temperature increases from 350° to 230°K.

Heat Capacity

4-43. Heat capacity is defined as the thermal energy required to raise the temperature of a substance one degree. The relative capacities of materials for storing thermal energy are more generally described in terms of specific heat. The specific heat of a substance is the heat capacity of one gram of the substance as compared with the heat capacity of one gram of water. Numerically, then, the specific heat is equal to the number of calories required to raise one gram of the substance one degree. The heat capacity of a quantity of matter varies directly with the number of atoms or molecules contained that are free to absorb thermal energy. At the same temperature, the average heavy atom has the same thermal energy per degree of freedom of motion as the average light atom. Thus in solids, where the density of atoms per unit volume does not vary nearly as much as the density of mass per unit volume, the lighter substances generally have the greater specific heats. (For instance, aluminum, which has an atomic weight of 27 and a density of 2.7 gm/cc, has a specific heat of 0.21 cal/gm deg C; whereas lead, with an atomic weight of 207 and a density of 11.3 gm/cc, has a specific heat of 0.03 cal/gm deg C.) If the change in the thermal energy of a system at thermal equilibrium is plotted as the ordinate against the temperature as the abscissa, the slope of the curve at any point is the instantaneous value of the heat capacity at that temperature. At temperatures where there is a change of state, the heat capacity of a substance may rise to a very high value. For example, at 0°C, the instantaneous heat capacity of ice water approaches infinity, since heat can be absorbed without a change in temperature.

Equivalent "Electrical Circuits of Crystal Ovens"

4-44. The relations among the various thermal parameters that affect the performance of a thermostatically-controlled oven can be more readily seen if we represent the equivalent thermal circuit by schematic diagrams, borrowing electrical symbols (see figure 4-11) to represent their thermal

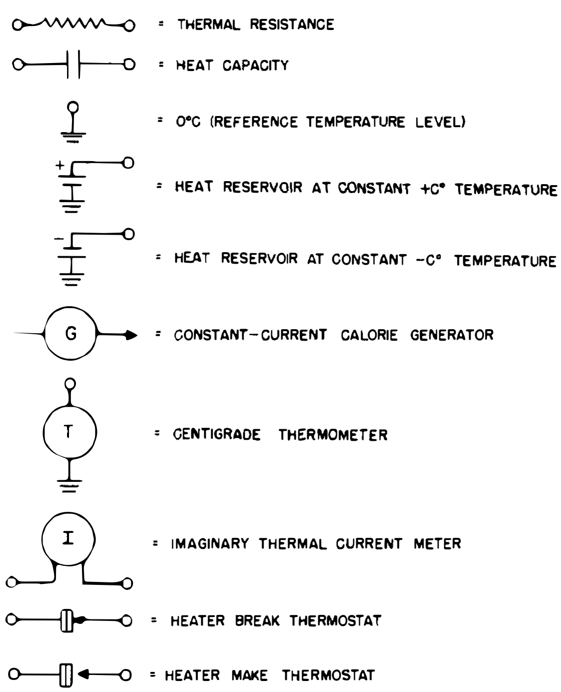


Figure 4-11. Electrical symbols applied to parameters of thermal circuits

analogues. Figure 4-12 is the schematic diagram of the "equivalent electrical circuit" of a representative constant-temperature crystal oven. The actual thermal circuit, of course, consists of continuously distributed heat resistance and capacity. A rigorous quantitative description would require the use of exponential functions and an analysis of the thermal transients. Nevertheless, reasonable approximations can be made and greater simplicity achieved if the circuit is represented by linear, lumped parameters, and steady state conditions assumed, as is done in figure 4-12. The symbols of the circuit parameters indicated in figure 4-12 are defined as follows:

- G_1 = a calorie generator having an output equal to the power losses in the crystal
- G_2 = a calorie generator having an output equal to the wattage of the heater
- T_1 = the temperature, or "difference of potential" between the crystal and "ground" (0°C)
- T_2 = the temperature at the walls of the crystal chamber
- T_3 = the temperature of the heater and thermostat
- T_4 = the ambient temperature, which is represented as determined by the connection of S_1 to the heat-reservoir "battery"
- T_5 = the temperature of the electrical terminals of the crystal unit
- I_1 = current meter reading, which in the steady state equals the output of G_1

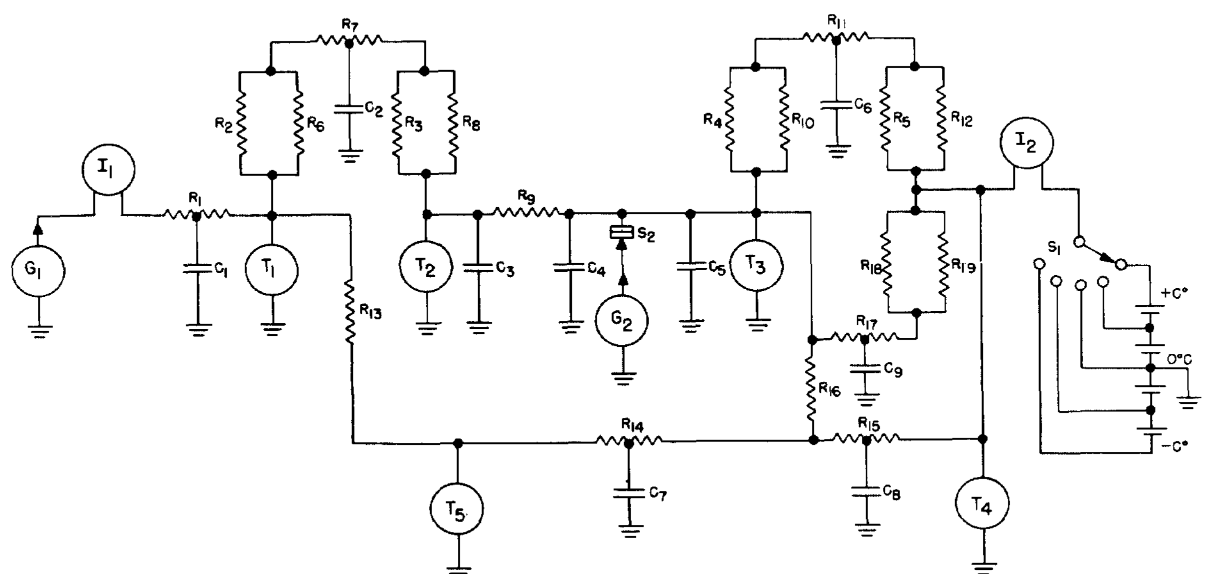


Figure 4-12. Equivalent electrical circuit of crystal oven

I_2 = average cal/sec passing from the heater and crystal to the outside

All the resistance values refer to thermal, not electrical resistances.

R_1 = effective lumped resistance of crystal and electrodes
R_2 = equivalent resistance to radiation from crystal to walls of holder
R_3 = equivalent resistance to radiation from holder to walls of inner chamber
R_4 = equivalent resistance to radiation from heater to outer walls of oven
R_5 = equivalent resistance to radiation from oven to ambient atmosphere
R_6 = effective lumped resistance from crystal and electrodes via air to walls of holder
R_7 = effective lumped resistance of walls of holder
R_8 = effective lumped resistance of air from holder to walls of inner chamber
R_9 = effective lumped resistance of walls of inner chamber and of heater surrounding the walls
R_{10} = effective lumped resistance of air from inner to outer walls
R_{11} = effective lumped resistance of outer walls
R_{12} = effective lumped resistance of air surrounding oven (normally reciprocal of equivalent convection conductance)
R_{13} = effective lumped resistance of wires supporting crystal
R_{14} = effective lumped resistance of crystal-unit electrical leads and terminals
R_{15} = effective lumped resistance of external circuit and electrical insulation
R_{16} = effective lumped resistance between terminal leads and the heat distributing layer of oven chamber
R_{17} = effective lumped resistance of base, including electrical ground connection
R_{18} = effective lumped resistance of air and mounting fixtures in contact with base
R_{19} = equivalent resistance to radiation from base of oven
C_1 = effective lumped heat capacity of crystal and electrodes
C_2 = effective lumped heat capacity of holder, except the electrical leads
C_3 = effective lumped heat capacity of inner walls of oven chamber
C_4 = effective lumped heat capacity of heater and outer heat-distributing wall of oven chamber
C_5 = effective lumped heat capacity of thermostat and miscellaneous fixtures in close thermal contact with outer heat-distributing wall of oven chamber
C_6 = effective lumped heat capacity of outer wall
C_7 = effective lumped heat capacity of electrical leads in crystal holder
C_8 = effective lumped capacity of external electrical circuit
C_9 = effective lumped capacity of base
S_1 = imaginary control varying the ambient temperature
S_2 = thermostat switch controlling heater

In general, the resistance values close to the crystal are larger than those farther removed because of the much smaller cross sectional area of the conducting path. On the other hand, the capacitance values farther out are much greater than the inner values because of the larger volumes contained. Because it is desired to keep the weight and volume as small as possible, as well as the time required to bring the oven to the operating temperature, those conditions that would tend to increase the heat capacity of all parts except the inner chamber wall (C_3) between the heater and the crystal are generally considered undesirable, and the design engineer is normally more concerned with providing sufficient insulation and a uniform distribution of the heat under steady-state conditions. Under steady-state, or "d-c" conditions the values of the capacities are of no significance, but since the heater is being alternately turned on and off, there is an "a-c" component in the heat flow; in this connection the capacity effects must be considered.

4-45. The principal function of the circuit in figure 4-12 is to maintain the temperature T_1 of the crystal unchanged when the ambient temperature T_4 is varied. To a first approximation, this end is achieved by interposing between the crystal and the outside the constant-temperature heat reservoir, C_4, which is kept "charged" at the desired operating temperature by the thermostatically controlled constant-current calorie generator, G_2. The on-off operation of the calorie generator causes the temperature of C_4 to cycle slightly above and below the operating mean; so, to attenuate the a-c component, an RC thermofilter is interposed between the C_4-reservoir and the crystal.

4-46. The performance of the circuit in figure 4-12 shall be described as dependent primarily upon the individual performances of six overlapping circuits; three of which are d-c circuits, two, a-c, and one is a transient circuit. One of the d-c circuits conducts the crystal power to the outside, the second conducts the heater power to the outside, and the third is the thermal link between the heater and the thermostat. Of the a-c circuits, one is the filter circuit between the heater calorie generator and the crystal—it attenuates the a-c component of the heater temperature; the other is the a-c path from the oven heat reservoir to the outside—it is effective in determining the cycling frequency. The transient circuit is essentially the two a-c circuits combined—it determines the warm-up time. Each of the d-c circuits is discussed separately. The a-c and warm-up circuits, because of their overlapping functions, are discussed jointly.

4-47. The resistive and capacitive parameters can be interpreted as having the effective lumped values that would be measured under steady-state conditions. In the d-c circuits, the heat capacities can be ignored as long as steady-state conditions are assumed. Only when there are fluctuations in the heat flow do the capacity effects need to be considered. For those oven elements that have relatively large ratios of specific heat to resistivity, such as the metallic parts, not too much error is introduced in the a-c circuits by treating the element entirely as a lumped "capacitor," having an effective heat capacity equal to its actual heat capacity. For those elements that have very small ratios of specific heat to resistivity, such as the air spaces, the error introduced in the a-c circuits by treating the element entirely as a lumped "resistor," having an effective resistance equal to its actual resistance, can also be considered negligible. Where the greatest tolerances must be allowed the lumped parameters, is in the interpretation of the a-c characteristics of those oven parts that have relatively high specific heats as well as high resistivities, such as plastics and other insulating compounds.

D-C PATH OF CRYSTAL POWER

4-48. Figure 4-13 is a simplified schematic of the equivalent d-c circuit of the crystal unit which conducts the crystal power to the outside of the crystal holder. The external reservoir symbolized by the battery connection can be interpreted as being any constant-temperature heat reservoir of temperature T_3, without regard to whether the crystal unit is oven mounted or not; otherwise, all symbols are the same as in figure 4-12. The heat from the constant-current generator G_1 divides between the three resistance paths, that part flowing through each branch being inversely proportional to the respective branch resistance. Note that as long as the heat flow and the resistances

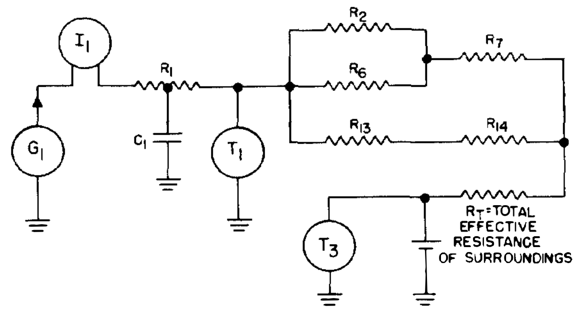


Figure 4-13. Thermal D-C path of crystal power

remain constant, so also does the temperature drop $T_1 - T_3$, so that a given change in the steady-state value of T_3 must cause exactly the same change in T_1.

4-49. Normally the crystal circuit is designed for a constant drive level, but if, for instance, the crystal is connected in an oscillator stage that is to be keyed by a push-to-talk microphone circuit, there would be little to gain by the use of an oven of high inherent stability. If high temperature stability is desired, a first requirement is that of a crystal circuit providing a constant drive. This, in turn, is best achieved by operating the crystal at the lowest drive level that is practicable. For a small (1-cm diameter) wire-mounted crystal unit, the principal leakage is through R_6, the air resistance. The temperature drop across R_6 for each milliwatt of drive will be on the order of 0.3°C. Should the drive vary by as much as ⅓ mw the temperature would vary by 0.1°C. This much variation is ten times more likely at a drive of 5 mw than at one of 0.5 mw. If the same sized crystal unit were evacuated, R_6 would become infinite, and all the leakage would be through R_2 and R_{13}. The total resistance could thereby increase ten-fold, so that a ⅓-mw variation in the drive would mean a temperature variation of 1°C. Should a drive of 3 mw for the same crystal be alternately turned off and on, the crystal temperature would vary by approximately 10°C, and a well-designed oven would be practically useless. If fluctuations in the drive are to be anticipated, optimum temperature control is to be had with the use of sandwich-type crystal units, even though these usually require higher drives than do wire-mounted units. Not only is the thermal resistance between the crystal and the holder negligible compared with that of the wire-mounted unit, but the large heat capacity of the sandwich electrodes, as compared with the thin metal films of the plated electrodes of the wire-mounted units, considerably

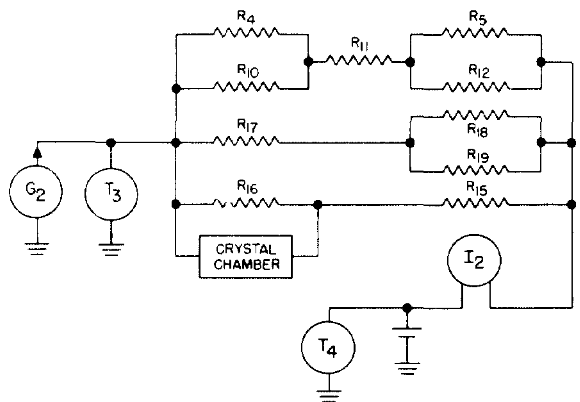


Figure 4-14. Thermal D-C path of heater power

increases the effective heat capacity (C_1 in figure 4-13) of the crystal, and hence can minimize the effects of brief fluctuations in the output of G_1. In the case of a low-frequency, wire-mounted crystal vibrating in a flexural mode, where it is necessary to evacuate the holder to prevent an excessive damping by the air, it is advantageous if a large area of the crystal is not plated. Otherwise, the low emissivity of the silver, or other metallic film, will cause R_2 to be excessive, thereby raising the temperature of the crystal and increasing its sensitivity to small fluctuations in the drive. For a given drive level, the larger the value of C_1, the more stable is the temperature of the crystal during brief fluctuations in either the crystal drive or the oven temperature. Also, the larger the magnitudes of R_2, R_6, and R_{13}, the less sensitive is the crystal to brief fluctuations in the oven temperature; but, on the other hand, the crystal will be more sensitive to changes in the drive level, whether or not these changes are of brief or long duration.

D-C PATH OF HEATER POWER

4-50. The thermal path by which the heater power escapes to the outside is represented schematically in figure 4-14. The symbols apply to the same parameters as in figure 4-12. The power requirements of the crystal oven equal the average rate of heat flow (I_2) from the heater to the outside. The equation for the leakage current is

$$I_2 = \frac{T_3 - T_4}{R_T} \qquad 4\text{—}50\ (1)$$

where R_T represents the total resistance from T_3 to T_4. I_1, the crystal power flow (see figure 4-12), can be considered negligible. A large part of the heat flows through R_{11}, the resistance of the outer walls and top of the oven, although some leakage is through R_{16} into the electrical circuit, and a large leakage occurs at the base through R_{17}. Because of the large radiation losses if the oven is inclosed in a plastic container, the total resistance through the walls and top can be approximately doubled if the outer walls are composed of polished metal instead of plastic, even though the actual resistance, R_{11}, of the outer oven walls, in itself, becomes negligible. For optimum operation, the oven must be shielded, with baffles if necessary, from forced convection currents in the ambient air; such as might be encountered from blowers, fans, etc. Where the space is available, as in large heavy-duty fixed-plant equipment, the oven should have the protection of two reflective insulating walls separated by a thick air space padded with loose-fill insulation of sufficient density to prevent convection currents between the walls. (Reflective surfaces in series are additive in their insulating effects.)

4-51. In an average aluminum-walled crystal oven, the heat leakage through the base, R_{17}, may well be as great as that through the other five sides of the oven combined. Partly compensating the large conductance of the base is the fact that convection currents in the air are retarded when the heat is escaping *under* horizontal surfaces, since the surface prevents the warmed layers of air from rising. Thus, the effective resistivity of the air beneath a relatively large base may be more than three times that at the top of the oven. Of course, if the air under the crystal oven is circulating due to convection currents initiated in other parts of the equipment in which the oven is used, this advantage will not be in effect. If the oven is a small socket-mounted device, the direct-thermal contact of the base with the socket eliminates most of the air surface, so that the effective conductivity of the base is much greater than if the same oven were mounted on legs, or were otherwise supported so that a large air space exists between the base and the chassis.

4-52. From the point of view of low operating power, it is desirable to keep R_{16}, the leakage path from the inner chamber walls to the electrical circuit, as large as possible. On the other hand, from the point of view of temperature control, as discussed earlier, R_{16} should be as small as possible, so that the temperature of the walls of the inner chamber is readily communicated to the terminals of the crystal unit. This is not easily done since the electrical insulation around the crystal leads also serves as thermal insulation. The problem is analogous to an attempt to maintain some point in an electrical circuit at ground potential, but with no other connection to ground than through the insulation.

4-53. A plastic sheath for a single crystal terminal will have a thermal resistance on the order of 800 thermohms—400 thermohms for each pair of terminals. For an oven that houses four crystal units, even though only one crystal is operating at a time, R_{16} would be on the order of 100 thermohms. This decrease in resistance means only an additional leakage from the heater, and not an increased effectiveness in the control of the temperature of the operating crystal. Insofar as the one crystal in operation is concerned, there is still approximately 800 thermohms between each of its terminals and the constant-temperature reservoir, as compared with perhaps an effective resistance of 400 to as low as 10 thermohms between each terminal and the ambient heat reservoir, depending upon the particular type of connection to the external circuit.

4-54. For a small plastic-enclosed, socket-mounted oven, similar to type HD-54/U, approximately 5 cm high, 3 cm wide, and 2 cm deep, the total resistance of the walls and top—the R_4, R_5, R_{10}, R_{11}, R_{12} combination—may be assumed to be on the order of 250 thermohms under ambient conditions of room temperature and no forced convection. The total resistance of the base, R_{17}, including that of the heater terminals, screws, ground terminal, in parallel with the resistance of the plastic material, can be estimated as approximately 100 thermohms; and this can be assumed to be in series with another 100 thermohms where most of the leakage is through direct contact with the socket. Thus, the total base resistance, but not including the leads from the crystal, itself, can be assumed to be 200 thermohms. The third leakage branch, $R_{16} + R_{15}$, can be assumed to total 600 thermohms. Since the only net flow of heat from the crystal chamber will be the power losses of the crystal, a perfectly designed oven would not have a net circulation of heat from the heater into one part of the chamber and out another—i.e. R_{16} would be zero. In the practical case there is a tendency, usually, for the top of the chamber to be warmer than the bottom, so that a net conduction of heat exists from the top to the bottom. Nevertheless, insofar as the heater power is concerned, the crystal-chamber path in parallel with R_{16} can be neglected. Thus, the total thermal resistance, R_T, can be considered to be that of three branches of 250, 200, and 600 thermohms in parallel, or a total of approximately 95 thermohms when no forced convection is present.

4-55. If it is assumed that the oven temperature is 75°C and that the ambient temperature is 30°C, then

$$I_2 = \frac{75 - 30}{95} = 0.48 \text{ cal/sec}$$

or

$$I_2 = 0.48 \times 4.186 = 2 \text{ watts}$$

Since there is a difference in temperature of 45°, the power consumption under no-convection conditions averages approximately 2/45 = .045 watt for each degree that the ambient temperature is lower than the oven temperature. With the ambient temperature averaging 30°, a 10-watt heater would be operating one-fifth of the time after the oven had reached equilibrium. Note that this equilibrium condition must hold irrespective of the sensitivity of the thermostat, or the heat capacity of the oven. If the same oven is operated under conditions of moderate forced convection, the total resistance can be more than halved; in which case, the power consumption may increase to as much as a 0.1-watt average for each degree difference between the ambient and oven temperatures. Under these circumstances, the maximum operating range for a 10-watt heater is 100°, which is equivalent to a minimum ambient temperature of −25°C for a 75°C oven. (At the minimum ambient temperature, the heater circuit closes permanently. A further drop in ambient temperature would be accompanied by an approximately equal drop in the oven temperature.) Even where no forced convection is present, the effective total resistance, R_T, of an oven tends to decrease as the difference between the operating and ambient temperatures becomes large. This is because the natural convection around the sides and at the top of the oven becomes greater as the temperature gradient at the outer surface becomes steeper. Partially counteracting the decrease in the equivalent air resistance is the fact that the equivalent radiation resistance tends to increase as the ambient temperature falls.

D-C CIRCUIT BETWEEN THERMOSTAT AND HEATER

4-56. The average crystal oven now in use is built with a hermetically sealed thermostat located either in the crystal chamber, itself (as is generally the case in ovens housing more than one crystal unit), or mounted on top of the chamber in a sealed container that makes good thermal contact with the roof of the chamber. In the former arrangement the temperature deviation can never be reduced below the sensitivity of the thermostat, regardless of how well the rest of the oven is designed, so that high precision in the control of the temperature cannot be achieved without the use of expensive thermostats. If the temperature deviation is to be reduced to a minimum without excessive cost, the thermostat must be so located that it operates before, rather than after, the temperature in the crystal chamber varies. However, the thermostat cannot be placed between the heater and the outside, for then the heat generator would lie between the crystal and the constant temperature point, A, of the d-c circuit, as illustrated in figure 4-15. The average heater temperature, T_H, and hence, the average crystal temperature, T_C, would vary with the changes in the IR drop across the resistance (R_1) between the heater and the thermostat. Since point A is maintained at a constant average temperature by the thermostat, the current through R_2 varies linearly with the ambient temperature. However, since I_H also flows through R_1, the heater temperature, T_H ($= T_A + I_H R_1$), must also change linearly with the ambient temperature. Thus, it is necessary that the thermostat either be in nearly direct thermal contact with the heater, or lie between the heater and the crystal. The former arrangement is usually the most to be desired in order to minimize the power requirements as well as the amplitude of the heater temperature cycles.

A-C CIRCUIT OF OVEN THERMOFILTER

4-57. If the temperature cycling amplitude is to be reduced to a minimum before it reaches the crystal, the oven can be designed to make use of a thermofilter. The thermofilter is the analogue of an electrical RC filter that is used to smooth out the ripples of a pulsating d-c voltage. Although a greater percentage of the resistance and capacity of the thermofilter is of a distributed nature than is the case for its electrical analogue, the thermofilter characteristics can be analyzed to a first approximation by assuming that the resistances and capacitances are in a lumped form.

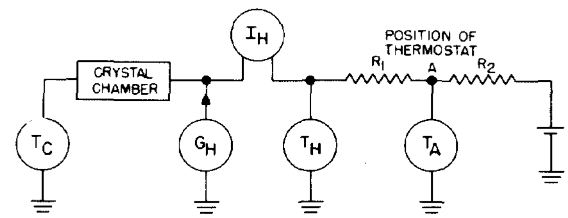


Figure 4-15. Thermal D-C path of heater-to-thermostat when thermostat is outside heater

4-58. Figure 4-16 is a simplified schematic diagram of an oven a-c circuit having a single section thermofilter, where it is assumed that the ambient temperature is at "ground potential" (0°C). R_A is the resistance of the air outside the oven, R_O is the resistance of the oven between the heater and the outside, R is the input resistance of the filter, R_{CC} is the resistance of the crystal chamber, R_{CH} is the resistance of the crystal holder, C_O is the capacity of the walls of the oven, C_H is the capacity of the heater, C_T is the capacity of the thermostat, C is the capacity of the filter, C_{CH} is the capacity of the crystal holder, and C_C is the capacity of the crystal. In general, in going from R_A to C_C, the resistances become progressively larger, and the capacities become smaller, with the exception of C, which should be large. I_G is the instantaneous calorie output per second of the heater when operating; I_H is the average d-c leakage to the outside, and I_{AC} is the peak a-c current through the filter. The component of the a-c current through R_{CC} and R_{CH} can be assumed to be negligible compared with the total I_{AC}. T_H is the temperature of the heater.

4-59. The peak-to-peak amplitude of the a-c component of the temperature T_H is determined by the backlash of the thermostat, and can be assumed to be constant. In the ideal case, the heater and the thermostat should at all times be at the same

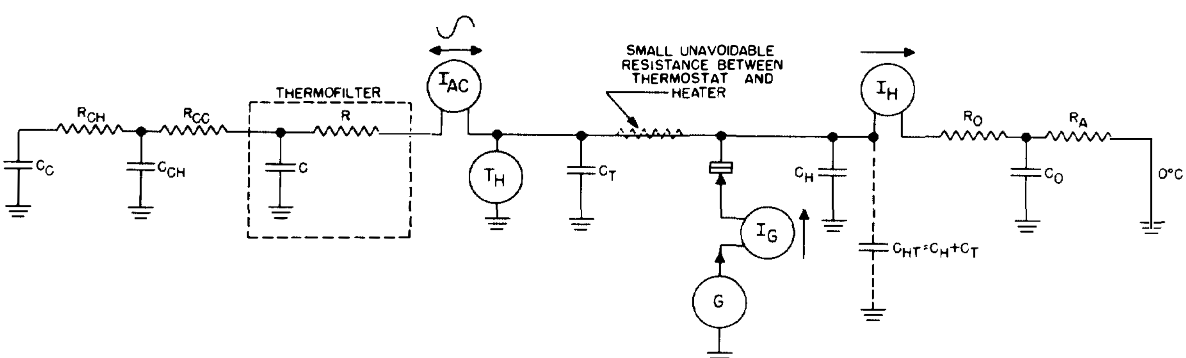


Figure 4-16. Oven thermal A-C circuit

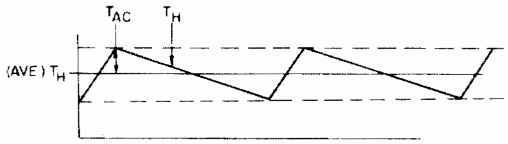


Figure 4-17. A-C component of heater temperature

temperature. In practice, there is always a thermal IR drop between the thermostat and the heater, so that the a-c component in temperature at the heater is always greater than the temperature cycle of the thermostat.

4-60. Referring to figure 4-16, if I_G is large compared with I_H, the rate at which C_{HT} $(= C_H + C_T)$ is "charged" can be assumed to be constant, and if the a-c component of the temperature is small compared with the temperature drop between the heater and the outside, the rate at which C_{HT} discharges can be assumed to be constant for a constant ambient temperature (0°C in the diagram). Thus, the a-c component of T_H can be represented by a saw-tooth wave as indicated in figure 4-17. By a Fourier analysis, such a wave is represented as the resultant of a sine wave of the same fundamental frequency, upon which is superimposed an infinite number of harmonics of varying amplitudes. Insofar as the oven filter circuit is concerned, the only component to consider is the fundamental; for if the thermofilter can attenuate the amplitude of the fundamental below the maximum deviation permissible for the crystal, then certainly the higher harmonics will also be sufficiently attenuated.

ATTENUATION FACTOR OF THERMOFILTER

4-61. In figure 4-16, C_{HT} can be assumed to be an alternating temperature generator having a sine-wave output at the fundamental frequency of the thermostat cycling, and a peak amplitude of T_{AC}. The filter circuit presents an impedance to the heat flow of $\sqrt{R^2 + X_C^2}$, where X_C is the thermal "reactance" of C. If R is assumed to be greater than $10X_C$, then I_{AC} can be assumed to approximately equal T_{AC}/R. Note that only the peak values of the a-c current and temperature need be considered. The a-c component of the temperature at C will thus be $I_{AC}X_C = T_{AC}X_C/R$, so that the attenuation factor is X_C/R. Since $X_C = 1/2\pi fC$, where f is the frequency, the attenuation is directly proportional to R, C, and f. Contributing to the attenuation—indeed, effectively forming two additional RC filter sections—are the $R_{CC}C_{CH}$ and the $R_{CH}C_C$ diffusive combinations of the crystal chamber and crystal unit.

THERMOSTAT-HEATER A-C CIRCUIT CHARACTERISTICS AFFECTING FREQUENCY OF TEMPERATURE CYCLE

4-62. The cycling frequency, f, depends upon the rate at which C_{HT} charges and discharges. The charging time is inversely proportional to I_G (I_H and I_{AC} assumed to be small by comparison); the discharging time is inversely proportional to I_H (I_{AC} assumed to be small by comparison); and both the charging and discharging times vary directly with C_{HT}. Since there is always a resistance path between the heater and thermostat and since the thermostat has a heat capacity separate from C_H, the rise in temperature at the thermostat must lag the rise at the heater. Because of this, I_G cannot be made indefinitely large, else the rise in temperature at the heater will far overshoot the thermostat cut-off temperature, and T_{AC} will become excessive. Also, the time gained on the charging half of the cycle could be more than lost because of the additional time required for discharge. Thus, the thermostat-to-heater resistance and capacitance are practical factors that limit the frequency and raise the a-c amplitude of the heater temperature. For a minimum T_{AC} and a maximum frequency, the thermostat must be mounted so that the conductance between it and the heater is a maximum. Another factor limiting the maximum practical cycling frequency is the fact that when a bimetallic thermostat is used, it is desirable that the temperature cycles have as long a period as possible, for, in general, the operating life is rated in the number of open-and-closed cycles that can be made before the thermostat becomes over-fatigued, and is not primarily dependent upon the actual number of hours at which the thermostat can be operated.

4-63. Since the oven is purposely designed to make I_H as small as possible, R_O and R_A cannot be decreased for the sake of increasing the cycling frequency. But if an oven is so constructed that the heat from the heater is evenly distributed on all six sides of the inner chamber, and that a near-perfect conductance exists between the heater and thermostat, the temperature deviation of the crystal at low ambient temperatures can actually be less than that at room ambient temperatures. This is because the consequent increase in f, due to the increase in I_H and decrease in discharge time, permits greater cycling attenuation by the filter. The frequency, however, can only increase as long as I_G remains large compared with I_H. Otherwise, the decrease in the time of discharge would be annulled by the increase in the time of charge.

4-64. More or less predetermined, is the capacity of the heater and the metallic surfaces that bound it. Although the outer shield can be made as thin as possible, thereby reducing C_H, the inner wall must be of sufficient thickness to provide a low resistance around the crystal chamber. Representative values of C_H for small ovens range from 2.5 to 25 cal/deg, depending principally upon the area of the heater walls, and the thickness of the outer sheath. If I_H is 0.25 cal/sec (approximately 1 watt), and T_{AC} is $\pm 5°C$, then the time of discharge of a 6-cal/deg C_H (ignoring the thermostat C_T) will be $10 \times 6/0.25 = 240$ sec, or 4 minutes. If I_G is 2.5 cal/sec, the charging time will be $10 \times 6/(2.5 - 0.25)$, or approximately 27 sec. Thus, f will be 1/267 cycle per second. Obviously with such a very low frequency, and with R of the filter limited to practical values of, at the most, only a hundred or so thermal ohms, an effective filter would require that an extraordinarily large C be contained in the small volume between the heater and the crystal chamber. However, if the thermostat is in excellent thermal contact with the heater, the effective T_{AC} can be made to approach the actual differential of the thermostat; in which case, not only is the cycling temperature reduced at the source, but the attenuation factor of the filter is improved proportionately by the increase in f.

IDEAL THERMOFILTER

4-65. It should be remembered that heat capacity expresses a *change* in heat for a *change* in temperature. In general, the heat capacity of a substance will be different at different temperatures. The *average* heat capacity of a body between two temperatures T_1 and T_2 is $\Delta H/(T_1 - T_2)$, where ΔH is the thermal energy required to raise the temperature of the body from T_2 to T_1. The *instantaneous* heat capacity at a given temperature is the ratio of an infinitesimal change in thermal energy for an infinitesimal change in temperature, dH/dT. Now, if at a particular temperature the thermal equilibrium of a substance suddenly shifts from a state of low potential energy to a state of high potential energy, the addition of a small quantity of heat will be absorbed in raising molecules from the lower to the higher energy level, so that the added energy is principally an increase in potential, rather than in kinetic energy. However, it is the kinetic energy of the molecules that determines the temperature, so that if a small addition of heat is entirely converted into potential energy, dT will be zero, and the instantaneous heat capacity dH/dT will be infinite.

4-66. In this manner a very large C can be obtained for a thermofilter if a substance is chosen that undergoes a reversible change of state at the operating temperature of the oven. Obviously a non-reversible action would be unsatisfactory, such as the decomposition of a compound, since it is necessary that the same process be repeated during each temperature cycle. Such changes of state as occur at the transition of a crystal from one lattice structure to another, or at the melting and boiling points of substances that do not decompose would permit very high values of C for a small quantity of the material.

4-67. The largest C for a given quantity of substance can be obtained at a boiling point, since the heats of vaporization are generally much greater than the heats of fusion or transition. But the problem of cooling the distillate and returning it to the heated chamber would require an expensive and cumbersome oven. Since heats of fusion are generally much higher than heats of transition, are absorbed during narrower temperature ranges, and are more easily found at a desired operating temperature, a large thermofilter capacity effective at the operating temperature appears to be more readily obtainable by surrounding the crystal chamber with a solid having its melting point within the differential range of the thermostat, but slightly higher than the operating mean. If the melting solid has a very sharp melting point, there is a danger that the mean temperature may rise above the melting point long enough to completely melt the solid, thereby losing the major filtering effect. To remove this danger, the filter can be composed of a mixture of two or more compounds of different melting points, so that, at equilibrium, the densities of the compounds relative to each other will be different in the solid and liquid phases of the partly melted mixture. Although the filtering effect will be diminished, the melting temperature will automatically tend to rise with the mean heater temperature as more of the mixture fuses.

4-68. The substance to use for an ideal heat reservoir, other than one having a melting point at the desired operating temperature, would be a stable electrical insulator having little tendency to react with metal, a low density, a large heat of fusion, a prompt rate of melting and crystallization, a low dielectric constant, a low cost of production, and not be difficult or disagreeable to handle. Recent experiments by C. P. Saylor and R. Alvarez of the National Bureau of Standards indicate the probable suitability of para-dibromobenzene.

4-69. The fact that a number of possible filter elements have a large percentage volumetric expansion on fusion suggests the interesting possibility of employing the expansion to open the heater circuit when the filter material is partially melted. A pure fusing element could thus, theoretically, provide thermostatic action by virtue of a cycling internal-enegry differential, rather than a cycling temperature differential. In other words, a change in the temperature of the sensing element of the thermostat would not be an absolute requirement in the ideal case.

4-70. To shorten the warm-up time and to minimize temperature gradients, good thermal conductivity should be maintained within a melting-point thermofilter reservoir; if necessary, by the use of wire mesh or radial fins. However, no through high-conductivity path should be permitted. A relatively high-resistance surface barrier should insulate the inner side of the reservoir from the side nearest the heater.

WARM-UP CIRCUIT OF OVEN

4-71. The warm-up circuit of the oven consists primarily of the thermofilter and thermostat-heater circuit shown in figure 4-16. Arbitrarily, we shall define the warm-up time to be the period required to bring the temperature of the crystal chamber to within 1 per cent of its mean operating value after the heater is first turned on. As a first approximation, this period can be divided into two parts. The first part consists of the time required for the heater, viewed as a constant-current generator, to charge the heater and thermostat capacities, C_H and C_T, to the operating temperature. The second part consists of the additional time required to bring the crystal chamber to within 1 degree of the operating temperature. Normally, a booster heater is provided which permits the first part of the warm-up time to be shortened to as much as one-fourth or more of the time that would otherwise be required. Letting C_{HT} in cal/deg equal the sum of C_H and C_T, I_N in cal/sec equal the average net rate of heat supplied the oven during the initial heating period (this can be assumed to be the total power from the two heaters minus one-half the average operating power after equilibrium has been reached), and ΔT equal the difference between the operating and ambient temperatures, the first part of the warm-up time is approximately

$$t_1 \text{ (in sec)} = C_{HT}\Delta T/I_N \qquad 4\text{—}71 \ (1)$$

4-72. To the extent that a crystal oven can be represented by the thermofilter circuit in figure 4-16, the second part of the warm-up time can be broadly generalized as the time required for the capacity, C, to acquire $100(\Delta T - 1°)/\Delta T$ per cent of its warm-up heat. To simplify the problem, we shall assume that no heat flows into C until after the first part of the warm-up period is completed. As in an electrical circuit, the product, RC, is a time constant equal to the time required for the capacity to receive 63 per cent of its equilibrium charge when connected in series with the resistance and a constant potential source. To receive $100(\Delta T - 1°)/\Delta T$ per cent of its equilibrium charge will require a time

$$t_2 \text{ (in sec)} = -RC \log_e\left(\frac{1°}{\Delta T}\right) \qquad 4\text{—}72 \ (2)$$

Thus, the total warm-up time by rule-of-thumb approximation is

$$t \approx t_1 + t_2 = \frac{C_{HT}\Delta T}{I_N} - RC \log_e\left(\frac{1°}{\Delta T}\right) \qquad 4\text{—}72 \ (3)$$

Equation 4—72 (3) is only approximate when $t_1 << t_2$ and when C is large compared with the distributed capacity of R. If C is attributable entirely to the distributed capacity of an insulating baffle, equation 4—72 (3) is not applicable—unless C and R are prorated from the distributed parameters. If only a general indication of the warm-up time is desired, let R equal the steady-state resistance, and let C equal one-half the actual total capacity of the baffle. The actual warm-up time of the crystal blank itself is a variable that will depend upon the fabrication of the crystal unit and its drive level. For most purposes it can be assumed that, with the aid of the crystal driving power, the temperature of the crystal blank will not significantly lag the rise in temperature of the crystal chamber during the warm-up period. Approximate values of $-\log_e(1°/\Delta T)$ for representative values of ΔT are given in the following table.

ΔT	$-\log_e(1°/\Delta T)$
3	1.0
5	1.6
10	2.3
20	3.0
30	3.4
40	3.7
50	3.9
60	4.1
70	4.3
80	4.4
90	4.5
100	4.6

Pin-to-Pin Electrical Capacitance of Crystal Oven

4-73. It should be remembered that the pin-to-pin capacitance of the oven is not necessarily the capacitance that the oven adds to the shunt capacitance of the crystal unit. For example, in figure 4-18, assume that C_1 and C_2 are both 4$\mu\mu$f and that C_3 is 2 $\mu\mu$f. It can be seen that if neither pin is grounded, the total pin-to-pin capacitance is 4 $\mu\mu$f; but if one pin is grounded, the total pin-to-pin capacitance is 6 $\mu\mu$f. Also, it can be seen when a crystal unit is inserted in its oven socket, that although the pin-to-pin capacitance of the oven is shunted across the crystal, the crystal shunt capacitance does not increase by that same amount. In effect, since the crystal pins are shielded by the oven receptacles, the oven capacitance substitutes for, rather than adds to the *external* pin-to-pin capacitance of the crystal unit.

Base Leakage of Small Ovens

4-74. The smaller the crystal oven, the more difficult it becomes to control the chamber temperature, not only because the surrounding heat capacity becomes smaller, but also because the percentage of heat leakage through the base becomes greater, resulting in steeper temperature gradients within the crystal chamber. Improved performance can generally be obtained by concentrating more than an average proportion of the heater windings near the base. An interesting and very successful innovation in this direction occurs in a recent oven design by B. C. Hill, Jr. of HEEMCO. In the Hill oven, the heater windings are extended around the base leads, which therefore are maintained at essentially the heater temperature and so exhibit much less tendency to

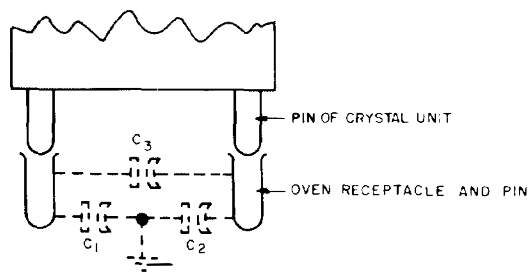


Figure 4-18. Pin-to-pin electrostatic capacitance of crystal oven

follow the changes in the ambient temperature. An entirely different approach, one which ingeniously exploits the fact that the temperature at the base changes more rapidly than at any other part of the oven, has been introduced by R. Beetham of the James Knights Company. The Beetham principle, which has been applied in the design of miniature crystal ovens, is to locate the thermostat at the base and in good thermal contact with it. This arrangement virtually eliminates the existence of steep temperature gradients within the crystal chamber; in addition, because the temperature of the base-mounted thermostat changes relatively rapidly, it permits the cycling frequency to be much higher than otherwise, thereby diminishing the amount of heat capacity required to attenuate the a-c component of temperature at the crystal. Both the base-heater and base-thermostat methods permit cycling temperatures at the crystal to be reduced to a few tenths of a degree C as the ambient temperature varies from —55°C to operating temperatures of 75 or 85°C.

PART II

TECHNICAL DESCRIPTIONS OF CRYSTAL OVENS

TECHNICAL DATA CHART OF CRYSTAL OVENS FOR USE WITH GROUP-I MILITARY STANDARD CRYSTAL UNITS

Mil Std Xtal Holder Accommodated	*No. of Holders Accommodated*	*Military or Commercial Type or Dwg No.*	*Oven Operating Temperature (°C)*	*Ambient Temp Range (°C)*	*Max Temp Deviation (°C)*	*Heater Voltage (V)*	*Provisions for Mounting Oven*
HC-6/U	1	HD-54/U	75	—55 to +55	—7, +6	27.5 dc	Standard lock-in base
	5	Bendix Radio Dwg L205628	75	—55 to +55	—10, +6	27.5 dc	Four thd studs on 1½ x 1¾ in. mtg centers
	13	Bendix Radio Dwg N205651	75	—55 to +55	—10, +6	27.5 dc	Four thd studs on 1¾ x 1^{13}/$_{16}$ in. mtg centers

CRYSTAL OVEN HD-54/U

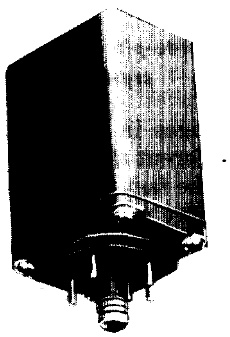


Figure 4-19. Crystal Oven HD-54/U

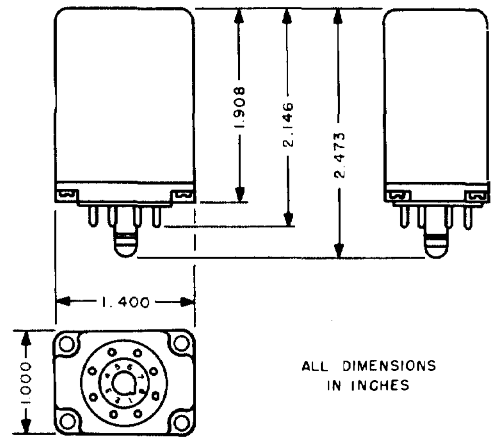


Figure 4-20. Dimensions of Crystal Oven HD-54/U

FUNCTIONAL DESCRIPTION

Crystal Oven HD-54/U provides temperature stabilization for a single HC-6/U-mounted crystal unit at a nominal operating temperature of 75°C, over an ambient range of −55°C to +55°C. The oven operates on a heater voltage of 27.5 volts, dc, and mounts in a standard lock-in socket. A booster thermostat with associated heating element is incorporated in the oven to shorten the warm-up period.

OPERATING CHARACTERISTICS

Operating Temperature: 75°C
Temperature Deviation: −7° to +6°C
Ambient Temperature Range: −55° to +55°C
Approximate Warm-Up (stabilization) Time: 6 min
Oven Temperature (inside crystal holder) During Warm-Up Time:

Oven Temp	*Warm-up Time*
90°C max	0 to 3 min
65° to 85°C	3 to 4 min
68° to 81°C	over 4 min

Power Requirements: 27.5 V, dc; 1.5 amp

PHYSICAL CHARACTERISTICS

Net Weight: 2 oz
Thermometer: None
Provisions for Temperature Adjustment: None
Oven Materials: Plastic cover and base
Provisions for Mounting Oven: Standard lock-in base
Oven Will Accommodate: One Crystal Holder HC-6/U

LOGISTICAL DATA

Army-Navy Nomenclature: Crystal Oven HD-54/U
Status:
Date of Status:
Cognizant Agency:
Govt. Specifications:
USAF Stock Class:
USAF Stock No.:
*Source of Supply:** Bendix Radio; Clark (commercial equivalent: Clark CO-10); Downing (commercial equivalent: Downing Single Crystal Unit Oven); Miller Labs (commercial equivalent: Miller Labs BM-100)

* See Appendix III for complete name and address.

BENDIX RADIO CRYSTAL OVEN L205628

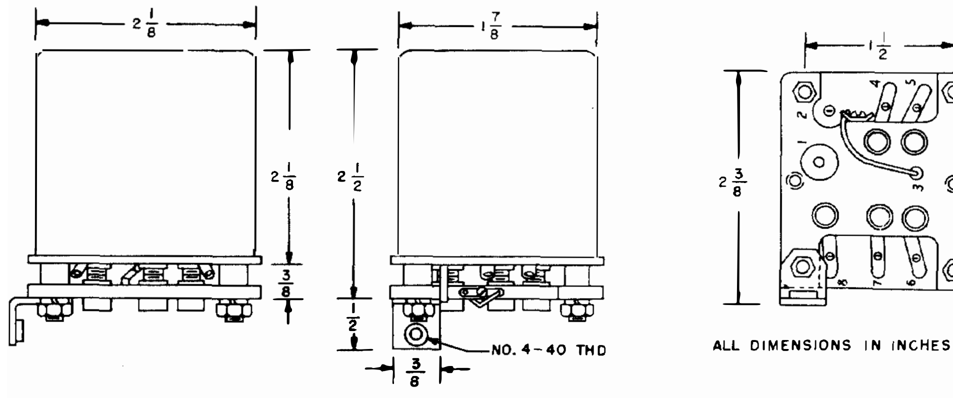


Figure 4-21. Dimensions of Bendix Radio Crystal Oven L205628

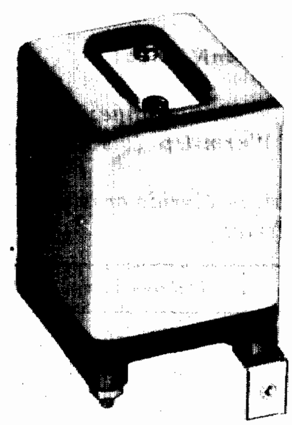


Figure 4-22. Bendix Radio Crystal Oven L205628

FUNCTIONAL DESCRIPTION

The Bendix Radio L205628 Crystal Oven is a multiple oven designed to provide temperature stabilization at 75°C, nominal, over an ambient range of −55°C to +55°C. Up to five HC-6/U-mounted crystal units can be accommodated. The oven operates from a heater voltage of 27.5 volts, dc. It was originally designed for use in Radio Sets AN/ARC-19 and AN/ARC-33.

OPERATING CHARACTERISTICS

Operating Temperature: 75°C
Temperature Deviation: −10° to +6°C
Ambient Temperature Range: −55° to +55°C
Approximate Warm-Up (stabilization) Time: 7 min
Oven Temperature (inside crystal holder) During Warm-Up Time:

Oven Temp	*Ambient Temp*	*Warm-up Time*
90°C max	+20° to +55°C	0 to 3 min
60° to 85°C	+20° to +55°C	3 to 4 min
68° to 81°C	+20° to +55°C	over 4 min
90°C max	−55° to +20°C	0 to 3 min
60° to 85°C	−55° to +20°C	3 to 5 min
65° to 81°C	−55° to +20°C	over 5 min

Power Requirements: 27.5 V, dc; 1.5 amp

PHYSICAL CHARACTERISTICS

Net Weight: 7 oz
Thermometer: None
Provisions for Temperature Adjustment: None
Oven Materials: Metallic cover, plastic base
Provisions for Mounting Oven: Four thd studs on 1½ x 1¾ in. mtg centers
Oven Will Accommodate: Five Crystal Holders HC-6/U

LOGISTICAL DATA

*Source of Supply:** Bendix Radio (Dwg No. L205628); Downing (commercial equivalent: Downing Five Crystal Unit Oven)

* See Appendix III for complete name and address.

OVENS

BENDIX RADIO CRYSTAL OVEN N205651

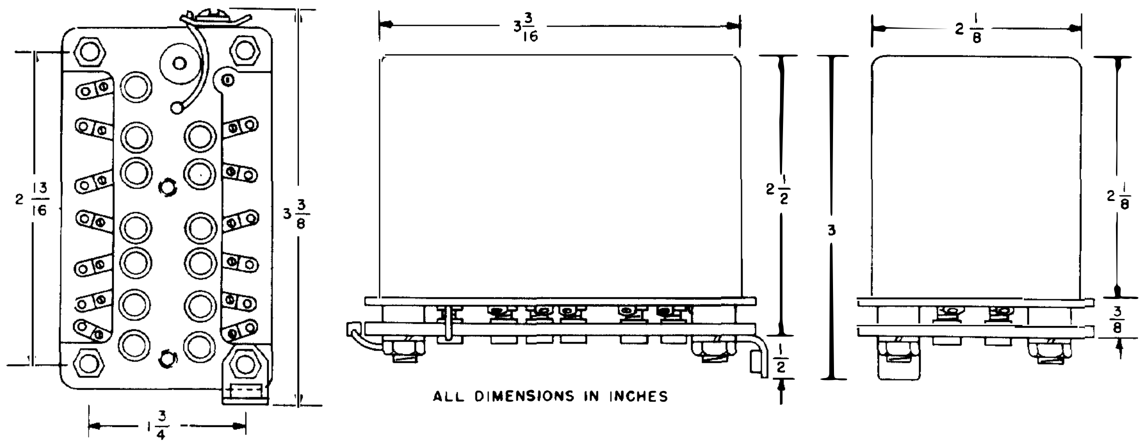


Figure 4-23. Dimensions of Bendix Radio Crystal Oven N205651

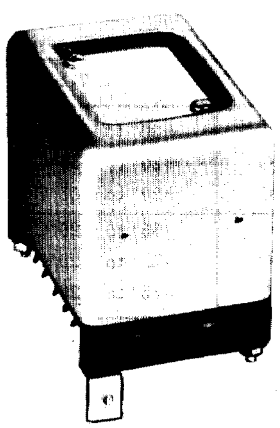


Figure 4-24. Bendix Radio Crystal Oven N205651

FUNCTIONAL DESCRIPTION

The Bendix Radio N205651 Crystal Oven is a multiple oven designed to provide temperature stabilization at 75°C, nominal, for up to thirteen HC-6/U-mounted crystal units in ambient temperatures from −55°C to +55°C. The oven operates from a heater voltage of 27.5 volts, dc. It was originally designed for use in Radio Sets AN/ARC-19 and AN/ARC-33.

OPERATING CHARACTERISTICS

Operating Temperature: 75°C
Temperature Deviation: −10° to +6°C
Ambient Temperature Range: −55° to +55°C
Approximate Warm-Up (stabilization) Time: 7 min
Oven Temperature (inside crystal holder) During Warm-Up Time:

Oven Temp	*Ambient Temp*	*Warm-up Time*
90°C max	+20° to +55°C	0 to 3 min
60° to 85°C	+20° to +55°C	3 to 4 min
68° to 81°C	+20° to +55°C	over 4 min
90°C max	−55° to +20°C	0 to 3 min
60° to 85°C	−55° to +20°C	3 to 5 min
65° to 81°C	−55° to +20°C	over 5 min

Power Requirements: 27.5 V, dc; 1.5 amp

PHYSICAL CHARACTERISTICS

Net Weight: 10 oz
Thermometer: None
Provisions for Temperature Adjustment: None
Oven Materials: Metallic cover, plastic base
Provisions for Mounting Oven: Four thd studs on $1\frac{3}{4}$ x $2\frac{13}{16}$ in. mtg centers
Oven Will Accommodate: Thirteen Crystal Holders HC-6/U

LOGISTICAL DATA

*Source of Supply:** Bendix Radio (Dwg No. N205651); Downing (commercial equivalent: Downing Thirteen Crystal Unit Oven)

* See Appendix III for complete name and address.