

AN EXPERIMENTAL INVESTIGATION OF
TEMPERATURE MEASUREMENT BY THE
SODIUM D-LINE REVERSAL METHOD

by

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Signature of Author _____

Signature of Professor in Charge of Research _____

Signature of Chairman of Department
Committee on Graduate Students _____

Department of Mechanical Engineering, May 19, 1950.

Watertown Arsenal
Watertown, Mass.
May 19, 1950

Professor C. R. Soderberg
Chairman of the Department Committee
on the Graduate School
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Soderberg:

In compliance with the requirements of the Faculty governing the Graduate School, I herewith submit my Thesis entitled: An Experimental Investigation of Temperature Measurement by the Sodium D-Line Reversal Method in partial fulfillment of the requirements for the Degree of Master of Science in Mechanical Engineering.

Very Respectfully yours,

William Carl Fuller

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It must be stated here that this thesis has depended greatly on the contributions of others, and it is to them that I wish to express my appreciation.

Professor Warren M. Rohsenow, Thesis Advisor, gave the original impetus to this work and provided many encouraging words of advice and encouragement as the investigation progressed.

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W.C.F.

Watertown, Mass.
May 19, 1950

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INTRODUCTION

The science of temperature measurement has not yet reached the point where it may be regarded as an open and shut case. This is especially true in the temperature ranges above 2000° F. At the same time, however, there have been notable advances in the science in the past 100 years, not the least of which is the Sodium D-Line Reversal Method of assigning temperature to hot gases. Like all means of measuring temperatures, the Sodium D-Line Reversal Method has its limitations. One such limitation is the fact that this procedure cannot be used to measure temperatures below a certain limit. Accordingly it was the purpose of this thesis to determine where this lower limit resides and, if possible, to extend this limit downward in order to reach the upper limit of commonly used thermocouples.

THEORY OF GASEOUS RADIATION

Molecules can be excited by a number of means and as they return to their normal states they emit radiation. This excitation may be caused by collision with particles which have undergone combustion, resulting in their high speed, or with particles which have been excited electronically. These are not the only means of excitation but are commonly found ones.

As regards a gas, this radiation may be divided into two types: if the molecules are caused to vibrate solely by their temperature level and if the emanations do not disturb equilibrium, it is called thermal radiation; if the emission is from molecules which are not in thermal equilibrium, it is called chemiluminescence. An example of the latter is the radiation from the atoms of sodium in a sodium vapor lamp. This excitation comes mostly as a result of electron bombardment and very little, by atomic bombardment. Were the temperature, in the ordinary sense, measured, it would be found to be around 500° Kelvin. The brightness temperature associated with the characteristic sodium D-line radiation, however, might be about $4,000^{\circ}$ Kelvin.

It is thus seen by the above example that care must be exercised in using a spectroscopic method to measure temperatures, although generally speaking any spectroscopic phenomenon occurring solely as a result of the temperature can be used to measure gas temperatures.

The S. L. R. method really had its beginning with the fundamental observation of Kirchhoff, that the dark lines in the solar spectrum correspond exactly to the bright lines in the spectra of various elements. In his own words: "In order to test in the most direct manner possible the frequently asserted fact of coincidence of the sodium lines with the

lines D of Fraunhofer, I obtained a tolerably bright solar spectrum, and brought a flame colored by sodium vapor in front of the slit. I then saw the dark lines D (of the solar spectrum) change, into bright ones. The flame of a Bunsen's lamp threw the bright sodium lines upon the solar spectrum with unexpected brilliance. In order to find out the extent to which the intensity of the solar spectrum could be increased without impairing the distinctness of the sodium lines, I allowed the full sunshine to shine through the sodium flame, and to my astonishment I saw that the dark lines D appeared with an extraordinary degree of clearness." Thus Kirchhoff realized that light from a hot object when passed through an absorbing vapor will give a spectrum in which the lines due to the vapor are either in absorption or emission depending upon the conditions of the hot body, and the vapor. Later he utilized a man-made light with the same observations.

By these results, he later formulated the well-known law bearing his name, that the ratio of the absorptive and emissive powers of any material for a given temperature is a constant. Realizing that the conditions as to whether absorption or emission lines appeared depended upon the relative hotness of the light source and the vapor, he was unable to verify that the condition of resonance (when neither bright nor dark lines appear - continuous spectrum) meant that the D-line brightness temperature of the source was equal to the true temperature of the absorbing medium, this due to lack of other means of measuring high temperatures. Fery, nearly a half century later, applied this technique to flame temperature measurement.

This method of flame temperature measurement has been tested and used by a number of investigators to the point where its reliability

is generally accepted, although there have been some dissenters such as David.¹³ It is believed that his criticism is adequately confronted with the facts by Lewis and von Elbe.¹⁴ As they point out, the mass of data showing a high degree of corroboration between this and other methods cannot be refuted.

Of late, the reversal method has been increasingly used especially in the high temperature fields of turbo or ram jet engines.

As heretofore stated, this investigation was intended to find the lower practical temperature limit to which the sodium D-line reversal method can be employed. Most investigators have reported results of measurements made at 2500° F. and beyond, neglecting to record whether it was possible to go lower. As would be expected, a lower limit is found where the degree of dissociation of the sodium ions from the salt injected into the flame does not reach a certain critical amount in order that the intensity of the D-lines is sufficient to be seen by an observer either in emission or absorption. Another limitation is due to the fact that the hot source, usually a tungsten filament lamp, cannot be calibrated below a certain temperature. This comes about as a result of the fact that below about 1900° F., the brightness of the lamp filament is so low as to make matching with the filament of an optical pyrometer extremely difficult if not impossible. This limit due to the sensitivity of the human eye is, of course, met again when the continuous spectrum of the lamp is viewed through the spectrometer.

Accordingly, the investigation proceeded in the direction of determining which, if any, sodium salts could be used in the range between 1900° F. and 2500° F. Several salts were used, but none were successful.

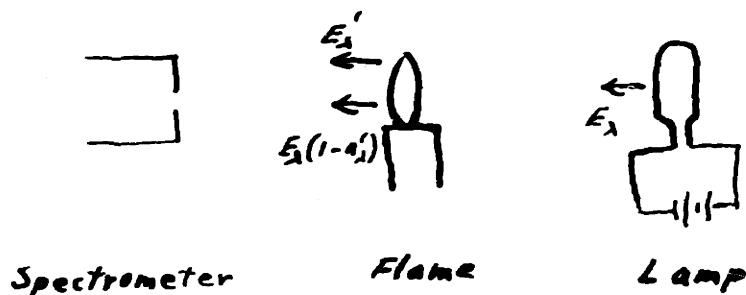
It is well to point out here that the figure of 2500° F. corresponds fairly closely to the boiling point at atmospheric pressure of the more common sodium compounds such as sodium chloride and sodium hydroxide. Both have been used as the absorbing mediums in the S. L. R. method by previous investigators. Finally it was decided to try metallic sodium since its boiling point is around 1600° F. at atmospheric pressure. This means proved very successful and readings were obtained at temperatures as low as 1950° F. It is believed that this lower temperature limit of possible operation has not previously been reported in the unclassified literature.

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THEORY OF THE SODIUM LINE REVERSAL METHOD

The theory behind the Sodium Line Reversal method is rather simple but there are four conditions necessary before the theory can be applied. The first is that the flame be non-luminous which implies chemical equilibrium, the second is that there be no temperature gradient in the direction normal to the flame, the third is that the sodium vapor be in temperature equilibrium with the gas or non-luminous flame whose temperature is desired, and the fourth is that the sodium vapor be injected only in such amounts as not to lower the gas temperature. Probably none of these conditions is ever found ideally, and the second condition is the most difficult to attain. If a gradient does exist, the Sodium Line Reversal method will give some sort of average of the temperatures across the flame.

The following schematic diagram will now be used to illustrate the theory:



Emissive power, in general, as used below, will be defined as the radiant energy (of wave length λ) per unit wave length interval emitted per unit time by a unit area of radiator throughout the solid angle 2π .

E_{λ} = Spectral emissive power of the lamp filament at a particular wave length, in this case, of the D-line.

E'_λ = Spectral emissive power of the sodium vapor in the flame at, of course, the D-line wave length.

a'_λ = Absorptivity of the sodium vapor in the flame at the D-line wave length.

ϵ_λ = Equivalent black body emissive power corresponding to the true temperature of the sodium vapor at the D-line wave length.

T' = True temperature of sodium which is assumed to be in equilibrium with the gas particles of the flame.

S_λ = Brightness temperature of lamp filament, in this case at the D-line wave length, where brightness temperature is defined as the temperature an equivalent black body would have for the same brightness, and brightness in a given direction at any point of an extended surface is the intensity of an element of the surface divided by the area of the element projected normal to the given direction.

It is to be shown that, when the condition of optical resonance occurs, the true temperature of the gas is equal to the D-line brightness temperature of the lamp and, if this temperature is known, the gas temperature is automatically obtained.

Let the spectral or monochromatic energy, which the slit receives, be written. Firstly, there is the energy which is received from the lamp but which is reduced by the absorptivity of the sodium vapor. The net effect equals $E_\lambda (1 - a'_\lambda)$. Secondly, there is the radiation from the sodium itself which equals E'_λ . The total energy reaching the slit of the spectrometer is thus equal to -

$$E_\lambda (1 - a'_\lambda) + E'_\lambda$$

It is seen that when the resonance condition results, i.e., when the slit just sees E_λ or the uninterrupted spectrum

$$E'_\lambda - a_\lambda E_\lambda = 0$$

$$E'_\lambda = a'_\lambda E_\lambda$$

$$\frac{E'_\lambda}{a'_\lambda} = E_\lambda$$

Physically this means that the flame is effectively radiating as much energy as it receives.

$\frac{E'_\lambda}{a'_\lambda}$ can also be set equal to E_λ by Kirchhoff's law (at a given temperature the ratio of emissive power to the absorptivity is the same for all bodies and is equal to the emissive power for a black body at the same temperature) and thus $E_\lambda = \epsilon_\lambda$. Basically this means that the lamp filament is radiating like an equivalent black body at the brightness temperature.

Now from Planck's equation:

$$E_\lambda = \frac{c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1}$$

where c_1 and c_2 are constants and e is the natural logarithm base.

Additionally by Planck's equation:

$$\epsilon_\lambda = \frac{c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T'}} - 1}$$

Since $E_\lambda = \epsilon_\lambda$, it is seen that $T' = S$, which it was intended to prove. Thus by obtaining the optical match and knowing the brightness temperature at the D-line wave length, the temperature of the gas is obtained.

APPARATUS

Furnace and Allied Equipment

Inasmuch as a source of hot gases was already in existence in the Heat Measurements Laboratory of M. I. T., it was early decided to use this source. This apparatus had been previously designed and constructed by Mr. John A. Clark in connection with his thesis entitled "An Analysis and Experimental Investigation of a Method for Determining the Thermodynamic Temperature of High Velocity Combustion Gases", M. I. T., 1949. Essentially the basic apparatus, to which a few modifications were necessary in order to apply the Sodium Line Reversal method, consisted of a refractory furnace, a fuel supply provided by two pre-mix burners, a secondary air inlet into the furnace in order to increase the mass flow, and a combustion tube by means of which the burned gases were led out of the furnace.

The refractory furnace was constructed of K-30 refractory brick and its general configuration may be ascertained by viewing D-1, which is reproduced from Mr. Clark's thesis.

The fuel-air mixture, the fuel being Cambridge City Gas (900 BTU/cu. ft.), was introduced into the furnace by means of two Maxon pre-mix centrifugal blowers which were driven by 110 volt, single phase, 60 cycle motors rated at 1/8 HP at 3400 RPM. These blowers are so constructed as to allow any desired fuel-air ratio by a setting of an air-inlet regulator valve. The mixture of fuel and air was piped by means of two standard 2 inch steel pipes directly into the furnace, the flame being ignited at the end of these pipes. Nozzles at the end of each pipe insured a stable flame. Due to the intense heat, it was

necessary to supply a continuous stream of water over the nozzles for cooling purposes.

A secondary air supply was introduced directly into the furnace in order to increase the mass flow, a B. F. Sturtevant, No. 1, double inlet blower driven at 3485 RPM at full load by a General Electric, 220 volt, 3 phase, 60 cycle motor (2 HP at 1520 RPM) being used for this purpose. In the pipe leading to furnace (5 inch flue ducting) a butterfly valve was provided to control the amount of secondary air input. This system can be seen in D-3.

The combustion tube, shown in the reproduced drawing D-2, was made of 18 - 8 stainless steel and was 4 3/4 inches I. D., 5 inches O. D. and 72 inches long. A quartz window 1 inch in diameter and 1/8 inches thick was originally placed on the stack 21 1/8 inches on center from the top of the stack. In order to measure the temperature of the hot gases in the combustion tube, the following modifications were made: First, another quartz window (1 inch diameter and 1/8 inch thick) was attached to the stack on a line diametrically opposed to the existing one in order that a line of sight through the hot gas could be obtained. This window was supported by a 1/2 inch projection of 18 - 8 stainless 1 inch standard pipe which was welded to the stack and threaded in order to take a steel cap, the window being held in a recess of the cap, which could be screwed up snugly against the window. In order that no gas leakage would take place, an asbestos paper gasket was provided between the window and the lip of the cap. Additionally two similar windows were placed in line 17 inches on center from the bottom of the stack in order that temperatures at two different levels could be measured. See D-3 and P- / for this arrangement.

To support the lens system and the comparator lamp at each level, two 1/2 inch by 1/2 inch by 12 inch long steel bars were welded 10 inches below the window centers on opposite sides of the stack. These bars provided an effective support for the standard Cenco (No. 72322) type bench rod clamp, especial care being taken to insure that the bars were properly aligned. See D-8 and P-1 for the arrangement at the upper level. This set up was a necessary expedient since space limitations and the configuration of the existing combustion stack made it unfeasible to take advantage of a standard optical bench.

The final modification to the combustion tube consisted in adding an extension of 6 inch flue piping to the top of the stack in order that the hot gases would flow directly into the exhaust system of the Heat Measurements Laboratory. This was done as a safety measure to prevent any of the toxic sodium vapors from settling in the laboratory with, as a result, possible injury to persons in the room. The extension consisted of a 90° elbow to which was attached a 10 inch horizontal section, a second elbow, and then a 14 inch vertical section on top of which a strut supported roof was placed to prevent direct impingement of the hot gases on the hood. Since the combustion tube diameter was 1 inch smaller than the flue pipe, it was necessary to incorporate a built-up gasket of asbestos string tightly wound on the last three inches of the combustion tube proper. Sodium silicate was applied to successive layers of the gasket to give added resistance to the high temperature.

Sodium Line Reversal Equipment

The sodium line reversal equipment was basically quite simple

and consisted of a spectrometer, a comparator lamp circuit, a lens system, and a means of injecting the sodium vapor into the gas stream.

The spectrometer was a Hilger constant deviation type (Model No. E 24301) with a slit length of .375 inches and an effective collimator diameter of $1 \frac{1}{8}$ inches, the constant deviation feature of the instrument being attained by means of its Pellin Broca, glass prism, which is mounted on a turntable such that by turning the table it was possible to obtain any of the visible wave lengths in the center of view. The slit width is unilaterally adjustable by means of a set screw arrangement. See P-2 for a picture of this spectrometer.

The instrument has a fairly high resolving power and it proved to be very easy to resolve the sodium doublet at 5890 and 5896 angstroms.

The capability of an instrument to resolve the doublet represents quite an advantage in the Sodium Line Reversal method inasmuch as it allows the operator to work with one or the other of the lines since resonance does not occur for both lines at the same time, for a given intensity of the comparator lamp. When a spectrometer which is incapable of resolving the doublet is used, the average value of the two lines, 5893 angstroms, must be assumed in converting from the brightness temperature as measured by the optical pyrometer to the D-line brightness temperature, with a resulting inaccuracy in the results of temperature obtained. Exactly how this inaccuracy results will become clearer after the conversion of the lamp brightness temperatures (as measured by the optical pyrometer) to the D-line brightness temperature is considered (see Samp. Calc.). The spectrometer was itself mounted on a flat asbestos board ($\frac{3}{4}$ inch thick) in which three set screws were placed in order to provide positioning and leveling of the instrument

relative to the optical system. This board in turn was placed on top of a steel table of the proper height corresponding to the two different window levels.

The comparator lamp used in this investigation was a General Electric, 4 volt, 20 amp, tungsten strip filament type lamp. This lamp was screwed into a standard mogul base which was mounted on a 1/8 inch thick asbestos board. This board was then bolted to a bar clamp by means of which the lamp assembly could be securely fixed relative to the quartz windows. Spacers were placed between the bar clamp and the asbestos board in order that proper alignment could be obtained. See D-5 and P-1 for this arrangement.

Voltage to the lamp was supplied from a 115 volt a.c. source which was stepped down to 5 volts by an Acme Delta transformer (Serial No. M-45, primary voltage, 115 volts; secondary voltage 5 volts; maximum secondary current, 20 amps). A variac (Superior Electric Company, 115 volt input, maximum secondary current, 7.5 amps) was incorporated in the circuit to provide an effective control over the input wattage to the lamp. By means of a Sorensen Regulator (115 volt output, Model 1000; Serial No. 1-227) the voltage to the variac was maintained constant at 115 volts. To facilitate calibration, a Weston ammeter (0-25 amps, Serial No. R34-749) was placed in the line between the transformer and the lamp. See P-3 for a view of the comparator lamp circuit components and D-9 for a schematic of the electrical system.

Before describing the lens system, it is well to state some of the considerations which must go into its selection. The only function of a lens system as used with a spectrometer is to fill the effective aperture of the collimator and as well to illuminate the slit length

in its entirety. In other words, a lens system must be used when the light source is either too small or too far away to fulfill the above requirements. With the configuration of the equipment at disposal, it was found to be necessary to use a lens system. Since simplicity without sacrifice to accuracy is always to be desired, an optical system was selected with this in mind. Accordingly for this investigation, one converging lens was used, being placed between the stack and the spectrometer. This method was previously used by E. Griffiths and J. H. Awberry with good effect (see Reference No. 1). In order that the lens selected would satisfy the condition of completely filling the collimator and the slit of the spectrometer, it is only necessary to apply simple geometry such that lines drawn from any point of the collimator lens through any portion of the slit must intersect an emitting area of the lens. A simple equation is given in Practical Spectroscopy by Harrison, Lord and Loofbourow (see Reference No. 16), which will give to a first order approximation the same results as by actually working out the graphical solution.

This equation;

$$H = \frac{x d}{F} + l \left(\frac{d}{F} + 1 \right)$$

where H = height of the lens

x = distance from the lens to the slit

d = diameter of the collimator

F = focal length of the collimator

l = slit length

was applied to the lens selected, a converging lens of 25 m.m. diameter and 68 m.m. focal length. This lens was of singlet construction; however,

there is no difficulty involved in using simple lens in conjunction with the Sodium Line Reversal method since a particular wave length of light only is being considered and the question of chromatic aberration as peculiar to lens of singlet construction does not enter once the lens is properly focused for this wave length. Accordingly with this lens operating at 12 inches from the tungsten filament, and imaging this source on the slit (image distance equaled 3.45 inches), it was found that the slit and collimator were adequately illuminated. Additionally it was determined that, for the complete system including the quartz windows, the slit of the spectrometer acted as the minimum aperture as it should for reliable temperature measurement. See D-8 and P-1 for this set-up.

The means of injecting the sodium vapor into the stream was actually quite simple in design, but it was this equipment which offered the most resistance to obtaining satisfactory results. Basically the apparatus consisted of a vertical well into which metallic sodium was loaded, a horizontal section welded to the well and a probe which placed the vapor stream in the center of the gas flow. The horizontal section was welded on one end to a plate which positioned the equipment on the combustion tube, whereas the other end was threaded in order that an inlet pipe from a helium bottle could be secured to the whole affair, it being necessary to pressurize the heater to overcome the static pressure in the combustion stack. Dry helium was used because of its inertness. Two glow bars were used to vaporize the metallic sodium, two hollowed-out K-20 bricks being used to enclose the entire heater. The bricks thus served the dual purpose of positioning the glow bars and preventing excessive external heat losses.

The well was a 3 1/4 inch length of 18 - 8 stainless steel tubing (3/8 inch O. D., 1/4 inch I. D.) which was welded shut on the bottom. The horizontal section was 1 1/2 inches long, made up from stainless steel stock, and had an internal diameter of 1/4 inch. The wall thickness was built up at the well joint in order to facilitate welding. To facilitate control of the amount of vapor going into the gas stream, a Chromel-Alumel thermocouple (#24 wire) was placed inside the horizontal section and centered over the well. This point was picked as the proper place to measure the vapor temperature since it should be expected that there would be a chilling effect produced by the incoming helium gas intermixing with the sodium vapor. By knowing this gross temperature (no cold junction was used) the partial pressure of the sodium vapor could be effectively controlled merely by increasing or decreasing the wattage on the glow bars. The thermocouple leads were connected to a d.c. millivoltmeter (Brown Instrument Company, Serial No. 37708, 0-80 millivolts) by means of which the approximate mixture temperature was read.

The probe was a 18 - 8 stainless steel tube, 1/8 inch O. D. and 1/16 inch I. D. The tube was welded perpendicular to the plate and projected 2 3/4 inches horizontally after which it was turned 90° on a one inch radius. The tube then projected approximately 3 1/4 inches vertically reaching a position on line with the lower extremity of the quartz windows. A small I. D. for the probe was desired in order to localize the vapor in the center of the gas stream of the stack. The plate was 1/4 inch steel plate (3 9/16 inches by 4 inches) and was securely bolted to a boss mounting on the stack, this mounting being used by the previous investigator working with the stack equipment as a heated

shield thermocouple support.

The two glow bars were $3/8$ inches in diameter and were mounted vertically on either side of the sodium well, being supported by the K-20 bricks. Power input was controlled by a General Radio variac (115 volt primary, maximum secondary current, 45 amps). See D-6 and P-46.

The helium supply was over 99% pure, but as a safety measure a desiccator utilizing activated alumina was placed between the bottle and the heater inlet. A standard Air Reduction Sales Company oxygen regulator was provided to reduce the pressure in the bottle to that needed in the heater. Since only a few inches of water was needed to pressurize the system, it was only necessary to crack the valve very slightly. (See D-8)

Heated Shield Thermocouple

To give an independent check on the temperatures as obtained in this thesis by the Sodium Line Reversal method, a shielded thermocouple was placed approximately two inches above the center line of the combustion tube. This thermocouple had been previously used by Mr. Clark and is described in great detail in his thesis (See Reference No. 12 and additionally the reproduced drawing D-7 in this thesis). It was provided with an effective means of preventing inherent radiation errors when a thermocouple is used at high temperatures and enclosed by metal surfaces at considerably lower temperatures. The arrangement consisted of three concentric tubes, the inner and outermost tubes being stainless steel while the intermediate tube was of ceramic construction. The innermost tube supported two Chromel-Alumel thermocouples, one being positioned in the center of the stream and the other being placed at the

inner wall. The electrical circuit of these couples was so arranged as to allow a direct measurement of the gas temperature with one position of a knife switch while the other position allowed a measurement of the difference in temperature between the stream and wall couples. By means of a heater coil wound on the outer periphery of the ceramic tube, any existing gradient between the two couples could be eliminated by controlling the current in the heater. At moderate and high mass flows, it turned out that the temperature difference was always zero without use of the heater. For this reason, the heating control was not used in this thesis. The thermocouple leads were led to a cold junction (0° Centigrade) and thence to a Leeds and Northrup Potentiometer (Serial No. 675378) by means of which the gas temperature as indicated by the couple was read.

DISCUSSION OF SODIUM VAPOR INJECTION SYSTEM

Since the obtaining of an effective method of introducing sodium vapor into the gas stream proved to be the most difficult problem encountered in this investigation, it is well to outline the history of this development. Because the author had not previously worked with Sodium Line Reversal equipment, it was decided to use, at the outset of the investigation, the simplest means at hand of placing the sodium vapor in the stream. These methods employed sodium salts, and for this reason provided an effective means of additionally determining whether sodium compounds could be used to attain measurements in the range of temperatures peculiar to the combustion apparatus used in the investigation - 2500° F. and lower. This upper limit of temperatures was due to the fact that stainless steel, of which the combustion tube was constructed, should not be exposed to temperatures much in excess of 2500° F. if complete burning out of the metal is to be prevented.

The first of the preliminary methods utilized sodium chloride, which was allowed to drop in a steady stream through a hole in the top of the refractory furnace. The salt was contained in a tin funnel to which a stainless steel tube had been attached. The funnel was positioned over the furnace by a conventional iron ring stand, and the stainless steel tube passed through a hole drilled in one of the bricks and directly into the furnace. After the burning in the furnace had begun, salt was poured into the funnel and allowed to drop by gravity head into the burning gases. In this manner, it was hoped that there would be sufficient coloring of the gas stream at the lower level windows (17 inches above the top of the furnace) to be seen in the spectrometer. For this method, however, no lines could be detected in the

view piece of the spectrometer. It is believed by the author that the absence of lines can be explained as a consequence of the relatively low temperatures at the lower window levels, estimated for this case at something less than 2300° F. In other words, the gases were not sufficiently hot to produce enough dissociation of sodium ions for the characteristic lines to be seen.

The next method was to support a crucible in the center of the combustion tube at the lower window level. The crucible was a 2 inch length of stainless steel tubing ($3/8$ inch O. D., $1/4$ inch I.D.) welded shut at the bottom. To support the crucible, two $2\ 1/2$ inch lengths of $1/8$ inch stainless steel welding rod were welded on each side of the top of the crucible. With the crucible in place, the rods rested on the quartz window supports. Runs were then made with a loading of each of the following salts; sodium chloride, sodium nitrate, and sodium bromate. With the comparator lamp off, faint lines were obtained from all the salts used; however, it was impossible to superimpose the lines on the continuous spectrum of the lamp to obtain either lines of emission (bright lines) or lines of absorption (dark lines). Again it was thought that the temperature of the gas was too low to give sufficient dissociation of the sodium ions.

After this preliminary experimentation had proven that salts could not be used for the temperature range attainable in the combustion tube, it was finally decided to try metallic sodium. The equipment has already been described under "Apparatus", but it is useful here to describe some of the difficulties encountered in its construction and use. Inasmuch as the probe wall thickness was quite thin ($1/32$ inches), difficulty was encountered upon welding of this unit to

the support plate. It proved impossible to weld this tube directly to the plate without closing up the tube. To surmount this problem, a hole was drilled in the plate large enough so that the heater end of the probe could protude outward past the plate by a small amount. Then a weld was made with no especial care being taken to maintain the identity of this portion of the tubing. It was only necessary to gring a flat on the weld and drill out the fused portion of the tube in order that there would be a clean passageway for the gases.

The most troublesome problem connected with the heater was in the proper design of a heating element. No less then five heating coils were designed, none of which operated satisfactorily for more than one or two usages. Since the heater well was of metallic construction, it was, of course, necessary to provide insulation between it and the coil. For the first two heaters, both designed to give a maximum temperature of 1800° F. at 115 volts and approximately 8 amps, Sauereisen No. 14 cement was applied directly to the well. The cement was allowed to air-dry for four or five hours after which it was baked in an oven at 350° F. The heater coil (Chromel A resistance wire which had been wound on a 1/8 inch arbor) was then set in place over the insulation and successive layers of Sauereisen applied to hold the coil in place. These outer layers of cement also served to prevent excessive heat losses. The coil on the first heater was wound from No. 24 wire. By using No. 26 wire for the second coil, the total length of the heater element was reduced since the smaller diameter wire (in this case No. 26) has more ohms of resistance per linear foot. With the shorter length of wire available for the second heater coil, there were fewer turns around the insulated well, and consequently more

spacing between wraps could be obtained. This change was made for the second coil after inspection of the first coil showed that there had been "arcing over" between successive helix windings, the intense heat having broken down the Sauereisen cement between windings. Like the first coil, the second failed at something less than the maximum power input. It was only necessary to apply 90 volts to attain the desired temperature in the heater well, around 1400° F., but after a few minutes at this voltage, burning out of the coil occurred.

Inspection revealed that the coil had deteriorated in localized areas, probably due mainly to the high temperature at the surfaces of the wire. Now additionally it was thought that the Sauereisen cement, itself, was possibly reacting with the metal of the coil; and, for this reason, a different insulating cement was used for the third coil - Nordite 162 alumina cement. In the construction of this coil, it was also decided to limit the amount of insulation between the well and the coil. Accordingly, a layer of 1/16" asbestos paper was wrapped around the well of the heater. Then a thin slurry of the Nordite cement was applied. After this first layer had dried, just enough additional cement was used to hold the coil in place. This layer of cement was baked dry, and no additional cement was added for external insulation. Instead a 3 inch length of alumina pipe (1 1/2 inch O. D., 1 1/4 I. D.) was mounted over the well and coil assembly. Kaolin wool was then packed around the top and bottom of the pipe to prevent air convection currents from developing between the outer periphery of the coil and the pipe. This coil likewise was constructed of such length, i.e., of such resistance as to give 1800° F. for a maximum of 9 amps at 115 volts. Again it took around 90 volts to obtain the required temperature in the well;

but, like the first two, a discontinuity in the heating element developed after a few minutes of operation at this temperature.

For the fourth coil, it was decided to go farther in the direction of reducing insulation around the well itself. This time the heater element (No. 20 resistance wire wound on 1/8 inch arbor and approximately 20 inches in length when removed from the arbor) was lined around the inside of a 3 inch length of 1 1/2 inch alumina pipe. The coil was held against the pipe by means of small wire staples which gripped individual loops of the coil wire and passed through drilled holes in the pipe. Then the ends of the staples were twisted together on the outside of the pipe, thus holding the coil securely to the inner wall of the pipe. The element was effectively held away from the stainless steel well by three spaced 3/16 inch ceramic thermocouple insulators, kaolin cement being stuffed around the top and the bottom of the pipe to prevent heat convection currents from flowing in the open space between the heater well and the element. Like the three elements before, this coil burned out on first usage, albeit at a slightly lower voltage than before.

The fifth coil proved to be slightly more successful than the previous four, in that two runs with the equipment were made before "burn out" occurred. It was constructed from a 12 foot length of No. 20 Chromel A resistance wire. This coil, which had a resistance of 7.62 ohms at room temperature, was wrapped on a 3/16 inch arbor to a length of ten inches, enough to provide four complete turns around the insulated well. The insulation as used was Nordite No. 162 alumina cement. A thin layer was applied, allowed to air-dry for two or three hours and then baked in an oven at 250° F. The coil was then

completely covered with this cement, every effort being made to reduce external heat losses. After this layer had properly dried, a layer of Sauerisen cement was added. Then with the heater installed on the combustion tube, kaolin wool to a depth of three inches was packed around it and tied securely with asbestos string. Whereas the previous elements had been designed for a maximum power of around 900 watts, it was decided to limit the power on this coil to around 700 watts (67 volts and 9 amps). For the first run during which operation was completely satisfactory, only 60 volts were necessary to obtain the desired temperature of the sodium. The injection of the sodium into the stream also was successful and temperature measurements were obtained. On the second run, the fifth coil failed at exactly the same wattage as used on the first run, the temperature in the well again reaching the desired figure of around 1400° F. See P-4a for a picture of the fifth heater.

At this point, it was decided that heating could not be successfully attained by the use of Chromel A resistance heating elements. Accordingly a furnace utilizing glow bars was constructed. Two $2 \frac{7}{16}$ by $6 \frac{1}{2}$ by 8 inch K-20 bricks were butted together and hollowed out to take the general shape of the vertical well and horizontal section. Then two vertical holes were drilled in the bricks to take two $\frac{3}{8}$ inch glow bars. These holes were drilled so as to position the glow bars $\frac{1}{2}$ inch on either side of the vertical well. The glow bars were connected in series with the power supplied through a General Radio Variac (115 volt primary, maximum current 45 amps). As before, the temperature of the sodium was obtained by use of a Chromel-Alumel thermocouple. See D-6 and P-4b for details of this particular heater.

PROCEDURE

Since the Sodium Line Reversal method depends on knowing the comparator lamp brightness temperature, it was first necessary to calibrate the lamp used in this investigation. The calibration was made, using a Leeds and Northrup disappearing filament-type of optical pyrometer (Serial No. 724724). In this calibration, the red brightness temperature as measured by the optical pyrometer was recorded for the corresponding current in the lamp circuit as indicated by the ammeter provided. These readings are plotted as D-11 in this thesis.

The first calibration took place after a few hours of aging the lamp. Later another calibration was made during which it was found that the lamp had not perceptibly changed its characteristics. This was to be expected, because during all the work of this investigation the lamp temperatures necessary were never over 2300° F., with a corresponding power approximately half its rated maximum. At these relatively low temperatures, it is known by experience that tungsten filament lamps hold up rather well. To determine the transmissivity of the quartz window on the lamp side of the combustion tube, temperature measurements were first made with the optical pyrometer sighted through this window. Then the window was removed and for the same current reading in the ammeter, the temperature was again read. Readings were made at two different current settings in order to minimize any errors in the reading of the optical pyrometer. (See "Sample Calculations" for this result). It should be noted that the optical pyrometer as used in the calibrations was not a primary standard, although it had been checked against an optical pyrometer which was calibrated at the National Bureau of Standards and thus the instrument

used may be thought of as a secondary standard. After all the equipment had been obtained and placed in order, the calibration was the only preliminary work necessary before actual runs were begun.

As a preliminary to each run, certain precautionary measures had to be taken. First and foremost was the proper positioning and aligning of the optical system and spectrometer. The lenses of the optical system and spectrometer and the quartz windows in the stack were cleaned very carefully with lens cleaning tissue. This operation was especially critical where the windows in the stack were concerned since quartz is known to vitrify when exposed to high temperatures. It is also a fact that certain types of contamination such as fingerprints will act to encourage vitrification. This condition results in a lower transmissivity of the windows and cannot be tolerated when accurate temperature measurements are desired.

Following this, the sodium heater was loaded with around 20 particles of metallic sodium (about the size of small peas - total weight approximately 3 grams). The heater was actually large enough to hold around 10 grams, but since sodium in even relatively small quantities can become quite dangerous, especially if any water is encountered, it was arbitrarily decided to limit the amount of sodium introduced for reasons of safety. This amount, however, proved sufficient to make runs for periods upwards of 30 minutes, this being adequate time for each run. To prevent oxidation, the sodium supply was stored under kerosene. As soon as the loading had been completed, the helium line was secured to the heater and thus the sodium was, for all practical purposes, under an inert atmosphere at all times, enough kerosene adhering to the particles to prevent oxidation during the

loading period and also during the time prior to the entry of the helium gas into the heater. Only a small amount of pressure was necessary and, since the regulator valve had a very fine adjustment, there was no difficulty in obtaining just the right amount of flow as could be determined by observing for lines with the spectrometer. The glow bar furnace was then positioned and voltage applied to begin the heating-up of the sodium.

One preliminary duty was necessary as regards the shielded thermocouple, and that was the filling of the thermos bottle with ice in order to provide for the cold reference junction of this system - preferably one hour before runs were to be made, in order for temperature equilibrium between the junction and the ice to obtain.

The combustion equipment was then started in the following manner: First pilot bunsen burners were ignited at the tips of the movable fuel inlet pipes, which upon starting were placed about 2 inches from the furnace. Then the two pre-mix blowers were started up with only air in the system. Before the gas valves were opened for each pre-mix burner, it had to be ascertained that the on-rush of air through the fuel inlet pipes had not extinguished the pilots since these flames were used to ignite the air-gas mixture coming from the pre-mixers. With the pre-mix blowers operating and the pilots still burning, one fuel valve at a time was slowly opened until combustion of the mixture started. Then the second fuel-air mixture was ignited in the same way. When a red glow could be detected around the base of the combustion tube, the fuel-inlet pipes were pushed fully up to the furnace openings and the pilots extinguished. A small amount of water was supplied onto the inlet pipe ends to prevent deterioration of the steel pipe. Following this, the secondary air blower was started and

and an initial setting of the butterfly valve made.

Power was then applied by means of the variac to bring the sodium up to a temperature of around 1400° F. Only a few minutes were necessary for temperature equilibrium to obtain in the combustion tube, after which the author began to look through the spectrometer for the "bright" sodium lines. Once they appeared, the lamp filament voltage was brought up to the point where no lines could be seen. The current in the circuit was then recorded by the author, and an assistant read the potentiometer for the temperature as measured by the heated shield thermocouple. For a voltage setting over and above the resonance condition, dark lines appeared in the spectrum.

Both the comparator lamp and the ammeter were conveniently mounted on the same steel table supporting the spectrometer. Several simultaneous readings were taken with the Sodium Line Reversal equipment and the shielded thermocouple for any one setting of the fuel valves and the secondary air supply. These parameters could then be varied in order to give higher or lower temperatures so that altogether different measurements could be obtained.

SAMPLE CALCULATIONS

Since the optical pyrometer measured brightness temperatures of the comparator lamp at the red wave length, in this case 6540 angstrom units, it is necessary to convert this brightness temperature to the D-line brightness temperature. The reason this must be done is apparent when it is recalled that, with this method, the D-line monochromatic emissive power of the lamp is being matched with the emissive power of the sodium vapor.

Now since the emissivity of the tungsten filament for a given temperature is not the same for different wave lengths, the monochromatic emissive power as seen by the optical pyrometer depends not only on the wave length and the temperature of the filament, but also on the emissivity of the lamp at the particular wave length. If the emissivity were constant for all wave lengths, then the brightness temperature as measured by the optical pyrometer would be the true temperature of the gas neglecting any absorption between the filament and the sodium vapor. Actually one quartz window was placed between the filament and the vapor, therefore the effect of its absorption must also be accounted for. No correction must be made for the window and lens between the vapor and the spectrometer, since these elements effectively reduce the filament brightness and the vapor brightness by the same amounts.

In the following computations, let

T = true temperature of lamp filament.

S_R = brightness temperature as measured by optical
pyrometer without quartz window at 6540 μ

S_{RW} = brightness temperature as measured by optical

pyrometer with quartz window at $.6540 \mu$

S_Y = brightness temperature at the D-line wave length,

$.5890 \mu$ without quartz window.

S_{YW} = brightness temperature at the D-line wave length,

$.5890 \mu$ with quartz window.

P_R = emissivity of tungsten filament at $.6540 \mu$

P_Y = emissivity of tungsten filament at $.5890 \mu$

$C_2 = 25800^\circ \text{ F. microns.}$

*Now by a special form of Planck's equation, the following must hold:

$$C_1 \lambda_R^{-5} e^{-\frac{C_2}{\lambda_R T}} = P_R C_1 \lambda_R^{-5} e^{-\frac{C_2}{\lambda_R T}}$$

Taking logs on both sides of this equation, the following expression is obtained:

$$\frac{1}{S_R} - \frac{1}{T} = - \frac{\lambda_R}{C_2} \ln P_R \quad (1)$$

A similar expression can be obtained for the yellow brightness temperature:

$$\frac{1}{S_Y} - \frac{1}{T} = \frac{\lambda_Y}{C_2} \ln P_Y \quad (2)$$

Subtracting equation (1) from equation (2):

$$\frac{1}{S_Y} - \frac{1}{S_R} = \frac{1}{C_2} (\lambda_R \ln P_R - \lambda_Y \ln P_Y) \quad (3)$$

To correct for the window absorption:

$$C_1 \lambda_R^{-5} e^{-\frac{C_2}{\lambda_R S_{RW}}} = \kappa_W C_1 \lambda_R^{-5} e^{-\frac{C_2}{\lambda_R T}} \quad (4)$$

$$\frac{1}{S_R} - \frac{1}{S_{RW}} = \frac{\lambda_R \ln \kappa_W}{C_2} \quad (5)$$

*The factor of 1 in the denominator has been dropped since $e^{-\frac{C_2}{\lambda T}}$ is very much greater.

A similar expression may be obtained for the D-line:

$$\frac{1}{S_Y} - \frac{1}{S_{YW}} = \frac{\lambda_Y \ln k_W}{C_2} \quad (6)$$

Subtracting equation (6) from equation (3):

$$\frac{1}{S_{YW}} - \frac{1}{S_R} = \frac{1}{C_2} (\lambda_R \ln P_R - \lambda_Y \ln k_W P_Y) \quad (7)$$

Equation (7) is the required relation which can be used to convert the temperatures as measured by the optical pyrometer to the readings of the Sodium Line Reversal Method.

Equation (5) is now utilized to obtain the transmissivity of the quartz window:

$$\ln k_W = \frac{C_2}{\lambda_R} \left(\frac{S_{RW} - S_R}{S_{RW} S_R} \right)$$

Two different settings of the comparator lamp circuit were used to measure S_R and S_{RW} with the optical pyrometer. For a reading of 9 amps in the circuit, the average of two or more measurements was -

$$S_{RW} = 1786^\circ \text{ F.}, S_R = 1808^\circ \text{ F.}, \text{ giving a } k_W = .844$$

For a reading of 11 amps, the values were -

$$S_{RW} = 2239^\circ \text{ F.}, S_R = 2253^\circ \text{ F.}, \text{ giving a } k_W = .895$$

The average value of the two k_W 's thus found was .87 and was used in equation (7) to obtain the plot of D-13. The values of emissivity were obtained from Reference No. 5 and are plotted in D-12. One calculation now follows to show exactly how the graph of D-13 was obtained:

Take the case for $S_R = 2500^\circ \text{ R.}$, for which from D-12, $p_Y = .458$, $P_R = .458$ ($k_W = .87$ from above).

$$\frac{1}{S_{YW}} - \frac{1}{2500} = \frac{1}{25800} \left[.6540 \ln .448 - .5890 \ln (.87 \times .458) \right]$$

$$\frac{1}{S_{YW}} = .0004 - \frac{1}{25800} (-.524 + .541)$$

$$\frac{1}{S_{YW}} = .0004 + \frac{.017}{25800}$$

$$\frac{1}{S_{YW}} = .0004 + .0000006$$

$$\frac{1}{S_{YW}} = .0004006$$

$$S_{YW} = 2496^{\circ} R$$

SUMMARY OF RESULTS

Run No. 1

Thermocouple Readings

Lamp Brightness
Temperatures

Temperature of Gases
as measured by S. L. R.

1950
1953
1956
1952
1951

1990
1990
1950
1950
1950

1986
1986
1946
1946
1946

Run No. 2

2179
2185
2187
2187
2187
2192

2225
2245
2225
2170
2170
2170

2220
2240
2220
2166
2166
2166

The data obtained in two runs are plotted in D-14, the Sodium Line Reversal temperatures being plotted as the abscissa and the shielded thermocouple readings as the ordinate. Additionally, a 45 degree line was drawn by means of which it can be determined from a glance the dispersion from the theoretically attainable results of coincident readings by the two independent methods.

CONCLUSIONS

It may be concluded from the experimental results that the Sodium Line Reversal method is quite reliable for the temperature range investigated (1950° F. to 2200° F.) and can be employed to obtain temperatures as low as 1950° F. Readings below this value were found to be impossible of attainment due to the low degree of brightness of the comparator lamp. By establishing the shielded thermocouple readings as the correct temperature of the hot gases at the center of the combustion tube and at the level of the line of sight of the spectrometer, the largest positive error (2 1/2%) occurred at a reading of the thermocouple of 2185° F. for a corresponding reading of the Sodium Line Reversal apparatus of 2240° F. The largest negative error (1.2%) was for a thermocouple reading of 2192° F. with a Sodium Line Reversal reading of 2166° F. A positive error was taken as the case when the Sodium Line Reversal method gave a high reading compared to the thermocouple and a negative error meant that Sodium Line Reversal method was giving temperatures lower than the thermocouple. It is felt that the assignment of the thermocouple readings as the correct temperature of the hot gases at the center of the tube and at the level of the spectrometer line of sight represents a valid assumption since, although the thermocouple was positioned approximately four inches above the line of sight of the spectrometer, the vertical temperature gradient of the hot gases at the center of combustion tube is thought not to be over 25° F. through this range of temperature. In other words, if the thermocouple had been placed (although impossible) at exactly the same level as the spectrometer, it would have read 25° F. higher than it actually did for a given temperature. Additionally it can be said that the gas velocities in the combustion tube never reach such

proportions as to introduce even an error of .1° F. as a result of the fact that a thermocouple placed in a moving stream reads the adiabatic stagnation temperature of the gases rather than the static temperature.

There are a few important conclusions concerning the technique and apparatus which should be noted. It proved rather difficult for the author to make one line of the doublet at a time to disappear. With more experience, however, it is thought that this difficulty could be eliminated. Alignment of the optical system and the probe in the gas stream was found to be critical. In preliminary runs, data was taken which showed that large errors could result if alignment was not checked before each run. At the same time it would have been desirable to have a more sensitive ammeter in the comparator lamp circuit. Readings of the instrument used could be made only to the nearest tenth of an amp. Since in the calibration of the lamp by the optical pyrometer it was found that a change of one ampere in the circuit would mean a change of approximately 200° F. in the brightness temperature of the lamp, an error in reading the ammeter of .1 amp would mean an error of 20° F. roughly in obtaining the red brightness temperature of the lamp. At the time, no instrument could be obtained which would give more sensitive readings than the one used. It is not known exactly how well the thermocouple was holding up during the course of investigation. Actually, temperatures of 2000° F. and above can be expected to cause deterioration of thermocouple accuracy, and it would have been advantageous to have calibrated this particular couple after several runs had been made. Unfortunately the time which would have been required to calibrate the couple was prohibitive as far as this thesis was concerned.

Finally it must be said that the plot of D-14 shows that both positive and negative errors resulted. This is just what would be expected when questions of technique are considered.

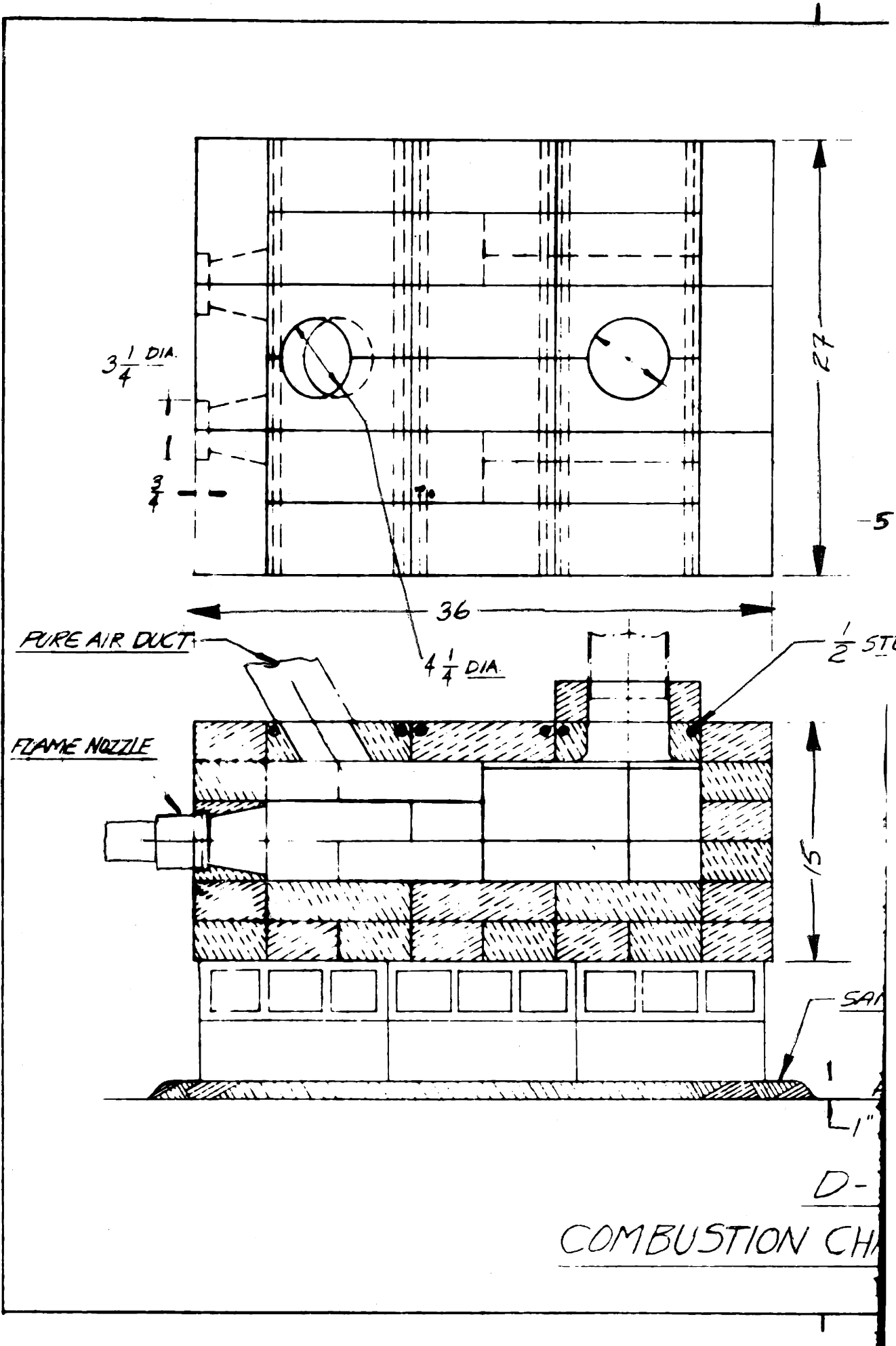
It is felt that, with more experience, the author could attain even better results than those reported.

Thus it is felt that additional runs with the equipment would not only lend itself to the gaining of better technique but would also serve to further check the Sodium Line Reversal method. These runs should, of course, vary over as wide a range of temperatures as possible (from 1950° F. upwards).

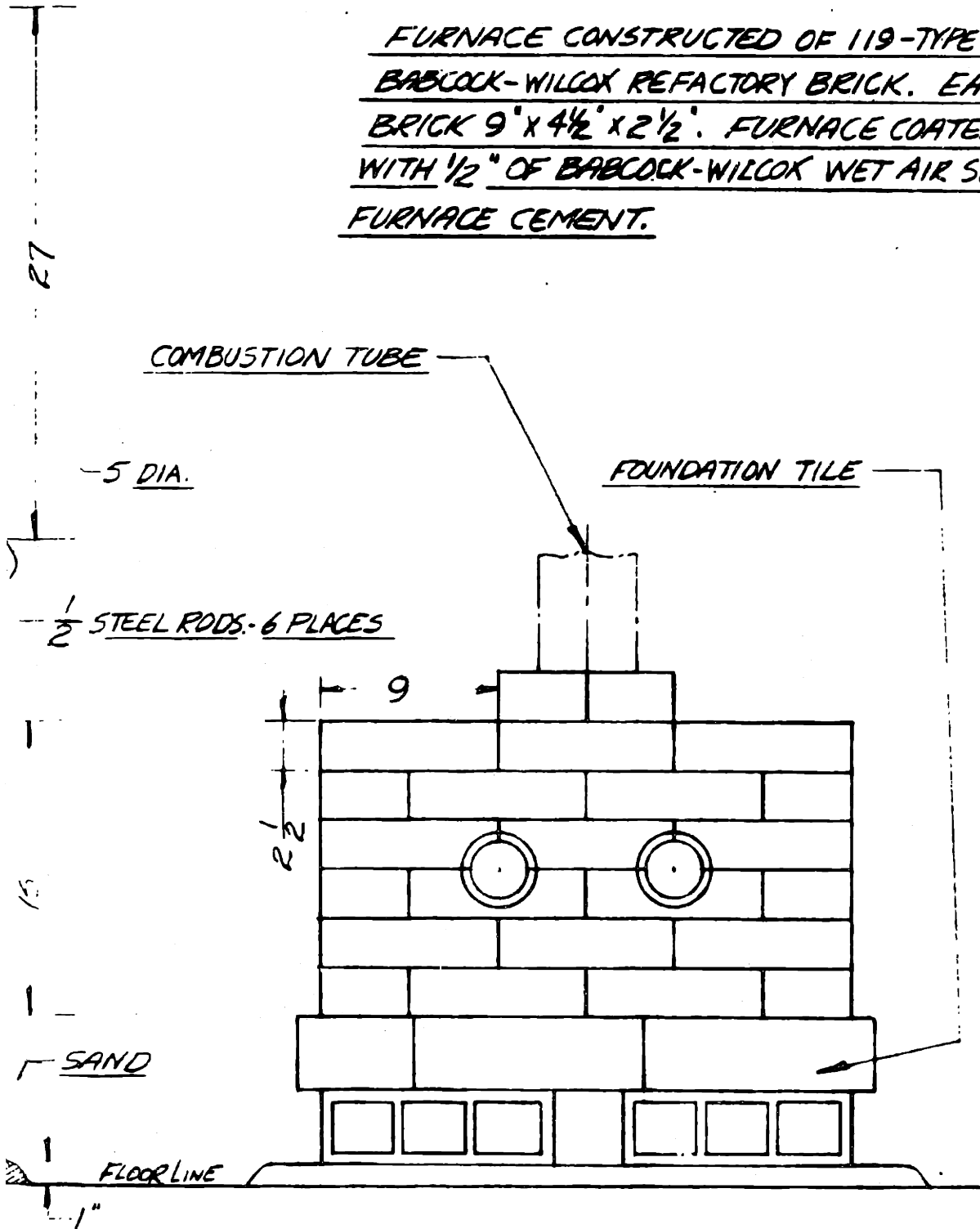
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FURNACE CONSTRUCTED OF 119-TYPE K-30
BABCOCK-WILCOX REFACTORY BRICK. EACH
BRICK 9" X 4 1/2" X 2 1/2". FURNACE COATED
WITH 1/2" OF BABCOCK-WILCOX WET AIR SET
FURNACE CEMENT.



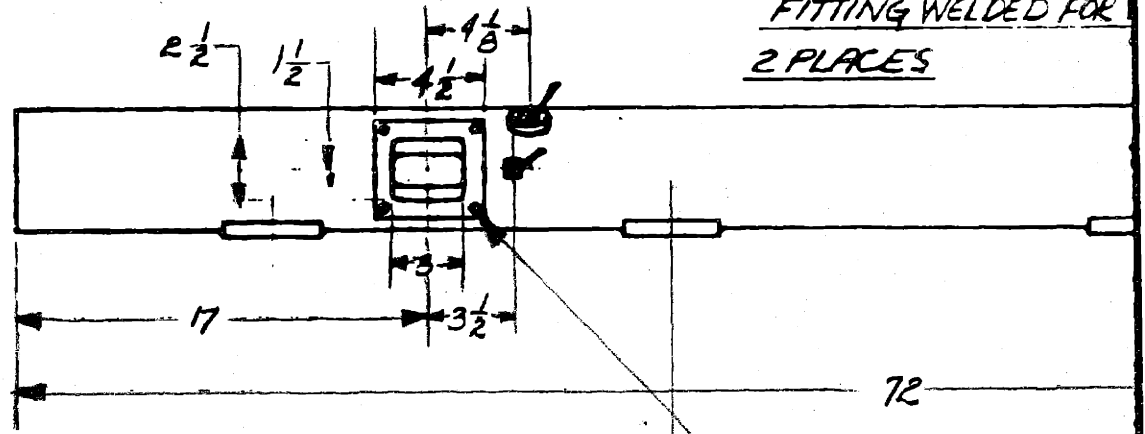
D-1

N CHAMBER or FURNACE

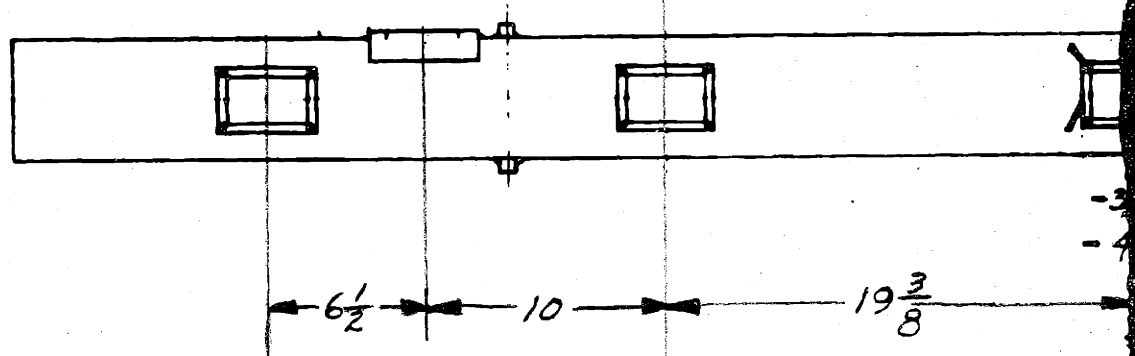
WINDOW

FLOW

FITTING WELDED FOR
2 PLACES



$\frac{1}{4}$ -20-TAP 4 PLACES



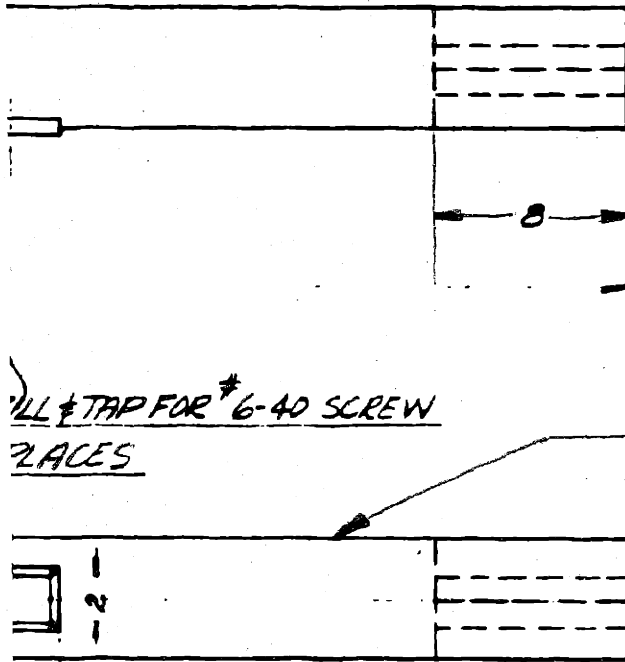
ALL STAINLESS STEEL

D-2

COMBUSTION TUBE

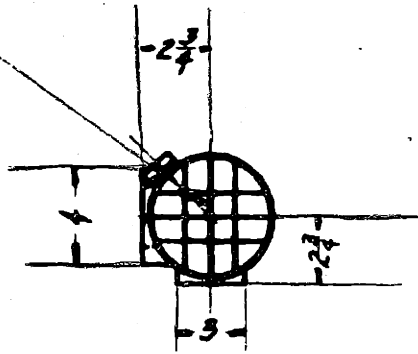
4 STRAIGHTENERS 1" SQ.

WALL STATIC PRESSURE TAP



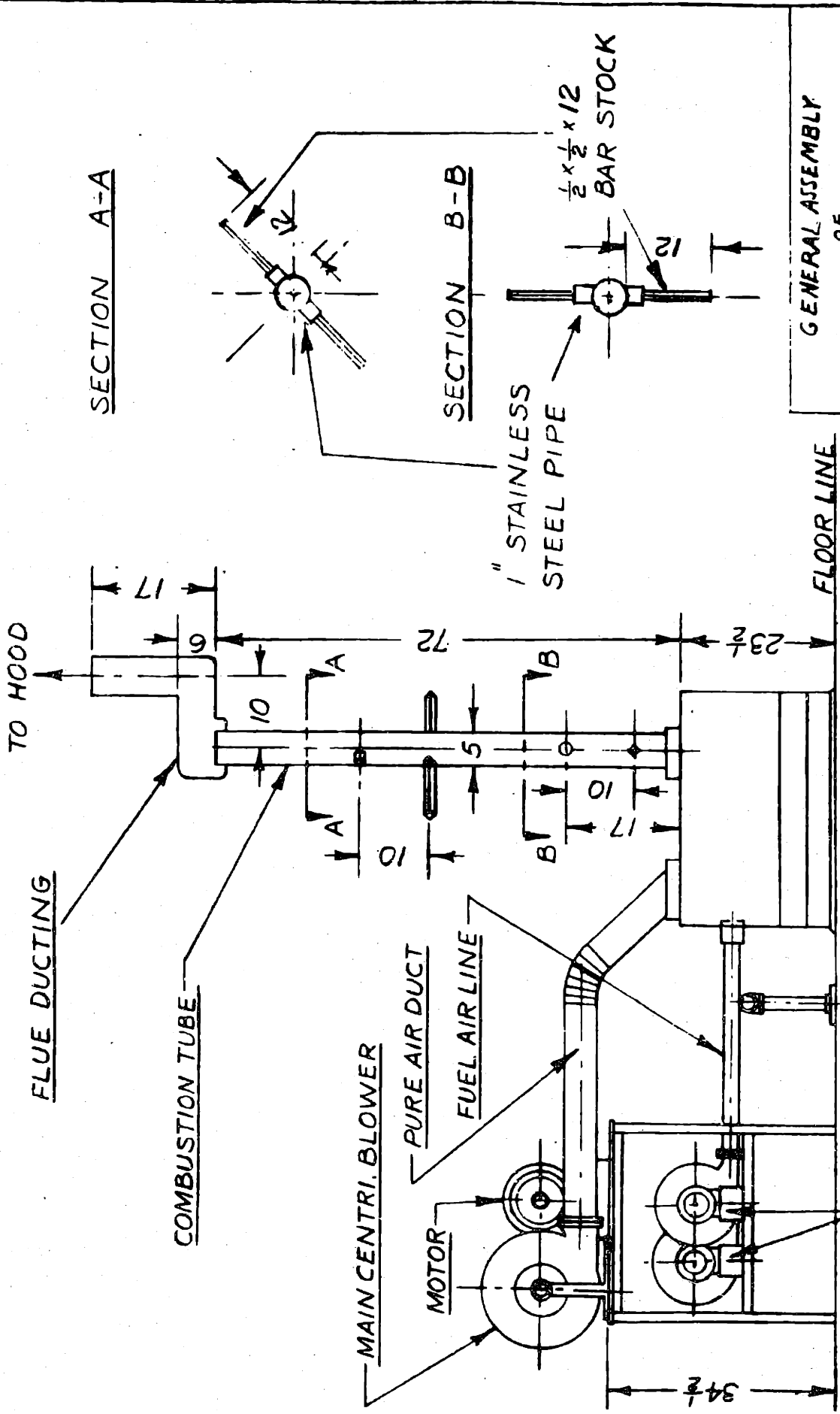
WALL TAP FOR #6-40 SCREW
2 PLACES

5" O.D. 4 3/4" I.D. TUBE



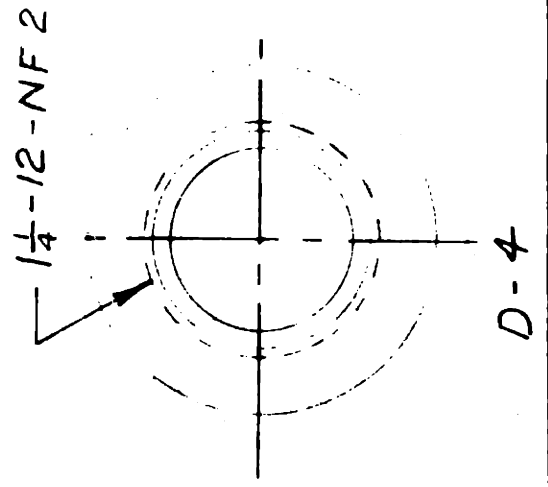
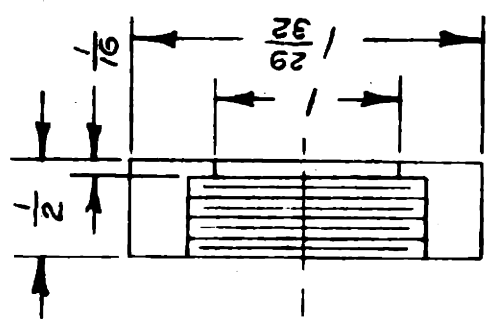
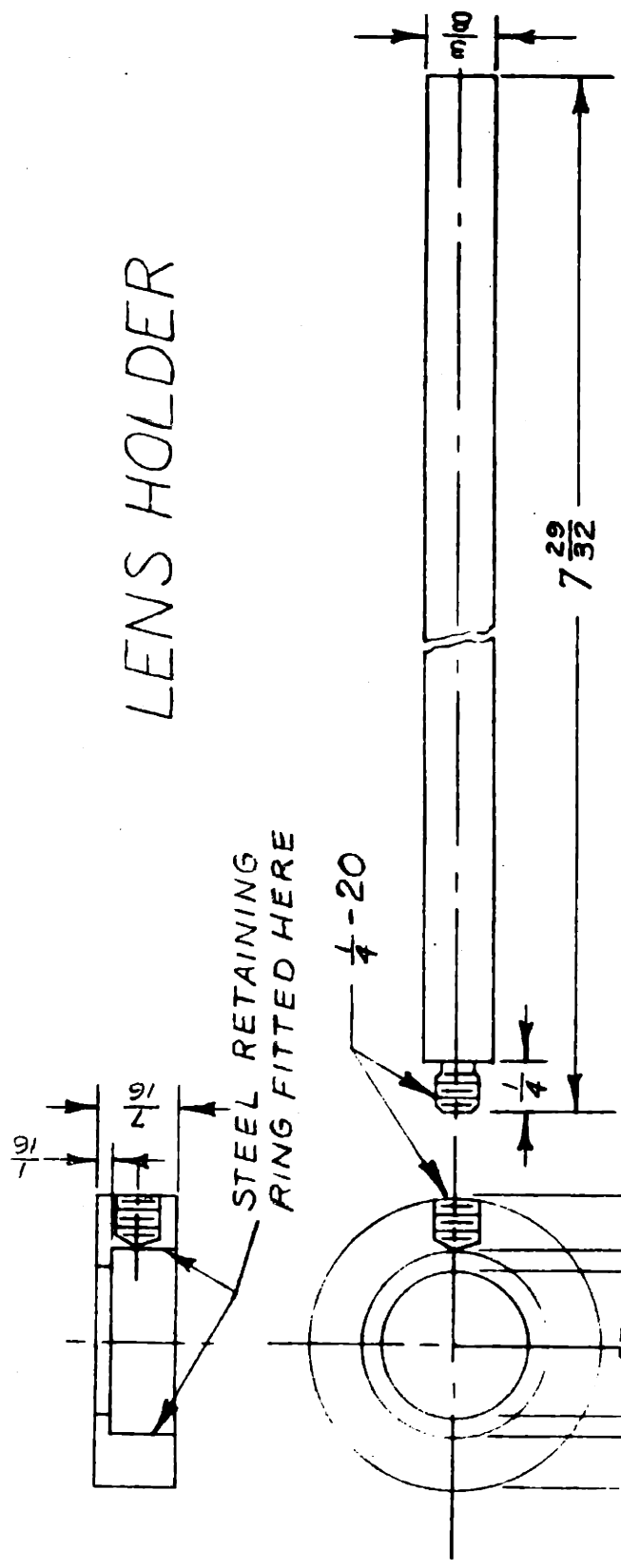
HEATED SHIELD THERMOCOUPLE MOUNTING
PAD - 3 PLACES.

UBE



GENERAL ASSEMBLY
OF
MODIFIED COMBUSTION APPARATUS
D-3

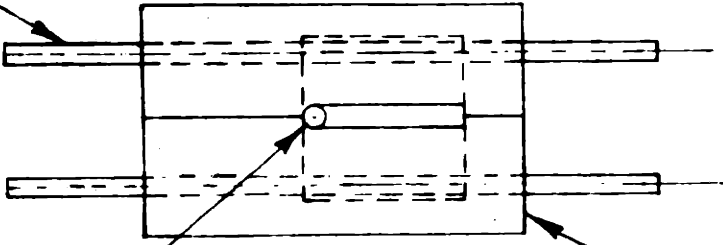
LENS HOLDER



WINDOW CAP

GLOW BAR FURNACE ASSEMBLY

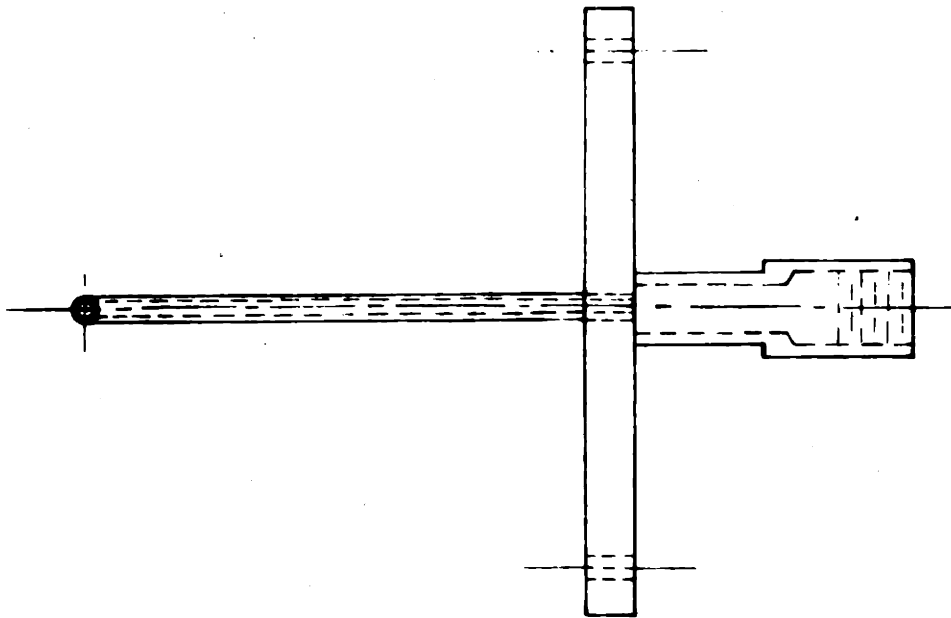
2 - $\frac{3}{8} \times 14$
GLOW BARS



HELIUM INLET

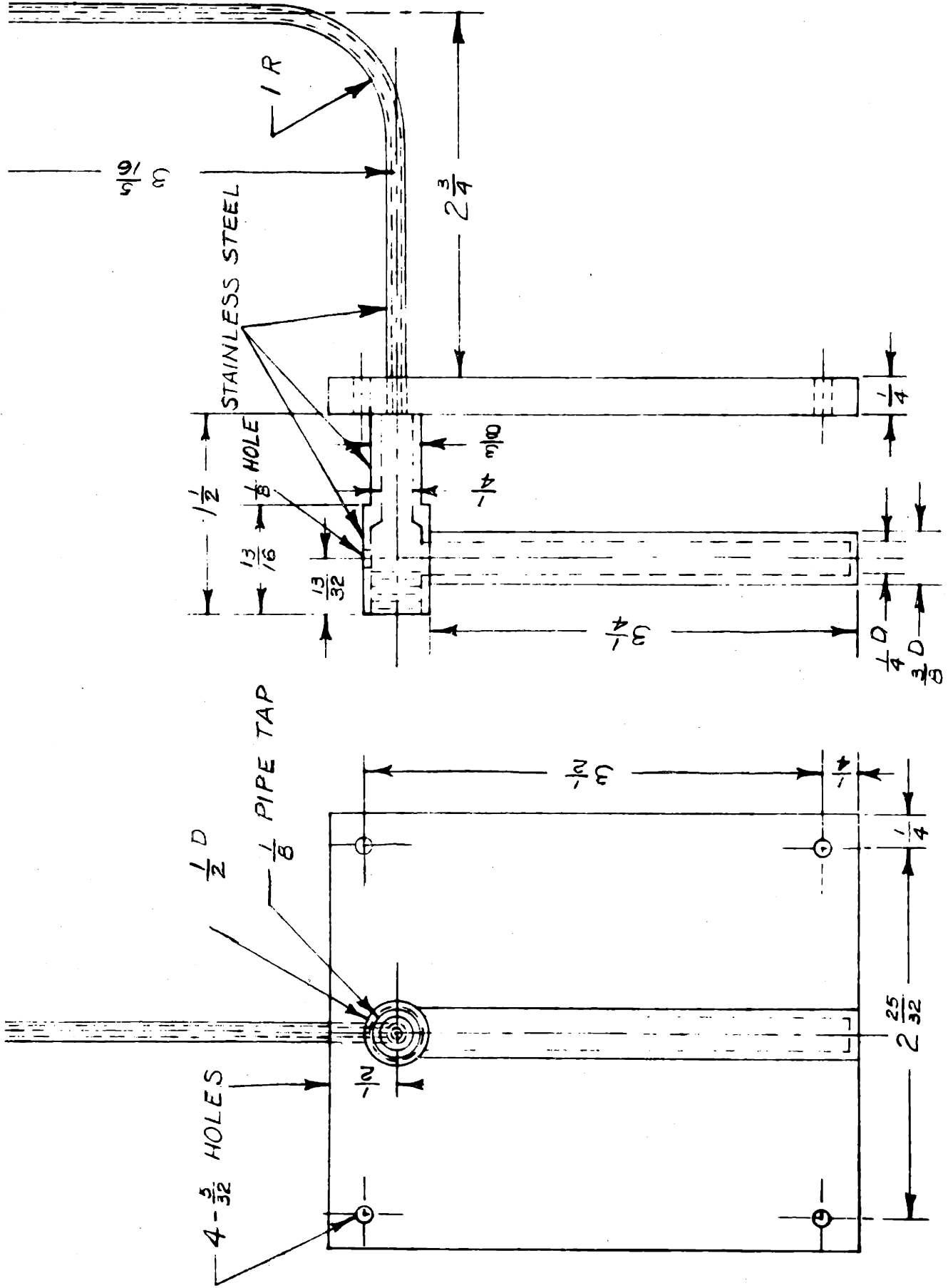
2 K-20 BRICKS $2\frac{7}{16} \times 6\frac{1}{2} \times 8$

SCALE: 4:1



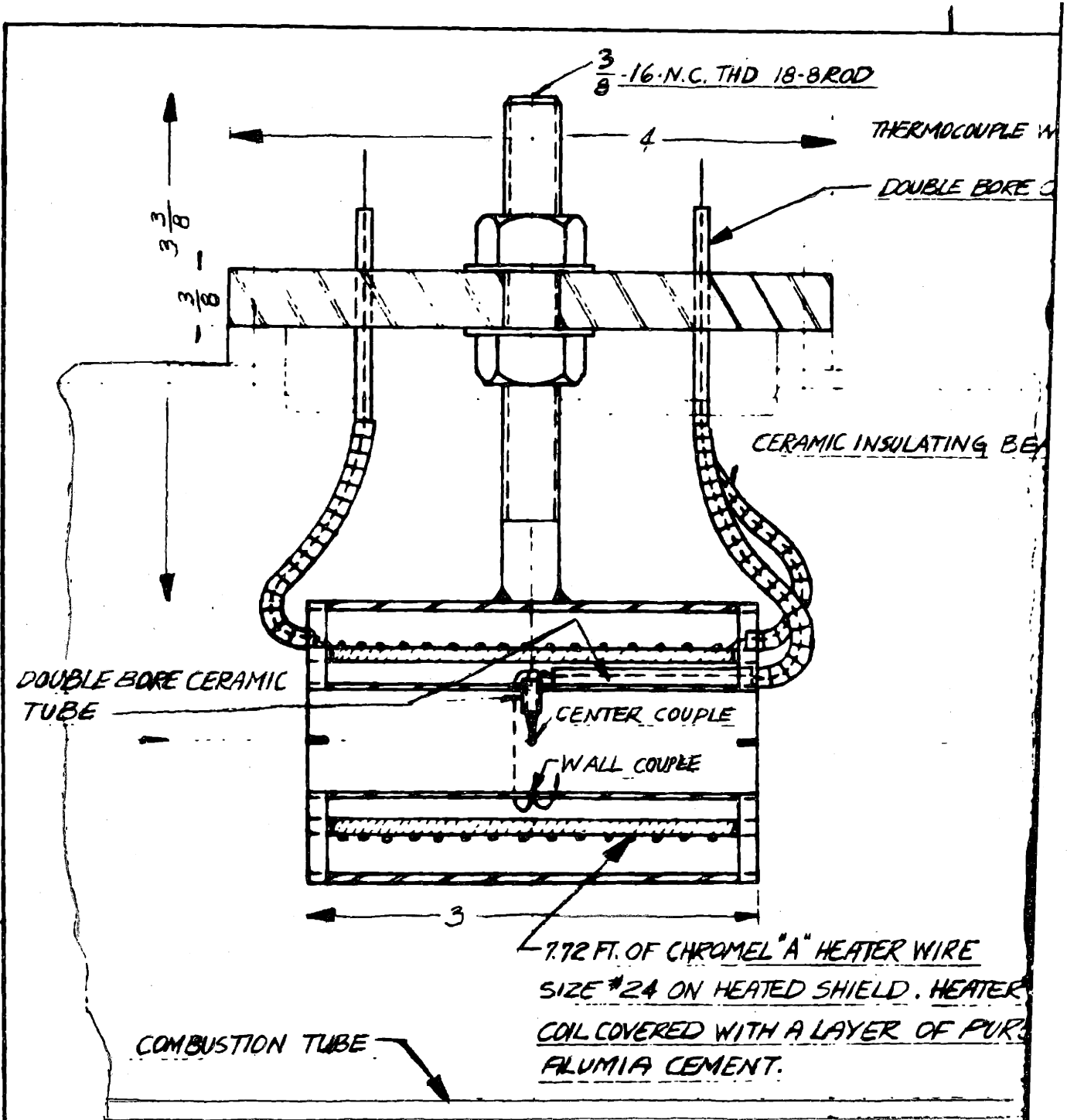
$\frac{1}{8}$ D
 $\frac{1}{16}$ D

SCALE: 1:1



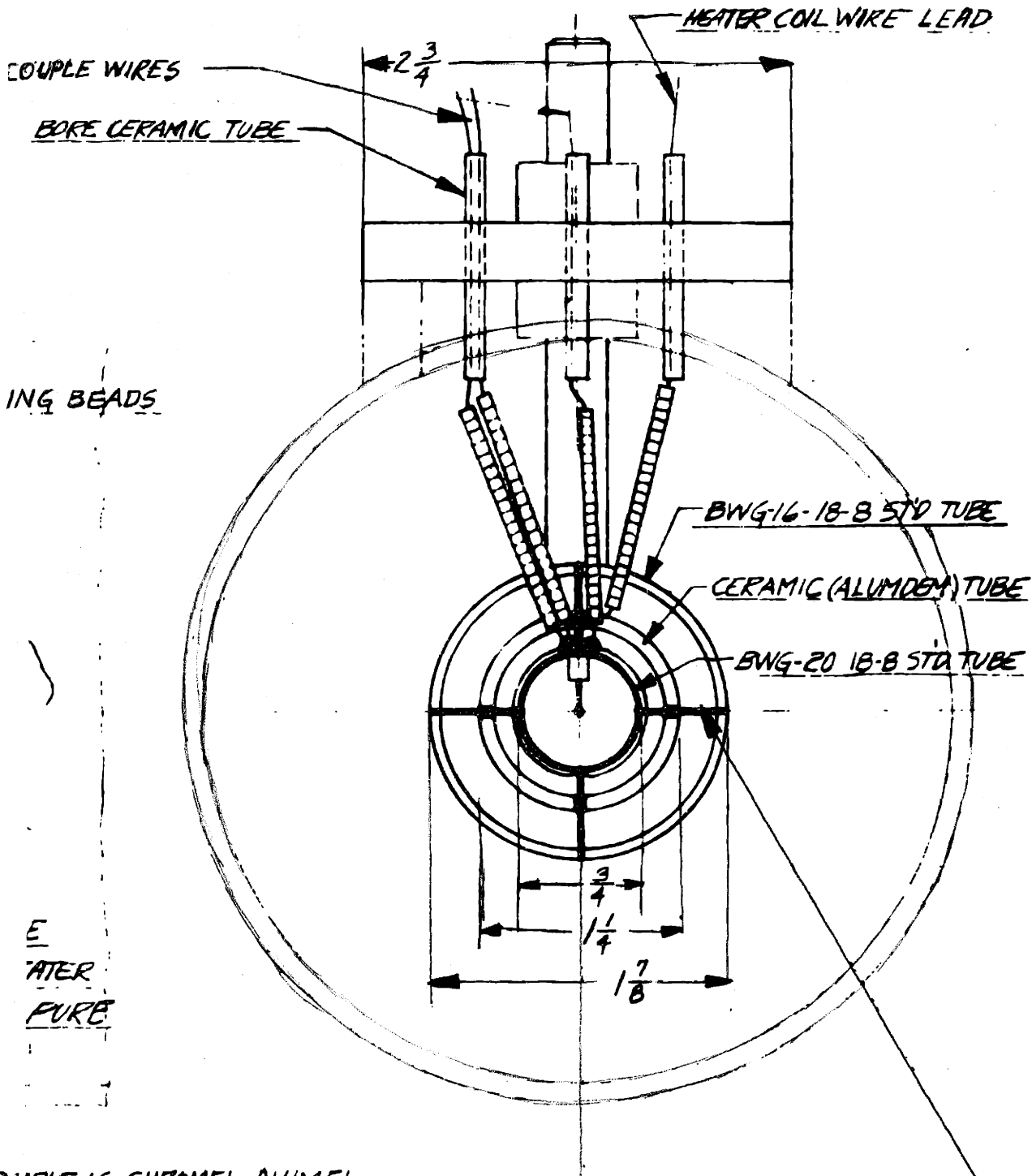
SODIUM INJECTION SYSTEM

D-6

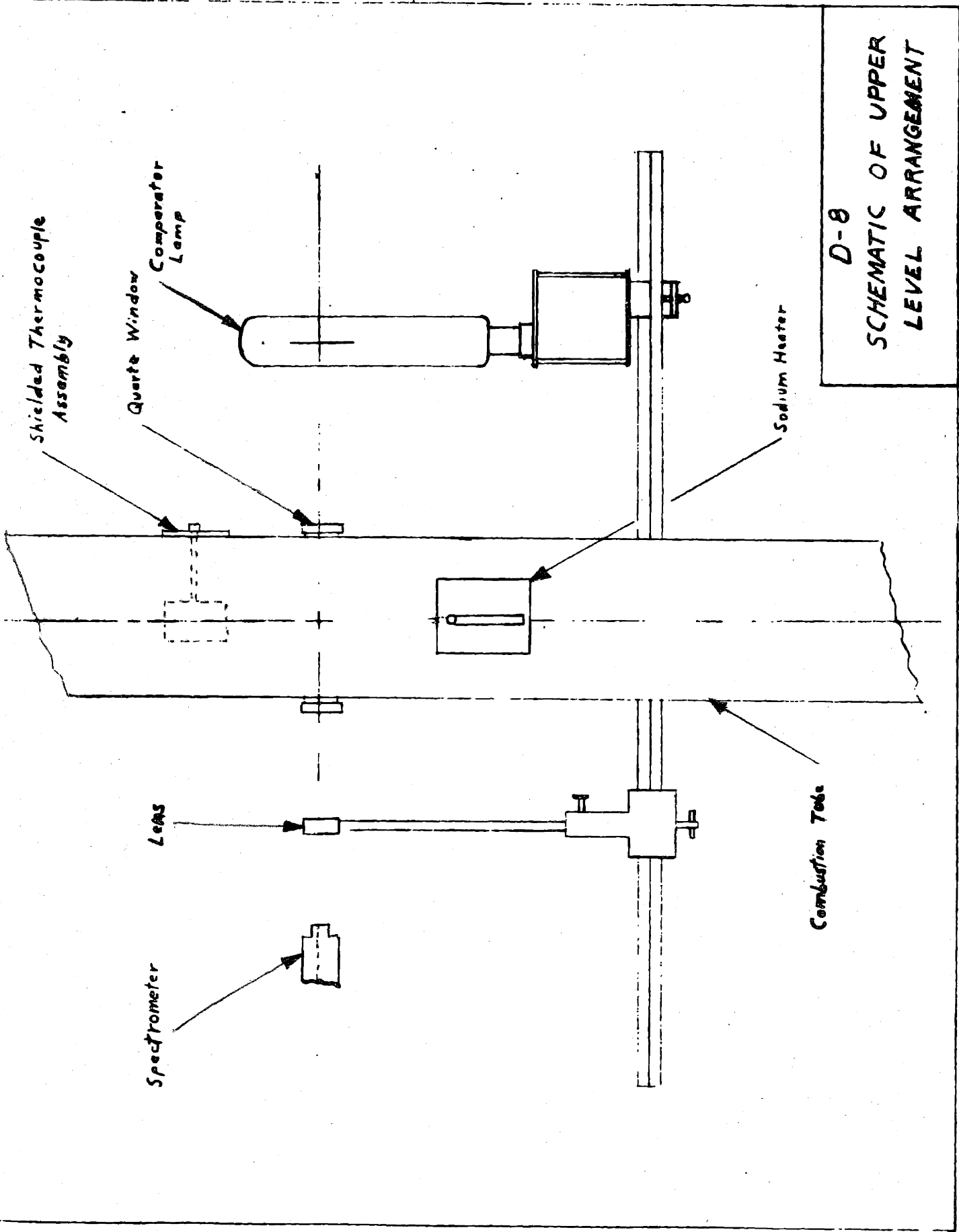


D-7

HEATED SHIELD THERMOCOUPLE



CONCENTRIC SHIELDS HELD IN PLACE BY RIBS
PRESSED INTO SLOTS CUT INTO THE TWO STEEL
SHEILDS. CERAMIC SHEILD FLOATS; HEATER COIL
COMPLETELY INSULATED FROM COUPLE BODY.



Shielded Thermocouple
Assembly

Quartz Window
Comparator
Lamp

Sodium Heater

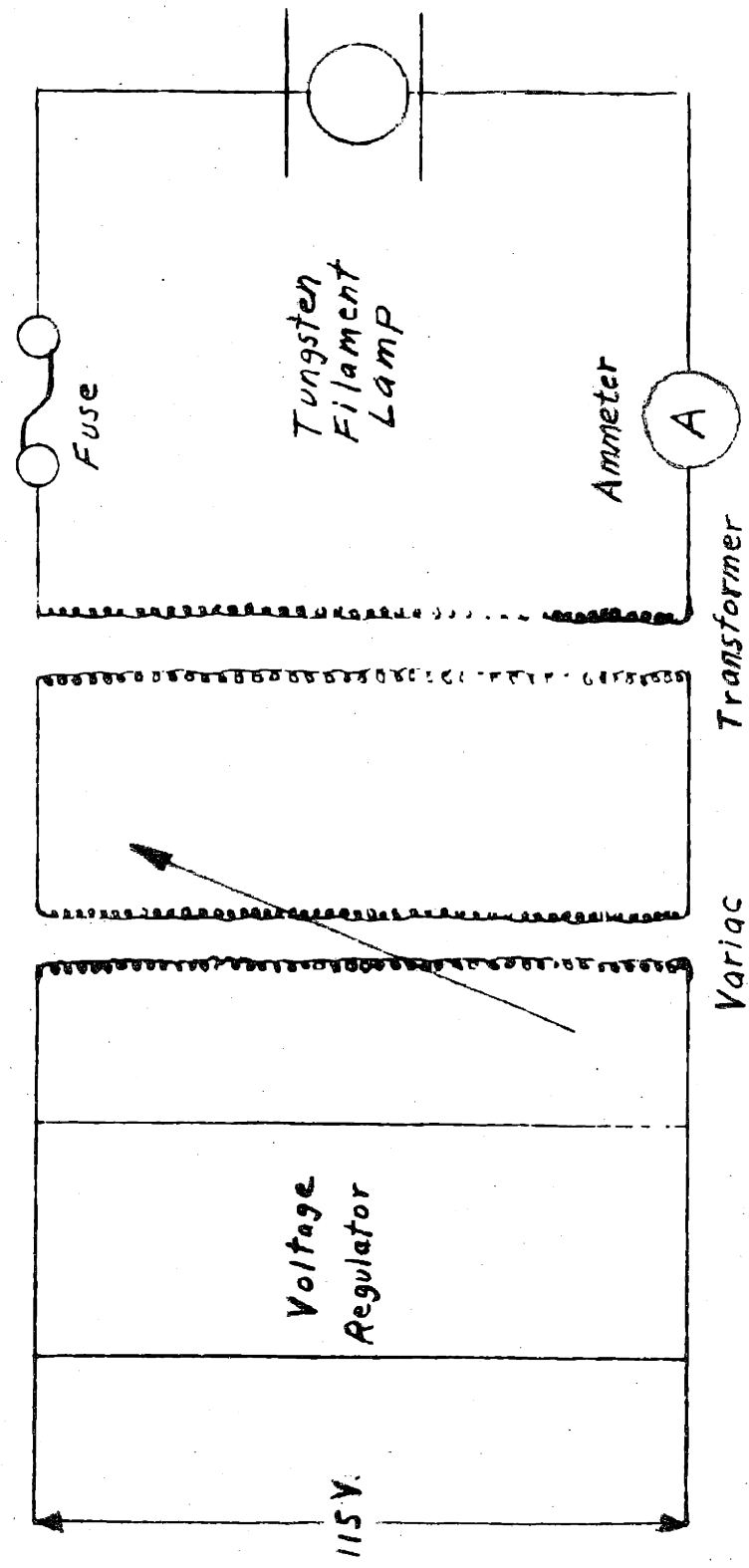
Combustion Tube

Lens

Spectrometer

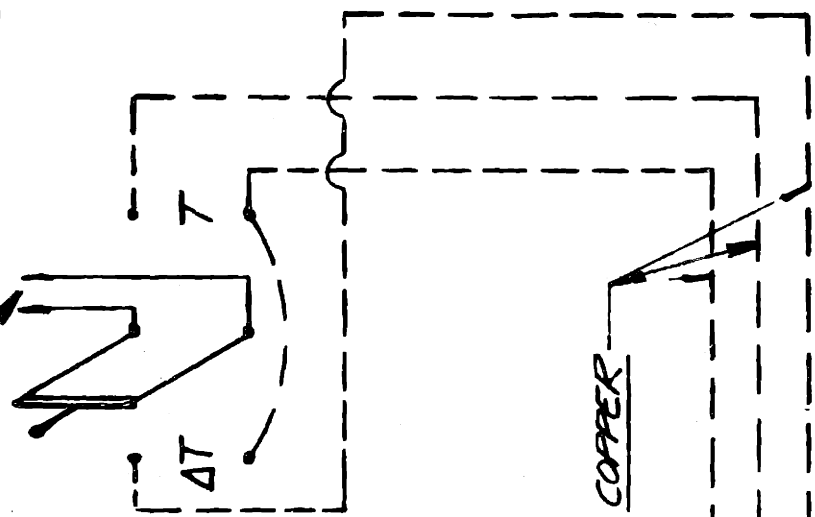
D-8
SCHEMATIC OF UPPER
LEVEL ARRANGEMENT

COMPARATOR LAMP CIRCUIT



D-9

TO POTENTIOMETER



CHROMEL

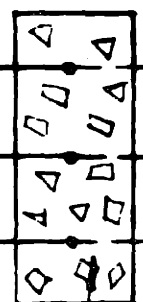
ALUMEL

CENTRAL
COUPLE

WALL COUPLE

WATER-ICE BATH
REFERENCE JUNCT.

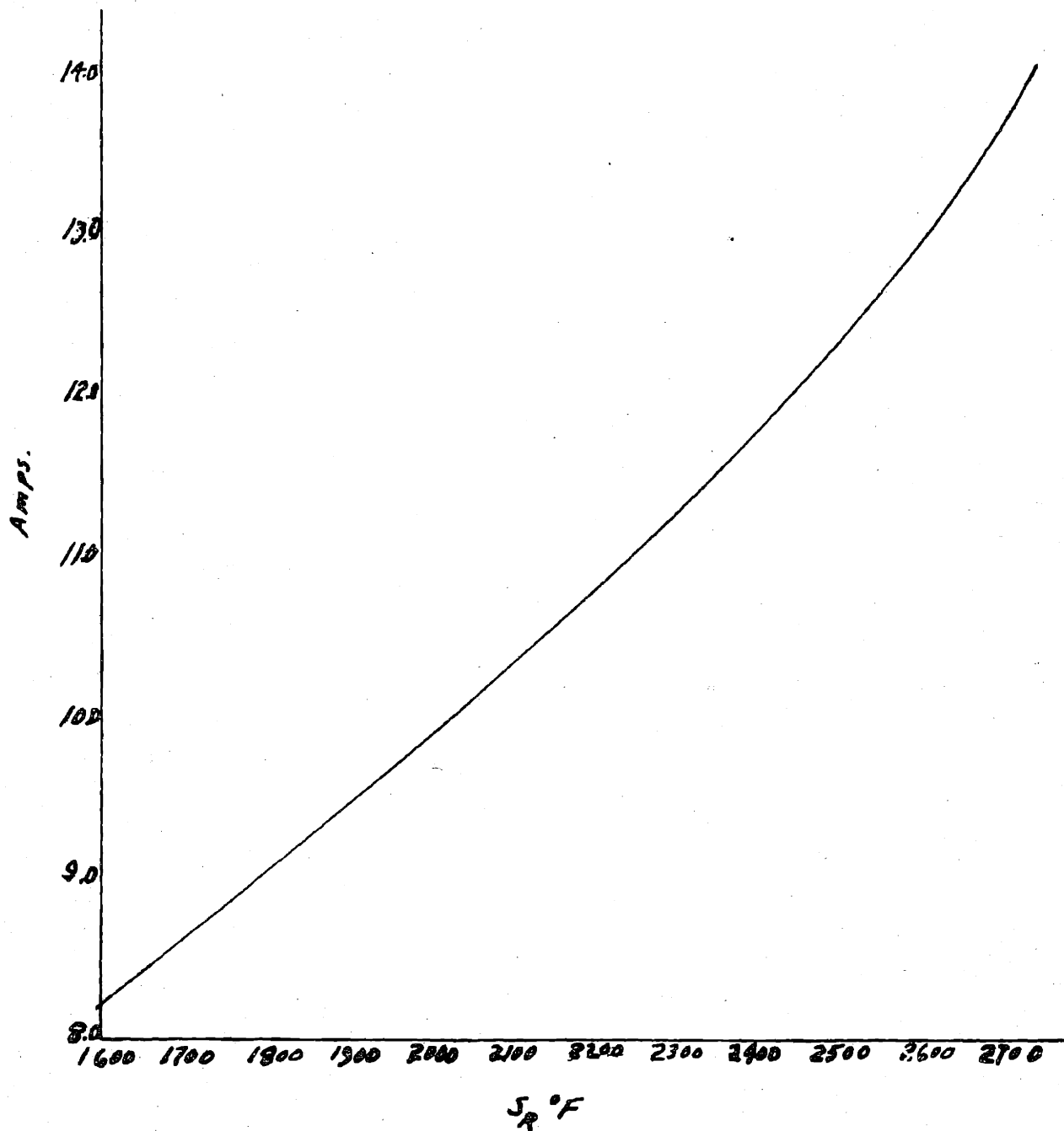
INNER SHIELD



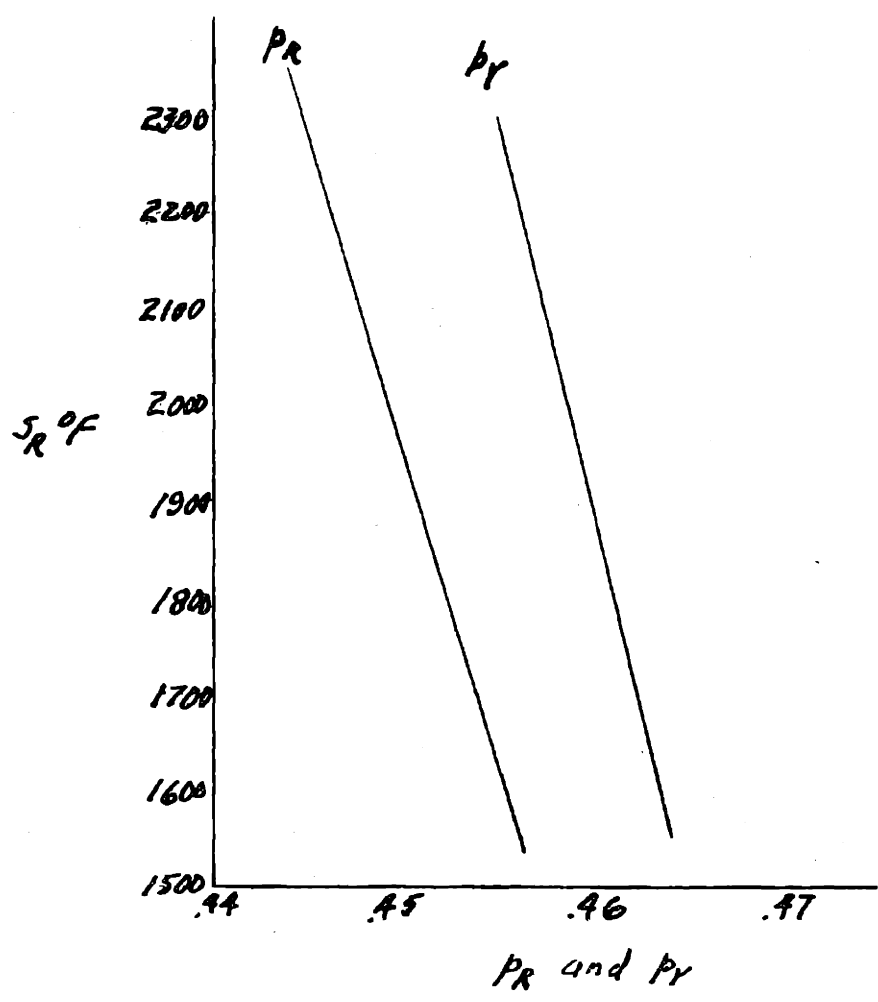
THERMOCOUPLE CIRCUIT

D-10

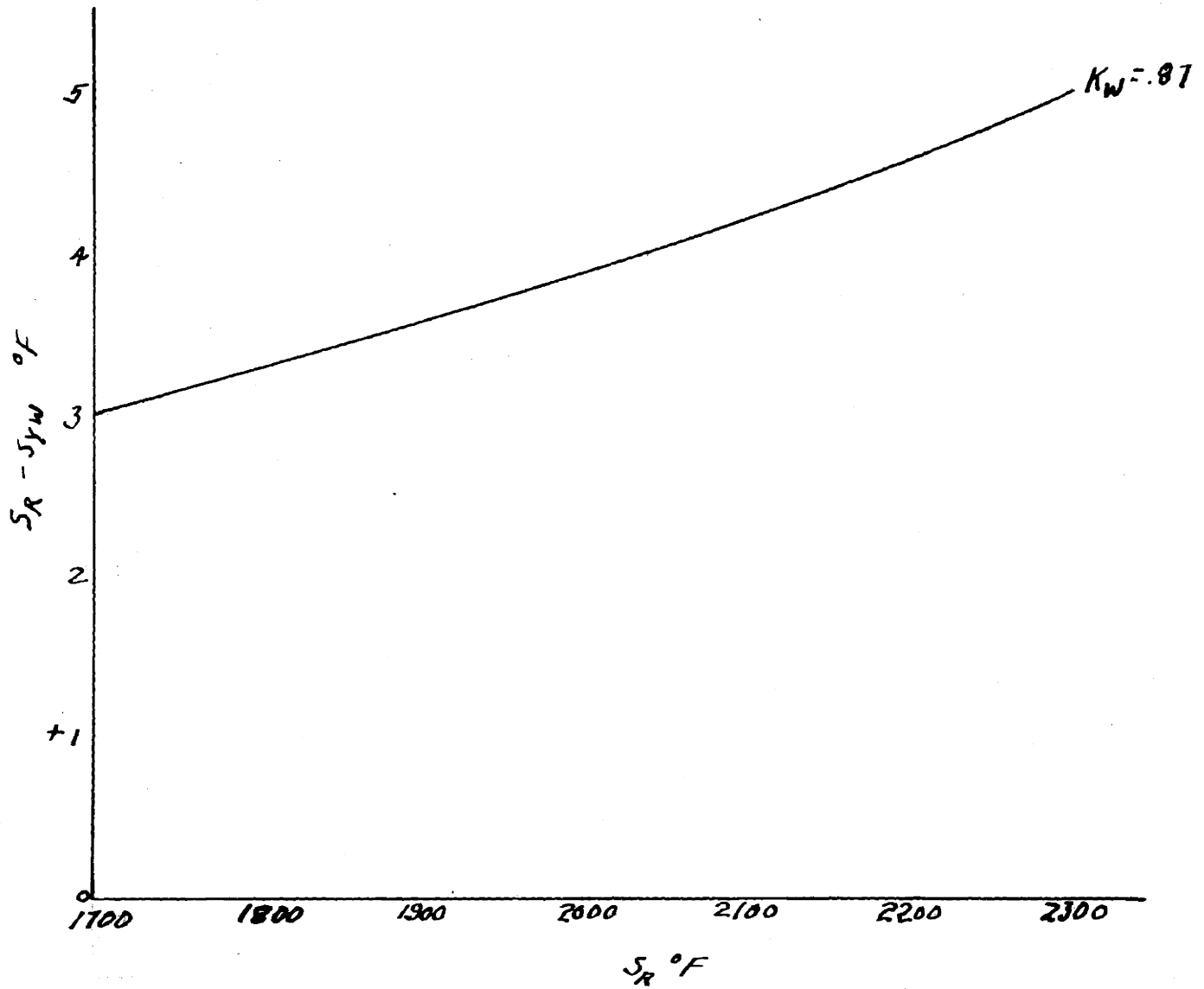
D-11
Lamp Calibration Data
B.T.'s Temperature vs.
Ammeter Reading



D-12
Emissivity of Tungsten
Filament Lamp for Two
Wave Lengths vs. B'rt's
Temperature
(Forsythe and Worthing)
(Astrophysics Journal)

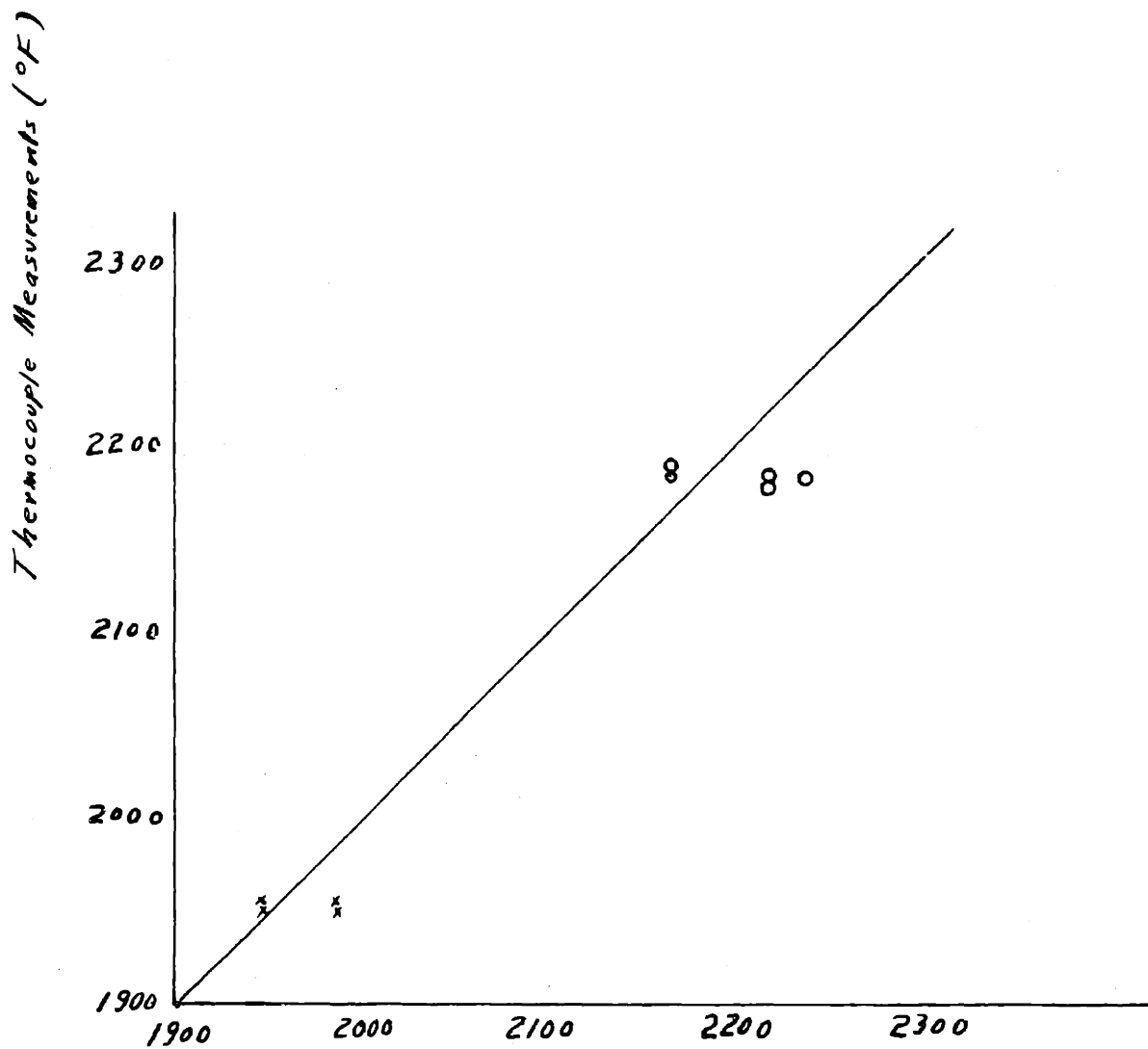


D-13
Temperature Correction Plot
Brightness Temperature vs.
Correction



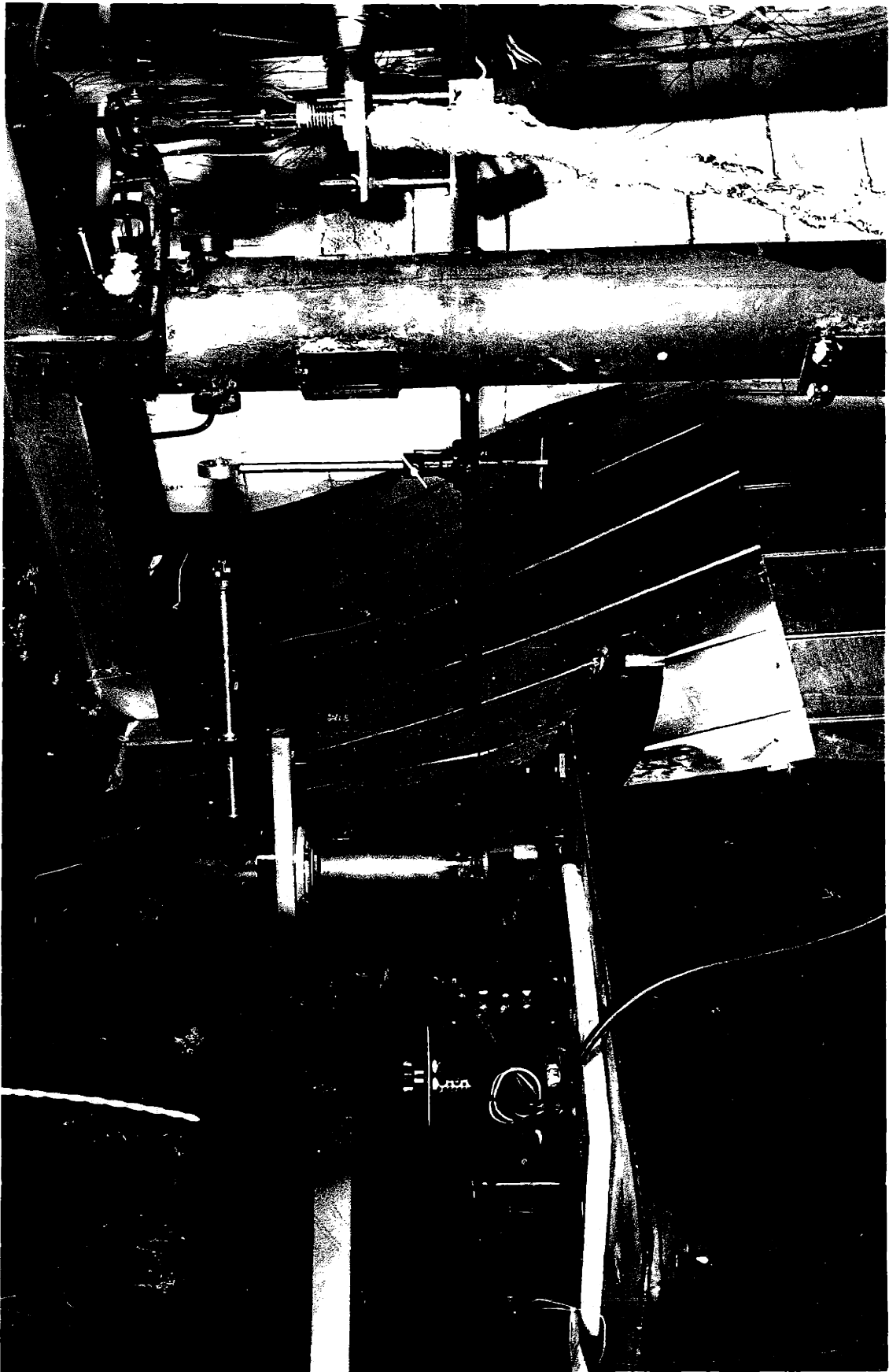
Plot of Sodium Line Reversal
Measurements vs. Thermocouple
Readings for Two Runs

x 1st Run
o 2nd Run

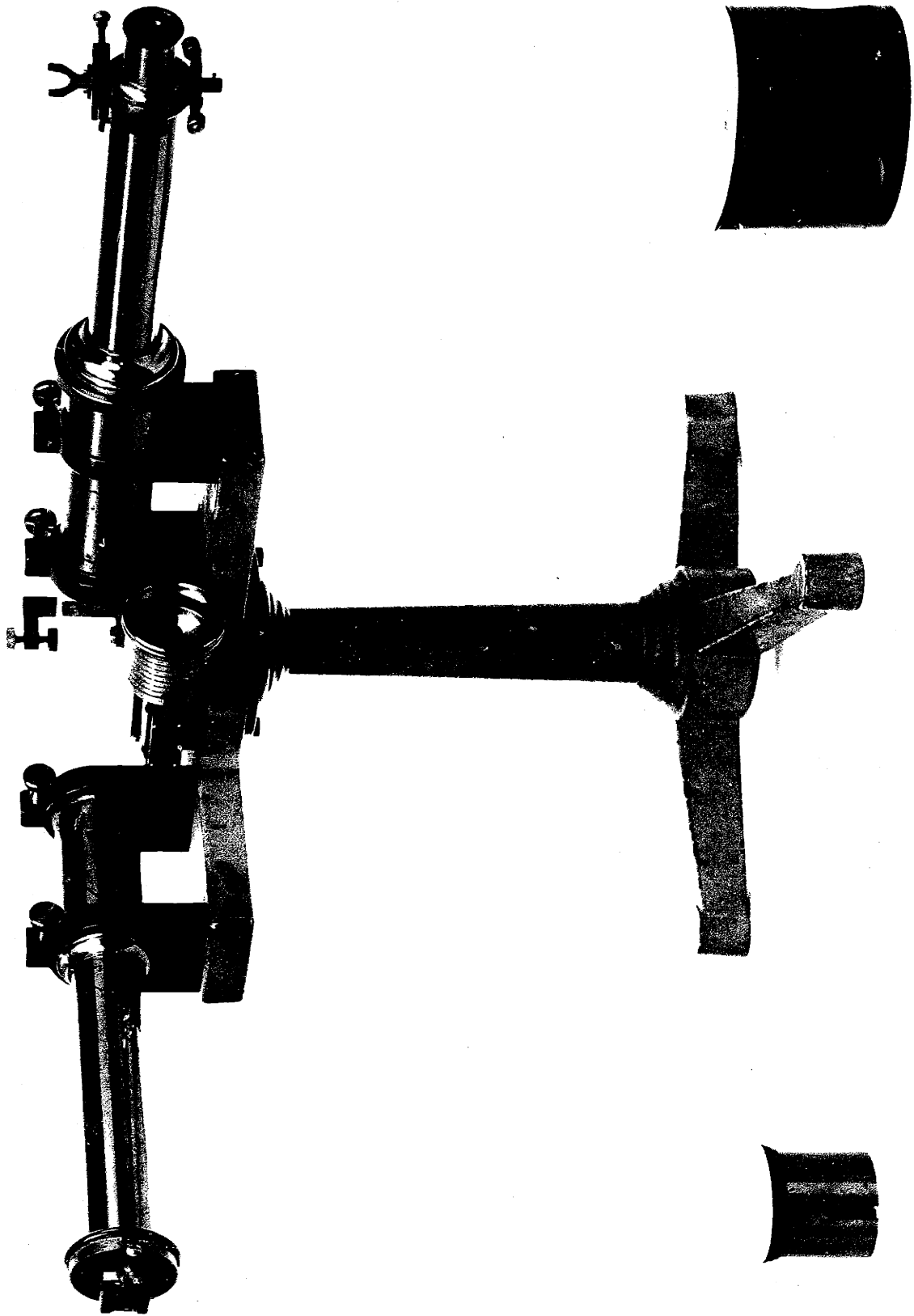


Sodium Line Reversal
Temperature Measurements (°F)

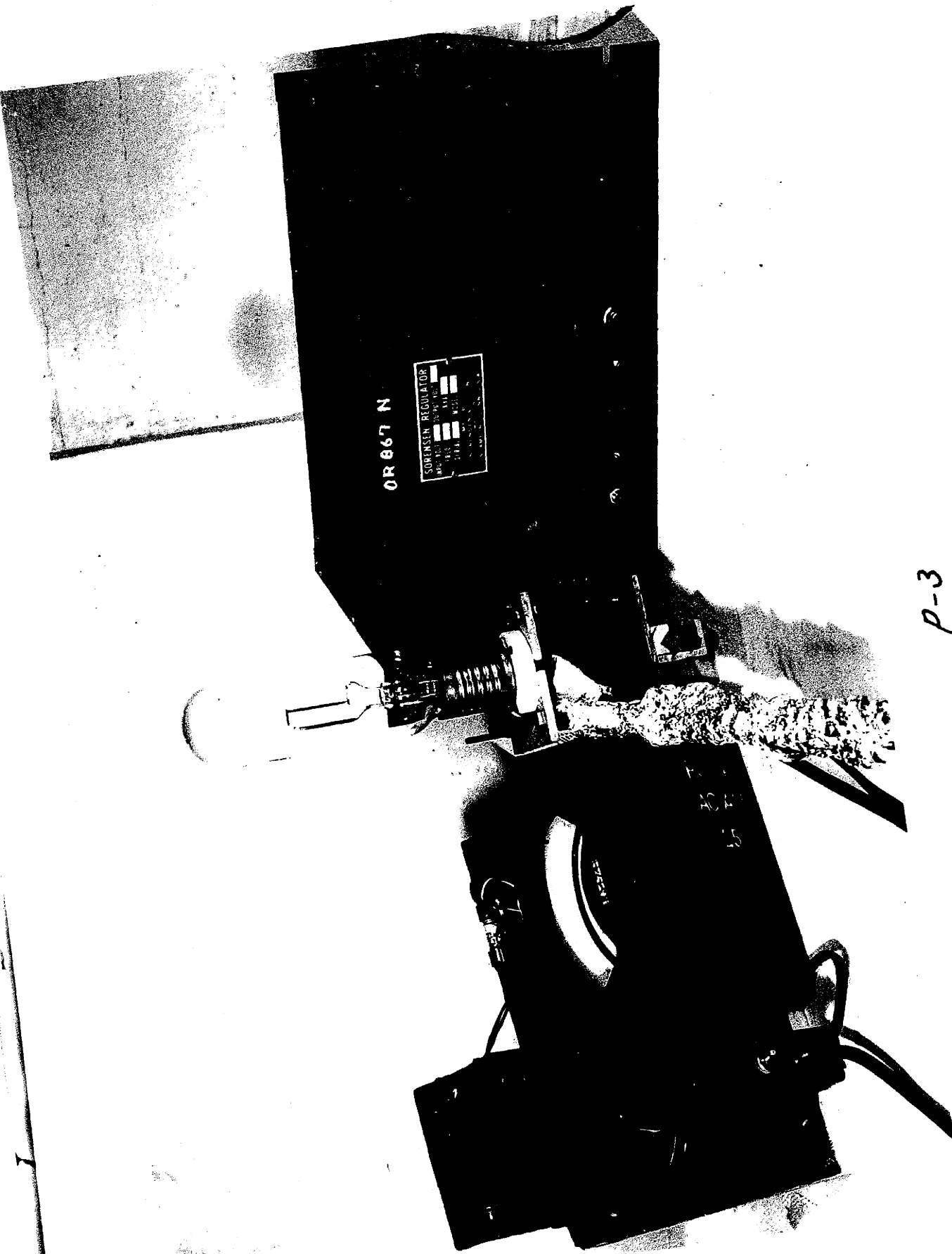
D-14



P-1



P-2



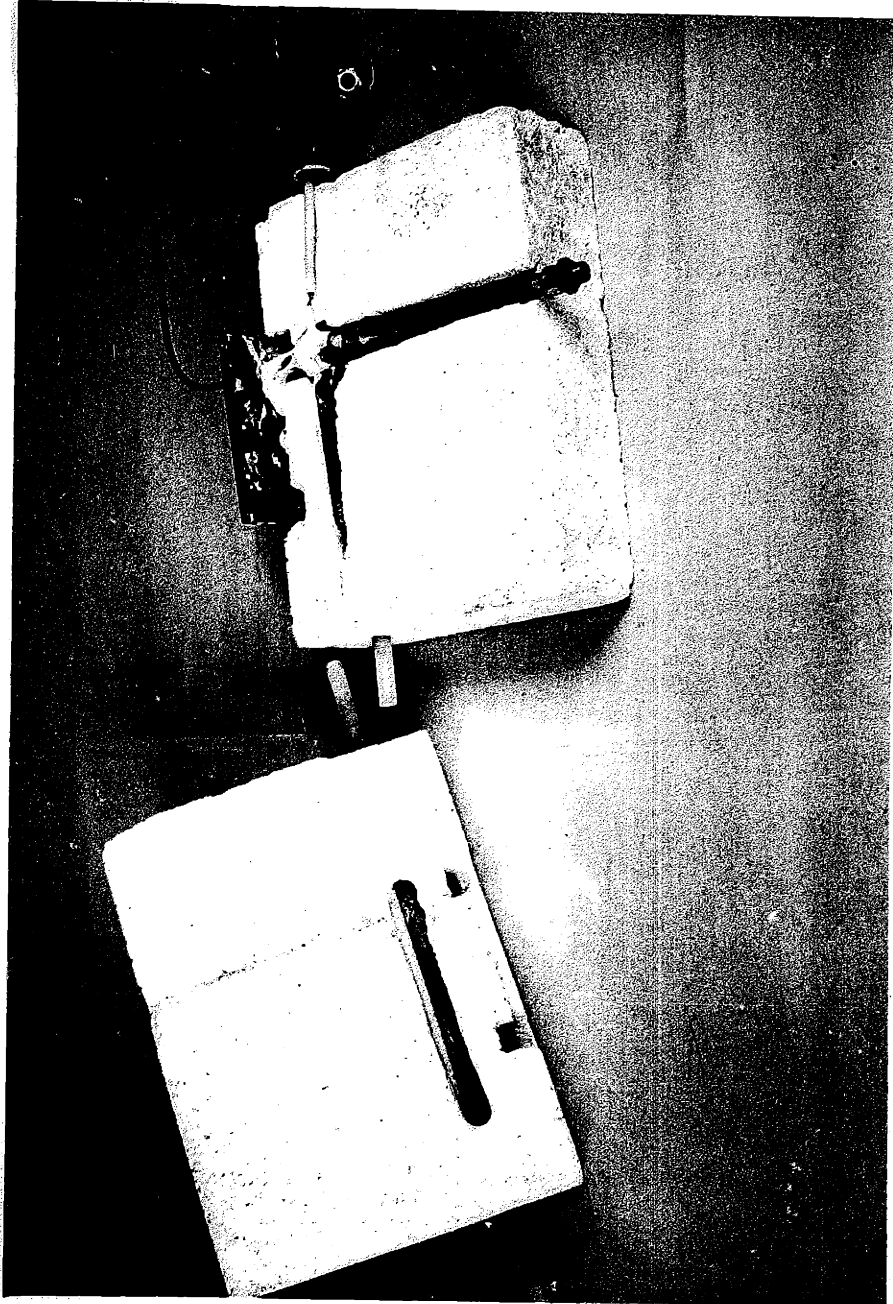
P-3

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P-9a

Handwritten notes on the left margin, including a large 'L' and some illegible characters.



P-46