The design and development of furnace linings for manganese alloys smelting.

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ABSTRACT

Due to the reaction of manganese alloys and slag with refractory materials and carbon in particular, the design of furnace linings for ferromanganese smelting has always been problematical. At the Meyerton Works of Samancor a systematic program has been followed to optimize the design of furnace linings, This objective was achieved by

1 Observations made during furnace relines.
2 Increasing the thermal conductivity of lining materials, thereby increasing heat flow through the lining in order to establish a freeze zone in the furnace.
3 Increasing the diameter of the furnace.
4 Measurement of temperatures in various positions in the furnace lining.
5 Making use of a computer model to predict the position of isotherms in the lining.
6 Improvement of workmanship during installation of furnace lining.

This paper will illustrate how the operation of the furnace can affect the wear pattern of the lining. If the electrical current in the furnace is not controlled, it can cause arcing to the side walls with detrimental effect to the lining.

During the development period the rating of our large furnaces has increased from 48 MVA to 81 MVA, however, during the same period the life of a furnace lining has increased by more than 150% and is expected to increase even more.

This paper will deal mainly with the design of linings for our large furnaces which are operating at loads in excess of 40 MW.

1 INTRODUCTION

The ferro-alloy industry in the world has grown exponentially during the last five decades. Simultaneously submerged arc furnace technology has improved and the size of furnace installations has increased tremendously. As one of the largest ferro-alloy producers in the world, Samancor has shared in this growth. To benefit from economy of scale, Samancor has also endeavoured to increase the size of new furnace installations. [1)]

The Meyerton Works of Samancor Limited has a full spectrum of furnace sizes ranging from 4,5 MVA to 81 MVA. In the process of increasing furnace capacity a new problem arose. It appeared that the design and size of furnace linings did not keep pace with the increased power input and therefore numerous hot metal breakouts occurred in the years following the installation of the new generation furnaces.

The Meyerton Works mainly produce high carbon ferromanganese and silicomanganese. The slag from these processes is extremely aggressive to refractory materials resulting in a continuous search for improved refractory materials. After discussions with suppliers of furnace linings it was evident that there was virtually no experience or information from literature available for this application. Samancor thus had to embark on its own programme to design and optimise their furnace linings. During this program a new concept of lining design was adopted which proved to be successful.

A systematic program was followed to solve the problem. This paper discusses the steps which were taken to optimise the design of furnace linings and gives an overview of the experience at the Meyerton Works of Samancor Limited.

2 OVERVIEW OF MEYERTON WORKS

Operations at the Meyerton Works started in 1942. Presently there are 10 furnaces producing manganese alloys. The new generation furnaces consist of M10 and M11 (commissioned in 1973/1974) and M12 furnace (commissioned in 1978.) It was after the commissioning of these large furnaces that the lack of proper lining design became apparent. This paper will deal mainly with the experience on these large furnaces as very few hot metal break-outs occurred on the small furnaces.

Most of the results presented in this paper will be from experience gained at M12 furnace as the new concept of lining design was first implemented on this furnace. The same principle was later applied at M10 and M11 furnace with success. Although lining design is not very critical on the small furnaces, the same design principles are presently applied when one of these small furnaces are relined.

Table I summarises the most important design parameters of the furnaces.

3 HISTORY OF PREVIOUS AND PRESENT LINING CAMPAIGN

It was after a hot metal break out on M12 furnace in November 1980 that a decision was made that a new approach in lining design was necessary to increase the life of the furnace linings. Up to that point in time the performance of furnace linings was unacceptable. Table II summarises the history of furnace linings installed prior to the beginning of 1981 as well as the tonnages produced on each lining.

During these lining campaigns there were numerous hot metal break-outs which were repaired. In the case of the third lining of M10 furnace a break-out occurred in the slag taphole area within 2 months after start-up of the furnace after the reline.

The life of the second lining on M11 furnace was prolonged by changing from ferromanganese to silicomanganese. In general it can be said that the side walls of the lining last longer on silicomanganese than on ferromanganese. This can be attributed to the fact that the reaction crucible is smaller when silicomanganese is smelted and therefore a natural protective wall is formed between the reaction zone and the side wall. On the other hand the wear on the hearth is more severe in the case of silicomanganese due to the higher reaction temperature and increased thermal load on the floor due to the smaller crucible.

During November 1976 the transformer capacity on M10 and M11 furnaces was increased from 48 MVA to 75 MVA. After the increase in transformer capacity, the furnace shell diameter was increased from 13,2 m to 15,6 m during the relinings of M10 in 1978 and M11 in 1977 respectively.

All the furnace linings which were installed after the new concept of lining design was implemented, are still in operation. Their history at the time of writing this report (February 1986) is outlined in Table III.

4 OBSERVATIONS MADE DURING FURNACE RELINES

During every reline extensive investigations were done and observations made of the lining being replaced in an effort to try and understand the mechanisms by which a lining is destroyed and the factors which influence the wear of a lining. Some of these studies have been reported previously [2]. Samples of different sections of the lining were also taken and analysed.

The results of all these studies and observations and the conclusions arrived at can be summarised as follows:

1 The reaction zone of the furnace was in the shape of a clover leaf fitted around the electrodes. In the area closest to the electrodes, the reaction zone was extending into the lining, and in the area furthest away from the electrodes, the lining was still intact and it had a layer of slag and partly sintered raw materials frozen on the surface.

It must also be noted that the electrode face to crucible (ELC) distance is smaller than the electrode face to face (ELF) distance (Table I)

This led to the conclusion that the inside diameter of the lining was too small. It was thus theoretically possible that a part of the electrode current could flow to the side wall which could cause erosion of the side wall.

2 In the production of manganese alloys in large furnaces it is common practice to operate with a slag layer in the furnace. In the case of the large furnaces the difference in height between the slag and metal tapholes is one meter. The wear of the lining was more severe in this slag layer area and this was probably caused by continuous attack of the slag on the carbon lining. It is well-known that manganese slag is very aggresive towards carbon. During the reline of M12 furnace in November 1980, it was observed that one layer of carbon blocks in the slag layer area had been completely dissolved.

3 Lining wear was also more severe in the taphole areas but this could be attributed to the use of oxygen lancing to open tapholes. Although taphole drills were normally used, oxygen lances were used when tapping problems occurred.

4 When ferromanganese was produced, lining wear always occurred on the side walls, with very little wear on the bottom wall. This was caused by the larger reaction zone and the relatively high MnO in the slag which reacted with the carbon lining. With the smelting of silicomanganese wear occurred mostly on the hearth. With silicomanganese the reaction zone is smaller which causes a higher thermal load on the hearth. Reaction temperature with silicomanganese is also higher. During the rebuild of M11 furnace in November 1982, it was observed that metal had penetrated through the carbon lining in the bottom wall and had frozen on the bottom shell plate.

From these observations it was clear that the furnace lining was too small and the obvious solution would be to increase the diameter of the shell. This would however increase the cost of a lining significantly, and there was also the risk that the lining would be too large causing a "cold" furnace and tapping difficulties. It would also not solve the problem encountered with silicomanganese i.e. wear of the hearth layer.

A new approach was therefore followed which will now be discussed.

5 THE NEW DESIGN

The theory of the new design is based on the principle of increasing the thermal conductivity of the lining material (decreased thermal resistance). In practice lining thickness (hence thermal resistance) will be reduced by lining wear until a state of quilibrium is reached. At this point heat flow from the hot face will be enough to cool the face down to below the temperature at which attack can take place. Therefore to preserve the greatest possible thickness of refractory lining, the rate of heat extraction from the hot face must be maximised. One means of achieving this is to use a lining material of high thermal conductivity. This reduces the thermal resistance of the lining and improves heat extraction from the working face. The heat is transferred to an external cooling system. Apart from abrasion the cause for attack is chemical and hence dependant on temperature. It follows that a reduction in temperature of the hot face will reduce the rate of attack. Slag can even freeze on the work face, hence forming a "natural" refractory lining.

This principle of increased heat flow is widely applied in blast furnaces. This concept was now used in the design of the new linings for the large furnaces, all of which are still in operation.

All linings installed prior to November 1980 were of a design which had a low thermal conductivity. This design is shown in figure 1. The overall thermal conductivity of the lining installed in M12 furnace during 1981 was increased and the thickness of the carbon lining was increased at the expense of the refractory bricks. However, one layer of refractory bricks was kept as a backlining. In the subsequent lining installation on M10 and M11 this principle was taken one step further when the refractory bricks were replaced with graphite tiles in the area where the risk was the highest for a hot metal break-out. This design is shown in figure II.

As a result of the observations made during the relines and the fact that the ELC is smaller than the ELF on the large furnaces, it was decided to reline M11 furnace with an increased diameter lining. At that point it was unknown whether the higher conductivity lining would have the desired effect on lining life. This proved to be a further improvement, although the furnace tend to be "cold" and tapping problems are sometimes experienced.

Another feature is a "well" of molten metal below the metal taphole. The furnace floor is lower than the metal taphole, hence the furnace cannot be drained completely and the furnace floor exposed to arcing from the electrodes. Also of importance is external cooling of the furnace steel shell. Water is used for sidewalls and forced air for the bottom. Proper cooling must at all times be maintained.

Although the new design implies a higher heat flow through the lining, there was no significant change in specific energy consumption per ton of product after the new lining was installed.

Table IV gives a comparison of the thermal conductivities of the different materials used for the former and new lining designs.

6 TEMPERATURE PROFILES

In the design of furnace linings it is common practice to construct a temperature profile through a cross-section of the furnace lining. The purpose of such a temperature profile is to determine the position of isotherms in the lining and to compare linings with different heat transfer coefficients.

The calculation for a temperature profile is derived from the theory for heat transfer through the wall of a cylinder with inner radius r_1 and outer radius r_2 and length ℓ [3)]

From the equation:

$$(T_1 - T_n) = (q/\ell)(1/2\pi)(\gamma)$$

where $$\gamma = \sum_{i=1}^{n-1} \frac{\log(r_{i+1}/r_i)}{k_i}$$

a value for q/ℓ can be calculated.

where T_1 = temperature on the surface of first layer

T_n = temperature on the surface of n-th layer

q = heat flux, W

n = number of layers

k_i = heat transfer coefficient of i-th layer

Then interface temperatures T_i , i = 1,2.. n-1 between the different layers can be calculated by means of the equation:

$$T_{i+1} = T_i - (q/\ell)(\frac{1}{2}\pi)\frac{\log(r_{i+1}/r_i)}{k_i}$$

It is assumed that the heat transfer coefficient remains constant with change in temperature.

A computer program with graphics facilities was written to facilitate computations. This facility was extensively used in the decision making process during the design phase of the linings. It was used to compare linings of different dimensions and materials as well as to calculate the effect of changes in hot face temperatures on the isotherms in the lining.

Figures III and IV show a comparison of temperature profiles between the 2 lining designs which were discussed in section 5. Figure III indicates temperature profile for the former lining (pre-1980) [compare figure 1] while Figure IV indicates the temperature profile for the new lining design with graphite tiles. [Compare figure II].

It can be seen that with the new designs the lower temperature isotherms are shifted deeper into the furnace, thus resulting in lower lining temperatures.

7 TEMPERATURE MEASUREMENTS

In order to monitor the wear rate of the lining and to determine how the actual temperatures in the lining correspond with the predicted values as derived from the temperature profiles, a number of thermocouples were installed in the lining. Readings from the thermocouples are continuously recorded on chart recorders and long term graphs are plotted. From these graphs temperature changes in the lining can be observed and interpreted.

A total of 19 thermocouples were installed in the side and bottom wall. Critical positions were selected e.g. in the side wall opposite each electrode, next to the tapholes and in the furnace floor underneath each electrode.

The thermocouples were installed in holes drilled into the carbon lining after installation of the lining. Some of the thermocouples are of the duplex type i.e. two thermocouples are installed in the same hole at different depths. This enables one to determine a temperature profile and compare it with predicted values.

From these temperature profiles it was evident that the theory was working in practice. When the two points as measured by the thermocouple are joined and extrapolated to the centre of the furnace, it shows that the hot face is inside the crucible and therefore the carbon lining is not exposed to normal hot face temperatures.

Another observation made was lower side wall temperatures and higher hearth temperatures when smelting silicomanganese which was in accordance with previous observations made during relines.

Operating conditions in the furnaces also had a significant effect on lining temperatures and will be discussed in the following section.

6 OBSERVATIONS DURING OPERATION

The thermocouples which were installed during the reline of the furnaces proved to be invaluable during the operation of the furnace. The temperatures were monitored continuously and correlations were found between trends in lining temperature and operating conditions.

It was determined that operating conditions could have a significant effect on the furnace lining temperature and hence the erosion rate of the lining. It appeared that chemical attack of the lining had no short term effect on the wear of the lining but only in the longer term, especially on the hearth of a silicomanganese furnace. It was however established that the distribution of electrical current in the furnace could play an important role on the wear of the lining, even in the short term as will be demonstrated in the next case.

During August 1982 a sudden increase in lining temperature was observed on M12 furnace. The increase in temperature was noticeable on all the side wall thermocouples but the rate of increase was higher opposite one of the electrodes. Simultaneously it was observed that the opening depth of the tapholes was shorter i.e. the distance to which a taphole was drilled before the slag or metal started to flow.

This was a very alarming situation as the temperature increased at a rate of 25°C per day and it was clear that if the trend were to continue, a hot metal break-out would occur within a few days. The temperature as recorded by one of the thermocouples in the side wall opposite the electrode is shown in figure V.

It was our diagnosis that this phenomenon was caused by "short circuiting" of electrical current from the electrode to the side wall, thereby overheating the side wall and causing wear of the carbon. In normal operation, the major part of the electrical current conduction is between electrodes and between the electrodes and the metal bath. Apart from the geometry of the furnace, these electrical conduction paths are normally determined by electrode penetration, resistance of raw materials and the presence of a coke rich layer (coke bed).

The action that was taken to rectify the situation was thus aimed at increasing the electrical resistance of the raw materials between the electrode and the side wall, and decreasing the resistance of the raw materials between the electrodes. The result of this would be to force the electrical current to flow between the electrodes.

In practice this was done by increasing the volume of recirculation slag in the raw materials charged between the electrodes and the side wall, thereby increasing the electrical resistance of the burden. In the raw materials charged to the centre of the furnace, the ratio of low resistance reductant to high resistance reductant was increased. M12 furnace has the facilities of charging different raw material batches to different zones of the furnace and therefore the above action was easy to implement. As can be seen in figure V a turning point was achieved within 4 days after action was taken and the temperature stabilised after a further 10 days. Similar cases have occurred subsequent to the above, but control over the operation is now aimed at preventing a reoccurence. From this experience it was clear that the theory of "electrical current wear" of a furnace lining is valid and it also explained many of the premature break-outs which occurred previously. The validity of this theory is amplified by another observation which was made after an electrode break. An electrode break occurred and the broken piece was presumably lying close to the side wall. This caused the lining temperatures in this vicinity to rise and this phenomenon continued until the piece of electrode which broke off was dissolved or had disintegrated.

A temperature profile was drawn to indicate the changes in isotherms in the lining during the temperature increase. This was done by joining two temperature points as measured by two thermocouples at different depths in the lining and extrapolating the line. This is schematically shown in figure VI. Line 1 is the temperature profile before the increase in temperature and line 2 is the temperature profile when the temperature was at a peak. During this period the workface temperature of 1 450°C moved 550 mm deeper into the lining which represents 38% of the total thickness of the lining. This resulted in a higher lining temperature and presumably a significant portion of the lining was eroded away. As a result of the action taken as described above, the process of erosion was stopped and the resulting lining temperature was lower than it was before the problem started.

9 INSTALLATION AND COMMISSIONING

Another critical aspect of the relining of a furnace is the quality of installation. Prior to installation proper specifications were drawn up. Specifications included types of material, thermal conductivity, physical properties, chemical properties and dimensional tolerances. It was required from the supplier of a lining to assemble the lining at his factory for inspection purposes prior to delivery.

During installation every care was taken to ensure high quality of workmanship. Supervision was adequate and all the joints between carbon blocks were measured for compliance with the specified tolerances. The design of the carbon blocks was done in such a way as to prevent "floating" of the blocks. Provision was made for expansion of the carbon lining and the steel shell. Holes were provided in the steel bottom plate to provide for moisture to escape. Special care was taken in the taphole areas and silicon carbide bricks were used to line the taphole area.

During the start-up of a furnace, the main factor to consider is linearity of temperature rise as well as an even heat distribution throughout the lining. As some sections of the lining are closer to the electrodes, a fast rate of heating can cause an uneven temperature rise, resulting in thermal stresses and cracking of the carbon lining. The power input into the furnace is therefore increased slowly while the thermocouple temperatures are used as a guide to increase power input.

10 CONCLUSION

There is now a better understanding of the mechanisms which are responsible for the wear and eventual break-out of a furnace lining. There is a better understanding of the thermodynamics involved and this can be used as a basis for further development work. In a submerged arc furnace, the electrical wear of the lining can be the predominant cause of a break-out, however it can be controlled to prolong the life of a lining.

By increasing the thermal conductivity of a lining further, the thickness of the lining can possibly be reduced, resulting in lower relining costs.

To conclude, much have been achieved with regard to optimising furnace lining design. However, the ultimate lining is yet to be designed and presents a challege for the future.

11 ACKNOWLEDGEMENTS

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TABLE I SUMMARY OF FURNACE PARAMETERS AND DIMENSIONS

FURNACE NO.	M1	M2	M3	M4	M5	M6	M7	M10	M11	M12
Power Rating (MW)	10,0	12,5	12,5	3,7	3,7	8,2	10,0	40,0	40,0	42,0
Shell diameter (m)	9,88	9,83	9,83	6,70	6,70	6,70	8,40	15,50	17,0	15,50
Crucible diameter (m)	7,38	7,74	8,30	4,27	4,30	4,67	5,89	12,60	13,90	12,60
Hearth area (m^2)	42,77	47,10	54,15	14,32	14,52	17,13	27,10	124,69	151,75	124,69
Electrode diameter (m)	1,092	1,27	1,27	0,781	0,781	0,89	0,89	1,9	1,9	1,9
Electrode face to crucible face (ELC) (m)	1,582	1,393	1,673	0,695	0,709	0,690	1,280	2,637	3,287	2,609
(ELF) Electrode face to face (m)	1,613	1,920	1,920	1,037	1,037	1,188	1,223	2,799	2,799	2,799
Hearth thermal load (kW/m^2)	234	265	231	258	255	479	370	321	264	321

TABLE II
HISTORY OF OLD DESIGN FURNACE LININGS

	DATE INSTALLED	DATE RELINED	PRODUCT	TOTAL TONS
M10 FURNACE				
First lining	October 1973	September 1977	HCFeMn	206 000
Second lining	April 1978	June 1980	HCFeMn	177 000
Third lining	November 1980	June 1982	HCFeMn	138 000
M11 FURNACE				
First lining	March 1974	April 1977	HCFeMn	172 372
Second lining	July 1977	November 1982	HCFeMn SiMn	219 000} 138 000} 357 000
M12 FURNACE				
First lining	July 1978	November 1980	HCFeMn	228 000

TABLE III
HISTORY OF PRESENT FURNACE LININGS

FURNACE	DATE INSTALLED	PRODUCT	TOTAL TONS
M10	April 1983	HCFeMn SiMn	104 000} 120 000} 224 000
M11	March 1984	HCFeMn	190 000
M12	February 1981	HCFeMn SiMn	461 000} 63 000} 524 000

TABLE IV
HEAT CONDUCTIVITIES FOR TWO TYPES OF FURNACE LININGS

LINING DESIGN	LAYER NO.	TYPE OF MATERIAL	HEAT CONDUCTIVITY (W/m^{o}K)
Pre 1980 design	1	Carbon blocks	18,38
	2	Carbon ramming	12,0
	3	Refractory bricks	2,3
	4	Brick fragments	1,4
	5	Steel shell	48,2
Present design	1	Carbon blocks	18,38
	2	Carbon ramming	16,75
	3	Graphite tiles	67,7
	4	Steel shell	48,2

FIG. I

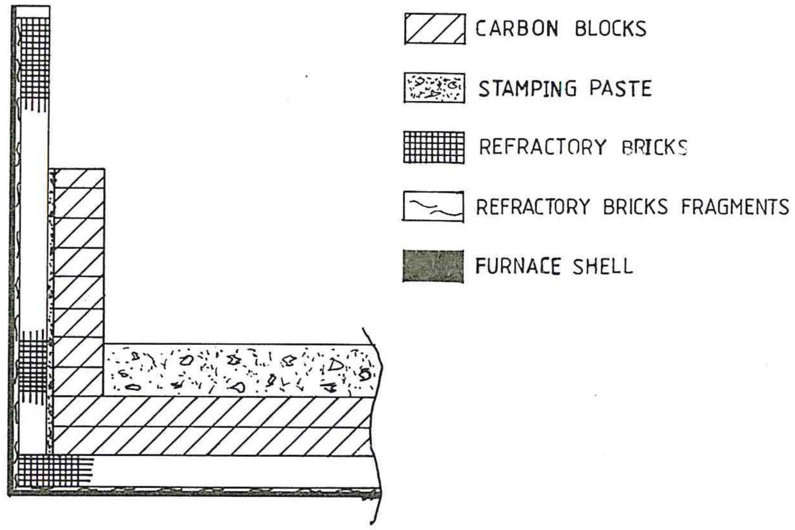

CARBON BLOCKS
STAMPING PASTE
REFRACTORY BRICKS
REFRACTORY BRICKS FRAGMENTS
FURNACE SHELL

FIG. II

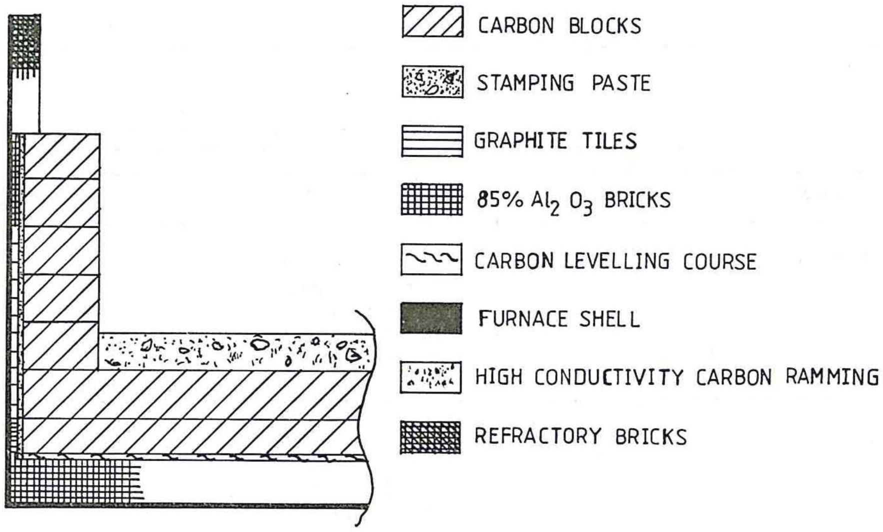

CARBON BLOCKS
STAMPING PASTE
GRAPHITE TILES
85% $Al_2 O_3$ BRICKS
CARBON LEVELLING COURSE
FURNACE SHELL
HIGH CONDUCTIVITY CARBON RAMMING
REFRACTORY BRICKS

FIG 3

TEMPERATURE PROFILE IN OLD DESIGN LINING

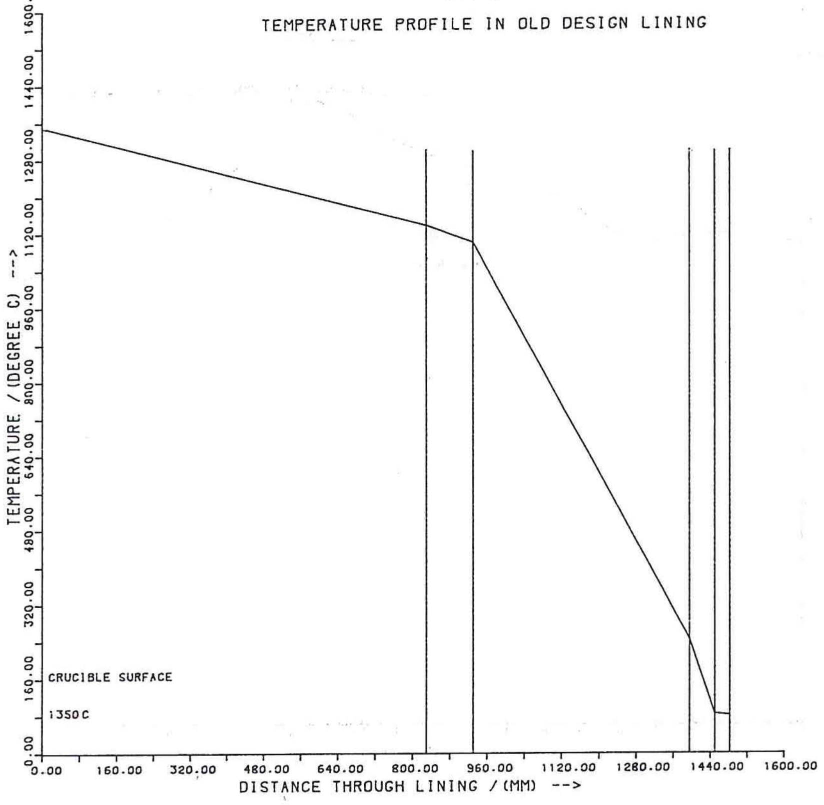
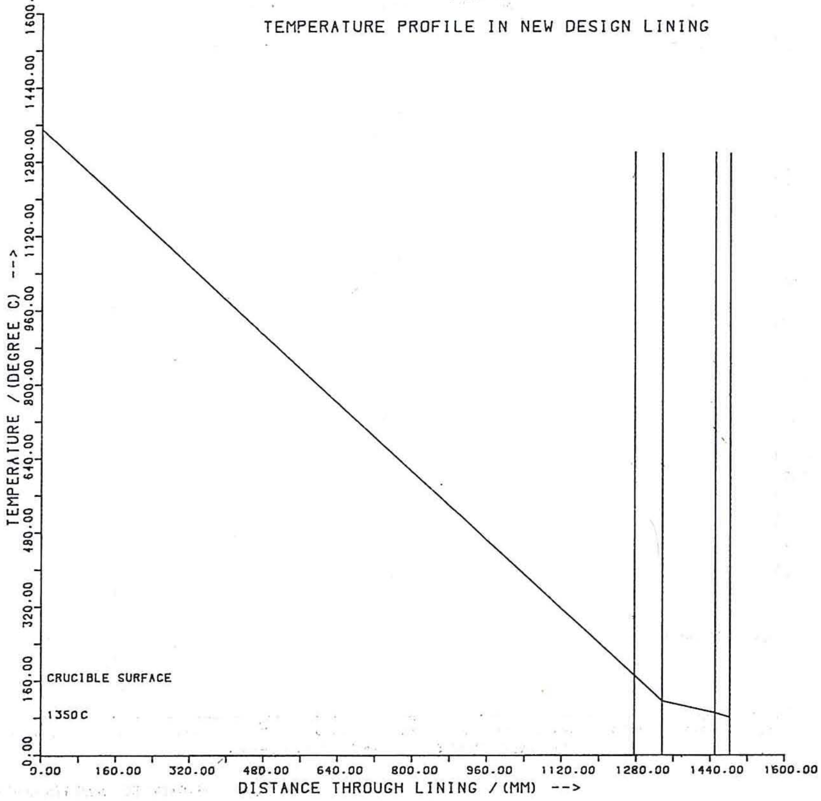


FIG 4

TEMPERATURE PROFILE IN NEW DESIGN LINING



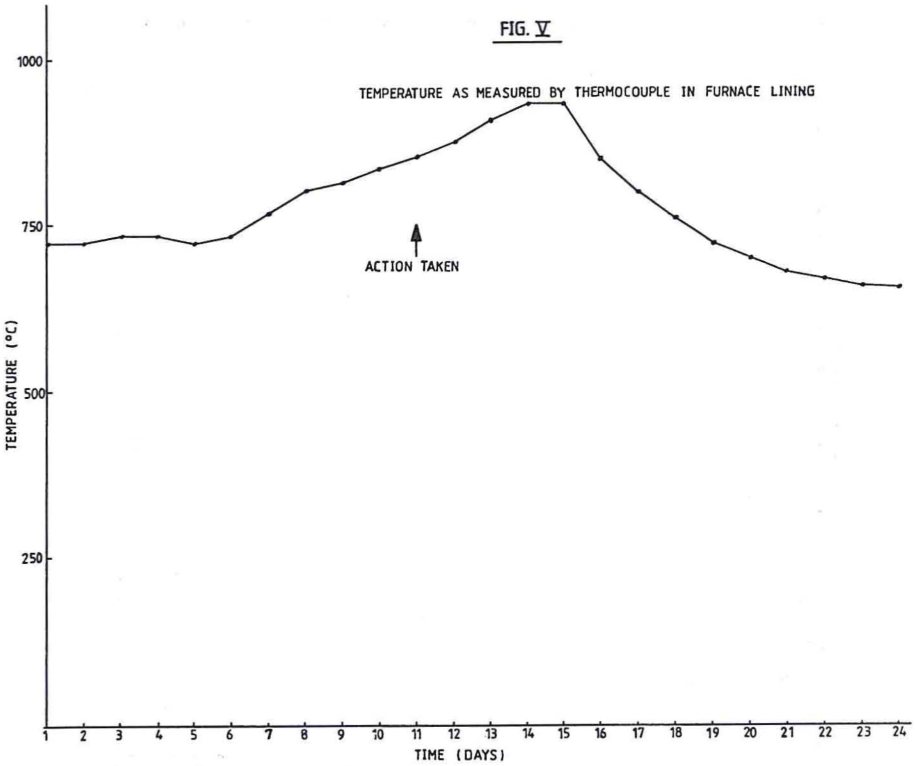


FIG. V
TEMPERATURE AS MEASURED BY THERMOCOUPLE IN FURNACE LINING
ACTION TAKEN
TEMPERATURE (°C)
1000
750
500
250
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
TIME (DAYS)

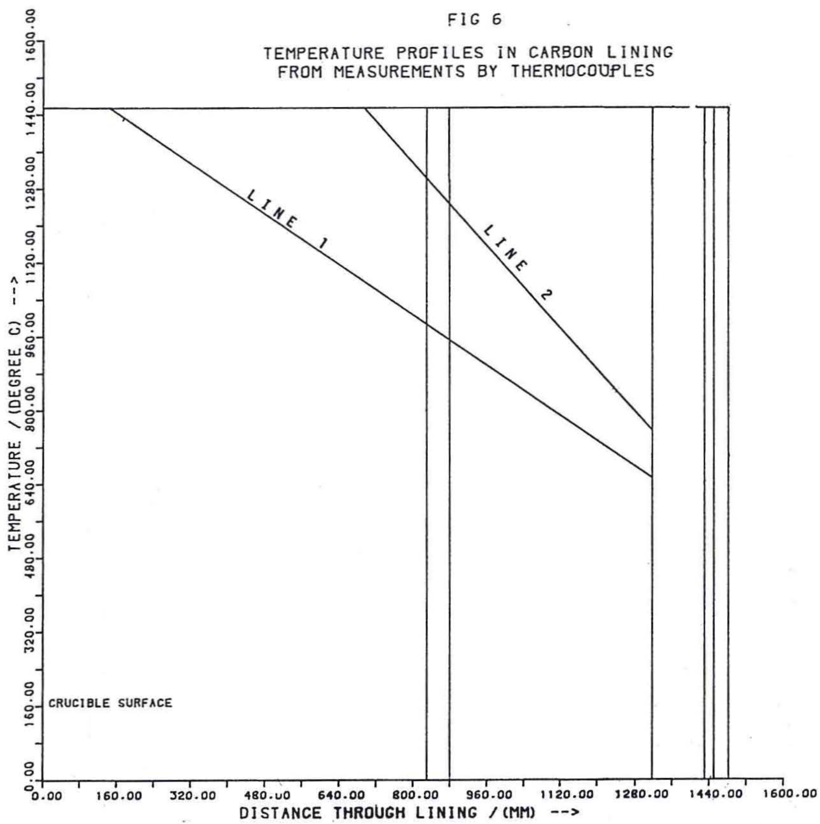


FIG 6
TEMPERATURE PROFILES IN CARBON LINING
FROM MEASUREMENTS BY THERMOCOUPLES
LINE 1
LINE 2
CRUCIBLE SURFACE
TEMPERATURE / (DEGREE C) -->
0.00 160.00 320.00 480.00 640.00 800.00 960.00 1120.00 1280.00 1440.00 1600.00
DISTANCE THROUGH LINING / (MM) -->