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DESIGN, CONSTRUCTION AND USE
OF AN APPARATUS
FOR THE MEASUREMENT
OF NORMAL TOTAL EMISSIVITY
OF SURFACES OF OPAQUE MATERIALS
AT ORDINARY TEMPERATURES

by

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ABSTRACT

Factors effecting the emissivity of surfaces are discussed. A standard apparatus for the measurement of emissivity is described.

The design features of the apparatus used are explained; and tests on several paints, tarred paper, asbestos paper, aluminum foil and copper, nickel and aluminum sheets are reported.

The tests conducted indicated that the performance of the apparatus was satisfactory except for very low emissivity surfaces.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iii
ABSTRACT	iv
I. INTRODUCTION	1
A. Mechanism of Thermal Radiation, Reflectivity, Absorptivity and Emissivity of Solid Surfaces	1
B. General Presentation of the Apparatus	6
1. The Main Features	7
2. Components of the Apparatus and Requirements for Good Performance	8
a. Thermopile Chamber	8
b. Blackbody Cone	8
c. Specimen Holder	8
d. Specimens	8
e. Measuring	9
3. Theory of Heat Radiation in the Apparatus	9
II. THE APPARATUS	15
A. General Description	15
B. Design Criteria and Details of Design	18
1. The Geometric Shape	18
2. Dimensions	18
3. Thermopile Receiver	19

	Page
4. Specimen Holder	21
C. Construction	22
1. Thermopile Chamber and Blackbody Cone	22
2. Thermopile Receiver	24
3. Specimen Holder	24
4. Water Circulation System	25
5. Steam Circulation System	25
III. TESTING	26
A. Preparation for Test	26
B. Setting Up the Apparatus	26
C. Test Procedure	27
D. Tests Made and Results	28
E. Discussion of Results	32
IV. CONCLUSIONS AND RECOMMENDATIONS	36
APPENDIX A: Determination of the Emissivity of the Blackbody Cone	38
APPENDIX B: Evaluation of Factor ϕ_2	41
APPENDIX C: Calculation of Angle Factors	44
APPENDIX D: Determination of Number of Junctions	46
APPENDIX E: Complete Dimensional Drawing	48
APPENDIX F: Test Data and a Sample Calculation	50
APPENDIX G: Instruments Used	54
BIBLIOGRAPHY	56
REFERENCES NOT CITED	57

I. INTRODUCTION

The radiant heat flow emitted by a surface can be calculated with the equation

$$W = \epsilon \sigma T^4$$

where W is the emittance, ϵ is the emissivity, σ is a physical constant and T is the absolute temperature. Accepted value of proportionality factor σ is 0.174×10^{-8} Btu/hr-ft²-°R⁴.

There exist materials in nature for which the value of emissivity, ϵ , ranges from about 0.02 for materials such as polished copper, gold and silver, to as high as 0.96 for asbestos board. Furthermore, different materials show different variations in their ϵ value under various conditions.

Temperature of the surface, its degree of roughness, and, if a metal, its degree of oxidation are the factors influencing ϵ . In the remaining part of this section these factors are summarized. Also the theory of the apparatus is given.

A. The Mechanism of Thermal Radiation, Reflectivity, Absorptivity and Emissivity of Solid Surfaces

Thermal radiation, or temperature radiation, consists of waves with wavelengths spread over a fairly large range

(0.1 to 100 μ)^{*}, the mean wavelength being a function of the temperature of the body. This mean wavelength decreases as the temperature increases. The greater part of the radiated energy lies in the infrared because most applications are concerned with temperatures less than 4000 K, in which case the mean wavelength is greater than the upper limit for the visible region (0.39 to 0.78 μ).

When radiant energy falls on a body, part may be absorbed, part reflected, and the remainder transmitted through the body. Most solid bodies absorb practically all the infrared energy penetrating their surfaces within a very thin layer. Electric conductors need a layer of the order of magnitude of 1 μ for the absorption, and a thickness of 1,000 μ is sufficient for most nonconductors. The thickness of majority of materials encountered in engineering is almost always greater than these values, so that none of the radiant energy is transmitted through the body.

All materials in nature also emit radiation, the quality and quantity depending upon the absolute temperature and the properties of the material composing the radiating body. According to Planck's law, the monochromatic emittance

* One micron is equal to one-thousandth of a millimeter.

of a black body at any temperature varies from 0 at $\lambda = 0$ through a maximum and back to 0 at $\lambda = \infty$ (λ denotes wavelength); its maximum value moves to shorter wavelengths with increasing temperature. The position of the maximum is inversely proportional to the absolute temperature (Wien's displacement law).

Electric conductors and nonconductors are basically different with respect to their infrared radiation properties. The conductors radiate comparatively little energy, whereas nonconductors radiate a rather large amount of heat. The emissivity and absorptivity change with wavelength for both groups. Figure 1 shows the monochromatic reflectivity ρ_λ for aluminum as an example of a conductor, and Fig. 2 gives ρ_λ for some nonconducting surfaces of engineering importance. The polished aluminum surface has a smaller reflectivity at shorter wavelengths than at longer wavelengths, and this holds for all metals. The absorptivity of metals is then greater at shorter wavelengths.

The variation of reflectivity of nonconductors with wavelength is much more irregular. It is a characteristic feature of almost all industrially important nonconductors that the reflectivity is generally lower at longer wavelengths. For nonconductors, the absorptivity decreases with temperature; for conductors, it increases (Fig. 3 and Fig. 4).

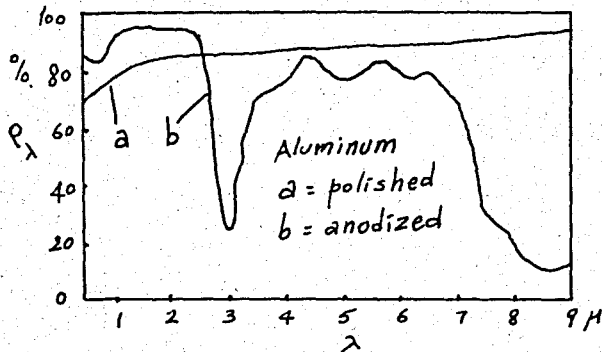


Fig. 1. Monochromatic reflectivity for aluminum as a function of wavelength. (1)*

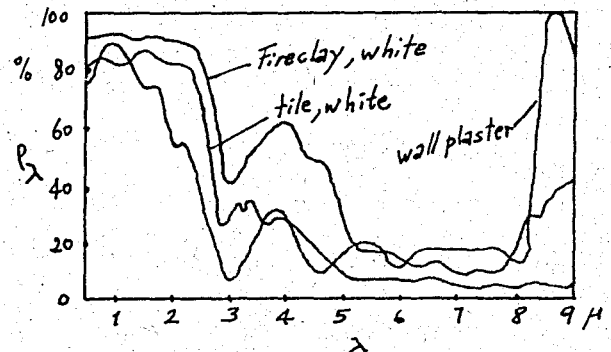


Fig. 2. Monochromatic reflectivity for different nonconductors as a function of wavelength. (1)

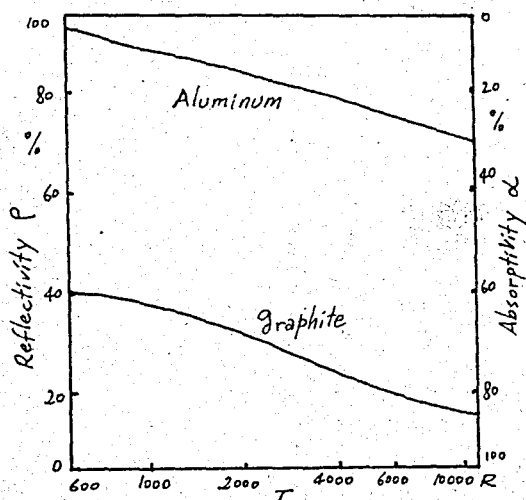


Fig. 3. Total reflectivity and absorptivity of different conductors for incident black radiation of the indicated temperature. (1)

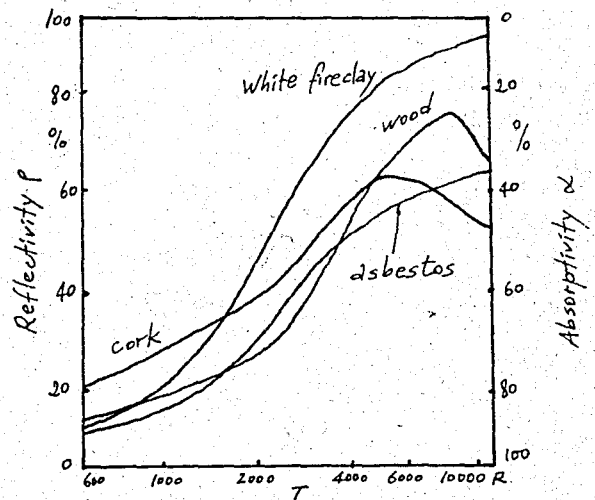


Fig. 4. Total reflectivity and absorptivity of different nonconductors for incident black radiation of the indicated temperature. (1)

*Parenthetical references superior to the line refer to bibliography.

The emissivities of highly polished metals are very low and a function of the product term $\rho_e T$, where ρ_e is the specific electrical resistance and T is the absolute temperature. A poorly polished specimen may have several times this theoretical minimum emissivity. It can be said that, in general, the emissivities of nearly all conductors increase with temperature and that of nonconductors tend to decrease. Fig.5

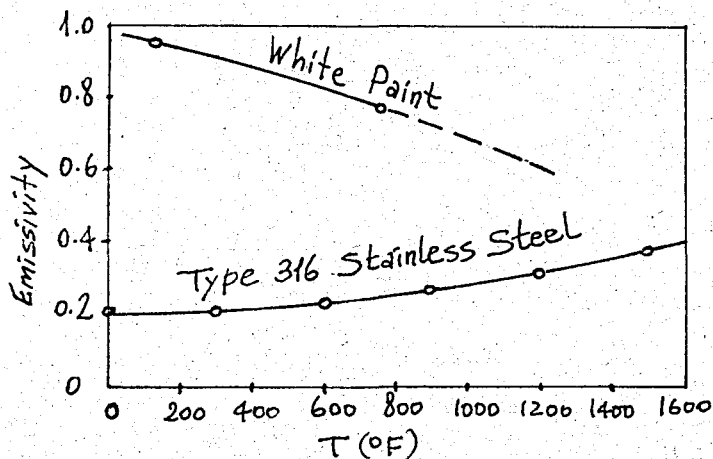


Fig.5. Total emissivity as a function of absolute temperature. (2)

illustrates the dependence of emissivity on the absolute temperature of the system. Although the values indicated by this figure are not from actual emissivity measurements (they were obtained by reflectance measurements), the trend of variations is typical.

In calculations of radiative heat-exchange in various engineering applications, one has sometimes to be concerned with radiative flux in a certain direction which

is described by the directional emissivity ϵ_{β} . Fig. 6 and Fig. 7 show the results of measurements on electric conductors and nonconductors heated to moderate temperatures. As it is seen from the figures, the directional emissivity

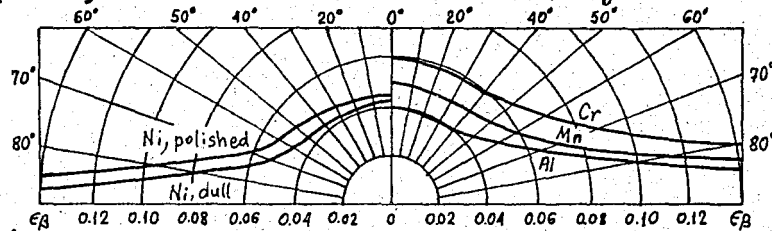


Fig. 6. Directional emissivity of solid materials. (1)

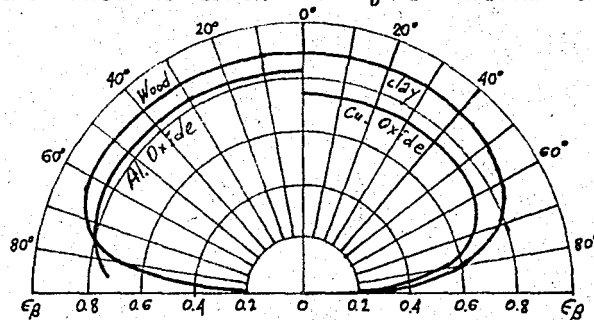


Fig. 7. Emissivity of materials in different directions. (1)

of nonconductors decreases rapidly as the angle β approaches 90° . For conductors, the emissivity first increases and then decreases to zero with increasing angle β . Emissivity values most widely reported in the literature are for a direction normal to the surface, and it is the normal total emissivity that is measured in this work.

B. General Presentation of the Apparatus

The apparatus presented here is a standard one, adopted

in 1961 under ASTM Designation number: C 445-61. (3)

1. The Main Features

This is an apparatus for measuring the normal total emissivity of surfaces of thin, opaque materials at ordinary temperatures.

The normal total emissivity of the specimen mounted on the specimen holder is determined from the emfs of the thermopile when it views the specimen and when it views the blackbody cone, both being at the same temperature when viewed. The equation used to calculate the emissivity is:

$$\epsilon_2 = \epsilon_{2b} \frac{emf}{emf_b} \quad (3)$$

where:

ϵ_2 = normal total emissivity of the specimen surface,

ϵ_{2b} = effective emissivity of the blackbody cone.

(see Appendix A for evaluation of ϵ_{2b}),

emf = thermopile emf value when viewing test specimen, and

emf_b = thermopile emf value when viewing blackbody cone.

The models used to obtain this approximate equation are explained later in this section.

2. Components of the Apparatus and Requirements for Good Performance

- a. Thermopile Chamber: Consists of an internal cone with an opening at the base and surrounded by a cylindrical jacket into which saturated steam is introduced at atmospheric pressure to heat the cone uniformly. The function of the thermopile mounted at the apex of the cone in a steam-surrounded steamtight housing is to measure the quantity of radiant energy emanating from any surface it views. The sensitivity of measurement is positively effected with the increase in the number of junctions constituting the thermopile.
- b. Blackbody Cone: Consists of a cone with interior surface painted and surrounded by a cylindrical water jacket.
- c. Specimen Holder: The function of the specimen holder is to maintain a specimen at the desired temperature and presenting it for viewing by the receiver.
- d. Specimens: It is necessary that test specimens should be prepared and handled in such a manner that surfaces to be tested are not soiled by the fingers or by foreign matter.

Test specimens of a thin flexible nature should be cemented to the specimen holder cover plate with a suitable

adhesive, such as thin rubber cement. After applying adhesive and specimen to the plate, the surface of the specimen should be covered with a sheet of clean paper, and rolled with a suitable roller to remove bubbles and assure uniform close contact of a specimen and cover plate.

e. Measuring: For measurements of steam and water temperatures accurate thermometers are sufficient.

The sensitivity requirement on the potentiometer output is $1 \mu V$.

3. Theory of Heat Radiation in the Apparatus

Considering the closed volume made by surfaces of the receiver, thermopile cone and the blackbody cone, represented by the subscripts R, 1, and 2, respectively (Fig. 8), radiant heat exchange calculations can be carried out between these surfaces. The temperature of the thermopile cone surface, T_1 , is $212^\circ F$, and that of blackbody cone, T_2 , is approximately $60^\circ F$. The temperature at the measuring junctions side of the receiver will reach, at steady-state, a certain value T_R . When surface 2 is replaced by a surface of different emissivity at the same temperature, different quantity of radiant energy will be emanated, resulting in a different T_R value. Since the temperature of the reference junctions side of the receiver is kept constant at T_1 , the change in T_R changes the tempera-

ture difference between the two sides, so the emf output changes.

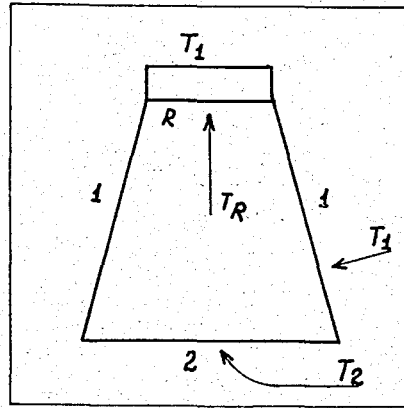
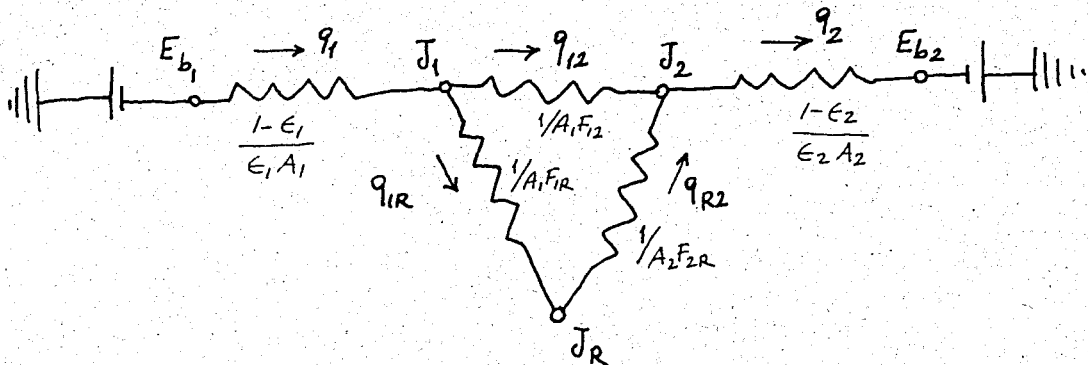


Fig. 8

The ratio of emfs obtained when viewing the specimen surface and the blackbody cone, both at the same temperature, is approximately equal to the ratio of the emissivities of the specimen surface and the blackbody. When the emissivity of the blackbody is known, the emissivity of that surface can be calculated.

Some models were developed to obtain the above mentioned relation.

In the first model, the surface of the receiver was considered as a reradiating wall and the system was represented by its electrical analogue as follows:



where q = radiant heat flow
 J = radiosity
 $E_b = \sigma T^4$
 A = area
 ϵ = emissivity
 F = angle factor

with the subscripts denoting the surfaces as indicated in Fig. 8.

The solution of the system resulted in the equation:

$$\sigma T_R^4 = \frac{A_1 F_{1R} \sigma T_1^4 + A_2 F_{2R} \sigma T_2^4}{A_1 F_{1R} + A_2 F_{2R}} - \left[\frac{F_{1R} \left(\frac{1}{\epsilon_1} - 1 \right) - F_{2R} \left(\frac{1}{\epsilon_2} - 1 \right)}{A_1 F_{1R} + A_2 F_{2R}} \right] q_1$$

with

$$q_1 = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\left(\frac{1}{\epsilon_1} - 1 \right) + \frac{A_1/A_2 F_{1R} + F_{2R}}{A_1/A_2 F_{1R} F_{12} + F_{12} F_{2R} + F_{1R} F_{2R}} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right)}$$

The values of A_1 , A_2 , F_{1R} , F_{12} , F_{2R} are fixed by the design, T_1 and T_2 are directly measured during the test, and T_R is

calculated from the emf output. (For the iron constantan thermocouples used, 1°F produces $30 \mu\text{V}$). Knowing ϵ_1 , the only unknown ϵ_2 can be calculated.

This model did not result in a relation similar to the one given in the standards. Furthermore, emissivities calculated by use of this equation were found to be far away from what had been expected. The reason is that there is certainly a heat flow through the wall R, so that refractory wall assumption does not work.

In the second model developed energy balance was made for the thermopile measuring junctions.

Radiant energy to cold surface at T_2 (direct radiation only; i.e. no reflection)

$$q_R = \epsilon_1 \epsilon_2 A_1 F_{12} \omega (T_1^4 - T_2^4)$$

is equal to the energy received from the environment at T_R , q_c (Fig. 9).

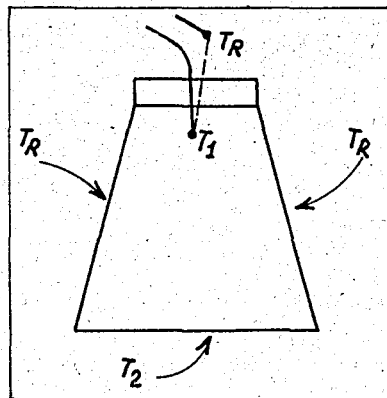


Fig. 9. Second Model

For small $(T_R - T_1)$, it was assumed that energy received from the environment is proportional to $T_R - T_1$:

$$q_c = a(T_R - T_1)$$

Since

$$emf = b(T_R - T_1)$$

it is found that $q_R = q_c = \frac{a}{b} (emf) = c (emf)$

$$\epsilon_1 \epsilon_2 A_1 F_{12} \propto (T_1^4 - T_2^4) = c (emf)$$

Applying this equation for the cases when specimen and blackbody cone were viewed and taking the ratio, it was obtained that

$$\frac{\epsilon_2}{\epsilon_{2b}} = \frac{emf}{emf_b} \frac{T_{1b}^4 - T_2^4}{T_1^4 - T_2^4} = \frac{emf}{emf_b} \phi_1$$

where T_{1b} is the temperature of the measuring junctions when the blackbody is viewed, and T_1 is that when the specimen is viewed.

With this model, it is seen that the approximated equation mentioned before results when $\phi_1 = 1$.

The third model was in fact a modification of the second, which took into account the multiple reflections. Following the same procedure, the equation:

$$\frac{\epsilon_2}{\epsilon_{2b}} = \frac{emf}{emf_b} \left[\frac{(1+f_{1b})T_{1b}^4 - (1+f_{2b})T_2^4}{(1+f_1)T_1^4 - (1+f_2)T_2^4} \right] = \frac{emf}{emf_b} \phi_2$$

was obtained, with

$$1+f_1 = 1 - \frac{\epsilon_1}{\epsilon_2} (1-\epsilon_2) F_{21} + (1-\epsilon_1)(1-\epsilon_2) F_{12} F_{21} - \dots ,$$

$$1+f_2 = 1 - \frac{\epsilon_2}{\epsilon_1} (1-\epsilon_1) F_{12} + (1-\epsilon_2)(1-\epsilon_1) F_{21} F_{12} - \dots ,$$

$$1+f_{1b} = 1+f_1 \text{ in which } \epsilon_2 \text{ is replaced by } \epsilon_{2b},$$

$$1+f_{2b} = 1+f_2 \text{ in which } \epsilon_2 \text{ is replaced by } \epsilon_{2b}, \text{ and}$$

T_1 and T_{1b} as defined above.

The factor ϕ_2 was plotted as a function of emf ratio for different values of ϵ_2 . (Appendix B).

The three models developed are discussed later more extensively.

II. THE APPARATUS

A. General Description

The equipment consists of four main parts: the apparatus itself, water circulation system, steam circulation system, and the system for mounting the several parts of the apparatus in a convenient way.

As shown in Fig.10, the apparatus itself is composed of a thermopile chamber, blackbody cone, and the specimen holder. See the photographs on page 17.

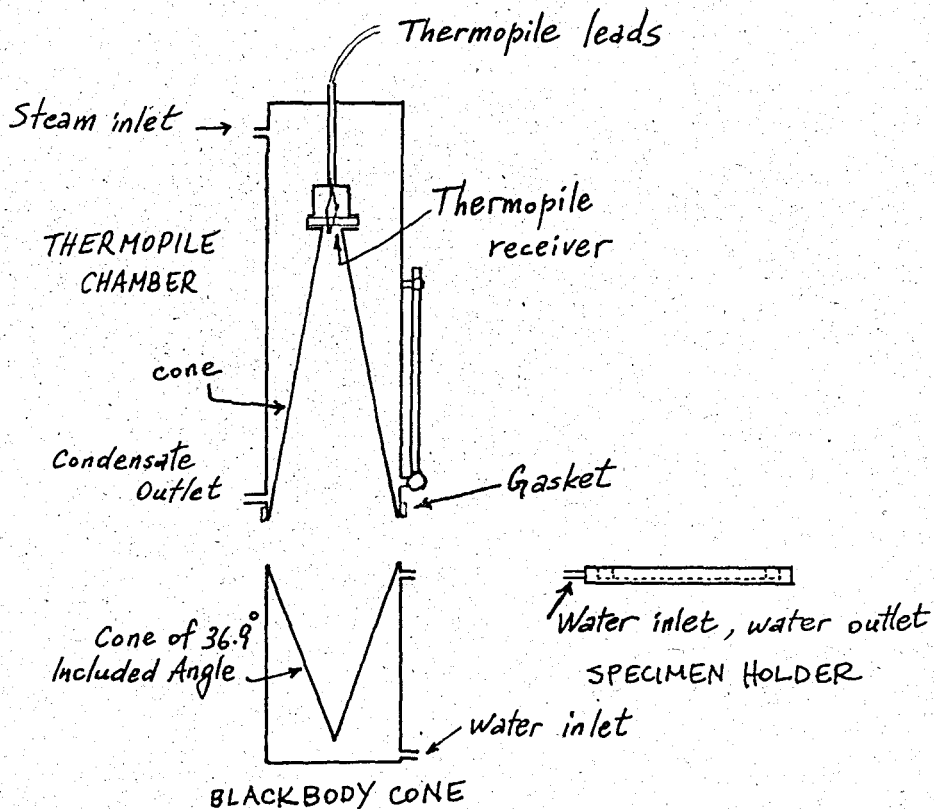


Fig.10. Principal features of normal total emissivity apparatus.

Thermopile chamber and blackbody cone have connections for steam and water circulations as shown in Fig.11 and 12, respectively.

The mounting system is composed of a ring around the thermopile chamber, three stands for hanging it, and a block of wood to sit the specimen holder on.

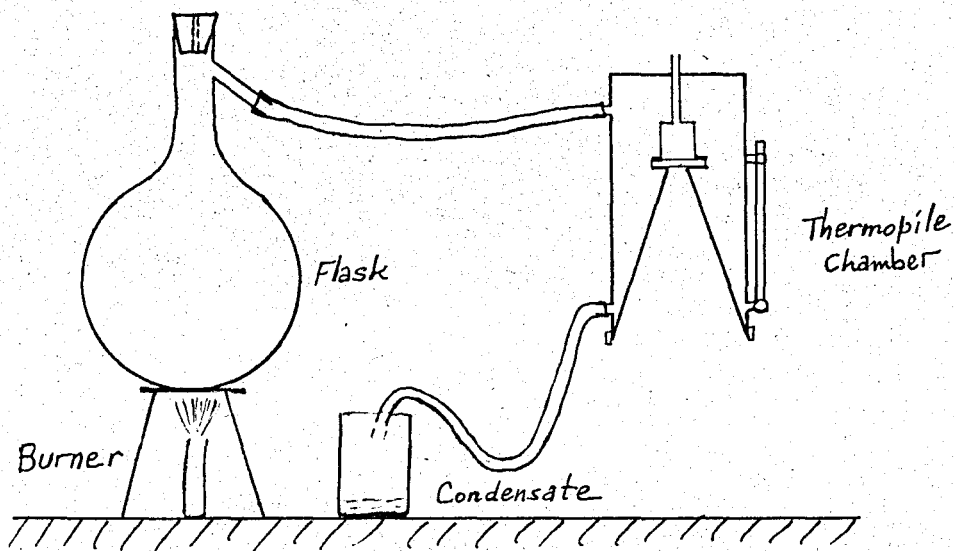


Fig.11. Steam circulation system

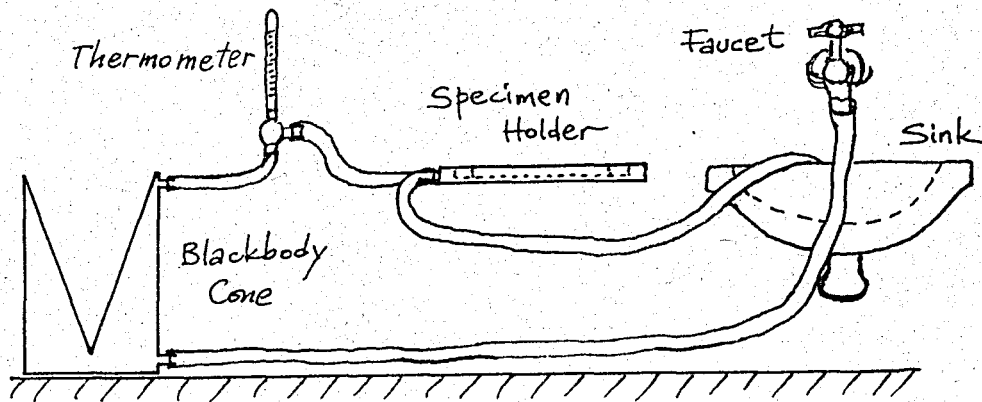


Fig.12. Water circulation system

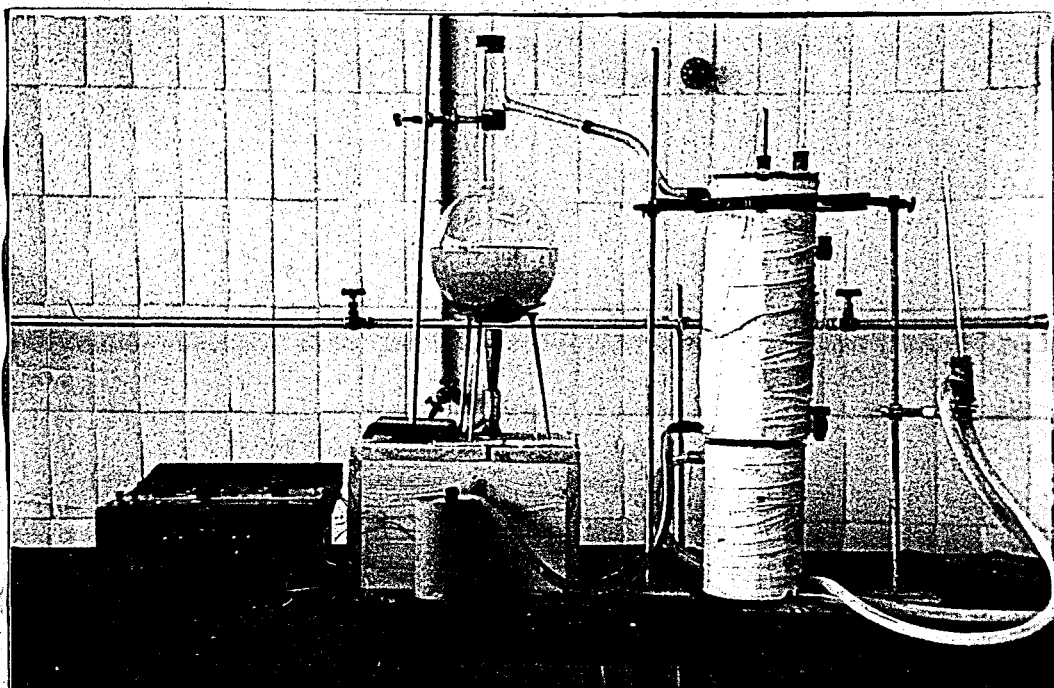


Fig.13. Thermopile chamber, blackbody cone, steam system and potentiometer circuit.

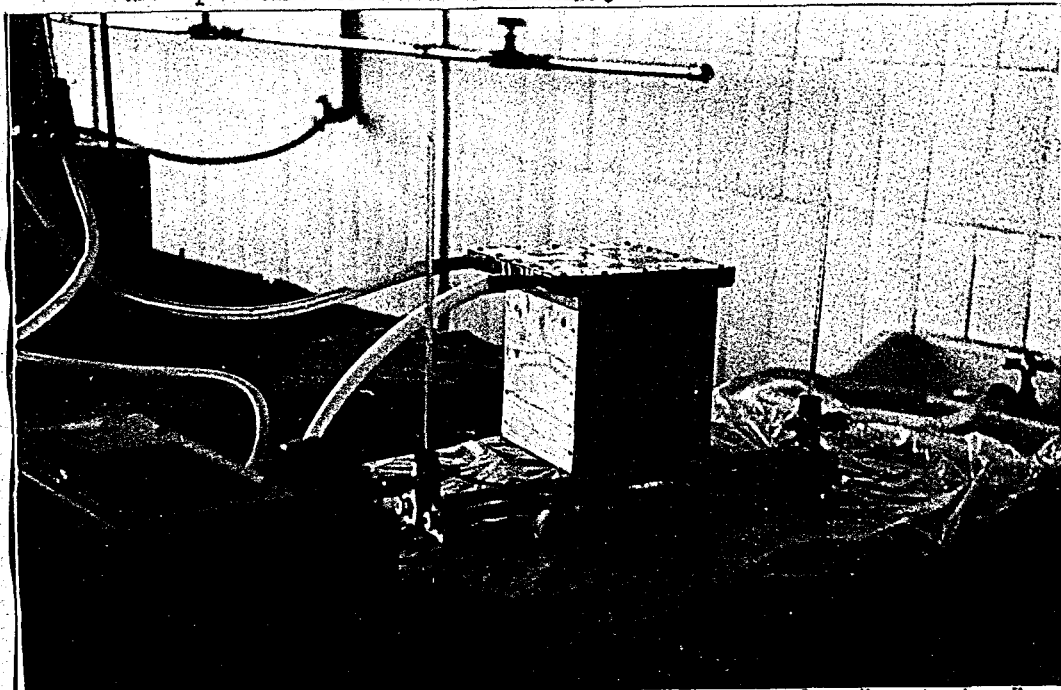


Fig.14. Specimen holder and water system with electrical heater in the circuit.

E. Design Criteria and Details of Design

ASTM standards (C 445-61) have been very useful in establishing the design criteria and were frequently consulted. Also the work of Gouffe⁽³⁾ was made use of.

1. The Geometric Shape

The shape of the blackbody was chosen to be a right circular cone, since the effective emissivity of the hypothetical plane surface representing the opening of a body was available for this shape. (See Appendix A).

Conical shape was chosen also for the shield inside the thermopile chamber. This shield fixes the solid angle of vision, and normal total emissivity is better approximated with this shape.

The specimen holder was chosen to be a square shaped, shallow water-cooled case with an open top closed by a removable hard copper cover plate on which specimens were mounted. With this shape, as indicated in the ASTM standards, uniformity of temperature of the cover plate was assured.

2. Dimensions

The diameter of the blackbody cone was chosen to be 6 in., with a corresponding height of 9 in. (height to base radius ratio is 3.0).

For the internal truncated cone of the thermopile chamber, with the same base diameter of 6 in., 1.5 in. was chosen as top diameter and 12 in. as the height.

The overall dimensions of the specimen holder were chosen to be 10 in. X 10 in. so that the requirement for the extension of the area of the specimen outside of the contact area of the thermopile cone gasket was met. (See Appendix E for complete dimensional drawing of these three units).

3. Thermopile Receiver

ASTM standards require that thermopile should have sufficient number of junctions at the receiver to generate an emf of at least 1 mv when the blackbody cone is viewed at room temperature and the thermopile cone jacket contains saturated steam at atmospheric pressure.

In order to determine the number of junctions of the thermopile necessary to give a sufficient output, it was first necessary to estimate the temperature of the measuring junctions side of the receiver.

As a first approximation to the problem, radiant heat exchange calculations were carried out between receiver surface, thermopile cone, and the hypothetical plane surface representing the opening of the blackbody cone, indicated by the subscripts R,1 and 2, respectively (Fig.15). All surfaces were assumed to be black, and surface R was a refractory.

The equation

$$(T_1^4 - T_R^4) / (T_R^4 - T_2^4) = F_{R2} / (1 - F_{R2})$$

where F_{R2} was the angle factor for surfaces R and 2, gives the temperature of the surface R as a function of F_{R2} . With

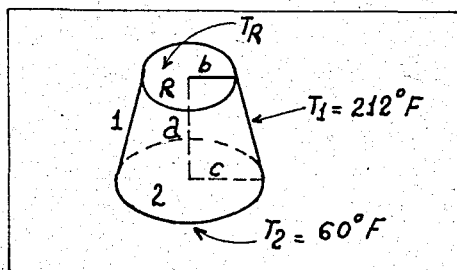


Fig. 15

the chosen dimensions, the value of F_{R2} was calculated to be 0.0641, giving $T_R = 205^\circ\text{F}$. (See Appendix C for calculation of angle factors and variation of T_R with F_{R2}).

Assuming that reference junctions of the thermopile were at 212°F , there became 7°F difference in temperature between the reference and measuring junctions. Considering the output of iron constantan thermocouple at 200°F (Cold junction at 32°F) which is $0.0303 \text{ mv } ^\circ\text{F}$, it was found that

$$\text{required no. of junctions} = \frac{1/0.0303}{7} = 4.7 \approx 5$$

By increasing the number junctions to 24, considering that heat conduction across the surface R is through the iron and constantan wires, and assuming that the following equation holds true:

$$q_{1R} + q_{\text{cond}} = q_{R2}$$

where q_{1R} = heat radiated by surface 1 and impinging on R,
 q_{R2} = that emitted by R and impinging on surface 2,

T_R was found to be 210°F . This value gave the required number of junctions as 16, resulting in a factor of safety of $24/16=1.5$.

Tests showed that this factor of safety estimated by various assumptions is quite close to the value obtained, which is 1.8.

Fig.16 shows the arrangement of junctions over the receiver.

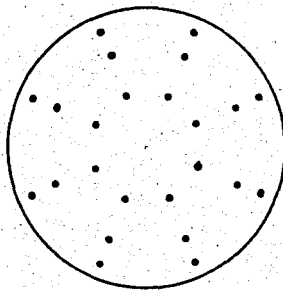


Fig.16

See Appendix D for calculations.

4. Specimen Holder

Water passage was chosen to be rectangular in cross section, with the idea that maximum area of the cover plate would be in direct contact with water.

Assuming $200 \text{ in}^3/\text{min}$ for volumetric flow rate Q ,

6 in/sec for water velocity V , and by using the continuity equation $Q=AV$, the required area was found to be 0.555 in^2 .

The width of the passage was then assumed to be 1.17 in. giving a height of 0.47 in. See Appendix E for the arrangement of water passage.

C. Construction

1. Thermopile Chamber and Blackbody Cone

The cones and cylindrical steam and water chambers were manufactured simply by rolling 1 mm thick copper sheet into the desired shape and by welding the two ends together. Filing of welded ends was necessary.

The top surface of the thermopile chamber was made removable, flanged to the body with 12 screws, with a rubber gasket in between. Also a hole was provided to insert a thermometer for measuring the steam temperature.

The thermopile housing, which is in the form of an inverted cup with a pipe at the top to bring the thermopile leads out, was manufactured in the same way and flanged with 6 screws to the apex of the cone through the fiber board, which constitutes the radiation shield between the reference and measuring junctions. To make the housing steamtight, 4 mm. thick rubber gaskets were provided on both sides of the

board, and the board was surrounded tightly by cellophane. The purpose of making the top surface and the housing removable was to easily dismantle the receiver whenever necessary.

Both chambers were insulated by 4 mm. thick asbestos board and 1 mm. asbestos paper, and the side walls were covered by white cloth.

The steam jacket had steam inlet and outlet connections of 1/2 in. inside diameter, made of copper pipes 1.5 in. long. Also a glass tube was mounted at its side to show the level of the condensate in the jacket. A ring of rubber, a material of low thermal conductivity was bonded to the periphery of the cylindrical jacket at its base to separate the thermopile cone from the blackbody cone or a specimen. Since the gasket should not be visible at the thermopile, the maximum separation distance was calculated and found to be 0.129 in.

The inside surfaces of the two cones were painted with two coats of black stove paint.

The cylindrical water jacket enclosing the cone had a water inlet connection at the bottom to introduce the flow of water tangentially and an outlet connection high in the jacket to assure complete venting of air, both made of copper pipes 1.5 in. long.

2. Thermopile Receiver

A circular fiber board of 3 in. diameter and $\frac{3}{4}$ in. thick was used to separate the measuring and the reference junctions of the thermopile. These junctions were distributed over 1.5 in. diameter circular area of this board, constituting the receiver. For this purpose, the receiver area was divided into 24 equal parts. 1 mm. diameter holes were drilled at the center of each and No. 24 copper and constantan wires, cut in about 2 in. long, were passed through these holes.

A 20 V d.c. battery system was used for making the beaded junctions. The enamel coating at the tips of the wires was scraped off and the wires were held with a pair of pliers. Using the graphite rod as negative and the two wires as positive, an arc was formed between the graphite and the tips of the wires. Sufficiently small beads were obtained in this way.

3. Specimen Holder

The specimen holder was made of cast bronze, with its 6 partition walls inside. To simplify the casting process, it was allowed for these walls vary in cross section thickness from 3 mm. at the top to 5 mm. at the bottom. Then two holes were drilled at the same side as inlet and outlet and copper pipes of $\frac{1}{2}$ in. diameter and 1.5 in. long were welded at these holes.

The cast unit was machined, afterwards, and finally insulated.

The cover plates of the specimen holder were made of a hard, 1.5 mm. thick copper sheet and mounted to the cast piece by 16 screws. As a gasket between the holder and the cover plate, 1 mm. thick sheet cork was used.

4. Water Circulation System

Plastic pipes were used to take water into the blackbody chamber, from there to the specimen holder, and from the specimen holder to the sink.

A thermometer with 0.5°F smallest division was located in the line between the blackbody and the specimen holder to measure the water temperature. For this purpose, a fitting with three openings was used. Thermometer bulb was inserted into the flow through a rubber plug.

5. Steam Circulation System

Steam was produced by boiling water in a 6 lt. capacity pyrex distillation flask. Same type of plastic pipes were used to take the steam from the side tube of the flask to the chamber and to collect the condensate at the bottom. Some steam leakages were allowed at the top of the chamber to assure atmospheric pressure. The steam temperature was measured by a thermometer 0.2°F smallest division.

III. TESTING

A. Preparation for Test

Preparation of the specimens is the main step. Test specimens of a thin flexible nature should be cut into 9in. X 9in. squares and cemented to the specimen holder cover plates. There are three cover plates provided for this purpose. After applying adhesive and specimen to the plate, the surface of the specimen should be covered with a sheet of clean paper and rolled with a roller to remove bubbles and assure uniform close contact of specimen and cover plate.

Test specimens of sheet metal having sufficient rigidity to remain flat during tests should be mounted directly on the specimen holder in place of the cover plate.

Test specimens should be prepared and handled in such a manner that surfaces to be tested are not soiled by fingers or by foreign matter.

B. Setting Up the Apparatus

The cooling water pipe is connected to the faucet. The terminals of the heater are connected to the power

supply. (The electrical heater mentioned here was used in some of the experiments to heat the water so that no condensation will occur. See discussions). After that, the blackbody is placed under the thermopile chamber.

C. Test Procedure

First the bunsen burner was ignited to heat the water in the flask for production of steam. Then the water circulation was started. Under existing conditions, steam production started in 1.5 - 2 hours after igniting the burner, and trial experiments indicated that at least 4 hours were required to obtain steady state conditions with steam flow, although the steam temperature in the chamber, as indicated by the thermometer, reached a steady value around 212°F in about 45 minutes.

It was seen during the trial tests that at steady state, the output did not remain constant but fluctuated. The reason was thought to be temperature drifts in the housing containing the reference junctions of the receiver. To prevent these drifts, the junctions were closely surrounded and the housing completely filled with cotton; the result turned out to be positive.

Under existing laboratory conditions, water temperature

decreased rapidly at first, and then this decrease slowed down and after about 2 hours, it essentially remained constant to within $\pm 0.2^{\circ}\text{F}$.

After steady steam and water conditions were attained, thermopile emf readings were taken at 15 minute intervals. The final steady value of this output, emf_p , obtained in about 4 hours, and the steam and water temperatures were recorded.

Then the test specimen mounted on the specimen holder which was put on the wood block was placed under the thermopile chamber. As indicated by the trial tests, 15 minutes were required to obtain a steady value for this output, emf. The values of emf, steam and water temperatures were recorded. The values for water temperature should not differ by more than 0.2°F for the two cases.

D. Tests Made and Results

12 tests were made to measure emissivities of black stove paint, light-cream "Sadolux" paint, tarred paper, asbestos paper, copper sheet, aluminum foil, aluminum sheet, and nickel. Two tests were made on the black paint, one with water at temperature 54°F and other at 69°F ; four tests were made on "Sadolux" paint, one of them being with water at 68.5°F , the others at lower temperatures. In each of these tests, two consecutive measurements were taken.

1. Black Paint

This is the paint with which the internal surfaces of the cones were painted. Measurement of its emissivity was necessary for the evaluation of effective emissivity of the blackbody cone.

Two tests were made. The dew point temperature of the air in the room was 53°F , as measured by means of a sling psychrometer*. The first test gave the value of ϵ as 0.86. The second test was carried with water at a higher temperature, and ϵ was calculated to be again 0.86.

The data for these and for all the subsequent tests are given in Appendix F .

2. Tarred Paper

This is a material (Ziftli Kâğıt) used in roofing. One test was made. Dew point was 54°F . The value of ϵ calculated from the test data is 0.93.

3. Asbestos Paper

This is an insulating material commonly used for electrical devices and in the laboratories.

The test gave the value of ϵ as 0.94.

* See Appendix G.

4. Copper Sheet

This is the cover plate of the specimen holder. The sheet was cleaned by dilute nitric acid to remove the rust, washed thoroughly and then dried.

The value of ϵ calculated from the test data is 0.38.

5. "Sadolux" Paint

This is the type of paint mostly used in painting metallic surfaces such as automobiles, radiators and pipes. Four tests were made on this specimen. Initially, one coat of this paint was applied to the cover plate and kept 24 hours to dry. Dew point temperature in the room was 59°F . The test gave the value of ϵ as 0.93. Then one more coat of the same paint was applied and kept again for 24 hours. The test gave a slightly higher value for ϵ , 0.94. Finally, a third coat was applied and measurement gave the result as $\epsilon = 0.94$, which proves that increasing the number of coats further will not effect the value of ϵ .

The last test on this specimen was made for three coats again, but water was heated to a temperature of 68.5°F , where the dew point temperature was 62°F . The test gave again the same value 0.94.

6. Aluminum Foil

This is a household material used for cooking purposes. One test was made on this specimen. Dew point temperature was measured as 62°F . The value of ϵ calculated from the test data is 0.34, with water at 69°F .

This value was found much higher than it was expected, therefore, another material of low emissivity, polished aluminum sheet, was tested.

7. Aluminum Sheet

This was the only rigid specimen mounted directly on the specimen holder in place of the cover plate. It had a bright surface.

The value of emissivity for this surface was calculated to be 0.21, again much higher than expected.

8. Polished Nickel Coat

The final test was made on highly polished nickel surface, which should have an emissivity of about 0.05, as indicated in the literature. But the test data gave a value for the emissivity as 0.24, again very high.

Possible reasons for these unexpected results are discussed below.

E. Discussion of Results

The apparatus reached the steady state at different emf values although the steam temperature indicated by the thermometer was almost the same. The reason for this can be explained by the fact that with a thermopile of 24 iron constantan junctions, 1°F difference in temperature produces $24 \times 30 = 720 \mu\text{V}$; a very small change in the temperature of the reference junctions results in a great change in the output. But there was no appreciable change during one test.

The tests conducted indicate that the results obtained with specimens of high and moderate emissivities are satisfactory since they lie in the region of values given in the literature .

The tests on "Sadolux" paint indicate that emissivity of the surface increases slightly as one goes from one coat to two coats, but there is no change with further increase in the number of coats.

The graphs in Fig. 17 show the variation of emf output with time and attainment of steady state conditions for the case of black stove paint. Similar variations were obtained in all the other tests.

Fig. 18 shows the variation of emf output with water temperature, steam temperature being constant. This is for

the test on black stove paint, and it is interesting to note here that the two curves for blackbody cone and the specimen have almost the same slope.

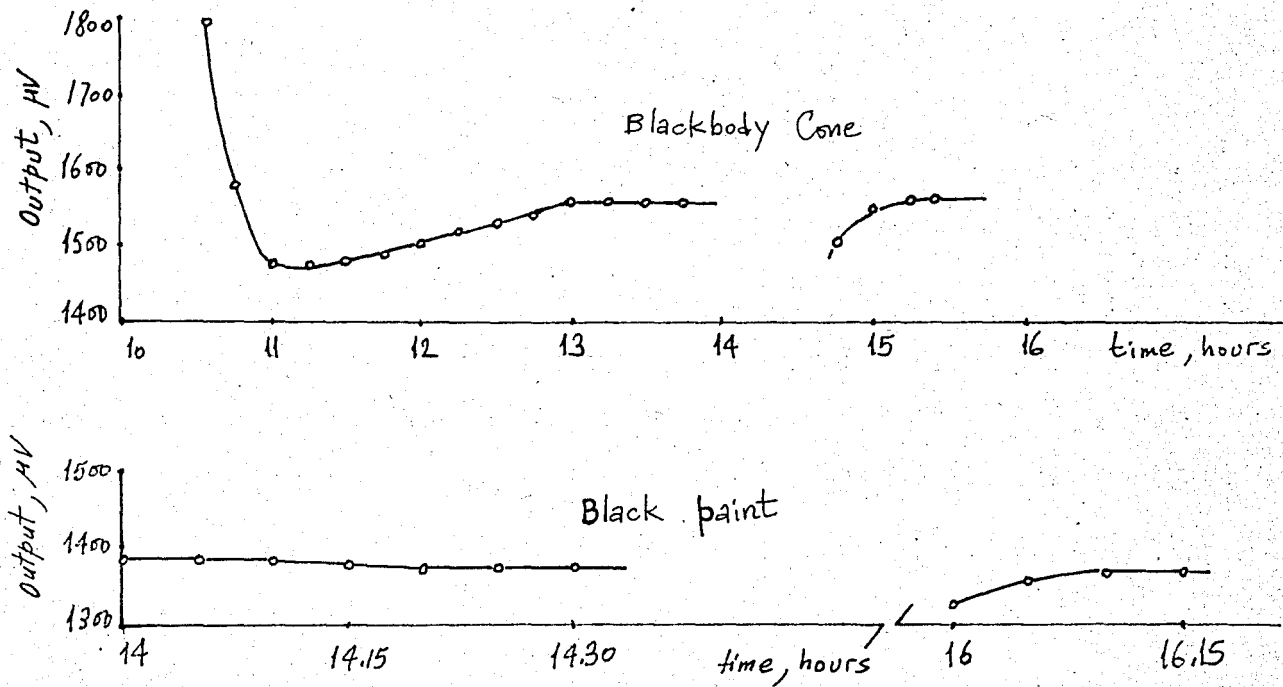


Fig. 17

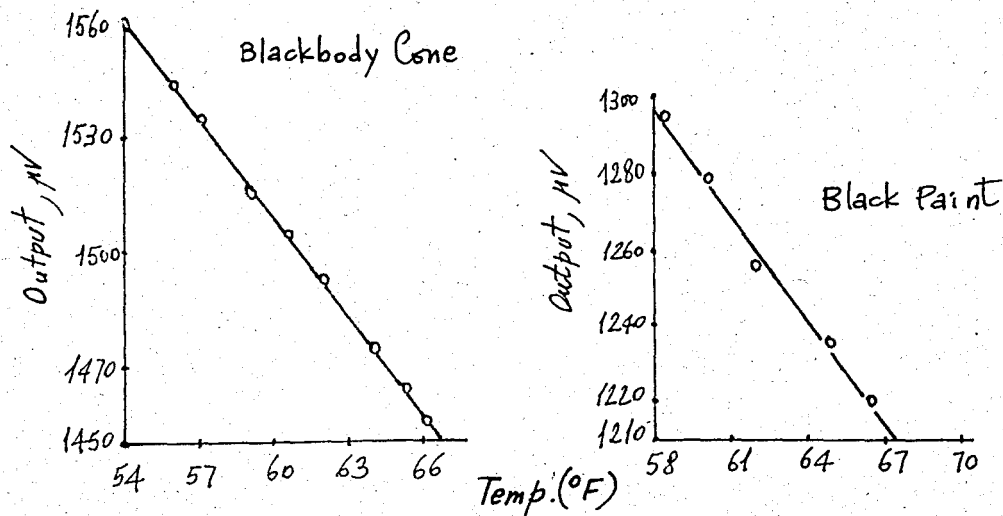


Fig. 18

The last three tests indicate that the apparatus does not work well with the specimens of very low emissivities. The specimens were handled with care, yet the results obtained were different from the tabulated values. The reasons were investigated:

a. Possible effect of moisture condensation was checked. For this purpose, the water was circulated through an electric heater, which raised its temperature to about 70°F; but no appreciable difference in the results were noticed. As an example, the emissivity of the black paint was found as 0.86 both when the water temperature was 69°F and when it was 54°F.

b. A theoretical model was developed with the intention of determining a factor in the governing equation which, if neglected, might cause an error in the case of low emissivity surfaces. This is the second model explained in the first section. Consideration of the factor ϕ_1 resulted in a correction in the right direction, but it was far from being sufficient.

c. A third theoretical model was developed which takes into account multiple reflections. Evaluation of the factor ϕ_2 of this model did not result in a sufficient correction.

d. In the theoretical models mentioned above, it had been assumed that the junctions were receiving heat from the environment by conduction and convection, leading to

a linear dependence of heat on the temperature difference; but it was certain that the measuring junctions were receiving heat from the environment also by radiation. Perhaps there might be a limitation to this assumption. An extensive literature search was made with regard to the theory of such an apparatus, but no reference was found.

e. It is possible that there are convection currents in the conical opening. If so, because of the low temperature at the bottom, the tendency of these currents would be to lower the temperature of the measuring junctions, causing an additional difference in temperature between the measuring and reference junctions of the receiver. This would result in an emf output of a certain amount regardless of the emissivity of the surface viewed. This may well be the reason for measuring high values with low emissivity surfaces, since the effect of a certain amount of additional emf will be quite significant when low outputs are measured.

f. Finally, the emissivity of the black paint used for inside surfaces of the cones was measured to be 0.86, which is less than 0.90, the minimum value suggested in the standards.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. The performance of the apparatus is satisfactory unless the emissivity is very low.

2. Unsatisfactory performance in connection with low emissivity surfaces has not been explained clearly.

Recommendations for this are :

a. More extensive literature search should be made for any theoretical limitations of the apparatus.

b. Inside surfaces of the cones should be painted with a paint of emissivity higher than 0.90 .

c. A specially manufactured, pure metallic surface, aluminum or nickel, should be tested both with a dull surface and with an extremely polished surface, and the results should be compared.

d. One way to verify experimentally the possible effect of convection currents would be to fold the measuring junctions against the receiver area. In the present design, those junctions stick out into the air and are exposed to convection currents. A reduction in the emf output, after the modification, would indicate that convection currents are significant.

3. The apparatus reaches steady state at quite a long time; one test takes about 6 hours.

- a. Better insulation of the thermopile chamber and the flask would reduce heat losses to the surroundings, and
- b. Using a larger boiler flask would enable one to carry out more than one test in one run.

APPENDIX A : DETERMINATION OF THE EMISSIVITY OF THE
BLACKBODY CONE⁽³⁾

The effective emissivity, ϵ_b , of the blackbody cone is determined as follows. The interior surface of the cone is given two coats of selected paint, and two coats of the same paint is applied to the surface of the cover plate of the specimen holder. Measurements of emf'_b and emf' are made as indicated in the text.

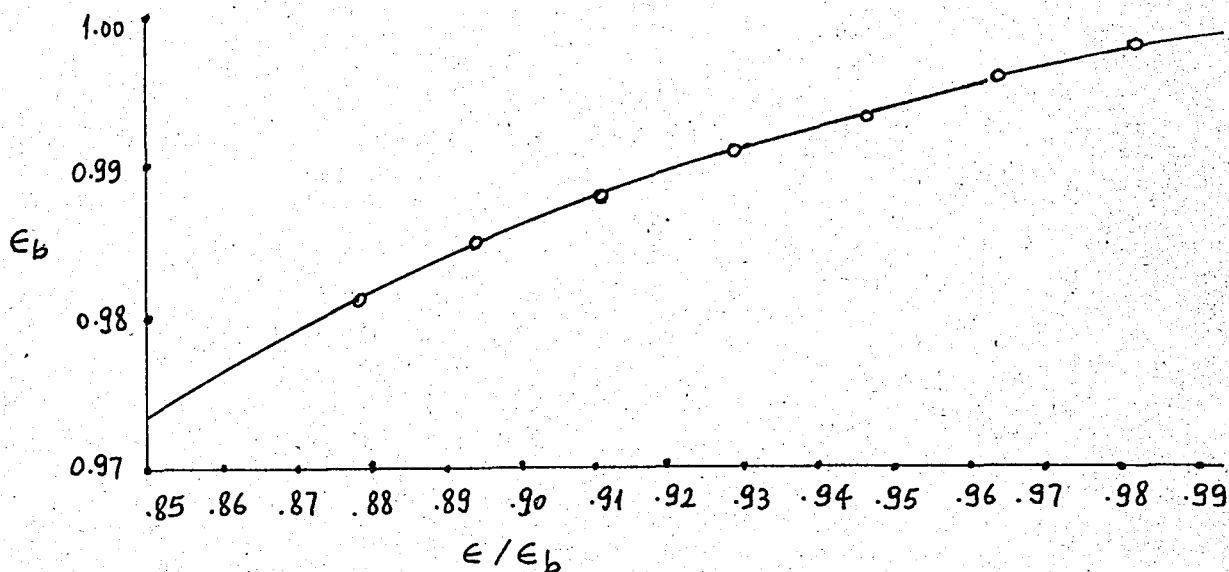
The effective emissivity of the hypothetical plane surface representing the opening of a right circular cone with a diffusely reflecting interior surface has been given by A. Gouffe'.

The table below gives calculated values of the effective emissivity ϵ_b of such a cone having an included angle of 36.9 deg for various values of the surface emissivity ϵ of the interior surface of the cone.

The ratio of $\text{emf}'/\text{emf}'_b$ is equal to ϵ/ϵ_b if the specimen and the cone have the same surface emissivity. Using the table, the values of ϵ and ϵ_b corresponding to the observed ratio of ϵ/ϵ_b can be determined by interpolation or extrapolation. Thus both the emissivity of the painted surface and the effective emissivity of the blackbody cone are determined for the paint and cone used. The values of ϵ_b are plotted below as a function of the ratio ϵ/ϵ_b .

ϵ	0.88	0.90	0.92	0.94	0.96	0.98	1.00
ϵ_b	0.985	0.988	0.991	0.993	0.996	0.998	1.00
ϵ/ϵ_b	0.894	0.911	0.929	0.947	0.964	0.982	1.00

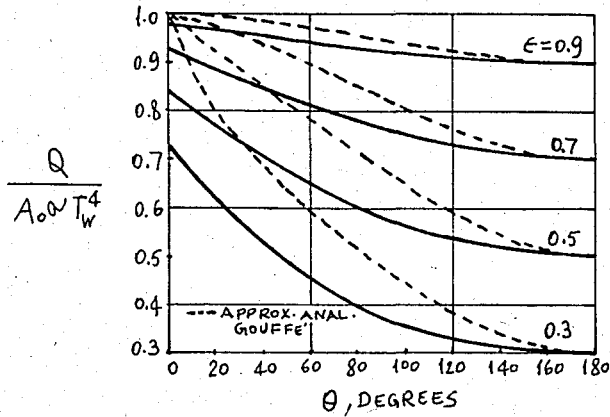
Effective emissivity of blackbody cone



Variation of ϵ_b with ϵ/ϵ_b

The graphic below illustrates the variation of effective emissivities of the openings of the cones with different cone angles, emissivity of the surface, ϵ , being a parameter ⁽⁴⁾. The ordinate axis, $Q/A_o \nu T_w^4$ represents an

apparent hemispherical emissivity of the cavity as a whole. The deviation of $Q/A_o T_w^4$ from ϵ is a measure of the magnitude of the cavity effect.



Efflux of radiation through cavity opening,
uniform wall temperature

APPENDIX B : EVALUATION OF FACTOR ϕ_2

In the third model developed in the first section, which took into account multiple reflections, radiant energy to cold surface at T_2 is given by :

$$q_R = \epsilon_1 \epsilon_2 \omega A_1 F_{12} \left\{ \left[1 - \frac{\epsilon_1}{\epsilon_2} (1 - \epsilon_2) F_{21} + (1 - \epsilon_1) (1 - \epsilon_2) F_{12} F_{21} - \dots \right] T_1^4 \right. \\ \left. - \left[1 - \frac{\epsilon_2}{\epsilon_1} (1 - \epsilon_1) F_{12} + (1 - \epsilon_2) (1 - \epsilon_1) F_{21} F_{12} - \dots \right] T_2^4 \right\}$$

This energy is equal to the energy received from the environment at T_R , q_c . It was assumed that for small $T_R - T_1$,

$$q_c = a (T_R - T_1)$$

$$\text{since } emf = b (T_R - T_1)$$

$$q_R = q_c = c (emf)$$

This results in

$$\frac{\epsilon}{\epsilon_b} = \frac{emf}{emf_b} \left[\frac{(1+f_{1b}) T_{1b}^4 - (1+f_{2b}) T_2^4}{(1+f_1) T_1^4 - (1+f_2) T_2^4} \right] = \frac{emf}{emf_b} \phi_2$$

where

$$1+f_1 = 1 - \frac{\epsilon_1}{\epsilon_2} (1 - \epsilon_2) F_{21} + (1 - \epsilon_1) (1 - \epsilon_2) F_{12} F_{21} - \dots$$

$$1+f_2 = 1 - \frac{\epsilon_2}{\epsilon_1} (1 - \epsilon_1) F_{12} + (1 - \epsilon_2) (1 - \epsilon_1) F_{21} F_{12} - \dots$$

$$1+f_{1b} = 1 - \frac{\epsilon_1}{\epsilon_{2b}} (1 - \epsilon_{2b}) F_{21} + (1 - \epsilon_1) (1 - \epsilon_{2b}) F_{12} F_{21} - \dots$$

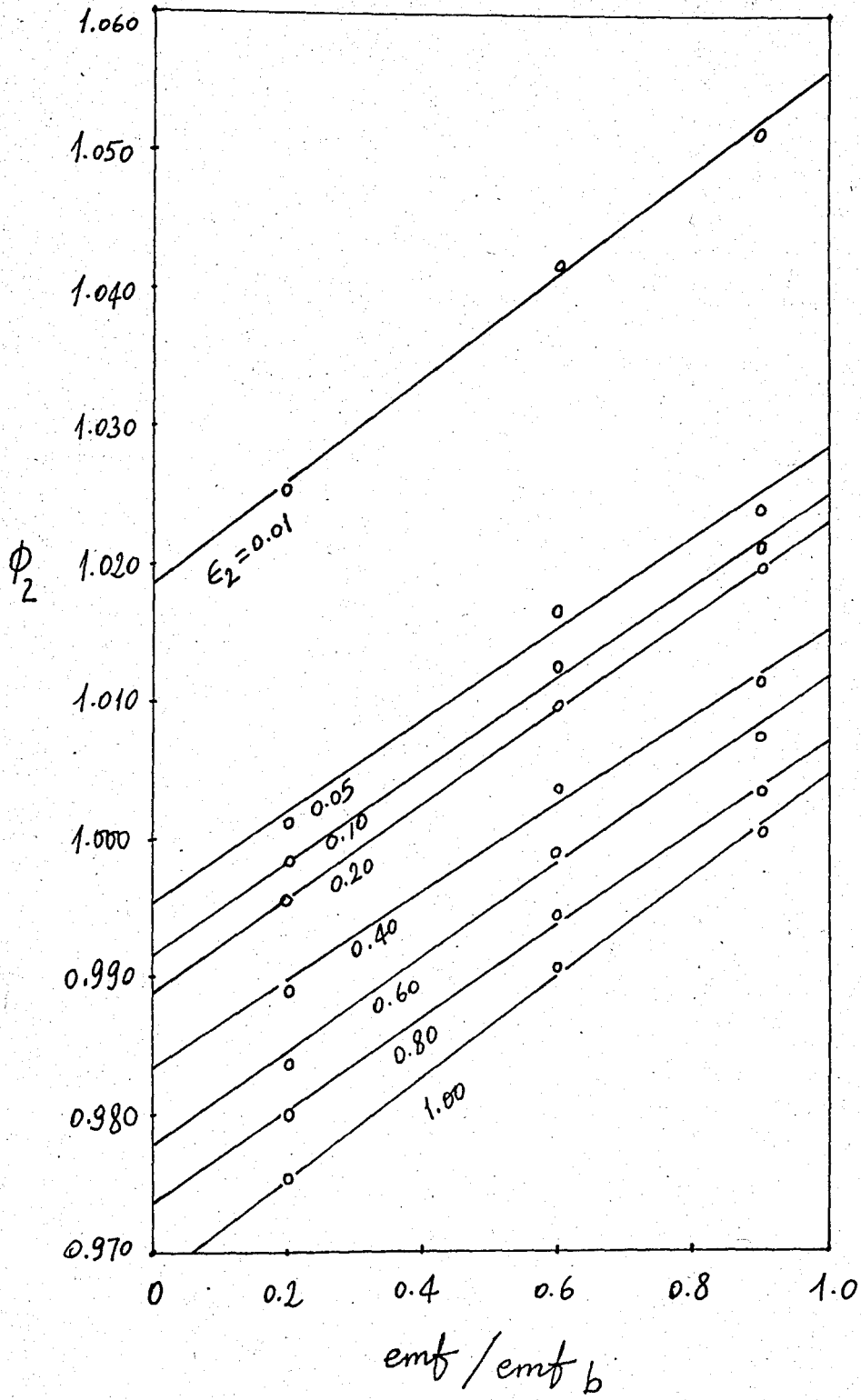
$$1+f_{2b} = 1 - \frac{\epsilon_{2b}}{\epsilon_1} (1 - \epsilon_1) F_{12} + (1 - \epsilon_{2b}) (1 - \epsilon_1) F_{21} F_{12} - \dots$$

By taking	$\epsilon_1 = 0.90$	$\text{emf}_b = 1.800 \text{ mv}$
	$\epsilon_{2b} = 0.98$	$F_{12} = 0.2906$
	$T_R = 672^\circ \text{R}$	$F_{21} = 0.000193$
	$T_2 = 531^\circ \text{R}$	

where F_{12} and F_{21} are the new angle factors calculated by considering as A_1 the area of the junctions only, the following values were obtained for $1+f_{1b}$, $1+f_{2b}$, $1+f_1$, and $1+f_2$:

$1+f_{1b}$	$1+f_{2b}$	ϵ_2	$1+f_1$	$1+f_2$
1	0.968	0.01	.983	1.000
		0.05	.997	.998
		0.10	.998	.997
		0.20	.999	.994
		0.40	1.000	.987
		0.60	1.000	.980
		0.80	1.000	.974
		1.00	1.000	.968

The factor ϕ_2 calculated this way was plotted against emf ratio for different values of ϵ_2 . This plot is given below.



APPENDIX C : CALCULATION OF ANGLE FACTORS.

Refer to Fig. 15 in the text for symbols and subscripts.

The angle factor for surfaces R and 2 is given by the equation

$$F_{R2} = \frac{(1+B^2+C^2) - \sqrt{(1+B^2+C^2)^2 - 4B^2C^2}}{2B^2}$$

where

$$B = b/a, \quad C = c/a$$

With $a=12$ in.

$b=0.75$ in.

$c=3$ in.

F_{R2} was found to be 0.0641 .

Using $F_{R1} + F_{R2} + F_{RR} = 1$

$$F_{21} + F_{22} + F_{2R} = 1$$

$$F_{11} + F_{12} + F_{1R} = 1$$

$$F_{RR} = F_{22} = 0$$

$$F_{11} \neq 0$$

and

$$A_R F_{R2} = A_2 F_{2R}$$

$$A_1 F_{12} = A_2 F_{21}$$

$$A_1 F_{1R} = A_R F_{R1}$$

the following results were obtained :

$$F_{21} = 0.996$$

$$F_{11} = 0.793$$

$$F_{2R} = 0.004$$

$$F_{12} = 0.1954$$

$$F_{1R} = 0.0155$$

In all of these calculations, A_R was taken as the area of the receiver, not the area of the junctions.

In the design of the thermopile receiver, it had been assumed that surface R was refractory and others were black. Under these assumptions, R exchanges the same amount of energy with A_1 as with A_2 .

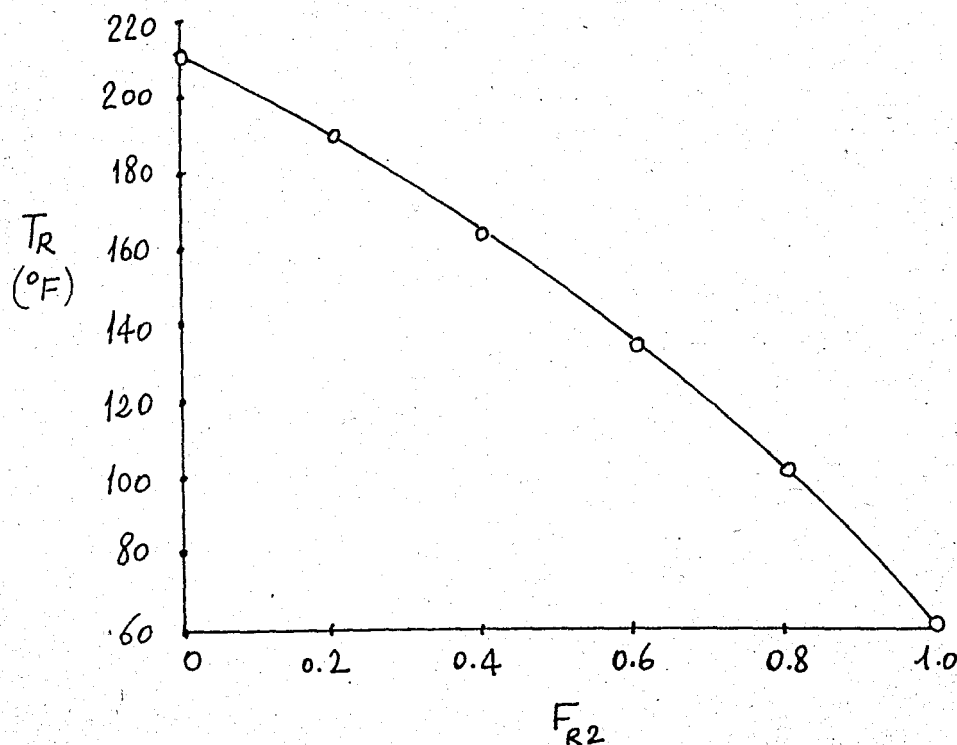
$$\text{Equation } \propto A_1 F_{1R} (T_1^4 - T_R^4) = \propto A_R F_{R2} (T_R^4 - T_2^4)$$

$$\text{gives } \frac{T_1^4 - T_R^4}{T_R^4 - T_2^4} = \frac{F_{R2}}{1 - F_{R2}}$$

Taking $T_1 = 212^\circ\text{F}$

$T_2 = 60^\circ\text{F}$,

the variation of T_R , temperature of the measuring junctions, with F_{R2} comes out to be as follows :



APPENDIX D : DETERMINATION OF NUMBER OF JUNCTIONS NEEDED

Refer to Fig. 15 for symbols and subscripts.

Temperature of the measuring junctions of the thermopile was calculated by assuming the following equation holds true:

$$q_{1R} + q_{\text{cond}} = q_{R2}$$

$$q_{1R} = A_1 F_{1R} \omega (T_1^4 - T_R^4)$$

$$q_{\text{cond}} = \frac{T_2' - T_1'}{\ell} k A$$

$$q_{R2} = A_R F_{R2} \omega (T_R^4 - T_2^4)$$

A = cross section of the wire = $\frac{\pi}{4} (0.024)^2$ sq. in.

ℓ = length of wire = 3/4 in.

$k_{\text{iron}} = 32$ Btu/hr-ft- $^{\circ}$ F

$k_{\text{cons}} = 15.5$ Btu/hr-ft- $^{\circ}$ F

$T_1 = 212^{\circ}$ F

$T_2 = 60^{\circ}$ F

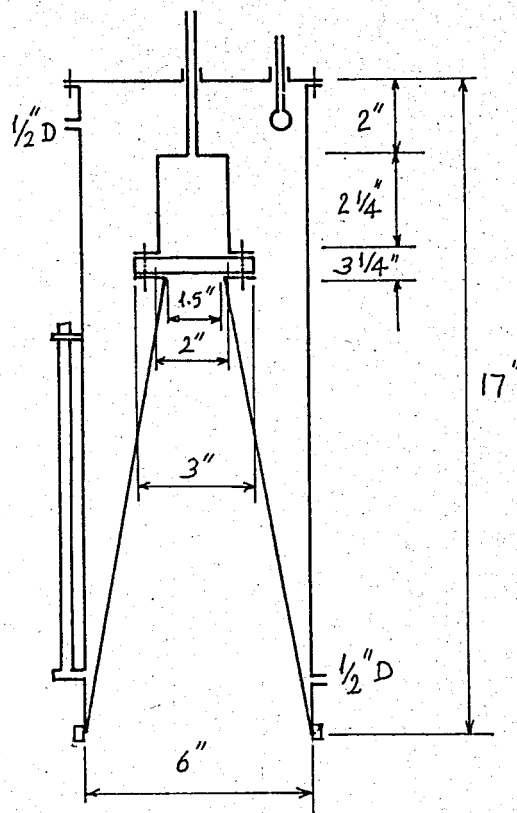
$T_2' - T_1' =$ Temperature difference between the two sides of the receiver

$$A_1 F_{1R} \omega (T_1^4 - T_R^4) + A k \frac{T_1 - T_R}{\ell} = A_R F_{R2} \omega (T_R^4 - T_2^4)$$

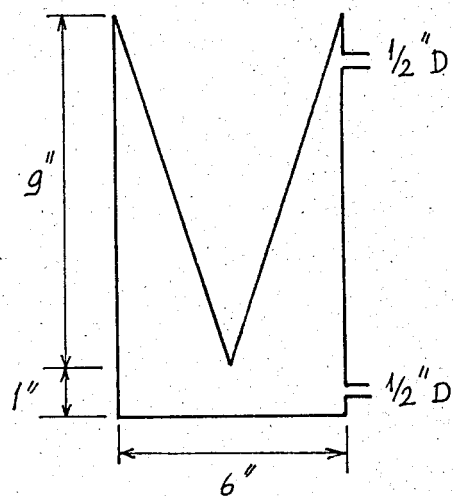
This equation gave $T_R = 210^{\circ}$ F with the above values of k , A , ℓ , and temperatures, for 24 junctions.

The required number of junctions with $T_R = 210^\circ F$ was 16, resulting in a factor of safety of $24/16 = 1.5$.

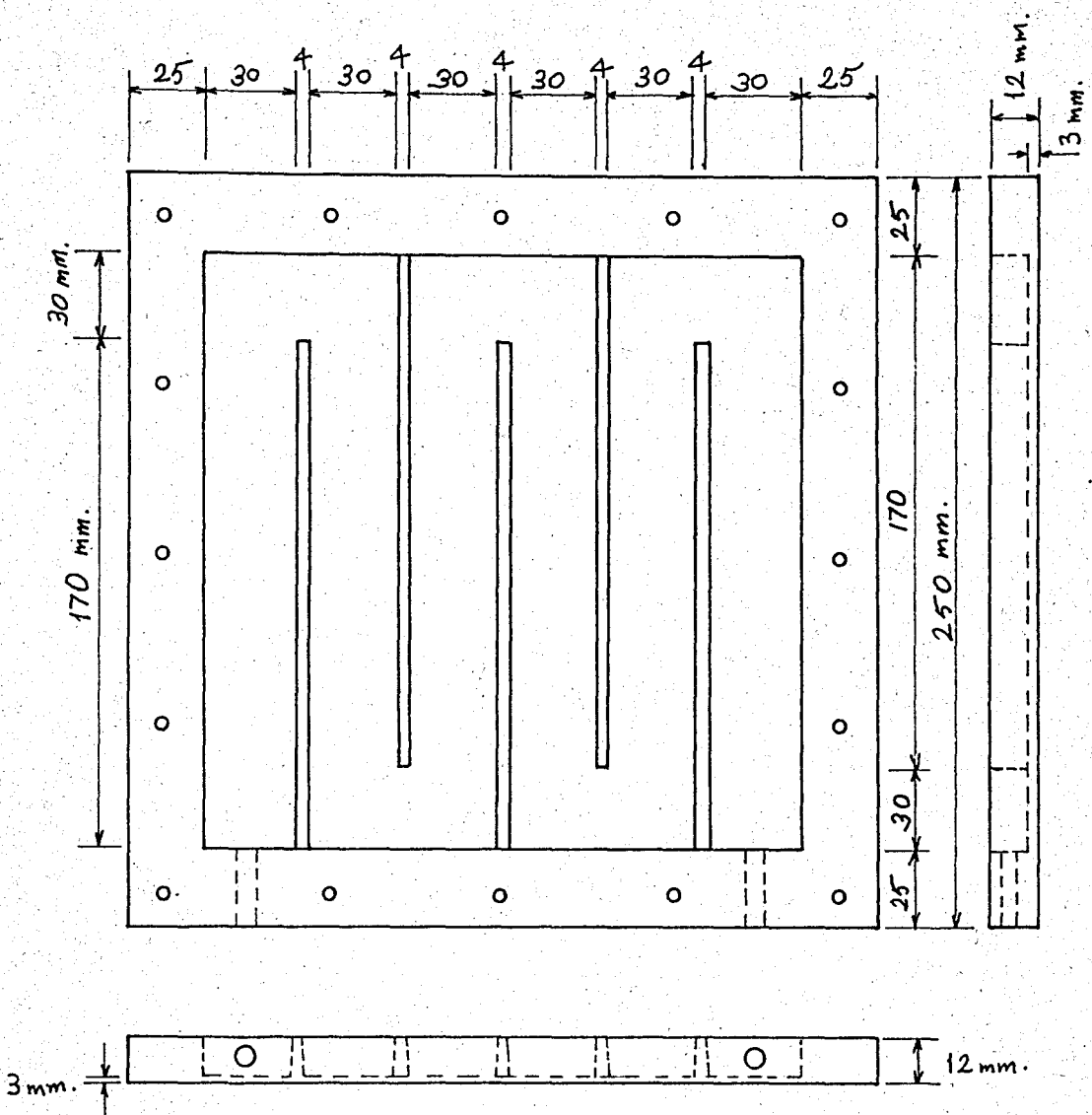
APPENDIX E: COMPLETE DIMENSIONAL DRAWING :



Thermopile Chamber



Blackbody Cone



Specimen Holder

APPENDIX F : TEST DATA AND A SAMPLE CALCULATION

In all of the data given below, time is in hours, water and steam temperatures are in degrees Fahrenheit, and emf values are in millivolts.

1. Black Paint

time	T _w	T _s	emf _b	time	T _w	T _s	emf
13.20	53.8	211.9	1.565	14.28	53.7	211.9	1.375
13.30	53.8	211.9	1.565	14.38	53.7	211.9	1.375
13.45	53.7	211.9	1.565				

$$\frac{\epsilon}{\epsilon_b} = \frac{\text{emf}}{\text{emf}_b} = \frac{1.375}{1.565} = 0.878$$

From the first graph in Appendix A, $\epsilon_b = 0.98$

$$\epsilon = (0.98)(0.878) = 0.86$$

2. Black Paint

time	T _w	T _s	emf _b	time	T _w	T _s	emf
13.40	69.0	212.0	1.842	14.10	69.0	212.0	1.621
14.00	69.0	212.0	1.842	14.15	69.0	212.0	1.621

$$\epsilon = 0.86$$

3. Tarred Paper

time	T_w	T_s	emf_b	time	T_w	T_s	emf
16.35	58.2	212.0	1.605	16.50	58.2	212.0	1.520
16.45	58.2	212.0	1.605	16.57	58.2	212.0	1.520

$$\epsilon = 0.93$$

4. Asbestos Paper

time	T_w	T_s	emf_b	time	T_w	T_s	emf
17.00	58.5	212.0	1.855	17.22	58.5	212.0	1.785
17.15	58.5	212.0	1.855	17.26	58.5	212.0	1.785

$$\epsilon = 0.94$$

5. Dull Copper Plate

time	T_w	T_s	emf_b	time	T_w	T_s	emf
15.15	59.4	212.2	2.049	15.55	59.4	212.2	0.791
15.30	59.4	212.2	2.044	15.57	59.4	212.2	0.791
15.45	59.4	212.2	2.044	16.00	59.4	212.2	0.791

$$\epsilon = 0.38$$

6. One Coat "Sadolux" Paint

time	T_w	T_s	emf_b	time	T_w	T_s	emf
20.50	60.6	212.0	1.411	21.25	60.6	212.0	1.341
21.00	60.6	212.0	1.411	21.30	60.6	212.0	1.341
21.40	60.5	212.0	1.411	21.33	60.6	212.0	1.341

$$\epsilon = 0.93$$

7. Two Coats of "Sadolux" Paint

time	T_w	T_s	emf_b	time	T_w	T_s	emf
15.15	63.5	212.0	1.395	15.40	63.5	212.0	1.330
15.30	63.5	212.0	1.395	15.48	63.5	212.0	1.330

$$\epsilon = 0.94$$

8. Three Coats "Sadolux" Paint

time	T_w	T_s	emf_b	time	T_w	T_s	emf
19.00	63.5	212.0	1.415	19.42	63.4	212.0	1.346
19.15	63.5	212.0	1.411	19.45	63.4	212.0	1.346
19.30	63.5	212.0	1.411	19.48	63.4	212.0	1.346

$$\epsilon = 0.94$$

9. Three Coats "Sadolux" Paint

time	T_w	T_s	emf_b	time	T_w	T_s	emf
17.30	68.6	211.8	1.294	17.55	68.5	211.8	1.234
17.45	68.5	211.8	1.294	18.00	68.5	211.8	1.234

$$\epsilon = 0.94$$

10. Aluminum Foil

time	T_w	T_s	emf_b	time	T_w	T_s	emf
14.55	69.0	212.0	2.048	15.20	69.0	212.0	0.701
15.05	69.0	212.0	2.048	15.30	69.0	212.0	0.701

$$\epsilon = 0.34$$

11. Aluminum Sheet

time	T_w	T_s	emf _b	time	T_w	T_s	emf
16.15	70.6	212.0	1.695	17.05	70.5	212.0	0.364
16.45	70.6	212.0	1.695	17.10	70.5	212.0	0.364

$$\epsilon = 0.21$$

12. Nickel

time	T_w	T_s	emf _b	time	T_w	T_s	emf
15.00	71.00	212.4	1.820	15.55	71.0	212.4	0.454
15.15	71.00	212.4	1.820	16.05	71.0	212.4	0.454

$$\epsilon = 0.24$$

APPENDIX G : INSTRUMENTS USED

1. Volt Potentiometer

Manufacturer : Leeds & Northrup Co., 4901 Stenton Ave.,
Philadelphia 44, Pennsylvania

Model : 8687

Serial No. : 1647111

Range : 0 to 1.601 and 0 to 0.1601 volt (two scales)

Accuracy : \pm (0.05 % of reading + 3V) for the small scale
 \pm (0.05 % of reading + 30V) for the big scale

2. Variable Autotransformer

Manufacturer : The Superior Electric Co., Bristol, Conn.

Type : 116 B

Frequency Range : 50/60 cycles

Phase : 1

Input Voltage : 120 V

Output Voltage : 0 to 140 V

Maximum Amperes : 10

Maximum Capacity : 1.4 KVA

3. Voltage Stabilizer

Manufacturer : General Electric Co., Fort Wayne, Indiana

Model : 9T91Y7158

Cycles : 50

Capacity : 0.5 KVA

Serial No. : Har. Filt.

Input Voltage : 95 to 130, 175 to 235, 190 to 260 Volts

Output voltage : 118 and 236 Volts

4. Sling Psychrometer

Manufacturer : The Welch Scientific Co., 1515 Sedgwick St.

Chicago

Inventory No. : 879

Range : 0 to 120°F

Smallest Division : 0.5°F

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