DESIGN OF REFRACTORY FURNACE LININGS SUBJECTED TO HIGH TEMPERATURE AND EROSION

THE DESIGN OF REFRACTORY FURNACE LININGS SUBJECTED TO HIGH TEMPERATURE AND EROSION WITH SPECIAL REFERENCE TO OIL FIRED STEAM GENERATORS

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CONTENTS

thesis - - The design of refractory furnace linings subjected to high temperature and erosion with special reference to oil fired steam generators.

I. INTRODUCTION

The design and operation of complete refractory lined furnaces for oil fired steam generators, is a field of study upon which much energy, effort and time has been spent without any definite and concise rules having resulted, to apply to the requirements of that class of user, perhaps the largest group favouring oil fired equipment, those industrial plants of small and medium size, producing from 1500 to 30000 pounds of steam per hour.

Unfortunately it would appear that only good draughting work goes into many designs of such furnaces, for it is astonishing to note, how far away from giving good results on the job some designs appear to be, when it comes to checking operation over a period of time. Textbooks and design manuals may be the basis of a good design, but they do not provide the answer to the noted fact that two layouts of identical design and equipment may provide examples of high and low cost furnace maintenance.

Upon reading the above statement, many designers will immediately exclaim that high maintenance in what seems to be a well designed refractory furnace is mostly the result of poor operation. Blaming the other fellow solves no problem. In the medium sized plant, (writing from very considerable experience) operators in most cases give reasonable attention to their work, but the scope of the work varies, and oftentimes the furnace suffers. Legislation may correct this in time, and eliminate the dangers associated with the diversified extraneous work given to many operators on the firing floor, but until such legislation is a fact, and even then, a furnace design should be based upon the principle to which all modern equipment aspires, namely that it be as fool-proof as possible under the worst possible operating conditions, and that the cost of replacement be at a minimum when damage does occur. Damage must be regarded by designers as an unavoidable accompaniment of furnace operation, as certain as the flames which blaze in that furnace, and not until this point of view is generally accepted, will good furnace designs of low maintenance cost be steadily produced.

II. CLASSIFICATION OF OIL BURNERS AND CHARACTERISTICS OF THEIR OPERATION:

(a) Classification It is impossible to embark upon such a study as this without giving a classification of oil burners, and an explanation, in a general manner, of the characteristics of their operation in a refractory lined furnace.

In preparing such a classification, a departure will be made from the usual practice of grouping burners according to mechanical design. So far as the eventual consideration of the refractory furnace is concerned, we need only group the burner units according to the type of flame developed by them in the furnace, and as there are only two such types, classification becomes very simple.

1. Conical flame type. (See Figs. 1 - 1A and 3)(pages 7 and 9)

This type of burner projects an expanding conical flame normal to the firing wall and parallel to the furnace floor. Combustion air is fed into the furnace around the flame, and through the burner mounting face plates.

Included in this classification are the standard diaphragm mechanical burners, all the spinning - cup types, and those gun type burners which have the combustion air led into the furnace around the oil gun. In the first and last mentioned of the above burners,

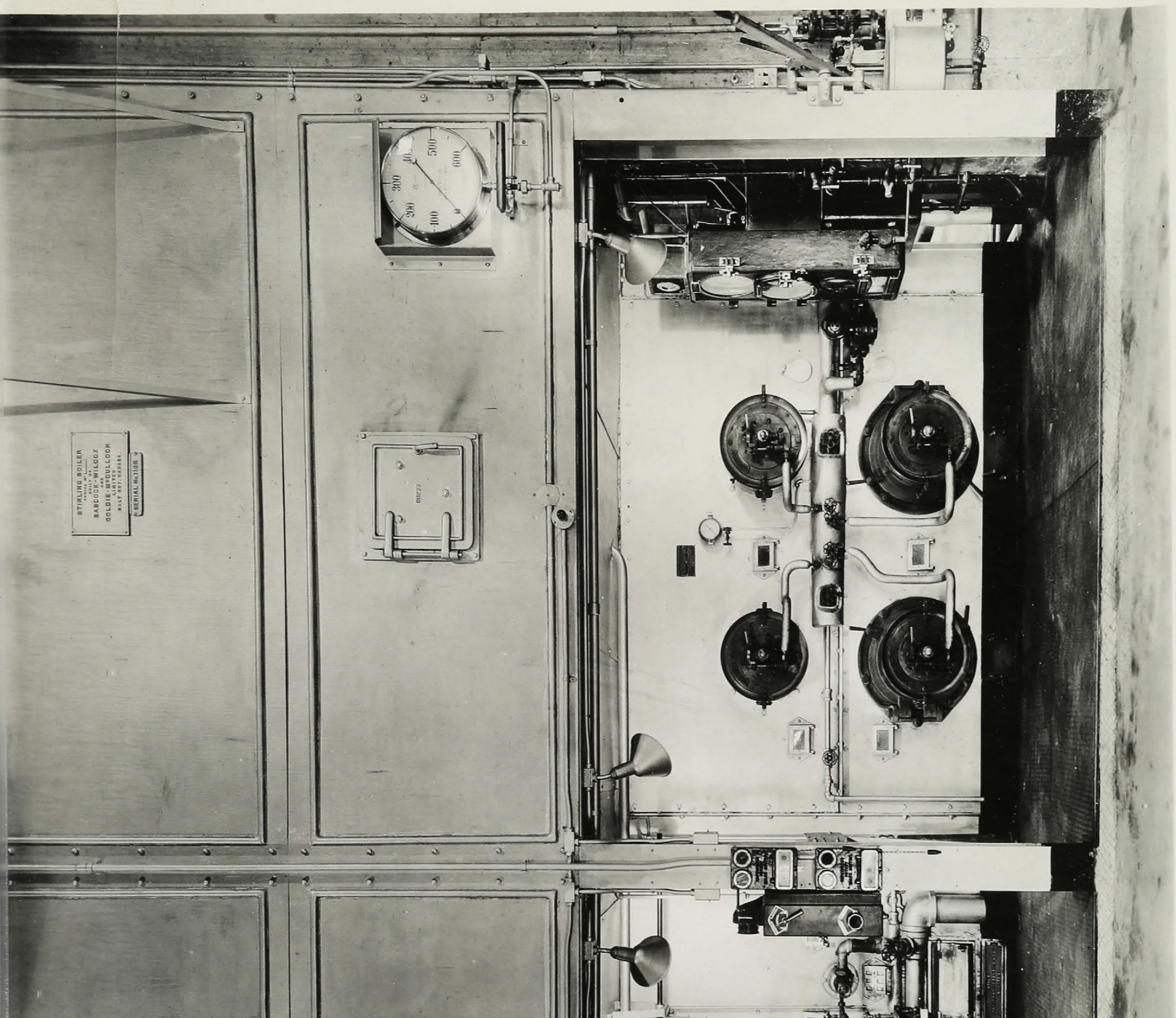


FIG. 1.

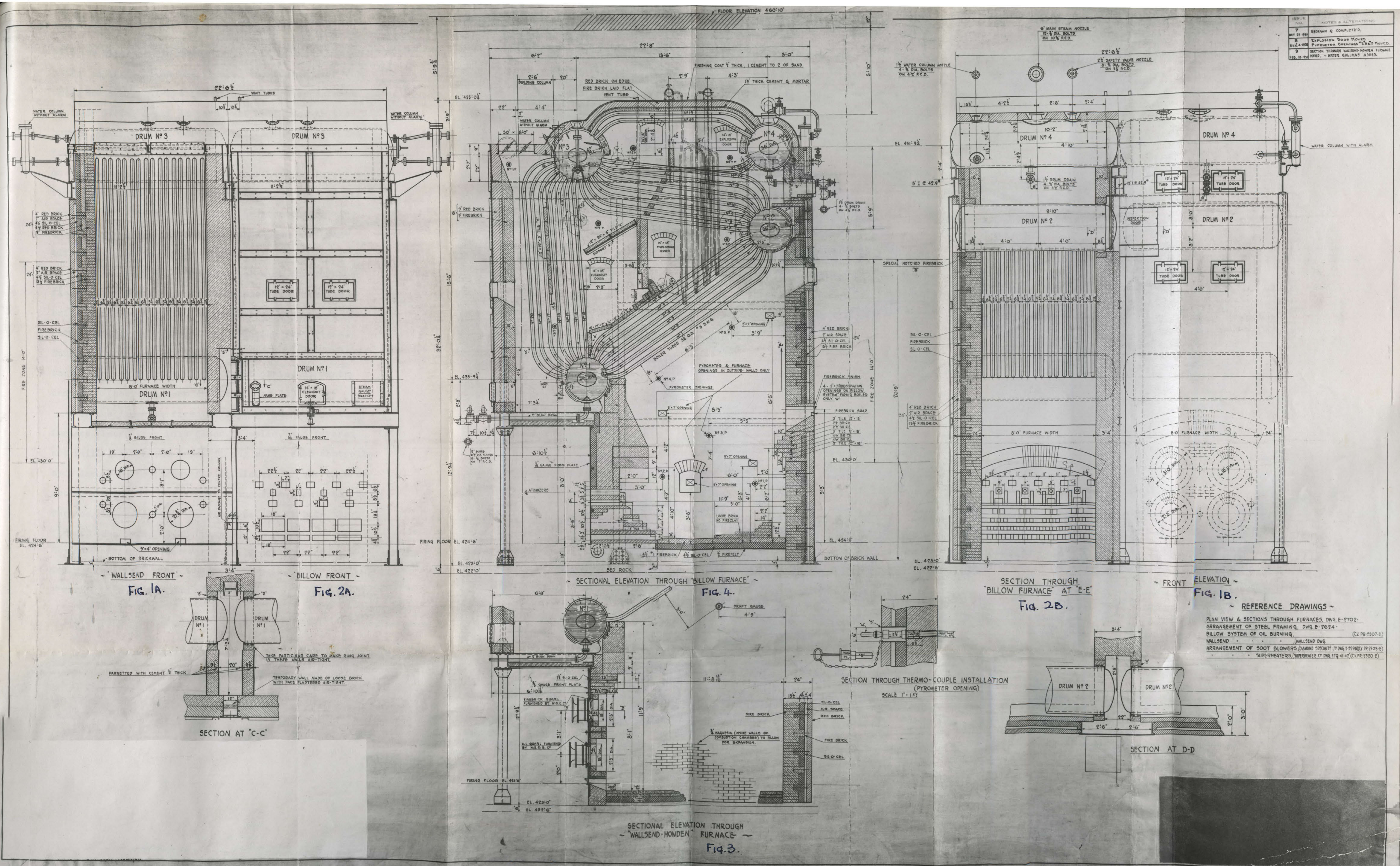
FIG. 2.

oil is fed to the nozzle at pressures between 75 and 150 lbs. per square inch, and the restricted area in the nozzle results in a finely atomized conical spray of oil. The spinning-cup type operates by having the fuel oil fed into the bottom of a cup. This cup is rotated at 1800 r.p.m. or more, by means of an electrical motor so causing the oil to run along the cup sides and be swirled into the furnace in a fine spray of expanding cone shape. The oil pressures used are somewhat lower than with the other two types, being ~~around~~ about 30 lbs. per square inch. In all cases, the combustion air enters around the ejector gun, and penetrates the conical atomized spray, circumferentially.

These burners are usually set symmetrically in the firing wall, and once the furnace is hot, continuous ignition is obtained from the radiant heat of the brick-work. Furnace ignition arches play no special part in the operation of these burners, though it is quite usual to find such arches in the furnace, and referred to as "ignition" arches. (See Sf and Sc in Figs.1b and 2b) (page 9)

2. <u>Flat flame types.</u> (See Figs. 2-2A and 4)(pages 7 and 9)

In the second type of oil burner, atomization of the oil is performed by mixing either air or steam with the oil stream, in a small chamber at the nose of the gun, near the point of entrance of the oil to the furnace. The nose of the oil gun is of special shape designed to project a flat flame, into the furnace, either parallel

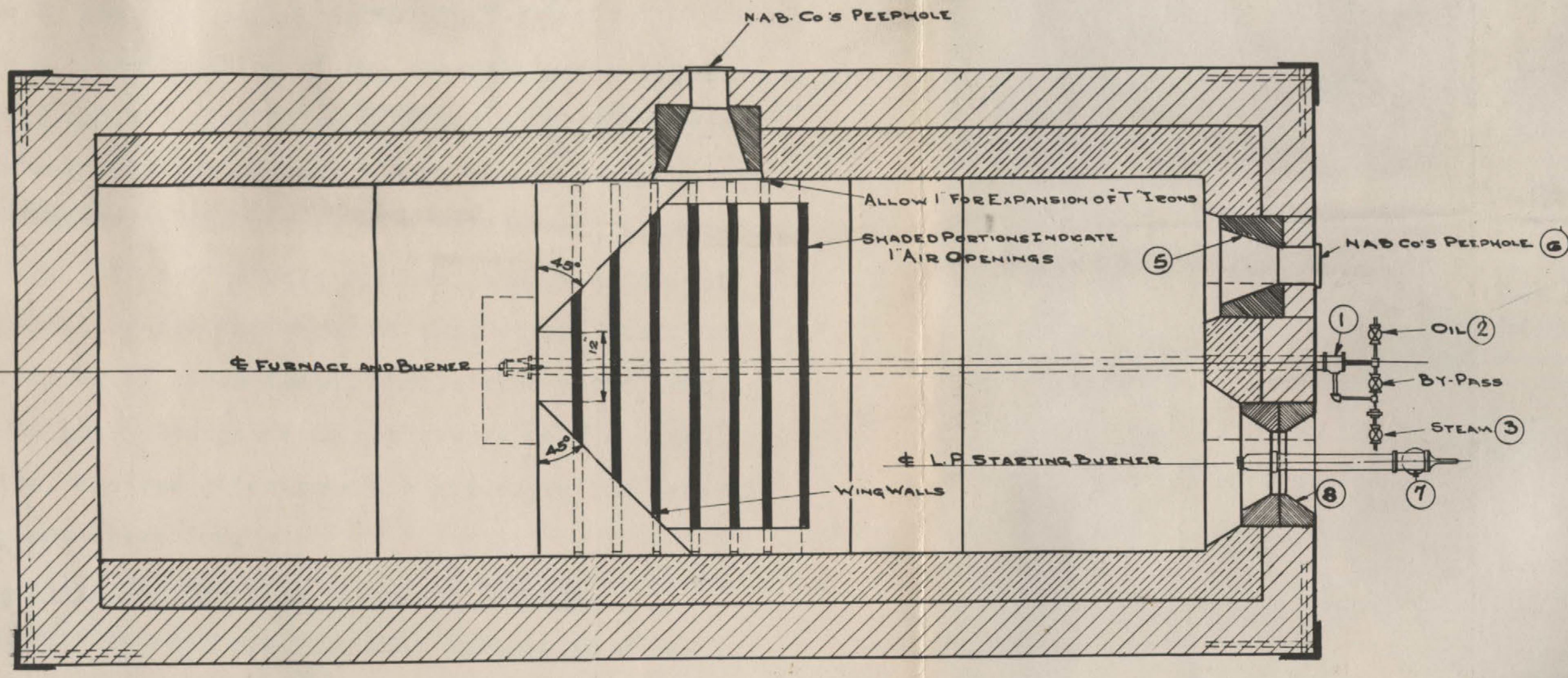

ISSUE NO.
NOTES & ALTERATIONS
7 OCT. 24·1930 REDRAWN & COMPLETE'D.
8 DEC. 4·1930 EXPLOSION DOOR MOVED PYROMETER OPENINGS "7, 8 & 9 MOVED.
9 FEB. 10·1931 SECTION THROUGH WALLSEND-HOWDEN FURNACE ADDED. ~ WATER COLUMNS ADDED.
FLOOR ELEVATION 460'·10"
DRUM Nº 3
DRUM Nº 1
DRUM Nº 4
DRUM Nº 2
~ "WALLSEND" FRONT ~
FIG. 1A.
~ "BILLOW" FRONT ~
FIG. 2A.
~ SECTIONAL ELEVATION THROUGH "BILLOW FURNACE" ~
FIG. 4.
SECTION THROUGH "BILLOW FURNACE" AT "E-E"
FIG. 2B.
~ FRONT ELEVATION ~
FIG. 1B.
SECTION AT "C-C"
SECTIONAL ELEVATION THROUGH ~ "WALLSEND-HOWDEN" FURNACE ~
FIG. 3.
SECTION THROUGH THERMO-COUPLE INSTALLATION (PYROMETER OPENING)
SCALE 1" = 1 FT
SECTION AT D-D
~ REFERENCE DRAWINGS ~
PLAN VIEW & SECTIONS THROUGH FURNACES, DWG. E-2702-
ARRANGEMENT OF STEEL FRAMING, DWG. E-2624-
BILLOW SYSTEM OF OIL BURNING, (C.V. PR-2507-E)
WALLSEND " " " " , (WALLSEND DWG.
ARRANGEMENT OF SOOT BLOWERS, (DIAMOND SPECIALTY LTD DWG. 3-2998)(C.V. PR-2503-E)
" " " SUPERHEATERS, (SUPERHEATER Cº DWG. STQ-41142)(C.V. PR-2520-E)

with the floor, or to cause downward inclination and slight impingement on the floor. Combustion air for these burners is always fed into the furnace through separate firing front dampers, set well beneath the burner level, so that this air will enter the furnace proper, beneath the flame level, and be forced to impinge on the under side of the flame, then passing into the flame, and mixing with it due to the draw towards the stack. It is to be noted that the atomization air quantity is small, compared to combustion air quantities, perhaps twenty per cent.

If the flame is fired parallel with the furnace floor, the furnace floor will consist of checkered brickwork through which the combustion air enters the furnace proper to rise and mix into the flat flame. Beneath the checkered floor is a second solid refractory floor which leads to the front plate, air entry dampers. (See Fig. 6-6b and 6c) (page 11)

If the flame is fired to impinge lightly on the furnace floor, then this floor is solid, and tuyeres are built through the front firing wall, each controlled by a damper on the front firing plate. These tuyeres are so placed that the air emitting from them into the furnace, impinges upon the flame before it hits the floor. (See Figs. 2A-2B (page 9)

Oil pressures used for these types of burners are usually less than forty pounds per square inch, and the pressure of the atomizing medium (steam or air) from 48

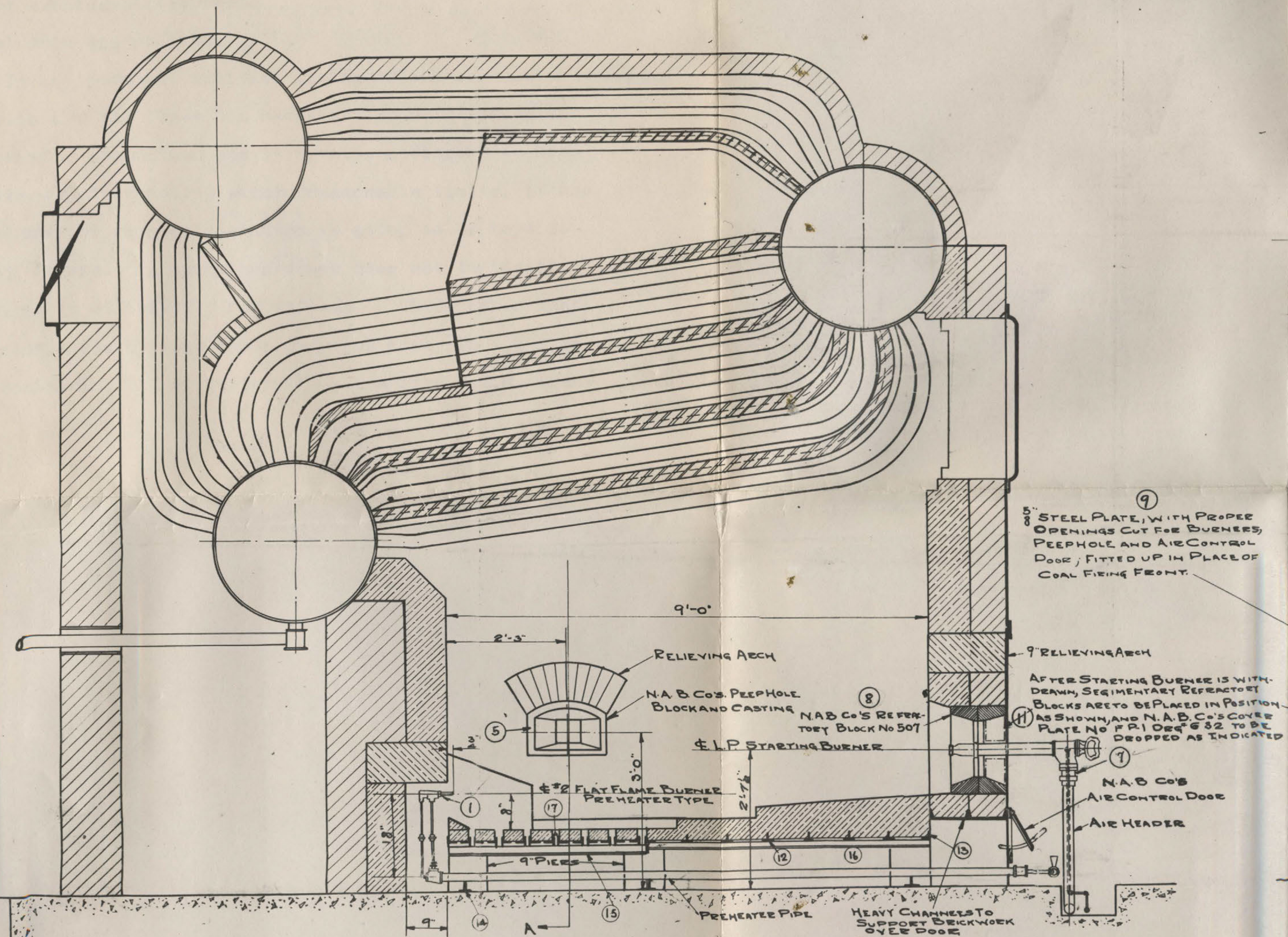


Plan Section.

Fig. 6A.

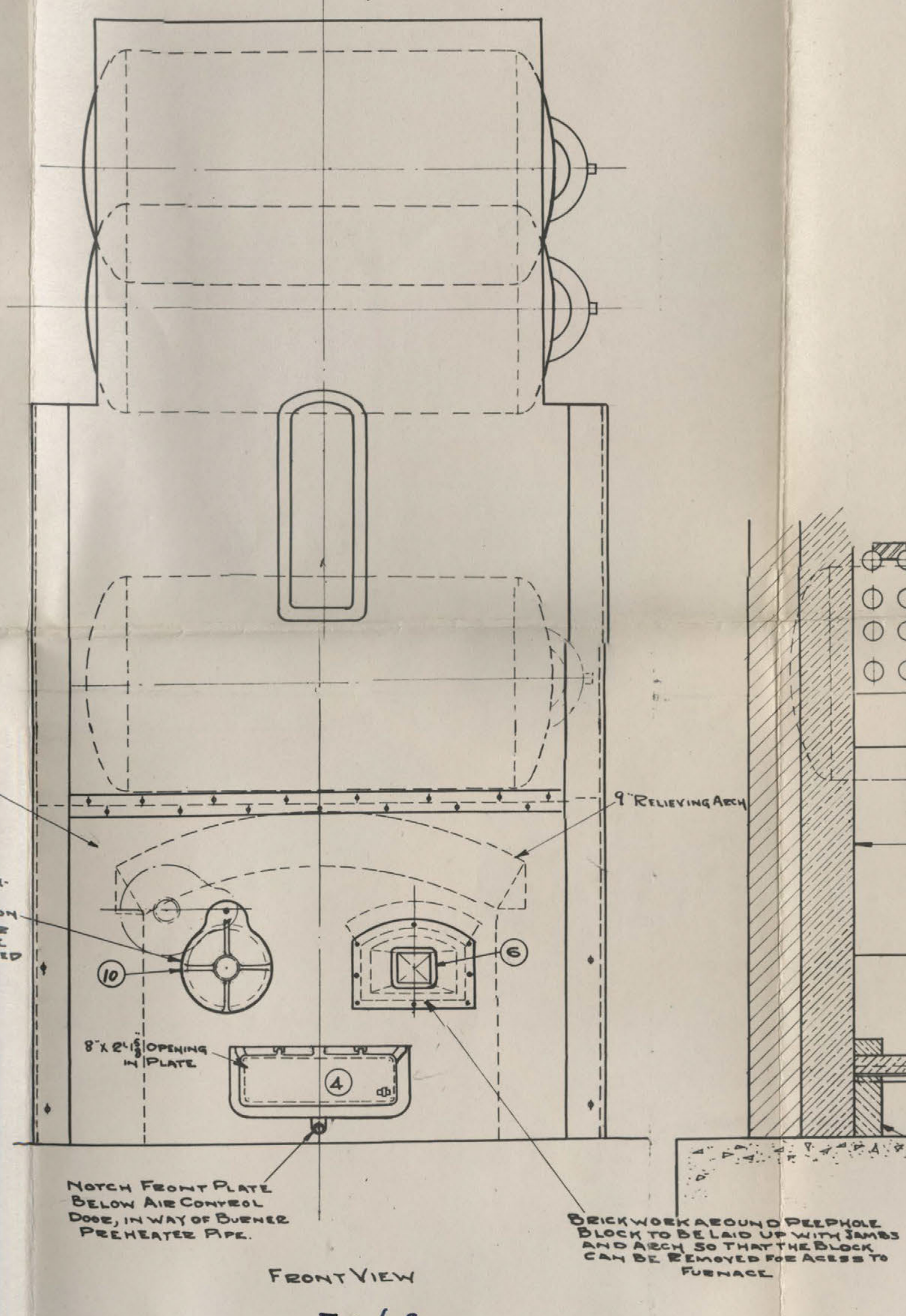
No	Amt	Description	Remarks
1	1	No 2 Flat Flame Burner	Preheater Type
2	1	1/2" Oil Firing Valve	
3	1	1/2" Steam Indicating Y.	
4	1	Air Control Door & Frame	Dwg No B-502
5	2	Peephole Blocks	Dwg No B-574 & B-465
6	2	Peephole Castings	Dwg No B-574 & B-465
7	1	Low Pressure Burner	
8	2	Refractory Blocks	Dwg No SK-507
9	1	Steel Boiler Front	(By Boiler Maker)
10	1	Cover Plate	Dwg No SK 632
11	1 Set	Segimentary Refractory	By Brick Setter
12	7	2" T Iron 4'-10" Long	By Owner
13	1	2" L Iron 4'-10 Long	By Owner
14	3	2" T Iron 2'-9" Long	By Owner
15	2	3" T Iron 3'-9" Long	By Owner
16	2	3" T Iron 5'5" Long	By Owner
17	7 Sets	2" T Iron 4'-10" Long (Bolted & Spaced)	By Owner (See SK #421)

Bill of Material
For One Boiler



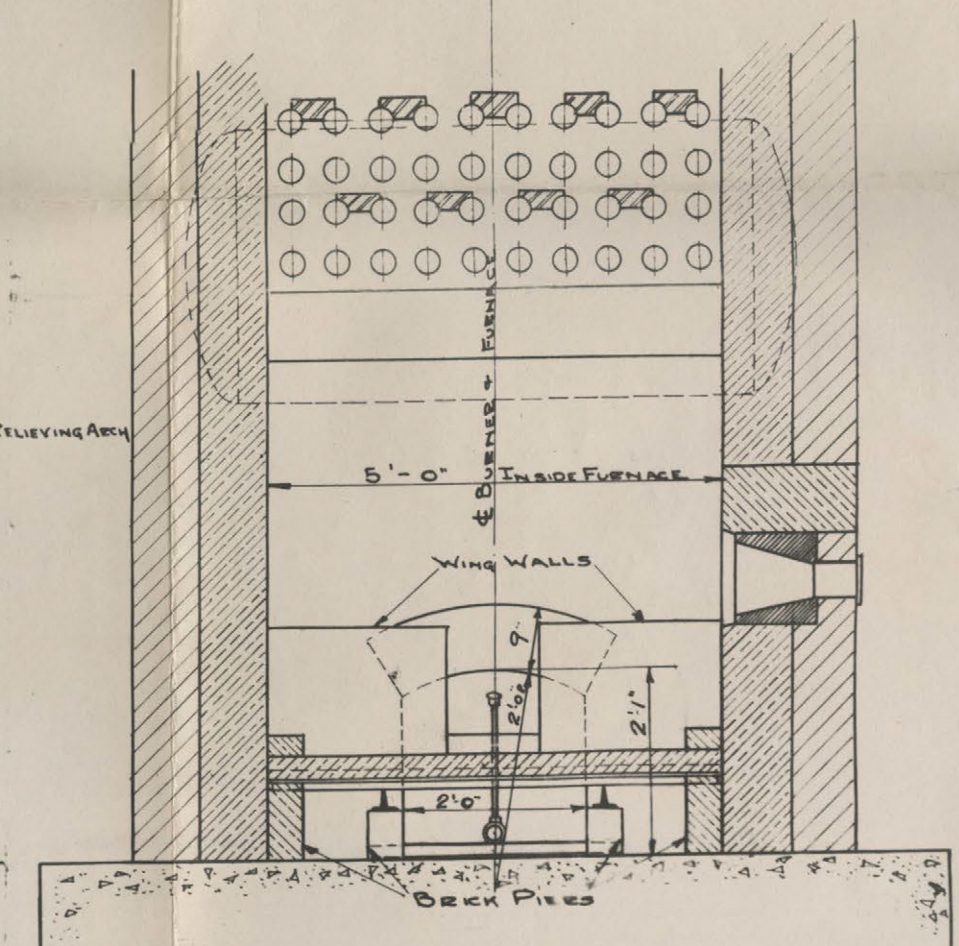
Sectional Elevation

Fig. 6.



Front View

Fig. 6C.



Section A-A

Fig. 6B.

ounces to 20 lbs. per square inch.

Such a classification of two general burner types, namely, the conical flame type, and the flat flame type, gives the only distinction which must of necessity be noticed when examining the design of a refractory furnace for oil burning. It may be said further, though it is not strictly a matter for the paper at this stage, that the characteristics of steam demand should also enter into furnace design. Designers do not always take a wide enough view, and ~~the~~ defect~~ions~~ are hidden in the general cost of plant operation.

(b) Operating Characteristics in the Furnace.

It should be realized that heat release in a refractory lined furnace, of sufficient intensity to generate steam in a water tube boiler, will eventually result in the necessity of repairs to that furnace. It matters not how well designed the furnace may be, repair eventually becomes necessary. Many designers forget this simple fact.

In any furnace, intimate mixing of the combustion air with the oil flame, is necessary to maintain clean (smokeless) combustion and it is also necessary to keep the excess air quantity within reasonable limits, if the efficiency of furnace operation is going to be kept at a good figure. A smokeless stack does not in itself indicate an efficiently run furnace. This factor must be accompanied by reasonable flue gas analysis - a flue due to superfluous excess air heating is quite as costly as any other method of operation, and should not be countenanced as a cure for other furnace operating difficulties.

Consideration will now be given to the travel and disposition in the furnace, of the flame of the conical flame type burner, taking two conditions of firing - the best condition and the worst condition - both being held at constant furnace efficiency. By this is meant that when under conditions which make it easy to maintain high furnace efficiency, and under other conditions which make it difficult to do this, the furnace efficiency be maintained high in the two cases (CO_2 at $13\frac{1}{2}$ per cent in each case) the probable effect of the flame shape upon the furnace should be discussed.

By reference to page 9 (Fig. 1B and 3) a typical design of an installation for this burner type can be seen. Obviously, this furnace when full of flame, presents the easiest problem for intimate air and flame mixture. Also, such a furnace condition - full of flame - presents the least difficulty in passing all the air through the flame, and controlling the furnace so that no air escapes the flame without mixing (stratification). When these conditions exist, clean firing (no smoke) and high furnace efficiency (low excess air) are easiest to maintain - and such conditions can be met by the requirements of a boiler under high steam demand.

Examination of this design clearly shows that with the conditions as stated, it is only necessary to project a long narrow dense cone of flame into the furnace, and to trap air for combustion behind the flame, this flame need only expand to tip the side walls near the rear wall in order to seal off the passage to the stack. Note that when the flame approaches the rear wall, much of its velocity and force of projection is spent. Air must be trapped across the furnace width in all cases to prevent stratification, but in this particular case, complete furnace volume may be used to accomplish this, because the flame volume is necessarily big to meet high steam demand.

Now an examination of the other case - the worst condition under which it may be necessary to fire the furnace. This is the condition of minimum steam demand, and in contrast to the last case, results in a small flame in the furnace. It must be remembered that flame size has no relation to either a clean fire, or good furnace efficiency. Under all conditions, these require intimate and turbulent flame and air mixture, and low excess air.

It becomes apparent at once that maintaining low excess air is a difficult problem with the small flame in the big furnace, and since the furnace must be designed to accommodate maximum steam ratings, much excessive furnace volume exists at low ratings, and hence high furnace efficiency (low excess air) is not so easy to maintain. However, it can be done, and is done in most cases, but the doing of it has a devastating effect upon the furnace.

To obtain high furnace efficiency ($13\frac{1}{2}\% CO_2$ in flue gases) with a small flame, a shallow, wide cone of flame must be developed close to the front firing wall, in an endeavour to so seal the width of the furnace with flame that no excess air may slip along the side walls. Any such air leakage contributes to high fuel loss in superfluous air heating (indicated by low CO_2) The result of such flame flattening operation - and it is unavoidable with this type of burner - is that the complete chemical reaction of combustion must take place very close to the front wall where the speed of flame travel remains high, and where impingement of the flame on the side walls and floor is likely to take place with definite force.

It must be realized in the above description, that between minimum and maximum steam demand, there exists all the intermediate ratings, and taking the case of the perfect operator giving adequate attention - that is to say robot automatic furnace control, it is impossible to avoid varying degrees of concentration of heat release. The designer must face this fact. He should agree that the operators have no control over this factor, even when operating at maximum furnace efficiency. This factor is solely dependent upon the variability of steam demand, and the disposition of the particular flame shape in the furnace. To these two features, rate of change of steam demand, and to flame shape is linked furnace maintenance.

Considering now the flat flame type of burner under the maximum and minimum conditions of steam demand. Examine Figs. 2A-2B and 4 (page 9). Note that each burner has its own set of individual air tuyeres below it, operated individually. These burners project flat flames downwards at an angle towards the floor. These flames, entirely covering the tuyere openings of each burner, seal off these combustion air entrances, and this air is forced to penetrate and mix with the flames to be able to enter into the furnace proper at all.

At the condition of maximum steam demand, the furnace is full of flame. The disposition of this flame is as follows. It impinges on the furnace floor at the end of the lower row of tuyeres, sealing the tuyere openings and sealing the furnace width from side to side. It travels along the furnace floor, in contact with the floor and the side walls adjacent to the floor, and as the flame moves towards the furnace back wall, it loses velocity due to floor friction and the distance of travel. This floor friction also causes rolling and turbulence. The flame eventually reaches the floor hump which deflects it up the back wall and reduces impingement on the back wall. The flame runs up the back wall, tipping it lightly because the flame velocity is considerably spent, until the back wall hump is reached. This deflects the spent flame back into the furnace at a point beneath the tubes of the first pass, so giving the final turbulent roll to the gases which utilize any residual unconsumed oxygen.

It is seen, therefore, that tuyere tips, the floor surface, the side walls close to the floor, the deflection humps, and the back wall, have to stand flame contact, but this contact is a rapidly decreasing force after the first impingement on the floor at the bottom of the tuyeres. Note the effect of the design to produce turbulence, and note how difficult it becomes to have air stratification without passing through flame. High furnace efficiency is easy to maintain with this furnace and flame shape.

Such a furnace should be designed so that at minimum steam demand, the flame covers the tuyeres to the first point of floor impingement since little travel along the floor should result at the minimum rating.

It is obvious too, that at the lower steam ratings, it is just as easy to maintain high furnace efficiency as at high ratings, and that furnace flame impingement varies directly as the steam demand, whereas in the conical flame type, it varies inversely as the steam demand.

On page 11 are shown drawings of a flat flame type of furnace for flame projection parallel with the floor. It is noteworthy that with this type of equipment, while it is possible to operate it efficiently at high load, it gives great trouble to maintain high furnace efficiency at low load. Reduced flame size results in vertical unconsumed air stratification almost impossible to eliminate, and the writer does not see the necessity of using such burners nowadays since other types are now designed taking care of every good factor, without the inherent disadvantages.

The foregoing description covers, in a general manner, the behaviour of the flames projected into the furnace by each of the burner types classified. These characteristics in each case will be shown later to be quite definite in operation, and no furnace should be designed without knowledge of the various points of wear, associated with each type of burner.

III. STANDARD BRICKWORK FURNACE DESIGNS AND AREAS SUBJECTED TO SEVERE SERVICE.

In Fig. 3 (page 9) is shown a design for the brickwork of a steam generator to meet a fluctuating steam demand varying between 8000 lbs. and 40000 lbs. of steam per hour. This design is typical for the conical flame type oil burner unit. Four burners are required to serve this furnace.

In Fig. 4 (page 9) is shown a design used to meet the same steaming characteristics, but suitable for the flat flame type of oil burner unit. This is also a four burner furnace.

In each case the fuel oil used for firing would be Bunker C heavy fuel oil, Beaume gravity 10° - 14°, (1.000-.972 spec. Grav.) An average analysis of this oil would be C-84% H_2 - 12.70%, O_2 1.20%, N_2 1.70% and S-0.40%. The calorific value of this oil would be from 18500 to 19000 B.T.U.s per pound of fuel oil. In Fig.7 (page 20) a graph is shown indicating the furnace efficiency to be aimed at, expressed as per cent CO_2 in resultant flue gases, with correlated excess air quantity. The theoretical air quantity for this oil would be approximately 14 lbs. of air per lb. of oil, and the safe minimum catalytic excess air used, would be 14 per cent, indicating that a flue gas containing 13½ per cent CO_2 should be maintained in the operation of this furnace. It will be observed later why the furnace efficiency should

FUEL OIL ANALYSIS $C - 84.00$ $H_2 - 12.70$ $O_2 - 1.20$ $N_2 - 1.70$ $S - 0.40\%$

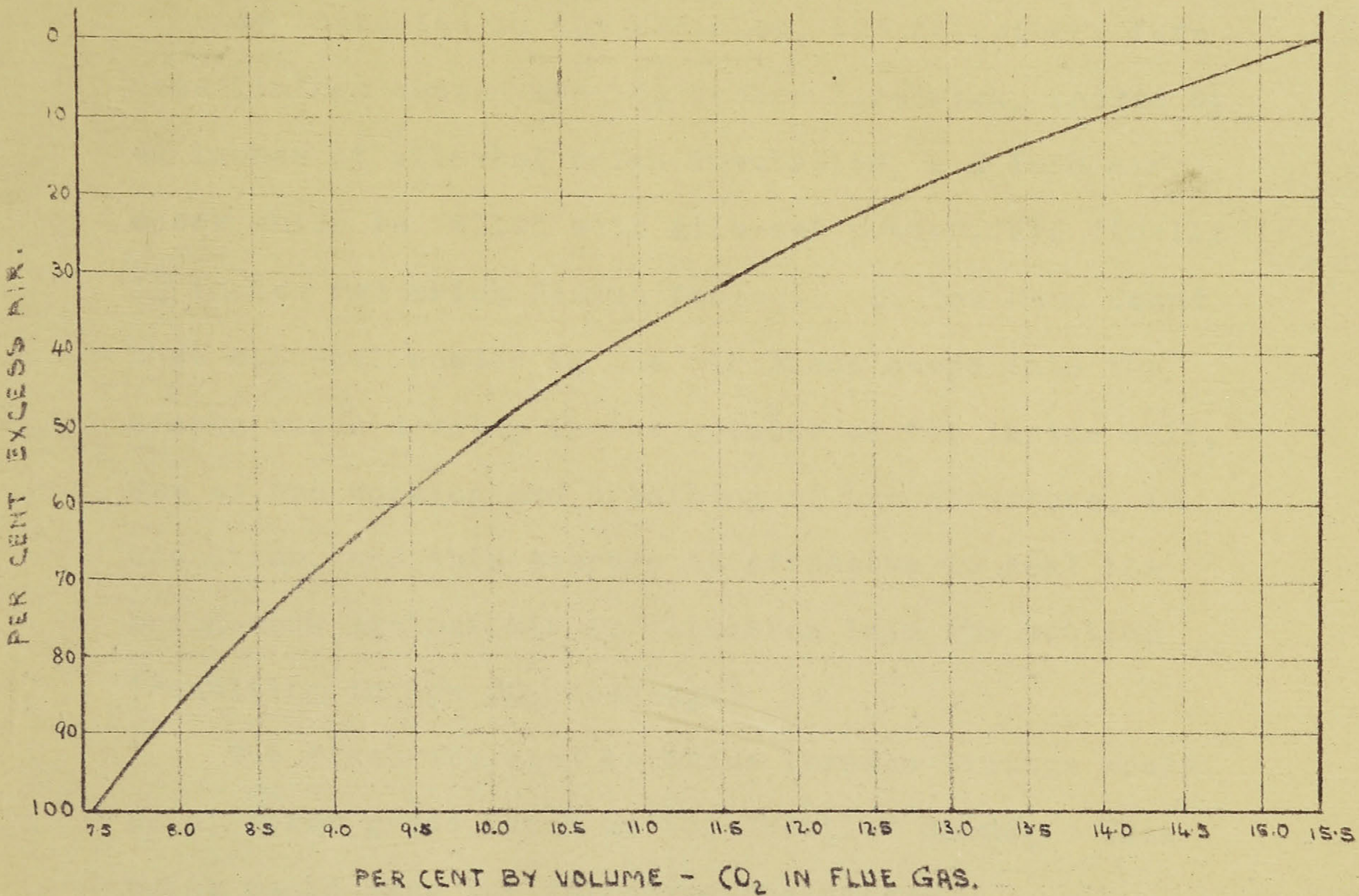


FIG. 7.

PER CENT CO_2	FLAME TEMP. °F.
19	4710
18	4465
17	4230
16	4000
15	3777
14	3543 +
13	3300 +
12	3080
11	2840
10	2600
9	2375
8	2135
7	1837
6	1660
5	1420
4	1165

FIG. 8

be limited to that represented by $13\frac{1}{2}$ per cent CO_2.

As indicated in the sketches, the refractory furnace linings chosen are $13\frac{1}{2}$ inches firebrick, backed by $4\frac{1}{2}$ inches of silo-cel brick insulation, a 2 inch air space which is filled with silo-cel powder, and finally $3\frac{3}{4}$ inches red brick finish facing. It has been found that silo-cel powder in the air space seeps into the cracks which develop in the outside of the inside wall, due to the working and breathing of the structure, in operation, and this seepage is effective to seal the brick-work against air infiltration into the setting (resulting in low CO_2 readings)

The firebrick used in these furnace linings would be of first grade, such as the "Nettle" brand. This brick would have the following analysis:-

Silica 51.30%. Alumina 43.69% Ferric Oxide 2.61%
Magnesia o.58% Lime 0.41% Titanic Oxide 1.50%
Traces of Potash and Soda
Refractory Test 3200 - 2930°F. (Cone 34-35-1760°C)
under a load of 50 lbs. per square inch.

The brick-work used would be bonded with an air setting cement. Due to the height of the side walls, approximately 30 feet, the loading on the brick would be about 30 lbs. per square inch, and it is found in practice that the initial heating up after erection requires less care, if an air-set bond is used in preference to a heat-set, during the construction of high units, because an air-set bond develops some strength during construction at room temperature.

Finally, regarding details of furnace brick-work mention of the position of the furnace "ignition" arches is made, to draw readers attention to those arches, marked Sc and Sf. A great deal of nonsense is written about ignition arches, and their value in the furnace to concentrate radiant heat at the focal point of initial combustion. It is rather expensive to build such arches, and they are potential sources of trouble. Having drawn attention to them because they are standard design practice, the matter will be left for the moment until data relative to their real operational value, and derived from special furnace tests, will be given later.

It is now necessary to deal with the subject of heat release in the furnace. Refractory lined furnaces, such as have been described, are usually subjected to a release of heat from oil fuel of 20000 B.T.U. per hour continuous operation, and 40000 B.T.U. per hour at peaks rated per cubic feet of furnace volume. The influence of this heat release upon the temperature of the face of the brick-work is of supreme importance, and any constraint in the proper use of the total furnace volume can raise very rapidly the temperature to which the refractory is subjected. Vitrification of the brick-work will begin to take place under such conditions of constraint.

The furnaces shown in the diagrams have volumes of 1440 cubic feet. At a generating peak rate of 40000 lbs. of steam per hour, the oil used would be approximately 2850 lbs. per hour, and taking this oil at

18500 B.T.U's per lb., the total heat release would be

$$2850 \times 18500 = 53,000,000 \text{ B.T.U's per hr.}$$

$$\text{or} = \frac{53,000.000}{1440} = 36,800 \text{ B.T.U/cu.ft/hr.}$$

At normal continuous steam ratings of 25000 lbs.of steam per hour,

$$\text{Heat release} = \frac{36800 \times 25}{40} = 23000 \text{ B.T.U/cub.ft/hr.}$$

It would be foolhardy to continue such peak operation for longer than an hour. This is fairly common knowledge, but peak operation is not the only condition which will result in this high heat release. Depending on the burner type, low steam ratings may create an identical condition, and no operator carelessness will be in any way to blame. This fact is oftener than not overlooked by designers.

Apart from heat release, another furnace condition will seriously vitrify the furnace walls. This condition is flame temperature. Wall surface temperature, though not equal to flame temperature can be computed as a function of it. Flame temperature is a function of the CO_2 content in the combustion gases. The table of Fig. 8 (page 20) shows this relationship and only such a furnace efficiency should be carried that will not cause serious wall vitrification. Herein lies a physical limitation militating against the perfectly efficient operation of a refractory furnace. There is no method by which this fact may be overcome in a plain refractory furnace, and therefore, to run an efficient furnace, it is necessary to accept some damage to refractory as part of the operation.

At this point, it is opportune to devote a few lines to the subject of vitrification, although more will be said about it later. Much has still to be found out regarding it, but some of what is known is of great importance in the oil fired furnace. Vitrification has good factors and bad factors, depending on the time to which the brick is subjected to a vitrifying temperature. If subjected too long to vitrification, the factors become all bad.

A little glazing of the surface of a refractory is advantageous, particularly if the glass can be run over the brick joints. But in carrying out such a surface glazing, the time factor in the subjection of the surface to high temperature must not be too long. Most firebricks will begin to glaze over 2400°F.

It is often noted that furnace walls which have been subjected to long high temperature, show tearing away at the brick joints due to contraction. This may be basically a feature of poor brick manufacture, and sometimes it only shows up in the boiler furnace, when temperature has been run too high for too long. This is a case of faulty original materials of construction being discovered by an occasional period of faulty operation.

A calculation will now be made of the heat loss through a furnace wall of the design just stated. This theoretical calculation may be in error some ten per cent, due to the neglecting of the mortar joints when figuring the composition of the wall. Also it must be remembered that the bricked-in steel structure of the boiler mitigates against the operation of the insulation. However, a comparison of these walls, and another to be described later, so far as theoretical heat transmission is concerned, is quite sound, when all are judged on the same theoretical basis. (See fig.5 page 26)

Firebrick---$13\frac{1}{2}$"--k- 0.74
Silocel Brick - $4\frac{1}{2}$"--k- 0.08
(burned diatomite)
Air space --- 2" --- k- 0.05
(packed with powdered diatomite)
Red brick --- $3\frac{3}{4}$"--k- 0.5
(finish facing)

Conductivity = k B.T.U/hour/sq.ft/Deg.^{o}F/Ft.
Face area = A sq. feet
transmitting heat
Thickness = L feet
Temp.difference = t
Heat flow = q B.T.U/hour/sq.ft.

The mathematical reasoning of the following is obvious, when it is remembered that once the wall is heated up to temperature, the heat flow through the complete wall thickness, is the same as through any of its component parts.

$$q = \frac{k_{av.} \times A_{av.} \times t}{L} \qquad \text{Let } R = \frac{L}{k_{av} \times A_{av}}$$

$$\text{then } q = \frac{t}{R}$$

which expanded to any part of the composite wall makes

$$q = \frac{t_0 - t_1}{R_a} = \frac{t_1 - t_2}{R_b} = \frac{t_2 - t_3}{R_c} = \frac{t_3 - t_4}{R_d}$$

$$\text{or } q = \frac{t_0 - t_4}{R_a + R_b + R_c - R_d} \; (?)$$

$R = \dfrac{L}{R \times A}$ in any particular case

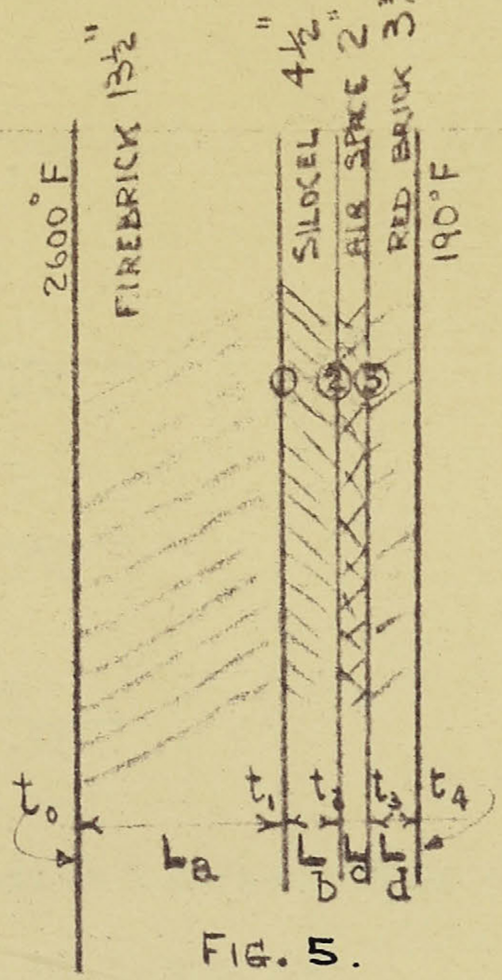
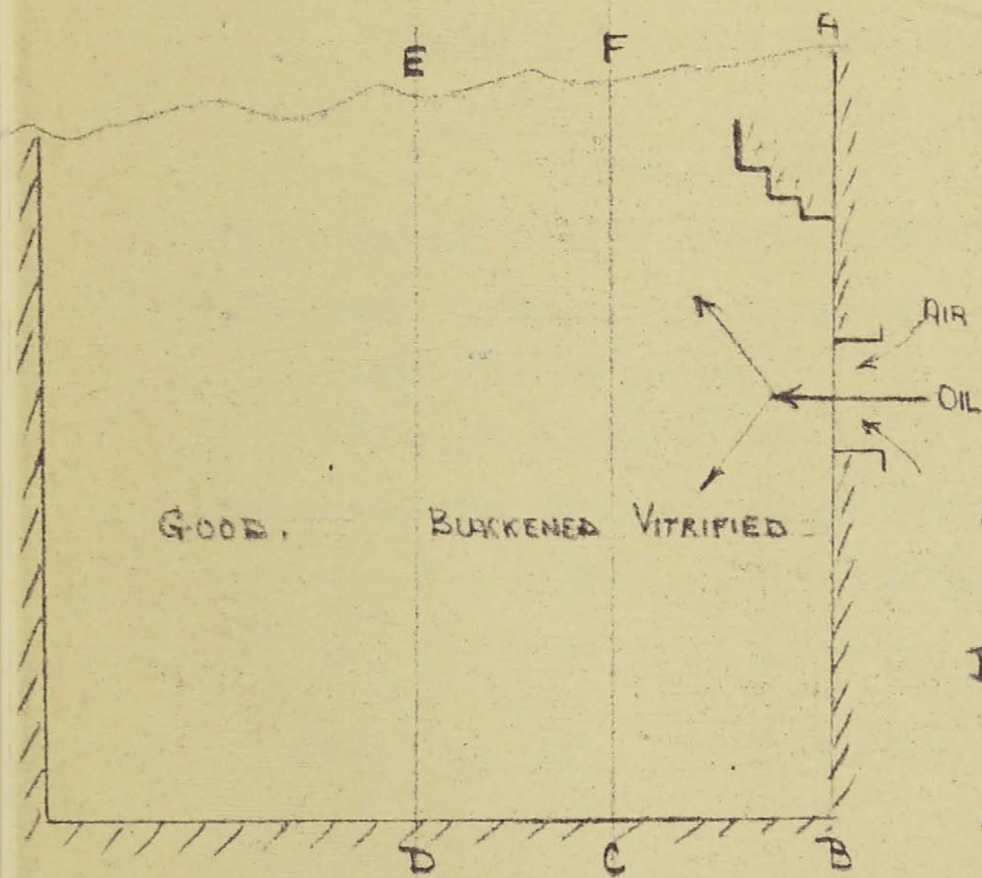
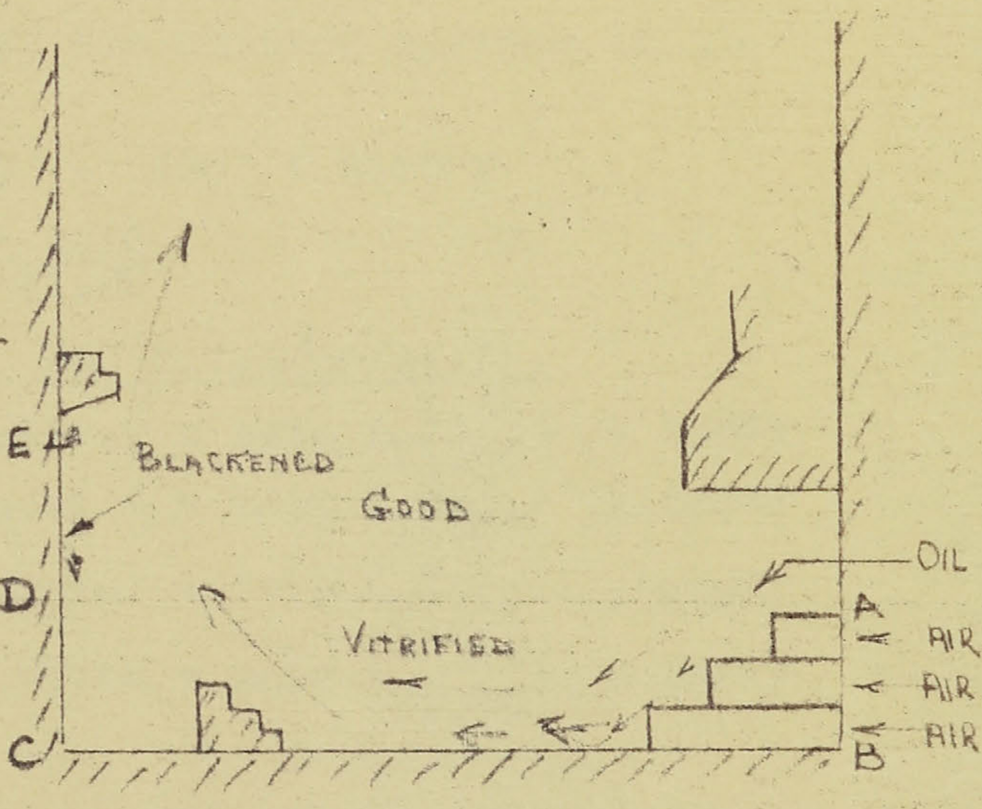


FIG. 5.



SCHEMATIC SECTION - CONICAL FLAME
SHOWING WEAR AREAS.

FIG. 3A.



SCHEMATIC SECTION — FLAT FLAME
SHOWING WEAR AREAS

FIG. 3B.

$$R_{\text{Firebrick}} = \frac{13.5}{12 \times .74} = 1.52$$

$$R_{\text{Silocel}} = \frac{4.5}{12 \times .08} = 4.7$$

$$R_{\text{Air Space}} = \frac{2.5}{12 \times .05} = 4.2$$

$$R_{\text{Red Brick}} = \frac{3.75}{12 \times .50} = 0.63$$

R_t = total resistance to heat flow = 11.05

let such reasonable figures be taken as

2600°F for furnace wall temperature, and

190°F for the temp. of the outside surface of the red brick

Then Total temp. drop = 2600 - 190 = 2410°F

$\therefore$ Heat transmission q into boiler room through furnace walls $= \frac{2410}{11.05}$ = 200 B.T.U/hr/sq.ft.

Temperature drop through firebrick $= 2410 \left(\frac{1.53}{11.05}\right) = 330°F$

" " " Silocel $= 2410 \left(\frac{4.7}{11.05}\right) = 1030°F$

" " " Airspace $= 2410 \left(\frac{4.2}{11.05}\right) = 920°F$

" " " Red Brick $= 2410 \left(\frac{.63}{11.05}\right) = 130°F$

Temperature at interface No. I = 2270°F

" " " No. 2 = 1240°F

" " " No. 3 = 320°F

To complete this section of the paper, there remains a description of the usual condition of the refractory in these furnaces, after having been continuously fired to meet the fluctuating steam load, previously mentioned, over a reasonable firing period (perhaps six months).

Fig. 3A (page 26) represents a schematic section through a furnace fired with a conical flame type burner. The firing wall AB and sidewalls for about a quarter of the furnace length, (area ABCF) will show the refractory very badly vitrified, and in an eroded, glassy and cracked condition. The bricks, at the edge of the bonding of the courses in area CDEF will be in bad spalled condition. The surface in this area will have a blackened appearance, and the whole area will be eroded, and softly crumpling, as compared to the glassy vitrification of the first mentioned area. The floor of the furnace will be vitrified towards the front half of the furnace. The sidewalls toward the rear, and the back wall, will be in fairly good shape, with that slight vitrification which is classed as good wall condition.

Repairs to the above furnace in area ABDE are quite difficult, because of the different heating up expansions of new and used brickwork. Also the cutting out of holes requires the removal of large areas, and between the necessary supporting of the upper wall above the repair spots, and the tying of the new brickwork into the back courses of brick, deeper in the wall section, some quite tricky workmanship is usually necessary to put a furnace in shape for another run. Such a normal repair will cost in the neighbourhood of five hundred dollars, if the furnace operation has been under automatic control, which reduces the human element to the limit.

In Fig. 3B (page 26) is shown a schematic section of a flat flame type furnace which will be compared as to operation under the same conditions as the other furnace.

In this case, the tuyeres and the floor deflection hump will show quite an amount of severe vitrification after a period of continuous firing. These are easy repairs since such brickwork is loose and unloaded. The floor from B to the deflection hump will show bad erosion, and will definitely lose thickness. This can be made up with any old scrap ground brick, mixed with silica sand and fused in place during each operation.

The area ABCD on each side wall will have a vitrified surface appearance, but will not be seriously damaged for at least four operating periods. Above level DA on the sidewalls will be in good shape. Area DE across the back wall, below the back wall hump, will show the same blackened crumply appearance mentioned with the other burner. A repair to this furnace after a six months operation, will be in the neighbourhood of one hundred and fifty dollars.

IV EXPERIMENTAL INVESTIGATIONS

With all the foregoing information in mind, it is evident that the three outstanding features requiring examination in furnace design are:-

(1) Reduction of first cost (capital cost) of furnace.

(2) Reduction of maintenance cost after operation.

(3) Elimination of the necessity for meticulous care during operation.

The experimental work which was thought might supply information leading towards these ends was divided into two classes:-

(a) Examination of Commercial Furnaces after operation under known firing conditions.

(b) Laboratory examination of standard fire-clay refractories, subjected to flame impingement

(a) Furnace Examination after firing under known Conditions

The plant used for these tests consisted of four boilers of maximum steaming rate, 40000 lbs. per hour each. Two of these furnaces were fired by four conical flame type burners each, and two by four flat flame type burners of downward inclination. The furnace walls were designed as shown in Figs. 3 and 4 (page 9).

Wall temperatures were taken with numerous thermo-couples set in the walls, in the chosen positions for the tests, while flame temperatures were taken with an optical pyrometer.

The testing work on these individual furnaces was carried out in such a manner that the furnace under test was given a boiler to fire, with the steam demand on it kept constant for the test period. Other boilers in the station carried the load fluctuations which the total steam service required, during the test periods.

Diagrams explaining these tests are shown on page 36 with reference to the furnaces of the conical flame type burners, while those on page 40 show the results of the tests on the furnaces equipped with the flat flame type burner. The readings shown against the diagrams are the averages of the readings taken at intervals varying from half an hour to two hours, over the period of time of the tests, and according to the judgement of the operators regarding changes in furnace conditions.

CO_2 in flue gases was indicated to the operators on a 24-hour recorder, and this recorder was checked twice per week by Orsat apparatus.

Test No. 1 (See Fig.9)

The steam load allocated to the boiler for this test was 8000 lbs. per hour. Two lower burners in the horizontal row (See Fig.1) were used for this steam demand, the two upper burner housings being plugged up to exclude air leakage as much as possible, and an endeavour was made to keep the CO_2 content in flue gases about 14 per cent. It is unlikely that under normal operation such a furnace condition would be carried at this low load, due to the fierceness of the heat between the resultant short flame and the front firing wall, but this particular operation was for a test case, and even under normal conditions whatever steps might be taken to alleviate the local over heating could only be done at the cost of fuel wastage, resulting from high excess air (low CO_2). The period of the test, now to be described, was two weeks.

Thermocouple positions on the inside wall surface were as indicated at P1, P2, P3, P4, P5 and P6 and the disposition of the flame in the furnace has been sketched. Note how wide this small flame must necessarily be made to seal off any such large furnace under low load, against air stratification. By air stratification, is meant the passage of combustion air to the stack, without this air mixing in the flame.

The flame cone in this test was therefore made wide but shallow, and gave impingement at point P2 on the side walls, and after three days being allowed to heat up the boiler thoroughly, a series of temperature readings at the hot refractory inside surfaces were taken over the following twelve days, at points P1, P2, P3, P4, P5 and P6. The constant steam demand of 8000 lbs. per hour was held 24 hours per day.

Fig. 9 indicates the average of the temperature readings at the various points. Examination of this furnace after it was cold showed that from point P3 towards F, vitrification had set in, and the refractory in the area around P2 and P1 was completely fused. Indications were that the refractory had been running down on the furnace bottom. During cooling, severe cracking had taken place in this vitrified area.

Of extreme importance was the fact that at points P2 and P3 no carbon deposition was evident, even though the impingement at P2 had pitted and cut the wall as well as melted it out.

The front wall surface F_1F and the furnace floor were badly vitrified, and the metal portions of the burner housing and the air director vanes built in the wall, were burned and wasted.

Test No. 2 (See Fig. 10)

In this test another boiler was taken and four burners used. The steam load to be carried was set at 13500 lbs. per hour, and the burners so arranged that the two lower burners projected flames which impinged on the side walls between points P3 and P4. The flames of the two top burners were softened somewhat to impinge midway between points P3 and P2. It should be noted that the thermocouple points were placed six inches above the centre line of the lower burners.

Because of the lower temperatures prevailing, a test of four weeks duration was undertaken with an average furnace condition represented by 13.7 per cent CO_2.

After the test was completed and the furnace was cooled for entry, it was found that from point P3 towards F, increasing vitrification was evident, but not so severe as in the previous test.

It was noticed, however, that there was a black sooty deposit between P4 and P3 in line with the upper burners, while in the line of the lower burners at the same distance, definite carbon deposition was evident. Several test bricks were carefully removed from the wall at this location and fractured for examination. Blackening of the texture close to the fired surface was evident, and there appeared to be a loss of bonding power in the brick.

It should be noted in this test that temperature is more uniform throughout the furnace, and a much better use is made of the furnace volume for combustion.

Test No. 3 (Fig.11)

The steam load on the boiler during this test was 25000 lbs. per hour. It was possible to hold the CO_2 at 13.5% by lengthening the flame such that impingement took place between points P4 and P5 on the sidewall and on the furnace back wall. It was expected that this impingement could be kept very soft on the sidewalls, because the flame cone in this test can be seen by reference to the diagram, to have been quite long, and the angle of contact small.

After examination, the furnace actually showed that no severe striking had taken place on the sidewalls.

After four weeks operation, it was evident that the heaviest impingement had been taking place on the back wall.

A sooty blackening of this wall was evident, while little except the edges of the brick at the joints appeared to have been affected on the side walls. Along the side walls, a light surface vitrification had taken place. It should become noticeable, as these tests are studied, that the longer the flame cone, the better the use made of the furnace volume, and the more uniform the wall temperatures throughout.

Test No. 4 (Fig. 12)

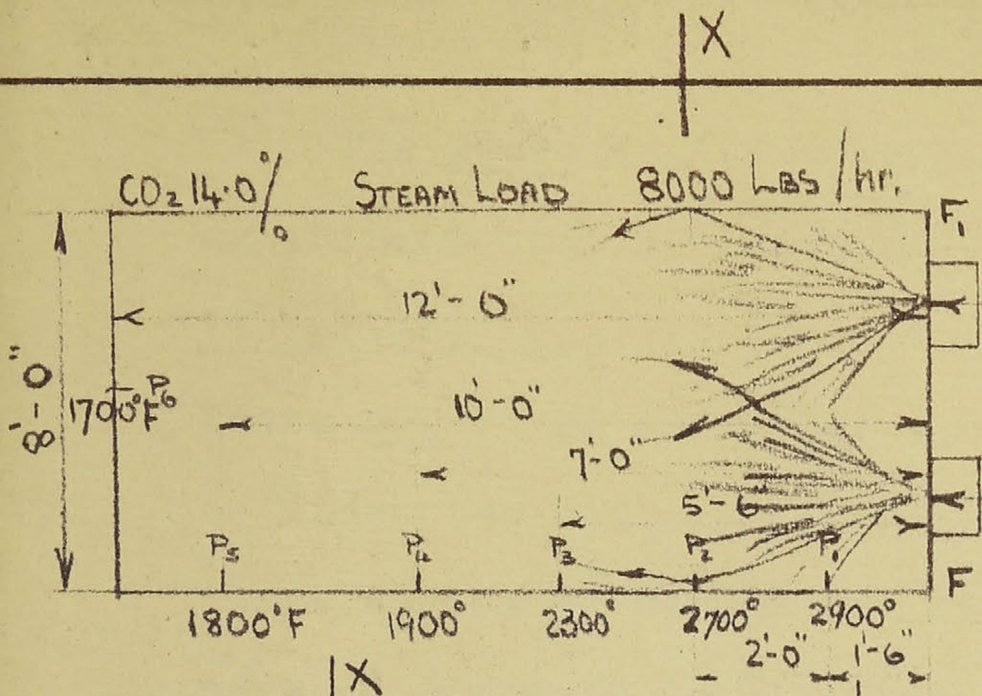
This test was run only for a period of 12 hours. The boiler used had a special series of marked new bricks set into the wall between points P4, P5 and P6. Over a period of two days, the furnace was brought up to temperature, and the steam load increased to 25000 lbs. per hr. as in the last test, with the burners set to give impingement as before. The CO_2 content of the flue gases was gradually lowered from 13½ per cent to 9½ per cent, while the steam load was increased over a period of 12 hours to 35000 lbs. per hour. The boiler was shut down after carrying this load for one hour and a half. It is necessary to explain that the CO_2 was lowered by permitting excess air, and this was done to deliberately lower the wall surface temperature.

It was found on entry, that carbon had piled up on the back wall, and was adhering there and to the side-walls. The test bricks on being cut out and fractured, indicated definite carbon penetration, and appeared to be moving towards disintegration.

Test No. 5 (Fig. 13)

This test was a repetition of test No. 2 (Fig. 10) except that the furnace walls after being laid up with new brick, were then coated with a chrome base cement. This cement was brushed on giving a coating from 1/16th to 1/8th of an inch thickness.

On examination of the furnace after four weeks operation, the surface blackening was still evident as in Test No. 2 but fractured bricks showed no penetration of the carbon.



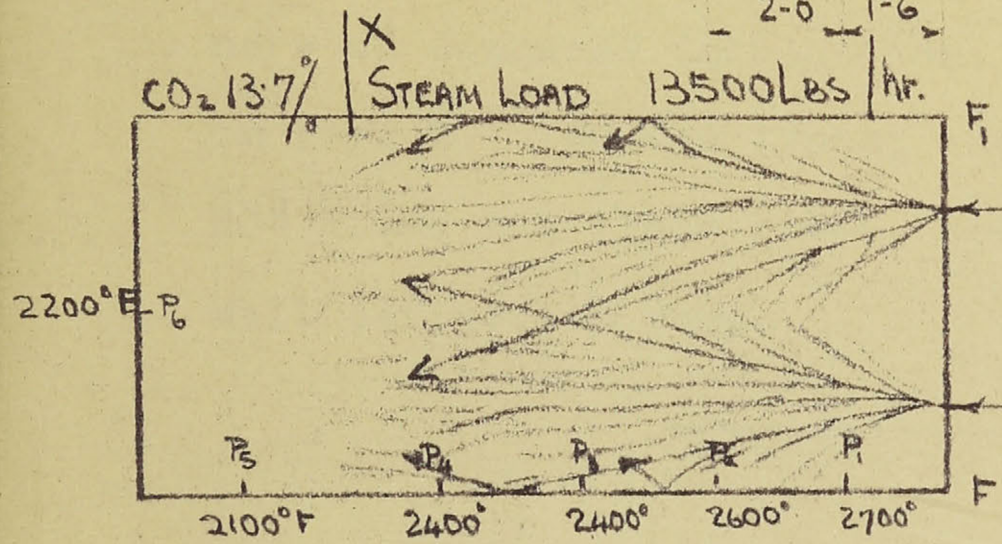
DURATION OF TESTS

TEST No. 1.

THREE WEEKS.

FIG. 9.

OPTICAL PYR.
ON FLAME 3500°F.

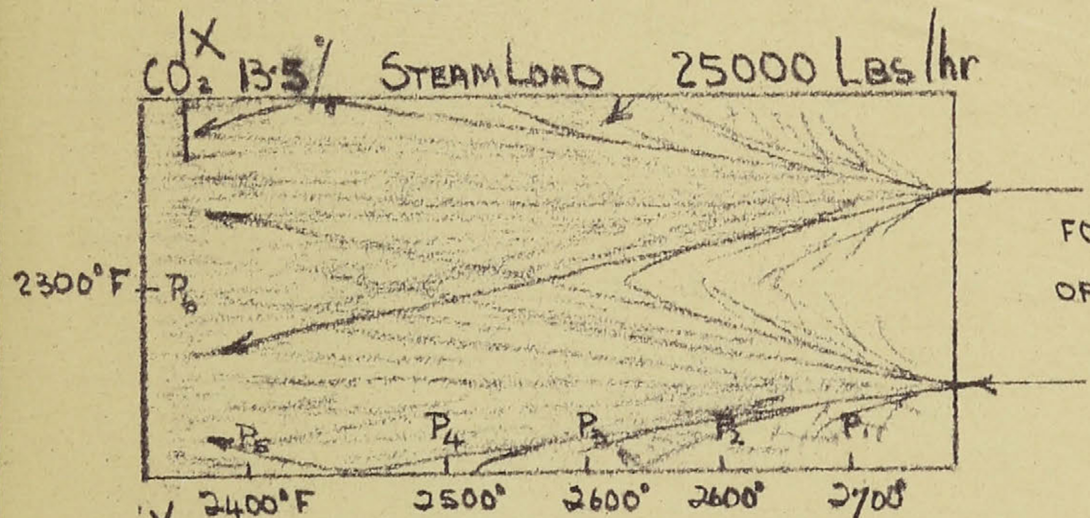


FOUR WEEKS.

TEST No. 2.

FIG. 10.

OPTICAL PYR.
ON FLAME 3300°F.

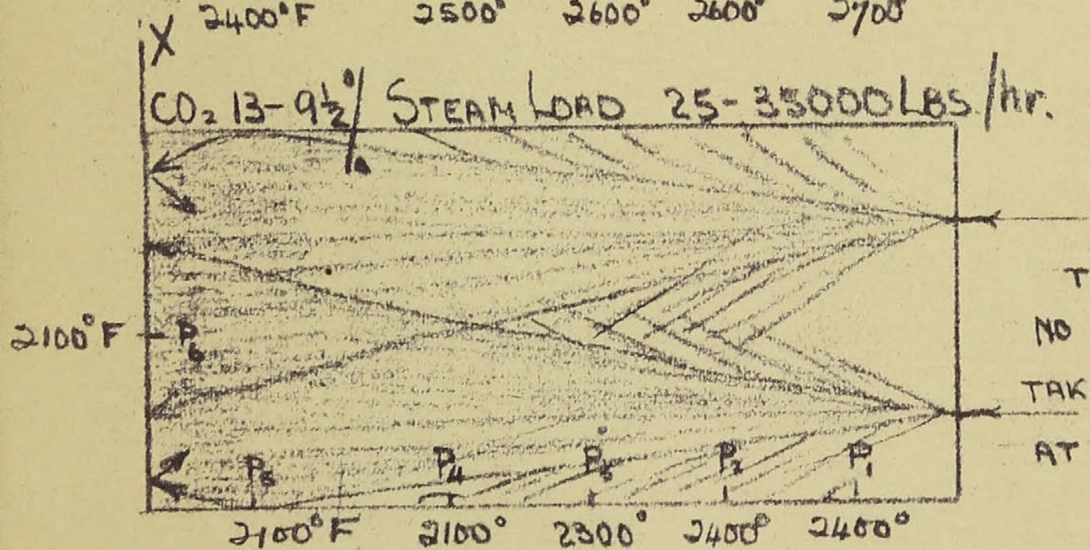


TEST No. 3.

FOUR WEEKS.

OPTICAL PYR.
ON FLAME 3200°F

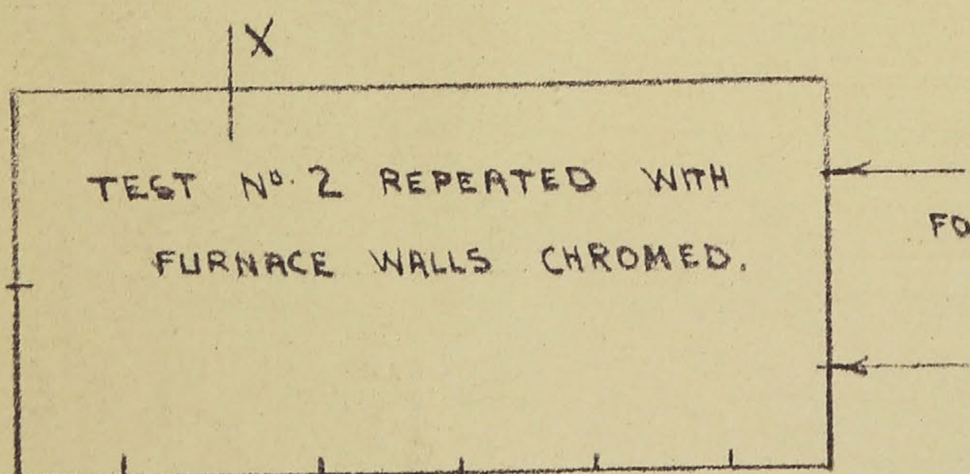
FIG. 11.



TEST No. 4.

TWELVE HOURS.
NO FLAME READING
TAKEN – WALL TEMPS.
AT 9½% CO_2.

FIG. 12.



TEST No. 5.

FOUR WEEKS.

FIG. 13.

The above series of five tests completed the operative experimentation on refractory surface condition in a conical flame type oil fired furnace. The series of four tests now to be described were carried out in the furnaces of other two boilers of similar size to those used for the first series of tests, but fired with flat flame type burners of downward inclination. Similar furnaces are shown in Fig. 2. In the tests, thermocouple placements were 20" above the floor level, with P6 at 20" below the rear wall deflection hump.

Test No. 6 (Fig. 14)

The steam load demanded of the boiler in this test was 8000 lbs. per hour and four burners were used. The best CO_2 which could be held was 13½ per cent. The duration of the test was taken to three weeks, and after the furnace was cool enough to enter, it was found that the steps of the tuyeres had suffered quite severe vitrification, and the floor at the point of impingement and change of flame direction, was eroded. The sidewalls at P1, P2 and P3 were vitrified, but not seriously enough to require repair. So far as the tuyere steps are concerned these are placed refractory, merely spot bonded after the furnace is built. Wall temperatures obtained in this test are shown in Fig.14.

Test No. 7 (Fig. 15)

With all burners operating, it was possible to handle a steam load of 13500 lbs. per hour and run the CO_2 at 14 per cent in the flue gas. In this case, no difficulty would have been presented in running the CO_2 up much higher. An increase of steam load with these burners does not require any change of flame shape. More fuel oil need only be fed to the burners, and a corresponding increase in combustion air permitted through the tuyeres, but no manipulation for change of flame shape is necessary. Note should be taken of the somewhat reduced wall temperature P2 at the tuyere exits in this case, compared with the last, and of the very marked tendency towards uniformity of wall temperature.

Examination of this furnace when cold, showed less fusion on the tuyere steps, particularly in depth of vitrification. This is due to the cooling action of the increased air quantity through the tuyeres. However, the floor suffered quite severely at the point of change of flame direction, as did the floor deflection hump. The floor surface and deflection hump, are, however, always made up of second grade brick, (often discarded old refractory) bedded in silica sand or a cheap fire-clay mix. The lower side walls of this surface showed surface vitrification. Carbon was beginning to be indicated on the floor deflection hump, though not at the impingement point in front of the tuyeres.

<u>Test No. 8</u> (Fig. 16)

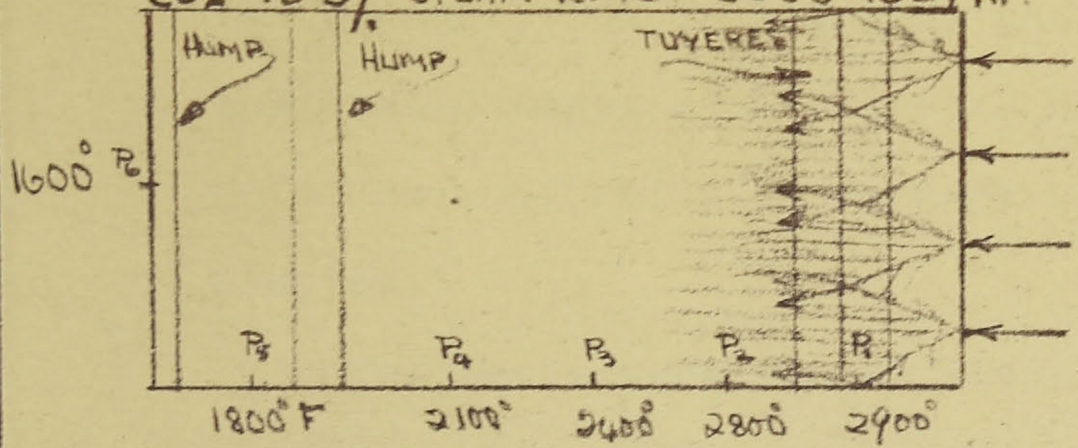
A four weeks test was run on a boiler steaming at the rate of 25000 lbs. per hour. Except for the heavier fire, and a further tendency towards uniform furnace temperature, little difference was noticed in furnace conditions and operation under this load.

However, on entering the furnace to examine the refractory, it was seen that as well as the wear and tear already described in the last test, the rear wall was beginning to soften up at P6 and carbon was depositing on the surface. There was definite penetration by carbon, of test bricks which had been set in this wall.

<u>Test No. 9</u> (Fig. 17)

The last test on the furnaces fired with a flat flame burner, was run on a boiler which, after a day steaming at 25000 lbs. per hour, was steamed for two days at 32000 lbs. per hour. Examination of the furnace when

CO_2 13·5% STEAM LOAD 8000 lbs/hr.

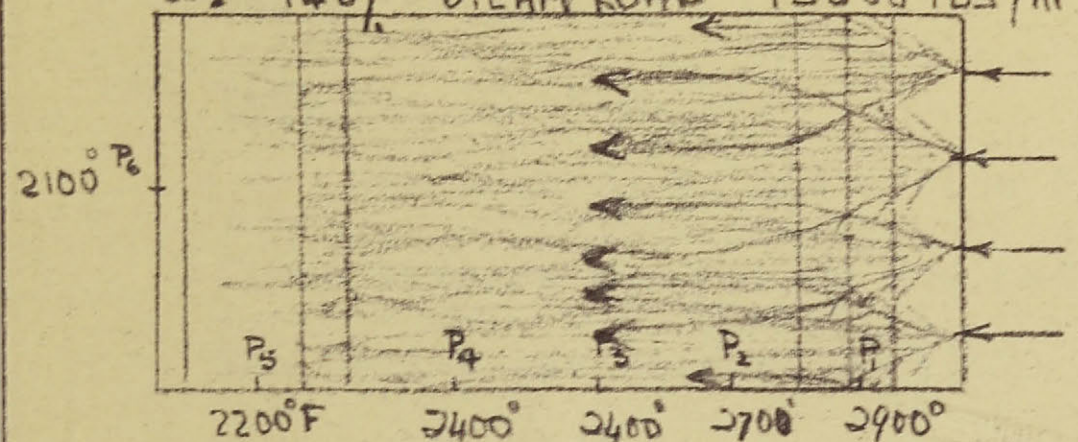


THREE WEEKS.
OPTICAL PYR
ON FLAME 3350°F.

TEST No. 6.

FIG. 14.

CO_2 14·0% STEAM LOAD 13500 lbs/hr

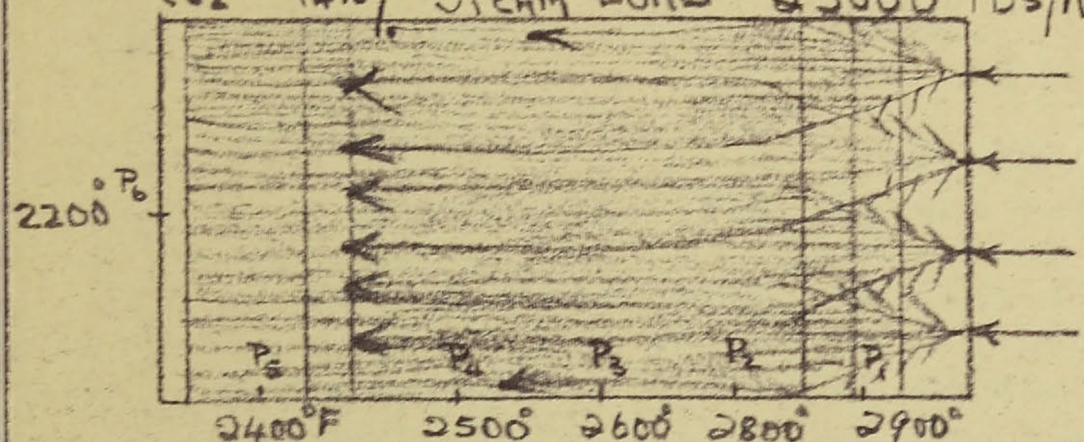


FOUR WEEKS.
OPTICAL PYR
ON FLAME 3400°F.

TEST No. 7.

FIG. 15.

CO_2 14.0% STEAM LOAD 25000 lbs/hr.

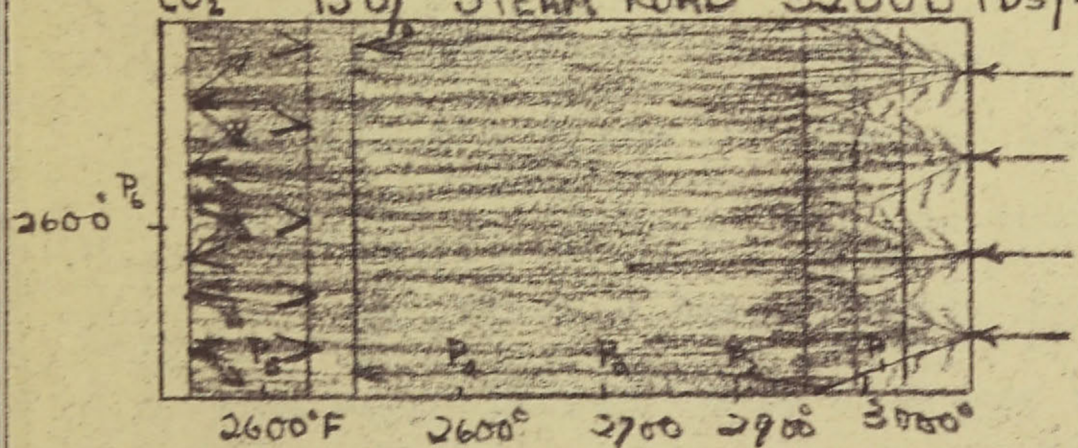


FOUR WEEKS.
OPTICAL PYR.
ON FLAME 3400°F.

TEST No. 8.

FIG. 16.

CO_2 13·0% STEAM LOAD 32000 lbs/hr.



TWO DAYS.

TEST No. 9.

FIG. 17.

TEMPERATURES AVERAGED TO NEAREST HUNDRED

IN ALL TESTS

cool showed complete surface vitrification throughout the furnace, but in bringing the boiler up to load, the bonded edges of the bricks had suffered spalling. Note the uniformity of furnace temperature during operation.

Two tests were run on these furnaces to try to find out the value of the so called ignition arches S_c (Fig. 3) and S_f (Fig. 4)

Test No. 10 (Fig. 19)

The arch S_c in one of the furnaces of the conical flame burners was raised and reduced as shown in Fig.19. The boiler was steamed at 13500 lbs. per hour for one week. No difference in operation from that described in Test No. 2 could be noted.

Test No. 11 (Fig. 18)

The arch S_f (Fig. 4) was reduced to half the width in this furnace, with the flat flame burner. The boiler was steamed for a week at a rate of 13500 lbs. per hour as in Test No. 7.

It was found in this case, that difficulty arose in keeping the flame inclined to impinge on the furnace floor in front of the tuyeres, and there was a distinct tendency to lower furnace temperature, and a difficulty in holding the CO_2 relation above 13.0 per cent.

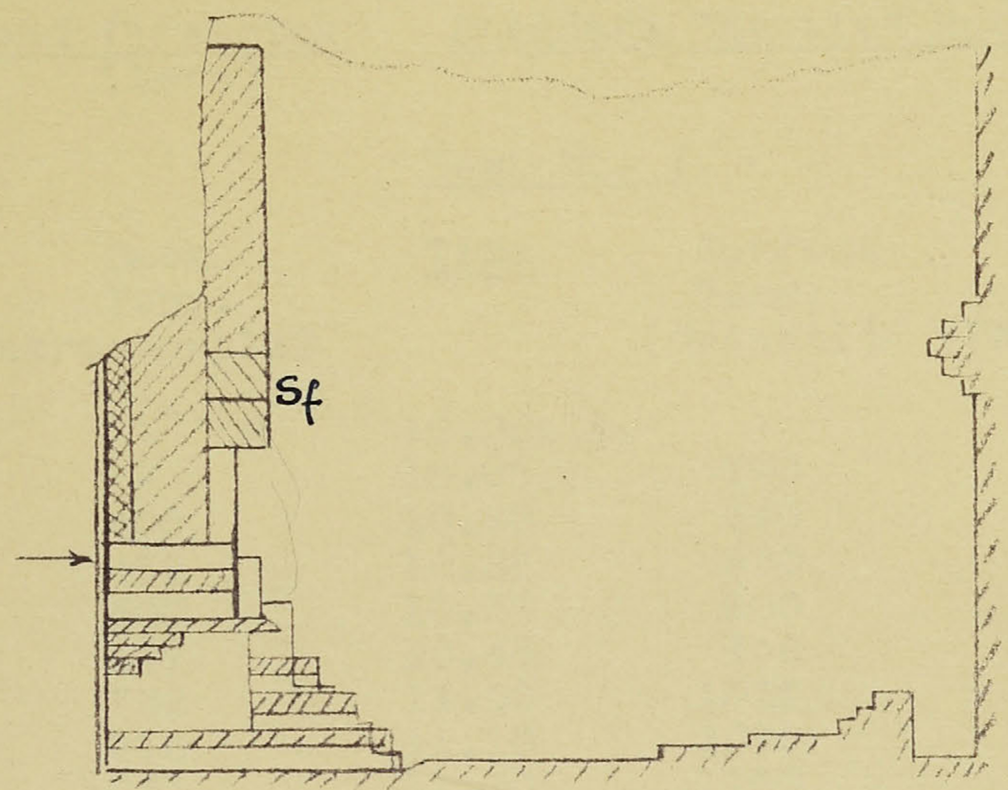
This fact can be explained in the following manner. This wide arch which is wrongly called an ignition arch, is very necessary to trap rapid expansion of gas which then exerts a local pressure on top of the flame to keep it down, so counteracting the rush of combustion air through the tuyeres, which air tends to raise the flame. It is obvious that a raised flame will permit excess air to slip beneath it, which will result in a high stack heat loss.

(b) Laboratory examination of Standard Fireclay Refractories

The laboratory tests now to be described were devised to accentuate the conditions under which carbon deposition on, and carbon penetration of, the walls of refractory furnaces was observed in the operating tests under commercial conditions. It was also a fact that the test furnace was intended to represent conditions of poorer plant efficiency than that operated for the commercial tests described in the previous pages.

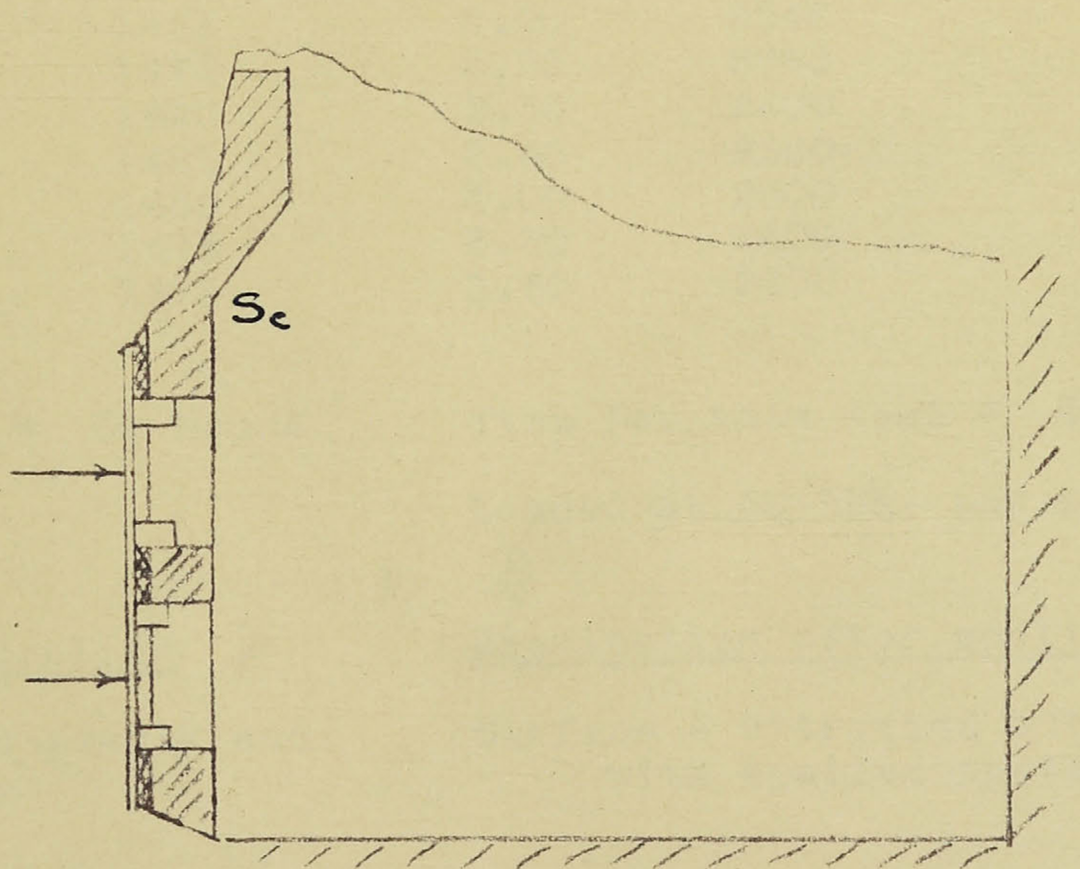
The laboratory furnace was built up as shown in Fig. 21 Page 51 and the oil burner used was a light fuel oil atomizing unit, of the conical flame type. The complete set up of furnace, burner and temperature reading equipment is shown on page 52 Fig. 22. The test firebricks were placed in the position marked T, and the load necessary to give 50 lbs. per square inch on the brick section, using the lever arrangement shown was 185 lbs. Standard fireclay refractory 9" x 4½" x 2½" was used of the "Nettle" brand. The insulating refractory used for tests was of the "Taylor" brand.

The various bricks were placed in position for each test and the furnace brought up to the various temperature conditions now to be recorded, and operated according to



TEST N° 11.

FIG. 18.



TEST N° 10.

FIG. 19.

NOTE

COMPARE THESE SKETCHES WITH FIG. 3. AND FIG. 4. AND NOTE THE REDUCED SIZE OF ARCHES S_c AND S_f.

the requirements of the test. Impingement was obtained by decreasing combustion air, and lengthening the flame after the required temperature was reached.

Standard "Nettle" Brand firebrick (bare)

Test No. 1

Time	Surface Temp. (Optical)	Back Temp. (Thermocouple)
10.00a.m.	- °F	- °F
10.05	200	-
10.15	600	400
10.20	871	452
10.30	926	500
10.40	1015	647
11.00	1100	752
11.15	1165	910
11.30	1228	1031
12.10	1640	1200
12.36	2000	1249
12.40	2313	1306
1.00	2380	1330
1.20	2480	1350
1.40	2506	1386
2.00	2543	1451
2.15	2600	1475
2.30	2545	1490
2.45	2573	1485
3.00	2600	1480
3.15	2582	1475
3.30	2591	1475

Time for this test = 5½ hours

No loading

Examination after cooling

Surface - vitrified evenly and surface glassy

Fracture - vitrification 1/10th inch deep and texture of brick excellent. No deterioration - colour straw.

Standard "Nettle" Brand firebrick (bare)

Test No. 2

Time	Surface Temp. (Optical)	Back Temp. (Thermocouple)
10.00a.m.	-	-
10.05	190	-
10.20	640	450
10.28	850	462
10.37	900	480
10.45	956	645
11.00	1035	850
11.10	1080	862
11.30	1150	1085
12.00	1785	1275
12.30	1940	1340
12.50	2250	1390
1.00	2365	1456
1.15	2410	1464
1.40	2486	1485
2.00	2548	1490
2.20	2560	1500
2.30	2600	1515
2.40	2560	1500
3.00	2500	1500
3.20	2600	1510
3.30	2600	1510

Time for this test = 5½ hours

Loaded at 50 lbs. per sq. in.

Examination after cooling

Surface - vitrified but rough with spalled spots vitrified

Fracture - vitrification depth about same as test 1. but colour nearer to white

Standard "Nettle" Brand firebrick coated with 1/16th inch of Chrome base cement

Test No. 3

Time	Surface Temp. (Optical)	Back Temp. (Thermocouple)
10.00a.m.	°F	°F
10.05	-	-
10.10	500	380
10.15	790	420
10.30	950	516
10.45	1076	614
11.00	1124	740
11.20	1260	805
11.30	1315	980
11.35	1340	990
11.45	1458	1100
12.00	1600	1195
12.30	2100	1390
12.50	2354	1364
1.10	2400	1480
1.15	2480	1500
1.25	2500	1510
1.30	2540	1515
2.00	2548	1520
2.15	2600	1540
2.30	2550	1536
2.40	2580	1536
2.55	2600	1536
3.00	2600	1536

Time for this test = 5 hours

Loaded at 50 lbs. per sq. in.

Examination after cooling

Surface - very slightly glazed

Fracture - no apparent depth of vitrification and brick texture straw yellow

Note:-

Tests Nos. 1, 2, and 3 were made with furnace conditions kept good and no flame impingement except perhaps in heating up to 1000°F. However it was found out that above 2300°F it was impossible to obtain flame impingement in this furnace and still keep the temperature on the up grade. The appearance of any smoke set back the temperature on the brick face at once.

Standard "Nettle" Brand firebrick (bare)

Test No. 4

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
12.00	-	-
12.05p.m.	200	-
12.20	650	420
12.30	800	636
12.50	1050	850
1.00	1120	974
1.30	1335	1050
1.45	1510	1080
2.00	1680	1100
2.30	1816	1120
2.95	2000	1148
3.00	2170	1250
3.15	2214	1360
3.30	2270	1380
3.45	2283	1410
3.50	2280	1410
4.00	2300	1420
4.10	2280	1415
4.20	2278	1410
4.30	2300	1410

Time for this test = 4½ hours

No loading

Furnace kept slightly smoking above 2000°F and flame impingement observed through sight hole.

Examination after cooling

Surface - blackened and carbon deposition at point of flame impingement.

Fracture - carbon penetration for at least ½ an inch at point of impingement - colour of structure darkened - bonding of grains loosened.

Standard "Nettle" Brand firebrick (bare)

Test No. 5

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
12.00	200	-
12.05p.m.	630	400
12.15	810	590
12.30	1000	840
12.45	1130	970
1.00	1380	1060
1.30	1540	1100
1.45	1650	1120
2.00	1820	1150
2.30	2100	1300
2.45	2150	1380
3.00	2160	1400
3.15	2200	1460
3.30	2240	1510
3.45	2270	1575
3.50	2300	1600
4.00	2280	1600
4.10	2270	1600
4.20	2280	1600
4.30	2280	1600

Repeat of Test No. 4 but loading = 50 lbs. per sq. in. applied.

Examination after cooling

Same results apply, but fractured brick showed penetration of carbon almost halfway through, and structure blackened and crumply.

Standard "Nettle" Brand firebrick coated with 1/16th inch of Chrome base cement

Test No. 6

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
12.00	200	-
12.05p.m.	630	400
12.15	800	550
12.30	1000	650
12.45	1130	740
1.00	1300	900
1.30	1520	930
1.45	1670	990
2.00	1800	1075
2.30	2000	1130
2.45	2080	1210
3.00	2150	1280
3.15	2240	1320
3.30	2270	1328
3.45	2260	1330
3.50	2200	1330
4.00	2250	1335
4.10	2280	1340
4.20	2300	1360
4.30	2300	1370

Repeat of Test No. 5

with same loading

Carbon deposition on Chrome surface but no penetration.

Structure on fracture showed straw yellow colour - whitish near the chrome cement.

Special Test

Those bricks which formed the top of the test furnace firebox were also the bottom of the return pass for the waste gases. In other words these bricks were heated on both sides (See Fig.21) (K) Page 51.

These bricks were removed and examined. They were vitrified through and through, were fractured in several places and had shrunk in size.

Note they had been heated for 29½ hours, with five cooling periods included.

Refractory Insulating Brick (bare)

Test No. 7

Time	Surface temp. (Optical) °F	Back Temp. (Thermocouple) °F
10.00a.m.	-	
10.05	250	180
10.15	640	240
10.20	900	410
10.30	1050	520
10.40	1110	585
11.00	1183	615
11.15	1236	810
11.80	1710	975
12.10	2074	1090
12.30	2321	1175
12.40	2405	1295
1.00	2486	1300
1.20	2556	1320
1.40	2580	1330
2.00	2540	1330
2.15	2570	1330
2.30	2600	1340
2.45	2600	1350
3.00	2580	1330
3.15	2580	1320
3.30	2580	1320

Time for this test = 5½ hours
No loading

Examination after cooling

Surface - vitrified uniformly

Fracture - vitrification 3/16 inch deep - colour straw white apparently in good condition.

Refractory Insulating Brick coated with 1/16th inch Chrome base cement

Test No. 8

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
10.00a.m.	-	
10.05	300	200
10.15	680	310
10.20	940	450
10.30	1075	575
10.40	1120	630
11.00	1190	695
11.15	1250	870
11.30	1785	1025
12.10	2100	1080
12.30	2330	1200
12.40	2456	1315
1.00	2475	1340
1.20	2490	1365
1.40	2540	1390
2.00	2540	1410
2.15	2540	1430
2.17	Collapse of Test Brick after 4 hours 17 mins.	

Loading = 50 lbs. per sq. in.

Examination of fracture
Dirty greyish white for 1½ inches

Note

Tests Nos. 7 and 8 made with no flame impingement, no carbon penetration and good furnace conditions.
These bricks have a very open structure, and are half the weight of a standard firebrick.

Refractory Insulating Brick (bare)

Test No. 9

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
10.30a.m.	-	-
11.00	1700	-
11.15	1890	360
11.30	2000	640
11.45	2020	915
12.00	2075	920
12.15	2185	1060
12.40	2185	1090
12.50	2245	1130
1.00	2265	1275
1.10	2250	1335
1.35	2250	1330
1.45	2240	1320
2.00	2225	1320
2.15	2225	1315
2.30	2225	1310
2.45	2225	1300
2.55	2225	1300
3.00	2225	1300

Time for this test = 4½ hours
Loading = 50 lbs. per sq. in.

Surface - Slight vitrification at edges. Carbon deposition from flame impingement

Fracture -
Carbon penetration to depth of ½ an inch and definite section deterioration.

Refractory Insulating Brick coated with 1/16th of an inch of chrome base cement

Test No. 10

Time	Surface Temp. (Optical) °F	Back Temp. (Thermocouple) °F
10.30a.m.	-	-
11.00	1875	-
11.20	1930	400
11.35	1980	500
11.50	1980	660
12.00	2080	800
12.10	2125	885
12.20	2210	1030
12.30	2250	1030
12.50	2202	1040
1.00	2125	1020
1.35	2210	1120
1.50	2210	1125
2.00	2186	1130
2.30	2210	1145
2.40	2210	1145
2.50	2210	1145
2.55	2210	1150
3.00	2210	1150

Time for this test = 4½ hours
Loading = 50 lbs. per sq. in.

Surface - No vitrification.
Carbon deposition from impingement

Fracture -
No penetration of carbon
Section good.

Note

In tests No. 9 and No. 10 it should be observed that the temperature in the furnace was run up very quickly. This was done because it was seen that the refractory insulating brick structure was not one which appeared to be subject to spalling.

It was decided to test this out by quick heating and the two tests were used to do this. No spalling was apparent.

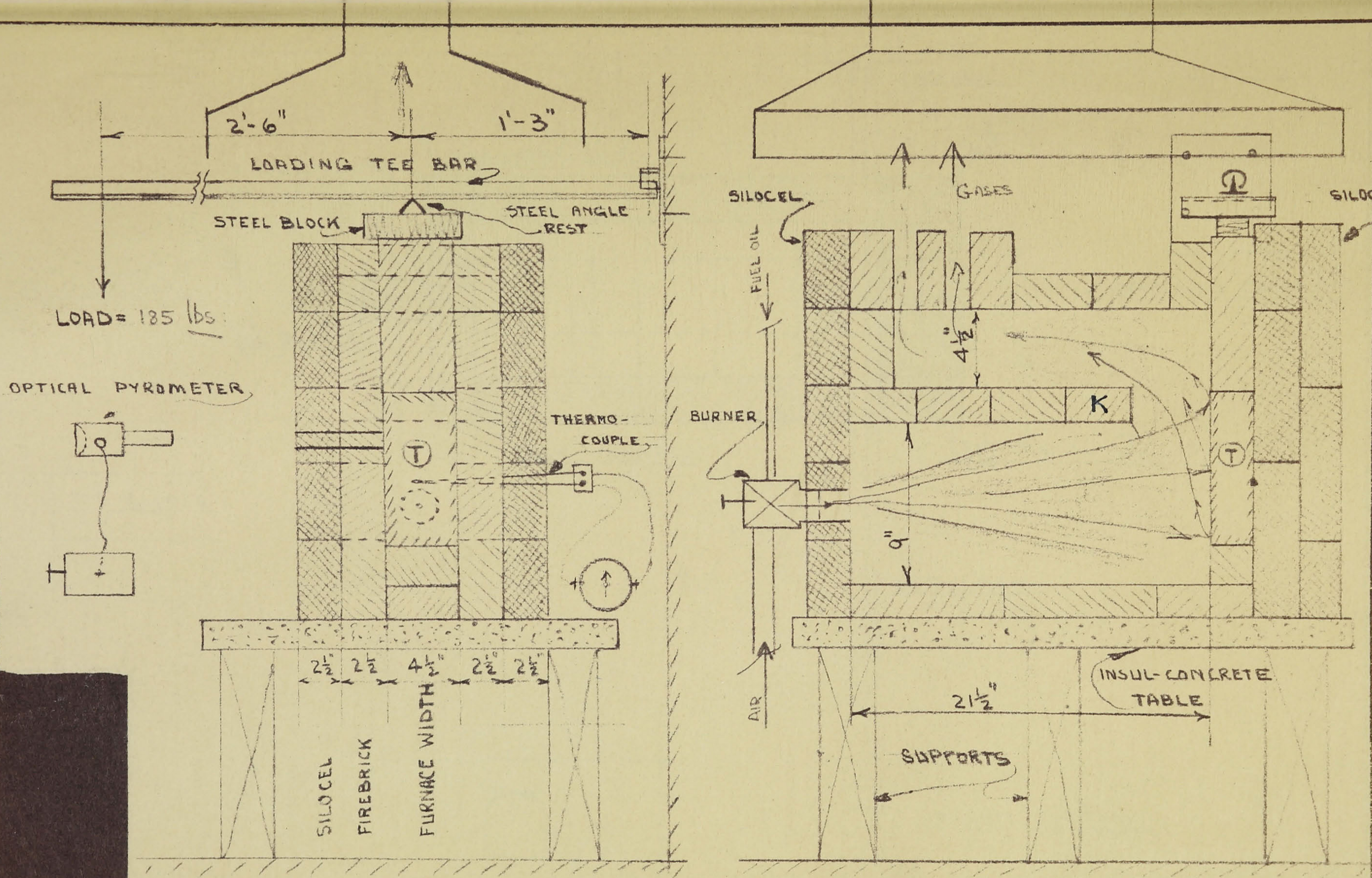
It would not have been possible to do this with the plain refractory firebrick, because the results might have been a mixture of spalling effect and carbon penetration.

Special Test

Between tests No. 6 and No. 7 the plain refractory bricks at point K (Fig.21) of the test furnace were removed and replaced by others which had been subjected to carbon penetration for two and a half hours at 2200°F.

After test No. 10 was complete the furnace was opened up - that is to say after about 20 hours heating, with four cooling periods, and it was found that considerable disintegration had taken place in the bricks at point K.

Very little serious vitrification had taken place, but carbon was dispersed throughout the entire brick section. The bricks were black in colour and were crumbling down.



SECTION THRO TEST FURNACE

NOTE.
TEST BRICKS PLACED IN POSITION (T)

FIG. 21.

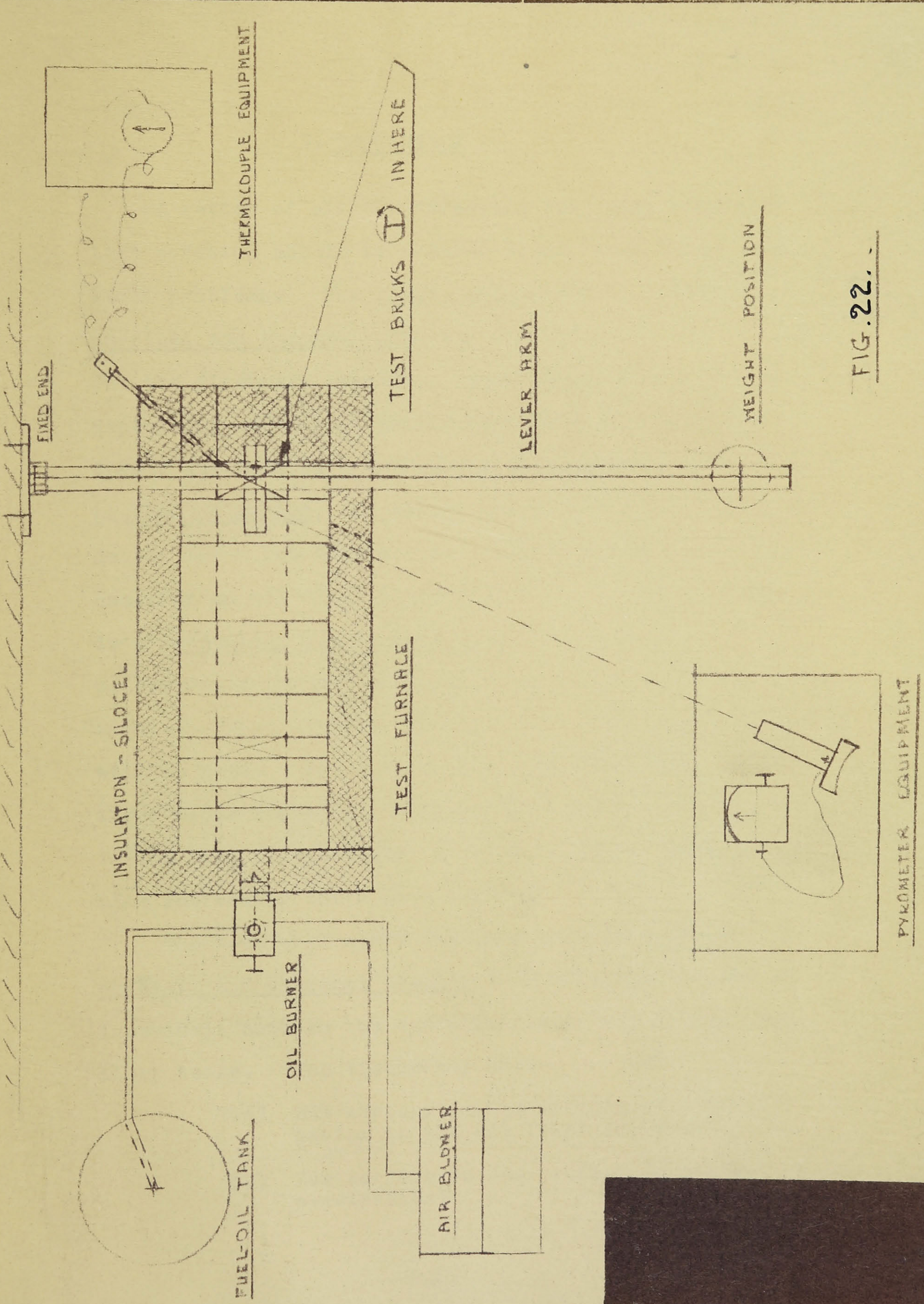

THERMOCOUPLE EQUIPMENT
TEST BRICKS (T) IN HERE
FIXED END
LEVER ARM
WEIGHT POSITION
INSULATION - SILOCEL
TEST FURNACE
PYROMETER EQUIPMENT
OIL BURNER
FUEL-OIL TANK
AIR BLOWER

FIG. 22.

V. CONCLUSION

A review of all the foregoing test work indicates that solution should be offered to at least three distinct problems. The first problem can be termed a physical and chemical problem, and refers to the reasons for the firebrick reactions under impingement, carbon deposition and carbon penetration between temperatures $2000^{\circ}F$ and $2300^{\circ}F$. The second problem can be termed a problem of design, and simply stated refers to a suggested design for a low cost and low maintenance refractory furnace, for an oil fired steam boiler. The third problem is a mechanical engineering problem and refers to the selection of proper firing equipment to suit the particular service, (type of steam demand) for which this equipment will be used. It is felt that a clear view on these three matters should contribute materially to reductions in the cost of operating oil fired boilers, while at the same time increasing their useful life.

The test work which has been described raises the physical and chemical problem in a threefold manner as is evident both in the operating tests and in the laboratory tests. The viewpoints are:-

(a) How serious is the problem of vitrification in the oil fired furnace?

(b) How serious is the problem of carbon penetration?

(c) What is the value of surfacing?

(a) Vitrification of firebrick in a furnace will take place if the temperature in the furnace is too high. In the oil fired furnace all the operative tests show that excessive temperature will probably be a local condition, and will not exist throughout the whole furnace. However, assuming badly chosen equipment, it is to be expected that vitrification of refractory even in spots may cause considerable damage. Serious overheating for an abnormal length of time, will reduce wall thickness by melting. Also at high temperature the fluxing glass loses bonding power, and the ability to support load.

The physical characteristics of a badly vitrified refractory, are reduction in volume on cooling, and a high glass development, which in turn means that resistance to spalling has been lowered. It is not surprising therefore, to observe that a wall which has been over heated in the furnace indicates on cooling, parted joints and cracked brick work, as well as a loss of refractory thickness, and misalignement of the brick courses.

There seems to be only one cure, and that is prevention of excessive temperature on the brick face. This can be most easily done by providing sufficient furnace volume for combustion and choosing suitable firing equipment.

One thing which can be read into the test work, is that if vitrification of refractory is taking place somewhere in a furnace, carbon deposition will not occur at that spot. All the operating tests verify this, and it is very important to emphasize it, because vitrification begins to show over 2400°F and it was impossible in these tests at least, to obtain carbon deposition above 2400°F. A little surface vitrification seems to be generally accepted as an advantage. Depth of vitrification is damaging.

(b) Regarding the question of carbon penetration, this is the condition most damaging to the refractory walls of oil fired furnaces. It is quite clear from all the operating and experimental work, that the upper limit of wall temperature at which carbon deposition takes place is around 2300°F. It should be noted that under these test conditions, the flame was around 3400°F, and when it was in contact with furnace walls at 2300°F or less, serious carbon deposition appeared only if the angle of contact was such that some definite impact took place. In the test work, when a distinct impact did not take place, neither did massive carbon deposition.

In the commercial furnaces used for the tests, conditions of operation were set at approximately 13½ per cent CO_2 in the flue gases, and although it is extremely difficult to ascertain the CO-CO_2 ratio in any flame,(this is a rapidly changing ratio) in the furnace proper at 13½ - 14 per cent CO_2 the Orsat test registered no CO. It has been generally accepted that flame colour is gas incandescence, when considering an oil fuel flame at 3400°F and not carbon particle incandescence. But it is evident from these tests that sufficient impingement on a wall of temperature 2300°F or less, gave a carbon deposit even in these efficient furnaces ($13\frac{1}{2}\%$ CO_2 - flame at 3400°F)

It is quite safe to estimate that in industry generally, seventy per cent of the oil fired boilers in the steaming range below 20000 lbs. per hour, operate with furnaces whose walls are not above 2350°F anywhere, and with CO_2 in the 10-12 per cent range, which gives perhaps 2-3 per cent CO present as well. The flame temperature would be correspondingly lowered in such a case to 2800°F approximately.

Extensive brickwork disintegration is always found in such low temperature furnaces, and the reason is the carbon penetration of the brickwork which if found in an efficient furnace as demonstrated, must certainly be aggravated in the less efficient ones. The laboratory experimental work, produced conditions not unlike the ordinary run of less efficient plant, and the carbon was seen to be literally driven into the refractory.

The question remains as to why carbon forms, even in the efficient furnace. The answer appears to be associated with the speed of the combustion reaction, and the temperature at which it takes place. It is suggested here that the idea of there being no carbon particles in the incandescent flame is not absolutely correct, and that a few minute carbon particles do actually reach the wall surface with the combustion reaction not quite complete. At 3400°F the amount may not be at all measurable, and any CO produced is probably well within the factor of error in an Orsat measurement, but nevertheless, the presence of this carbon at all, must be accompanied by an amount of CO no matter how infinitesimal.

A little deviation will be made here to discuss the speed of combustion reactions. The reactions concerned are:-

1. $CO_2 + C = 2\,CO - 70000$ B.T.U.

2. $C + O_2 = CO_2 + 174000$ B.T.U.

Taking equation No. 2

At $662^{o}F$	the relative velocity of completion of this reaction	= 1
" $752^{o}F$	" " " " " "	= 10
" $932^{o}F$	" " " " " "	= 400

Investigators have established the above, basing the units of relative velocity on the time taken to complete the reaction at $662^{o}F$.

It therefore may be assumed that above $2300^{o}F$ the completion of this reaction takes place instantaneously, and that the direct formation of CO does not take place, provided the O_2 can be supplied fast enough. However, two things may happen. Either a temporary deficiency of O_2 may decrease the heat release of the reaction (2) by permitting unconsumed C particles to mix with the CO_2 present, which will then permit reaction (1) to operate, and so further decrease temperature because this reaction is endothermic. Amorphous carbon will also be a product of such a reaction. On the other hand if it be supposed that very correct O_2 is fed to the furnace, then efficient operation is obtained and excess air is at a minimum. The flame temperature will, however, run high, and dissociation of CO_2 into CO and O_2 can take place.

It is apparent therefore that under good or bad conditions amorphous C, CO, and CO_2 may exist together, and in all probability a minute quantity of unconsumed carbon is also added from high velocity flame.

How far metallic oxides in the brick promote further deposition of carbon is a moot question, but it is known that in a C - CO - CO_2 mixture metallic oxides <u>may</u> cause further deposition of carbon. Impingement of a hot flame upon a hot surface is known to have catalytic action upon the gases in the flame, but it is also creditable to believe that serious impingement of a flame at 3400°F on a relatively cold wall (2000-2300°F) might give a "cold" shock which could so halt the completion of reactions that piling up of carbon would be possible, and be accumulated by the continuation of high velocity impingement.

It has been shown in the tests that no carbon seems to be able to exist at the wall if the temperature on it is above 2400°F. This can be explained by the fact that to obtain the 2400°F at the wall, the flame temperature must be high, and that the dissociated CO_2 in the flame probably provides enough O_2 to speed the combustion of the few C particles present. Also there will be a reduction of "cold" shock at the higher wall temperature.

It was also noticeable in the tests that where impingement was slight, even at wall temperatures below 2300°F, the carbon penetration and deposition was not so serious as with more definite impingement. It may be assumed that when the impingement is slight the speed of flame travel must either be slow, or the flame has further to travel before impact, and the reactions in each case have more time to complete themselves, and less carbon therefore remains unconsumed in the flame to appear at the wall as a deposit.

Regarding how carbon penetrates the brick structure, no evidence has appeared to show that it is not forced by impact into the hot structure of the refractory as solid carbon. On the other hand, the amount of metallic oxide necessary to act as a catalyst for the accumulation of carbon from a C - CO - CO_2 interaction, is a matter still under investigation in several metallurjical laboratories. One thing quite certain, is that observation of fractured bricks showed that the more definite the impingement, the more did the carbon deposit accumulate on the brick surface, and the deeper was the brick structure blackened by the penetration of carbon. It is possible for CO to enter the brick, but all the visual evidence pointed to the major problem as the penetration of solid carbon in particle form. CO does react with "iron spots" in refractory brick to form C and CO_2 in certain cases of poor quality brick, but any good hard burned firebrick should have low reactive iron oxide and be inert towards CO. Otherwise the brick should not be used.

This paper is mainly concerned with the establishment of what happens in the process of firing and with the reduction of damage cost. It may be taken, therefore, that the accumulation of a foreigh solid like carbon, in the brick structure, is accelerated by the external driving force of flame impingement, and the eventual result will be the disintegration of the firebrick from bursting.

It is also clear that the damage will be done at the "cool" wall locations, when definite impingement exists there. Since impingement can only be removed at the expense of furnace efficiency, particularly at medium and low loads, it is at once seen that the carefully operated plant as well as those which only receive moderate attention, are all affected similarly by this most damaging phase of furnace operation.

(c) Referring again to the test work, <u>Surfacing the brick</u> with chrome does not prevent vitrification trouble. However, any such dense facing which will suffer high temperature and is inert to the underlying brick, does diminish very considerably carbon penetration, though it will have no effect in reducing carbon deposition. This will still continue when flame impingement with sufficient impact on surfaces below 2300°F exists.

It therefore becomes evident from the above work that the criticism usually heaped upon the head of an operator, when carbon shows on the walls of an oil fired furnace, may be unmerited. Of course, such criticism is based on the mistaken assumption that carbon on the side-walls and carbon at the burner tip, results from the same fault, carelessness. The latter carbon deposit is definitely careless operation, but the wall deposit is not necessarily so, and so far as this deposit is concerned, attention should be given to the furnace when cold, in preparing the walls to resist carbon penetration. Also attention in the design stage for simplification of repair, when such repair will become necessary, as eventually it must, is also indicated from the work described.

In discussing the subject of <u>design of refractory furnace linings</u>, no matter for what type of burner, it is apparent that again three main features should receive consideration. These three features are associated intimately with each other, and it is difficult to give them order of precedence, so they will be set down here, in the order in which they will be discussed, namely, minimum maintenance cost, reduction of heat loss through the furnace walls, and initial capital cost.

From what has gone before, it has been established that wear and tear in an oil fired refractory furnace cannot be avoided, even in the best operated job. In accepting this statement, the necessity for repair must also be accepted. It has been shown that a lightly loaded refractory will stand service longer than a severely loaded one. It is also apparent that in the usual designs of furnace asshown in Figs. 3 and 4 the lower courses of refractory are heavily loaded by having to carry the weight of the wall above. The heaviest loaded refractory is therefore located in the furnace, where the service demanded is most severe, and where most repair is required. To pick out and replace an area of burned or eroded furnace wall, which area is carrying all the load of the upper courses above it, is not an easy matter. It is, of course, an operation which can be done, but it requires skill. Tying into the inner brick of the wall, avoiding damage to inner insulation, and overcoming expansion troubles on reheating the furnace, are some of the factors to be taken care of. In other words, skilful repairs are expensive repairs, and since steam boilers run from six to eight months at a firing, such a repair if necessary, usually covers a considerable area of brickwork, and is not in the class requiring the replacing of only half a dozen bricks.

As it is of importance practically, consider what the floor of the furnace for a downward inclination flat flame burner becomes in operation. It becomes a "wear target". It takes the high velocity impact and erosion of the flame, but it is easy to make-up to thickness again, merely by spreading on the surface some broken up reject bricks mixed with sand and clay.

It would seem that in the principle of a wear target, or refractory screen, is to be found the answer to the lowering of repair costs in any oil fired furnace. This screen should cover the boiler walls proper, and stand around the furnace to a height of some eight feet from the floor. It should cover at least three sides of the furnace in every case, the firing wall being excluded in some cases. This refractory screen need only be standard firebrick on edge, making a 2½" thick free-standing wall. It should be free from the main walls except where it would be caught at the top to prevent toppling over. Expansion should be taken up in the floor support. At 8 feet high, the lowest course of brick would have a negligible load of 8 lbs. per sq. in. The side of the screen exposed to firing should be carefully surfaced with a chrome base cement. This screen could be easily replaced, and repaired, and would protect the main boiler walls from the rigours of the firing area in the furnace.

It is considered that such a screen would certainly reduce furnace repair costs. The possible building troubles of such a screen are twofold, being the necessity of finding a method to take up the relative expansion vertically, between the free-standing screen and the loaded refractory wall behind it, and at the same time holding the screen at the top, to keep it from toppling over into the furnace. It is suggested that satisfactory solutions to these problems are shown in Fig. 20, page 65a

It may be thought that the toppling over of the screen is unlikely. However, it must be guarded against, because the oil fired furnace suffers from the peculiarity of gas vibration. This is supposedly caused by incorrect impingement of combustion air on the oil flame. It has a rapidly repeating explosive effect which has been known to shake down heavily built walls. The subject presents a field for investigation, because the effect of gas vibration in oil fired and gas fired furnaces, if not immediately rectified, can only be described suitably as devastating.

The firing wall, or wall carrying the burners, could in some cases be built with a refractory screen like that suggested for the other three walls; however, in other cases due to the design of the firing equipment this is not practicable. It is suggested as a general principle, that the furnace side of firing walls should be built of monolithic plastic refractory, and not refractory brick. In most cases damage to this wall will be caused by vitrification, and a monolithic wall, though more expensive than a refractory brick wall, may be patched with the addition of further plastic very simply.

In discussing the question of heat loss through the boiler walls, a similar figure to that already calculated on page 27, will be taken as acceptable, namely 200 B.T.U. per hour per sq. foot. In the design shown in Fig.20 the resistance to heat flow works out as follows:-

$$R \text{ firebrick } \frac{4.5}{12 \times 74} = .52$$

$$R \text{ refractory insulating brick } \frac{4.5}{12 \times 31} = 1.21$$

$$R \text{ silocel } \frac{4.5}{12 \times 08} = .47$$

$$R \text{ air space } \frac{2.75}{12 \times .05} = .46$$

$$11.03$$

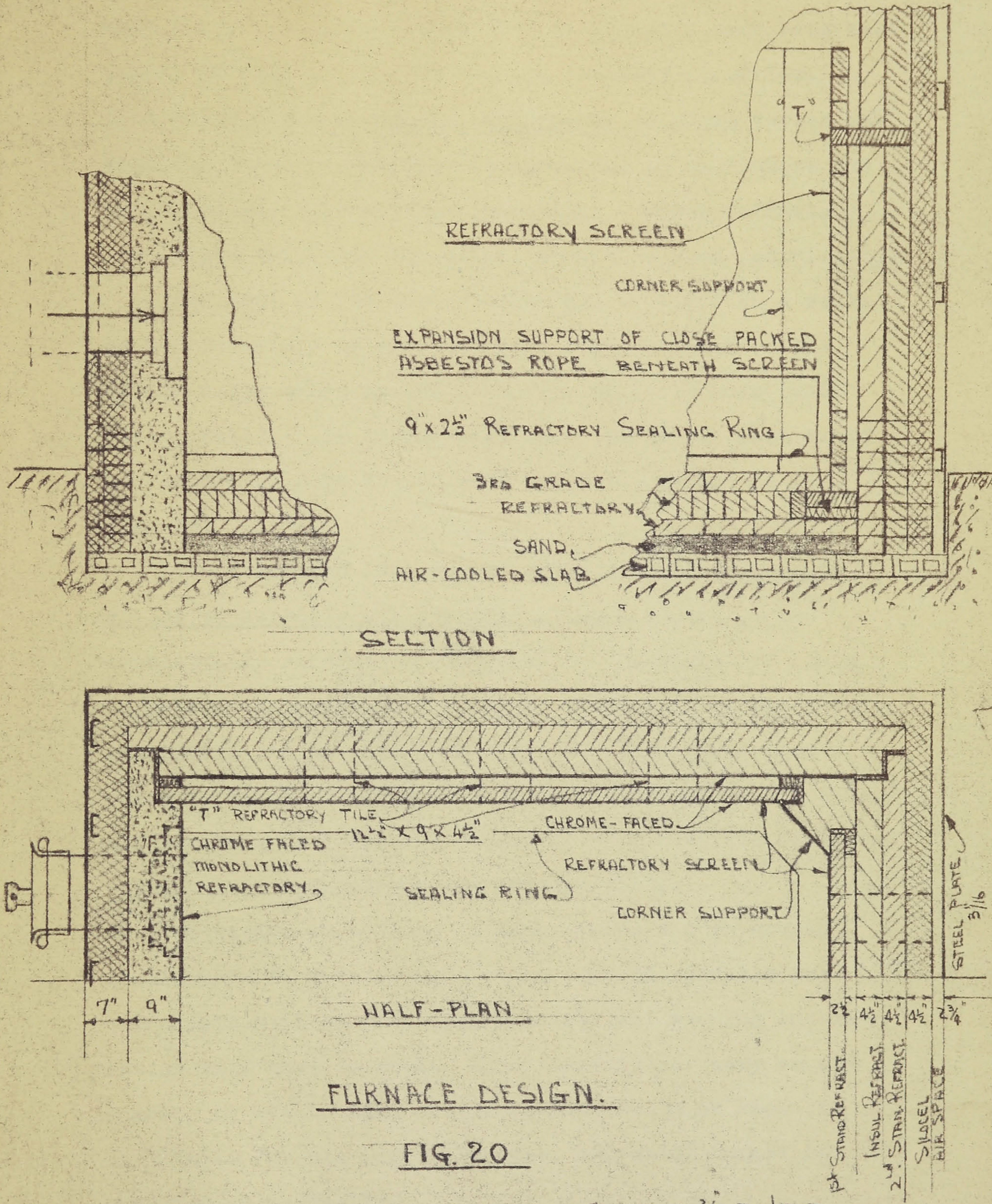
R_t = Total Resistance to heat flow.

Compare this heat resistance figure to that for the standard design (Fig. 5, page 26) when under the same temperature conditions, R_t was 11.05. It is seen that this wall $16\frac{3}{4}$ inches thick is equal to the standard wall of $24\frac{1}{4}$" thickness, so giving a reduction of 30 per cent in wall thickness.

With regard to load, the intensity of loading on the hot inside courses is lowered by 54 per cent, since a standard firebrick weighs 8 lbs. while a refractory insulating brick of the same size weighs approximately 3.7 lbs. It has been assumed throughout that both sides of the refractory furnace screen would come to the same temperature. This is not quite true, as the screen would increase to some small extent, resistance to heat flow through the wall, in the very hot area of the furnace.

Finally in this discussion of furnace design, there has to be considered initial construction cost. Without elaborating upon the matter, the plain statement will be made that any additional money demanded by good design features, in the comparison of different layouts, can be considered well spent money. Reasonable reduction of heat loss and provision for easy repairs, are well worth the initial cost of a good wall lining. However, it must be kept in mind that a one hundred per cent insulated wall, will probably lead to failure under load of the furnace lining, if the furnace temperature is inadvertently permitted to run to 3100°F for any length of time, no matter what specification is attached to the firebrick. At least 250° variation may be found on any collapse test, when the previously tested bricks are put in place, and bonded in a wall. It is not unusual to find a refractory brick which will stand a load test of 50 lbs. per sq. inch for four hours at 3150°F, to collapse in service at 2900°F under a load of 30 lbs. per square inch after twelve hours.

With regard to the price of insulation, and partic-



FURNACE DESIGN.

FIG. 20

SCALE:- 3/8" = 1 FOOT

ularly refractory insulators, the very strong point often made for their use, is that they absorb very much less heat during heating up periods than do standard firebrick. This feature has no bearing whatsoever on steam boiler operation, since boiler furnace operation is continuous and not a rapidly intermittent operation. Hence refractory insulators which are expensive, should be used judiciously.

The cost of the boiler brickwork of Fig.3 or 4 would be approximately 15 per cent more than the cost of the design using walls as shown in Fig. 20 (with monolithic firing wall). It is expected that the repair cost would be reduced by some 75 per cent using the design as in Fig. 20.

The third and last consideration, that of the selection of suitable oil firing equipment cannot be too emphatically stressed. Those engineers whose job it is to select equipment, are probably consulting or executive engineers, and as such they will be subjected to high pressure sales effort, and even fellow executive pressure, all striving to force the choice of some specific equipment without time being given for careful study.

Operative experience in many plants and on record, should make it very evident as to what the service requirements will be that each specific oil burning installation will have to meet. Unfortunately for many an operator, he has to take over equipment which he knows is unsuitable for his particular use, and which cannot be operated economically.

The experimentation and testing work just completed, emphasizes most clearly that economy of furnace operation, be it in fuel economy, or low cost maintenance (and it should be both) are definitely associated with the fluctuations of the steam demand on the boiler. The furnace efficiency should be maintained high at all steam loads, to conserve fuel, but in maintaining this efficiency, the furnace walls should not be subjected to damage which is costly to repair.

It is not difficult to prognosticate the probable curve of steam demand for any specific plant. This can be obtained from experience and record. Steam demand curves come into three categories. Those which have very high short period peaks, and comparatively low long period average flows, those which have long period high steam demand, with short period minimum demand, and finally the continuous demand type of steam load, of little variation. There is, however, one all important feature, connected with all types of steam demand, and that is, that the furnace and firing equipment must be able to meet the maximum call for steam.

Examination of operative tests Nos. 1 to 4 of the preceding work, demonstrates beyond argument that the short time peak demand, followed by long periods of low steam flow, cannot be met economically with a conical flame type burner. To suit this load type when so equipped, the operator must run his furnace for long periods with a short flat conical flame if he wishes to obtain high furnace efficiency, and in doing so, the refractory walls will be very soon ruined. The alternative operation with this type of burner, is to narrow the flame cone, to remove impingement on the sidewalls and the high temperature on the front wall. The result of such an operation will certainly save refractory wear, but will result in a high stack heat loss, due to the excess air which will slip past the small narrow flames in the large furnace. (See Fig.23, page 69)

It, therefore, becomes quite evident that a conical flame type burner should be used only when high steam demand is the major run of the load, with respect to time. In other words, a conical flame type burner, fits a continuous steam service, or base load service, where peaks in the steam demand are not often encountered. In this service such a burner makes most use of the complete furnace volume, and it can be seen that it is under the conditions of long heavy, full flame with small impingement angle that refractory wear resulting from the use of this type of burner is at a minimum, and furnace efficiency at a maximum.

The flat flame type of burner with downward inclination indicates from the tests given it, as recorded in the previous pages, that ability to follow a rapidly fluctuating steaming curve at high furnace efficiency with minimum refractory damage, is a feature of this type of equipment. No attempt is made here, to infer that no damage occurs. As a matter of fact, we have seen quite clearly that damage occurs to tuyeres and floor under all conditions of firing, and to the back wall at high load. But the floor may be made up of refractory rejects grouted in with sand and clay while the tuyeres are hand placed brick carrying no load, and are not integral with any complicated wall structure. Repairs are therefore easy and cheap.

Furnace efficiency can be maintained high from minimum to maximum load, and tuyere wear and tear, though not floor wear and tear, decreases with increasing steam demand, due to the combustion air acting as a cooling medium. Continued high rating will cause wear and tear on the rear wall (See Test No. 8) but refractory screening has been suggested for this.

This type of burner should quite definitely be chosen for a plant whose steam demand will be of the fluctuating type.

Final Remarks

Throughout this paper no mention has been made of water cooled, and air cooled furnace linings. These present an entirely different problem from the solid refractory furnaces which have been dealt with. Also it is doubtful if it is economic to consider water cooled furnnaces in units below steam ratings of 60000 lbs. per hour, and except in very definite locations, this load would probably be handled by some method of coal firing.

The actions of stoker fired and pulverized fuel equipment upon refractories are also different problems due to the fluxing action of slags, and involve a study of water screens of one type or another.

These problems which have been discussed in this paper relative to oil fired units, are meant to be associated solely with this type of firing and none other.

SCALE OF PREVENTABLE FUEL LOSSES

PURE CARBON FUEL — FLUE TEMP. 500°F

$\% CO_2$	Fuel Loss
15 %	0.0%
.8	0.15
.6	0.32
.4	0.48
.2	0.65
14.0	0.83
.8	1.01
.6	1.19
.4	1.38
.2	1.58
13.0	1.78
.8	1.99
.6	2.20
.4	2.42
.2	2.65
12.0	2.89
.8	3.13
.6	3.38
.4	3.65
.2	3.93
11.0	4.21
.8	4.49
.6	4.78
.4	5.08
.2	5.39
10.0	5.74
.8	6.09
.6	6.45
.4	6.83
.2	7.23
9.0	7.67
.8	8.11
.6	8.56
.4	9.04
.2	9.54
8.0	10.08
.8	10.62
.6	11.19
.4	11.81
.2	12.45
7.0	13.14
.8	13.86
.6	14.63
.4	15.45
.2	16.32
6.0	17.25
.8	18.23
.6	19.25
.4	20.43
.2	21.66
5.0	23.00
.8	24.43
.6	26.00
.4	27.71
.2	29.67
4.0	31.62
.8	33.90
.6	36.41
.4	39.15
.2	42.30
3.0	46.05
.8	50.10
.6	54.90
.4	60.45
.2	66.90
2.0	74.70
.8	84.30
.6	96.30

YOU COULD NOT RAISE STEAM WITH LESS THAN 1½ % CO_2

THIS SCALE WILL SHOW LOSS FOR MOST FUELS EXCEPT NATURAL GAS

FIG. 23.

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