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INVESTIGATION OF REFRACTORY FAILURE
IN A BOILER COMBUSTION CHAMBER

by

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MINERAL PROCESSING DIVISION

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INVESTIGATION OF REFRACTORY FAILURE IN A BOILER COMBUSTION CHAMBER

by

M. Palfreyman*

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SUMMARY

The failure of the refractory lining in #2 boiler combustion chamber at the Canadian Forces Base, Stadacona, Halifax, N.S. was reported by Mr. M. Fainstat of Combustion and Power Equipment Limited, Montreal, Quebec. The above company had contracted to carry out the conversion of 3 boilers from coal to oil firing. Failure of the refractory lining in #2 boiler combustion chamber was observed after being in operation from April 28 to May 10, 1971. Samples of materials were taken from various points in the damaged combustion chamber and consisted of damaged refractories, glassy and semi-fused matter, and fly ash which was lodged between the boiler tubes above the combustion chamber.

Chemical analyses were performed on some of these samples (including a sample of the fuel oil in use) and melting point determinations were made using a Leitz heating microscope.

High-temperature reactions between the coal ash and the refractories were studied.

The results of these determinations showed that failure of the refractories was due to fluxing and erosion by the fly ash which had melted after falling from lodgements between the boiler tubes into the combustion chamber.

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INTRODUCTION

A refractory failure occurred in the combustion chamber on #2 boiler at the Canadian Forces Base, Stadacona, Halifax, N. S., on May 10, 1971. This boiler is one of three which are employed at Stadacona for raising steam for heating purposes.

When the refractory failure occurred, all three boilers were under conversion from coal to oil firing, the conversion being carried out by Combustion and Power Equipment Limited, Montreal, Que.

After conversion, #2 boiler was lit on April 27, 1971, and was shut down on April 28, 1971, because oil was dripping from the end of the burner. Some adjustments were made to the burner according to instructions issued by the Contractor(1), and the boiler was re-lit on April 29, 1971. The boiler was steamed until May 10, 1971 when it was again shut down for the same reason. The burner was subsequently removed for inspection. At the same time, an inspection of the combustion chamber was performed, and the following observations were made(1).

The entire chamber appeared as though painted black. The front wall, burner cone, side walls, and floor were all cracked. On one side wall, the front layer of brick appeared to have moved inward. The entire floor was covered with a hard, black, glassy material to a depth of 1.25 inch (3.18 cm). On both side walls, a lava-like material appeared to have run downwards from the tube area, cutting grooves into the brickwork and severly eroding the latter in the stepped region (see below). At the same time, this material had filled the expansion joints in the brickwork.

At this point the boiler was kept inactive pending further inquiries. The cause of failure of the refractory lining was not apparent at this stage, and the suggestion was made that the refractories employed were perhaps of inferior quality.

In mid-June an approach was made to the Mineral Processing Division, Mines Branch, by Mr. M. Fainstat, Vice-President of Combustion and Power Equipment Limited, with a view to an investigation being made into the cause(s) of failure of the combustion chamber refractories. The results of this investigation are reported below.

Construction of Combustion Chamber

A cross sectional diagram of the boiler combustion

chamber as viewed from the target wall is shown in Figure 1.
Only the right side is shown, the left side being a mirror image.
The stepped region of the side wall, referred to above, can be
clearly seen.

The working lining of the combustion chamber is Jay
Bee Fine Super Duty Firebrick supplied by Kaiser Refractories.
The physical and chemical properties of this brick, as published
by the manufacturer, are given in Table 1. The top of each wall
is protected by Maxbond Plastic refractory which is also supplied
by Kaiser Refractories. Maxbond is basically a fire clay bonded
with sodium silicate which imparts air setting properties.

Condition of Combustion Chamber After Failure

The combustion chamber was oriented in a north-south
direction along its length with the burner on the north wall.
Hereinafter the burner wall will be referred to as the front wall,
the south wall is the target wall and the two side walls are the
east and west walls.

The conditions of the walls and floor, after the shut
down on May 10, 1971, are shown in Figure 2. Particular attention
should be paid to Figure 2(d) which shows an accumulation of a
slag-like material above the refractory brickwork. This material
appears to be resting on the plastic refractory used to cap the
brickwork.

Some enlarged photographs of the damaged refractories
in the combustion chamber of Boiler #1 are shown in Figures 3-6.
This boiler suffered a similar fate, though the damage was not
as extensive as with Boiler #2.

Both the front and target walls showed the least damage.
This is probably due to the fact that both are vertical walls
with no stepped regions which would allow the accumulation of
falling material to take place. Furthermore, they are protected
by overhangs formed by the boiler tubework as shown in Figure 7.
The dotted rectangle in Figure 7 depicts the approximate position
of the firebrick lining.

Inspection of Damaged Combustion Chamber

Numerous samples of refractory, both damaged and un-
damaged, were provided by Mr.M. Fainstat; in addition, the author
inspected the combustion chamber on June 29, 1971. During this
inspection, it was observed that considerable fly ash was lodged
around the boiler tubes above the combustion chamber. In the
higher regions, the ash was in the form of a brittle porous mass.

On the overhang above the oil burner, the ash had den-
sified to a hard clinker, forming a layer 12 to 18 in. (30.5 to
45.7 cm) thick. This layer was laced with deep, sharp-edged

TABLE 1

Physical and Chemical Properties* of
Jay Bee Fine Super Duty Firebrick

Identity	Jay Bee Fine
Class (ASTM: C 27	Dry Press
Method of Manufacture	Dry Press
Manufactured at	Mexico, Missouri
Physical Properties	P.C.E. (Pyrometric Cone Equivalent) (ASTM: C 24) ----- 33-34 (3.83°F, 1750°C) Hot Load Deformation - % (ASTM: C 16) 2640°F (1450°C) ------ 1.5 - 3.0 Reheat (% Linear Change) (ASTM: C 113) 5 hours @ 2732°F (1500°C) -- 0.2 to + 0.5 5 hours @ 2910°F (1600°C) -- 1.0 to + 0.5 Cold Crushing Strength psi, (ASTM: C 133) ----- 2100 - 3500 Modulus of Rupture, psi, (ASTM: C 133) ----- 1050 - 1500 Panel Spalling (ASTM: C 122) Super Duty (3000°F, 1650°C) ------- < 8% Bulk Density, (lb/cu ft) (ASTM: C 20) ----- 142 - 145 Apparent Porosity, - % (ASTM: C 20) ----- 11 - 14 Apparent Specific Gravity (ASTM C 20) ----- 2.59 - 2.61
Chemical Analysis (Ignited)	Alumina (Al_2O_3) --------------- 42.76% Silica (SiO_2) -------------- 53.15% Iron Oxide (Fe_2O_3) ----------- 1.07% Lime (CaO) --------------------- 0.47% Magnesia (MgO) ---------------- 0.57% Alkalis ----------------------- 0.87% Titania (TiO_2) ---------------- 1.11%

* As quoted by Kaiser Refractories.

SCALE: $\frac{1}{2}'' = 1'-0''$

A — 8" Common red brick
B — 2½" M-23 Insulating firebrick
C — 1½" H.T. Block insulation
D — 9" Jay Bee Fine Super Duty firebrick
E — Maxbond plastic refractory

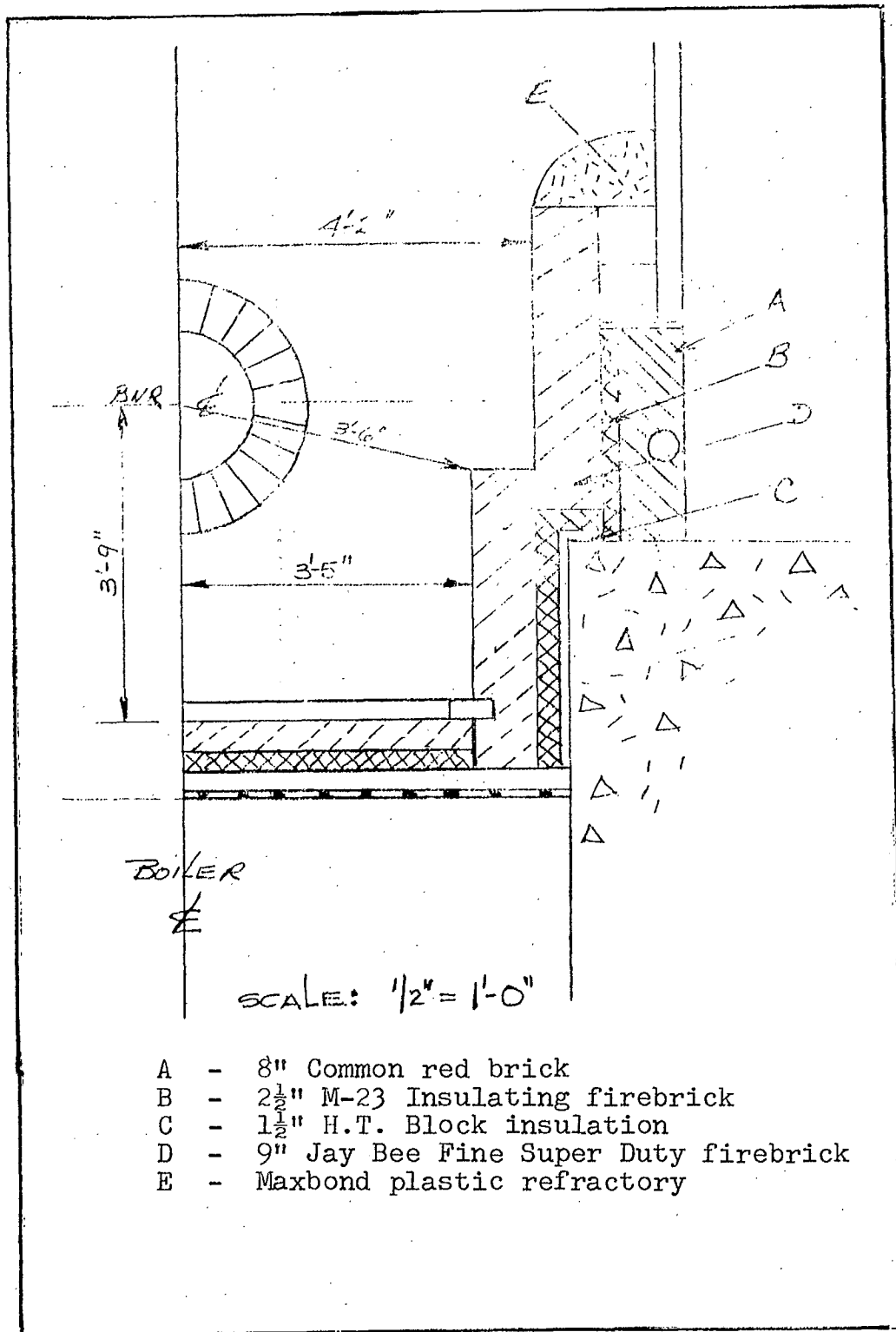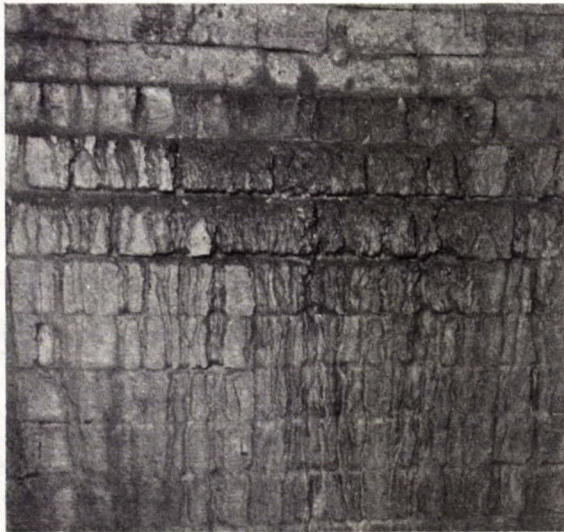Figure 1.   Cross Section of Boiler Combustion
            Chamber.

a) West wall and floor. The white objects are pieces of paper which were inserted into a crack running along the floor and up the wall. Front view is shown in (c).

b) West wall, showing erosion of brickwork and mortar. Note gauging caused by rivulets of molten material running down the wall. Erosion is particularly severe in the stepped region.
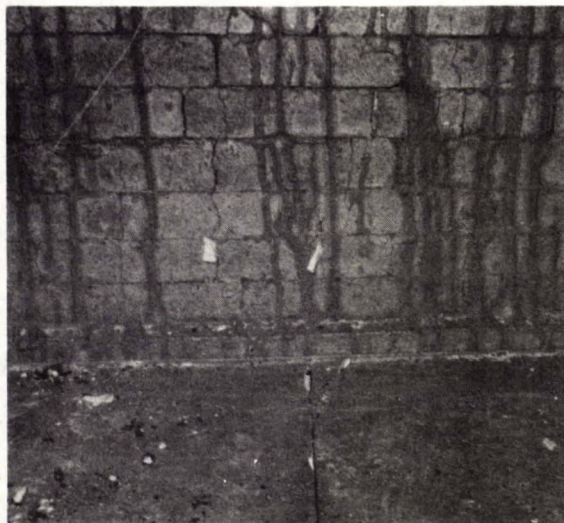
c) West wall, bottom section, showing cracking of wall and floor.

Figure 2. Appearance of Combustion chamber after Failure.
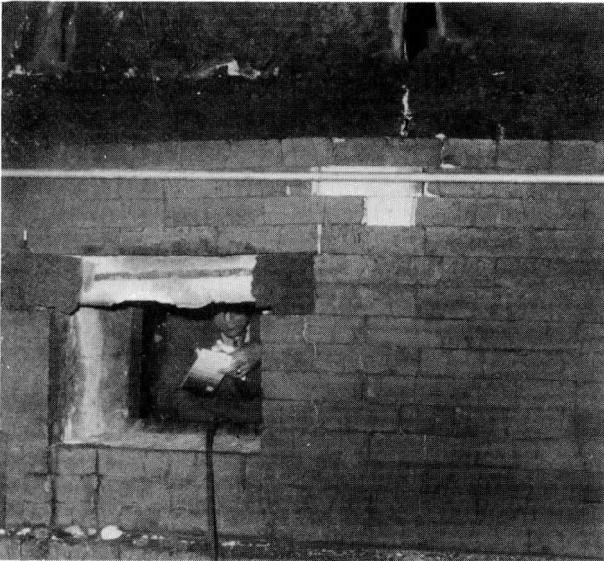
d) East wall, top section. Note accumulation of slag above wall at left of picture.

e) Front wall, bottom section.

Figure 2 (cont'd). Appearance of Combustion Chamber after Failure.

Figure 3. Damage to west wall in combustion chamber of Boiler #1.
Note Glazing of brickwork and accumulation of molten
material on steps.

Figure 4. Damage to east wall in combustion chamber of Boiler #1.
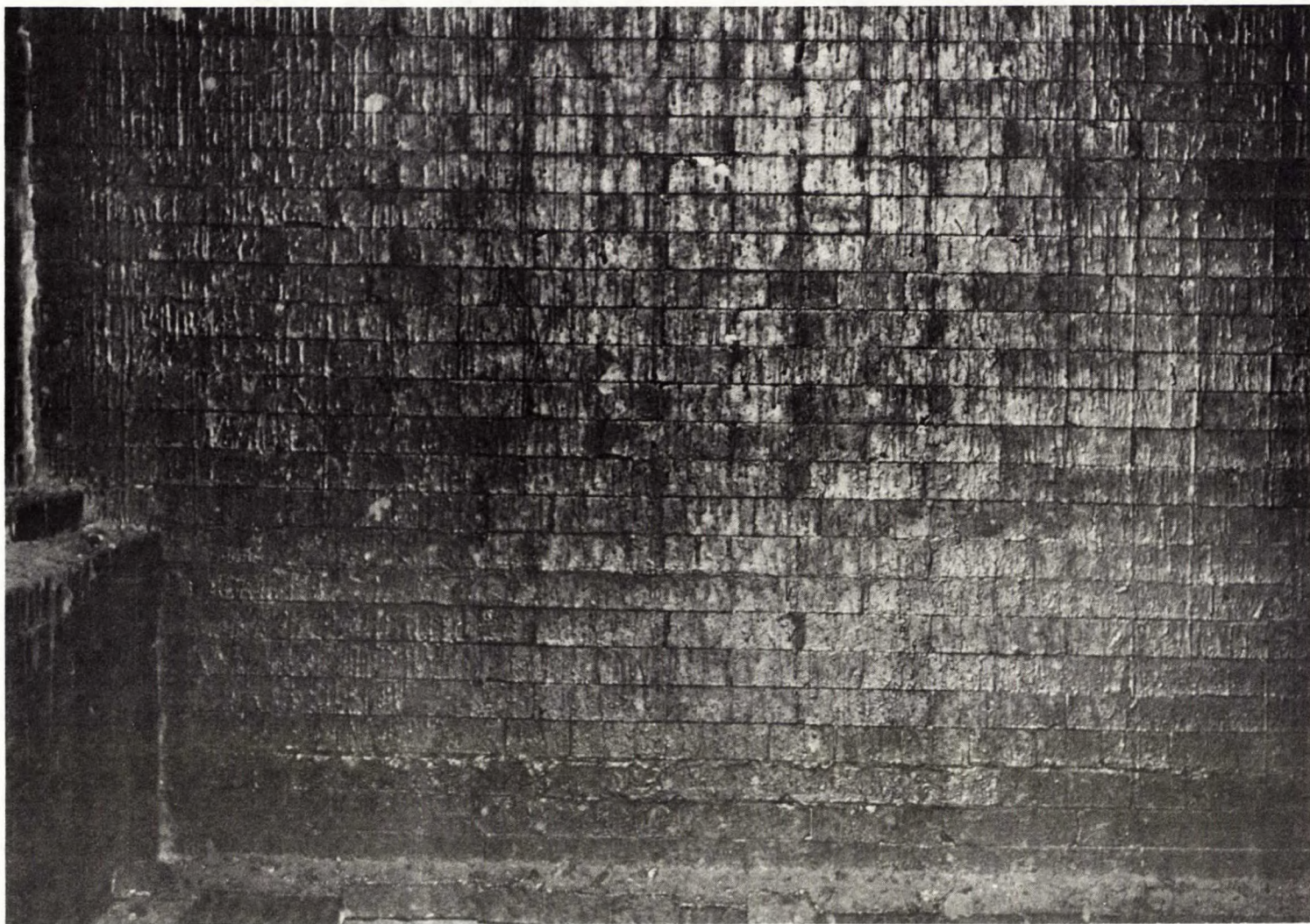
Figure 5.   Target wall of Boiler #1.
             Note that brickwork is glazed but not
             severely damaged.

Figure 6. Floor of combustion chamber in Boiler #1. Note heavy accumulation of slag-like material.

BOILER TUBES

B&W TYPE "G"
WATERTUBE BOILER
MCR 35,000 PPH

MT-20 BURNER

3'-9"

Figure 7. Showing position of boiler tubes and approximate
position of refractory lining (Dotted Rectangle)
Note: Numbers refer to the areas from which samples
were taken for examination.

cracks up to 1/32 in. (0.08 cm) wide. Lumps of material which were lying on the floor of the the combustion chamber appeared to be of the same texture as that lodged over the burner.

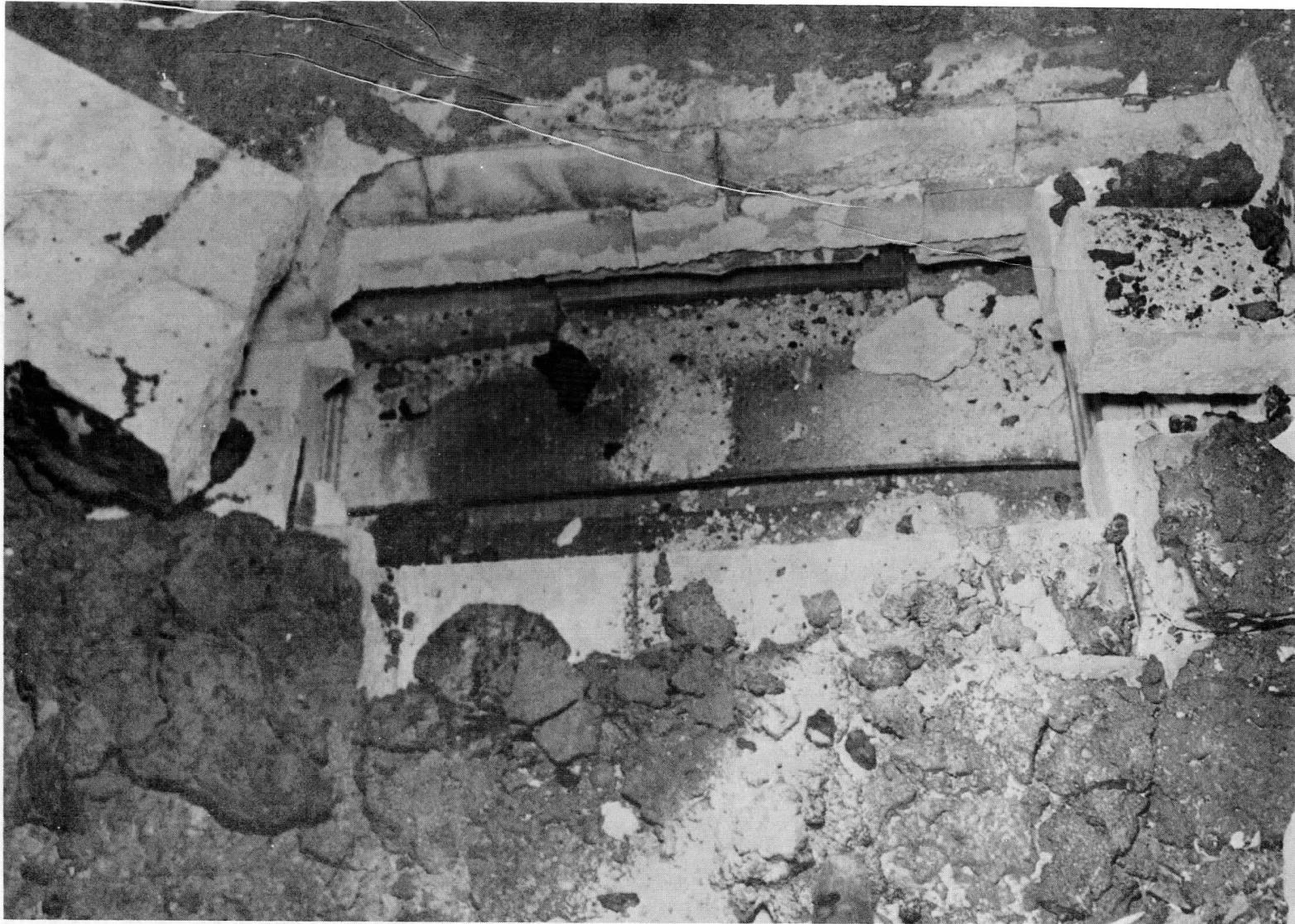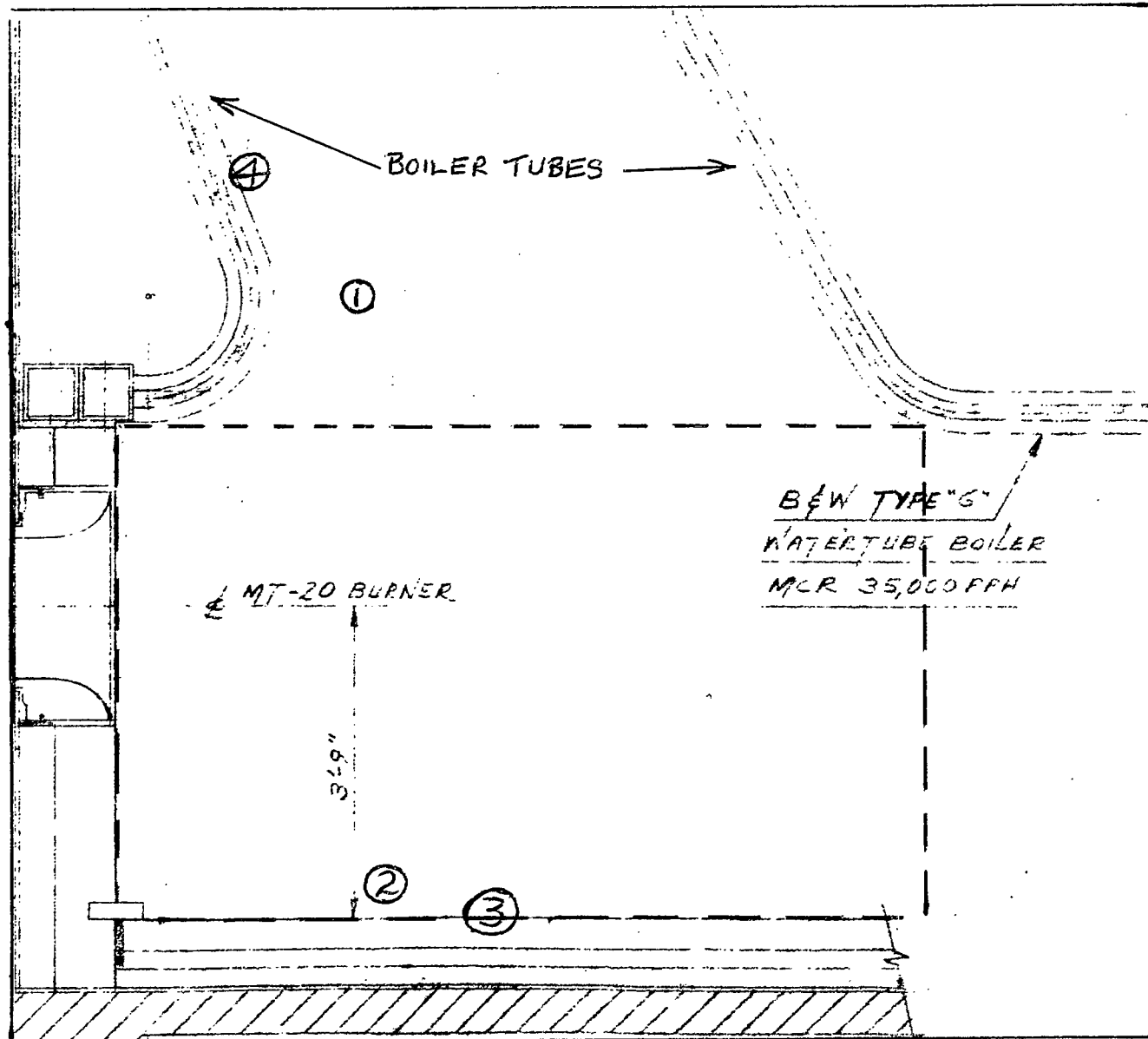## Experiments to Determine Cause of Failure

Because the failure of the combustion chamber refractories appeared to be the result of melting of one or more of the materials present, it was decided to determine the individual melting points of these materials. At the same time, it was felt that useful information could be obtained by studying the effects of heating the various materials to high temperatures when placed in close contact with each other.

Determination of Melting Points

From the samples provided by Mr. Fainstat, the following specimens were selected for examination: -

ash from the boiler east wall close to the front wall (Area #1 in Figure 7);

slag from the top layer of material on the floor (Area #2 in Figure 7);

dense glassy material from the floor (Area #3 in Figure 7);

slag from the front and rear of the west wall (Area #4 in Figure 7);

unused Jay Bee Super Duty firebrick;

mortar removed from undamaged brickwork;

undamaged plastic refractory (Maxbond).

These specimens were examined with the Leitz heating microscope and subjected to chemical analysis.

The Leitz heating microscope consists essentially of a light source, a resistance wire furnace, and an optical viewing system. The maximum temperature at which the furnace can be operated is 3183°F (1750°C).

The important features of the microscope are shown in Figure 8. The microscope specimens consist of 0.125 in. (0.32 cm) right cylinders, which are pressed in a hand press from the powdered samples. For this purpose, the samples taken from the combustion chamber were first ground to pass 200 mesh (Tyler) screens. The specimens are placed on a Pt/18% Rh plate which is positioned on the end of the thermocouple sheath as shown in Figure 8(c). In the furnace, the specimen can be viewed during
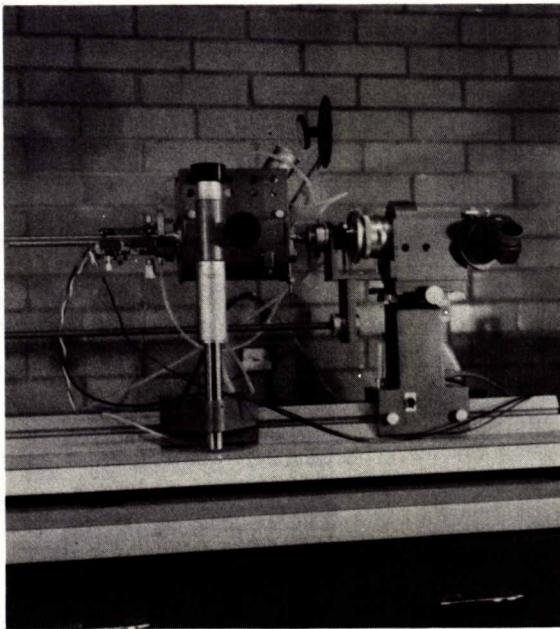
a) General view of Furnace (left) and optical assembly (right).
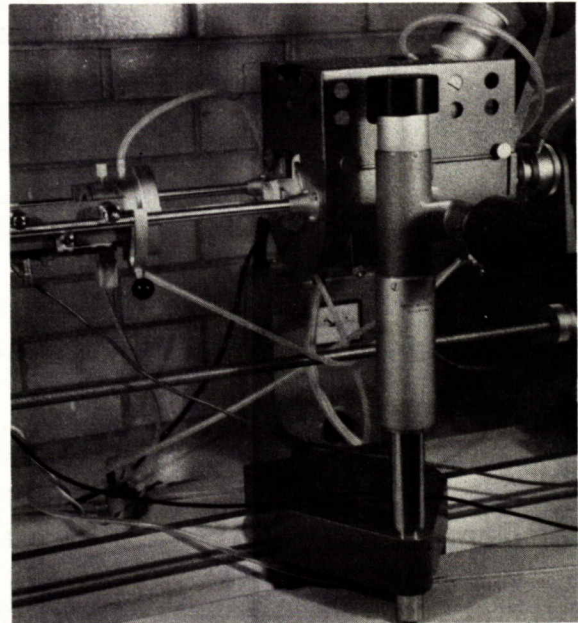
b) Thermocouple housing and furnace.
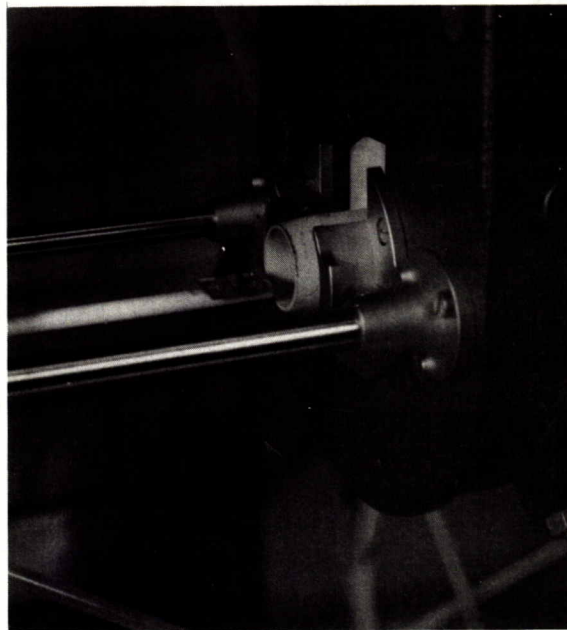
c) Showing location of specimen on thermo-couple sheath.

Figure 8.   Leitz heating microscope, furnace and optical assembly.

the heating cycle. The temperature is indicated on an illuminated scale included in the field of view. The temperatures were checked with a slide-wire potentiometer and found to be within 9°F (5°C) of the values indicated on the scale.

Heating was carried out at a rate of 18°F (10°C)/min. until the specimen melted. The changes which occur on heating the fly ash (Sample 1) in air are shown in Figure 9. The specimen shrinks up to 2282°F (1250°C), bloats from 2372°F (1300°C) to 2516°F (1380°C), and finally melts. The melting point is taken to be the hemispherical point(2) which in this case was 2624°F (1440°C). The changes in brightness of the specimen are due to differences in surface radiation and to the fact that a blue filter was inserted between the specimen and the ocular at 2192°F (1200°C).

Figure 10 shows the changes in the unused Jay Bee firebrick (Sample 5) on heating in air. The melting point lies between 3146° and 3155°F (1730° and 1735°C) indicating a P.C.E. of Cone 33.

The changes which occur in the Maxbond Plastic refractory (Sample 7) on heating in air are shown in Figure 11. The melting point is approximately 2850°F (1566°C) indicating a P.C.E. of Cone 20. This material softens and distorts under its own weight at about 2696°F (1480°C).

Figure 12 shows the changes which occur in the glassy material from the floor of the combustion chamber (Sample 3) on heating in air. Shrinkage commences between 2190° and 2280°F (1200° and 1250°C) after which bloating takes place from 2370° to 2550°F (1300° to 1400°C). The melting point is approximately 2550°F (1482°C).

Study of Effects of **Fly** Ash on Refractories at High Temperatures

To study the effects of heating the fly ash in direct contact with the combustion chamber refractories, the heating microscope was again employed.

A specimen of the ground fly ash was placed on top of a similar specimen of ground refractory and the two were heated together at 18°F/min. (10°C/min.).

The results of heating the fly ash in contact with the Jay Bee Super Duty firebrick can be seen in Figure 13. Fusion of the ash takes place as observed in Figure 9 though the firebrick specimen appears unchanged up to 2642°F (1450°C). At 2660°F (1460°C) the molten ash begins to run off the firebrick specimen as indicated by the formation of a meniscus at the bottom of the setting. This process continues until at 2735°F (1502°C) the flat top of the firebrick specimen shows above the
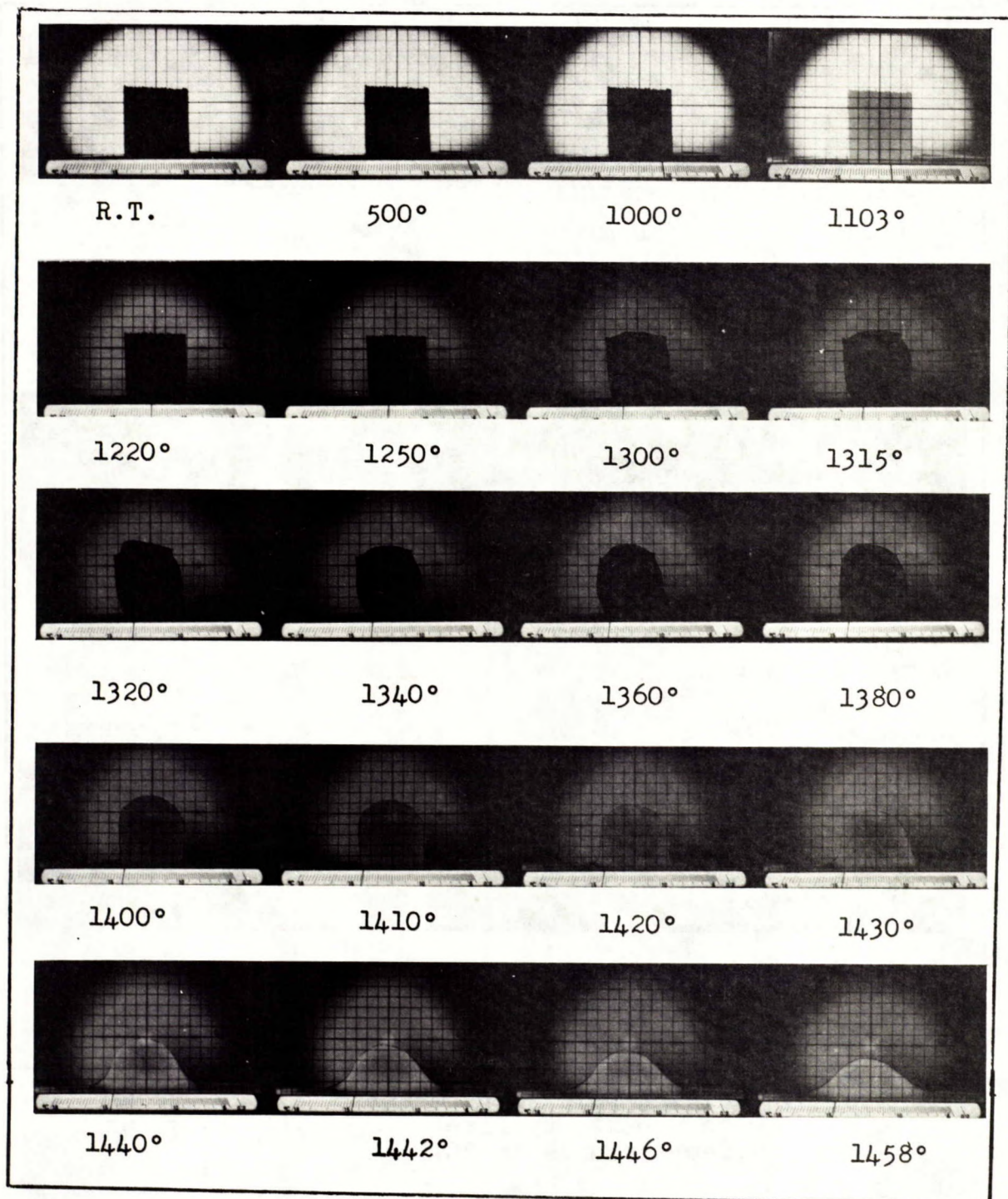
Figure 9. Melting point determination of fly ash (Sample 1) in air (Temperatures in °C).
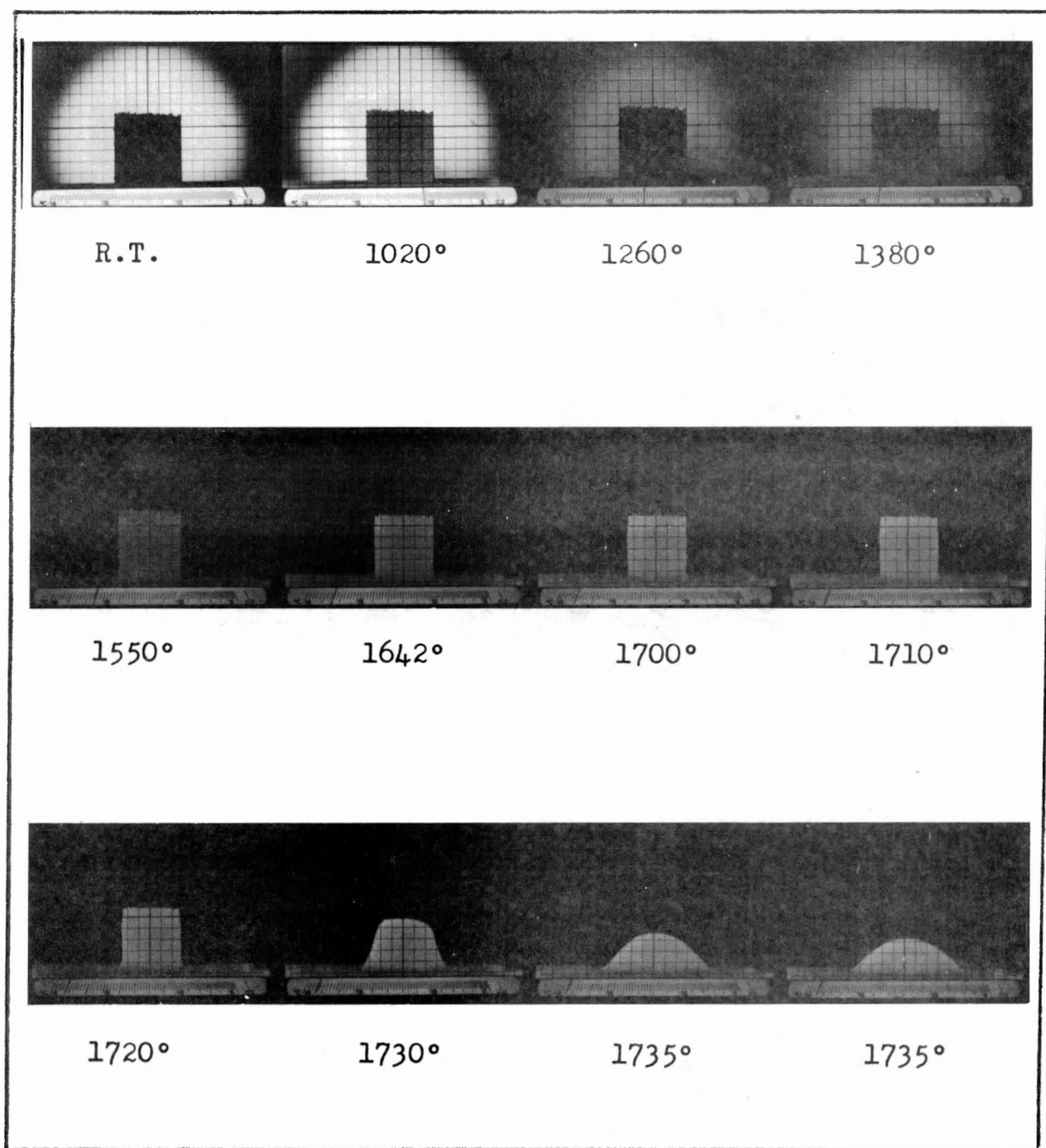
Figure 10. Melting point determination on unused Jay
Bee Super Duty firebrick (Sample 5) in air
(Temperatures in °C).

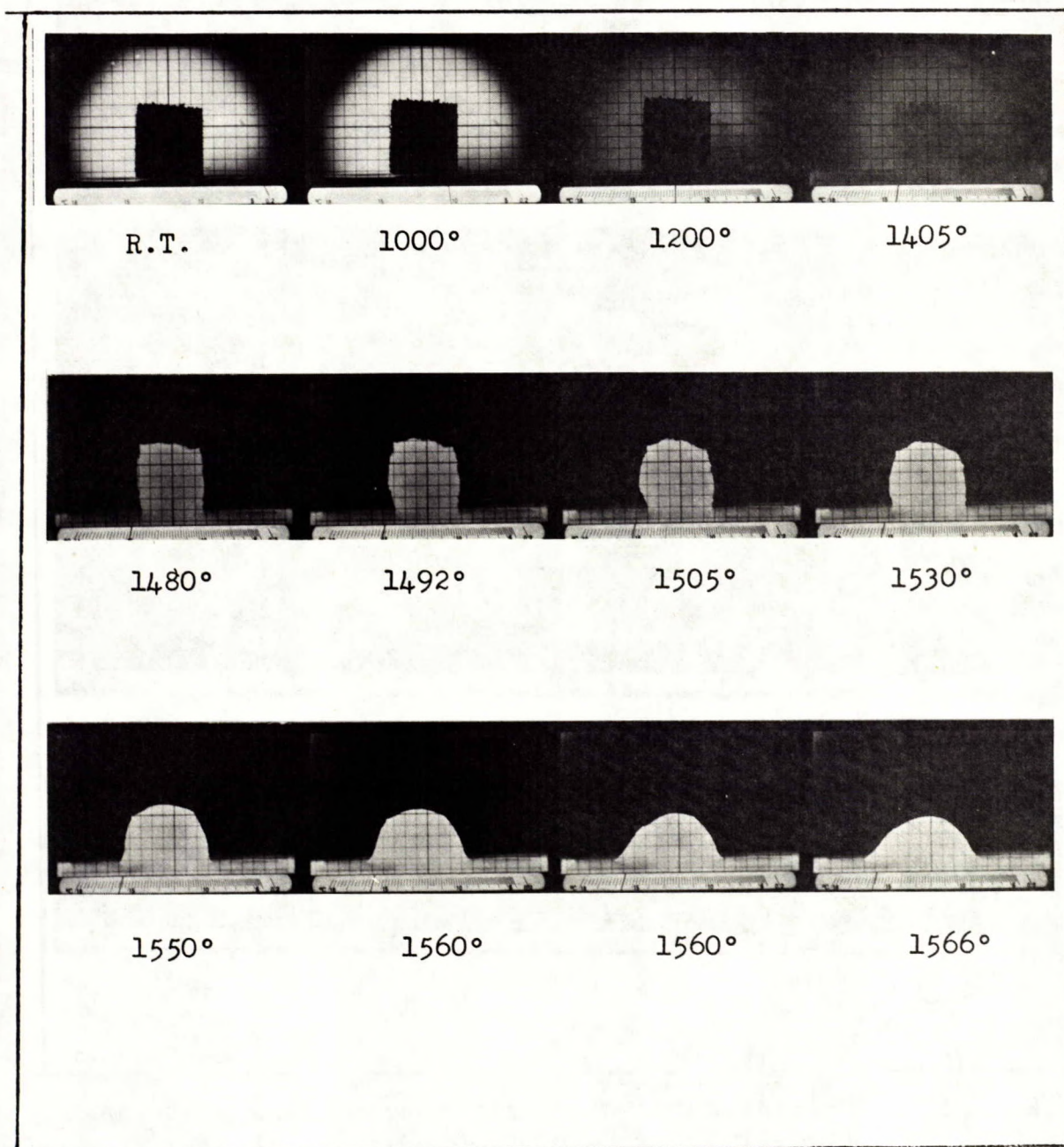Figure 11.   Melting point determination on plastic
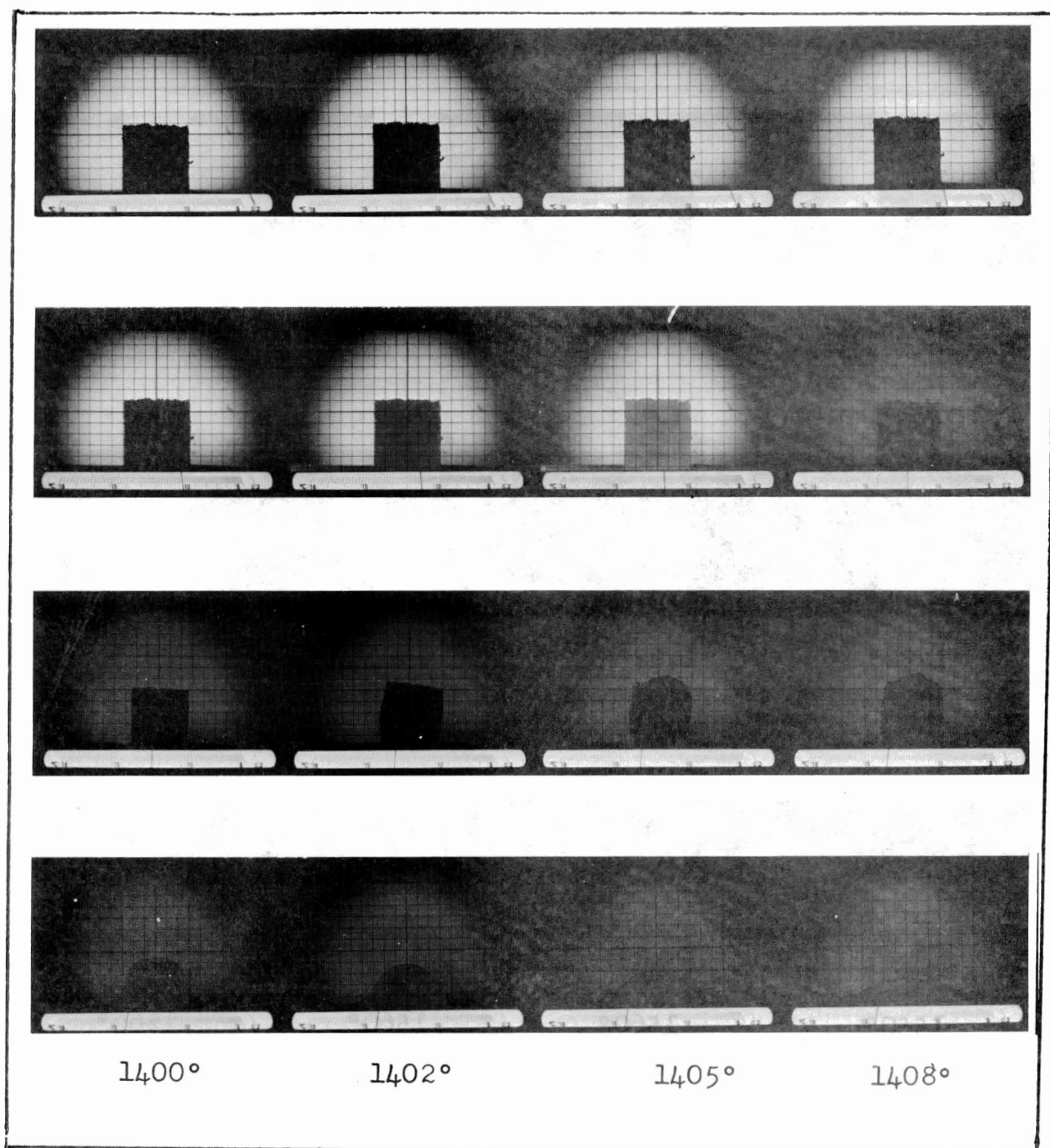refractory (Maxbond) (Sample 7) in air
(Temperatures in °C).

Figure 12. Melting point determination on glassy material
from floor of furnace (Sample 3), in air.
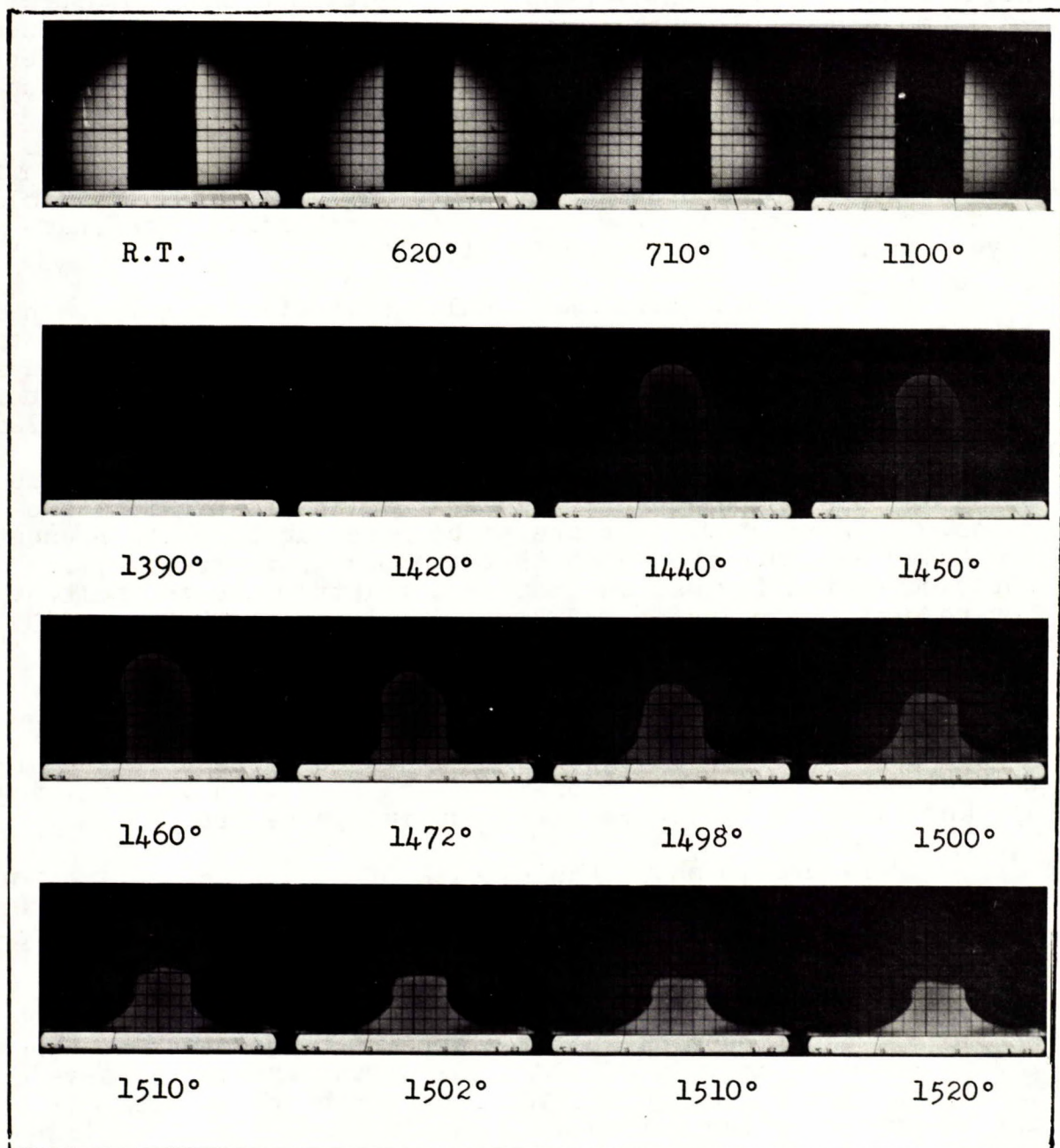(Temperatures in °C)

Figure 13.   Melting of fly ash (Sample 1) on unused Jay
             Bee Super Duty firebrick (Sample 5) in air.
             (Temperatures in °C) (ash specimen in top).

meniscus. Some erosion has occurred as indicated by the rounding off of the corners. Shrinkage of the firebrick specimen alone would occur at this temperature due to sintering of the minus 200 mesh material (Figure 10). Severe erosion appears to commence at 2768°F (1520°C). The heating rate employed here was high, such that the experiment was completed within 2½ hours. It is most probably that severe erosion of the firebrick would occur at temperatures lower than 2758°F (1520°C) if sufficient time were allowed. However, it seems clear that for erosion to occur, the ash must be in the fused state.

The results of heating the fly ash in contact with the refractory mortar are shown in Figure 14. They are very similar to those obtained with the super duty firebrick. Note that severe erosion occurs at 2822°F (1550°C).

Figure 15 shows the results of heating the fly ash in contact with the Maxbond Plastic refractory. It is evident that this material is much less resistant to attack by the molten ash than either the Jay Bee Super Duty firebrick or the refractory mortar. Note the configuration of the specimen at 2660°F (1461°C). This was not observed in Figure 13 or Figure 14 at the same temperature, and it suggests that the viscosity of the liquid phase at this temperature is higher than in the previous two cases. However, there appears to be more liquid phase present. The above evidence indicates that the plastic refractory is attacked by the fly ash as soon as the latter becomes molten. Severe erosion begins at 2678°F (1470°C) and at 2732°F (1500°C) the refractory specimen has practically disappeared.

The above determinations were performed by heating the specimens in air, i.e., in an oxidizing atmosphere. However, during the operation of the boiler it is possible that the atmosphere in the combustion chamber may not have been as oxidizing as air and in fact may have been reducing in nature.

Figure 16 shows the results of heating a specimen of fly ash in contact with a specimen of the unused Jay Bee super duty firebrick in an atmosphere of nitrogen. Under these conditions the fly ash shows practically no bloating tendency though some liquid phase is present at 2444°F (1340°C) as indicated by the bubble on the right hand side of the specimen. Erosion of the firebrick specimen appears to commence at about 2678°F (1470°C) and, at 2735°F (1502°C), the erosion is severe. Therefore, under these conditions the firebrick is less resistant to attack by the molten ash than if heated in air (Figure 13).

The results of heating fly ash in contact with the firebrick in a natural gas atmosphere are shown in Figure 17. Between 1472° and 1526°F (800° and 830°C) the ash specimen began to disintegrate into a loose powdery mass and, at 1640°F (893°C), the firebrick specimen was almost completely enveloped. Heating was discontinued at this point to avoid damaging the furnace tube.
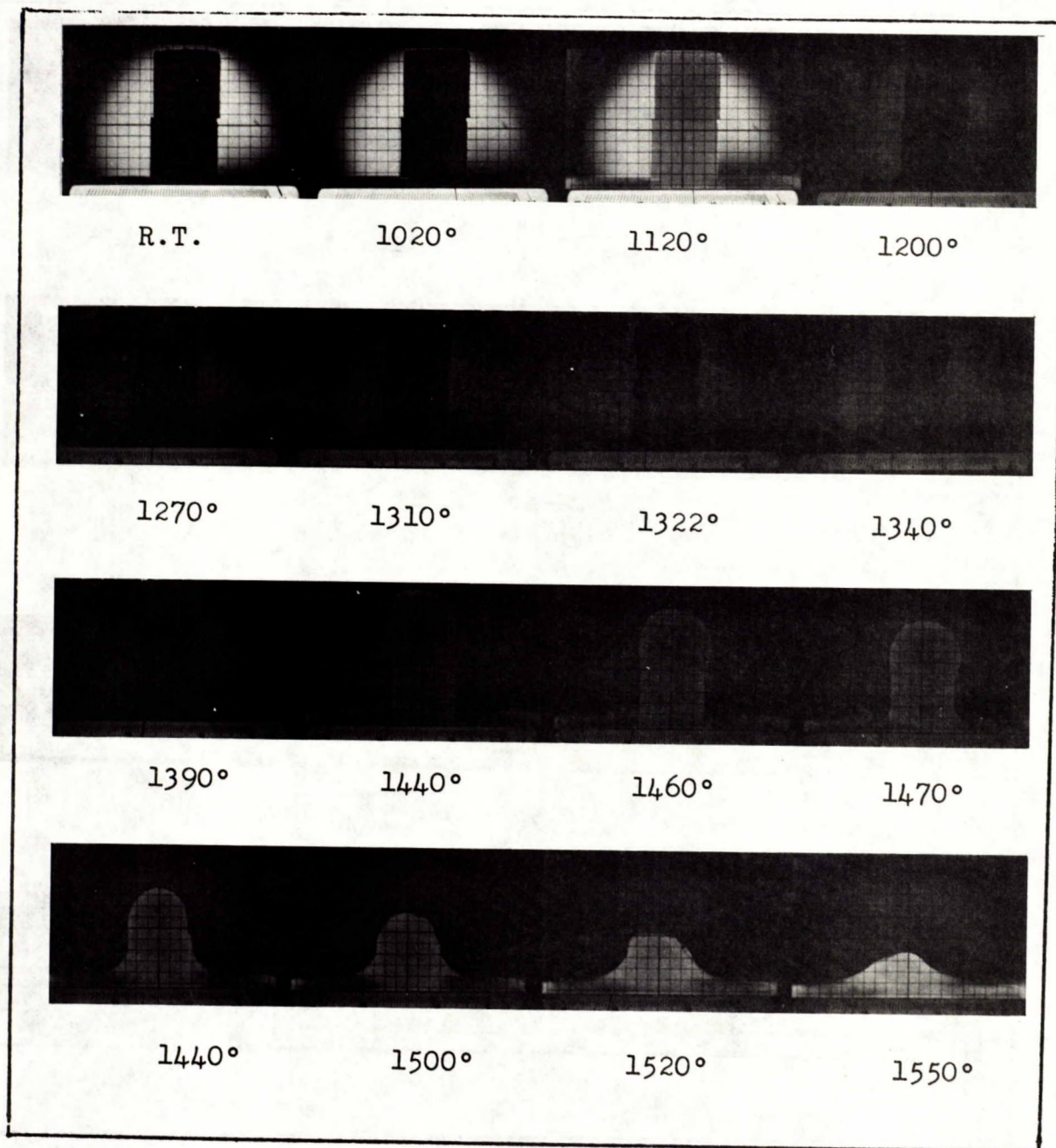
Figure 14. Melting of fly ash (Sample 1) on re-
fractory mortar (Sample 6) in air
(Temperatures in °C).

- 22 -
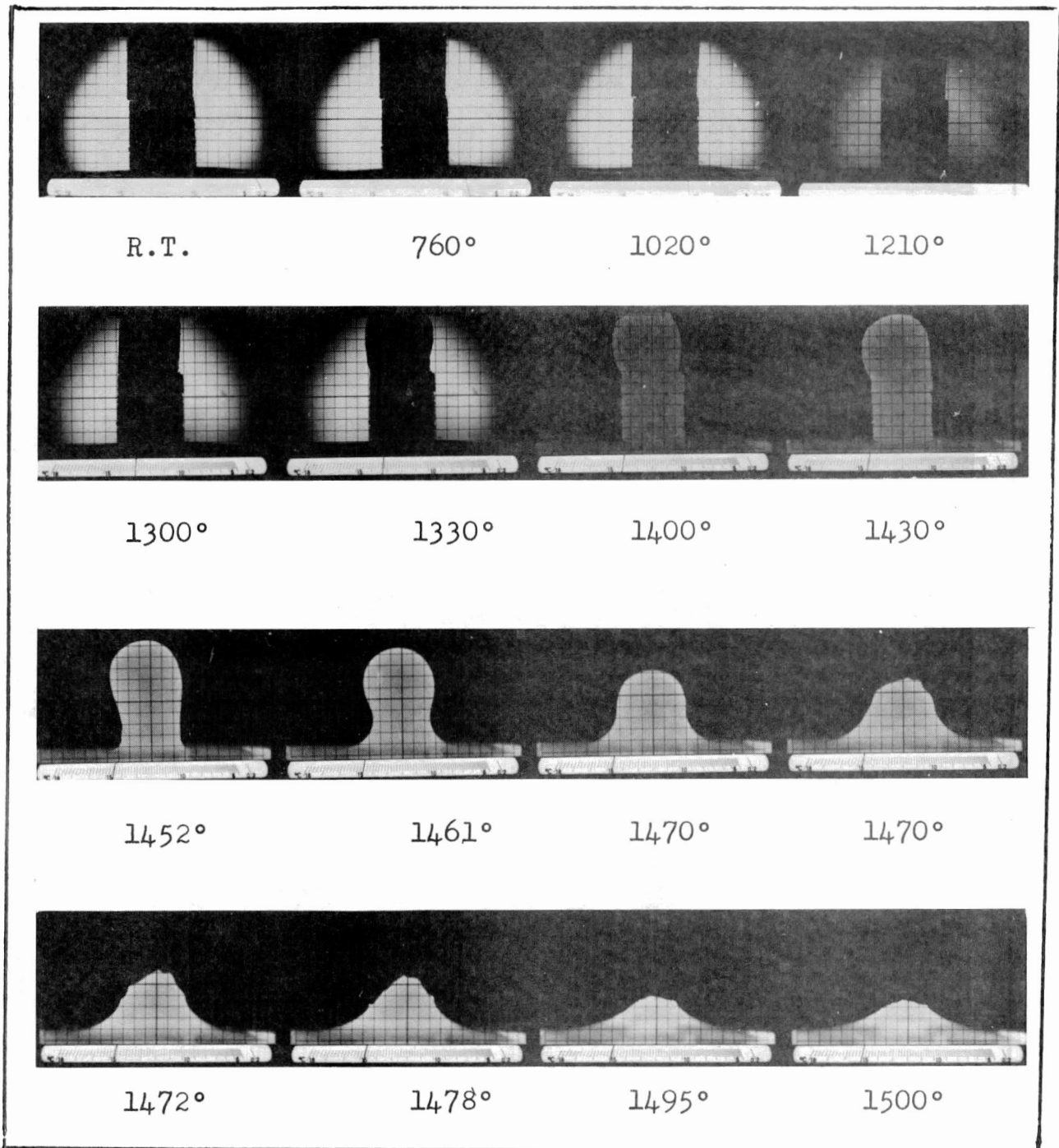
Figure 15. Melting of fly ash (Sample 1) on Maxbond
Plastic refractory (Sample 7) in air
(Temperatures in °C).

Figure 16. Melting of fly ash (Sample 1) on unused Jay Bee Super Duty firebrick (Sample 5) in nitrogen. (Temperatures in °C).

R.T.   600°   800°

830°   842°   893°
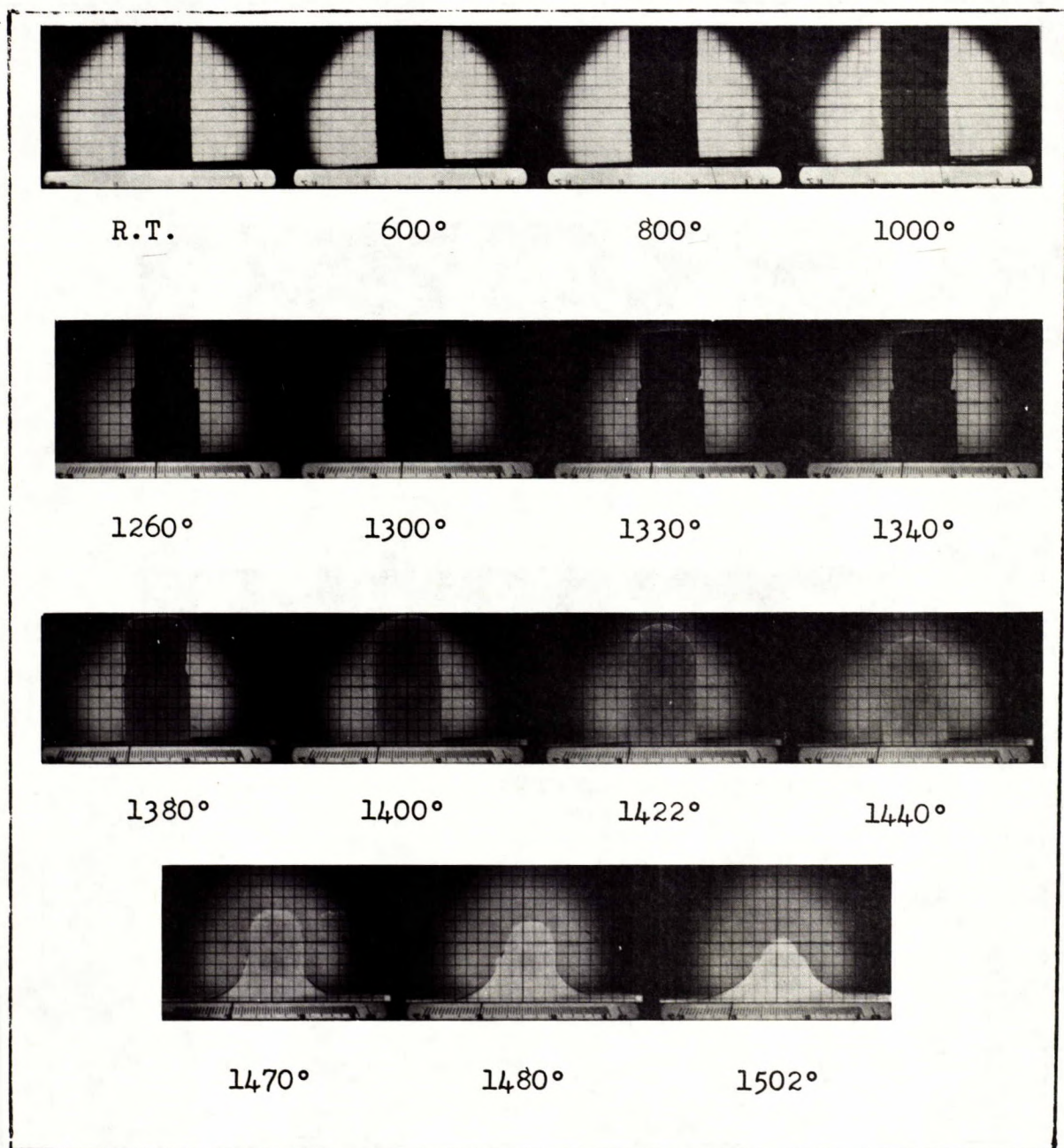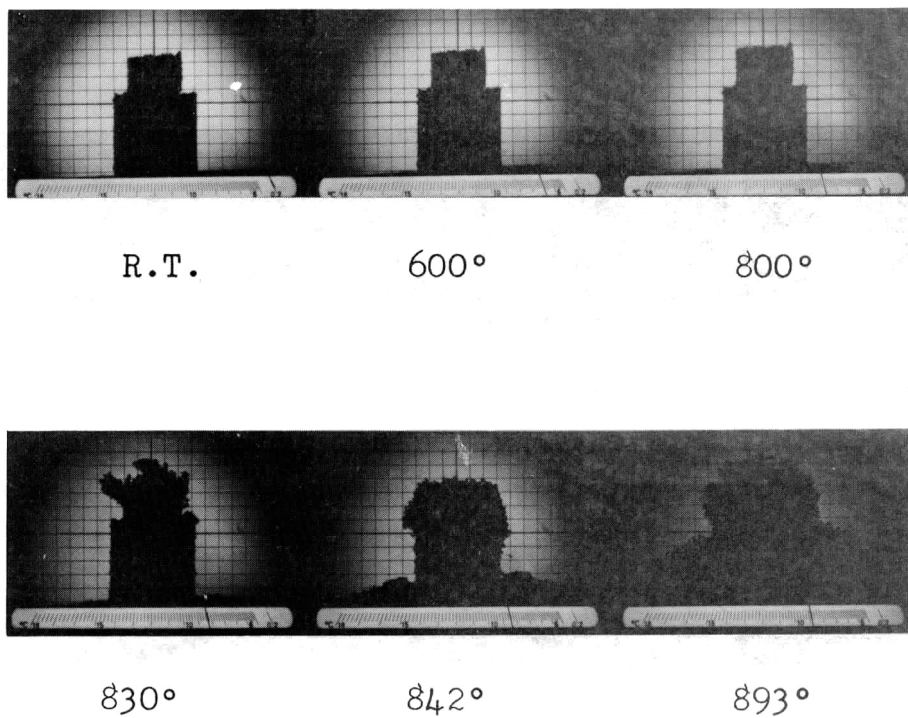
Figure 17.   Heating of fly ash (Sample 1) on unused Jay
             Bee Super Duty firebrick (Sample 5) in
             natural gas. (Temperatures in °C).

(a)
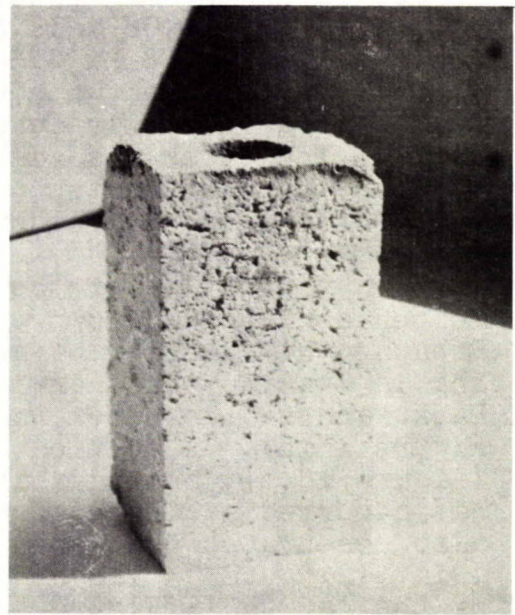
(b)
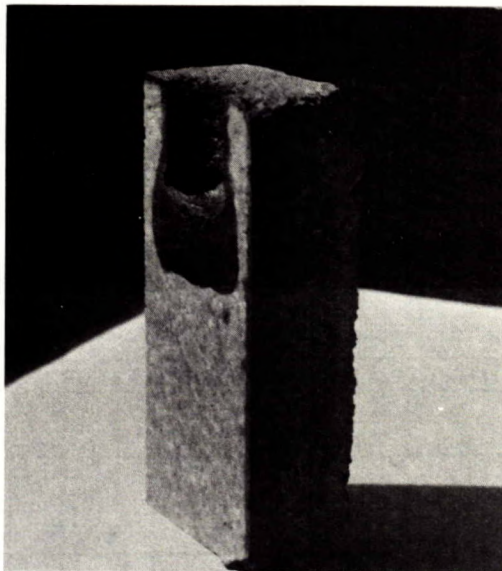
(c)

Figure 18.   Results of heating fly ash in air to 2894°F
             (1590°C) in a cylindrical cavity cut in unused
             Jay Bee Super Duty firebrick. a) Showing groov-
             ing of brick caused by flow of molten ash.
             b) Showing reverse face to be undamaged. c)Sec-
             tion through cavity showing increase in diameter
             at bottom of cavity due to fluxing, and deep
             penetration into brick.

To study the effects of the molten coal ash on the firebrick in the manufactured state, a block measuring 2 x 2 x 4½ in. (5.08 x 5.08 x 11.4 cm) was cut from an unused brick and a 1.5 x 1 in. (3.81 x 2.54 cm) cylinder was drilled in one end. The hole was packed with powdered fly ash and the block was heated in an electric furnace in air to 2894°F (1590°C) for 9 hours. The block was tilted slightly out of the vertical so that any flow of molten ash would damage only one face. The results of this test are shown in Figure 18.

Grooving of the front face of the block caused by the molten ash running downwords can be seen in Figure 18(a). Because the quantity of ash was limited, the extent of the grooving is less severe than if the flow had been continuous. The back face of the block was completely undamaged as seen in Figure 18(b). A section, cut through the centre of the cavity (Figure 18(c), showed that a considerable increase in diameter had occurred at the bottom. Furthermore, the molten ash had also penetrated downwards into the block to a depth of about 1 in. (2.54 cm). The needle-like crystals, seen at the bottom of the cavity in Figure 18(c), were identified by X-ray Diffraction Analysis as mullite, $(3Al_2O_3 \cdot 2SiO_2)$.

Chemical Analyses

Chemical analyses were performed on the fly ash (Sample 1), the material from the top layer on the floor (Sample 2), the glassy material from the floor (Sample 3), and the material from the front end near the west wall (Sample 4). The results of the analyses are given in Table 2.

TABLE 2

Chemical Analyses of Samples from
Damaged Combustion Chamber

Sample No.	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3* (%)	Na_2O (%)	K_2O (%)	V_2O_5 (%)
1	28.06	19.24	47.83	1.02	1.29	0.045
2	46.18	40.94	12.71	0.51	0.64	0.54
3 **	36.92	28.47	30.63	0.82	1.12	0.61
4	29.80	18.54	45.83	1.12	1.29	0.41
* Represents total iron. ** 2.13% Gain in weight on ignition.						

A chemical analysis was also performed on the fuel oil employed in the firing of the boiler. The results of this analysis are given in Table 3. Some physical properties of the fuel oil are also reported in Table 3.

The analysis of Sample 2 in Table 2 indicates that it is probably composed largely of firebrick. Note that the vanadium content increases as the material descends from the boiler tubes (fly ash) to the floor of the combustion chamber (glassy material). The vanadium is evidently picked up from the fuel oil because the latter contains almost exactly the same quantity (% V_2O_5 basis) as the fly ash (Sample 1).

TABLE 3

Chemical Analysis and Physical
Properties of Fuel Oil

Element	S	V	Na	K
Weight %	2.03	.0242	.0019	N.D.

Viscosity at 122°F (50°C) *		
Centistokes	650	
Saybolt Furol Sec.	307	
Specific Gravity, 60/60°F (15.6°C)	0.975	
Gravity, °API, 60°F (15.6°C)	13.6	

* Viscosity limits of a No.6 fuel oil are between 45 and 300. Saybolt Furol Sec. at 122°F (50°C).

DISCUSSION

From the evidence presented above it is clear that the failure of the combustion chamber refractories was the result of fluxing by molten fly ash.

If the ash surrounding the boiler tubes had been removed after the conversion to oil firing and before the boiler was put into service, the situation would never have arisen. While the boiler was coal-fired the side walls had no stepped region; therefore falling material could not find a lodgement

and, would pass into the ash pit. It is possible that there are pieces of fused ash in the ash dump.

The vanadium in the fuel oil has evidently aggravated the situation because the material from the floor of the furnace melts at a temperature 104°F (40°C) lower than the ash itself and its vanadium content is almost fourteen times that of the ash. The formation of aluminum vanadate ($AlVO_4$) by reaction of vanadium pentoxide (V_2O_5) with the alumina, in the ash or in the firebrick, would increase the fluxing action(3). The material (Sample 3) from the floor of the combustion chamber showed a gain in ignition in air (Table 2), which is probably due to oxidation of carbonaceous material. This indicates that the atmosphere under the burner flame may have been reducing. It has been shown (Figures 13 and 16) that under these conditions the attack by the fly ash on the Jay Bee Super Duty firebrick is more severe; this would account for the heavy build up of glass on the floor.

The question remains as to what caused the ash to fall once the source of build-up, i.e., coal firing, had been removed. Experiments with the heating microscope have shown that considerable bloating of the ash occurs when the temperature reaches 2372°F (1300°C). Local over-heating could have loosened some of the ash on the boiler side walls if combustion of fuel had occurred in the higher regions of the chamber. It is more likely that this could have caused loosening of the ash lodged on the overhang above the target wall.

Contraction and expansion on shutting down and lighting up the boiler could also have loosened the ash. The cracks, observed by the author in the slag lodged on the front wall, were most probably caused by thermal stressing of the material.

It has been demonstrated that heating the ash in a strongly reducing atmosphere causes powdering to take place. There was no evidence of powdering in the upper regions of the damaged chamber, indicating that loosening had not occurred by this means.

A fourth factor to be considered is vibration of the structure during the relining and conversion operations. This together with thermal dimensional changes seem the most likely causes of loosening of the ash.

In any future conversions of this type, it should be mandatory that fly ash be completely removed before the installation is put into service.

CONCLUSIONS AND RECOMMENDATIONS

The failure of the combustion chamber refractories was due to fluxing by fly ash which had fallen from lodgements in the tube-work above the combustion chamber and fused the high-temperature region.

In future conversions, all traces of ash should be removed prior to putting the installation into service.

When using fuel oils with high vanadium contents, great care should be exercised to obtain the optimum dispersion and combustion conditions, even in the absence of fly ash. If partially burned droplets of oil are allowed to fall directly onto the refractories, the latter will be attacked, over a period time, by the vanadium pentoxide formed when complete combustion of the droplets subsequently takes place. Under these conditions the life of the refractories affected would be expected to vary inversely with the vanadium content of the oil.

ACKNOWLEDGEMENTS

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