UNIDIRECTIONAL SOLIDIFICATION STUDIES

OF

INGOT MOULD CAST IRONS

by

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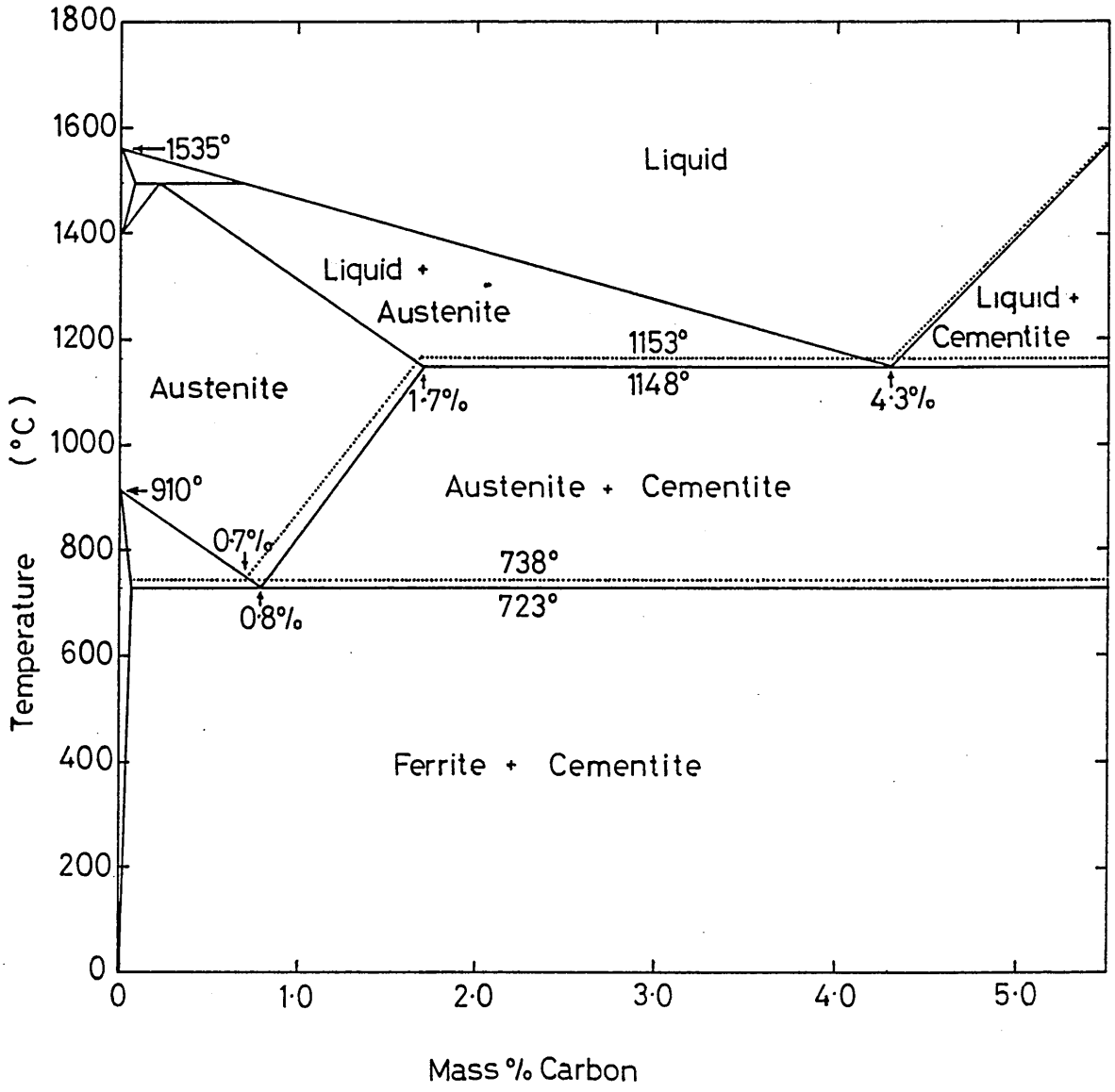
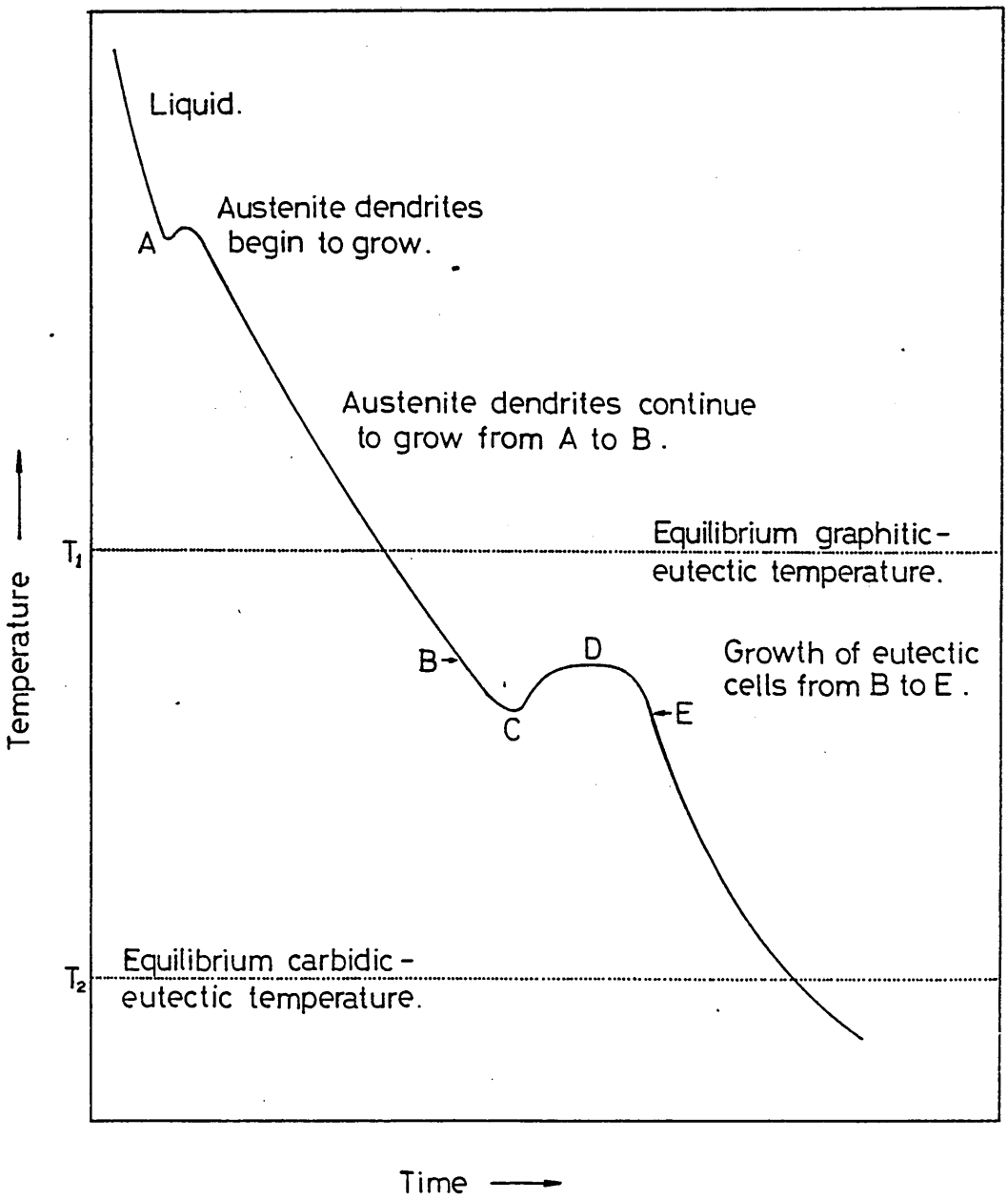


——— The iron - Fe_3C system .

····· The iron - graphite system .

Figure 2 : A schematic cooling curve for a hypoeutectic grey cast iron.



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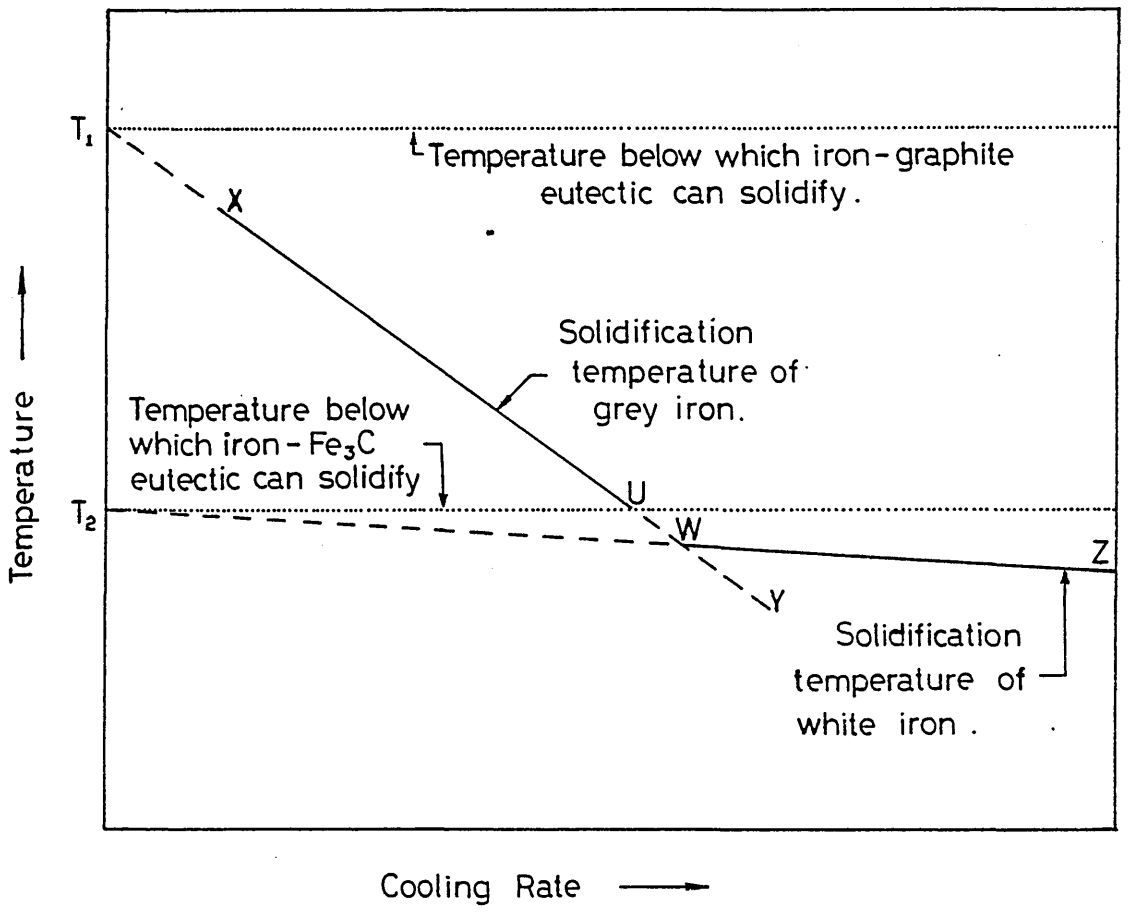
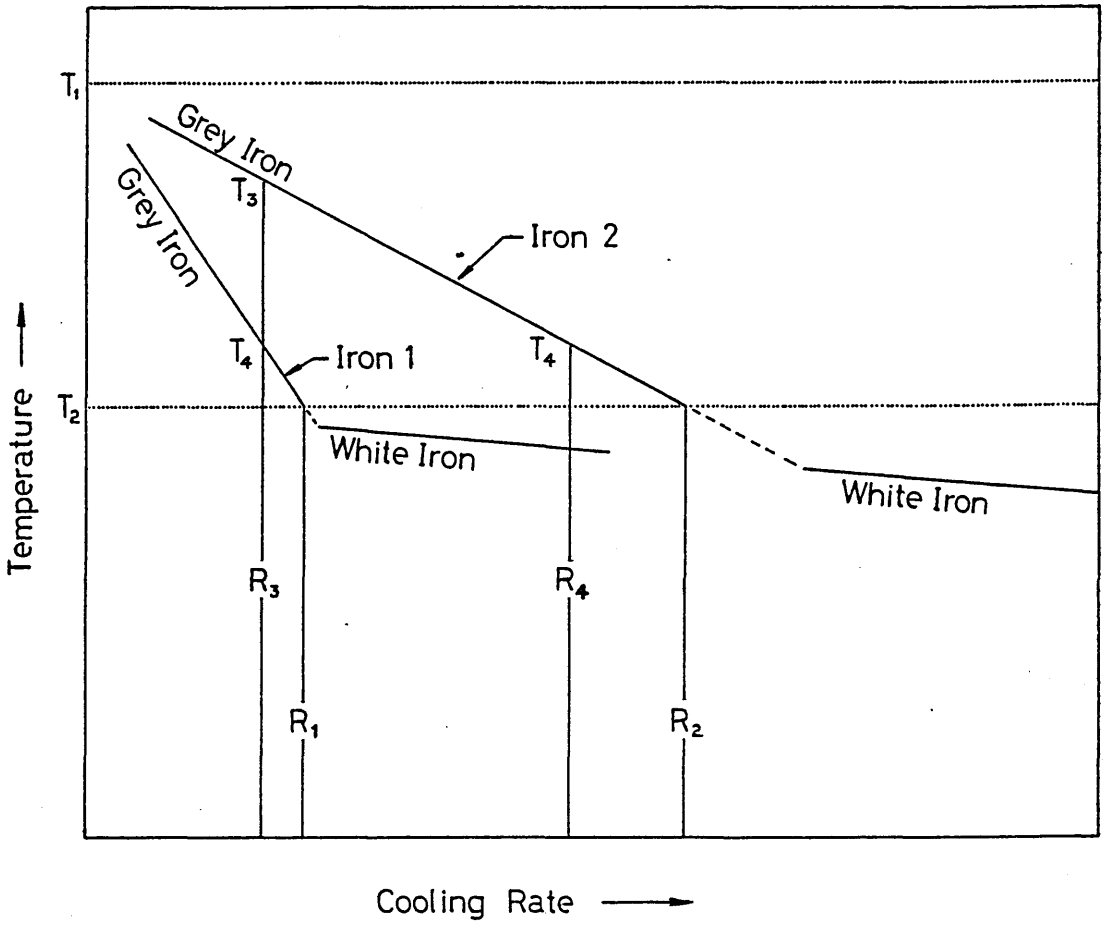


Figure 4 : The effect of nucleation rate on the eutectic solidification temperature with various rates of cooling .



Iron 1 : A cast iron which has not been inoculated.

Iron 2 : An inoculated cast iron with a nucleation rate greater than that of Iron 1.

Figure 5 : The effect of silicon on the eutectic equilibrium freezing temperatures (after Morrogh [1]).

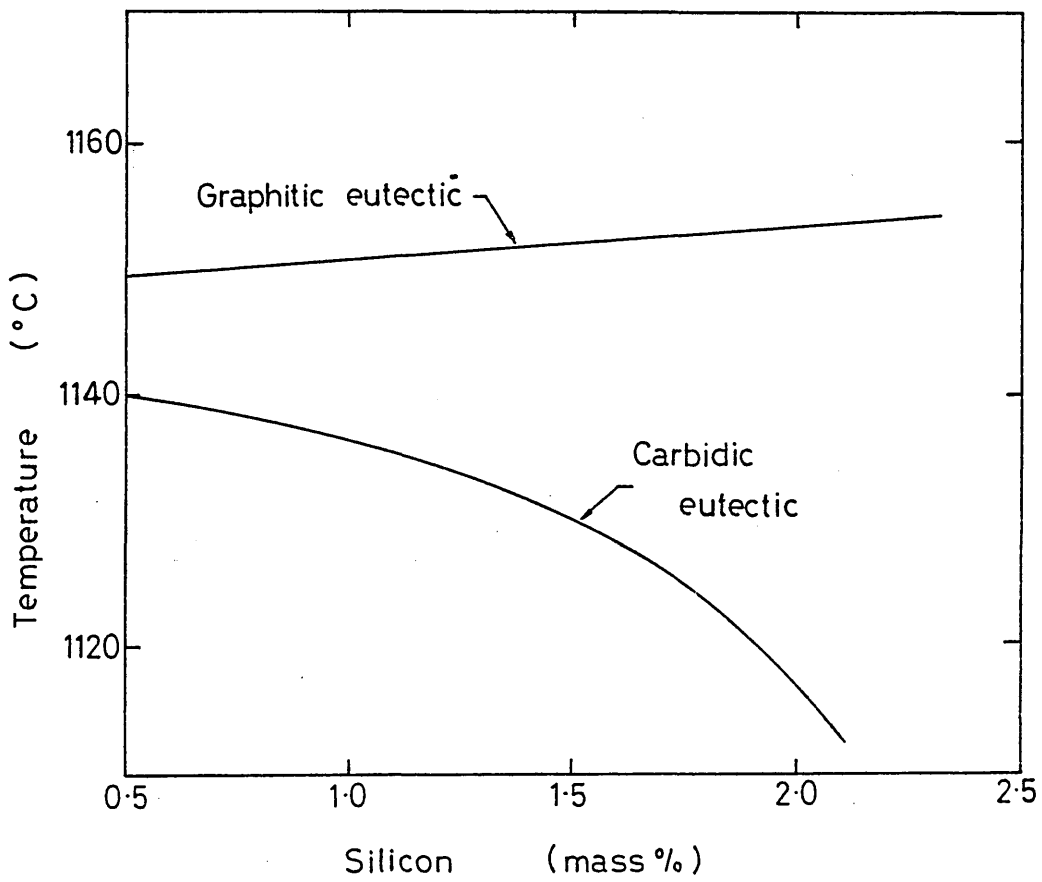


Figure 6 : The effect of chromium on the eutectic equilibrium freezing temperatures (after Morrogh [1]).

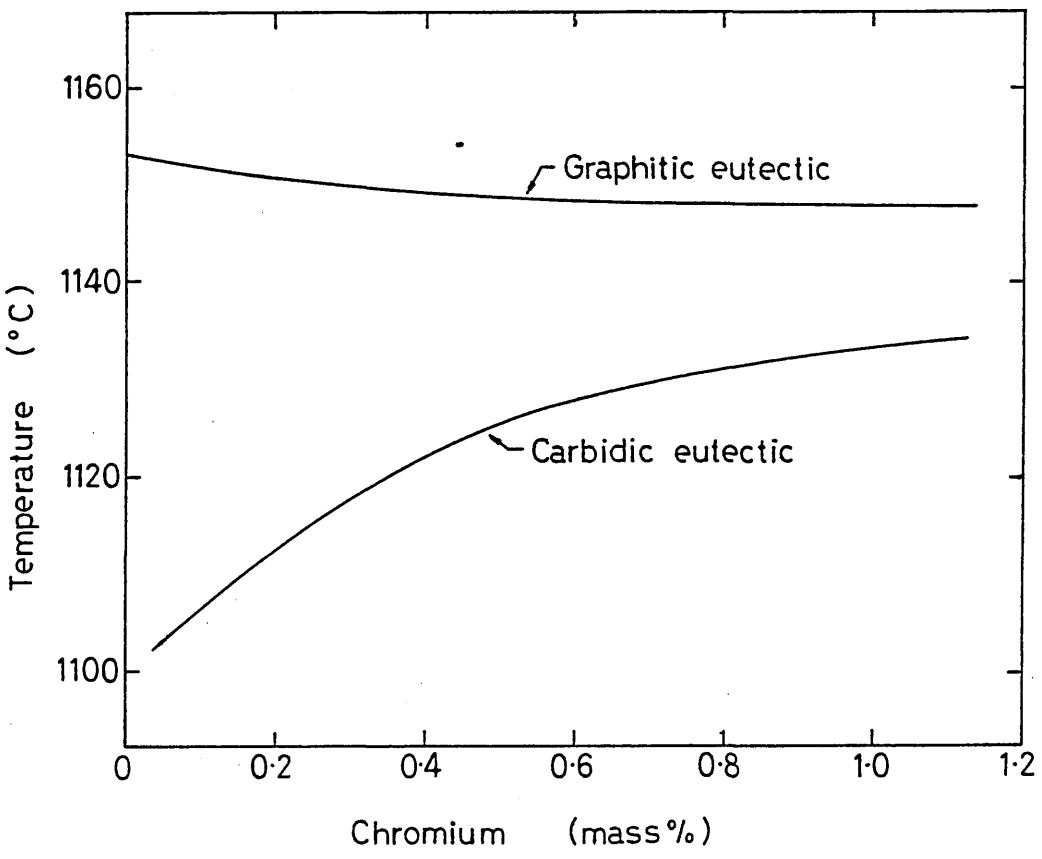


Figure 7 : Sectional views of the furnace as used in the initial experiments.

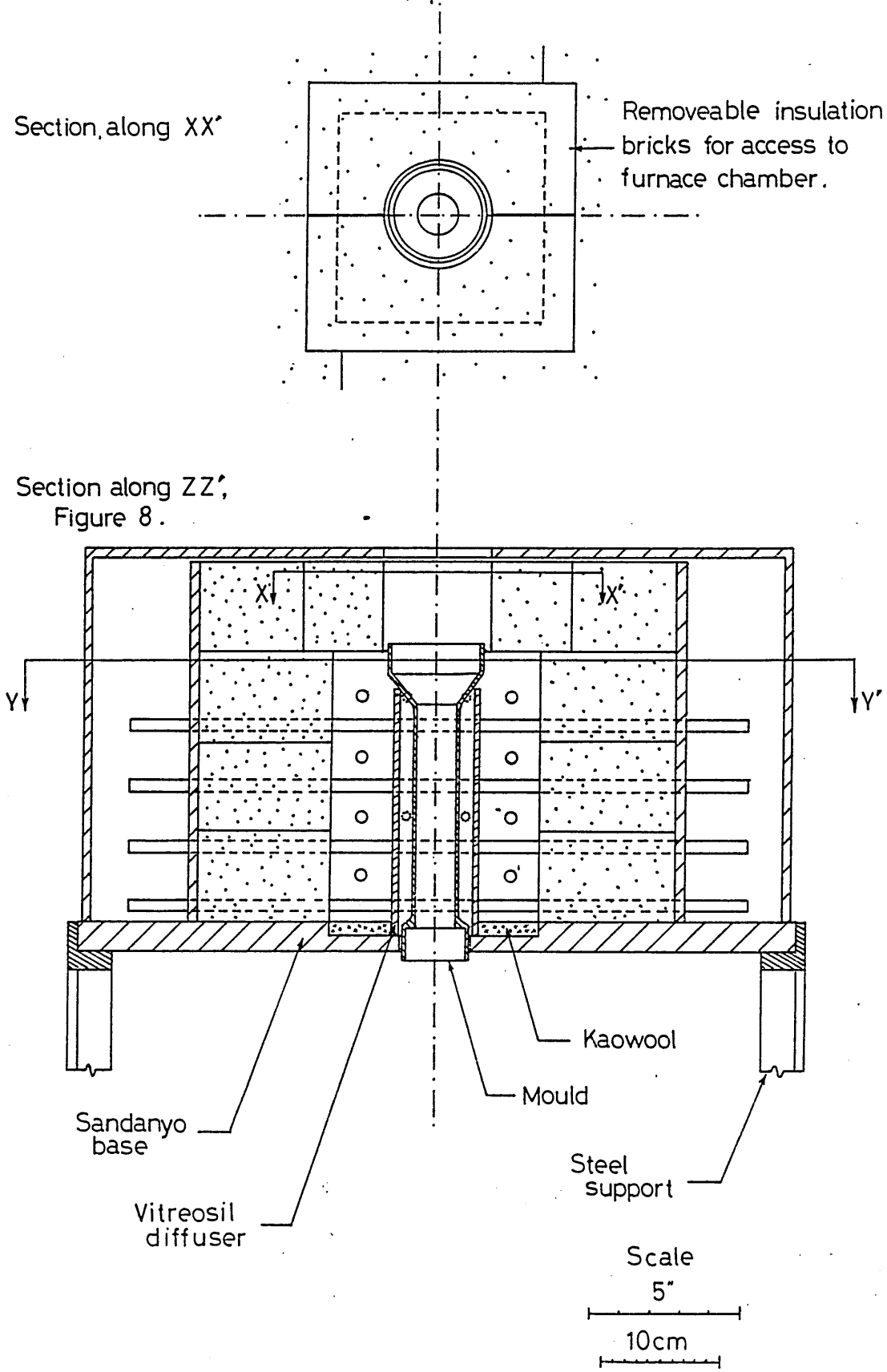


Figure 7A : Sectional views of the finally modified furnace.

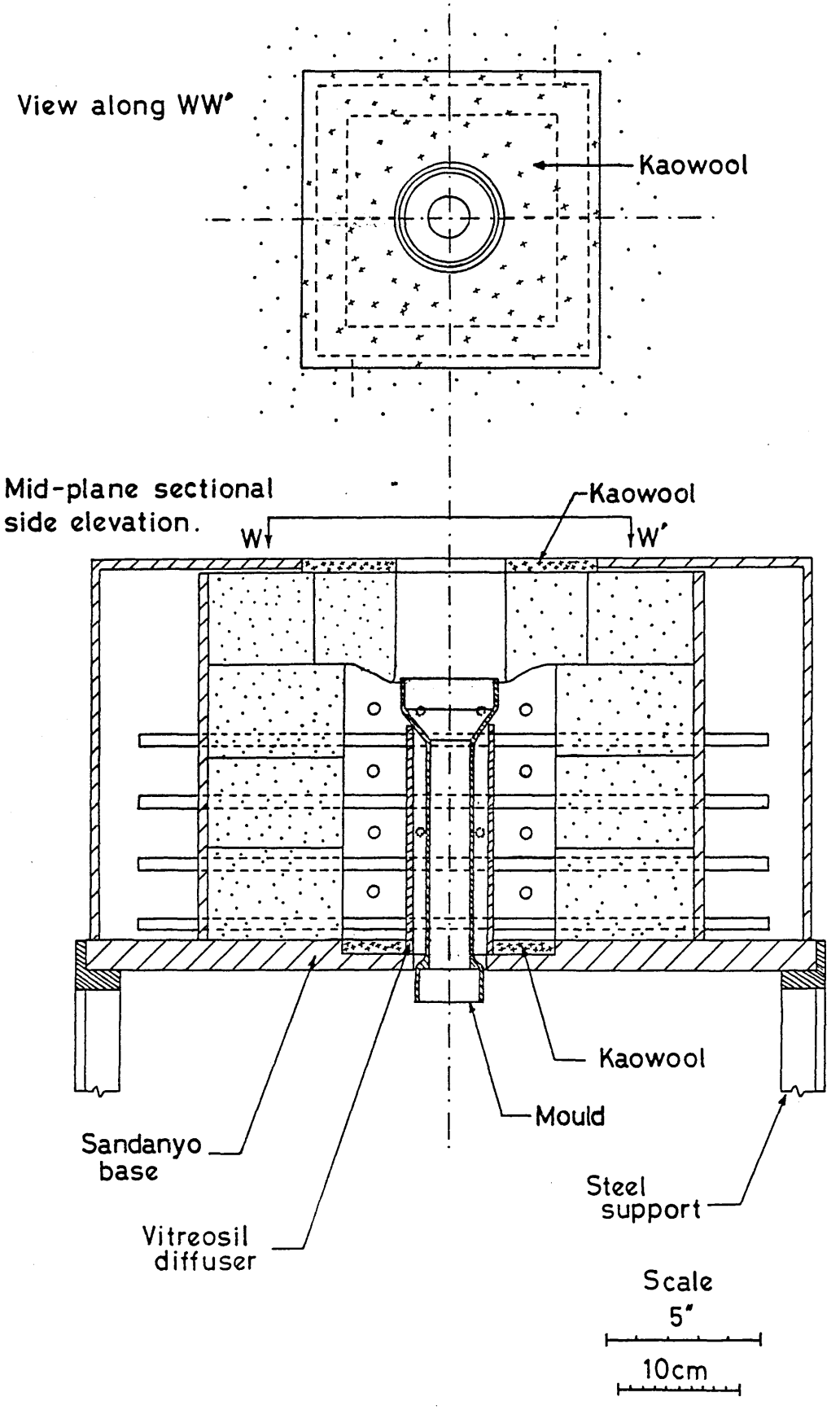
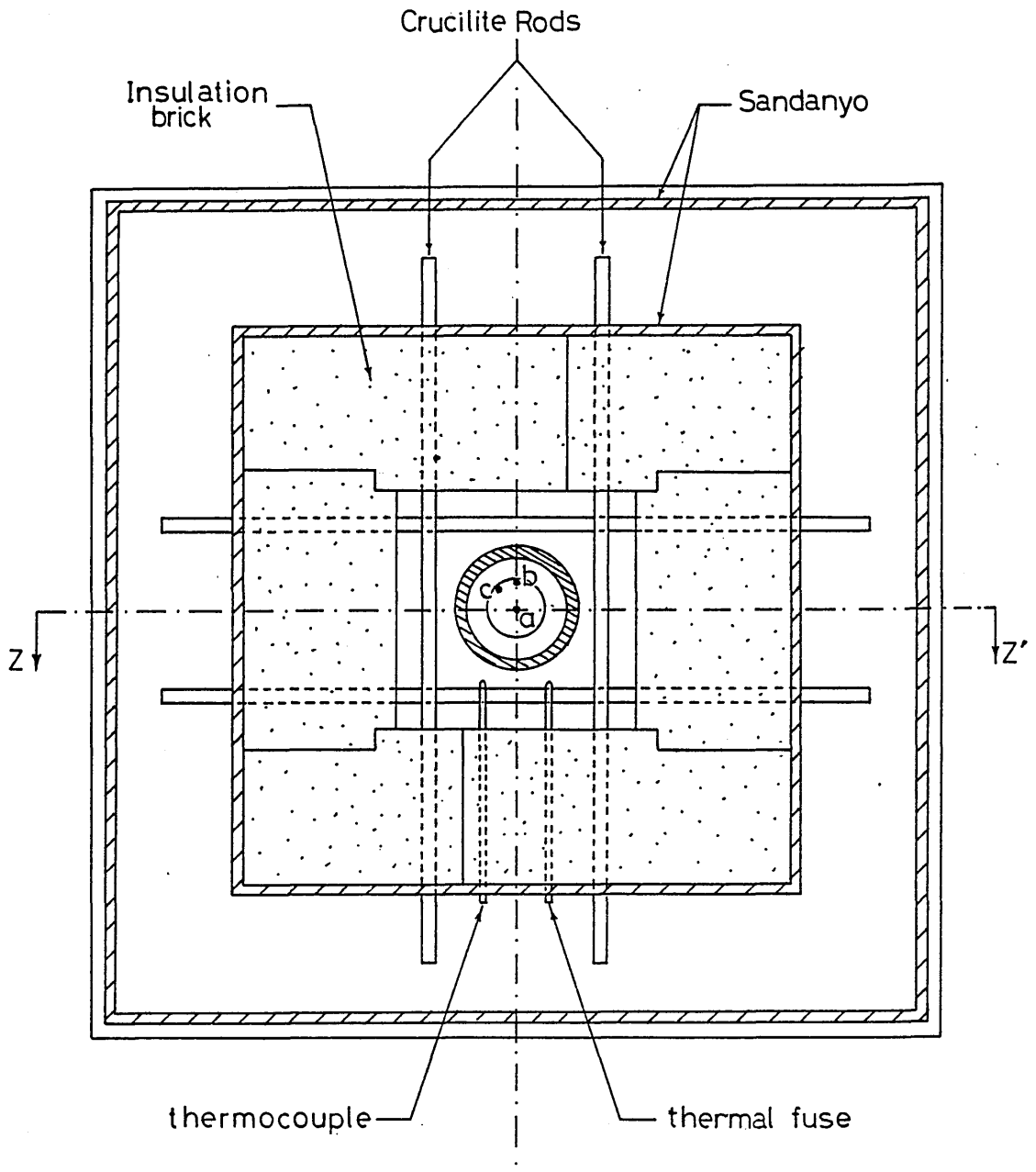


Figure 8 : A sectional plan view of the furnace .



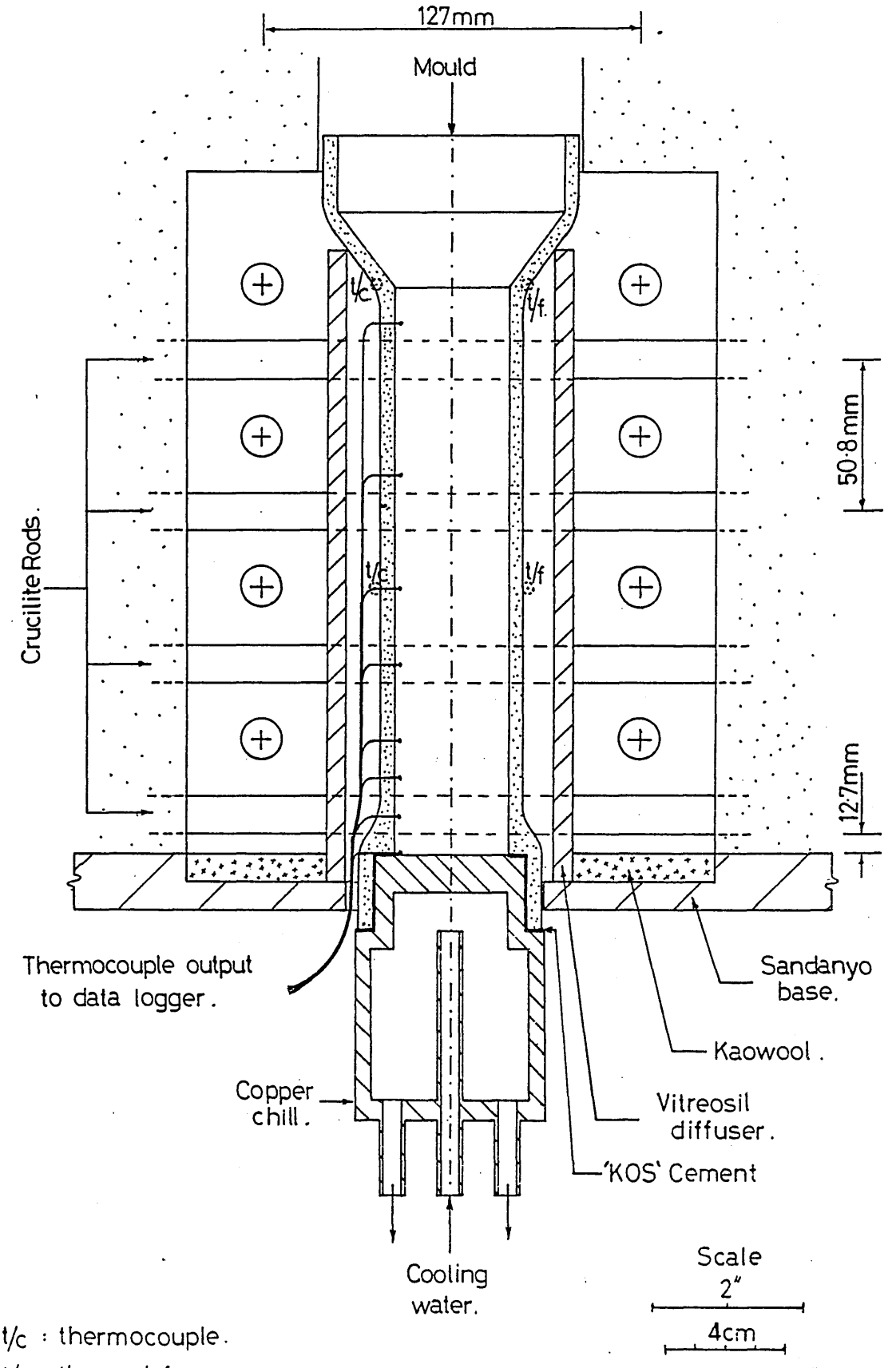
Section along YY', Figure 7 .

Scale :

5"

10cm

Figure 9 : A detailed sectional view of the mould inside the furnace used in the initial experiments.



t/c : thermocouple.

t/f : thermal fuse.

Figure 9A : A detailed sectional view of the mould inside the finally modified furnace .

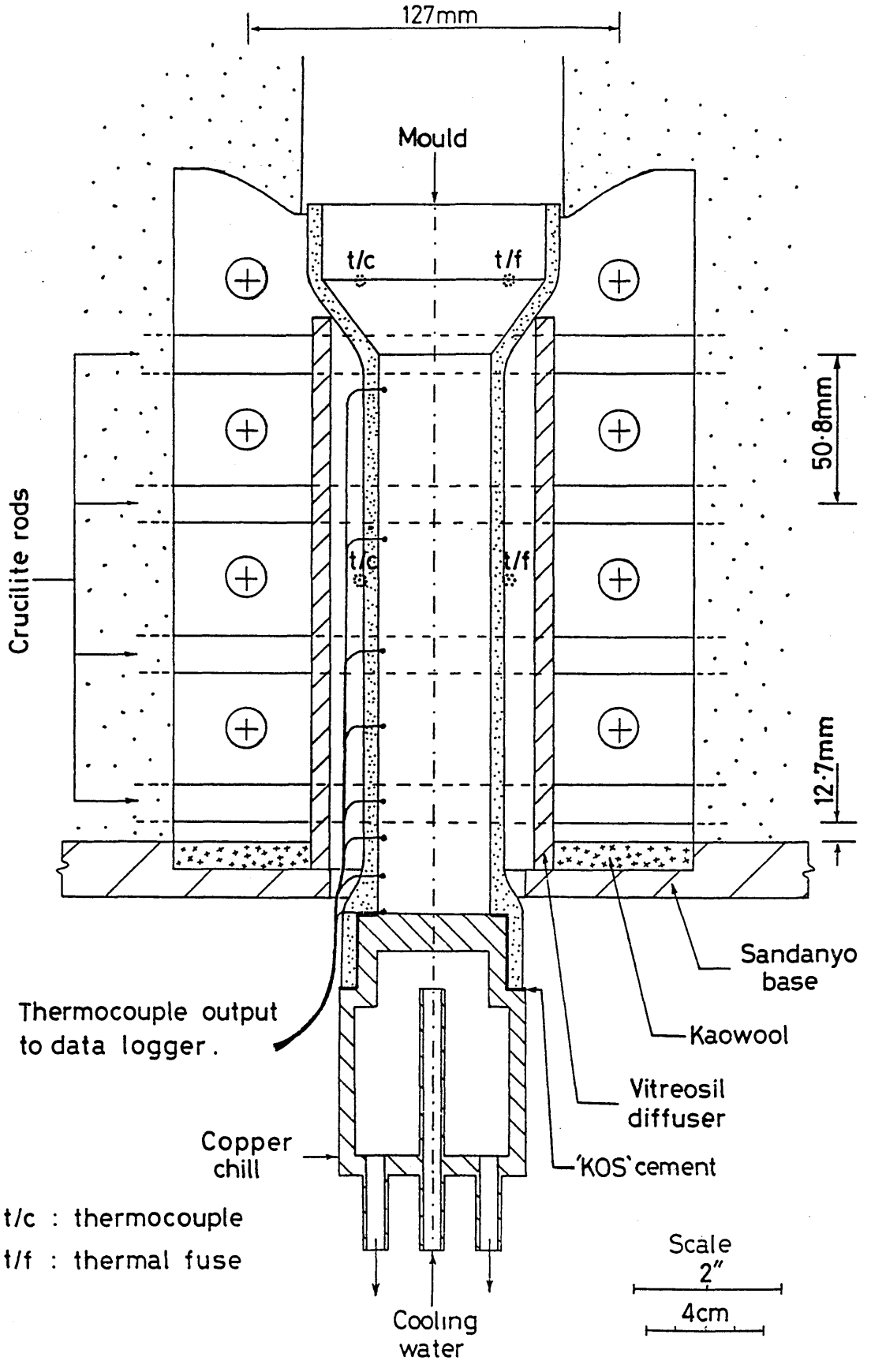


TABLE I - MATERIEL COMPOSITIONS

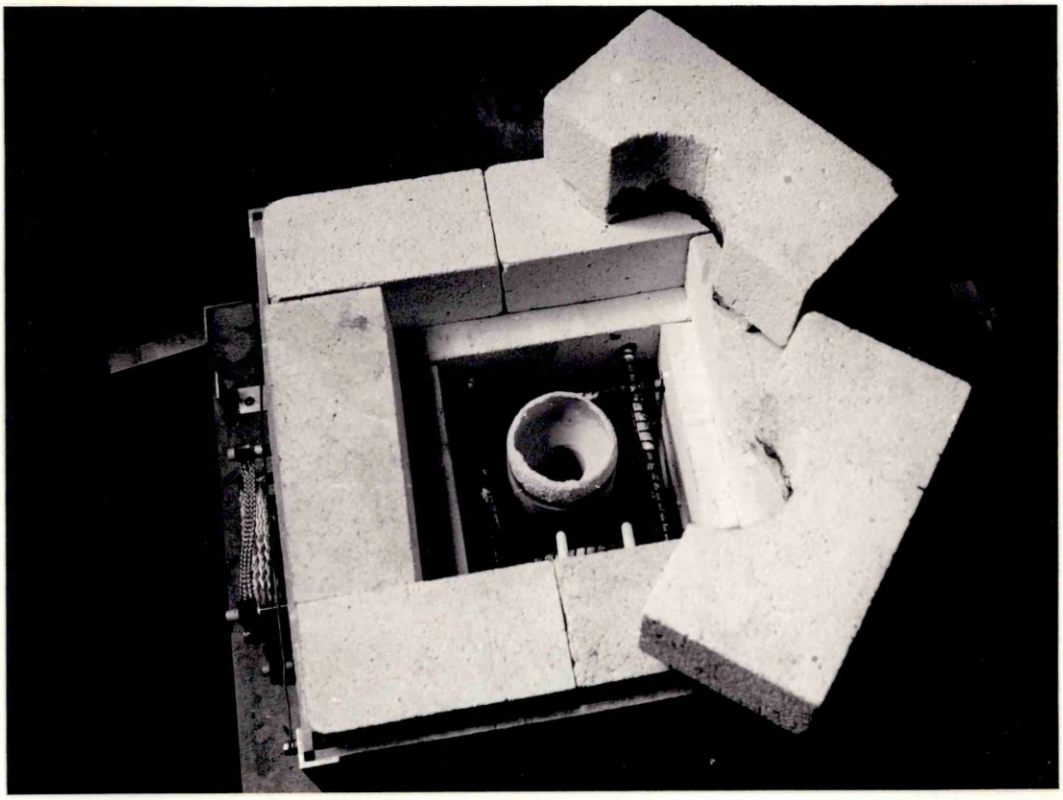
MATERIEL	COMPOSITION (MASS PER CENT)																
	Fe	C	Si	P	Mn	S	N_2	Ni	Mo	Cr	Ti	B	MgO	Al_2O_3	CaO	SiO_2	FeO
Warner Iron I	95.86	3.74	0.11	0.025	0.18	0.025		0.045	0.015								
White Iron II	97.003	2.2	0.04	0.162	0.415	0.18											
B.S.C.Base Iron III	94.706	3.8	1.23	0.02	0.2	0.04	0.0036										
Iron Sulphide	75.3					24.7											
High N_2FeMn	11.67	0.68	0.54		81.3		5.81										
Low N_2FeMn	17.09	0.10	1.11		81.7												
High C FeCr	22.78	5.93	1.69							69.6							
Ferrotitanium	84.75										15.25						
Chromium										99.8							
Ferroboron	80											20					
Rammed H.F. Lining													84.6	10.0	2.0	1.8	1.3

PLATE 1

The two central bricks are removed to show the ceramic mould seated upon the vitreosil diffuser within the furnace hot zone. The bricks have been deepened, by addition of insulating cement and a thin layer of brick, to compensate for the lowering of the mould into the furnace hot zone (Section 3.2.1). The Crucilite elements (2 sets of 4 pairs) intersect at right angles.

PLATE 2

The ceramic mould is held rigidly in place in the furnace cavity by inserting a Kaowool plug between the mould and the two central insulating bricks.



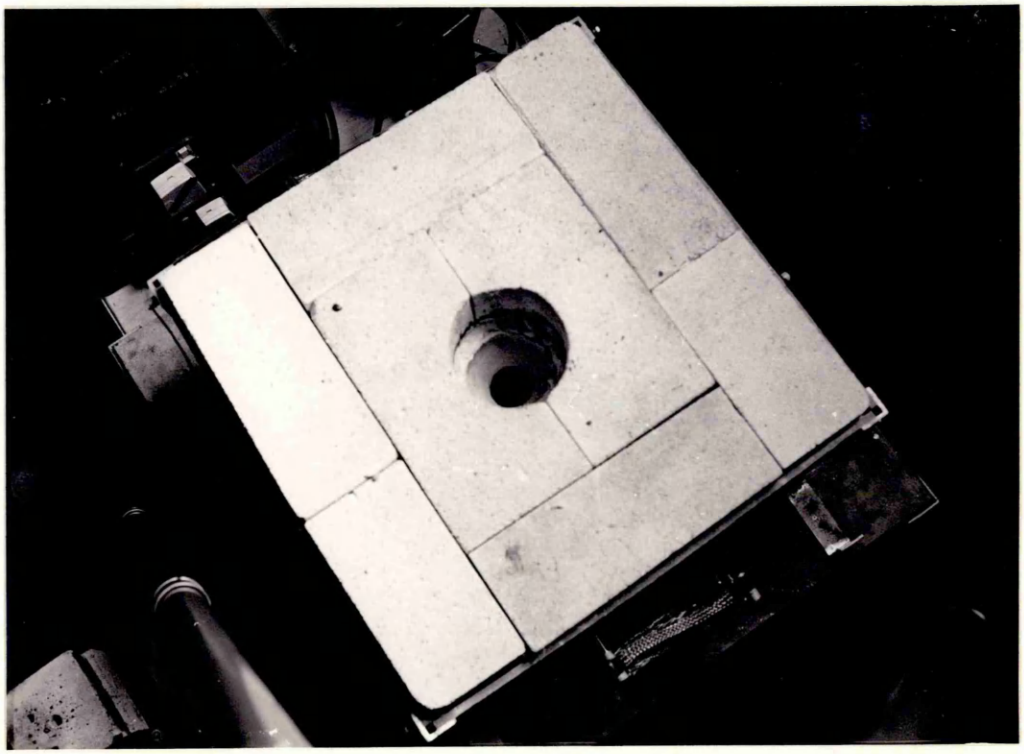
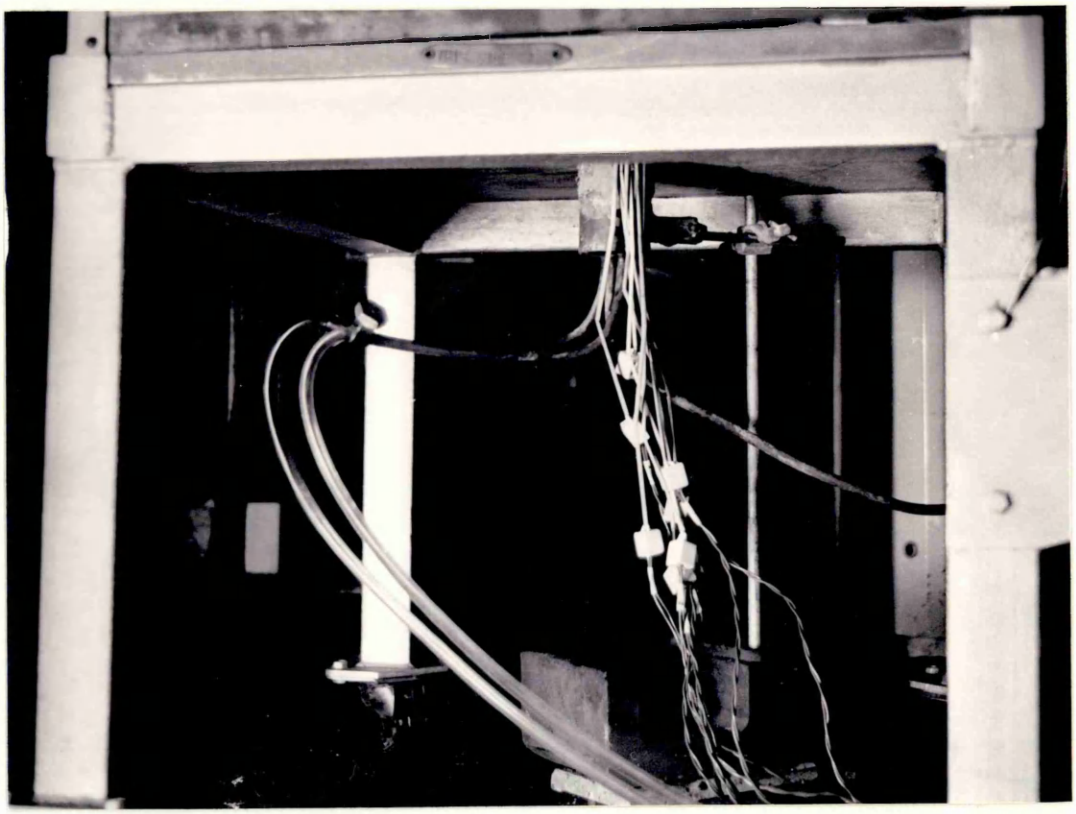


PLATE 3

Unidirectional heat flow is induced by the presence of a water cooled copper chill held in position at the base of the mould by a clamp stand. A steel furnace support permits the location of the copper chill and connection of the thermocouples to the compensating leads.

PLATE 4

The supported copper chill and the modified (earthed) thermocouple arrangement (Section 3.10.2). All thermocouples and compensating leads are wrapped with aluminium foil and earthed via an external source (See Plate 17).



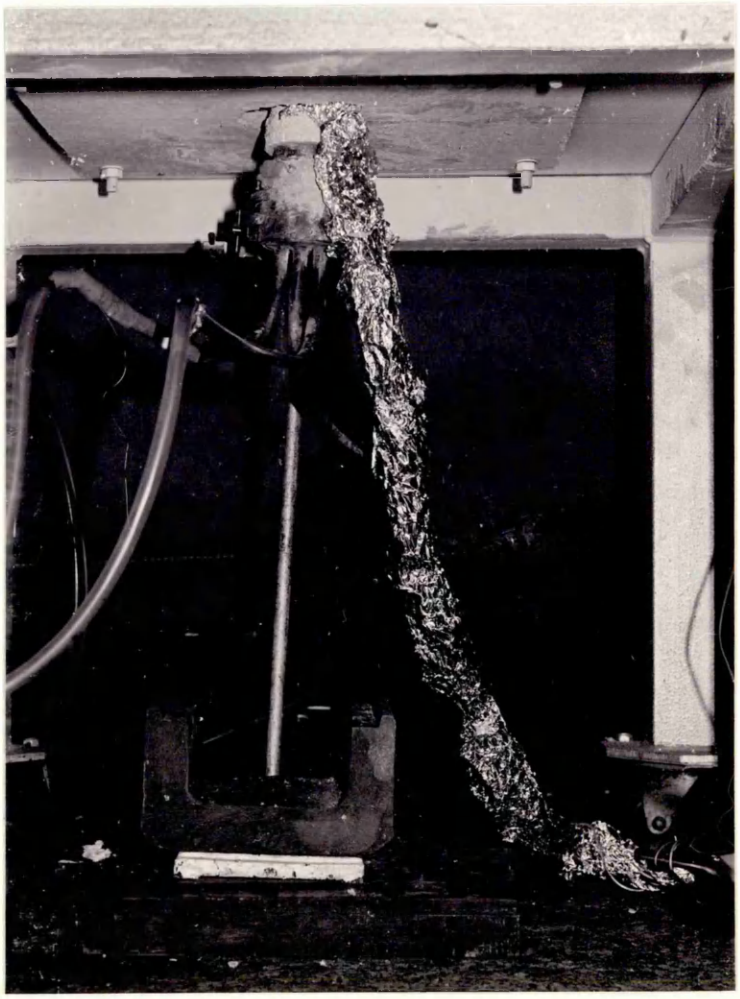
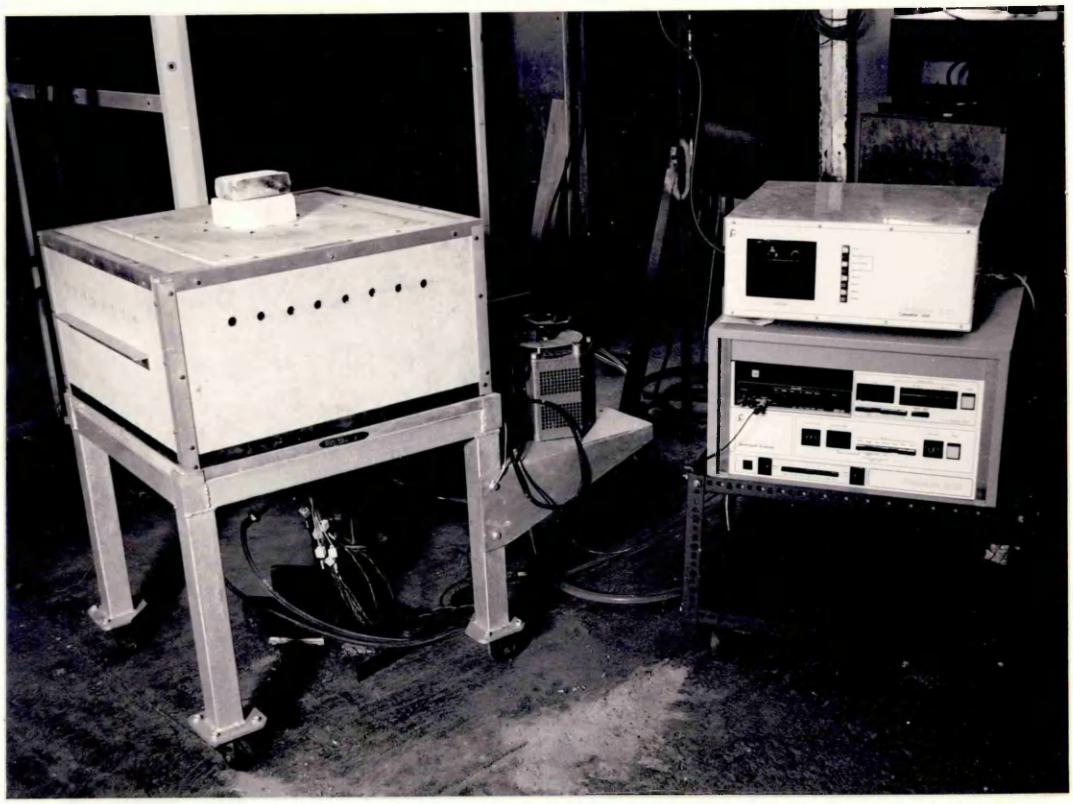


PLATE 5

The mould preheating furnace, the Credshire 500 Analoguer and the 200 cassette unit. The furnace's outer removable Sandanyo cover provides protection for the Crucilite heating elements and electrical connections.

PLATE 6

The protective Sandanyo cover is removed permitting access to the mould cavity (prior to the modifications (see Plate 9)), the 16 Crucilite rods and the electrical connections.



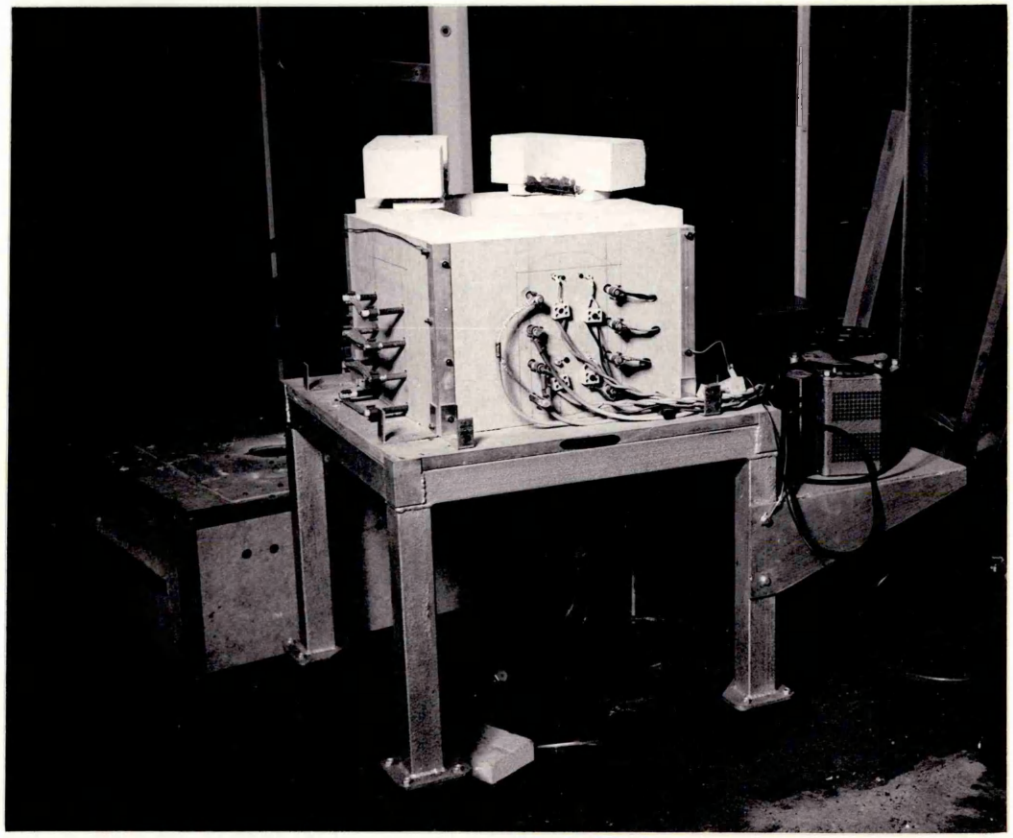
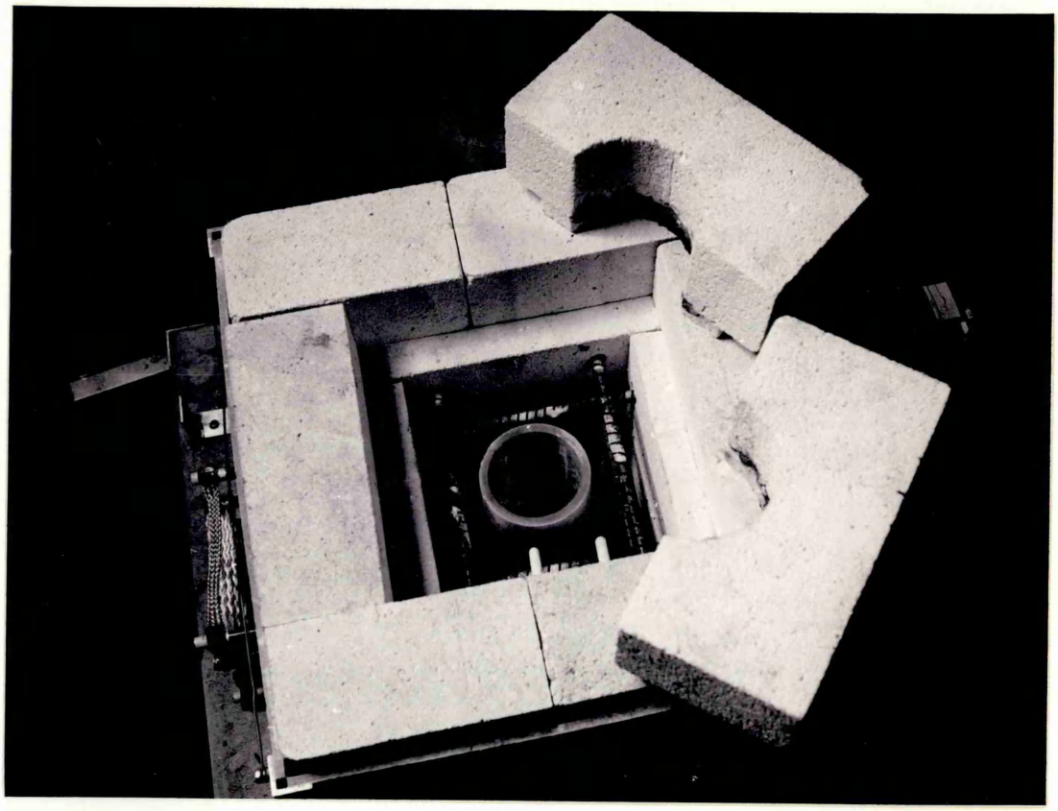


PLATE 7

The two central bricks removed to expose the Crucilite heating rods and vitreosil diffuser in the furnace hot zone. These bricks were deepened to compensate for repositioning the mould in the furnace hot zone to prevent thermal losses via the feeder head (see Section 3.2.1).

PLATE 8

The mould in position in the furnace. A Kaowool seal between the mould and the deepened central bricks ensures mould rigidity and prevents metal penetration to the hot zone during teeming. The number 8 thermocouple position is just visible at the top of the vertical sample section, on the furnace diagonal.



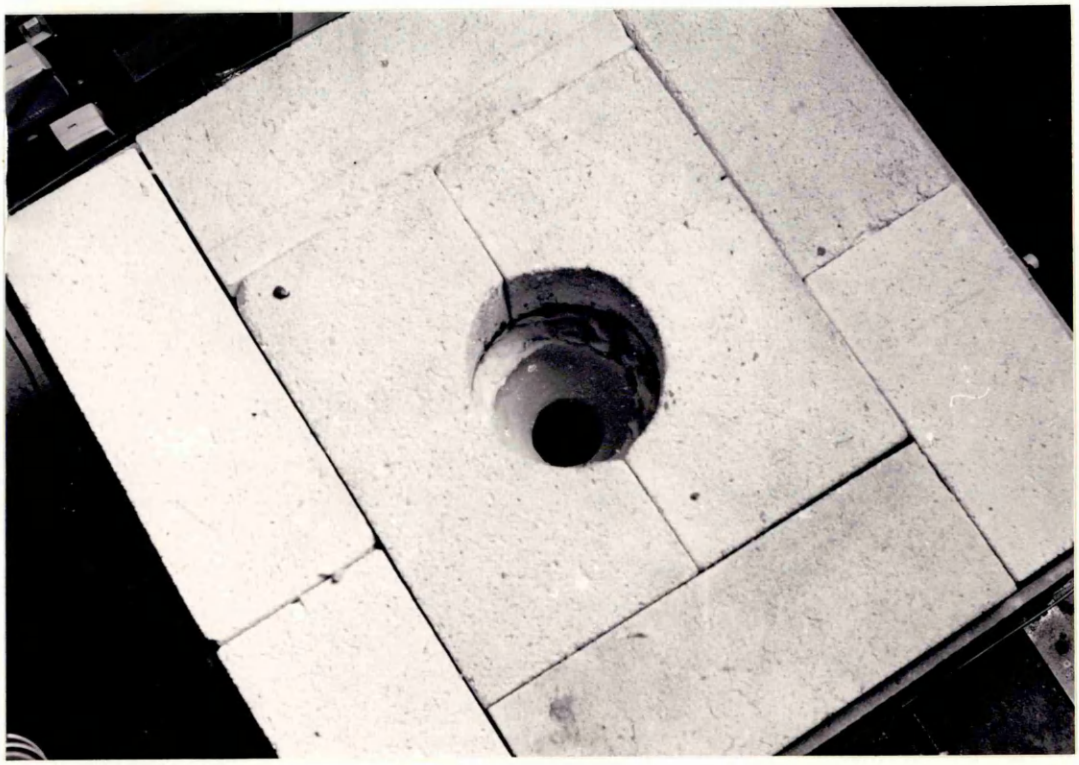


PLATE 9

A 237.5mm square hole cut in the furnace's outer Sandanyo cover permits access to the furnace hot zone without necessitating total removal of the cover.

PLATE 10

The Kaowool seal between the mould and the bricks prevents metal penetration to the hot zone and ensures mould rigidity. The new arrangement for access to the hot zone and the earthing of the melt (Sections 3.2.1 and 3.10.2 respectively) is evident.

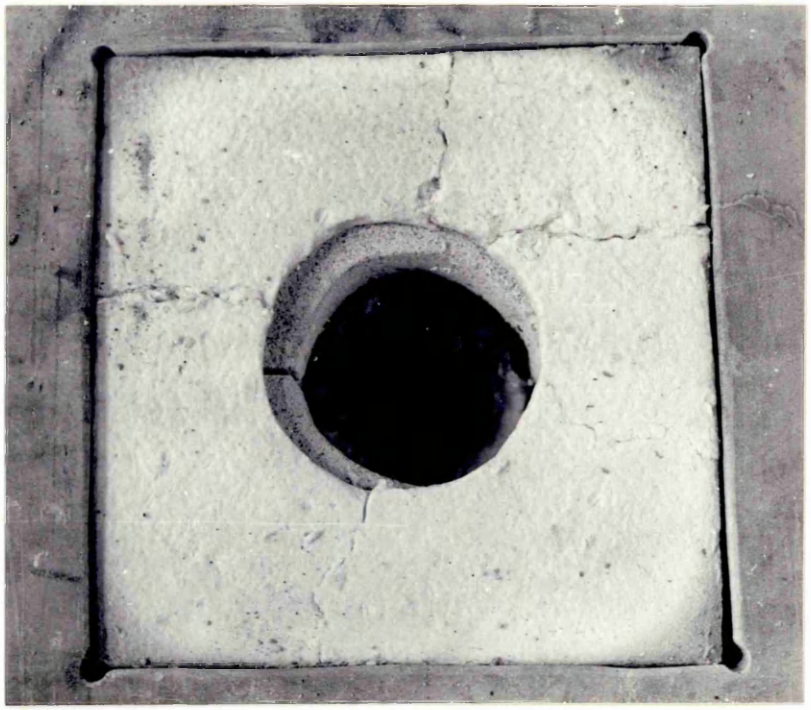
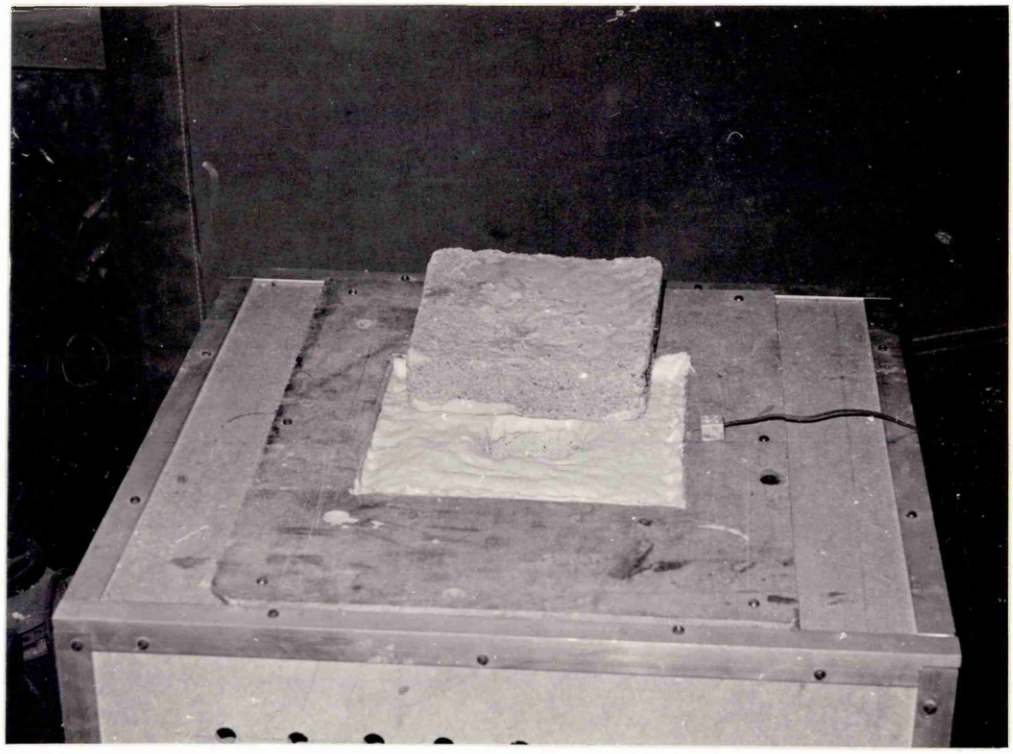


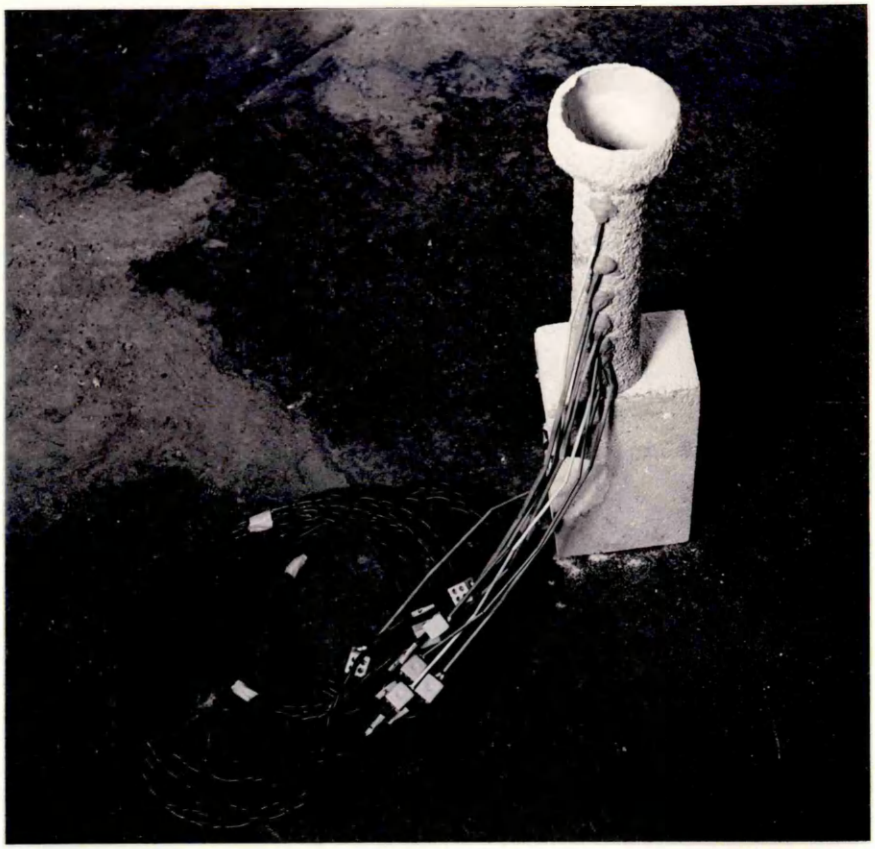
PLATE 11

A Kaowool insert, placed on top of the two central bricks and the melt earthing wire, re-establishes the thermal insulation at the top of the furnace partially destroyed by the 'access' hole. The central Kaowool plug situated in the area above the feeder head is supplemented by an insulating brick.



PLATES 12 AND 13

The ceramic mould with Pt./Pt. 13% Rh. thermocouples cemented in position (Table 6b) using 'KOS' thermal cement. The cement seal prevents metal penetration from the mould cavity to the furnace hot zone. The thermocouple wires are silica sheathed.



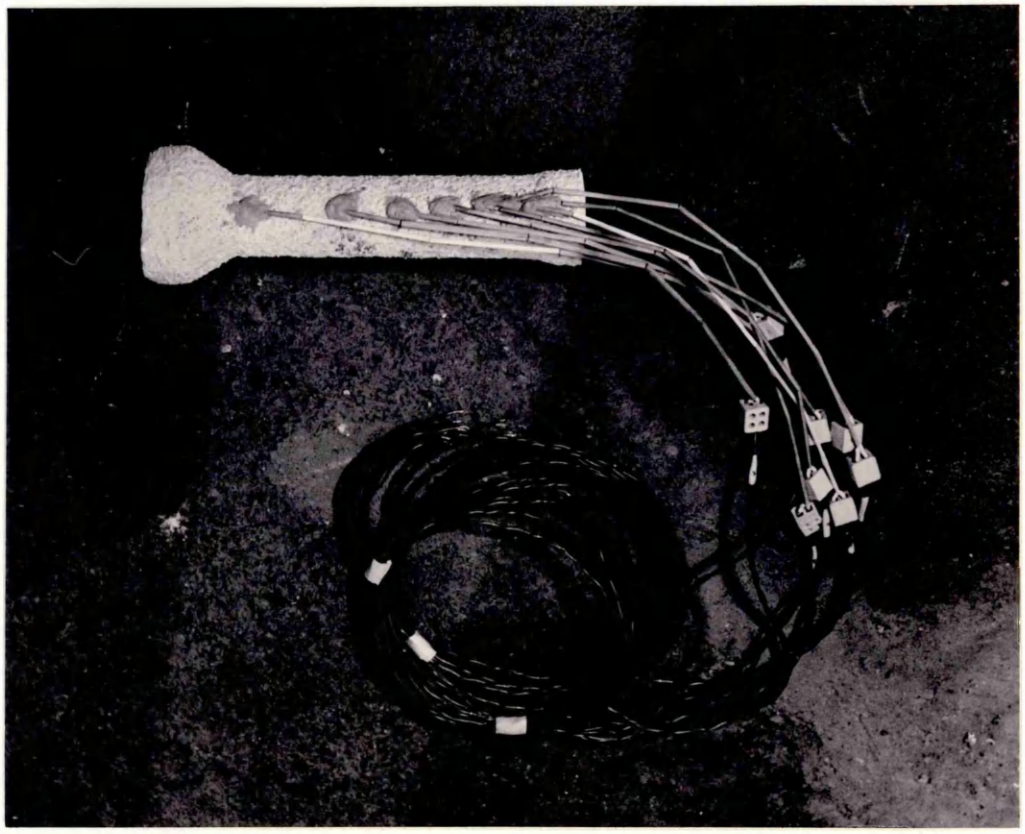


PLATE 14

Teeming the molten cast iron from the transfer ladle to the mould situated in the mould preheating furnace.

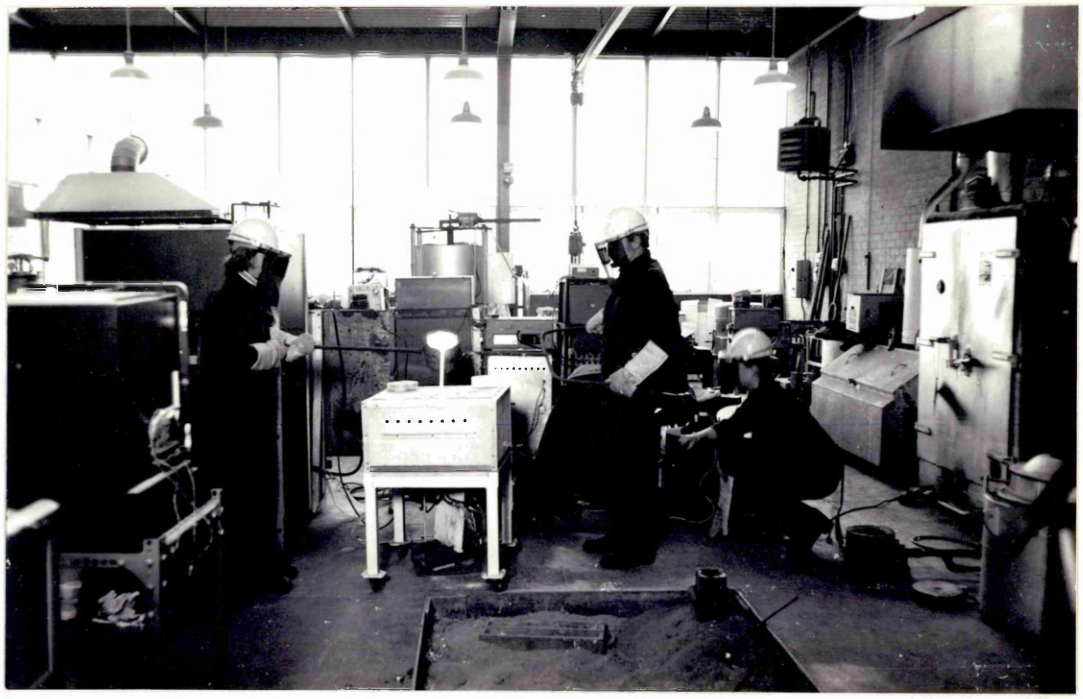
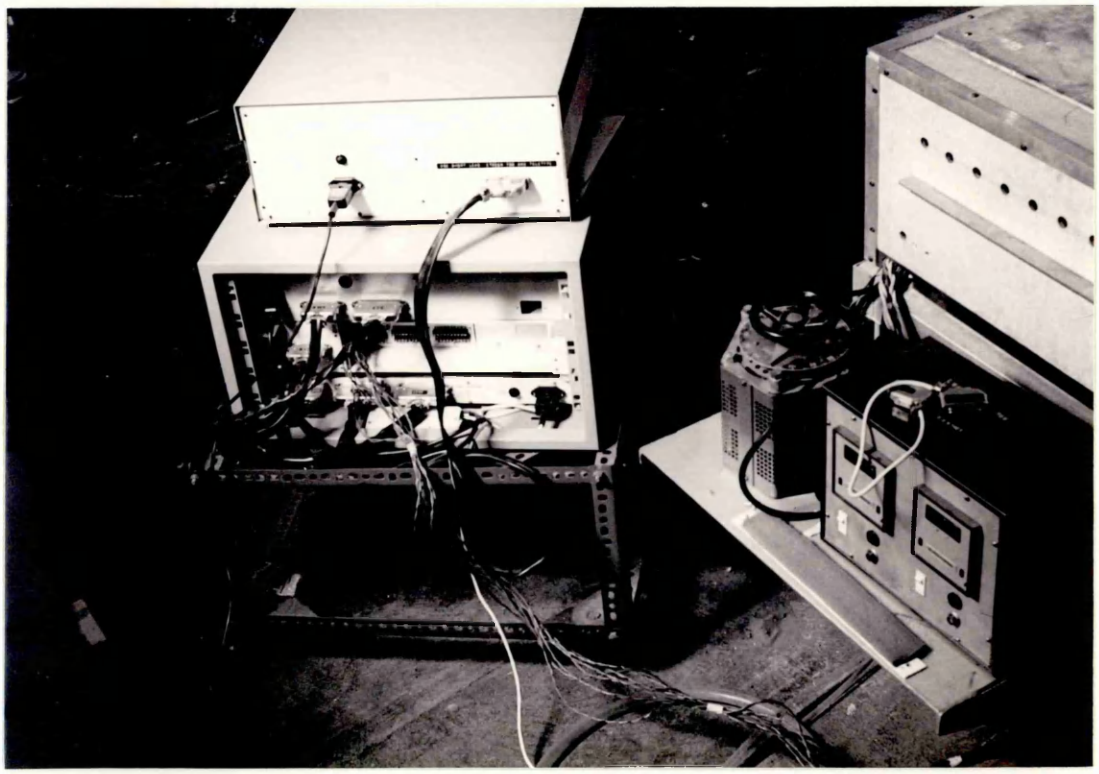


PLATE 15

The two rear panels which complete the 'isothermal box' at the rear of the data logger are removed to show the patchboards and the thermocouple connections.

PLATE 16

The two panels in position at the rear of the data logger. The compensating leads protrude through the foam plastic gland which completes the isothermal chamber.



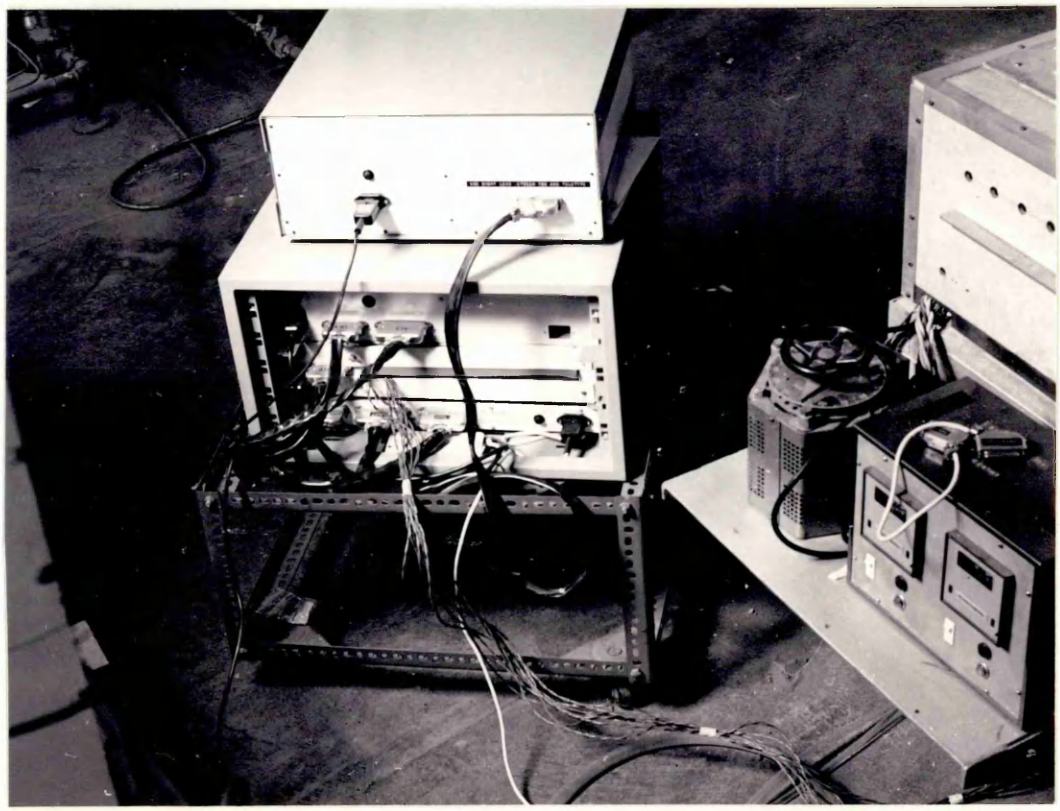


PLATE 17

The furnace and the rear of the Credshire 500 Analogue Scanner. The isothermal chamber is complete and the thermocouple compensating leads are earthed via an aluminium foil sheath which, together with the melt earth lead (Plates 10 and 11), is connected to the external earth.

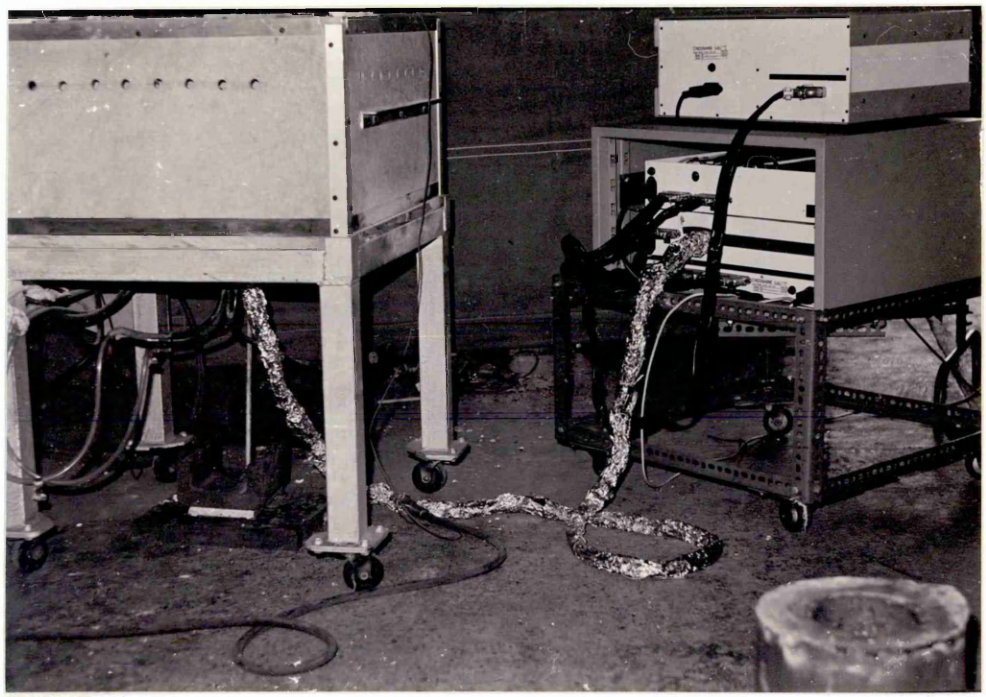


TABLE 2 - MOULD PREHEATING FURNACE SPECIFICATIONS

PARAMETER	HORIZONTAL DIMENSIONS (mm)	DEPTH (mm)
Sandanyo Furnace Base	650 square	18.78
External Sandanyo Cover	601 square	306.8
Original Access Hole	95 diameter	
Final Access Hole	243 square	
Internal Sandanyo Box (Hot Zone Casing)	436 square	305.5
Outer Brickwork	406 square	305
Brick Size (Hot Zone)	101.5 square	75.1
Top 2 Removable Bricks	225.3 x 112.65	75.1
Hole in Removable Bricks	95 diameter	75.1
Hot Zone Cavity	107.8 square	225.3
Original Diffuser	70 diameter	197
Final Diffuser	70 diameter	177.8

TABLE 3 - CRUCILITE ELEMENT SPECIFICATIONS

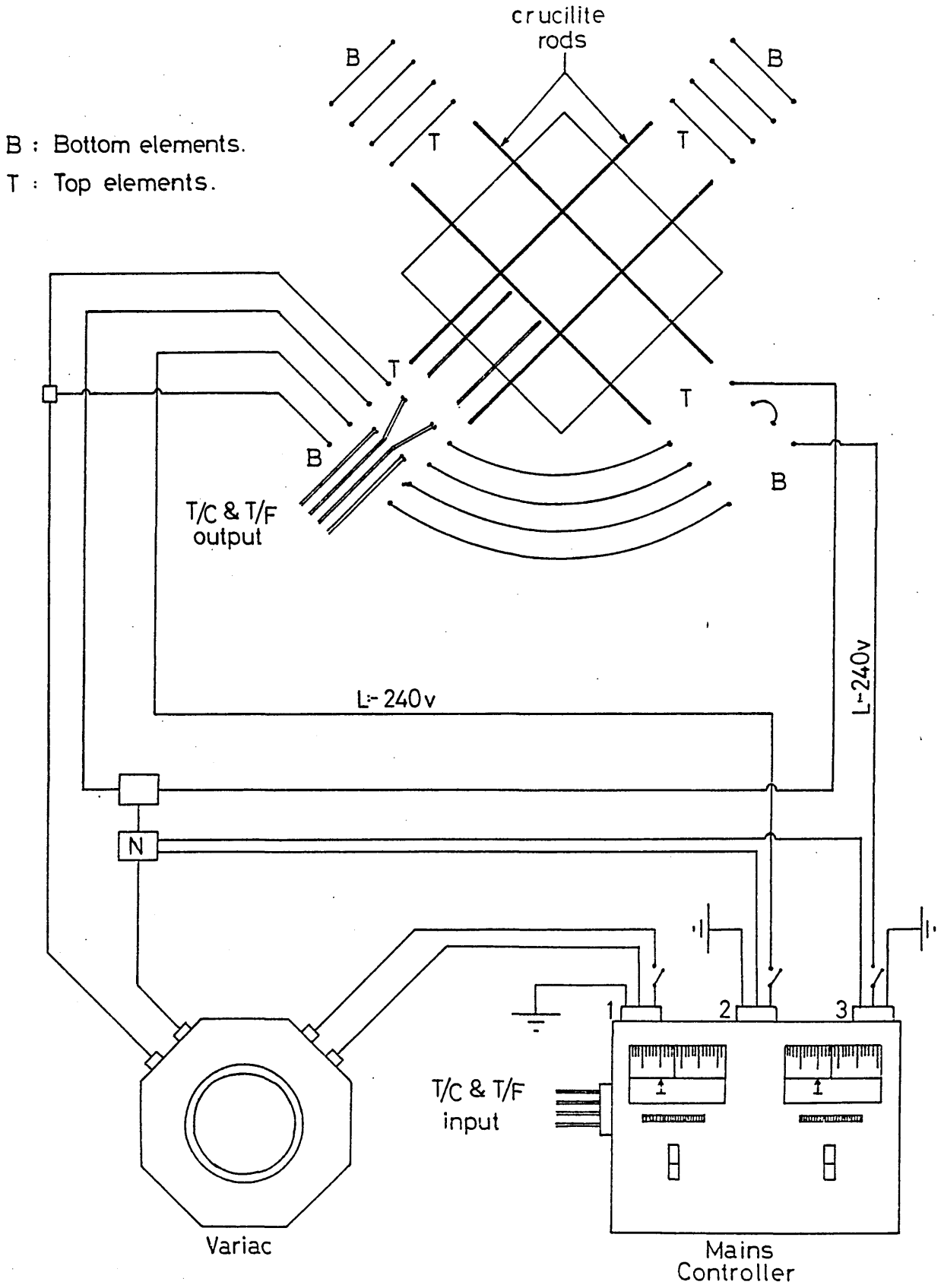
PARAMETER	DIMENSIONS (mm)
Rod	10.0 diam. x 540 length
Rod Hot Zone Length	184.2
Horizontal Axial Spacing	127.0
Vertical Axial Spacing	25.4
Vertical Displacement of Basal Elements	12.7

TABLE 4 - RADIAL TEMPERATURE DISTRIBUTION WITHIN THE MOULD CAVITY IN THE PRESENCE OF THE ORIGINAL VITREOSIL DIFFUSER

DISPLACEMENT* mm (inches)	TEMPERATURE IN °C					
	THERMOCOUPLE POSITION W.R.T. HEATING RODS					
	(a)	(a)	(b)	(b)	(c)	(c)
254 (10)	830	837	863	861	790	779
228.6 (9)	896	920	914	909	890	889
203.2 (8)	935	961	949	947	950	945
177.8 (7)	978	986	983	980	982	981
152.4 (6)	1001	1000	1001	1000	1001	1001
127 (5)	1007	1008	1006	1008	1007	1008
101.6 (4)	1008	1009	1009	1010	1010	1011
76.2 (3)	1008	1007	1007	1007	1008	1009
50.8 (2)	1001	987	1000	992	997	1004
25.4 (1)	985	986	985	987	982	992
0 (0)	949	956	954	952	949	958

* The 'displacement' of the thermocouple hot junction is measured vertically from the pseudo-chill interface.

Figure 10 : Overall furnace circuit diagram.



T/C : thermocouple

T/F : thermal fuse.

Figure 11 : Circuit diagram for middle furnace elements.

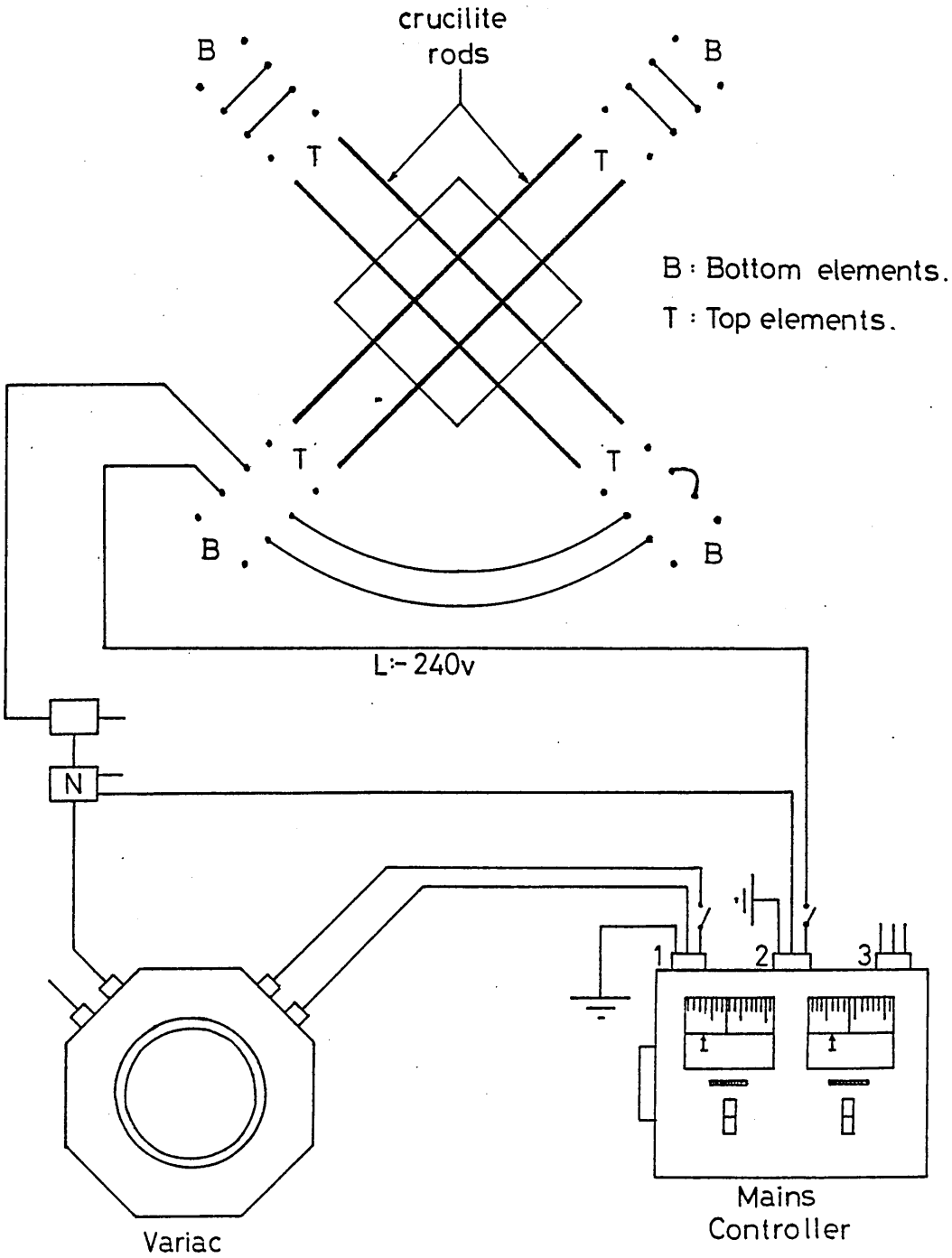


Figure 12 : Circuit diagram for top and bottom furnace elements .

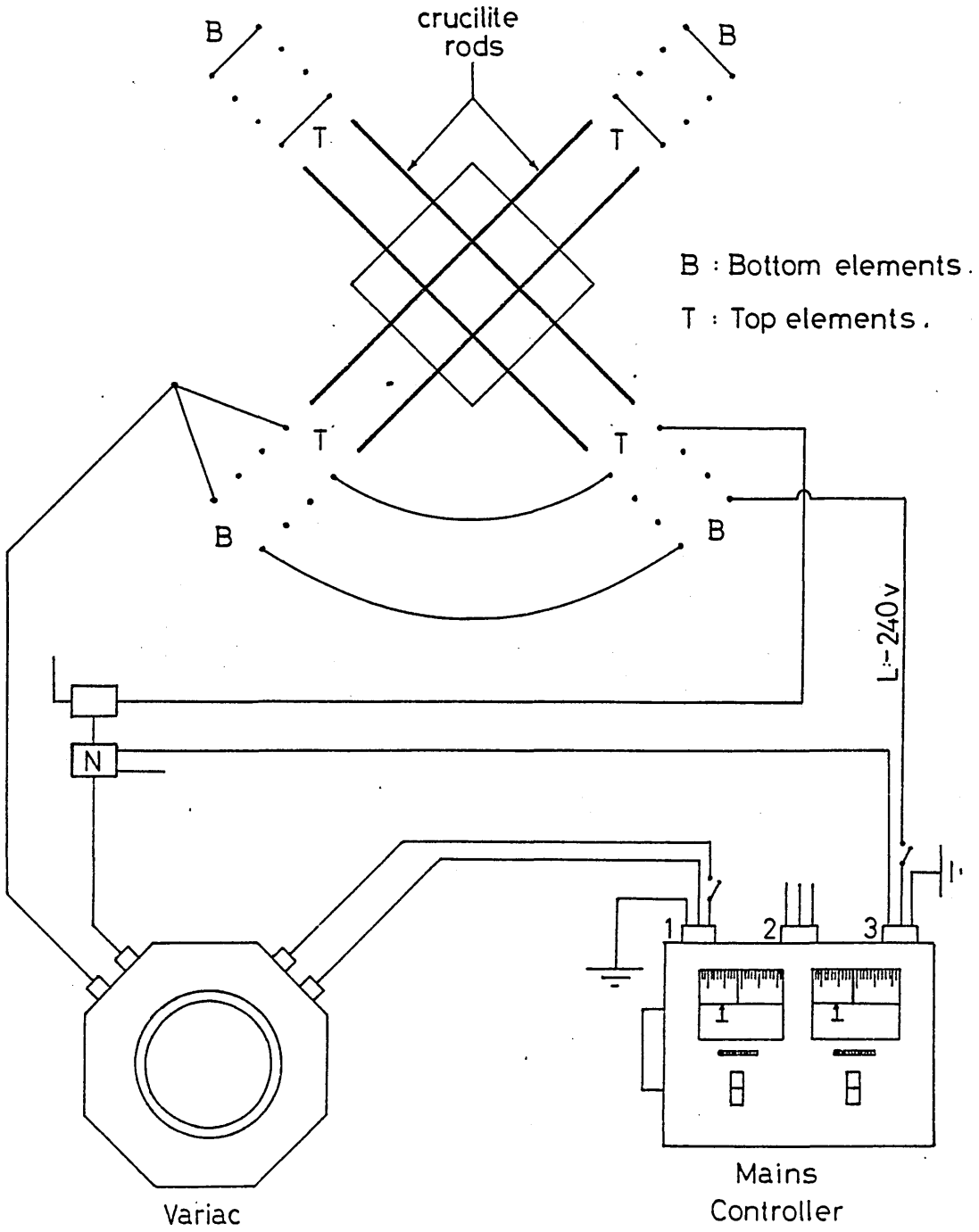


Figure 13 : The internal profile of the mould .

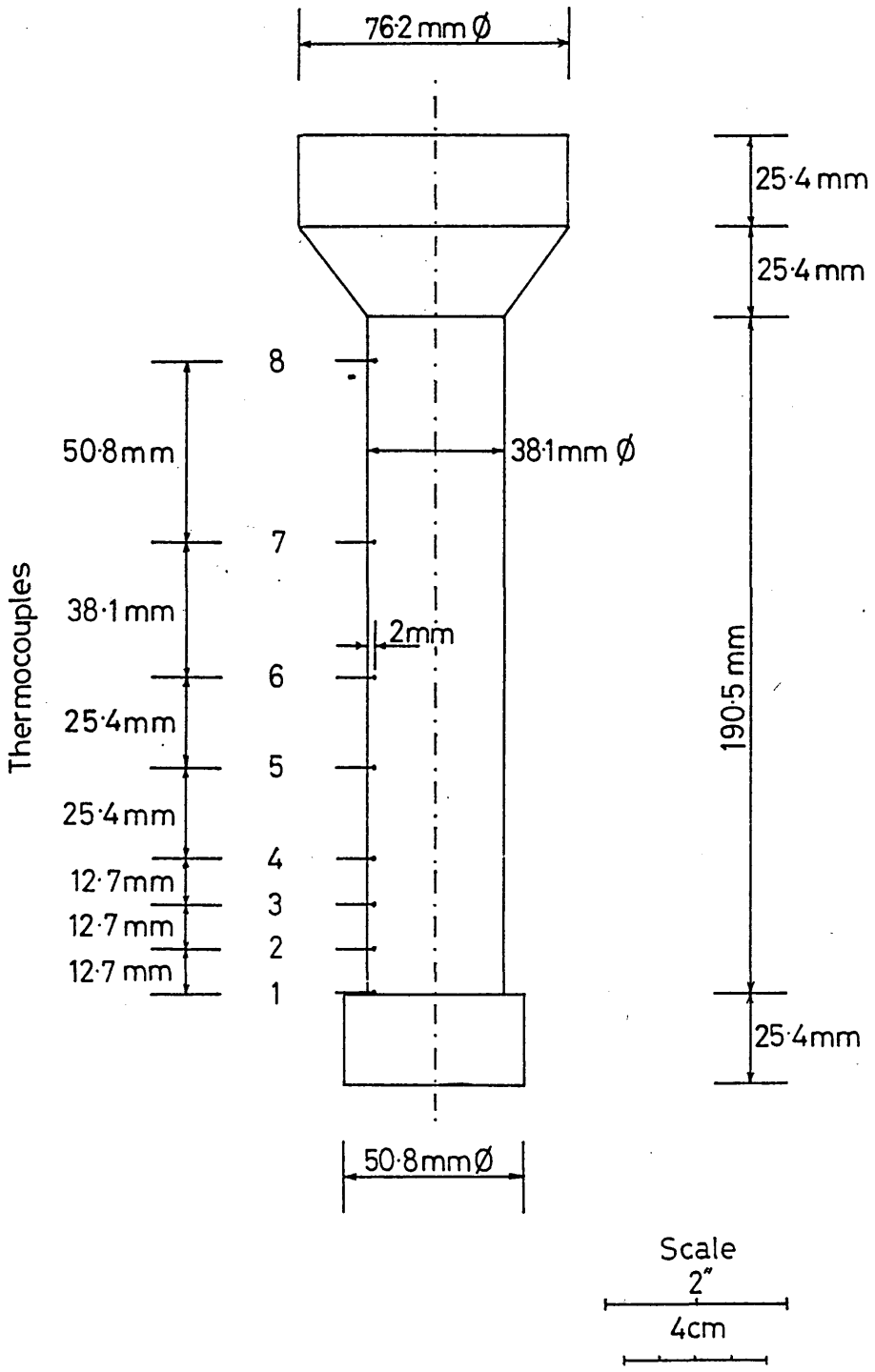


TABLE 5 MOULD SPECIFICATIONS

MOULD COMPONENT	HEIGHT (mm)	INTERNAL DIAMETER (mm)
Feeder Head	50.8	Upper 76.2 Lower 38.1
Sample Section	190.5	38.1
Chill Seat	25.4	44.5
Overall	267.0	-

TABLE 6 MOLOCHITE SUSPENSION

Solution Composition (cm^3)	:	4546 Syton; 6 Lissapol; 12 Octanol
Specific Gravity	:	1.85 (100 mesh suspension)
Powder Specifications	:	200 and 100 mesh

TABLE 7 COPPER CHILL SPECIFICATIONS

CHILL PARAMETERS	HEIGHT (mm)	EXTERNAL DIAMETER (mm)
Overall	88.9	-
Locating Section	25.4	44.5
Base Section	63.5	63.5
Inlet Pipe/ Chill Face Separation	9.5	-

TABLE 8 THERMOCOUPLE ASSEMBLIES

INITIAL ASSEMBLY	POSITION IN MOULD		FINAL ASSEMBLY
(a)	mm	(inches)	(b)
k	190.5	(7.5)	
	177.8	(7)	8
j	152.4	(6)	
i	127.0	(5)	7
h	101.6	(4)	
	88.9	(3.5)	6
g	76.2	(3)	
f	63.5	(2.5)	5
e	50.8	(2)	
d	38.1	(1.5)	4
c	25.4	(1)	3
b	12.7	(1.5)	2
a	0	(0)	1

Thermocouples: Pt - Pt, 13% Rh; 0.50mm diameter wire

TABLE 9 - THE EFFECT OF CARBON 'PICK-UP' ON THE COMPOSITION OF INDUCTION MELTED CAST IRON

SUSCEPTOR SPECIFICATION (MELT NUMBER)	CARBON CONTENT (MASS %) SAMPLING TIME				COMMENTS BASE MELT III (TABLE 1)
	0	5	10	15	
Cold Uncoated (1)	-	4.36	-	4.57	Excessive Carbon 'Pick-up' necessitates the use of 'Zircon' coated Susceptors.
Hot Uncoated (2)	4.12	4.35	4.40	4.40	
'Zircon' Coated (3)	3.68	3.78	3.79	3.792	Spalling prior to melting the metal.
Hot 'Zircon' Coated (4)	3.69	3.64	3.742	3.84	Spalling prior to charge addition.

TABLE 10 - THE VARIATION OF CARBON, SULPHUR AND MANGANESE CONTENT WITH HOLDING TIME AFTER MELTING IN A PRE-HEATED 'ZIRCON' COATED GRAPHITE SUSCEPTOR - MELT PRACTICE A

MELT NO.	SAMPLE TIME (Mins)	COMPOSITION (MASS %)			COMMENTS
		C	S	Mn	BASE MELT COMPOSITION III - TABLE 1
5	0	4.24	0.492	0.18	S Addition as FeS, Table 1 = 1.65%
	5	4.24	0.645	0.18	Total S = 1.668%. S loss = 0.018% (15 mins.)
	10	4.19	1.425	0.15	Mn addition = 0. Total Mn = 0.2%
	15	4.13	1.650	0.17	Mn loss = 0.03% (15 mins)
6	0	4.26	0.176	0.88	S Addition = 0.185%. Total S = 0.203%
	5	-	-	-	S Loss: (gain 0.013% after 10 mins.)
	10	4.57	0.216	0.88	Mn Addition (High N_2Fe-Mn Table 1) = 0.8 mass% Mn.
	15	-	-	-	Total Mn = 1.00%. Mn loss 0.12% (10 mins.)

TABLE II. A SUMMARY OF THE PROCEDURES FOR MELTS 6 TO I7.

MELT NO.	MELT PRACTICE (3.7)	IRON COMPOSITION TABLE I	ADDITIONS TABLE I % S, % Mn % Cr. as FeCr:PURE	POURING TEMP. °C.	T/C. POSITION TABLE 8	FURNACE CONDITIONS CONSTRUCTION (3.3)	FURNACE CONDITIONS TEMP. °C	FURNACE CONDITIONS OFF-TIME (MINS.) (3.3)	DATA LOGGER (3.I0)	FIGURE NUMBER	FRACTURE PLATE NO.	FRACTURE COLOUR	COMMENTS
6	A	III	0.185% S 0.878% Mn	I250	I27mm only	Unsectioned	–	–	I	–	–	Grey	Mould supported outside the furnace by clamp stands. This demonstrate effectiveness of KOS cement in sealing the T/Cs and Cu chill in place. casting was used to develop the fracture technique.
7	A	I	–	I320	a	"	II50	5	I	I4	I8	Grey	Cooling rates were generally too high. The furnace 'switch-off' times delayed.The cooling curves show heat loss from the top of the casting incomplete filling of the feeder head.
8	A	I	3% pure Cr.	I240	a	"	II50	I8	I	I5	I9	White	D/L malfunction. Complete cooling curves were only obtained for T/Cs. 'b' only. The fracture showed evidence of non-unidirectional heat flo ensate for this the mould preheating furnace was sectionalised.
9	A	II	–	I240	b	"	II50	–	–	–	–	–	The melt 'ran-out' due to the mould cracking.
FURNACE COOLING PROFILE – NO METAL IN THE MOULD							II50	5,24,42.	2	I6	–	–	Inflections on the cooling curves showed the effectiveness of section the furnace on reducing the cooling rate. The D/L malfunctioned after
I0	A	II	–	I250	b	Sectioned	II50	I3,4I,58	2	–	20	Grey	No cooling curves were obtained due to the D/L malfunctioning.
II	B	II	0.00I% Bi FeCr. Pure	I480	b	"	II50	I3,4I,58	2	–	–	–	The melt 'ran-out' due to the mould cracking, possibly as a result of temperature required for the addition of Bi to the melt. Hereafter, ch additions are to be made to achieve a white iron structure.
I2	B	II	2.7I% 2.6%	I300	b	"	I250	6,24,38	2	I7	2I	White	Variations of ± 600°C indicated that the data logger had malfunctioned casting exhibited a good unidirectional alignment of structure.
I3	B	(I2) II&III	3.03% 2.89% 3.03% 2.89%	I3I0 I3I0	b b	" "	I250 I250	– –	2 2	– –	– –	–	The data logger malfunction precluded the obtaining of cooling curves. casting was very porous and was subsequently melted down for Melt I5.
I4	B	III	3.09% 2.50%	I3I0	b	"	I250	5,33,4I	2	I8	22	White	The melt was earthed through the no. 8 T/C via a C.R.O.. The D/L perfo satisfactorily. Inflections on the cooling curves concurrent with the 'switch-off' times suggests excess heat input. The 'switch-off' times mu further delayed. The cast structure was satisfactory.
I5	B	(I3) II&III	I.80% I.00% 2.8% from melt (I3)	I3I0	b	"	I250	0,I4,3I	2	I9	23	White	The melt was earthed via the D/L patch-board. The performance was sati Cooling curve inflections suggest the need for further reducing the 's times of the top elements.The cast was reheated and the output from th T/C was monitored via a C.R.O.. The cast structure was satisfactory.
I6	B	III	3.24% 2.33%	I300	b	"	I250	0,I4,25	2	20	24	White	The data logger was not earthed. The melt was isolated from earth by s the clamp stand on a Sandanyo board. The D/L performed satisfactorily. positioning of the no. 7 and 8 thermocouples suggests heat loss from t the casting. Hereafter a Kaowool plug is to be placed above the feeder
I7	B	III	3.I0% 2.40%	I3I5	b	"	I250	0,I4,25	2	2I	27	White	The earthing of the system was as for melt I6. The no. 7 and 8 T/Cs. w electrically insulated by Silica sheaths. Temperature variations of ± observed. Inflections encountered on all cooling curves indicate a nee further reduce the furnace 'switch-off' times to 0,I2,20 mins.. Struct

C.R.O. – Cathode Ray Oscilloscope D/L – Data Logger T/C – Thermocouple

ELEMENT	SEPARATION METHOD	ABSORPTION	TITRANT	COMMENTS
Carbon (error ± 1% of reported composition)	Roasting turnings to produce $CO + CO_2$	Dimethyl Formanide Methanolamine (to absorb H_2O) and indicator	Non-aqueous. Tetrabutyl ammonium hydroxide (N/10) *Problems could be incurred if graphite is weighed with iron.	The titrant severs the $CO + CO_2$ bonds with hexagonals thus altering the alkalinity*
Sulphur (error ± 1% of reported composition)	Roasting turnings to produce SO_2	Weak peroxide solution	Sodium tetraborate	
Phosphorus (error ± 0.002%)	Turnings dissolved to precipitate the phosphomolybdate which removes alkalinity	Standard caustic soda solution	Back titration - Nitric acid to end Point.	Back titration produces alkalinity which is proportional to the phosphorus percentage
Chromium (error ± (0.005%)	Turnings produce Cr 7 by oxidation on hot plate.	Cr 7 reduced to Cr 3 with ferrous ammonium sulphate.	Back titrate with excess iron sulphide solution which reoxidises chromium to Cr 7 state.	Solution colour changes from green to yellow.
Silicon (error ± 1% of reported composition)	Silicon (turnings) is hydrated to silica; filtered on to a pulp pad, carbonaceous material is removed by burning at 900°C. The silica remaining is weighed and converted to silicon percent by multiplying by a factor compensating for the oxygen. (Inhomogeneity causes problems).			
Manganese (error ± 1% of reported composition).	Colourimetric. Turnings dissolved in spekka acid ($H_2SO_4 + H_3PO_4$). The magenta solution is analysed on an absorption spectrophotometer.			
Titanium (error ± 1% of reported composition	Colourimetric. Turnings are dissolved in sulphuric acid; Hydrogen peroxide is used to colour the solution yellow (time is required for completion); The solution is analysed on an absorption spectrophotometer. Segregation is likely in the sample. Analysis is viable for soluble and total but not combined titanium. Time dependent titration.			
Nitrogen	Kjeldahl process. Error impossible to ascertain as stated (3.10.2). This was performed on both types of samples (Performed by B.S.C.).			
Titanium	Both wet and spectrographic methods were used by B.S.C. using turnings and white samples respectively. The result quoted is for total and soluble titanium.			

TABLE 13 - SPECIFIED PERFORMANCE DATA

CREDSHIRE 500 ANALOGUE SCANNER

Max. Signal Input	:	100 volts
Type	:	D.C. or Peak A.C.
Channel Arrangement	:	100 Dipole (5 x 20)
Max. Scan speed	:	10 Channels/sec
Min. Scan speed	:	1 Channel/sec
Scan Mode	:	Auto or Manual
Max. No. Channels	:	999

TABLE 14 - PERFORMANCE DATA - 220 DRIVE CASSETTE UNIT.

Character Storage	50,000
Single Line Accommodation	70 Characters
Out-put Format	9 Characters/Channel
Print-out Format/Channel:	Characters
Channel No.	2
Polarity	1
Temperature	5
Space	1
	9
Time	4 at each line end
Max. Word Count	(70 - 4 =) 66
Word Count/Line - Present Work	4
Total Scan	2 Lines

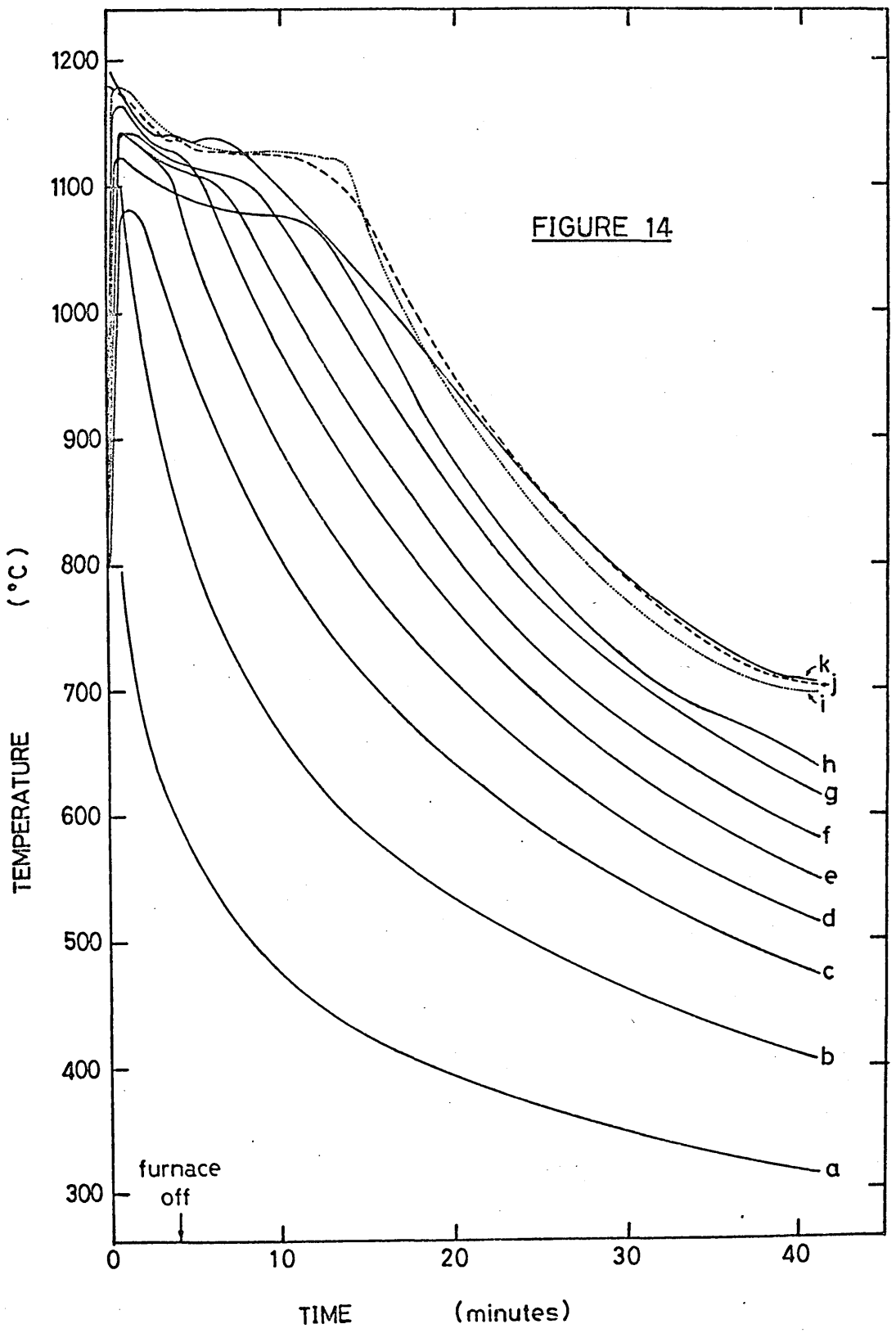


FIGURE 14
TEMPERATURE (°C)
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
TIME (minutes)
furnace off
a
b
c
d
e
f
g
h
i
j
k

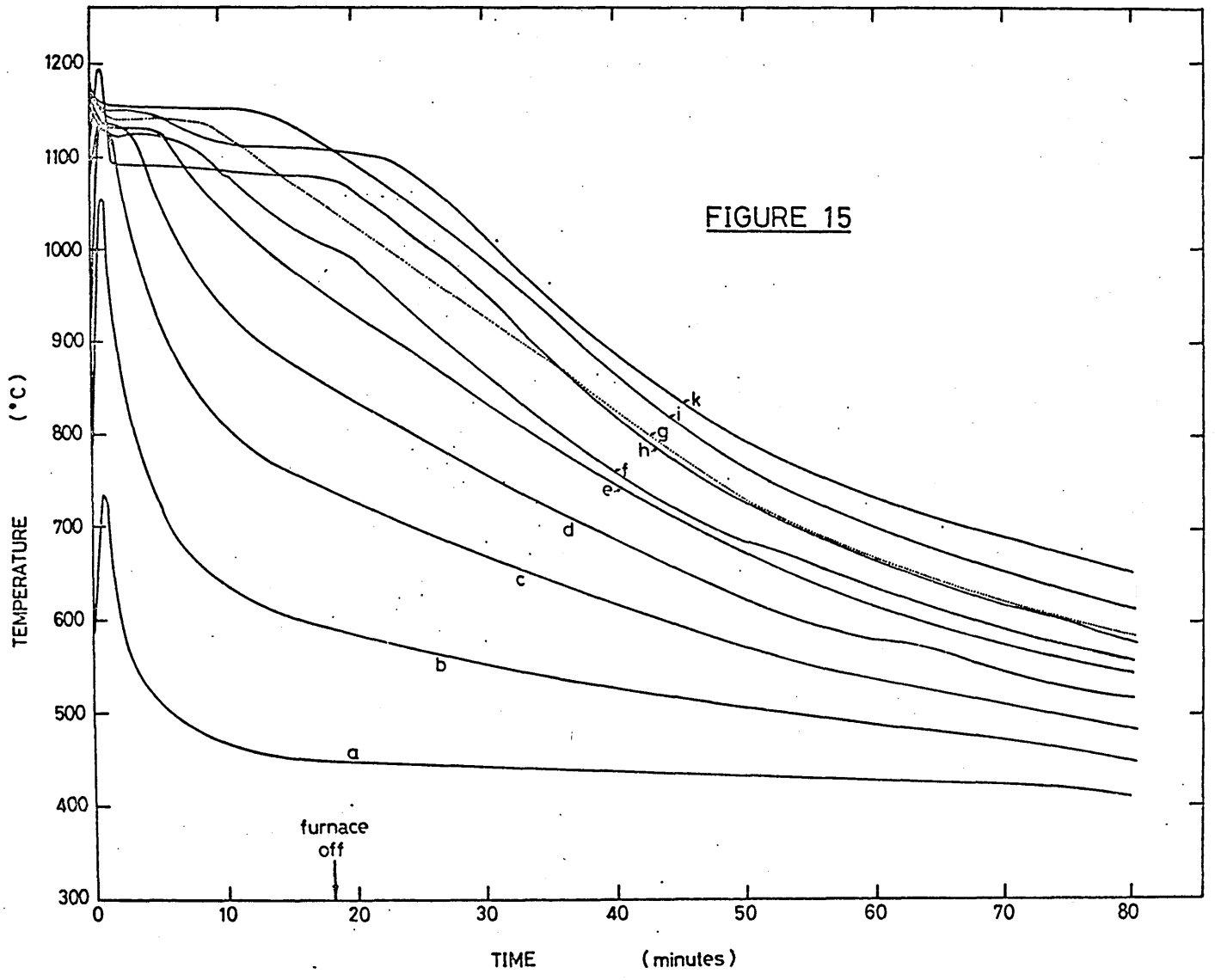


FIGURE 15
TEMPERATURE (°C)
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
TIME (minutes)
furnace off
a
b
c
d
e
f
g
h
i
k

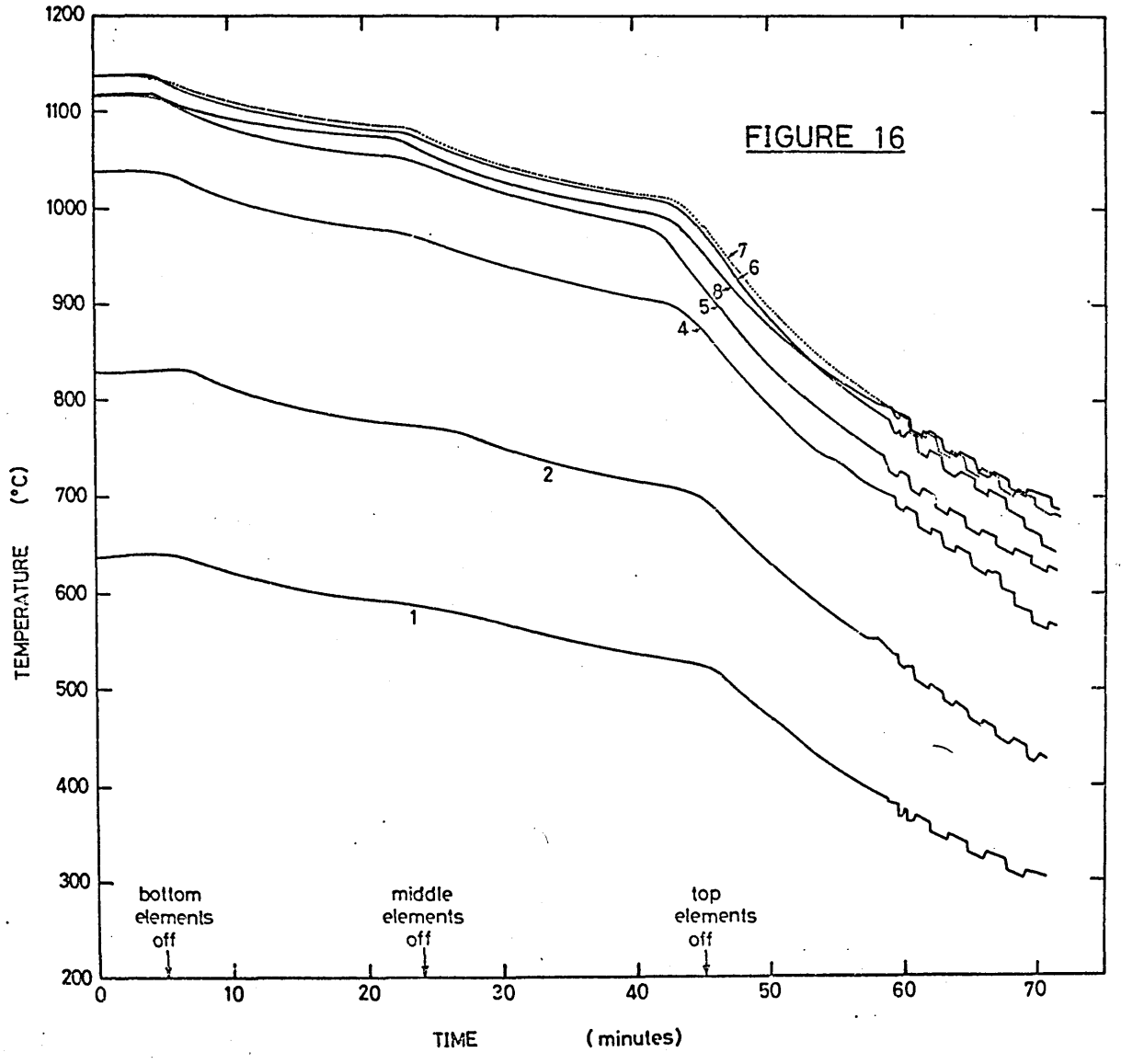


FIGURE 16
TEMPERATURE (°C)
1200
1100
1000
900
800
700
600
500
400
300
200
0
10
20
30
40
50
60
70
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
4
5
6
7
8

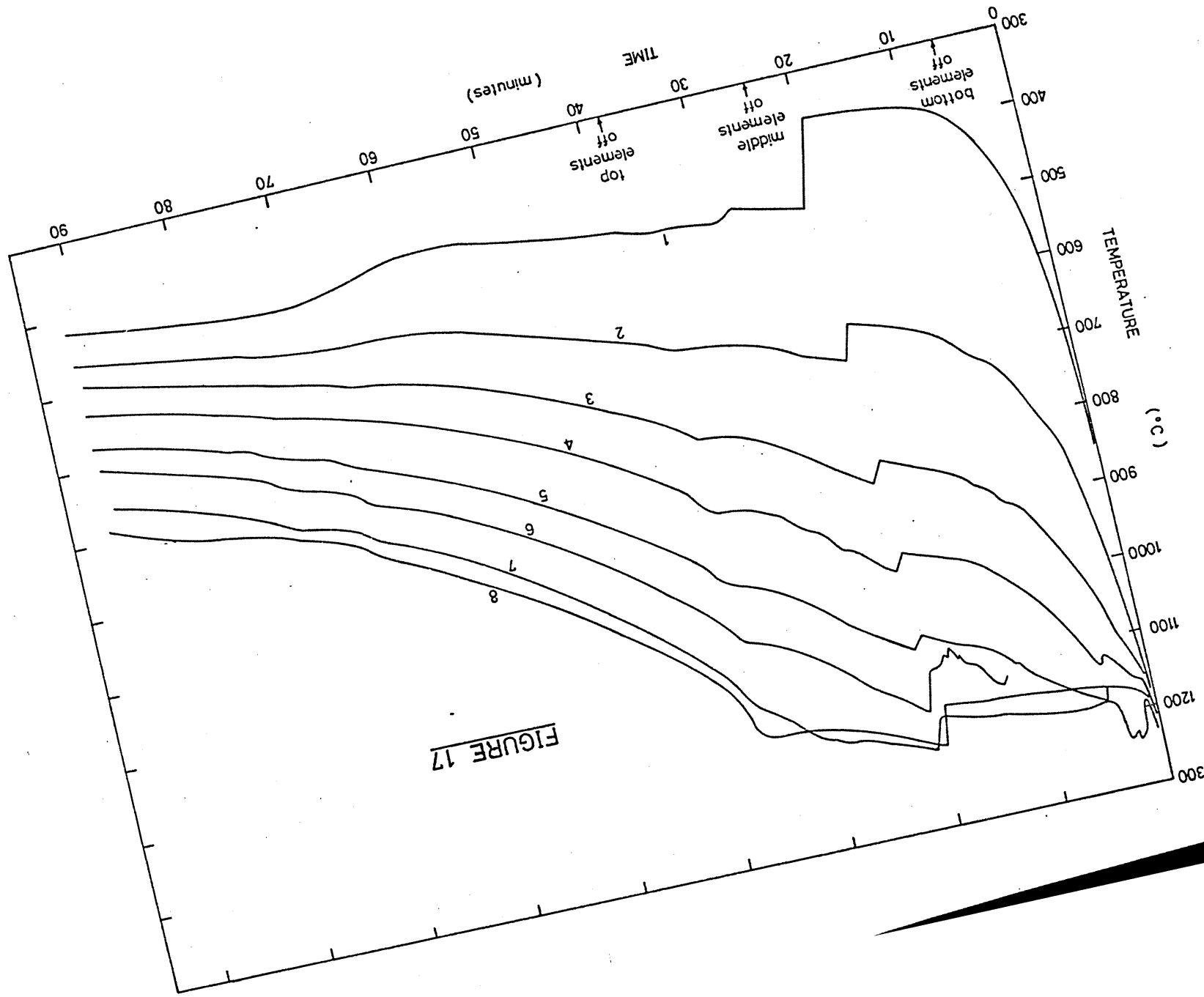

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 17

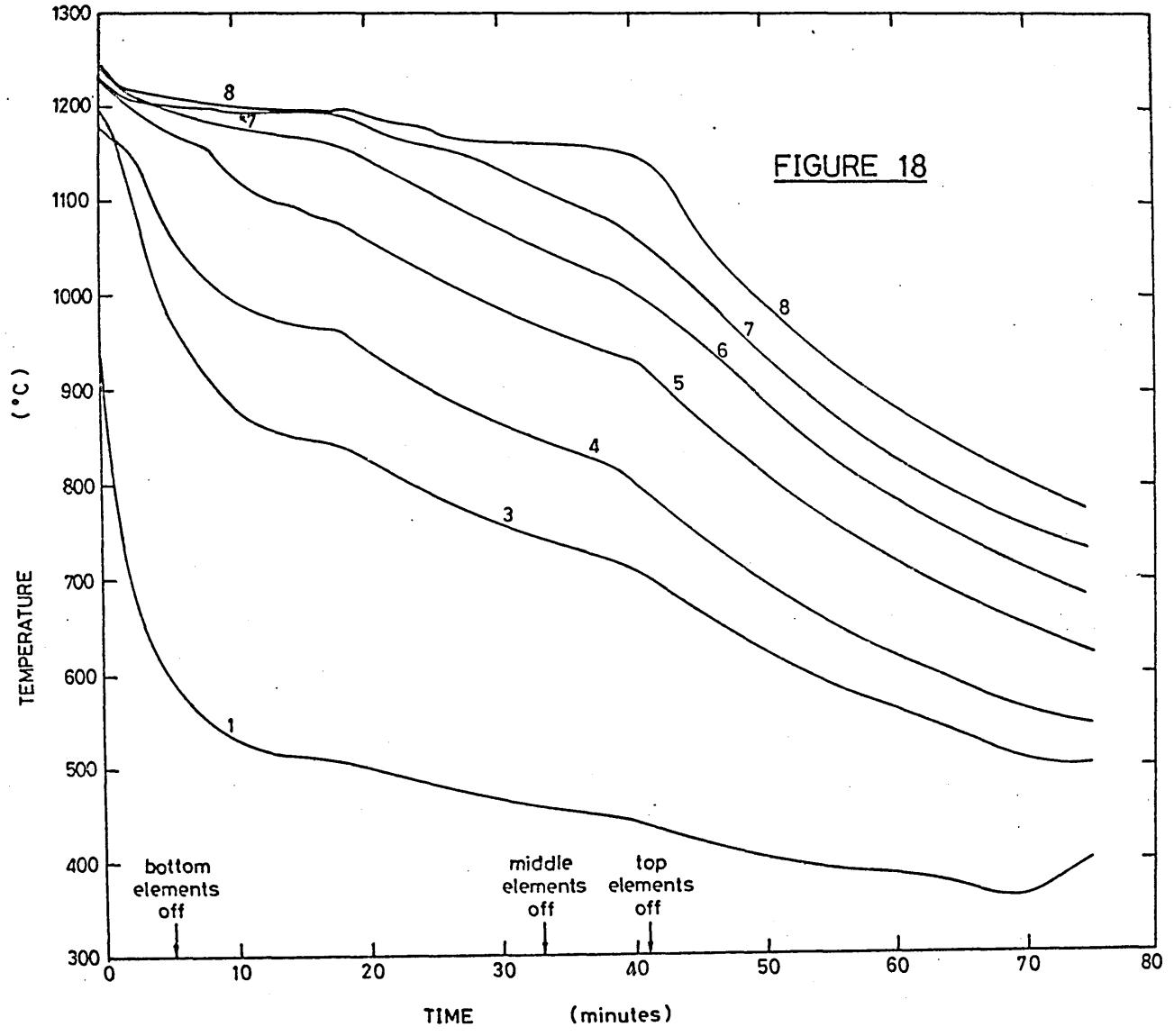


FIGURE 18
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
3
4
5
6
7
8

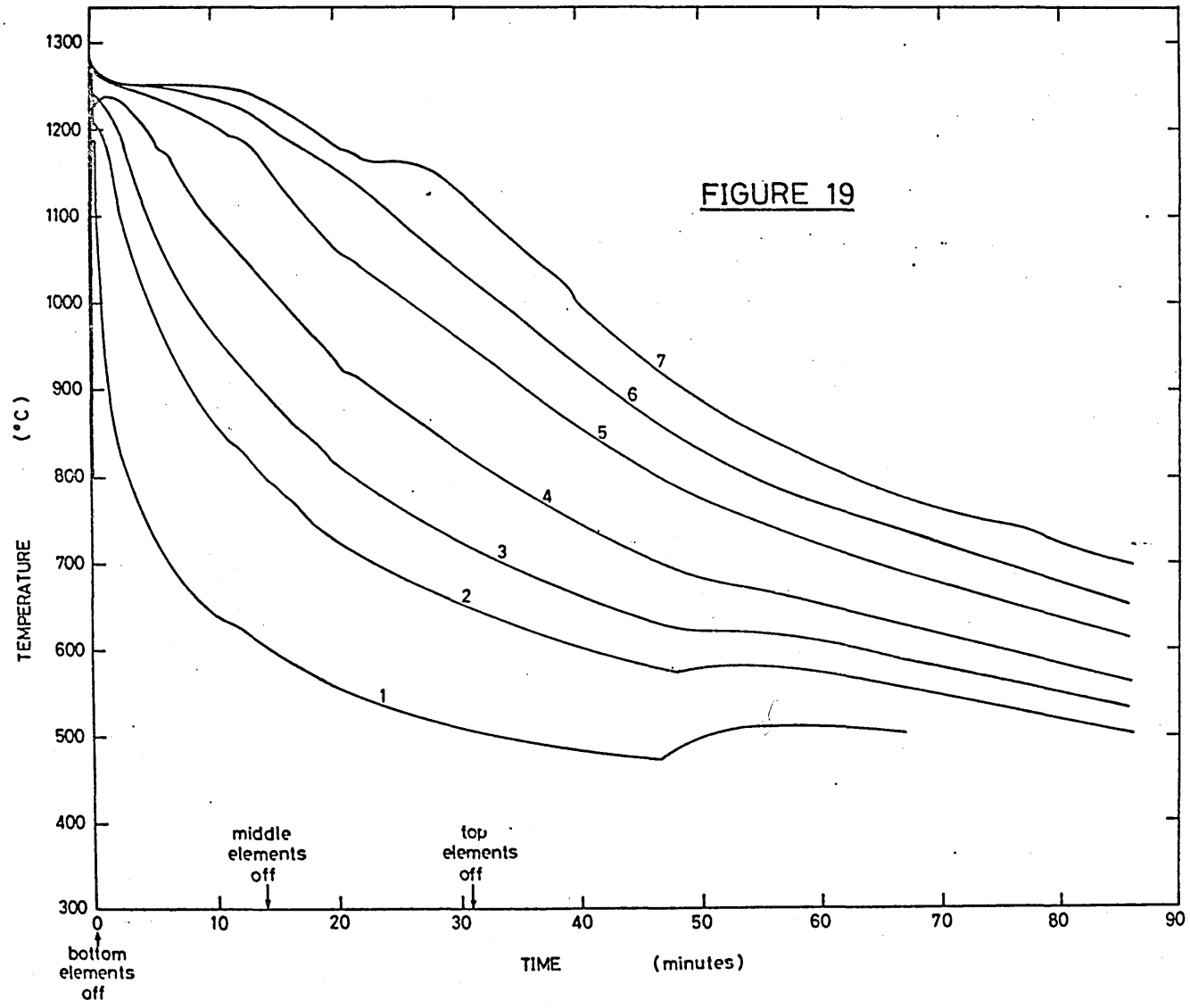


FIGURE 19
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
TIME (minutes)
1
2
3
4
5
6
7
bottom elements off
middle elements off
top elements off

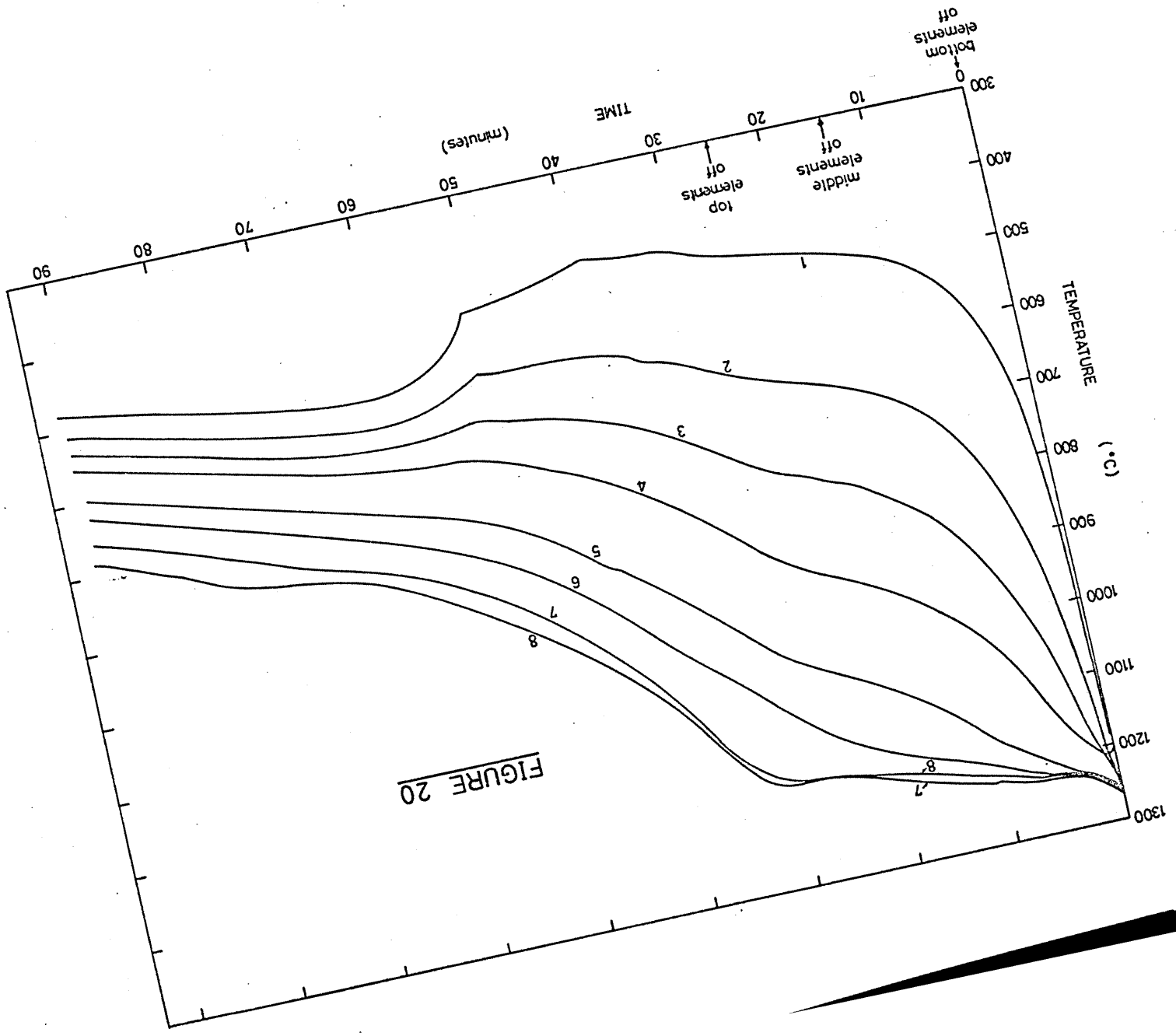

TEMPERATURE (°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME (minutes)
10
20
30
40
50
60
70
80
90
top elements off
middle elements off
bottom elements off
0
1
2
3
4
5
6
7
8

FIGURE 20

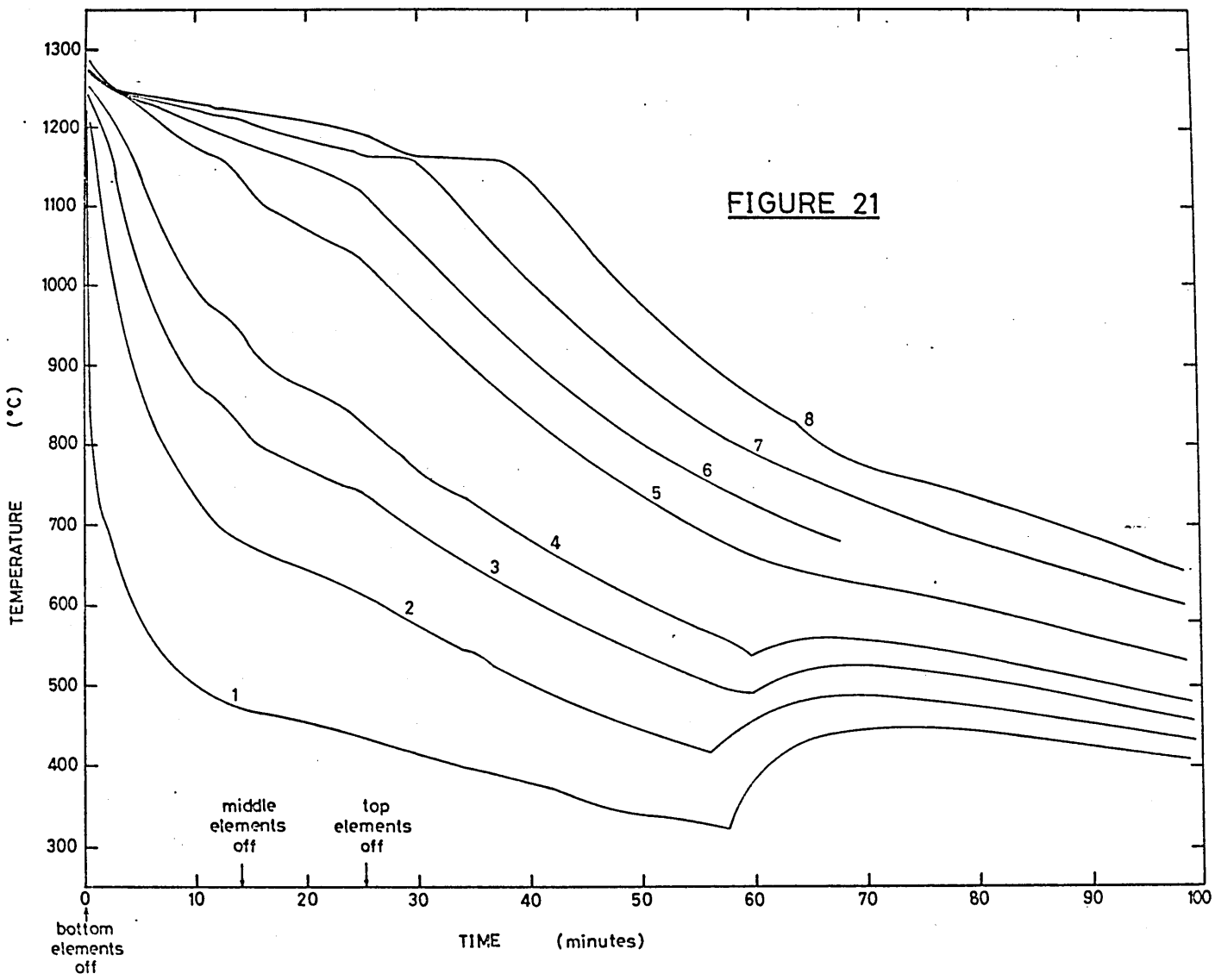
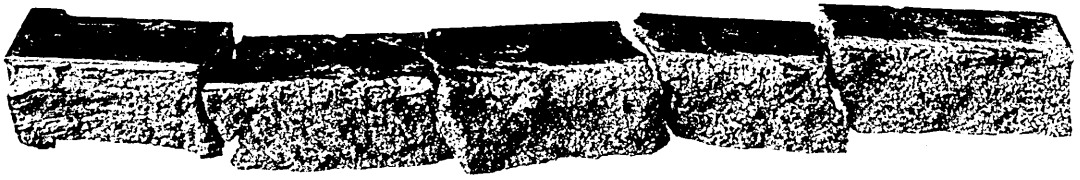
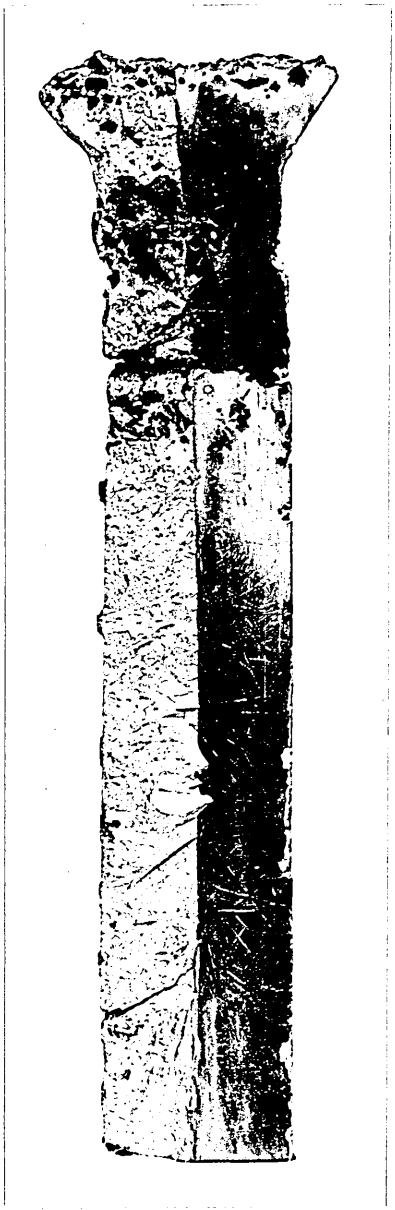
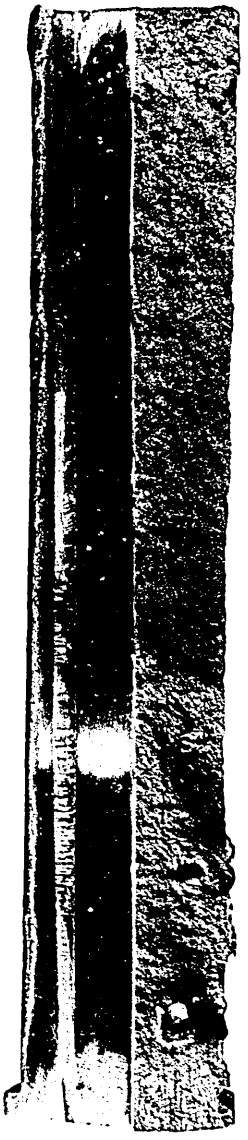
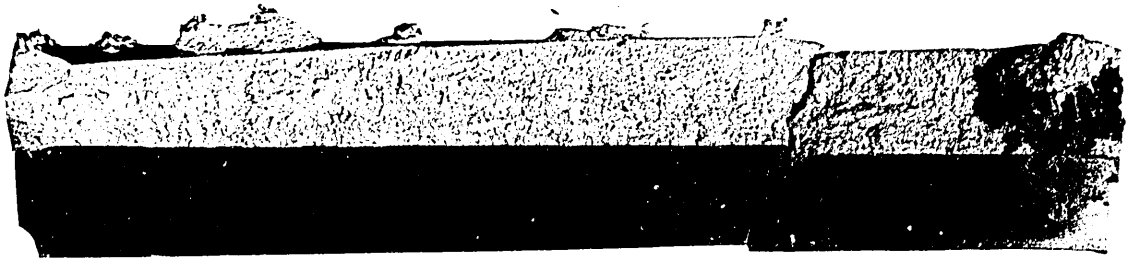


FIGURE 21
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
TIME (minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8









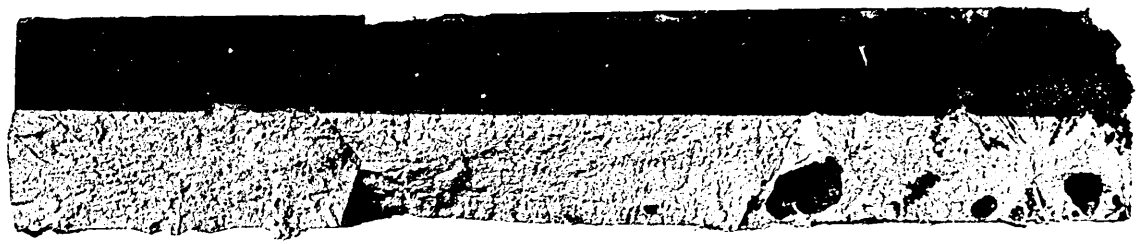


PLATE 83

C1. 127.1mm (19.05mm)

x 16

6.28°C/Min

PLATE 84

C1. 127.1mm (9.525mm)

x 63

6.28°C/Min

PLATE 85

C1. 177.8mm (19.05mm)

x 16

4.43°C/Min

PLATE 86

C1. 181mm (28.6mm)

x 16

4.35°C/Min

PLATE 79

B1. 182mm (36.6mm)

x 32

4.29°C/Min

PLATE 80

C1. 33.5mm (7mm)

x 16

32.51°C/Min

PLATE 81

C1. 63.5mm (9.525mm)

x 16

12.33°C/Min

PLATE 82

C1. 89mm (14mm)

x 63

9.79°C/Min

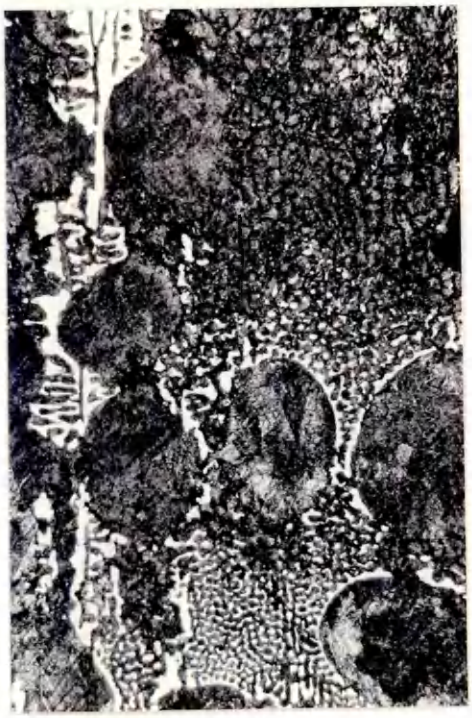


PLATE 75

B1. 89mm (26.1mm)

x 63

9.79°C/Min

PLATE 76

B1. 127.1mm (28.6mm)

x 63

6.28°C/Min

PLATE 77

B1. 127.1mm (31.1mm)

x 63

6.28°C/Min

PLATE 78

B1. 177.8mm (28.6mm)

x 63

4.43°C/Min

PLATE 71

B1. 38.1mm (29.6mm)

x 63

25.62°C/Min

PLATE 72

B1. 63.5mm (30.1mm)

x 16

12.33°C/Min

PLATE 73

B1. 64.5mm (29.6mm)

x 16

12.11°C/Min

PLATE 74

Enlargement of Plate 73

x 160

12.11°C/Min

PLATE 69

A3. 177.8mm (19.05mm)

x 16

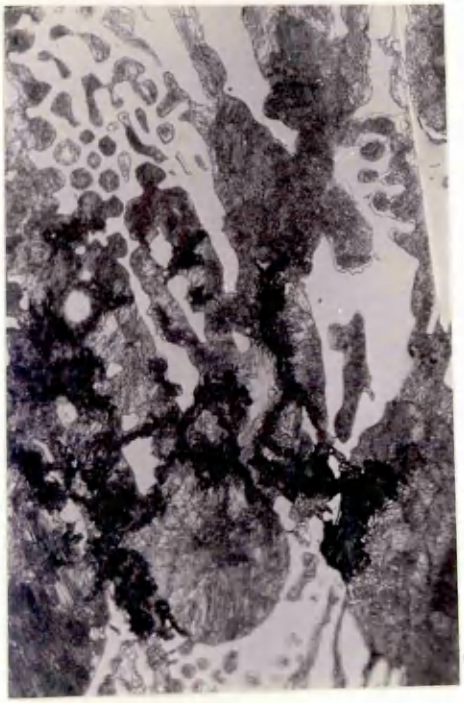
4.43°C/Min

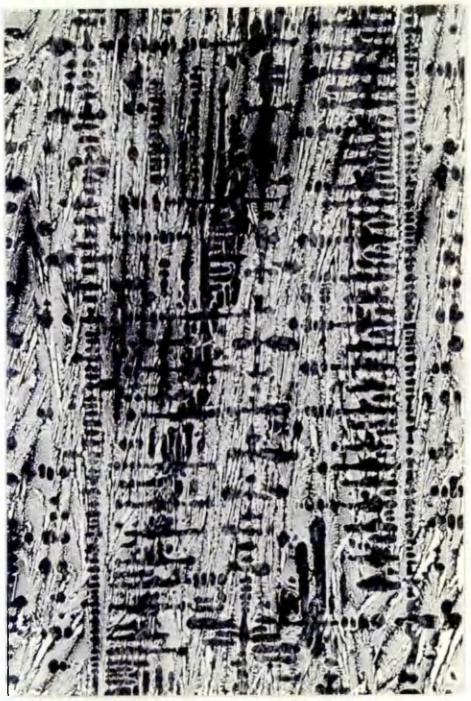
PLATE 70

A3. 177.8mm (15mm)

x 16

4.43°C/Min





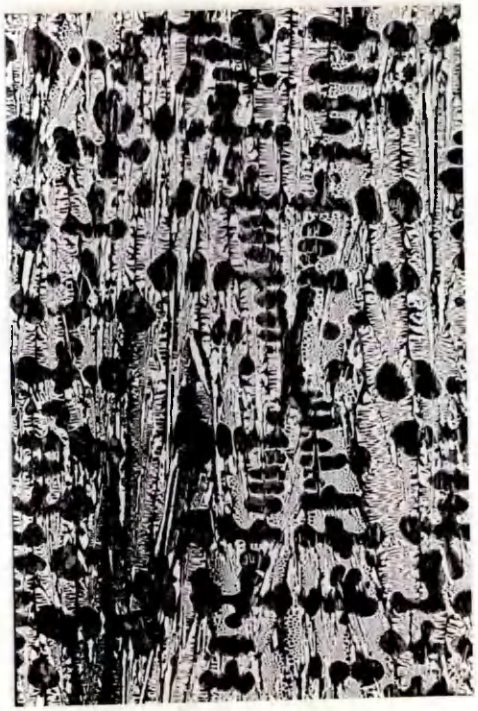


PLATE 65

A3. 38.1mm (9.525mm)

x 160

25.62°C/Min

PLATE 66

A2. 25.4mm (9.525mm)

x 16

48.10°C/Min

PLATE 67

A3. 63.5mm (19.05)

x 16

12.33°C/Min

PLATE 68

A2. 89mm (19.05mm)

x 16

9.79°C/Min

PLATE 63

A1c. 0mm (10mm L.H.S.)

x 16

635°C/Min

PLATE 64

Enlargement of Plate 63

x 63

635°C/Min

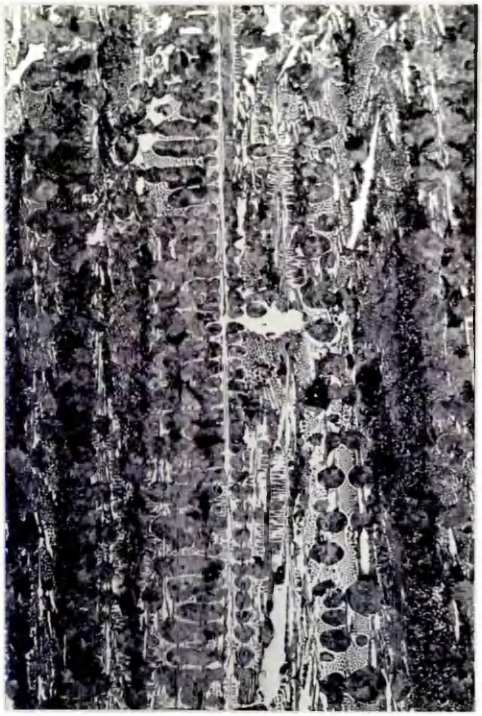


PLATE 60

A1a. 45mm (9.525mm)

x 16

21.18°C/Min

PLATE 61

A1a. 158mm (18.05mm)

x 16

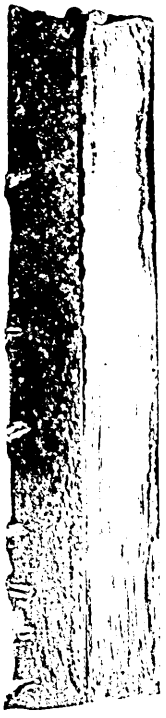
5.50°C/Min

PLATE 62

A1b. 81mm (17mm)

x 16

10.42°C/Min



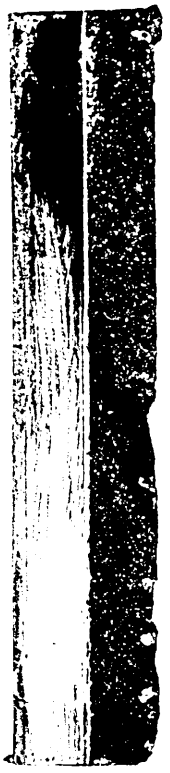


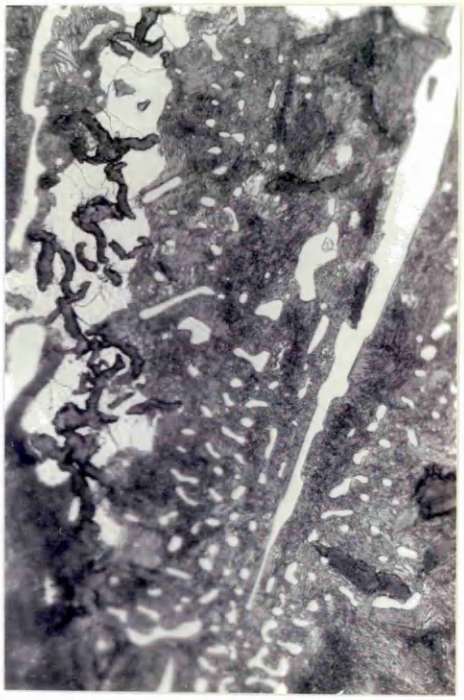
PLATE 59

ADDITIONAL BASE LOW NITROGEN CASTS

Cast A1a

Cast A1b

Cast A1c



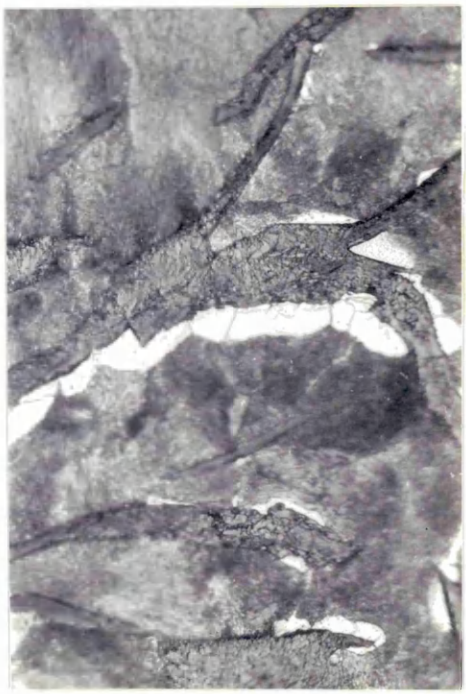


PLATE 56

A1. 185mm (19.05)

x 160

4.17°C/Min

PLATE 57

A1. 185mm (9.525mm)

x 63

4.17°C/Min

PLATE 58

A1. 185mm (10mm)

x 160

4.17°C/Min

PLATE 52

A1. 89mm (19.05mm)

x 16

9.79°C/Min

PLATE 53

Enlargement of Plate 52

x 63

9.79°C/Min

PLATE 54

A1. 127.1mm (19.05mm)

x 63

6.28°C/Min

PLATE 55

A1. 177.8mm (9.525mm)

x 63

4.43°C/Min

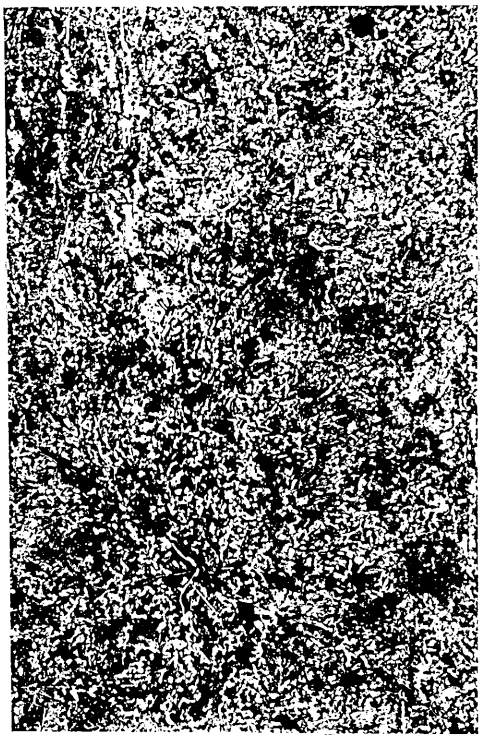


PLATE 49

A1. 89mm (9.525mm)

x 16

9.79°C/Min

PLATE 50

Enlargement of Plate 49

x 160

9.79°C/Min

PLATE 51

A1. 127.5mm (9.525mm)

x 32

6.17°C/Min

PLATE 46

A1. 63.5mm (34.1mm)

x 16

12.33°C/Min

PLATE 47

Enlargement of Plate 46

x 160

12.33°C/Min

PLATE 48

Enlargement of Plate 46

x 160

12.33°C/Min

PLATE 44

A1. 38.1mm (9.525mm)

x 16

25.62°C/Min

PLATE 45

Enlargement of Plate 44

x 160

25.62°C/Min

PLATE 40

A1. 25.4mm (19.01mm)

x 16

48.1°C/Min

PLATE 41

Enlargement of Plate 40

x 63

48.1°C/Min

PLATE 42

A1. 38.1mm (28.5mm)

x 63

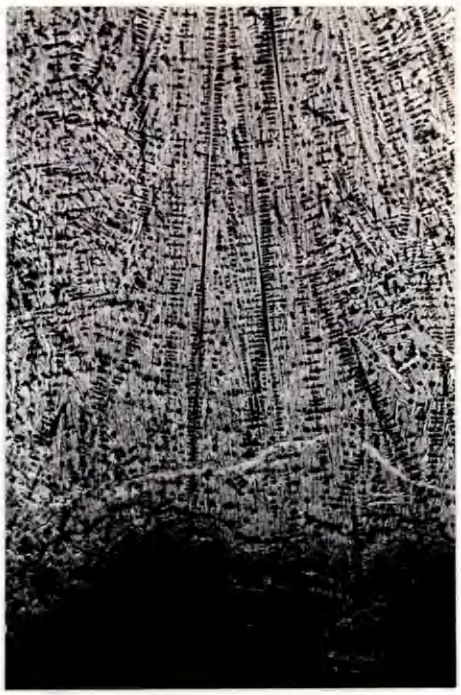
25.62°C/Min

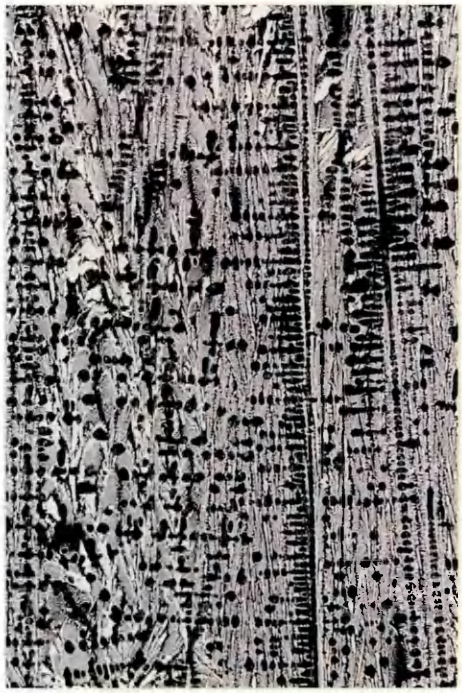
PLATE 43

Enlargement of Plate 42

x 160

25.62°C/Min





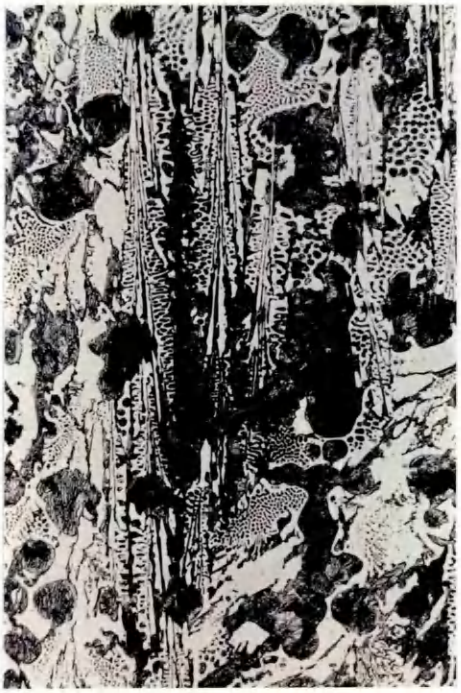


PLATE 36

A1. 0mm (19.05mm)

x 16

635°C/Min

PLATE 37

A1. 12.7mm (19.01mm)

x 16

123.97°C/Min

PLATE 38

Enlargement of Plate 37

x 63

123.97°C/Min

PLATE 39

Enlargement of Plate 37

x 160

123.97°C/Min

The details of the following microstructures, etched in 2% nital, are given as follows:-

Cast number, distance from the chill, (distance from the T/C edge) and magnification.

Cooling rate through the 'solidification arrest' - 1160°C - 1100°C.

The photographs are orientated with the chill/metal interface towards the bottom of the plates.

A1

B1

C1

E1

F1

G1

A2

B2

C2

E2

F2

G2

PLATE 35

Fractured Castings for the Low Nitrogen Melt Programme

Figure 62 : The variation of overall cooling rate between 1160 and 700°C with distance from the chill-melt interface.

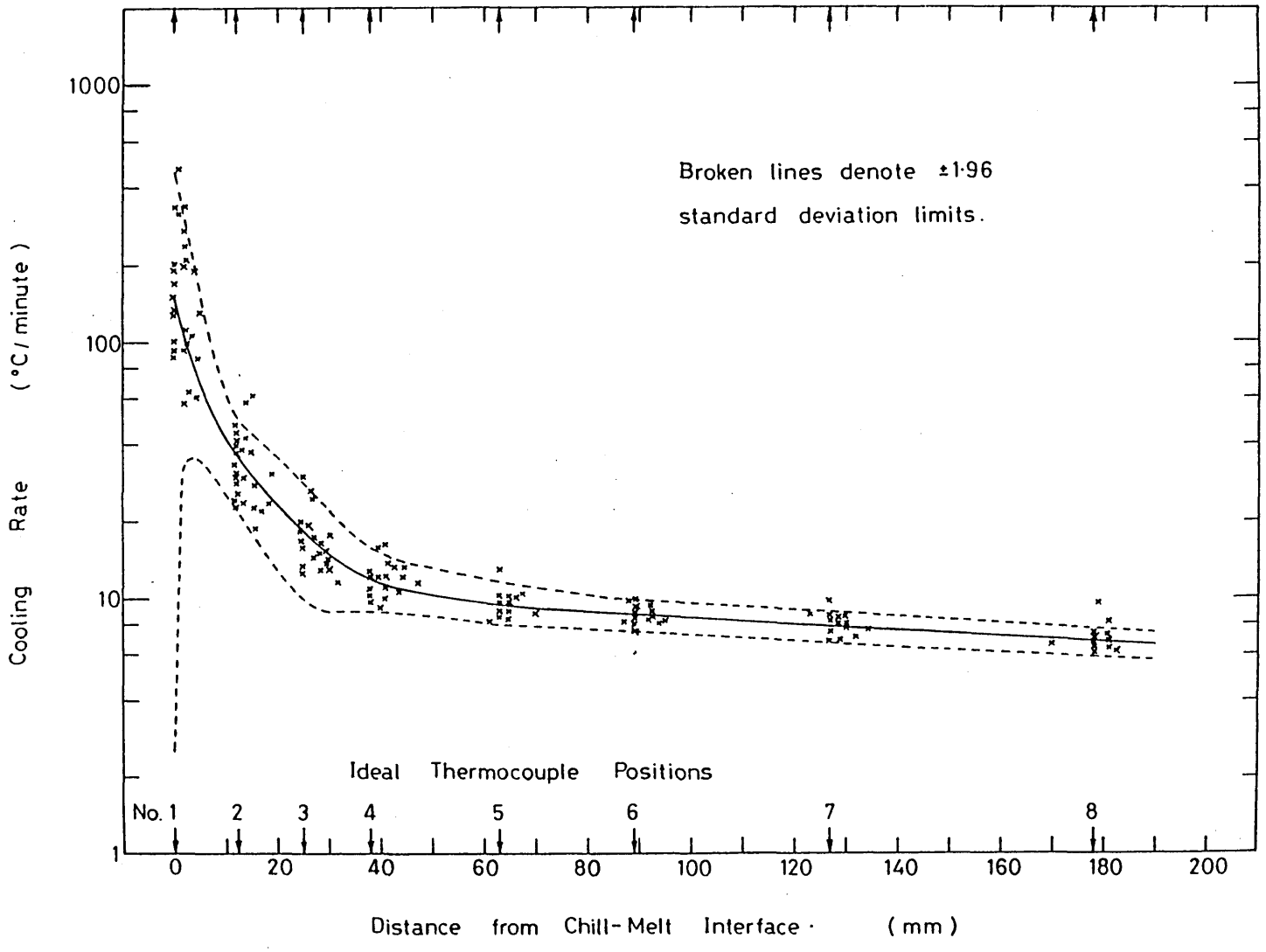
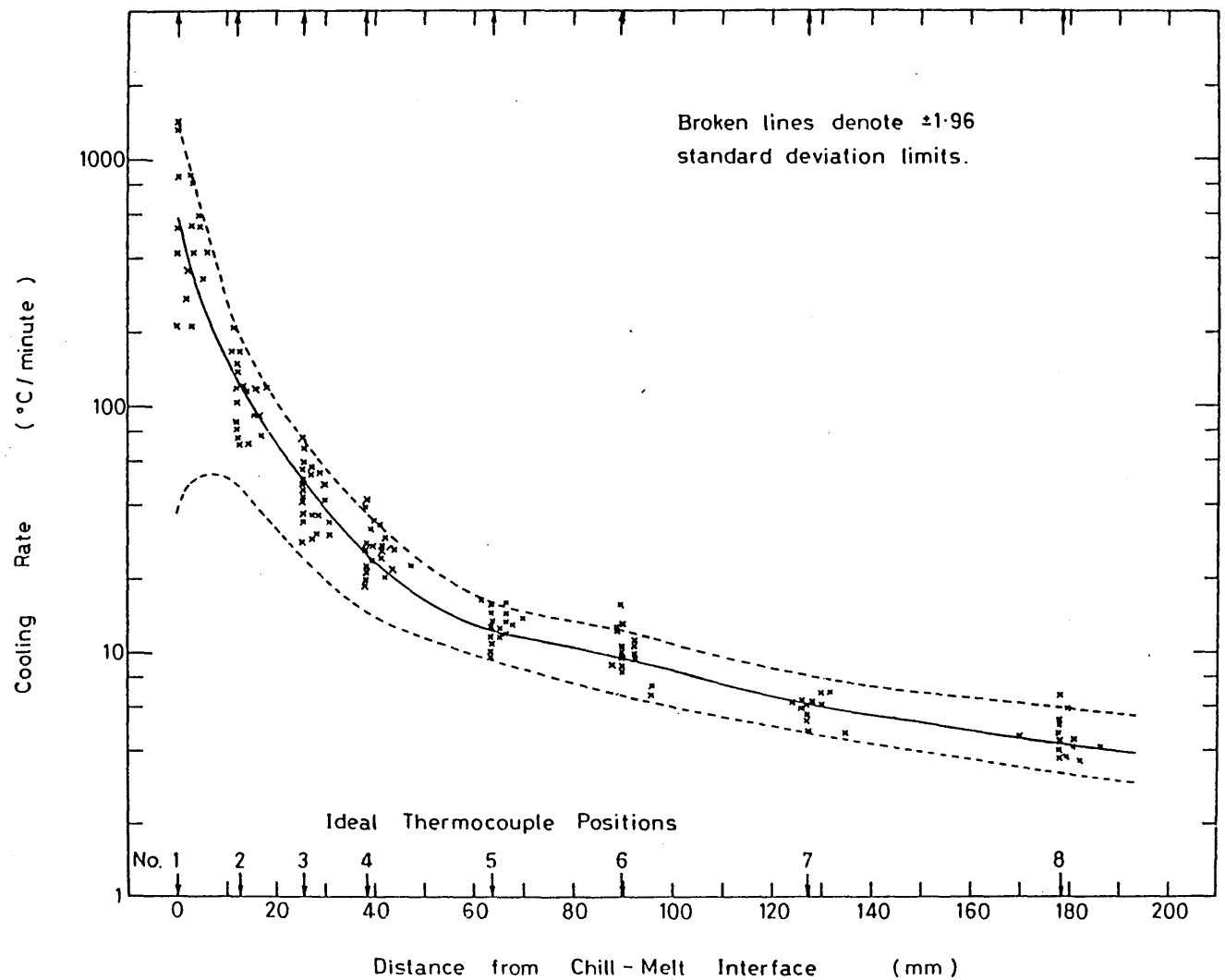


Figure 61 : The variation of overall cooling rate between 1160 and 1100 °C with distance from the chill-melt interface.



STATISTICAL ANALYSIS OF COOLING RATES

Statistical Function	Thermocouple Number (1160-1100°C)								Thermocouple Number (1160-700°C)						
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7
$\bar{x}$	635	123.97	48.10	25.62	12.33	9.79	6.28	4.43	156.48	35.97	18.59	11.83	9.67	8.81	7.78
V	117750	1474.75	145.07	35.71	2.28	1.92	0.58	0.34	6166.65	56.23	23.99	0.39	0.94	0.48	0.38
σ	343.15	38.4	12.04	5.98	1.51	1.39	0.76	0.59	78.53	7.50	4.90	0.63	0.97	0.69	0.61
1.96σ	672.57	75.27	23.61	11.71	2.96	2.72	1.49	1.15	153.92	14.70	9.60	1.23	1.91	1.36	1.20
$\bar{x}+1.96\sigma$	1307.57	48.70	71.71	37.33	15.29	12.51	7.77	5.58	310.40	50.67	28.19	13.06	11.58	10.17	8.98
$\bar{x}$	635	123.97	48.10	25.62	12.33	9.79	6.28	4.43	156.48	35.97	18.59	11.83	9.67	8.81	7.78
$\bar{x}-1.96\sigma$	206.52	199.24	24.49	13.91	9.37	7.07	4.79	3.28	2.56	21.27	8.99	10.60	7.76	7.45	6.58
	Logarithmic Values														
$\bar{x}+1.96\sigma$	3.1165	2.2994	1.8556	1.5271	1.1844	1.0973	0.8904	0.7466	2.4919	1.7048	1.4501	1.1159	1.0637	1.0073	0.9533
$\bar{x}$	2.8028	2.0933	1.6822	1.4086	1.0910	0.9908	0.7980	0.6464	2.1945	1.5559	1.2693	1.0730	0.9854	0.9450	0.8910
$\bar{x}-1.96\sigma$	1.5748	1.6875	1.3890	1.1433	0.9717	0.8494	0.6803	0.5159	0.4085	1.3278	0.9538	1.0253	0.8899	0.8722	0.8182

Where $\bar{x}$ is the mean of those melts whose thermocouples coincide with the aim positions.

v is the variance of the cooling rates.

σ is the standard deviation.

1.96σ is the statistical significance limit - any results exceeding $|\bar{x} \pm 1.96\sigma|$ will be statistically significant

TABLE 18

ACTUAL THERMOCOUPLE DISPLACEMENT (mm)

im Dist.	0	12.7	25.4	38.1	63.57	89	127.17	177.8
st/TC No.	1	2	3	4	5	6	7	8
A1	0	15.9	27.4	38.1	63.5	89	127.17	177.8
A2	0	12.7	25.4	38.1	63.5	89	127.7	177.8
A3	0	12.7	25.4	38.1	63.5	89	127.17	177.8
B1	0	12.7	25.4	38.1	63.5	89	127.17	177.8
B2	0	12.7	25.4	38.1	63.5	89	127.17	177.8
B3	0	12.7	25.4	38.1	63.5	89	127.17	177.8
C1	0	12.7	25.4	44	67	92	128.5	181.0
C2	3	15.7	27.4	40.1	63.57	89	127.17	178.0
C3	4.5	14	26.4	38.1	63.57	89	127.17	178.0
E1	0	12.7	25.4	38.1	63.57	89	127.17	178.0
E2	0	12.7	25.4	38.1	63.57	89	127.17	178.0
E3	3	12.7	25.4	38.1	63.57	89	127.1	170
F1	2.5	17.0	30.0	41.5	63.57	92.5	130.5	187
F2	3	19	30.0	41.0	70	94.0	132	178/181.5
F3	3	15.7	31.0	41.0	66	92	130.17	181
G1	1.5	14.5	29.5	44.0	63.57	92	127.17	178
G2	1.0	12.7	28.0	41.0	65.5	89	127.17	178
G3	5.0	12.7	25.4	47.6	63.5	95.5	134.5	182
A1'	2.5	-	25.4	39	-	-	127.1	179
A2'	3.5	12.7	28.4	42.5	63.5	89	127.1	178
A3'	6.5	12.7	29.0	41.0	65	-	-	178
B1'	2.0	13.7	25.4	38.1	65.57	89	127.17	178
B2'	0	12.7	25.4	38.1	63.5	89	127.17	178
B3'	0	12.7	25.4	38.1	63.5	89	127.17	178
C1'	5	16.7	30	43.5	63.5	89	127.17	178
C2'	2	14	29	41.6	64.5	87	127.17	177.8
C3'	3	14	27.5	39.1	63.5	89	123.17	177.8
D1'	4	16	32	39.6	61	89	129.1	178/181.5
D3'	4.5	19.7	31	38.1	63.57	95	127.1	178
F1'	0	12.7	25.4	38.1	63.5	89	127.1	178
F2'	0	16.0	27.4	42.6	67	89	128	178
F3'	3	15.7	25.4	41.1	68	92	130.2	181

ADDITIONAL CASTS

A1a	-	17	30	45	70	87	125	-
A1b	0	12.7	25.4	38.1	63.5	81	135	185.5
A1c	-	-	-	-	-	-	-	-
E1a	0	12.7	25.4	38.1	63.7	89	127.1	177.5
C1a	NO GRAPH →							
F2a	0	12.7	25.4	38.1	63.7	89	127.17	178
A1a'	7	20	32.5	46	63.5	89	133.5	-
B3a'	3	12.7	25.4	38.1	63.5	89	127.17	178
C2a'	NO GRAPH →							

HE COOLING RATES (°C/MIN) FOR THE 1160° - 700°C TEMPERATURE RANGE

ct.	Thermocouple Number							
	1	2	3	4	5	6	7	8
	85.87	23.50	14.57	11.50	9.61	8.52	8.09	7.34
	128.80	32.20	15.33	11.38	9.25	8.47	7.76	7.11
	153.33	45.35	13.33	12.20	10.06	9.47	7.89	7.08
	201.25	46.00	29.54	10.81	8.77	7.84	7.49	6.48
	357.78	42.37	16.43	11.97	9.88	8.59	7.74	6.57
	94.71	38.80	16.60	12.48	9.50	8.56	7.97	6.56
	189.41	41.28	20.38	13.59	10.66	9.58	8.61	7.19
	357.78	61.92	25.76	15.86	-	10.13	8.16	7.24
	184.00	57.50	18.94	11.80	8.80	8.13	7.37	6.63
	169.47	24.03	12.15	-	9.31	8.90	8.52	7.12
	-	-	20.25	11.42	9.94	8.87	7.80	7.08
	233.33	35.00	16.43	12.39	9.31	8.75	7.56	6.52
	189.76	32.20	14.04	13.86	9.64	8.77	7.76	6.69
	64.4	24.77	14.90	-	8.94	7.93	7.12	6.34
	111.04	28.75	14.98	12.15	9.85	8.99	8.01	6.78
	322.00	42.93	16.51	12.11	10.39	8.66	7.69	6.52
	460.0	26.83	13.31	10.59	8.92	8.50	7.39	6.55
	61.92	25.56	13.53	11.22	-	8.26	7.29	6.22
1'	115.00	34.26	20.40	13.70	11.22	10.46	9.97	9.70
'	109.15	27.29	14.77	9.25	8.75	8.13	6.97	6.22
3'	134.17	48.79	15.56	11.46	9.33	8.70	8.05	7.40
'	94.71	38.33	19.88	12.88	10.46	9.17	8.01	6.91
2'	94.71	38.33	19.88	12.88	10.46	9.17	8.01	6.91
3'	115.83	38.80	16.86	11.14	9.31	8.82	7.82	6.44
1'	178.89	22.68	14.98	10.88	9.17	8.59	7.51	6.61
2'	57.00	24.39	14.84	10.66	8.82	8.17	7.35	7.35
3'	268.33	32.53	17.22	12.06	13.14	9.82	9.12	7.42
1'	-	18.72	12.11	10.06	8.13	7.52	6.84	6.63
3'	89.44	30.67	16.68	11.38	8.97	8.07	6.93	6.11
1'	89.44	30.67	16.68	11.38	8.97	8.07	6.93	6.11
2'	137.02	37.44	20.77	13.55	10.35	9.33	8.15	6.75
3'	191.67	60.67	29.82	16.60	11.03	9.79	8.52	8.26
	ADDITIONAL CASTS							
1a	-	-	-	-	-	-	-	-
1b	-	47.35	16.26	10.59	8.50	8.52	7.82	6.97
1c	-	42.93	24.39	17.22	14.12	12.83	11.03	10.09
3a	NO	GRAPH						
1a	78.54	26.18	17.50	11.03	8.99	8.19	8.24	6.44
2a	189.41	67.08	20.13	13.76	10.13	9.12	8.05	6.91
1a'	73.8	20.13	12.93	9.79	9.61	8.90	8.05	7.52
3a'	-	42.93	20.00	11.71	9.50	8.50	7.42	6.64
2a'	NO	GRAPH						

THE COOLING RATE (°C/min) FOR THE 1160-1100°C TEMPERATURE RANGE

st.	Thermocouple Number							
	1	2	3	4	5	6	7	8
1	≈420	93.33	30	22.95	12.17	10.5	5.75	4.19
	840	105.0	38.18	22.22	12.8	8.57	5.86	3.96
3	-	168.0	46.67	23.6	15.7		5.92	5.25
1	-	-	≈60	26.25	11.67	8.94	6.32	4.77
2	1400	120.0	38.18	27.1	14.48	9.66	6.56	4.31
3	420	105	35	30	13.13	9.13	9.33	4.33
1	525	76.36	49.41	28	15.85	10.5	6.89	4.40
2	840	140	54.62	35	-	10.5	6.0	4.0
3	600	168	70	28.97	13.77	12.73	6.18	6.67
1	≈420	150	44.68	-	10.24	8.62	6.30	4.97
2	-	-	60	40	13.77	9.13	6.51	4.57
3	210	140	56	30	10.63	10.63	6.22	4.67
1	≈525	93.3	42	30	12.54	9.77	6.27	4.18
2	420	120	-	28	13.55	10.5	6.36	4.52
3	420	60	30	28	12.35	9.55	7.0	4.2
1	-	120	36.52	27.1	14.0	9.77	6.46	4.33
2	-	210	52.50	24.71	10.37	8.94	5.81	4.23
3	323	89.36	28.97	27.70	-	7.57	4.86	3.65
1'	840	84	56	24.71	12.35	7.18	5.68	3.89
2'	525	140	36.52	21	12.35	13.13	6.56	3.98
3'	≈420	168	31.11	26.25	11.67	8.57	6.18	4.31
1'	280	120	42	19.09	12.35	10.00	6.56	4.77
2'	-	-	-	-	-	-	-	-
3'	420	87.5	42.00	16.80	12.73	9.23	6.41	4.00
1'	-	76.36	49.41	22.70	11.35	-	-	4.33
2'	350	70	52.50	25.45	12.73	9.13	6.09	3.75
3'	-	-	52.50	28.97	9.55	8.66	6.56	4.35
1'	-	-	-	33.6	16.80	10.77	6.18	4.24
3'	-	70	33.60	20.49	11.35	7.18	5.75	3.75
1'	420	76.36	-	-	-	10.37	5.32	4.24
2'	420	120	-	28.00	13.55	10.50	6.36	4.52
3'	840	140	76.36	35.00	13.13	11.35	7.00	5.53
ADDITIONAL CASTS								
1a	-	-	-	-	-	-	-	-
1b	-	175	56	26.25	8.7	10.19	6.77	4.52
1c	300	100	44.21	15.11	17.14	9.27	5.32	-
1a	420	84	70.0	76.25	13.13	8.84	10.91	4.04
2a	-	≈280	52.5	32.31	14.0	10.0	6.18	4.26
3a		NO GRAPH						
a'	420	76.36	40.0	16.15	11.20	8.24	5.68	4.16
a'	-	168	70.0	24.0	16.8	10.24	6.27	7.64
a'		NO GRAPH						

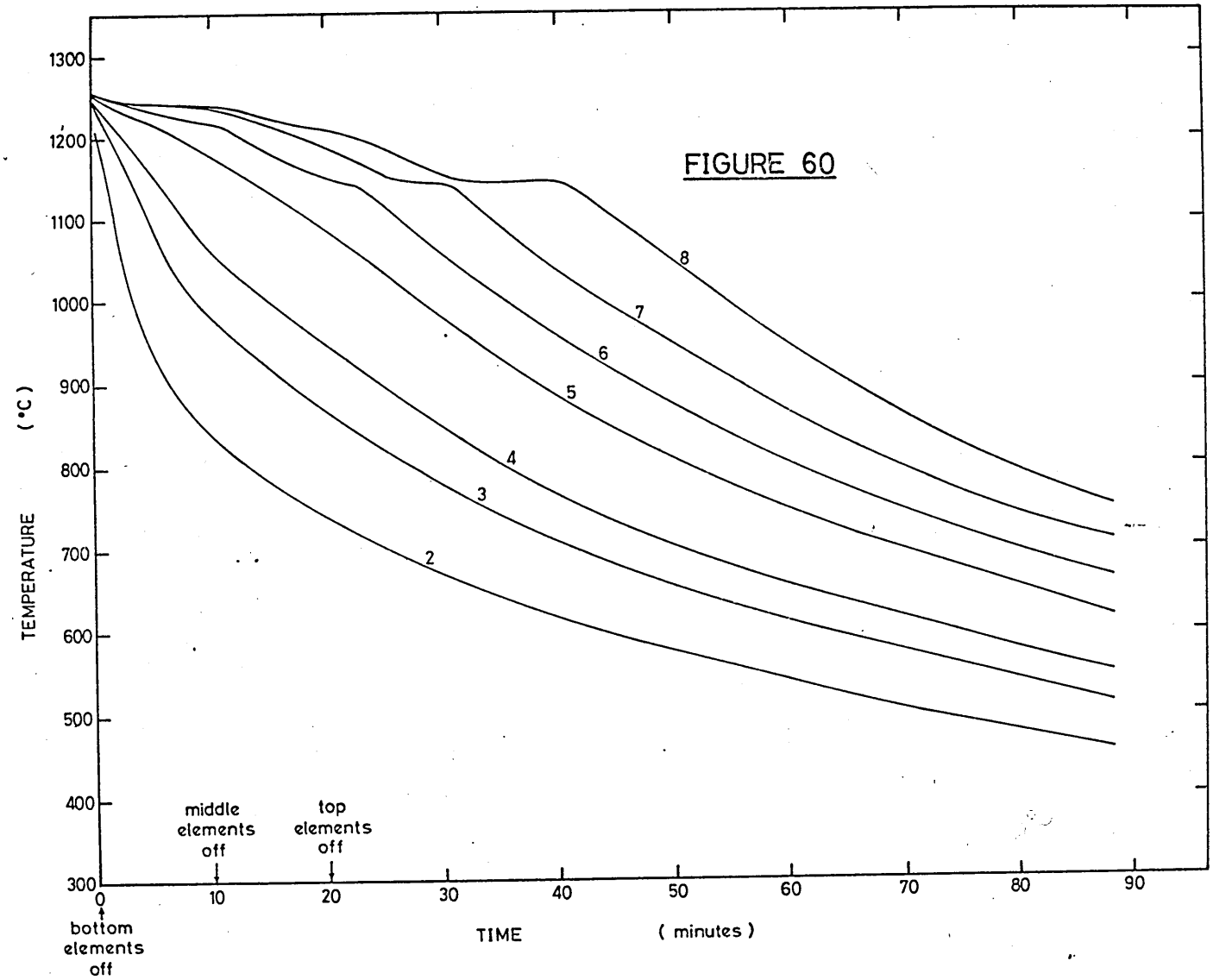


FIGURE 60
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
TIME (minutes)
bottom elements off
middle elements off
top elements off
2
3
4
5
6
7
8

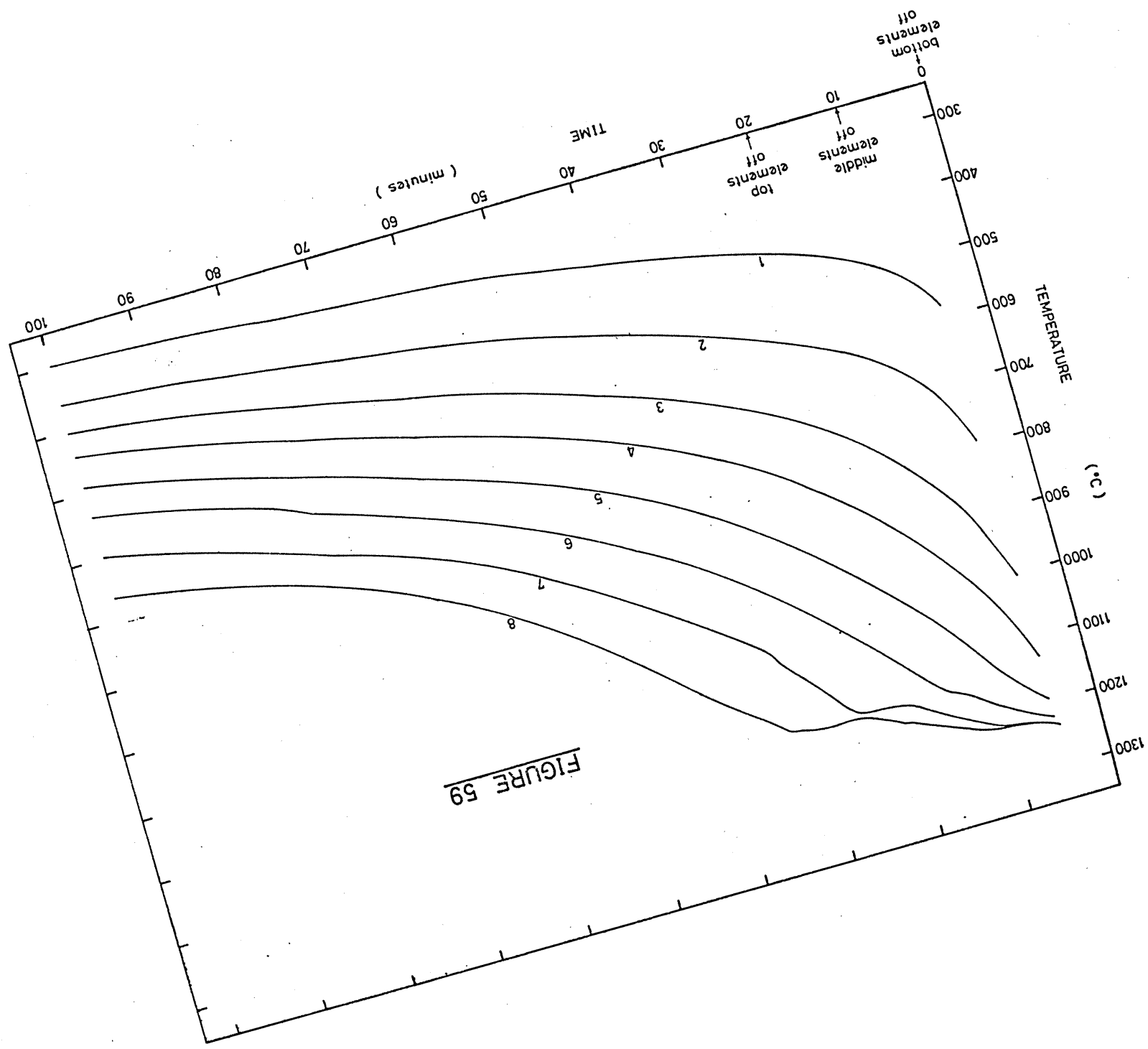

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 59

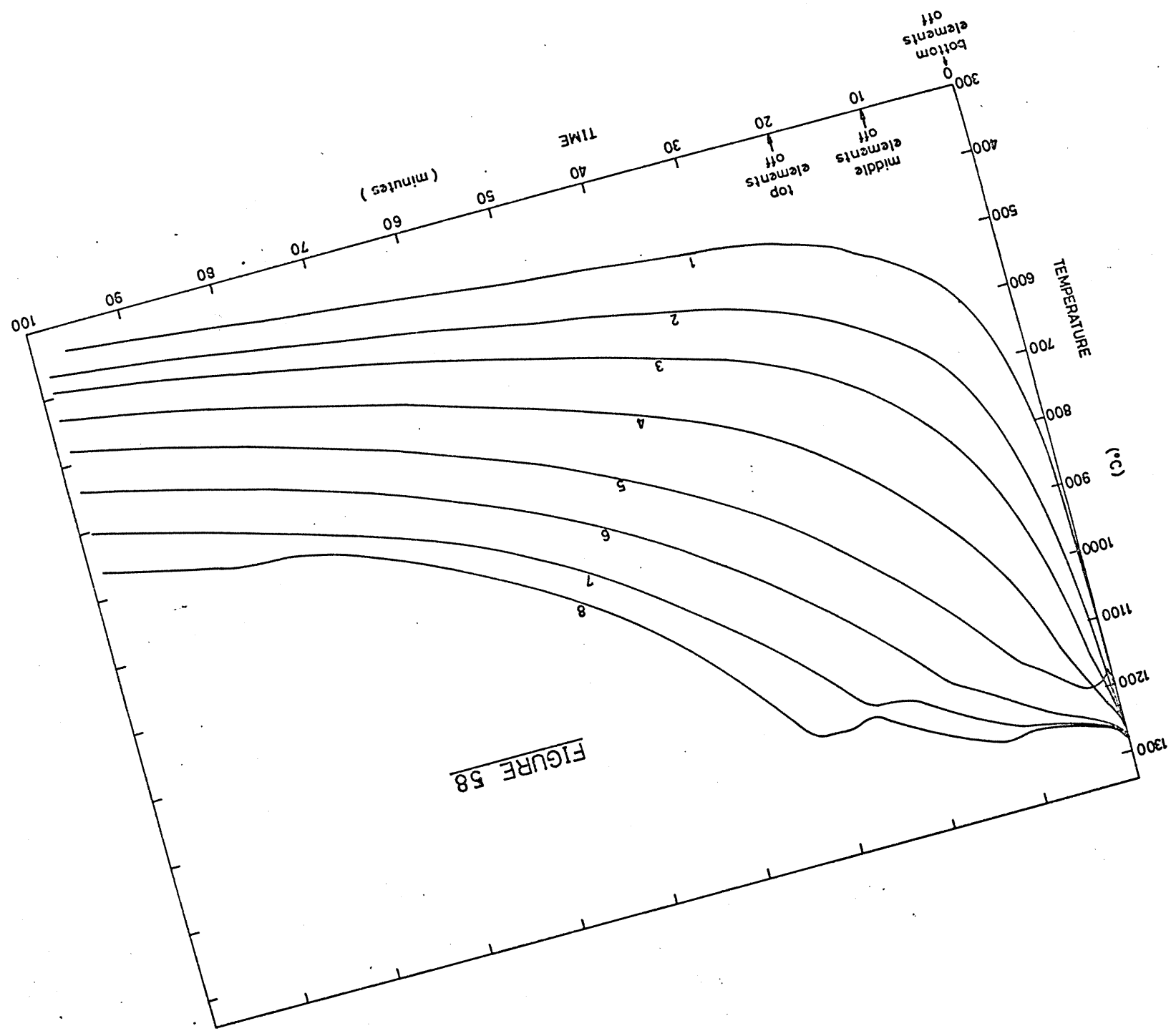

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 58

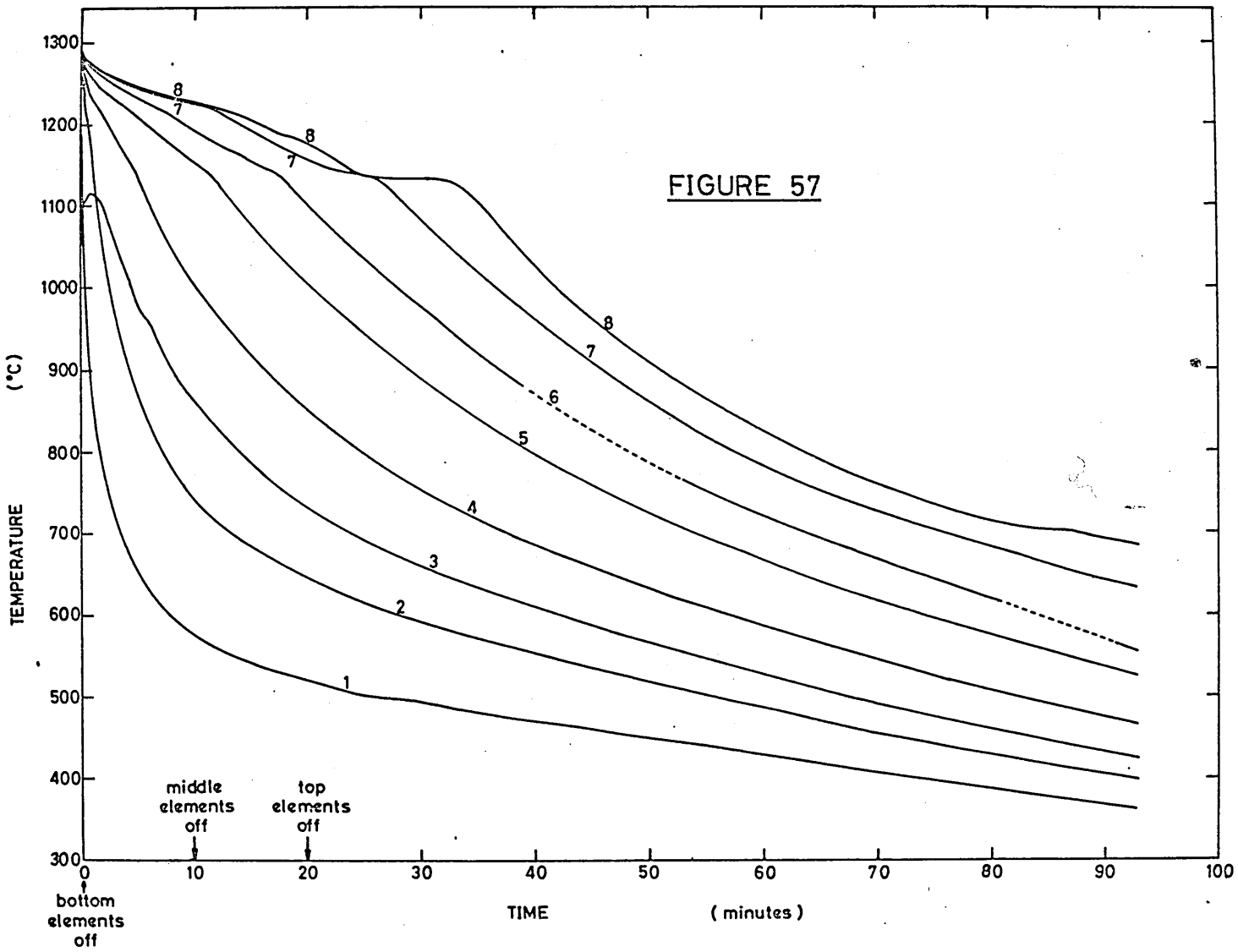


FIGURE 57
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

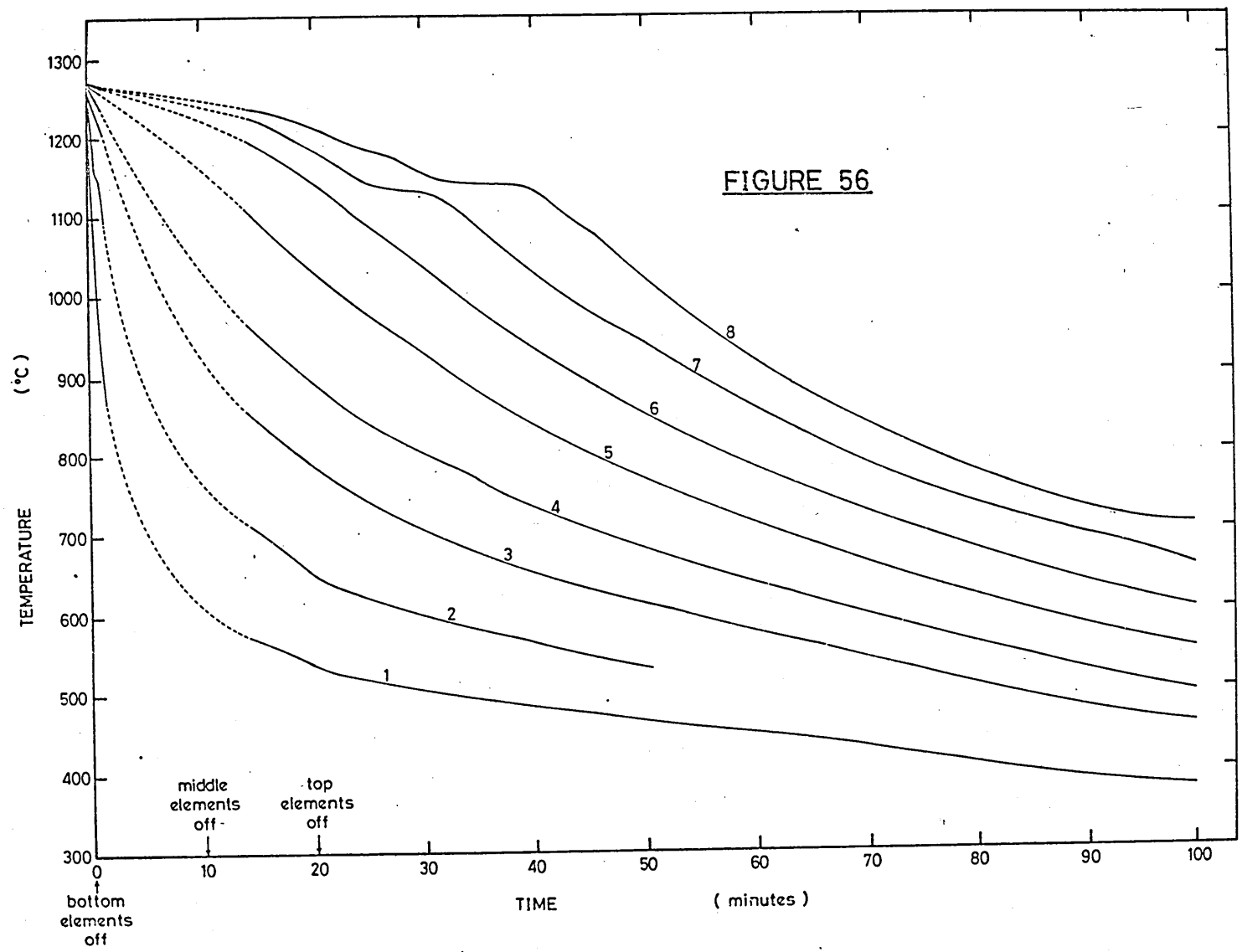


FIGURE 56
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

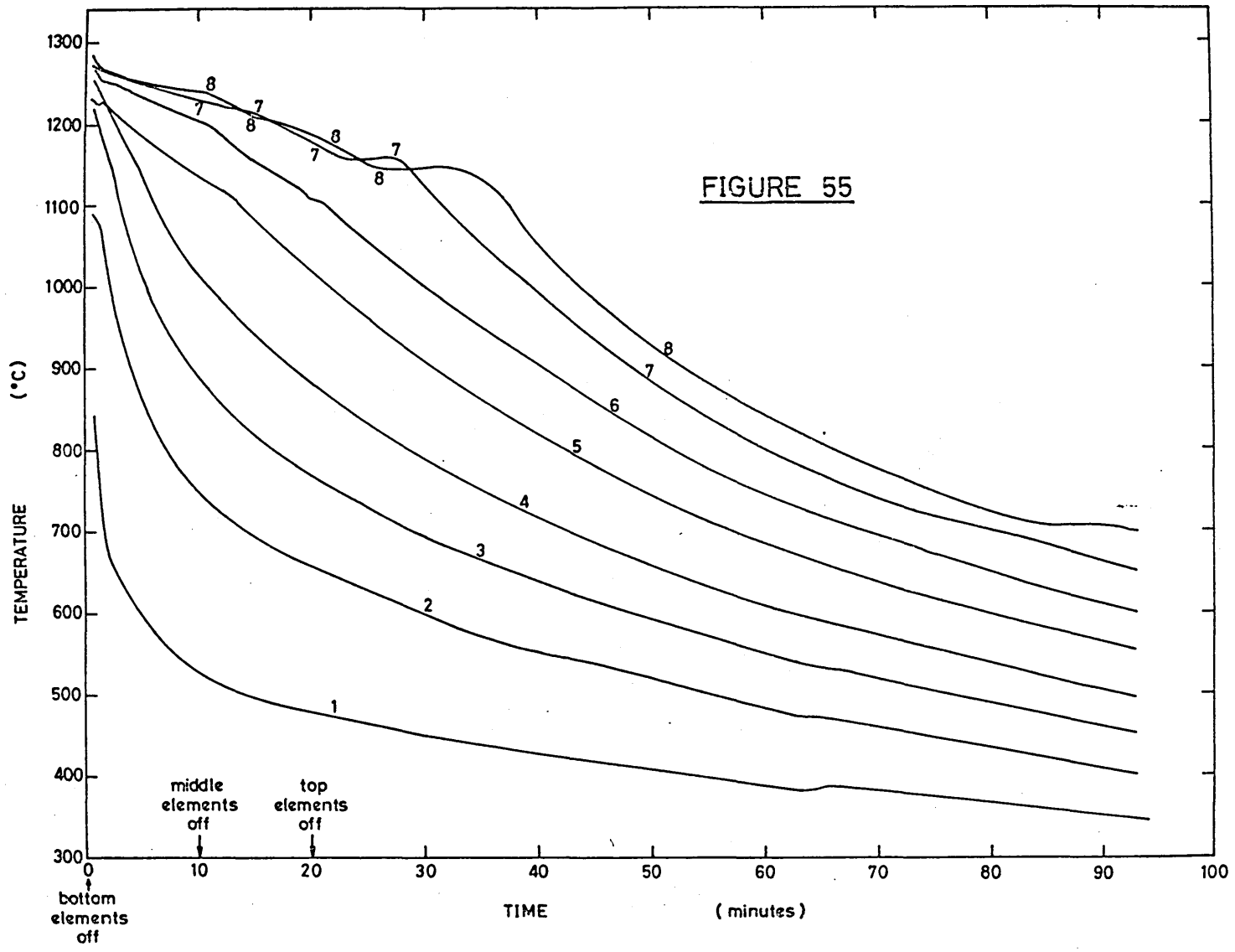


FIGURE 55
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

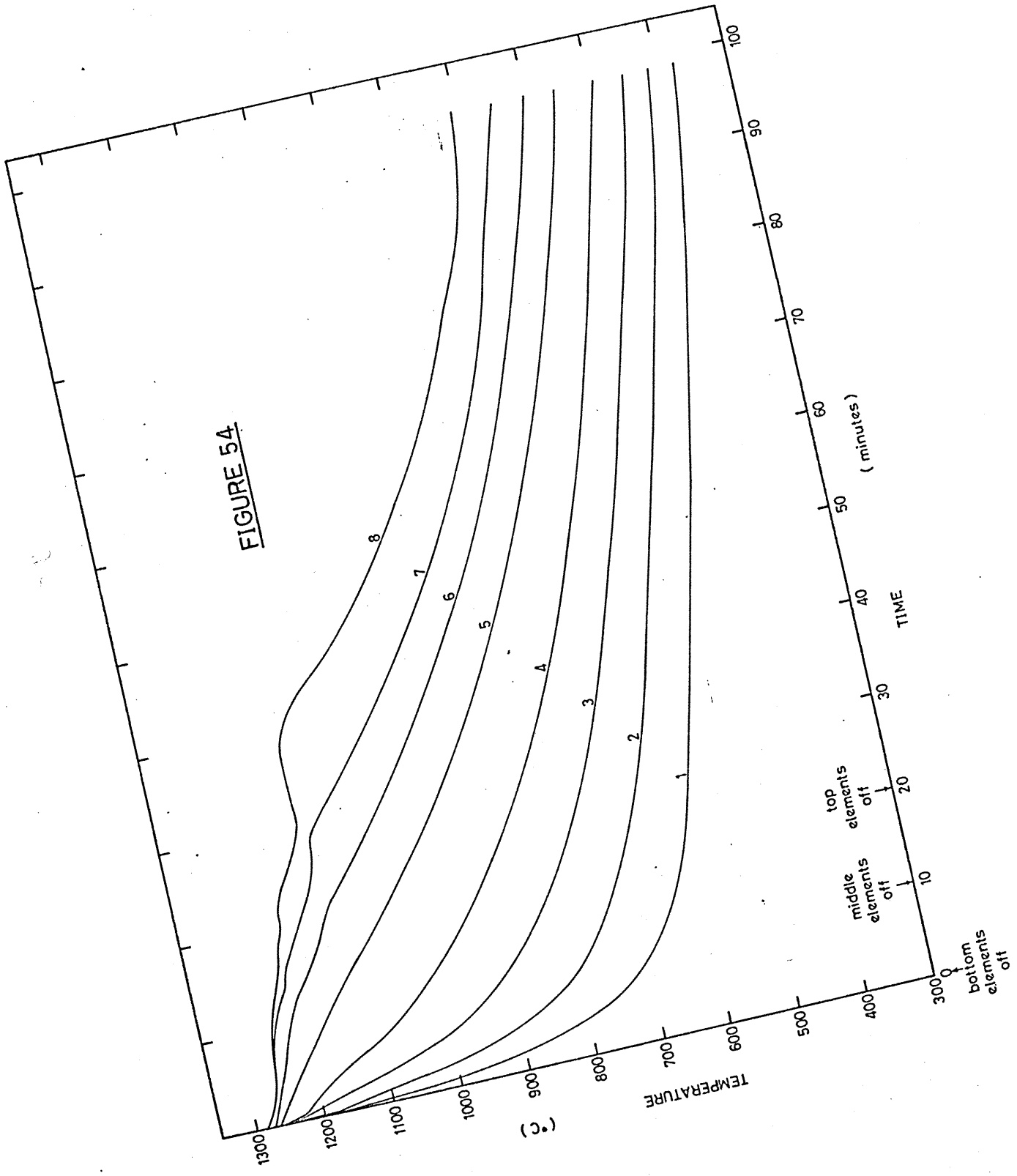

TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
top elements off
middle elements off
bottom elements off
TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
1
2
3
4
5
6
7
8

FIGURE 54

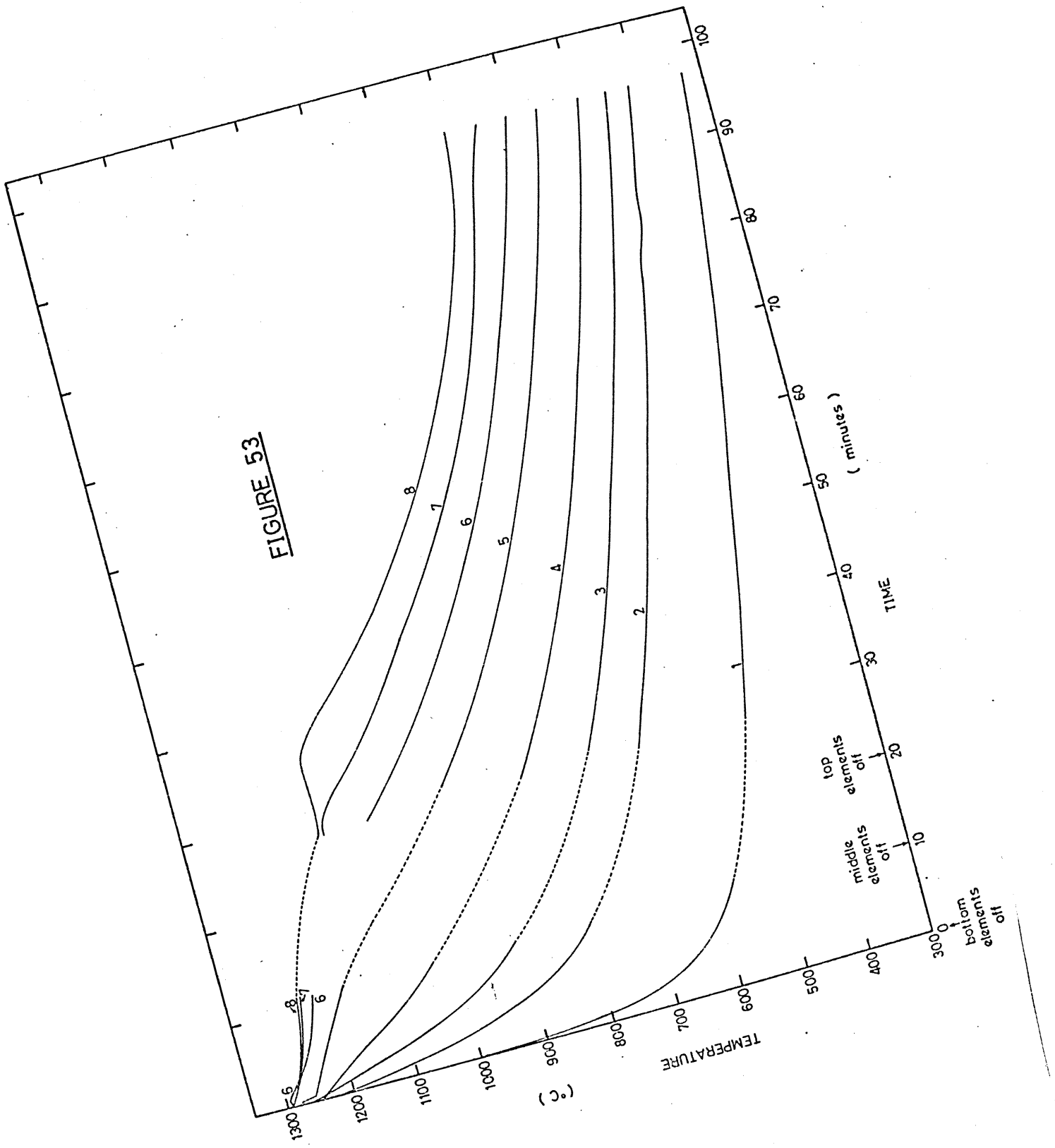

TIME
(minutes)
100
90
80
70
60
50
40
30
20
10
0
top elements off
middle elements off
bottom elements off
TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
1
2
3
4
5
6
7
8

FIGURE 53

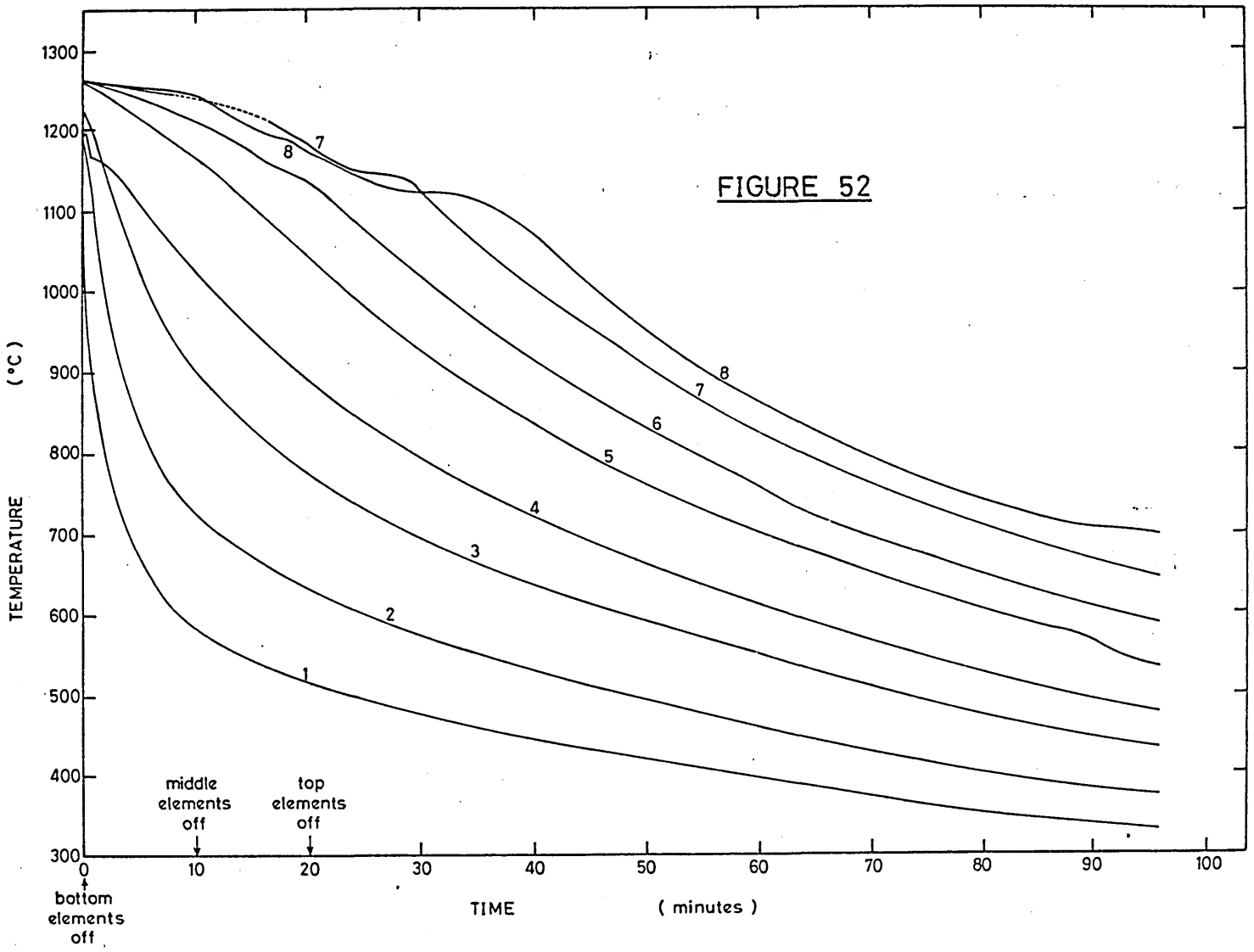


FIGURE 52
TEMPERATURE
(°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME
(minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8
7
8

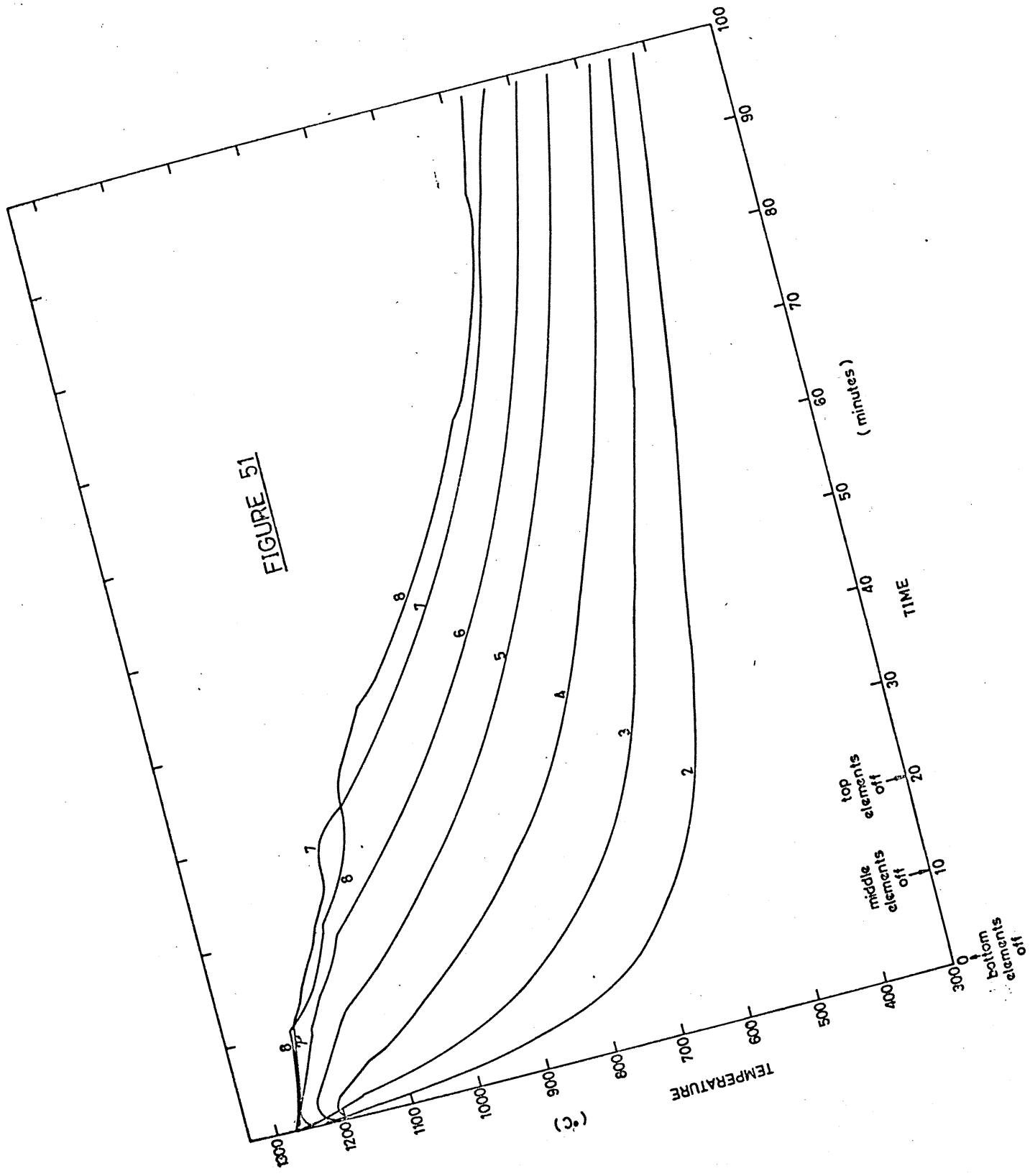

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 51

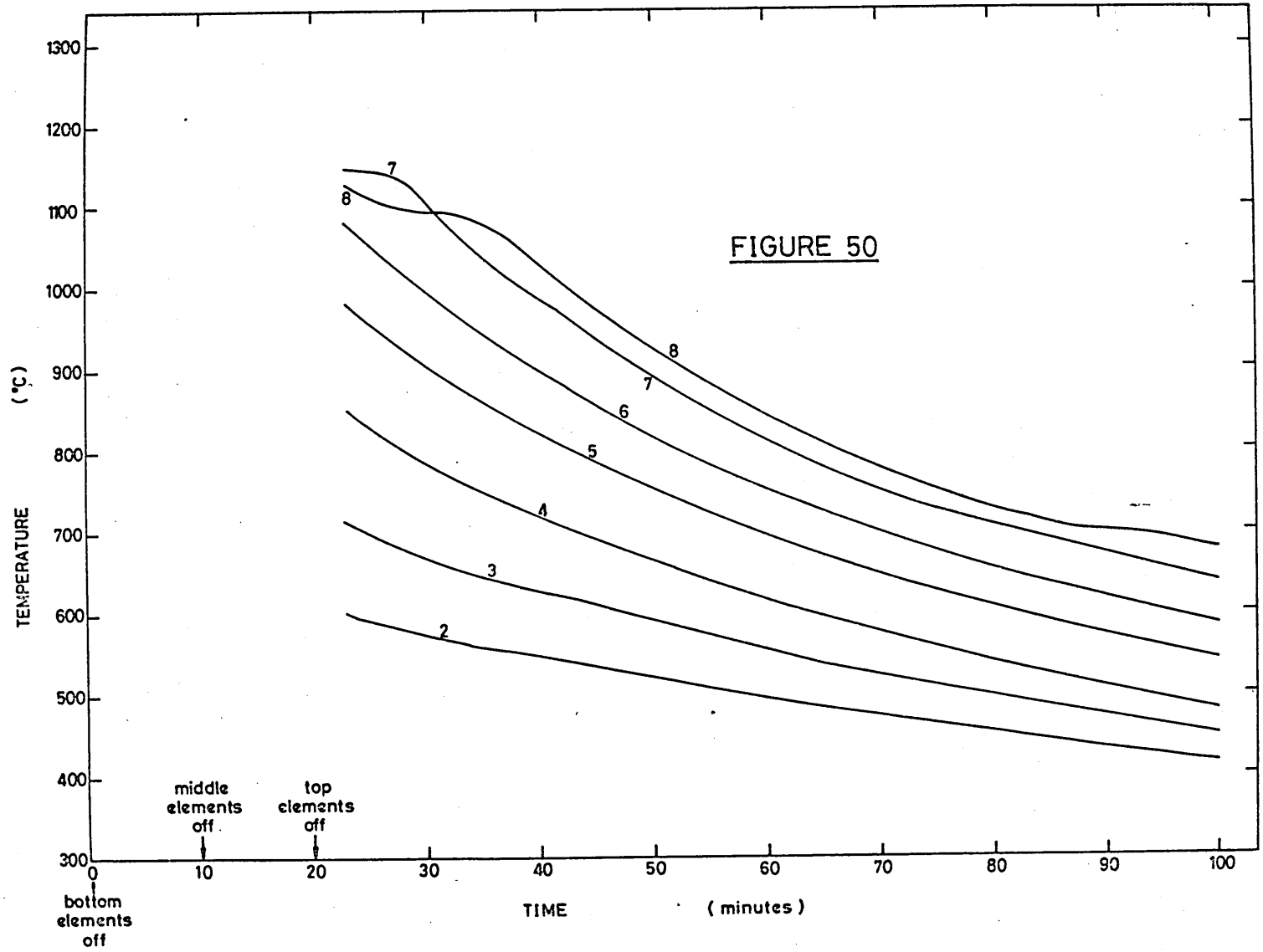


FIGURE 50
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
2
3
4
5
6
7
8
7
8

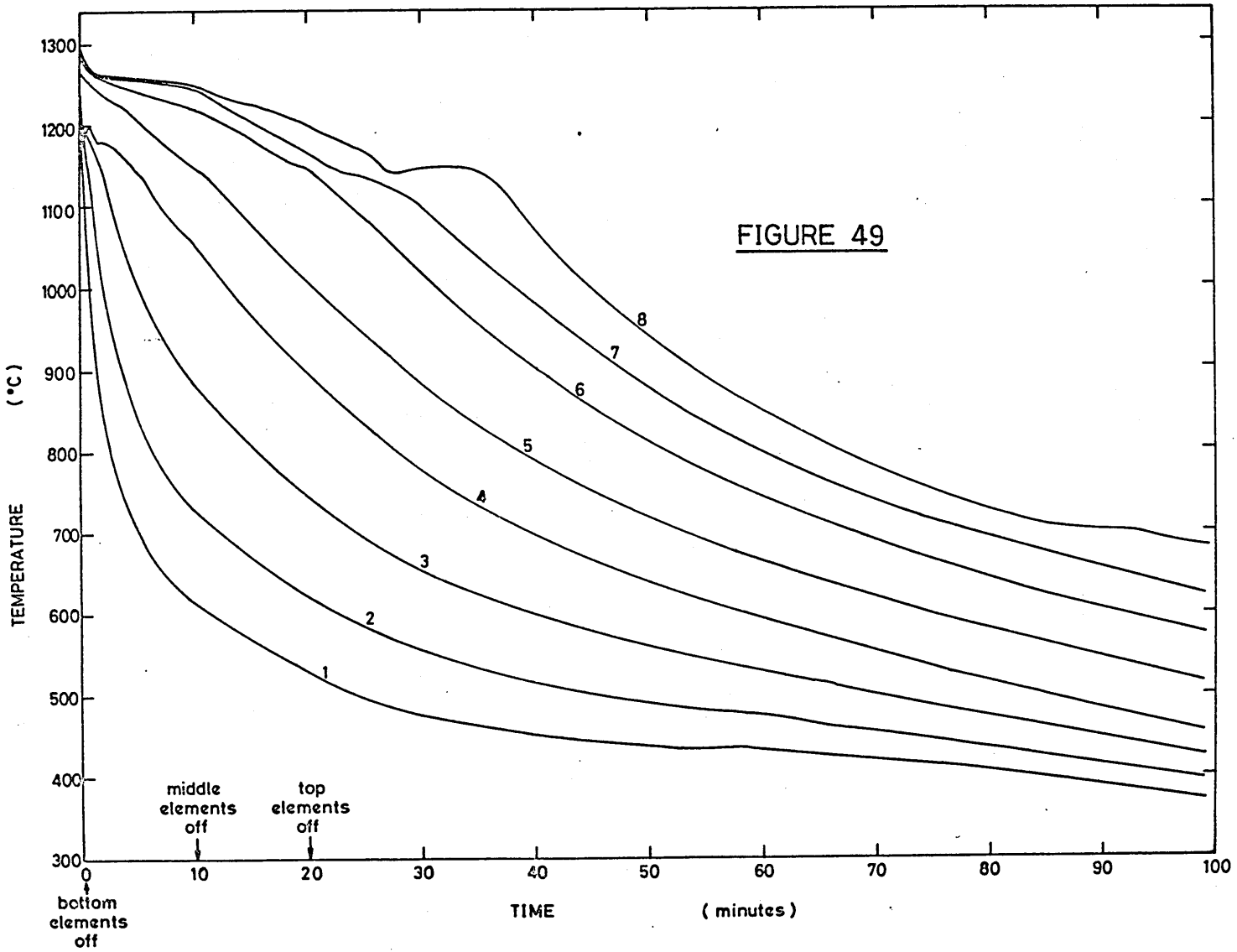


FIGURE 49
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

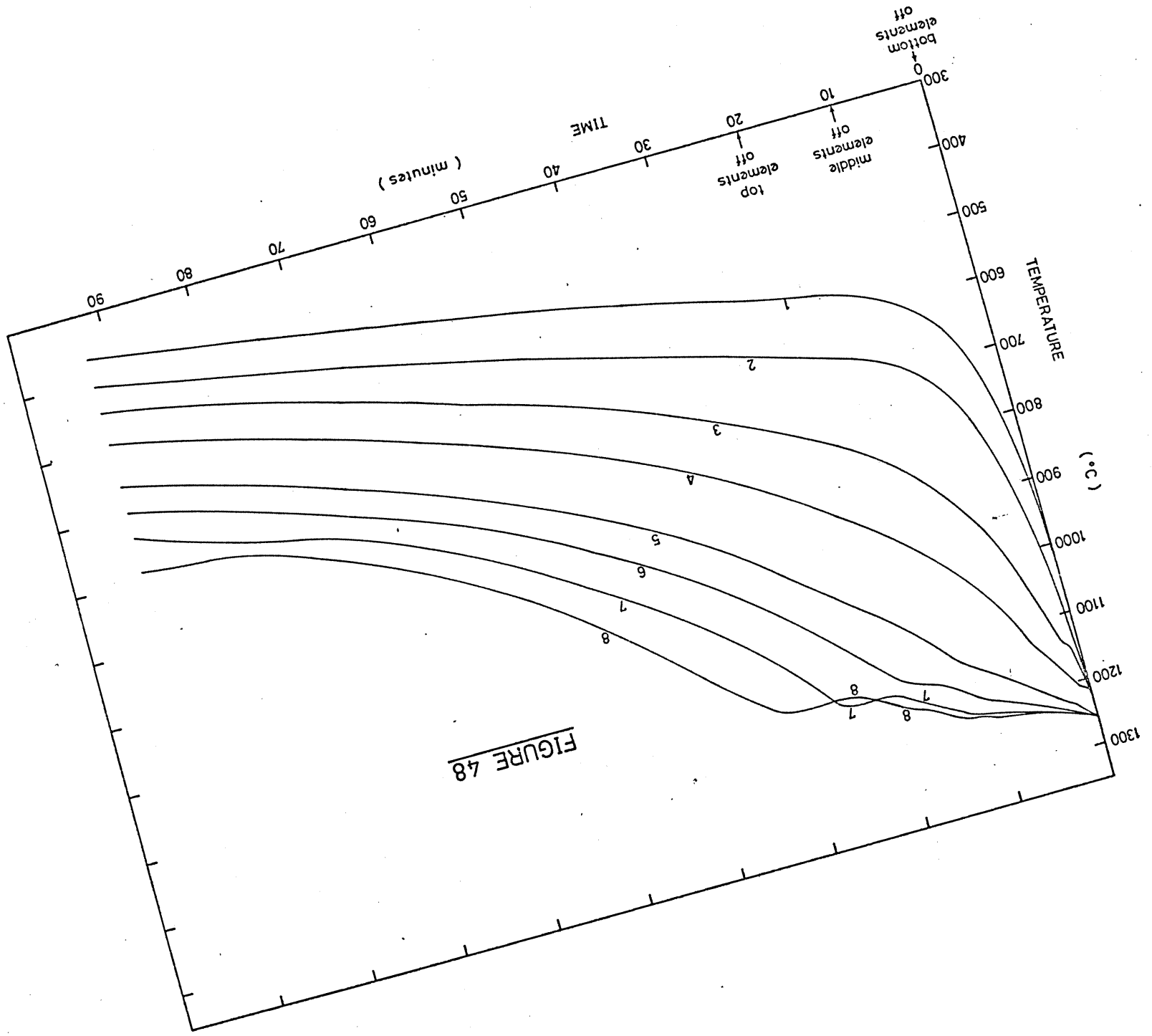

TEMPERATURE
(°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 48

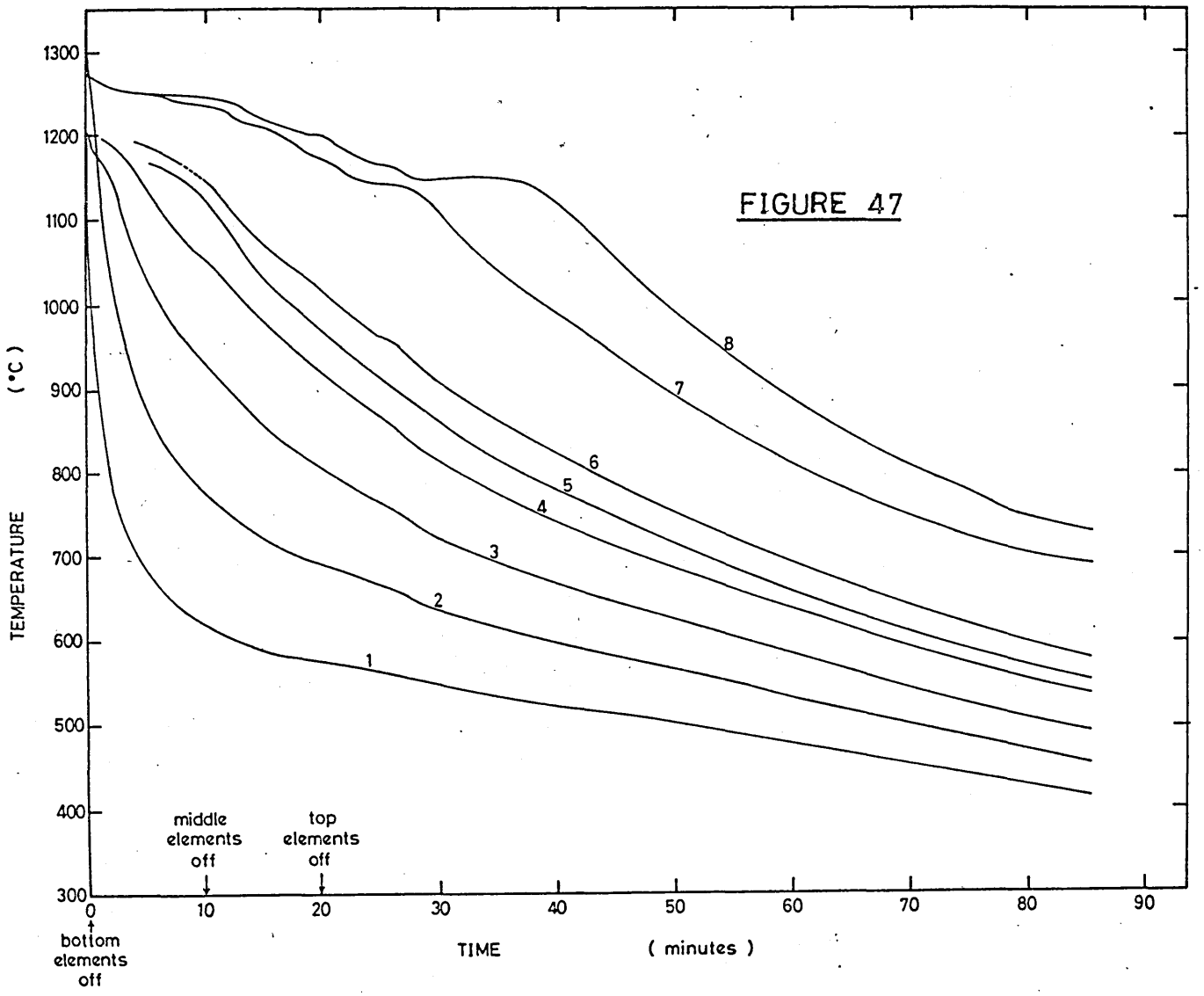


FIGURE 47
TEMPERATURE
(°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
TIME
(minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

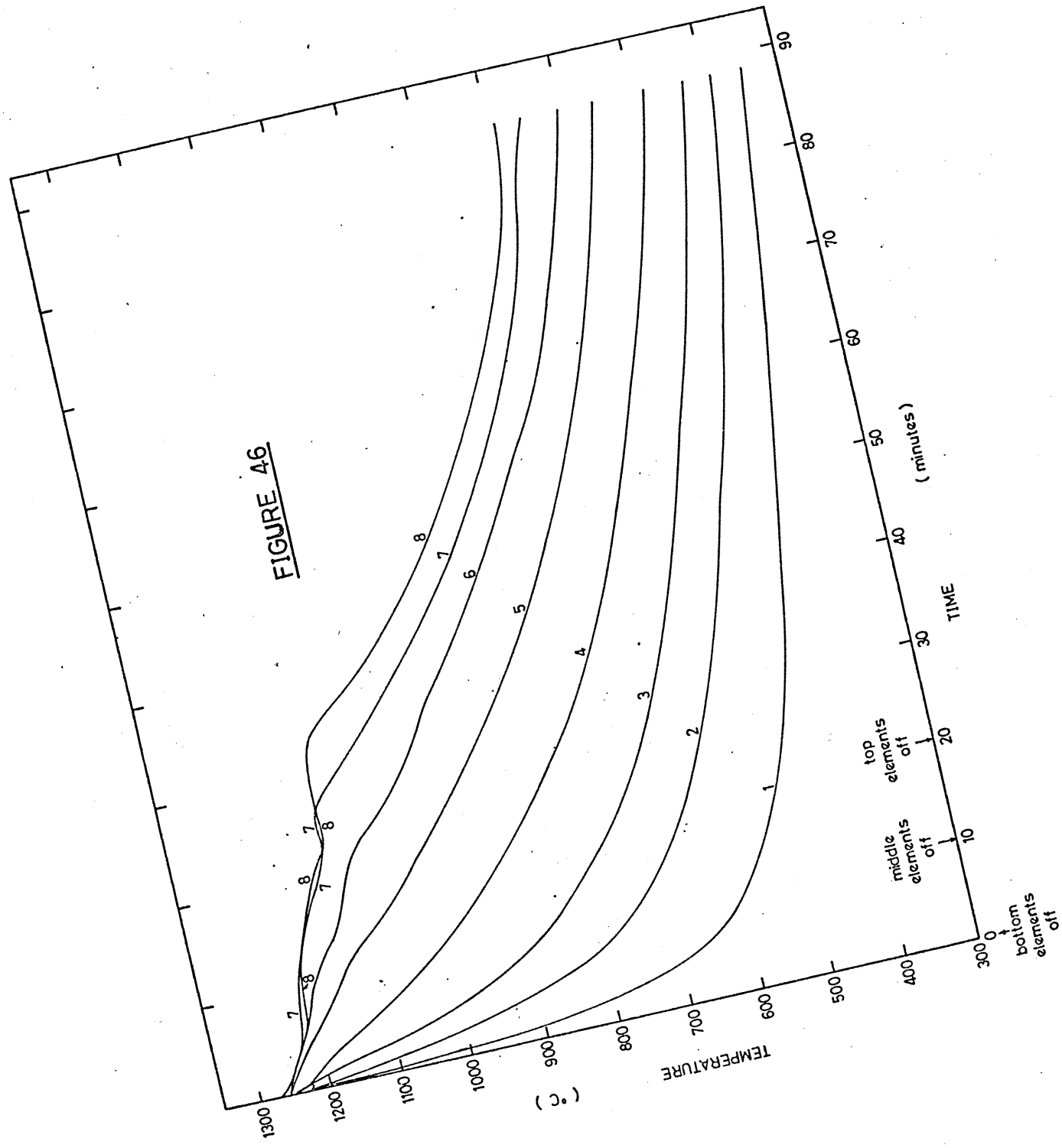

TEMPERATURE
(°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
top elements off
middle elements off
bottom elements off
1
2
3
4
5
6
7
8

FIGURE 46

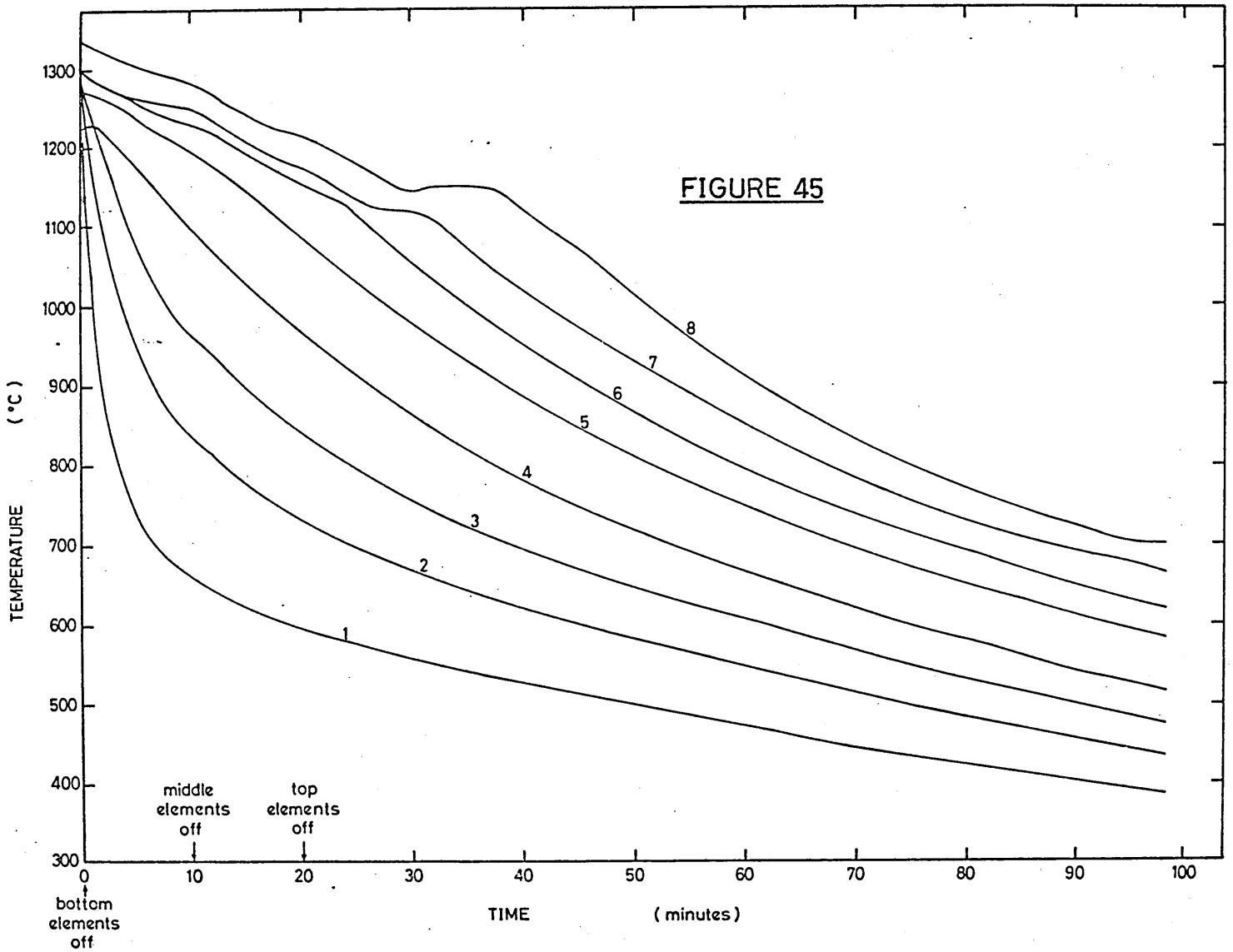


FIGURE 45
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

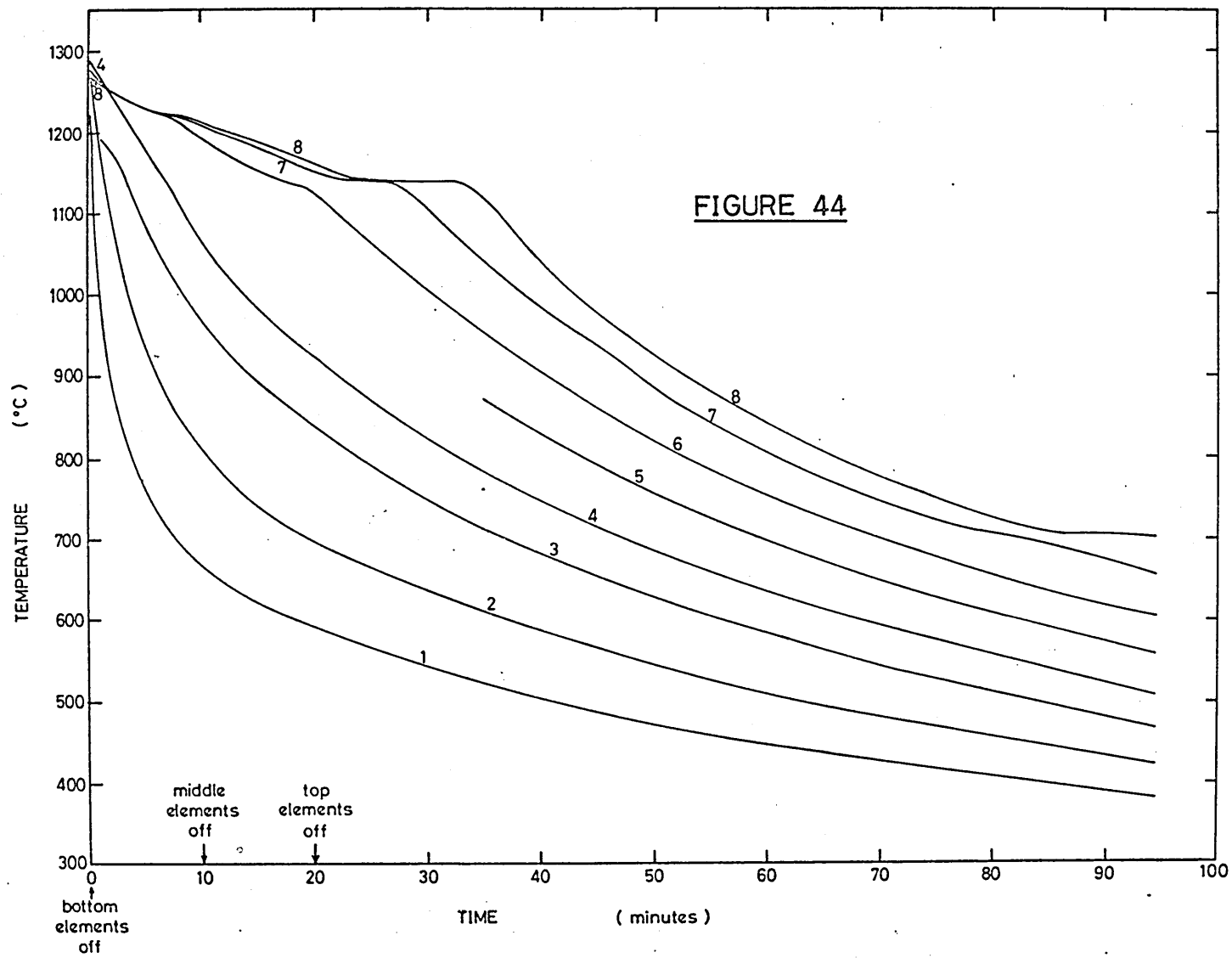


FIGURE 44
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

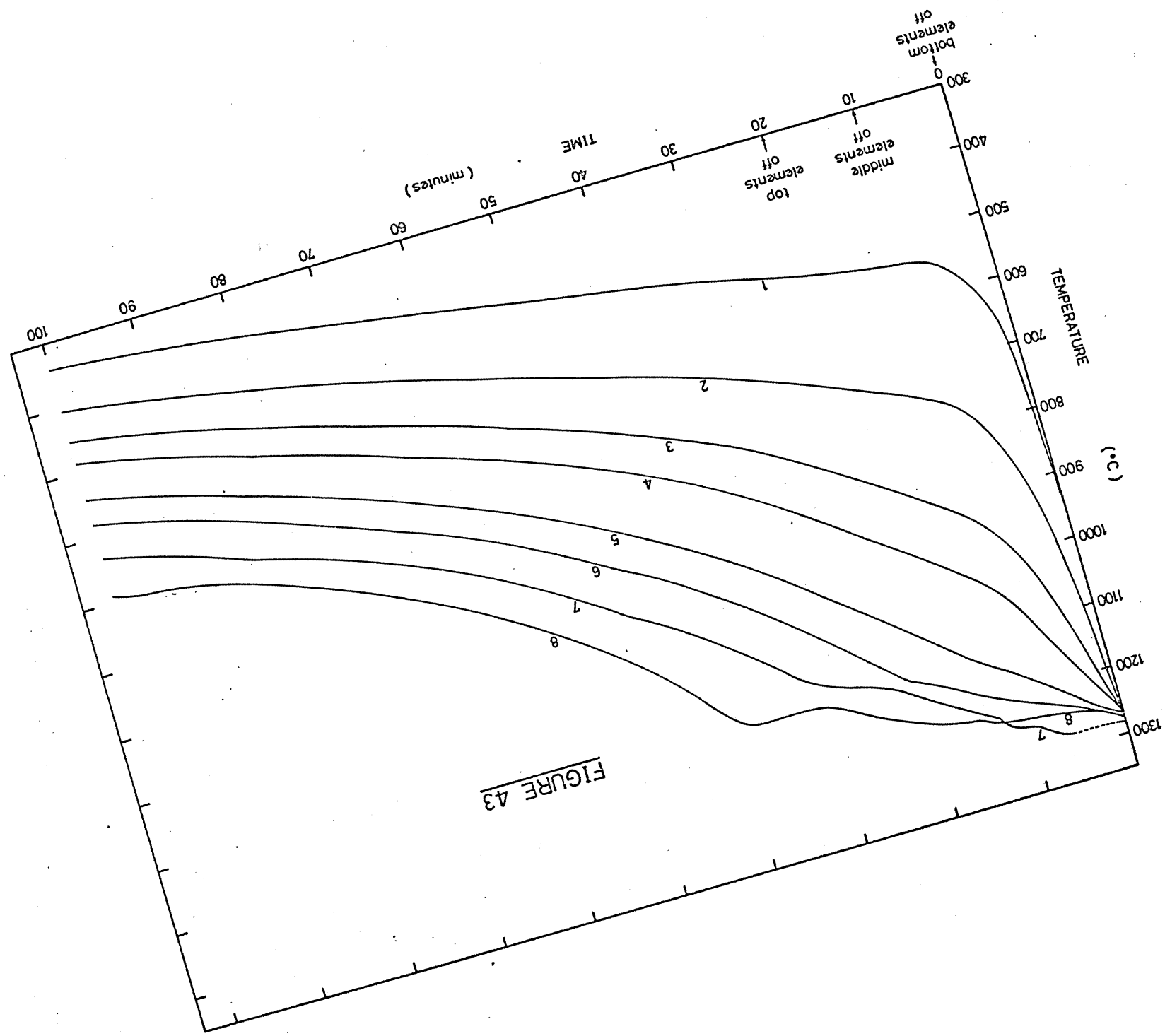

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 43

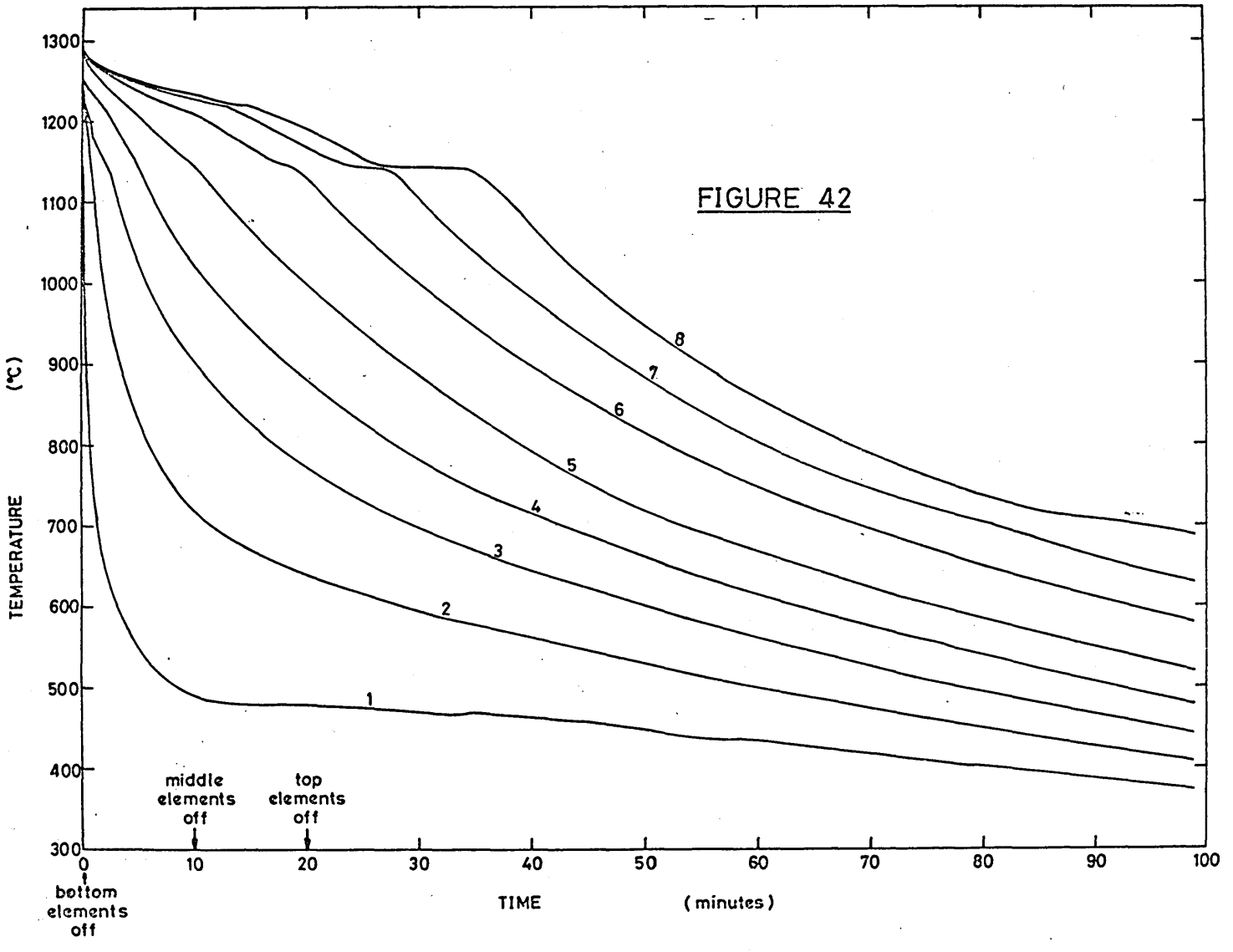


FIGURE 42
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

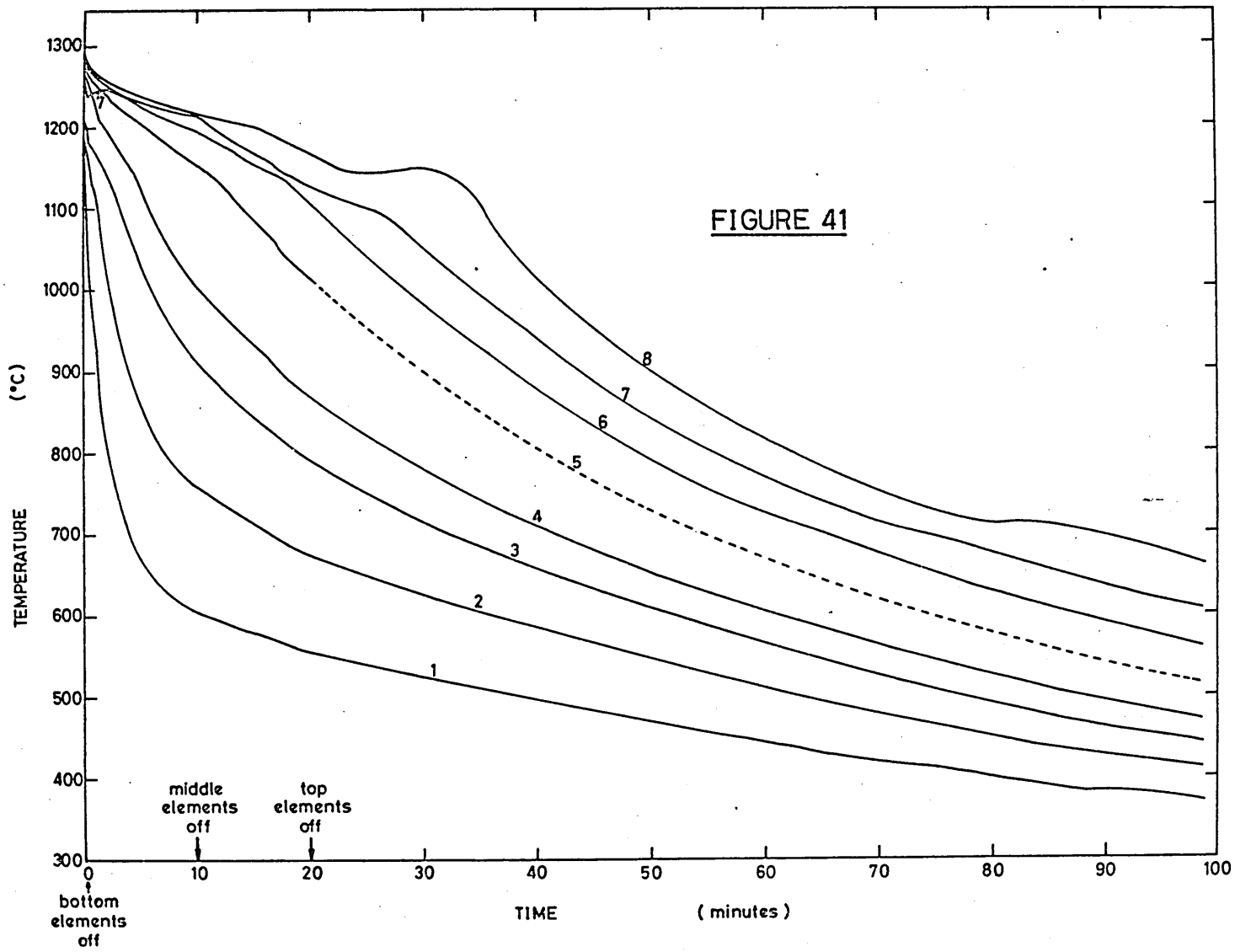


FIGURE 41
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

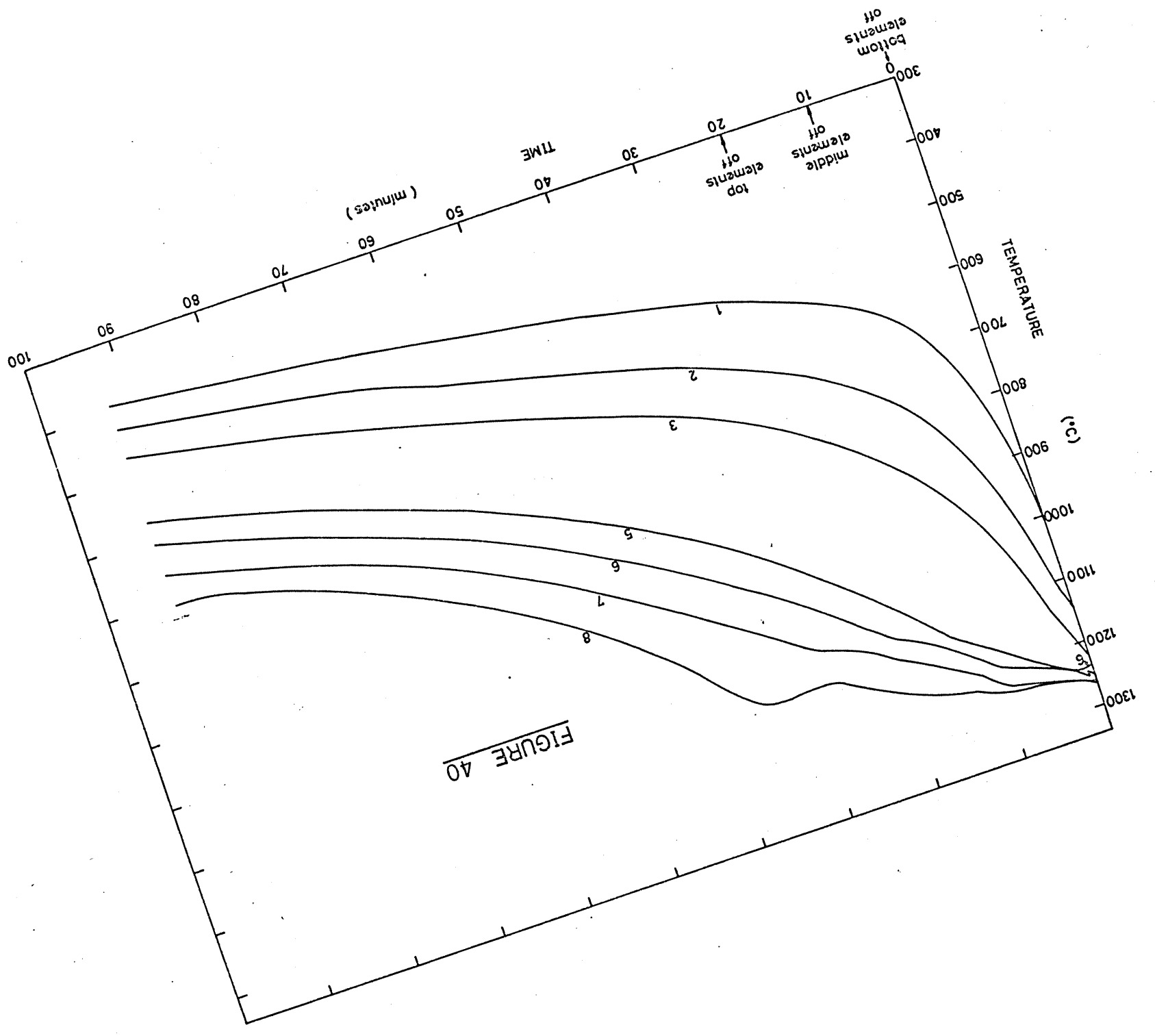

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 40

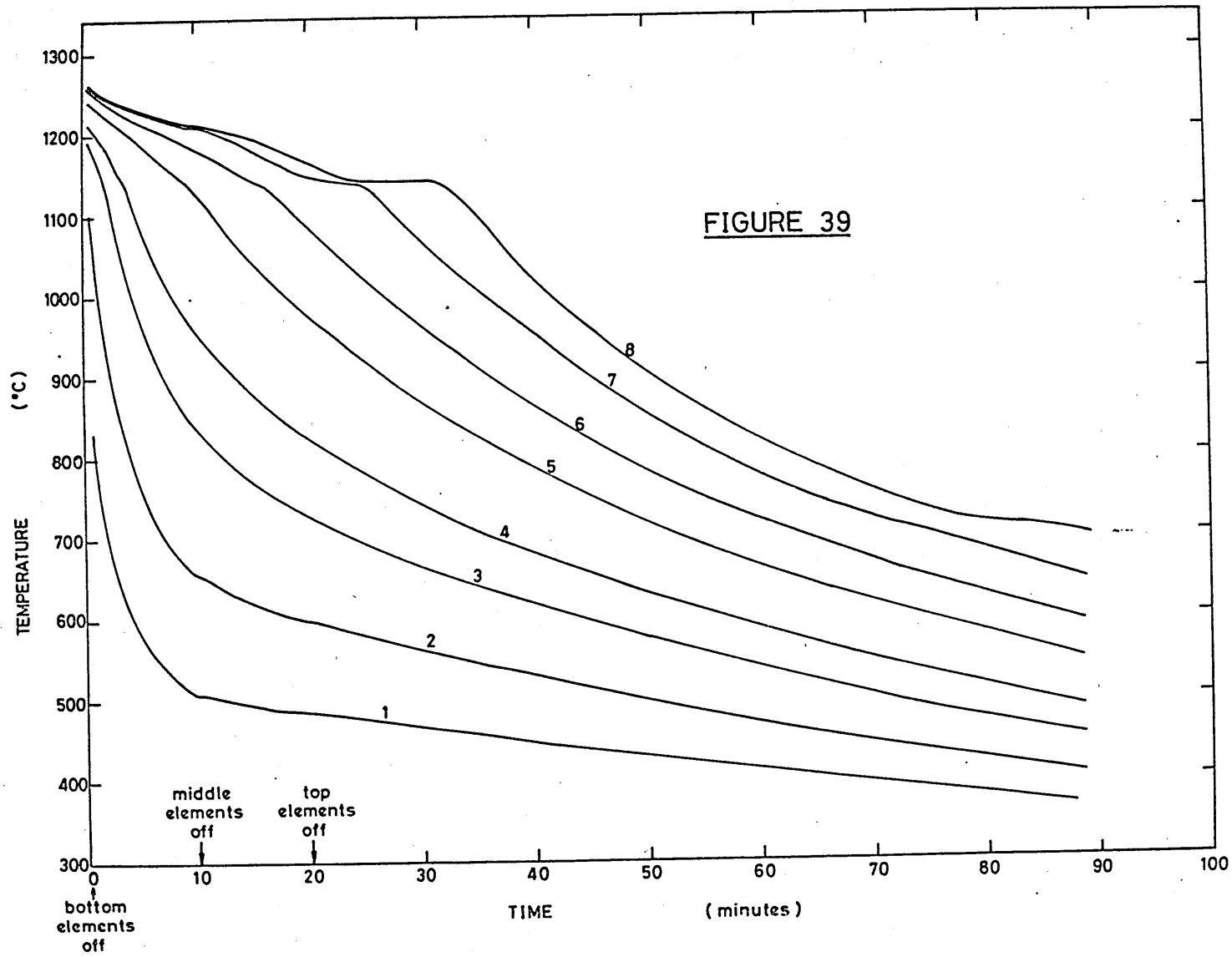


FIGURE 39
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

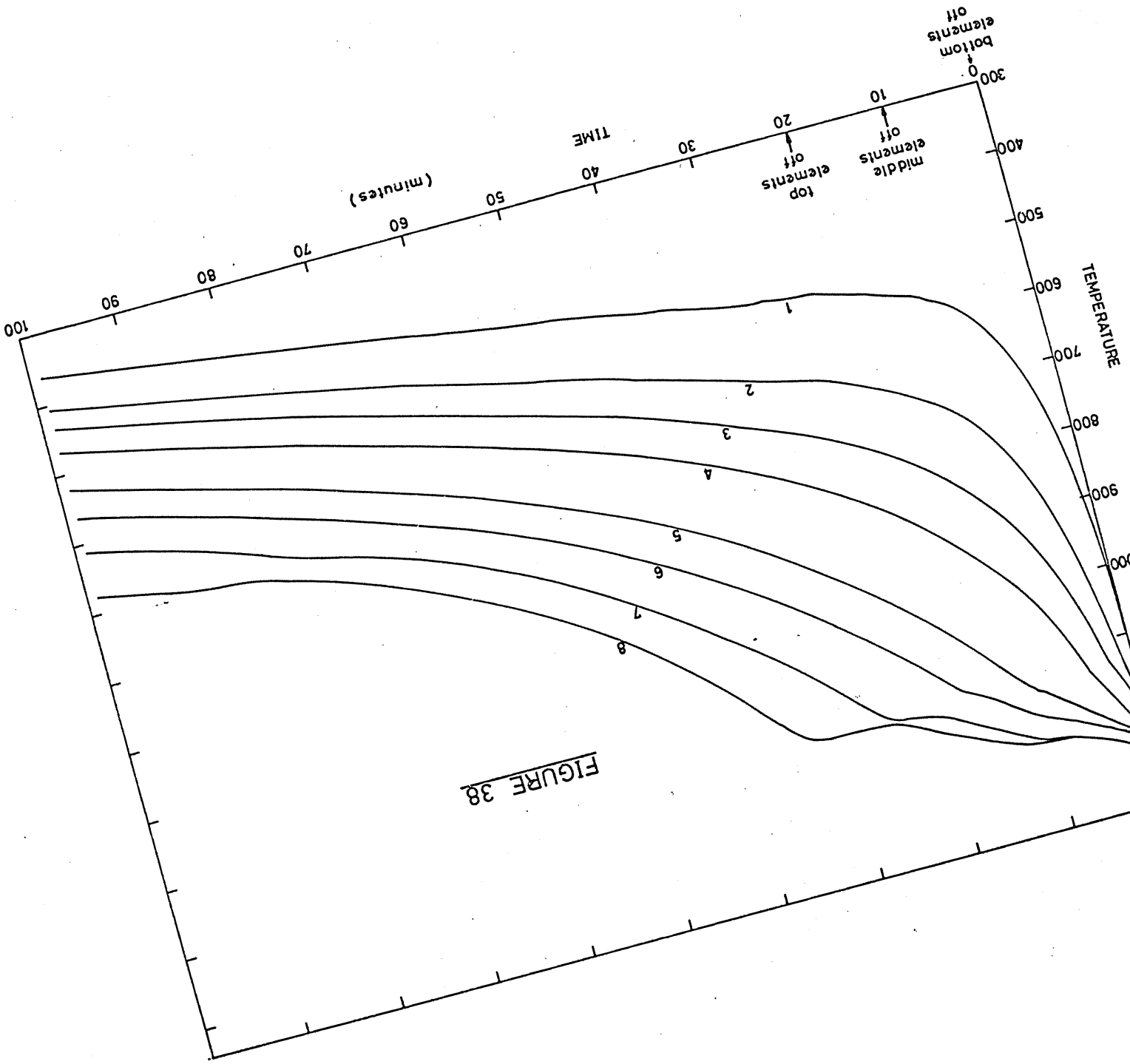

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 38

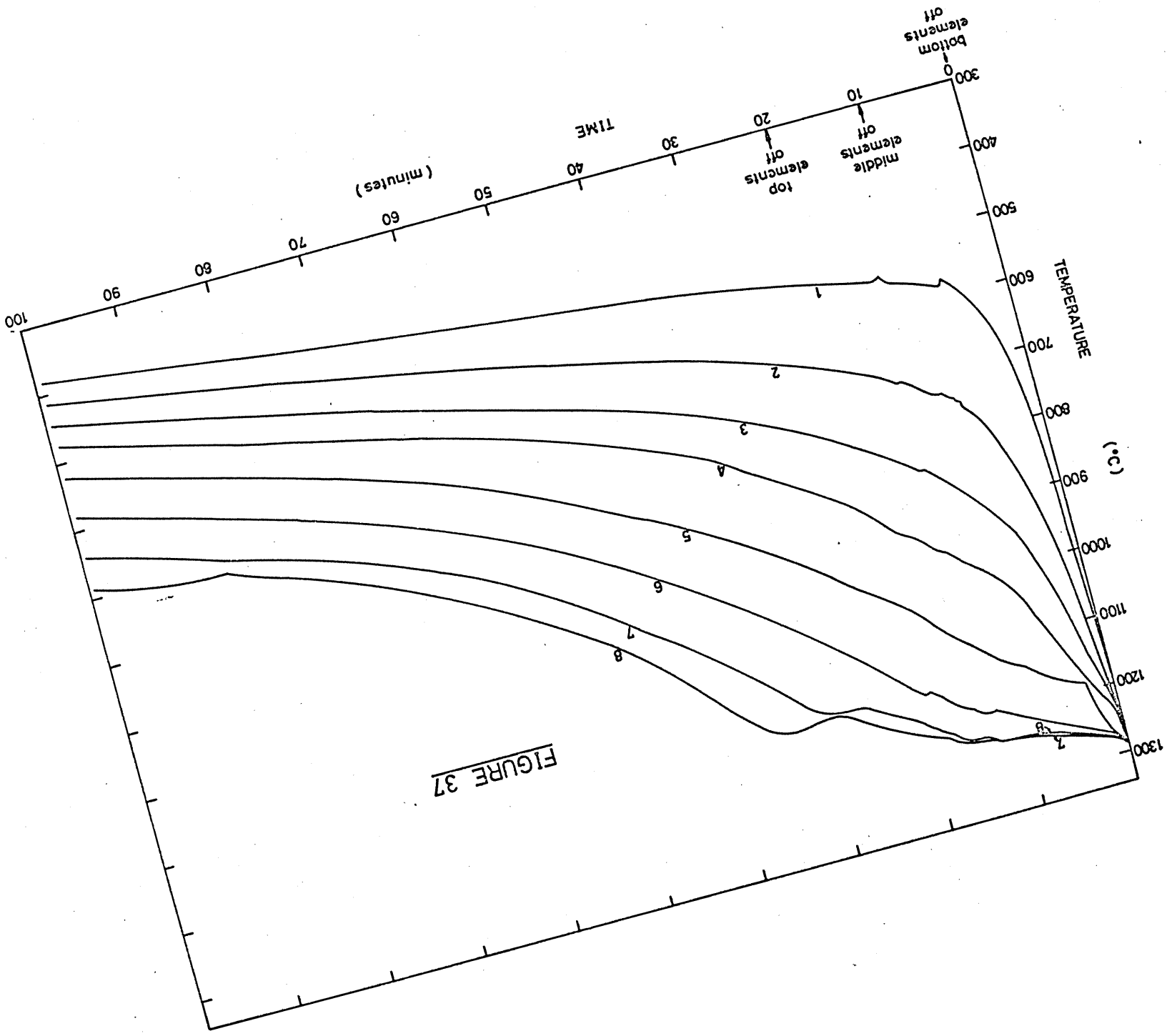

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 37

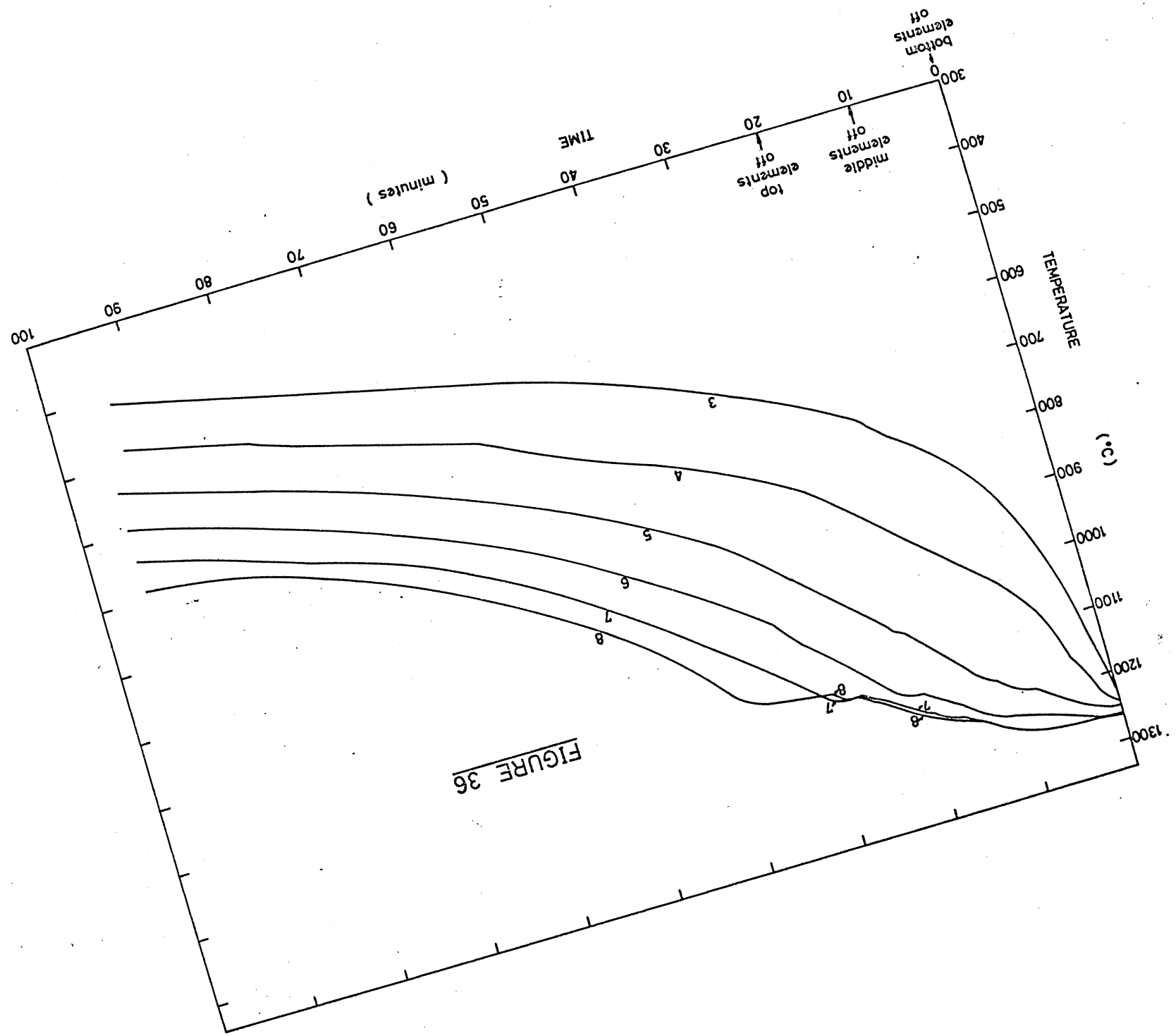

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
3
4
5
6
7
8
7
8
7
8

FIGURE 36

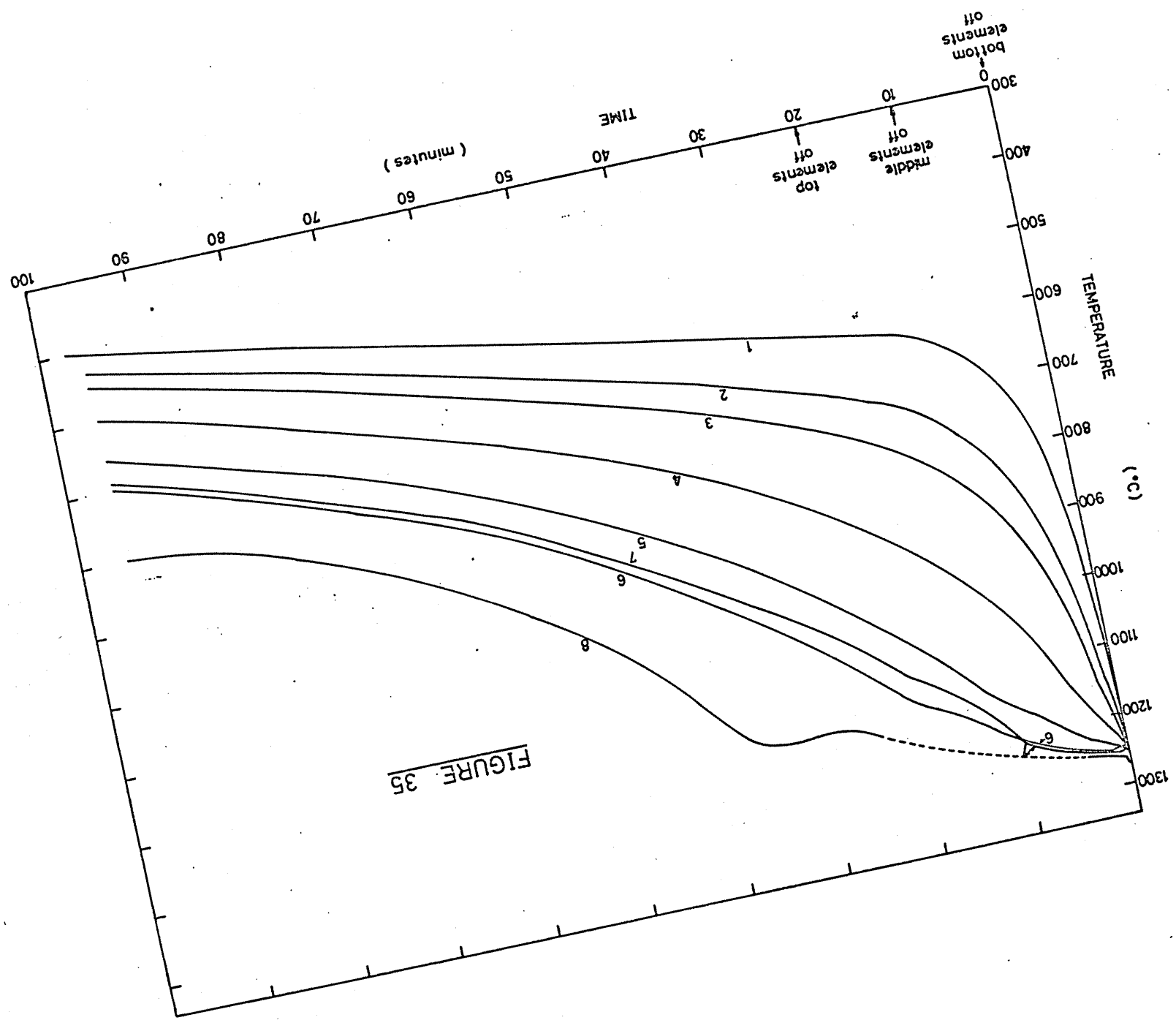

TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
300
400
500
600
700
800
900
1000
1100
1200
1300
TEMPERATURE
(°C)
1
2
3
4
5
6
7
8

FIGURE 35

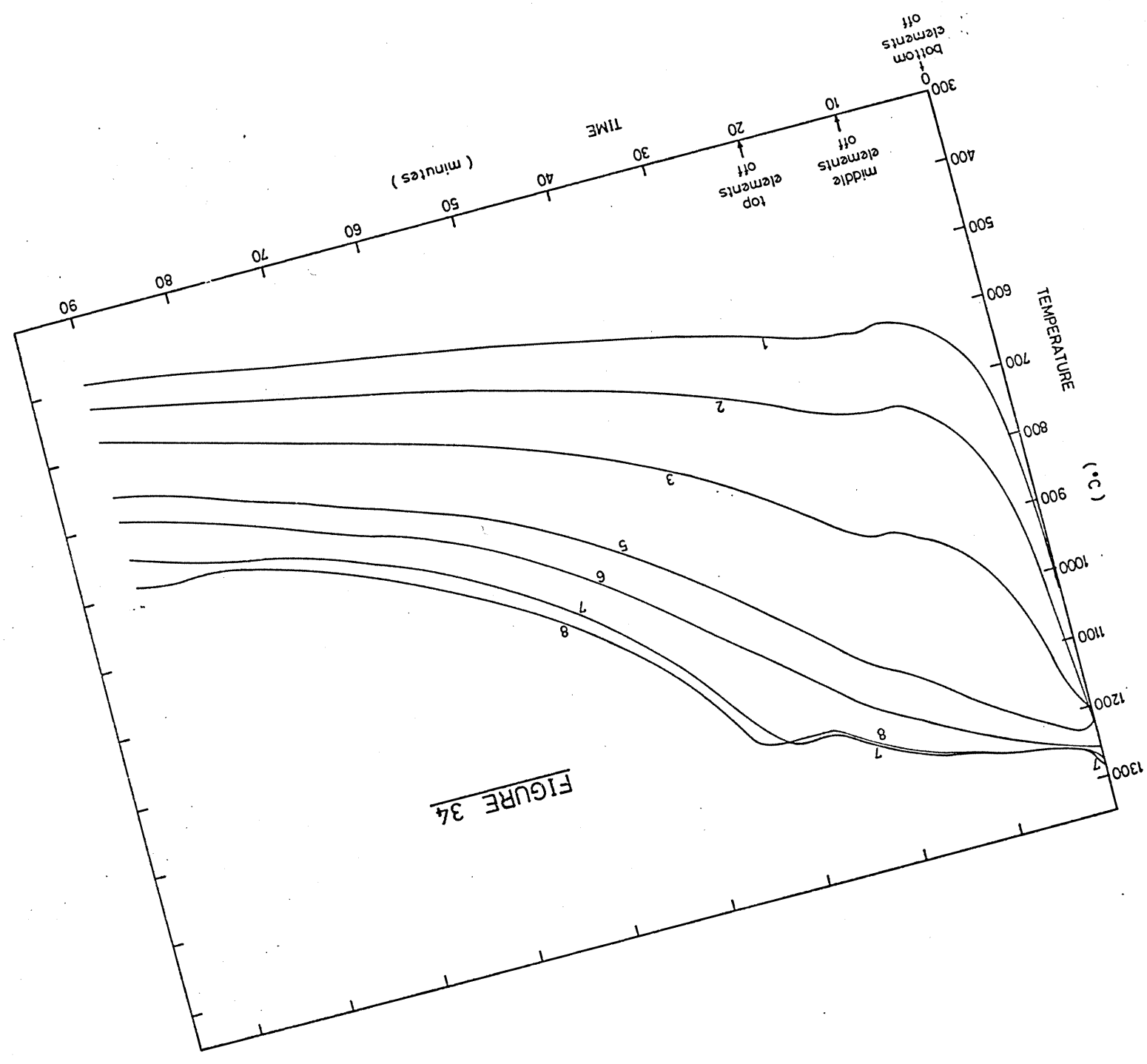

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8
7
8

FIGURE 34

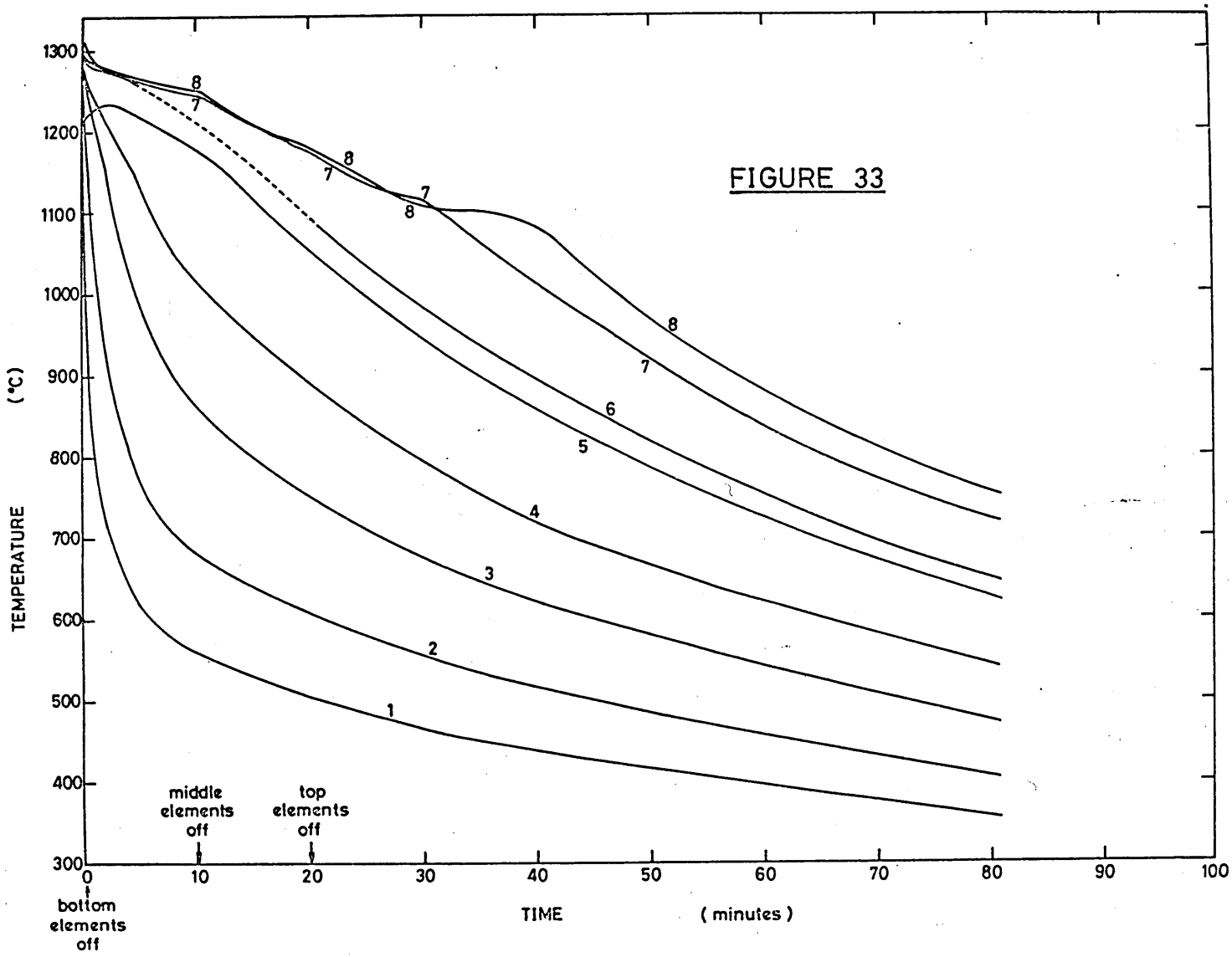


FIGURE 33
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

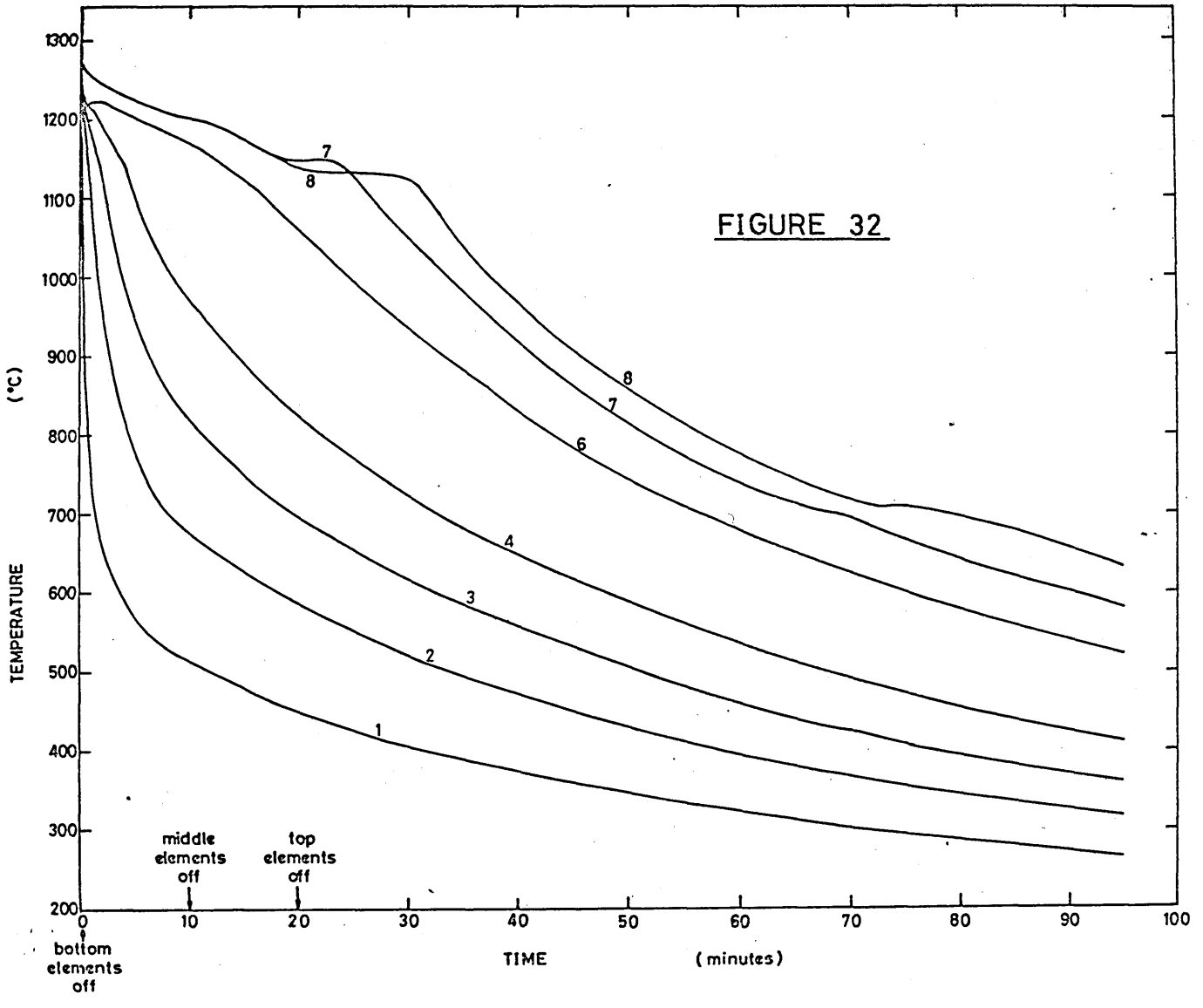


FIGURE 32
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
6
7
8
7
8

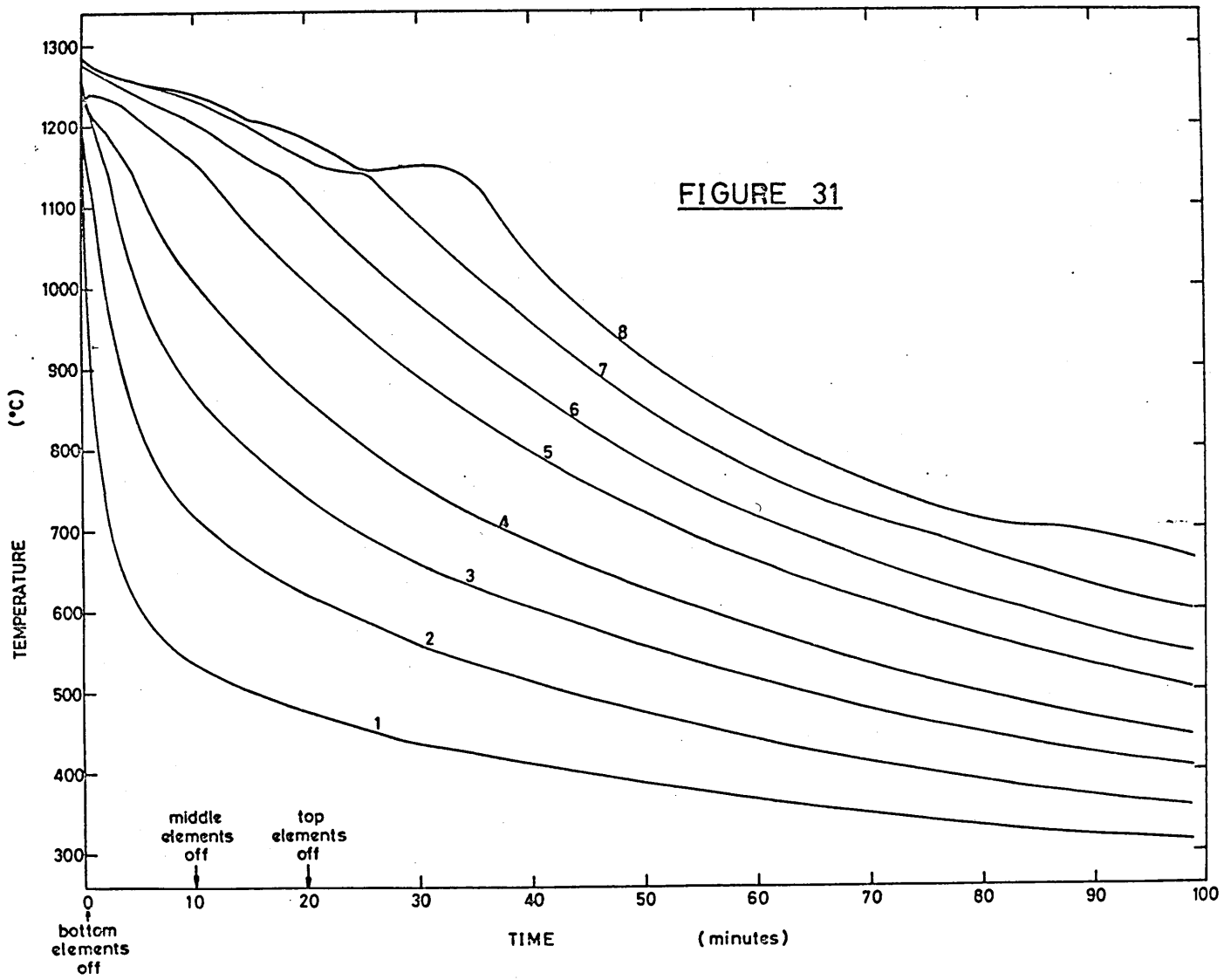


FIGURE 31
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

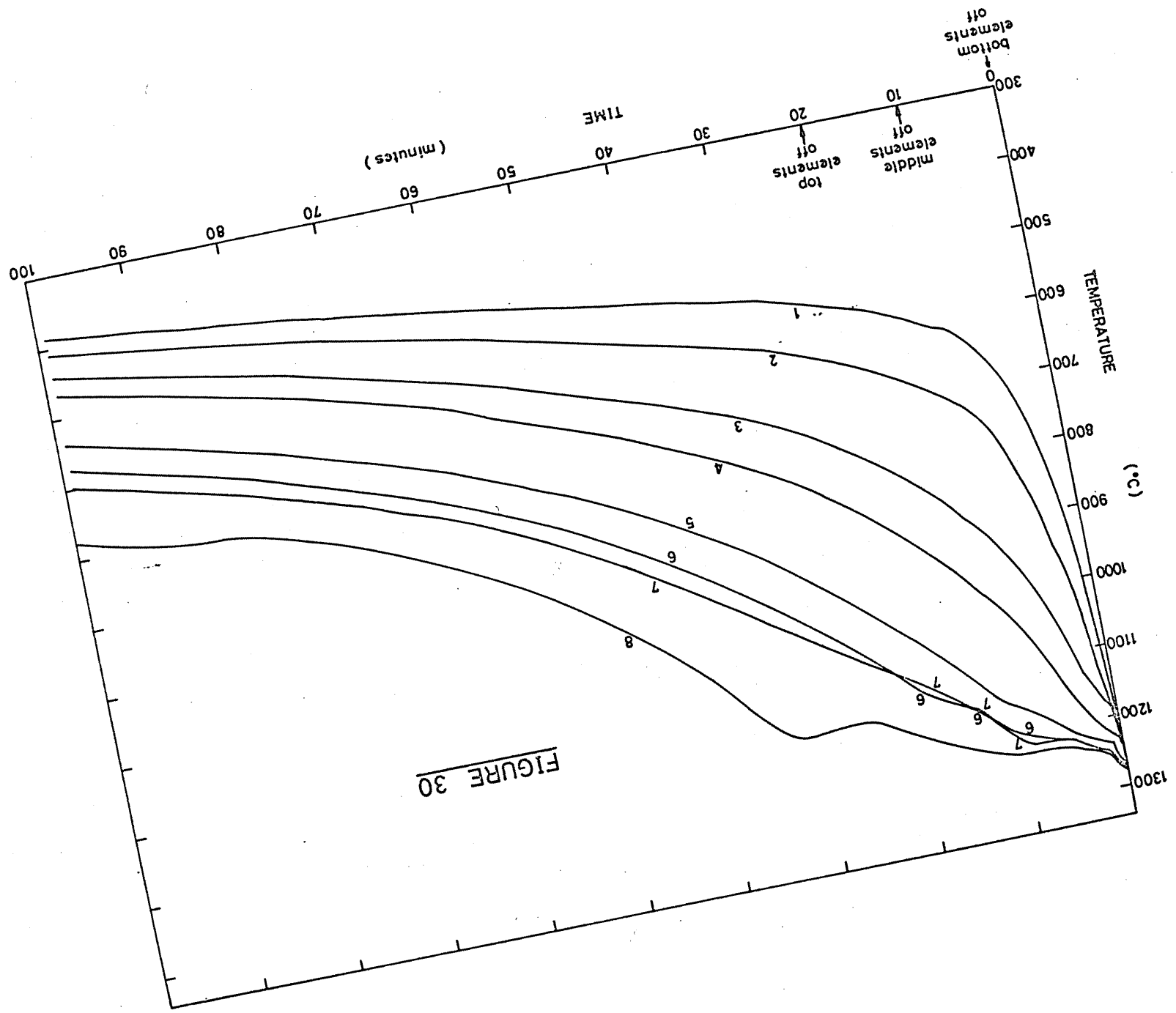

TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

FIGURE 30

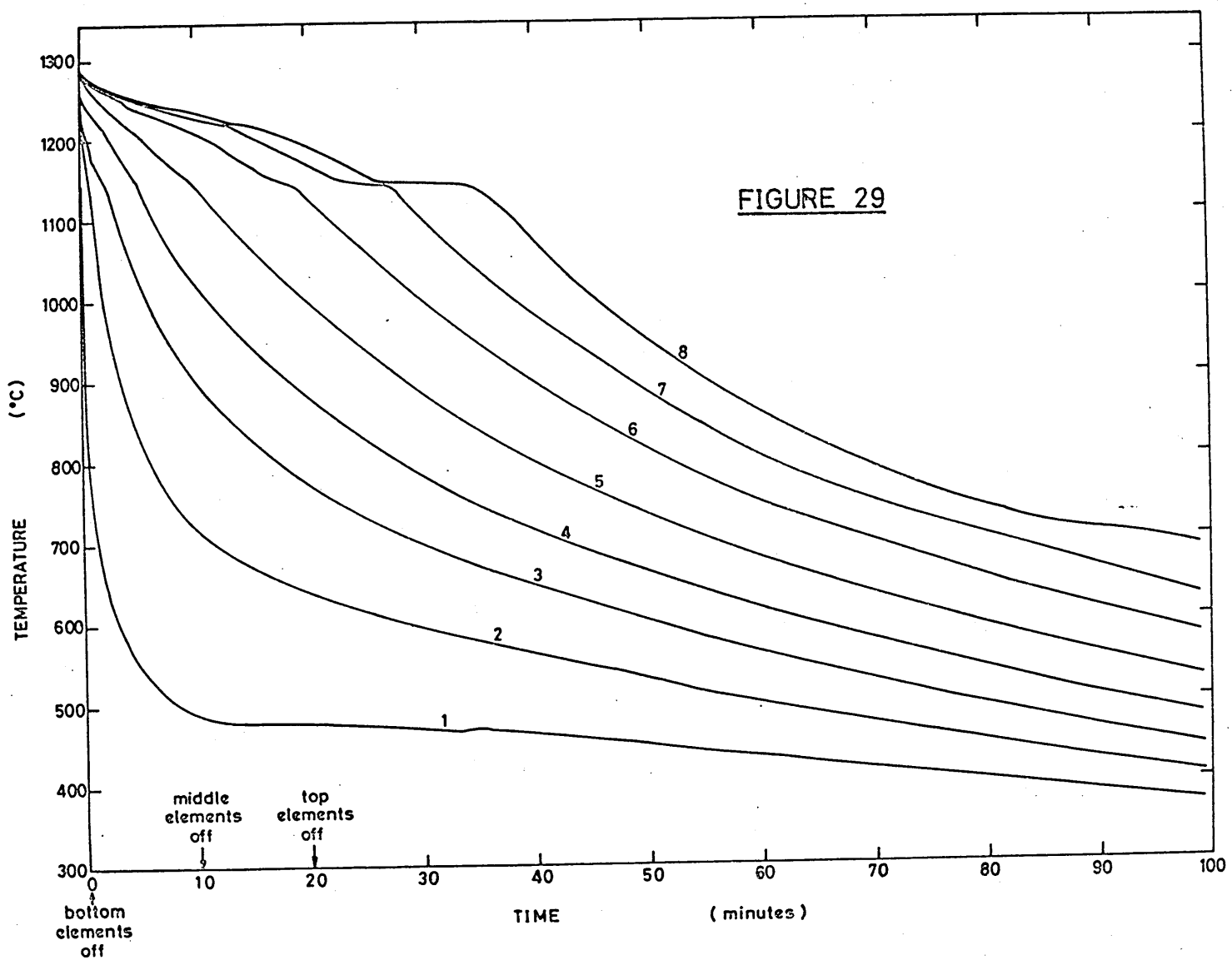


FIGURE 29
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

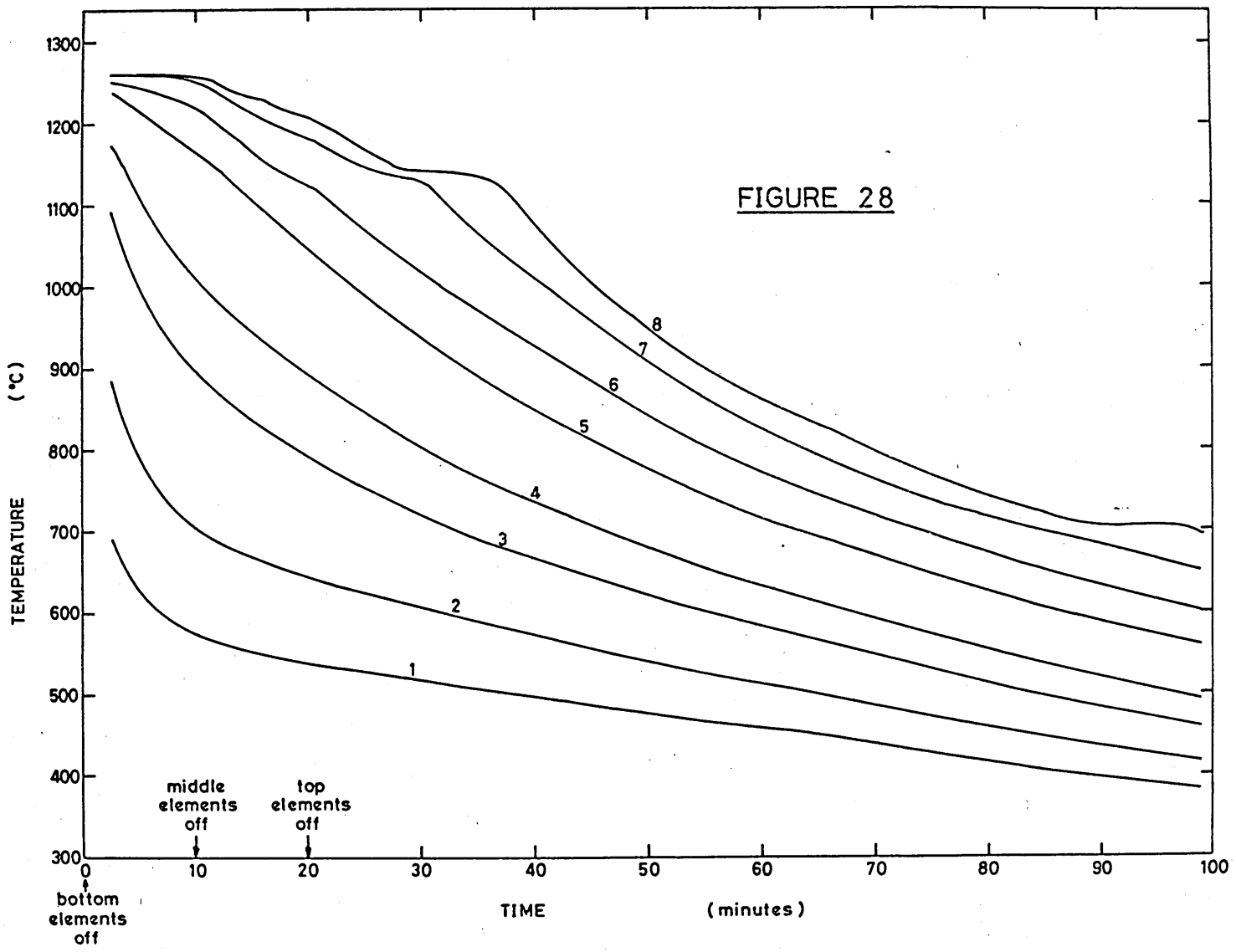


FIGURE 28
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
100
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

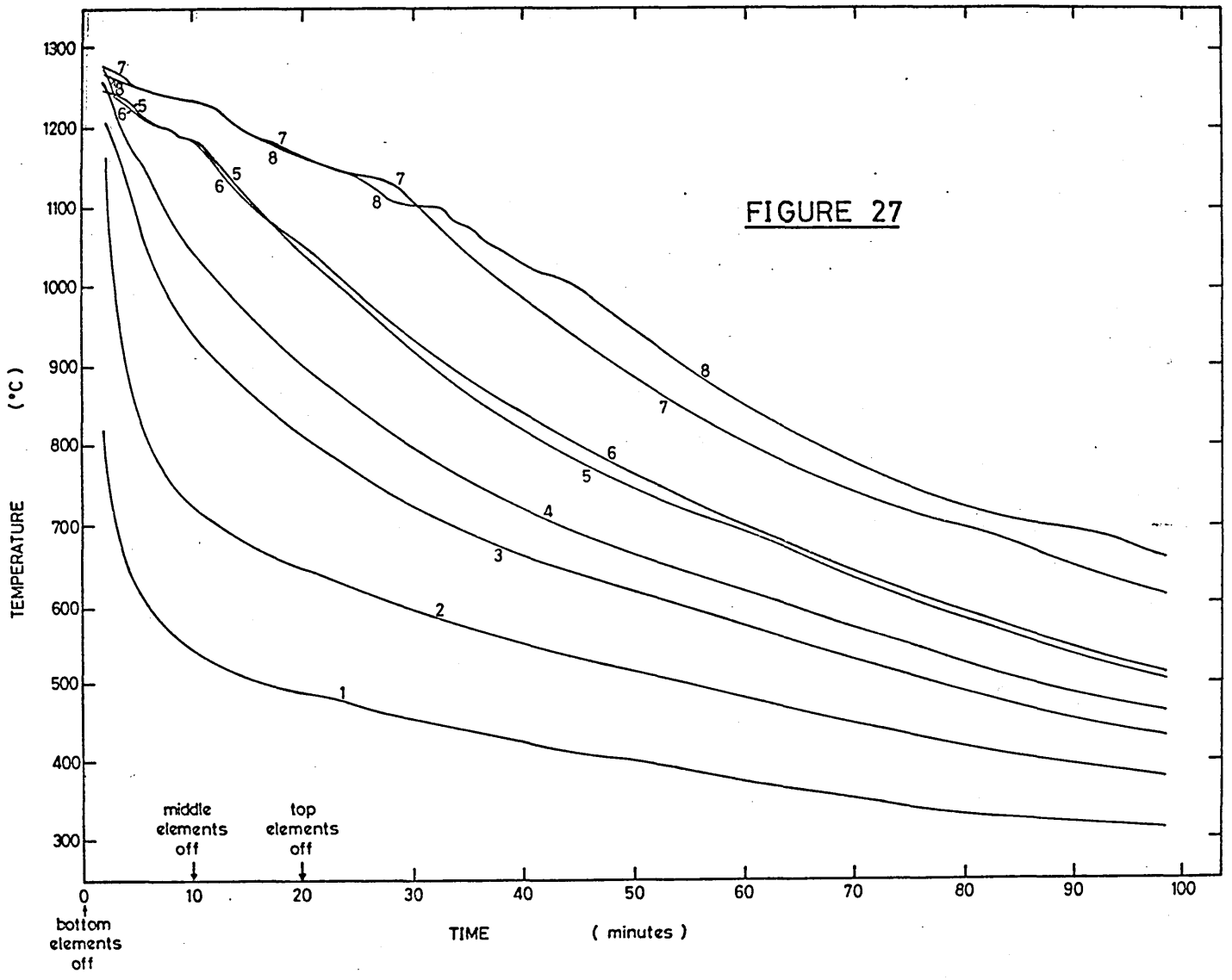


FIGURE 27
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
TIME (minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

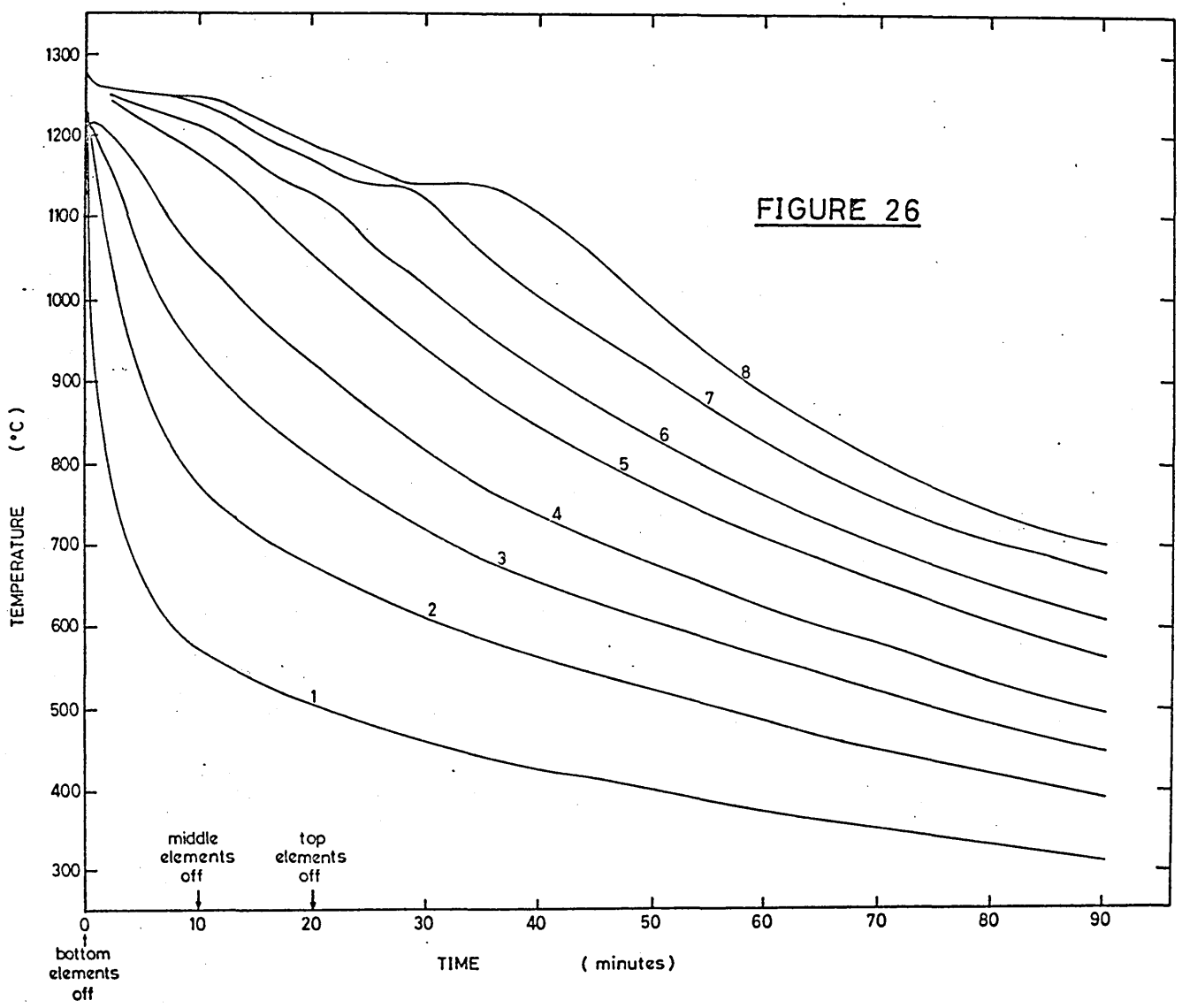


FIGURE 26
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
90
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

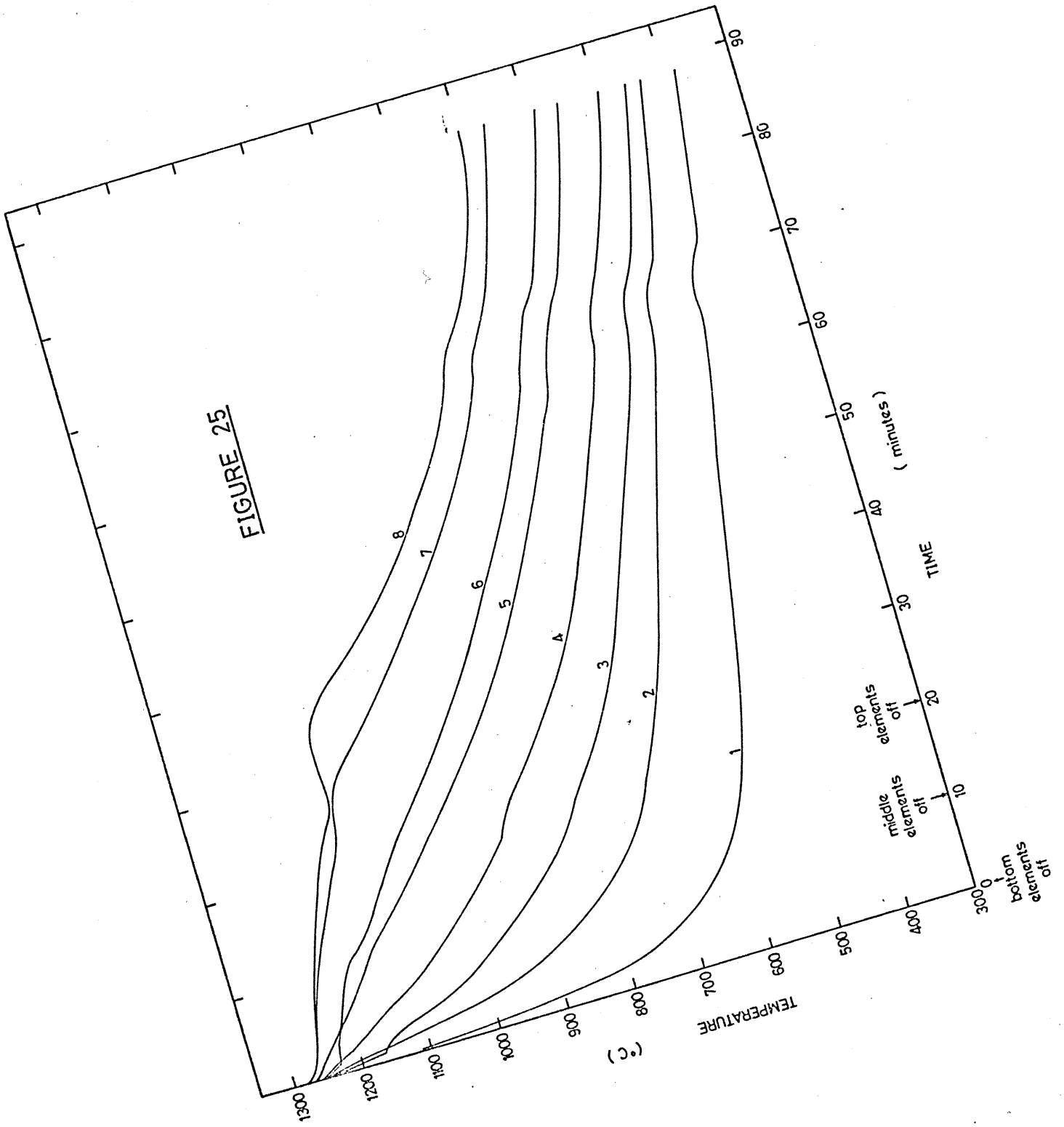

TIME (minutes)
0
10
20
30
40
50
60
70
80
90
top elements off
middle elements off
bottom elements off
TEMPERATURE (°C)
300
400
500
600
700
800
900
1000
1100
1200
1300
1
2
3
4
5
6
7
8

FIGURE 25

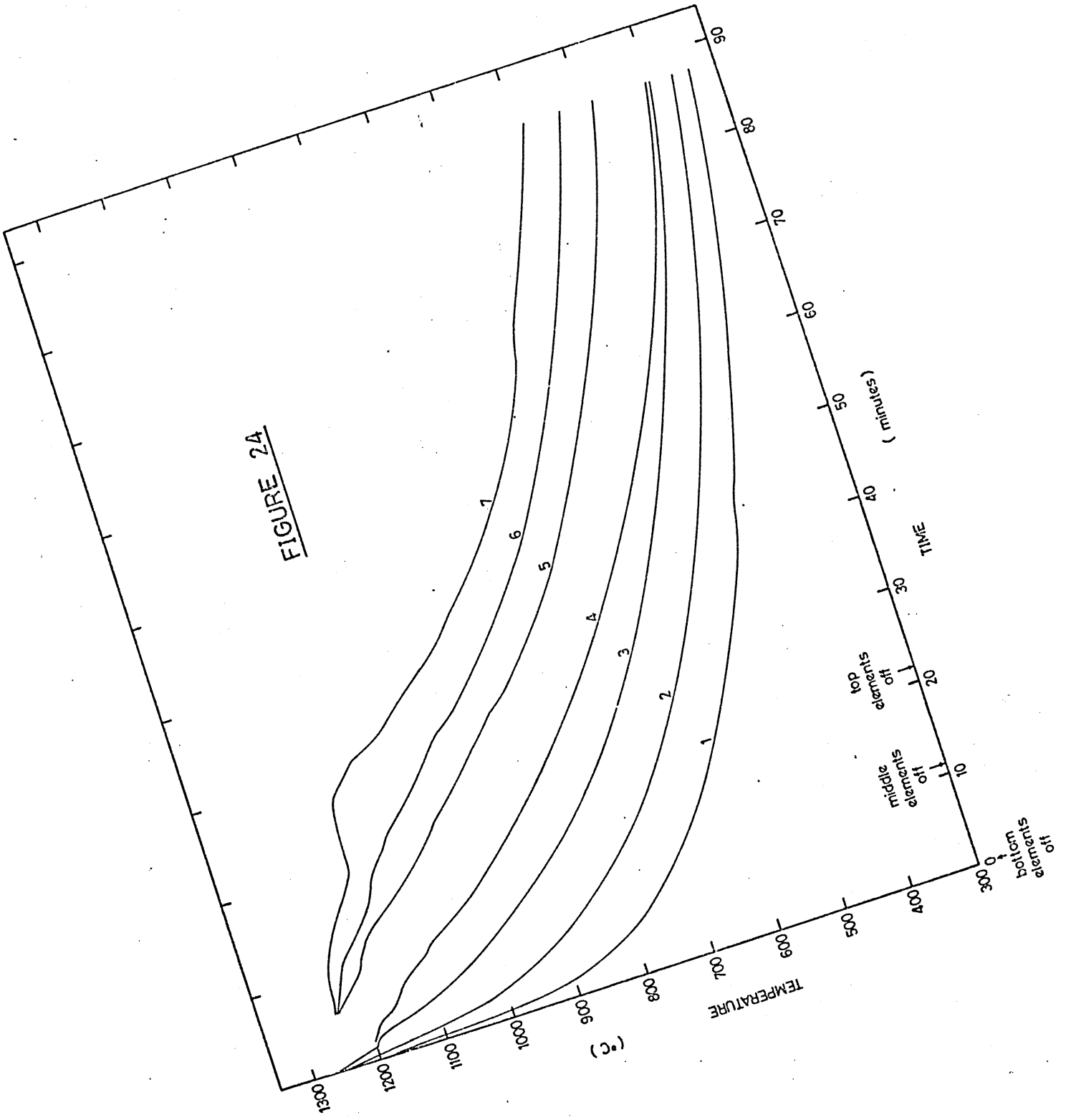

TIME
(minutes)
90
80
70
60
50
40
30
top elements off
20
middle elements off
10
bottom elements off
1
6
5
4
3
2
1
TEMPERATURE
(°C)
300
400
500
600
700
800
900
1000
1100
1200
1300

FIGURE 24

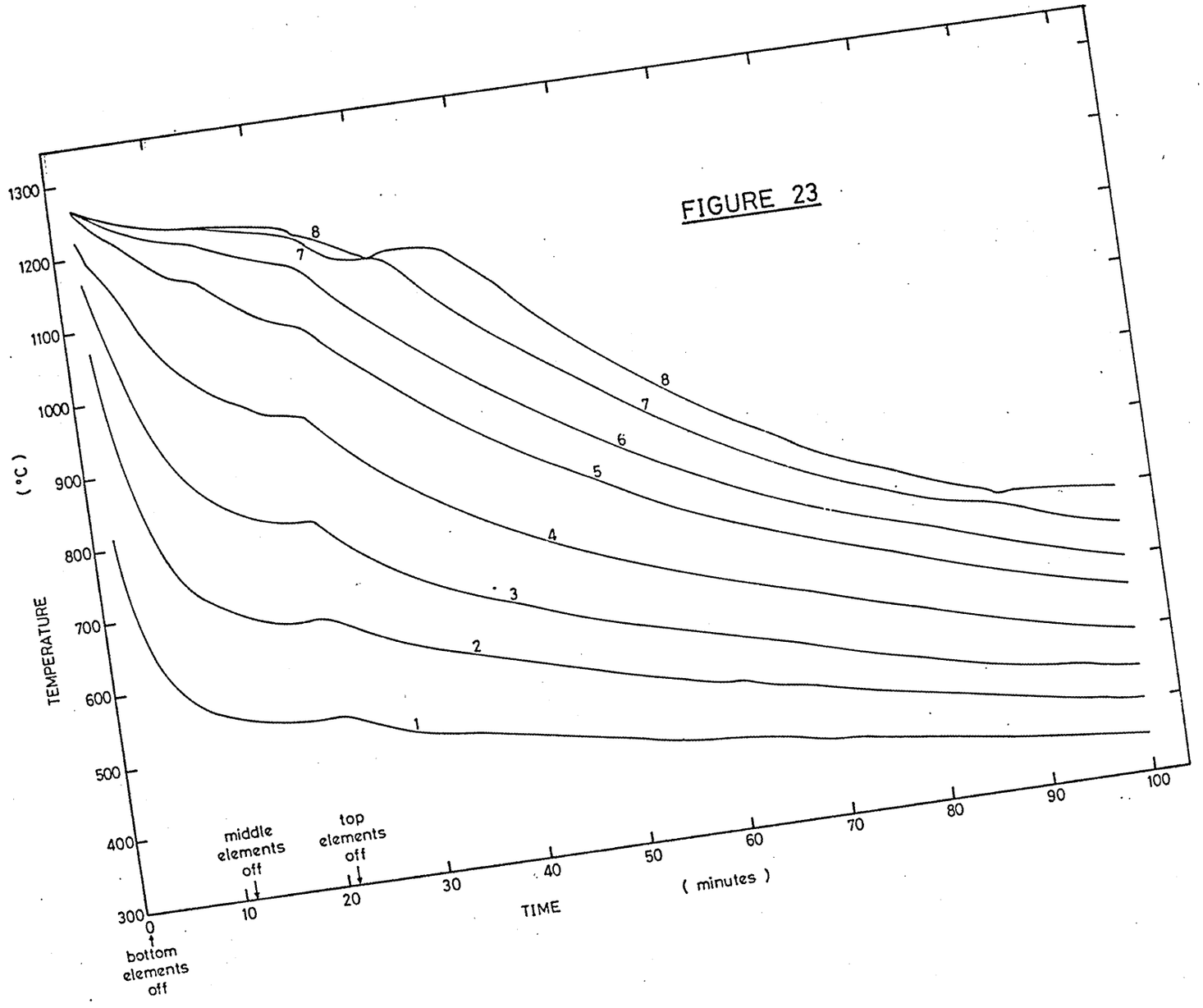


FIGURE 23
TEMPERATURE
(°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
TIME
(minutes)
0
10
20
30
40
50
60
70
80
90
100
bottom elements off
middle elements off
top elements off
1
2
3
4
5
6
7
8

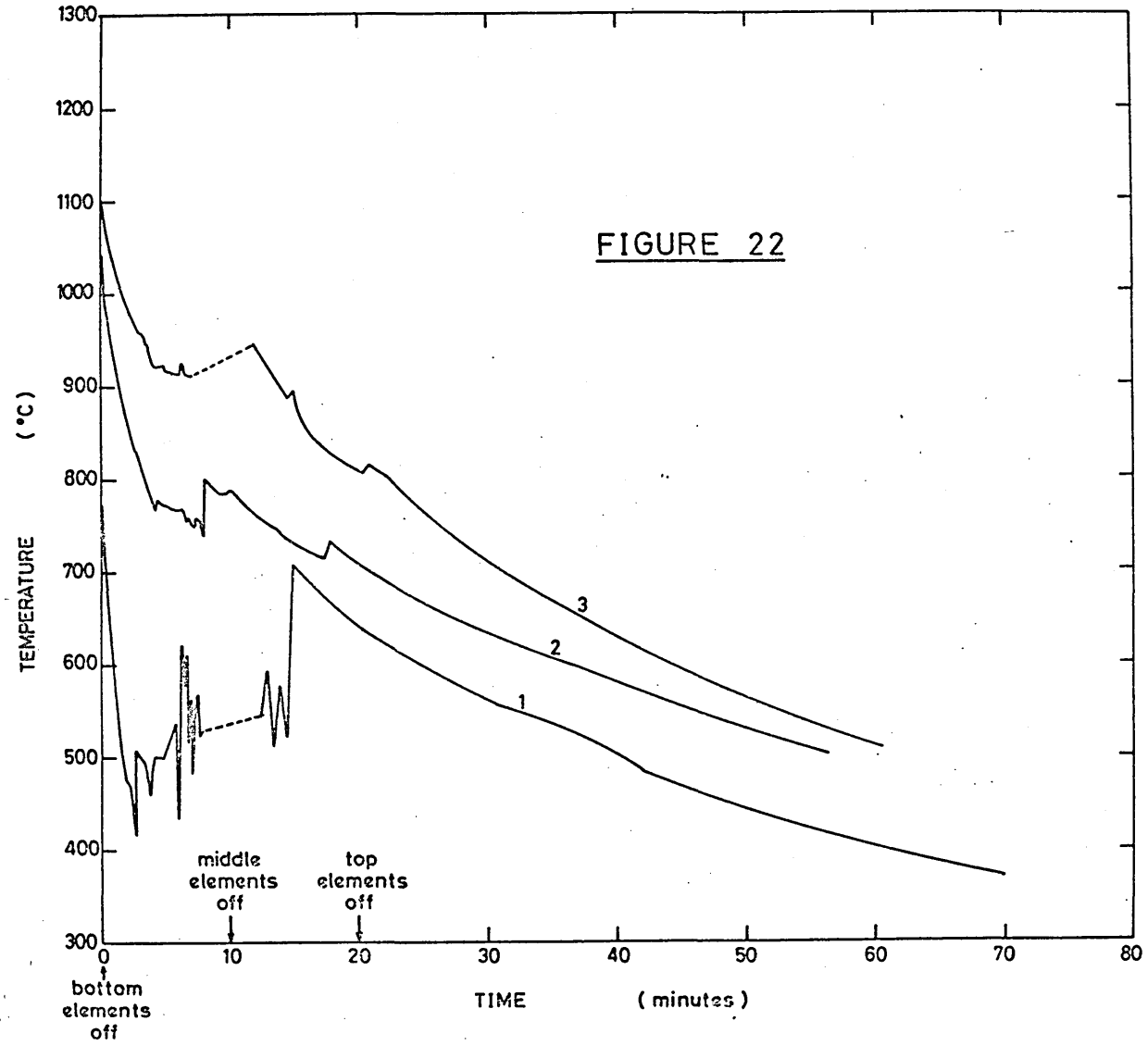


FIGURE 22
TEMPERATURE (°C)
1300
1200
1100
1000
900
800
700
600
500
400
300
0
10
20
30
40
50
60
70
80
TIME (minutes)
bottom elements off
middle elements off
top elements off
1
2
3

COOLING CURVES FOR THE GREY IRON MELT PROGRAMME (FIGURES 22-60)

The following cooling curves have been obtained from the grey iron melt programme castings and are correlated as follows:-

LOW NITROGEN CASTINGS

Figure No.	Cast No.
22	A1a
23	A1b
24	A1c
25	A1
26	A2
27	A3
28	B1
29	B2
30	B3
31	C1
32	C2
33	C3
34	E1a
35	E1
36	E2
37	E3
38	F1
39	F2a
40	F2
41	F3
42	G1
43	G2
44	G3

HIGH NITROGEN CASTINGS

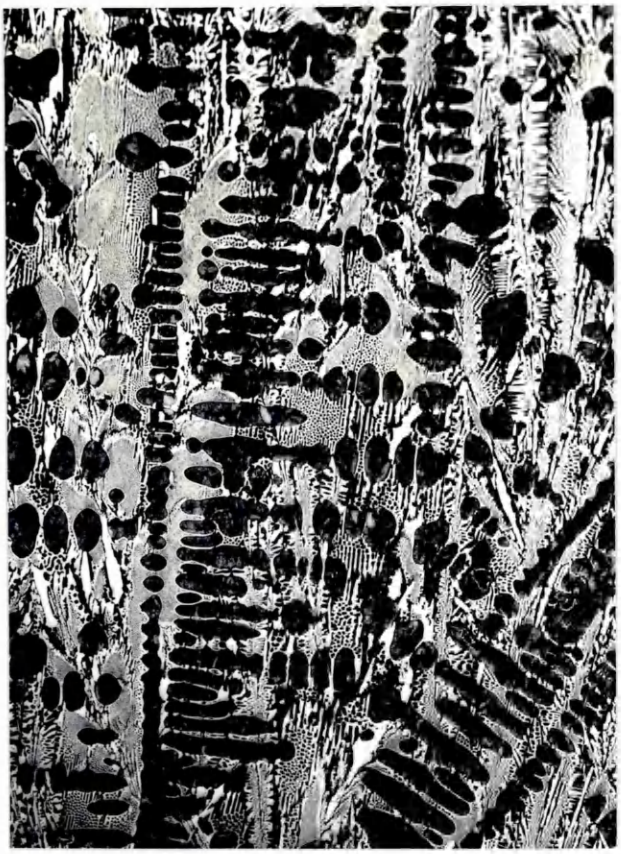
Figure No.	Cast No.
45	A1a'
46	A1'
47	A2'
48	A3'
49	B1'
50	B2'
51	B3a'
52	B3'
53	C1'
54	C2'
55	C3'
56	F1'
57	F2'
58	F3'
59	D1'
60	D3'

Table 15 - Continued

Cast	Elements										Cooling Curve Figure	Fracture Plate No.
	C	Si	Ti	N	P	Si	Mn	Cr	B	Al		
		TABLE 15b HIGH NITROGEN MELTS										
A1a'	3.80	0.02	-	.0112	0.02	0.95	0.83	0.07	0.004	<0.001	45	159
A1'	3.80	0.03	-	0.012	0.02	1.04	0.86	0.05	0.005	<0.001	46	139
A2'	3.80	0.05	-	0.0118	0.02	1.00	0.89	0.05	0.005	<0.001	47	139
A3'	3.80	0.09	-	0.010	0.02	0.92	0.82	0.06	0.005	<0.001	48	139
B1'	3.80	0.18	0.093	0.0084	.015	0.87	0.87	0.07	0.005	0.001	49	139
B2'	3.70	0.06	0.091	0.0091	0.01	0.95	0.85	.035	0.003	0.001	50	139
B3a'	3.70	0.11	0.094	0.015	0.02	0.90	0.86	0.04	0.005	0.001	51	-
B3'	3.65	.115	0.090	0.009	0.02	0.84	0.80	0.06	0.005	0.002	52	139
C1'	3.60	0.02	0.120	0.009	0.02	0.85	0.74	0.05	0.005	<0.002	53	139
C2'	3.70	0.05	0.112	0.010	0.02	0.84	0.78	0.05	0.005	0.002	54	139
C2a'	3.57	0.06	0.130	0.010	0.02	0.79	0.825	0.05	0.005	0.002	-	-
C3'	3.60	0.10	0.130	0.009	0.02	0.83	0.80	0.06	0.005	0.002	55	139
D1'	3.60	0.26	0.180	0.008	0.018	0.78	0.82	0.06	0.005	0.001	59	139
D3'	3.68	0.15	0.210	0.009	0.016	0.89	0.80	0.05	0.004	0.004	60	139
F1'	3.60	.021	0.410	0.009	0.01	0.80	0.74	0.05	0.003	0.001	56	139
F2'	3.64	0.06	0.380	0.0091	0.02	0.78	0.80	0.03	0.003	0.002	57	139
F3'	3.65	0.10	0.380	0.0091	0.02	0.75	0.79	0.07	0.001	0.002	58	139

Table 15 - Cast Compositions for the Grey Iron Melt Programme

Cast	Elements										Cooling Curve Figure	Fracture Plate No.
	C	S	Ti	N	P	Si	Mn	Cr	B	Al		
	TABLE 15a LOW NITROGEN MELTS											
A1a	3.42	0.02	-	0.005	0.02	0.97	0.86	0.11	0.003	0.001	22	59
A1b	3.55	0.02	-	0.0048	0.02	1.17	0.84	0.08	0.003	<0.001	23	59
A1c	4.02	0.02	-	0.0056	0.02	1.16	0.87	0.08	0.003	<0.001	24	59
A1	3.90	0.02	-	0.0064	0.02	1.01	0.80	0.09	0.005	<0.001	25	35
A2	3.80	0.045	-	0.0057	.026	1.05	0.82	0.08	0.004	<0.001	26	35
A3	3.80	0.104	-	0.006	0.02	0.95	0.80	0.08	0.003	<0.001	27	35
B1	3.65	0.03	0.091	0.0047	0.02	0.94	0.85	0.06	0.002	0.002	28	35
B2	3.75	0.06	0.091	0.004	0.02	0.955	0.92	0.05	0.005	0.001	29	35
B3	3.65	0.10	.0915	0.0051	0.02	0.91	0.85	0.06	0.005	0.001	30	35
C1	3.75	0.015	0.143	0.0044	0.02	1.00	0.80	0.04	0.003	0.002	31	35
C2	3.80	0.068	0.137	0.0049	0.02	1.04	0.80	0.04	0.003	0.002	32	35
C3	3.80	o.110	0.137	0.0046	0.02	0.95	0.80	0.04	0.002	0.001	33	35
E1a	3.80	0.02	0.293	0.0038	0.02	1.01	.825	0.08	0.004	0.002	34	133
E1	3.65	0.022	0.330	0.005	0.02	0.80	0.76	0.05	0.005	0.001	35	35
E2	3.60	0.045	0.316	0.005	.019	0.80	0.70	0.05	0.003	0.001	36	35
E3	3.70	0.098	0.316	0.004	.018	0.87	0.80	0.05	0.003	0.002	37	35
E3a	3.52	0.120	0.340	0.004	0.02	0.90	0.80	0.05	0.003	0.002	-	134
F1	3.60	0.024	0.390	0.0041	0.01	0.90	0.81	0.04	0.002	0.007	38	35
F2a	3.75	0.050	0.390	0.0046	0.02	0.97	0.76	0.05	0.002	0.002	39	136
F2	3.60	0.050	0.390	0.0045	0.01	0.94	0.80	0.04	0.004	0.002	40	35
F3	3.70	0.100	0.377	0.0047	0.02	0.99	0.77	0.04	0.002	0.002	41	35
G1	3.80	0.017	0.490	0.004	0.02	0.90	0.85	0.06	0.003	0.004	42	35
G2	3.80	0.060	0.408	0.003	0.02	1.20	0.78	0.08	0.004	0.001	43	35
G3	3.80	0.100	0.435	0.003	0.02	1.02	.805	0.08	0.004	0.001	44	35



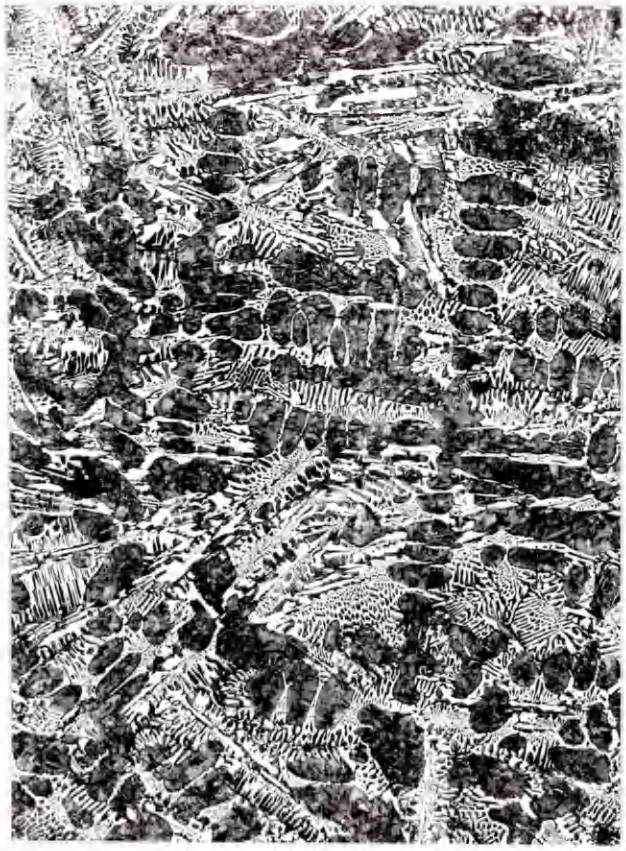
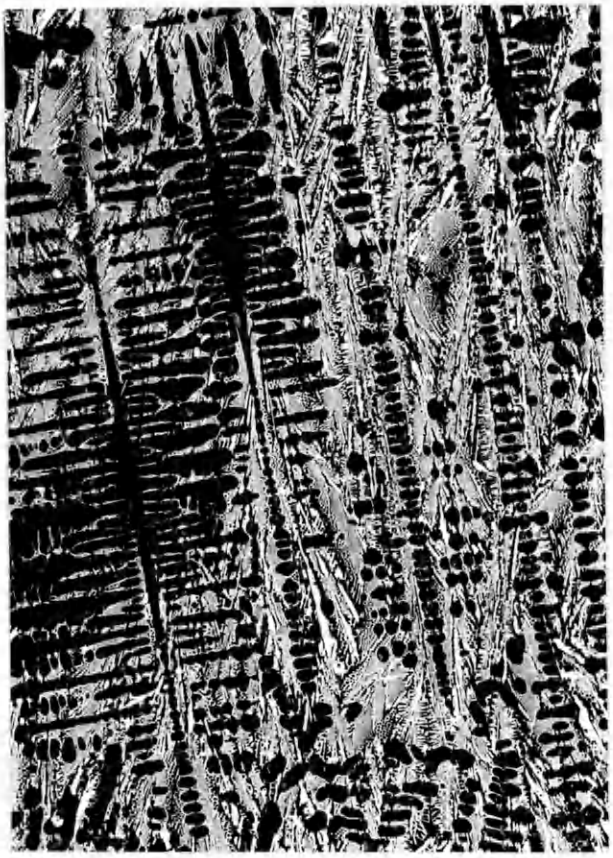


PLATE 32

Melt 17, 101.6mm (9.525mm) x40

PLATE 33

Melt 17, 177.8mm (9.525mm) x 40



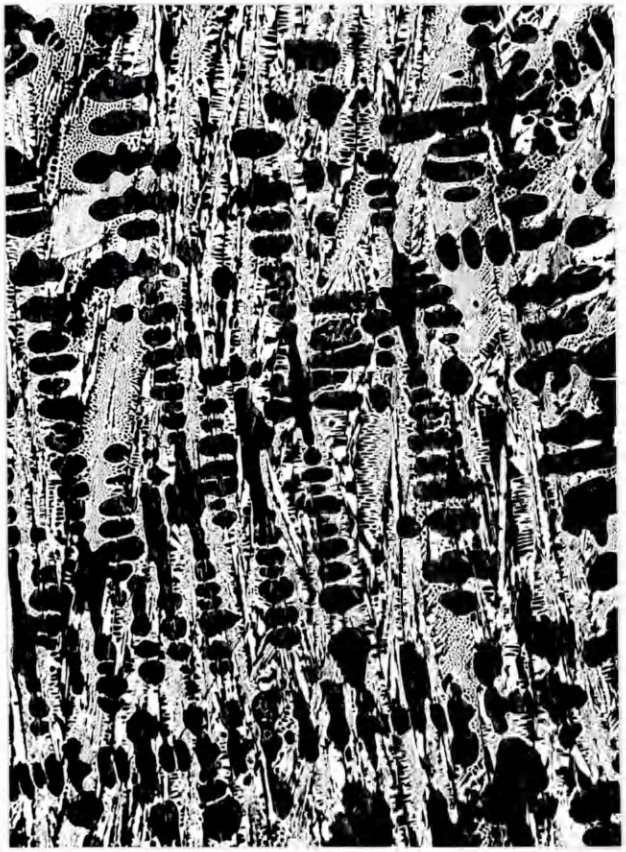
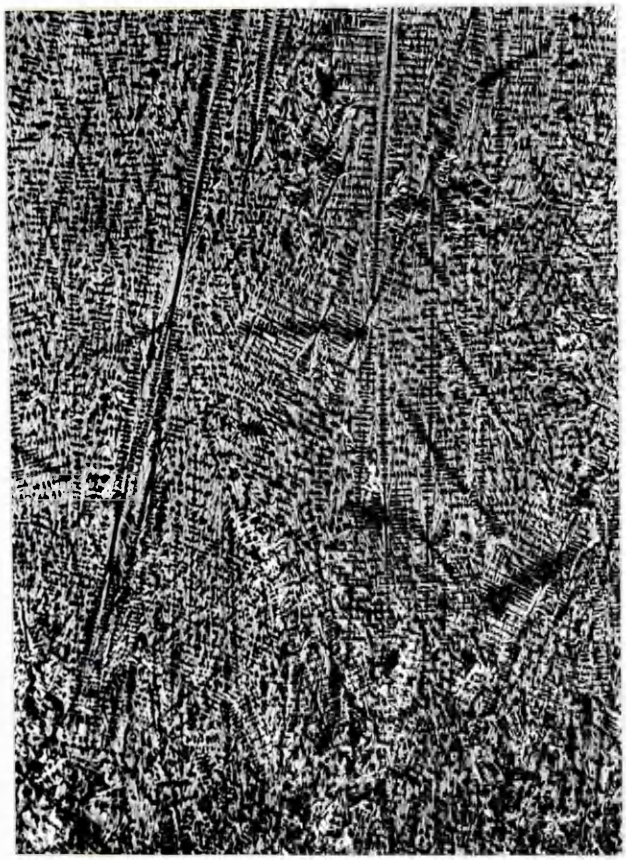


PLATE 30

Melt 17, 35mm (9.525mm)
X 50

PLATE 31

Melt 17, 63.5mm (9.525mm)
X 50



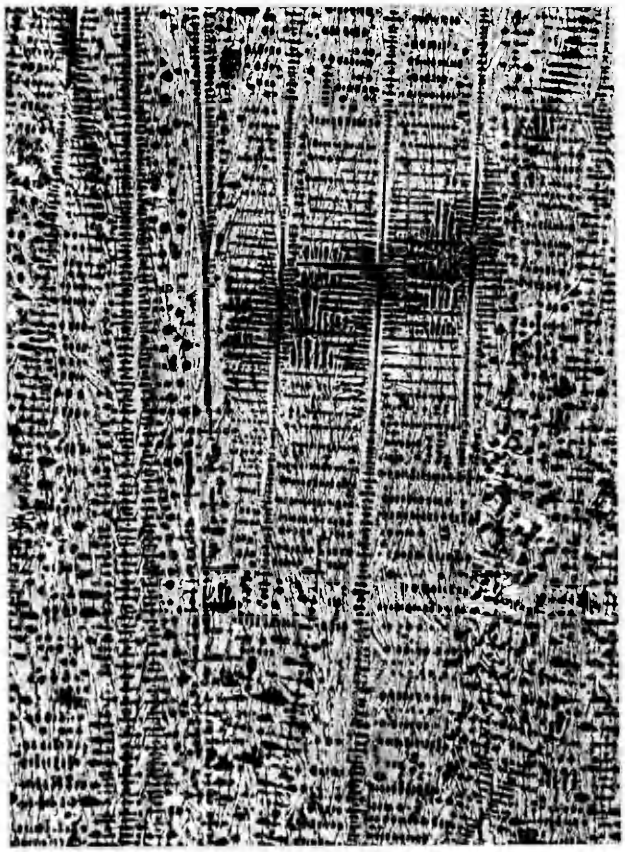


PLATE 28

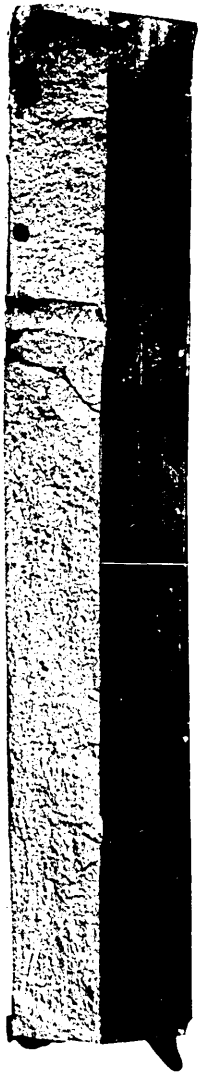
Melt 17, 0mm (9.525mm)

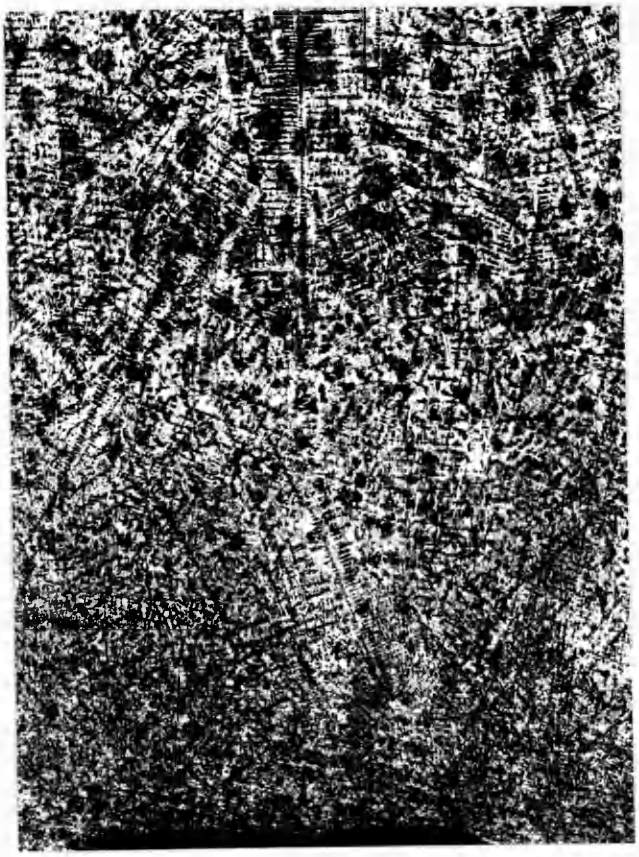
X 50

PLATE 29

Melt 17, 10mm (9.525mm)

X 50





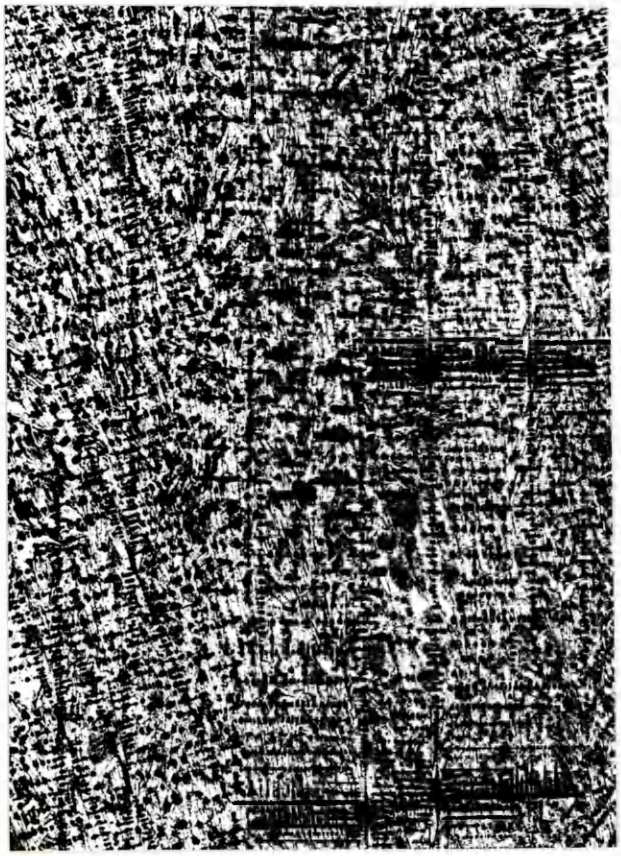


PLATE 25

Melt 16, Omm (9.525mm)

X 50

PLATE 26

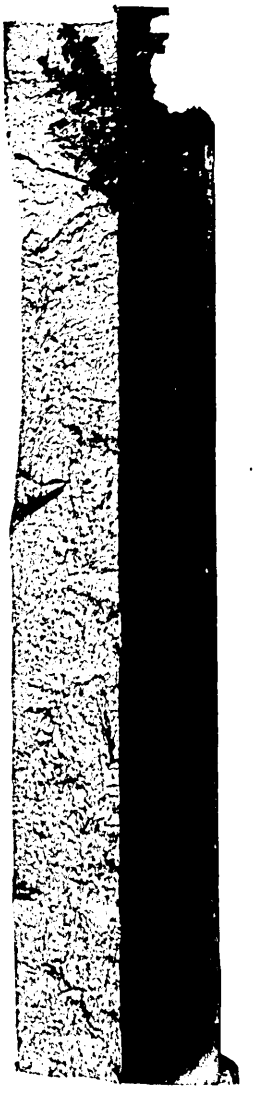
Melt 16, 12.7mm (9.525mm)

X 50

The details of the following microstructures, etched in 2% nital, are given as follows:-

Cast number, distance from the chill, (distance from the T/C edge) and magnification.

The photographs are orientated with the chill/metal interface towards the bottom of the plates.



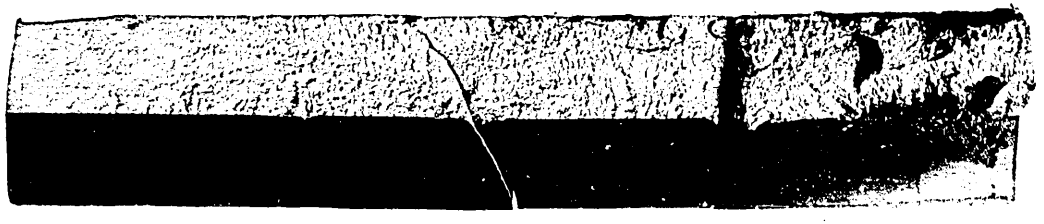


PLATE 87

C1. 185mm (32.1mm)

x 63

4.17°C/Min

PLATE 88

C1. 181mm (20.5mm)

x 16

4.35°C/Min

PLATE 89

C1. 181mm (20.5mm)

x 63

4.35°C/Min

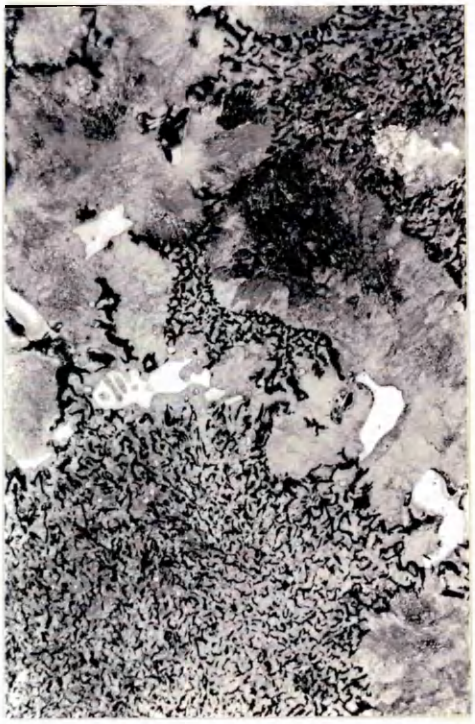


PLATE 90

G1. 0mm (28.6mm)

x 16

635°C/Min

PLATE 91

G1. 44mm (28.6mm)

x 16

21.88°C/Min

PLATE 92

F1. 63.5mm (32.1mm)

x 16

12.33°C/Min

PLATE 93

G1. 118mm (25.1mm)

x 16

6.89°C/Min

PLATE 94

E1. 89mm (34.1mm)

x 63

9.79°C/Min

PLATE 95

F1. 89mm (30.1mm)

x 16

9.79°C/Min

PLATE 96

Enlargement of Plate 95

x 63

9.79°C/Min

PLATE 97

G1. 89mm (19.05mm)

x 16

9.79°C/Min

PLATE 98

E1. 127.1mm (21.1mm)

x 16

6.28°C/Min

PLATE 99

Enlargement of Plate 98

x 63

6.28°C/Min

PLATE 100

Enlargement of Plate 98

x 160

6.28°C/Min

PLATE 101

F1. 127.1mm (35.1mm)

x 16

6.28°C/Min

PLATE 102

G1. 136mm (25.6mm)

x 16

5.82°C/Min

PLATE 103

F1. 177.8mm (24.6mm)

x 16

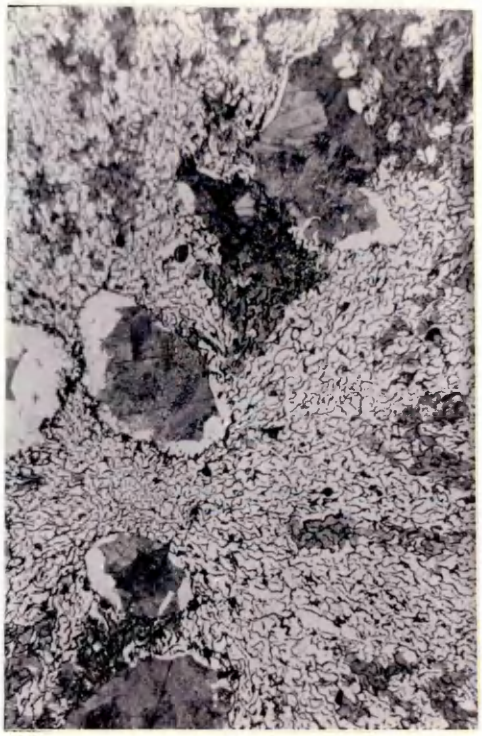
4.43°C/Min

PLATE 104

Enlargement of Plate 103

x 160

4.43°C/Min



MICROSTRUCTURAL CRITERIA FOR THE LOW NITROGEN GREY IRON CASTINGS

Sulphur Levels	Cast Groups					
	A	B	C	E	F	G
1	12.7	12.7	26	38.1	38.1	38.1
2	12.7	25.4	25.4	38.1	38.1	25.4
3	27.4	38.1	26.4	30.4	12.7	28.7

Table 20(a) Streamer Graphite Start (mm)

Sulphur Levels	Cast Groups					
	A	B	C	E	F	G
1	25.4	38.1	33.5	44	63.5	75
2	25.4	49.1	38.1	73	58	38.1
3	63.5	63.5	38.1	63.5	50	47.6

Table 20(b) 'Grey' Start (mm)

Sulphur Levels	Cast Groups					
	A	B	C	E	F	G
1	63.5	64.5	89	127.1	127.1	136
2	63.5	76.1	63.7	141	116	127.1
3	73.5	107.1	90.5	127.1	127.1	127.1

Table 20(c) Graphitic Cell Start (mm)

Sulphur Level	Cast Groups					
	A	B	C	E	F	G
1	A	D	A/D	D	D	D
2	A	A/D	A/D	D	D/Deg.	D/Deg.
3	A/D	A/Dpred	A/D	D	Dpred/ A/Deg.	D/Deg.

Table 20(d) Type of Graphite at 177.8mm

pred.=predominantly

deg.=degenerate

PLATE 105

B2. 63.5mm (28.6mm)

x 16

12.33°C/Min

PLATE 106

B2. 112mm (28.6mm)

x 160

7.38°C/Min

PLATE 107

B2. 127.1mm (28.6mm)

x 63

6.28°C/Min

PLATE 108

B2. 127.1mm (33.1mm)

x 32

6.28°C/Min

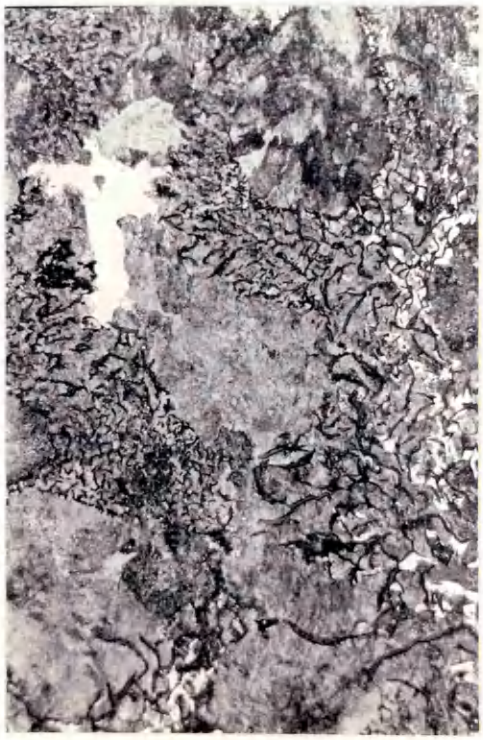


PLATE 109

B2. 178mm (19.05mm)

x 63

4.40°C/Min

PLATE 110

B3. 153.6mm (34.1mm)

x 160

5.25°C/Min

PLATE 111

B3. 184mm (30.10mm)

x 16

4.25°C/Min

PLATE 112

B3. 178mm (31.1mm)

x 16

4.40°C/Min

PLATE 113

C2. 45.1mm (28.6mm)

x 16

21.18°C/Min

PLATE 114

C2. 145mm (27.1mm)

x 16

5.52°C/Min

PLATE 115

C2. 187mm (19.05mm)

x 63

4.15°C/Min

PLATE 116

Enlargement of Plate 115

x 160

4.15°C/Min

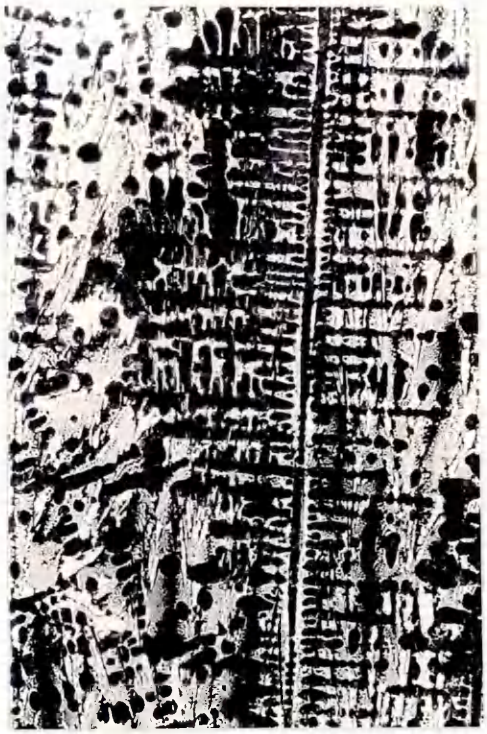


PLATE 117

C3. 38.1mm (22.1mm)

x 16

25.62°C/Min

PLATE 118

Enlargement of Plate 117

x 63

25.62°C/Min

PLATE 119

C3. 164mm (33.1mm)

x 16

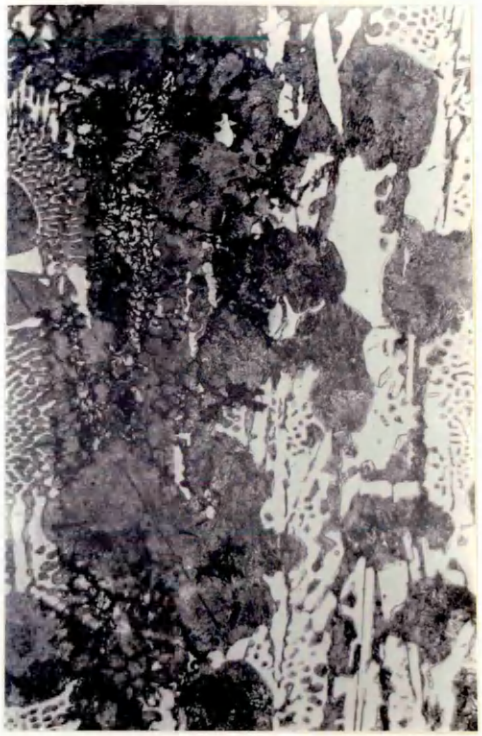
4.84°C/Min

PLATE 120

E2. 42.5mm (5mm)

x 160

22.91°C/Min



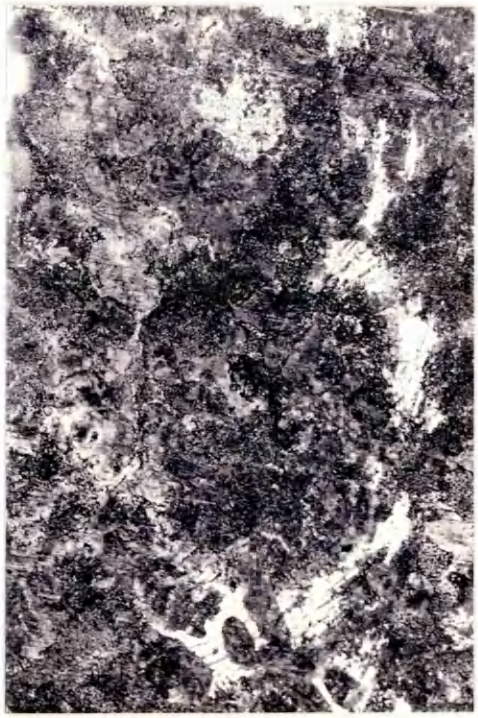


PLATE 121

E3. 63.5 mm (35.1mm)

x 160

12.33°C/Min

PLATE 122

E3. 127.1mm (19.05mm)

x 160

6.28°C/Min

PLATE 123

F2. 70mm (9.525mm)

x 16

11.56°C/Min

PLATE 124

F2. 181.5mm (26.1mm)

x 63

4.32°C/Min

PLATE 125

F3. 66mm (9.525mm)

x 16

12.02°C/Min

PLATE 126

F3. 63.7mm (19.05mm)

x 63

12.30°C/Min

PLATE 127

F3. 127.1mm (9.525mm)

x 32

6.28°C/Min

PLATE 128

F3. 177.8mm (11mm)

x 16

4.43°C/Min

PLATE 129

G2. 65.5mm (22.6mm)

x 16

11.97°C/Min

PLATE 130

Enlargement of Plate 129

x 63

11.97°C/Min

PLATE 131

G2. 127.1mm (22.1mm)

x 63

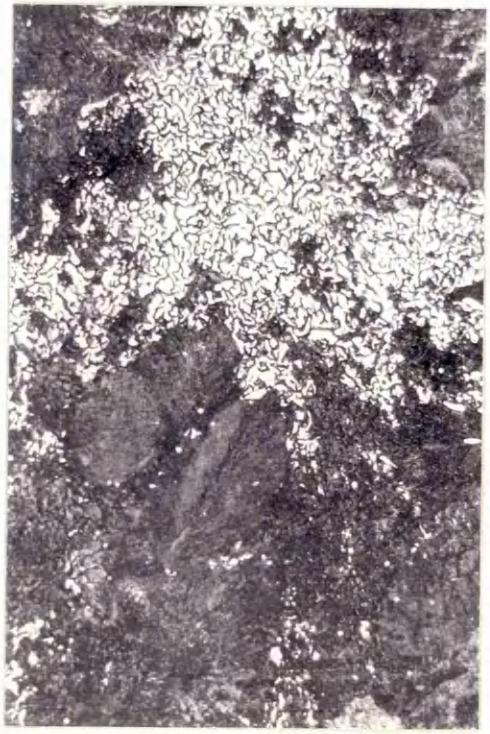
6.28°C/Min

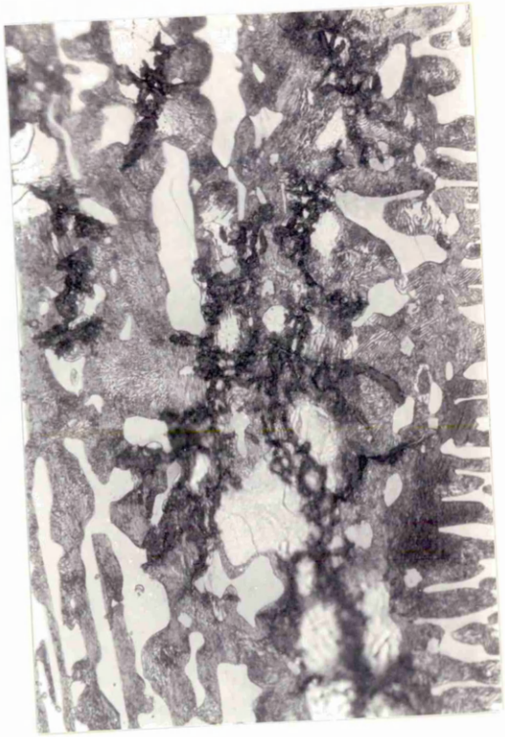
PLATE 132

G2. 177.8mm (15.0mm)

x 160

4.43°C/Min





ADDITIONAL LOW NITROGEN CASTS

PLATE 134

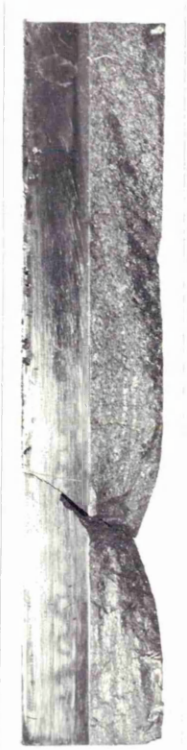
Cast E1a

PLATE 135

Cast E3a

PLATE 136

Cast F2a



MICROSTRUCTURAL CRITERIA FOR THE ADDITIONAL CASTINGS

Criteria	Cast Groups					
	A1a	A1b	A1c	E1a	E3a	F2a
treamer Start (mm)	17	>12.7 <25.4	-	12.7	63.5	25.4
Grey' Start (mm)	54	20	-	63.5	178	52.1
ell Start (mm)	70	50	0	127.1	-	100
raphite at 177.8mm	A & D	A & Dpred	Large A	D & Deg.	D & Deg. round T/C	D

Table 21 a Low Nitrogen Melts

Criteria	Cast Groups		
	E1a'	B3a'	C2a'
(a) Streamer Start (mm)	25.4	25.4	12.7
(b) 'Grey' Start (mm)	38.1	63.5	38.1
(c) Cell Start (mm)	127.1	127.5	127.1
(d) Graphite at 177.8mm	A & Small amount D	A & D	Fine A & D & Deg.

Table 21 b High Nitrogen Melts

PLATE 137

E3a 177.8mm (6mm)

x 160

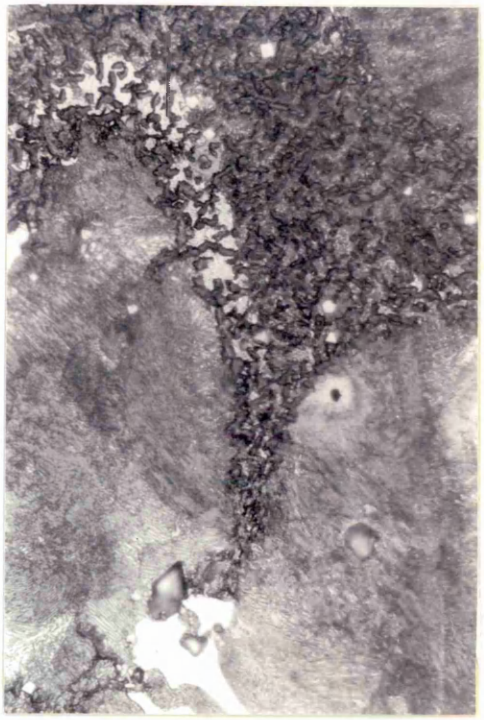
4.43°C/Min

PLATE 138

F2a 64.8mm (9.525mm)

x 63

12.08°C/Min



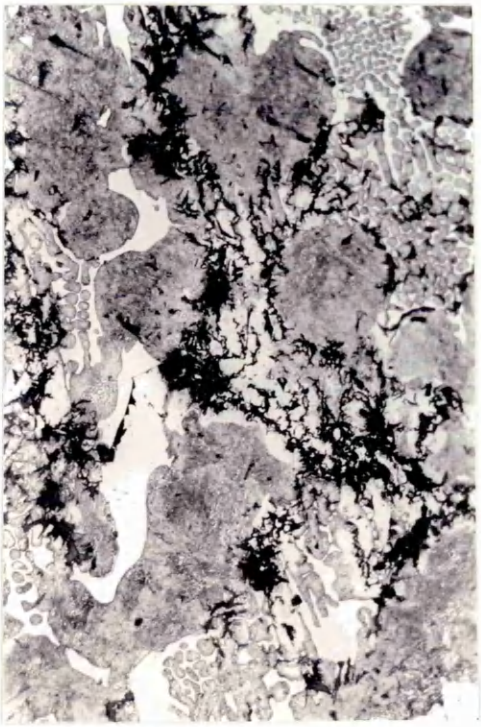


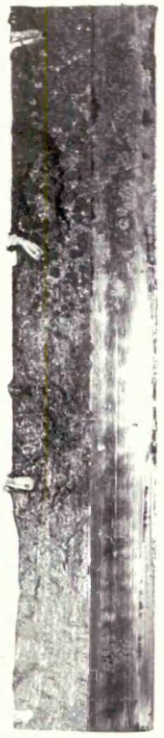
PLATE 139

FRACTURED CASTINGS FOR THE HIGH NITROGEN MELT PROGRAMME

A3′

B3′

C3′



D3′

F3′

MICROSTRUCTURAL CRITERIA FOR THE HIGH NITROGEN GREY IRON CASTINGS

Sulphur Level	Cast Groups				
	A'	B'	C'	D'	F'
1	25.4	38.1	16.7	16.0	38.1
2	25.4	25.4	12.7	-	38.1
3	29.0	15.5	21.5	25.4	28.4

Table 22a Streamer Graphite Start (mm)

Sulphur Level	Cast Groups				
	A'	B'	C'	D'	F'
1	41.1	89	38.1	39.6	-
2	42.5	38.1	38.1	-	-
3	63.5	38.1	38.1	57	130.2

Table 22b 'Grey' Start (mm)

Sulphur Level	Cast Groups				
	A'	B'	C'	D'	F'
1	89	105	63.7	89	127.1
2	89	63.5	63.5	-	106
3	127.1	89.0	92	89	130.2

Table 22c Graphitic Cell Start (mm)

Sulphur Level	Cast Groups				
	A'	B'	C'	D'	F'
1	A	Feathery D & Deg.	Deg. & A	>A & Some D & Deg.	Deg.
2	A	> A & D	>A & Bit D	-	Deg. D
3	A & Deg. & Broad	A/D/ Deg./ Mesh	>D and A	A and Broad D	Deg.

Table 22d Graphite Type at 177.8 (mm)

PLATE 140

A1' 89mm (28.1mm)

x 32

9.79°C/Min

PLATE 141

Enlargement of Plate 140

x 160

9.79°C/Min

PLATE 142

A1' 187mm (31.6mm)

x 160

4.15°C/Min

PLATE 143

A1' 179mm (34.1mm)

x 160

(Enlargement of Plate 144)

4.37°C/Min

PLATE 144

A1' 179mm (34.1mm)

x 16

4.37°C/Min

PLATE 145

A1' 179mm (9.525mm)

x 32

4.37°C/Min

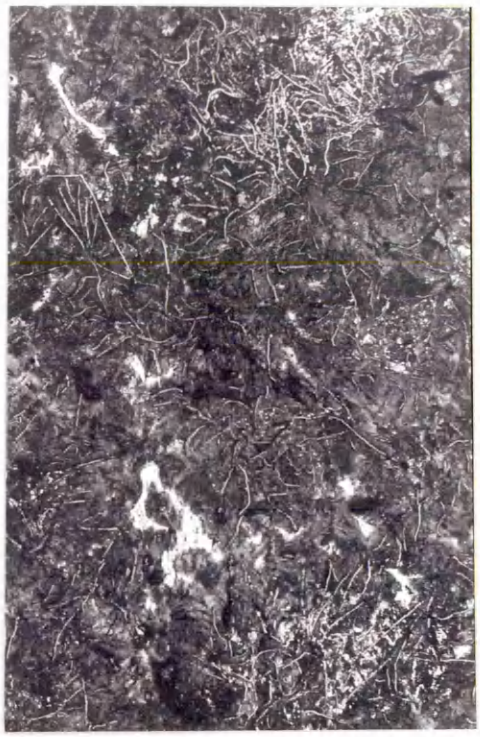


PLATE 146

A1' 179mm (19.05mm)

x 63

4.37°C/Min

PLATE 146A

Enlargement of Plate 146

x 160

4.37°C/Min

PLATE 147

A2' 63.5mm (9.525mm)

x 63

12.33°C/Min

PLATE 148

A2' 127.1mm (19.05mm)

x 160

6.28°C/Min

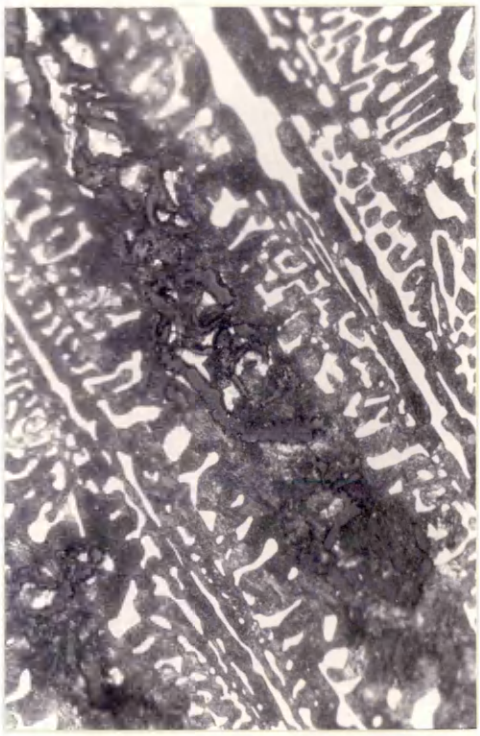


PLATE 149

A2' 177.8mm (19.05mm)

x 63

4.43°C/Min

PLATE 150

A2' 182mm (22.6mm)

x 160

4.29°C/Min

PLATE 151

A2' 177.8mm (9.525mm)

x 160

4.43°C/Min

PLATE 152

A3' 63.5mm (9.525mm)

x 160

12.33°C/Min

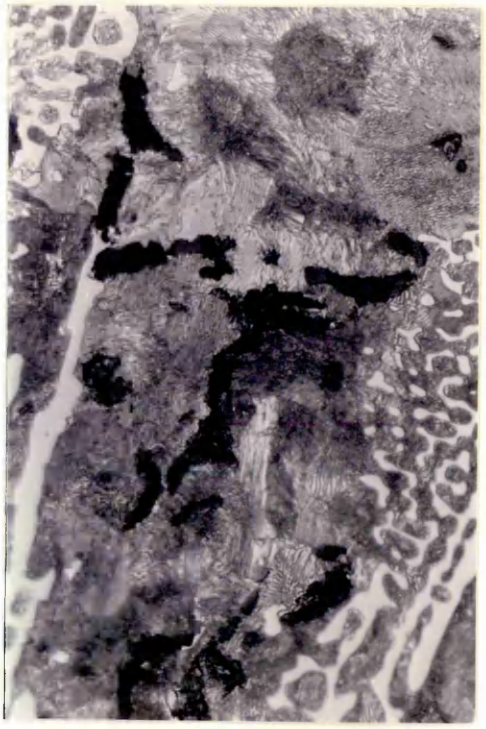


PLATE 153

A3' 177.8mm (35.1mm)

x 160

4.43°C/Min

PLATE 154

A3' 181mm (28.6mm)

x 63

4.35°C/Min

PLATE 155

THE FRACTURED CASTING OF CAST A1a'

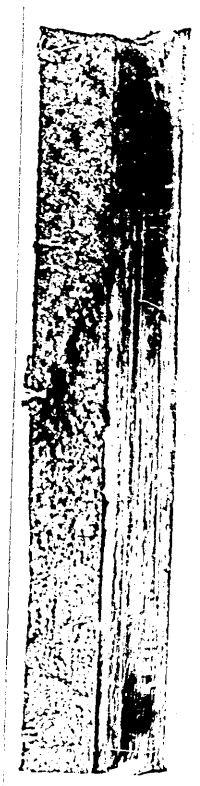


PLATE 156

A1a' 38.1mm (5mm)

x 160

25.62°C/Min

PLATE 157

B1' 89mm (16mm)

x 16

9.79°C/Min

PLATE 158

B1' 89mm (16mm)

x 160

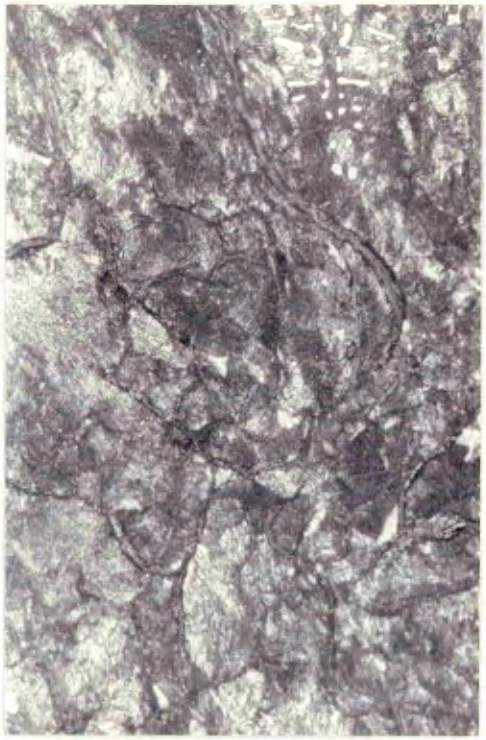
9.79°C/Min

PLATE 159

B1' 127.1mm (28.6mm)

x 63

6.28°C/Min



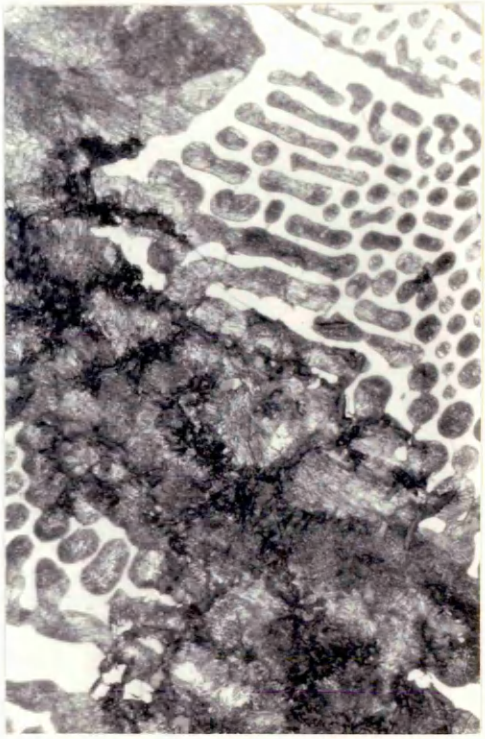


PLATE 160

B1' 177.8mm (28.6mm)

x 63

4.43°C/Min

PLATE 161

B2' 42.5mm (9.525mm)

x 16

22.91°C/Min

PLATE 162

B2' 38.1mm (10mm)

x 160

25.62°C/Min

PLATE 163

B2' 63.5mm (31.5mm)

x 160

12.33°C/Min

PLATE 164

B2' 89mm (33.1mm)

x 32

9.79°C/Min

PLATE 165

B2' 177.8mm (1.5mm)

x 63

4.43°C/Min

PLATE 166

B3' 25.4mm (19.05mm)

x 160

48.10°C/Min

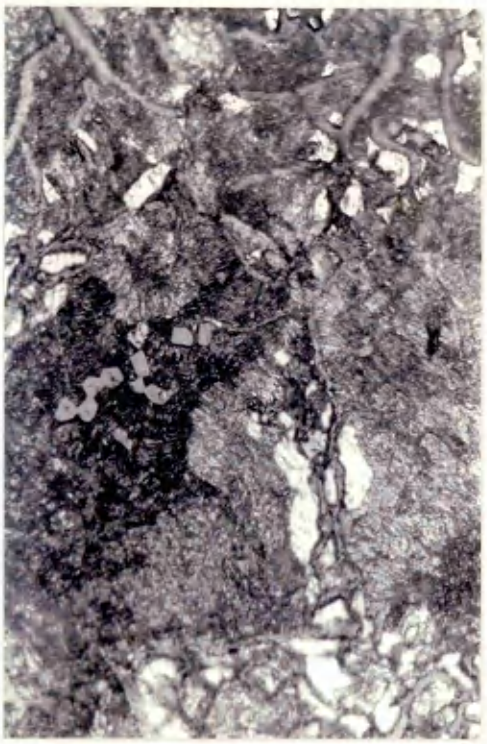


PLATE 167

B3' 63.5mm (19.05mm)

x 63

12.33°C/Min

PLATE 168

Enlargement of Plate 167

x 160

12.33°C/Min

PLATE 169

B3' 89mm (19.05mm)

9.79°C/Min

PLATE 170

B3' 127.1mm (27.6mm)

x 63

6.28°C/Min

PLATE 171

B3' 177.8mm (12.5mm)

x 160

4.43°C/Min

PLATE 172

C1' 127.1mm (13mm)

x 63

6.28°C/Min

PLATE 173

C1' 127.1mm (31.1mm)

x 63

6.28°C/Min

PLATE 174

C1' 177.8mm (5mm)

x 32

4.43°C/Min

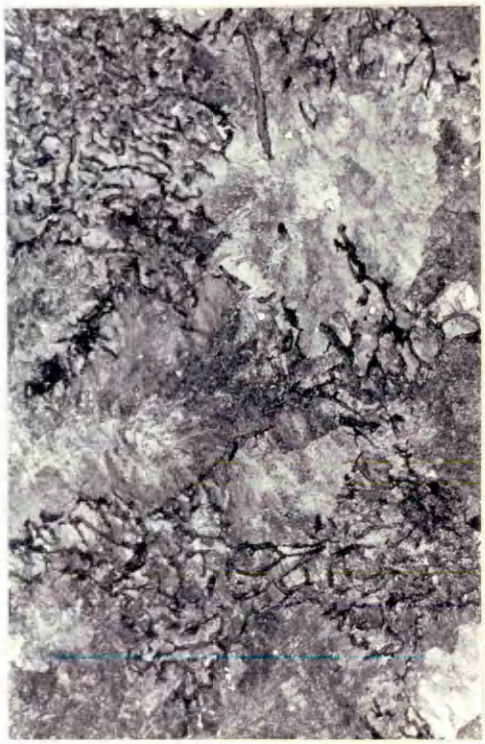


PLATE 175

C2' 177.8mm (24.6mm)

x 63

4.43°C/Min

PLATE 176

C3' 177.8mm (23.1mm)

x 16

4.43°C/Min

PLATE 177

D1' 63.5mm (23.6mm)

x 160

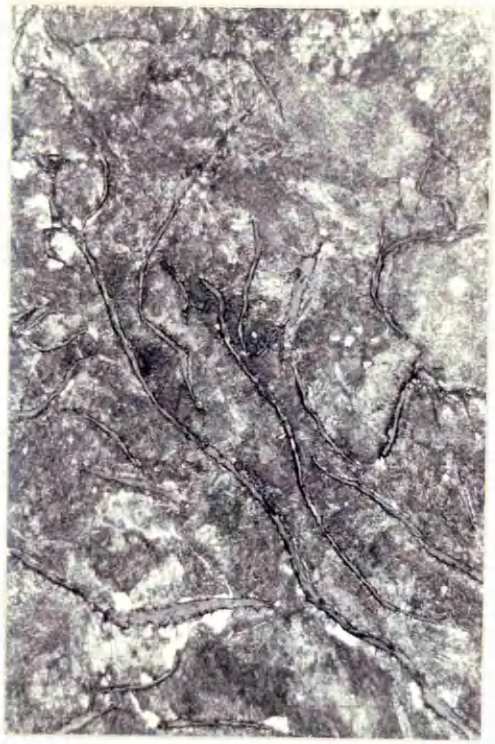
12.33°C/Min

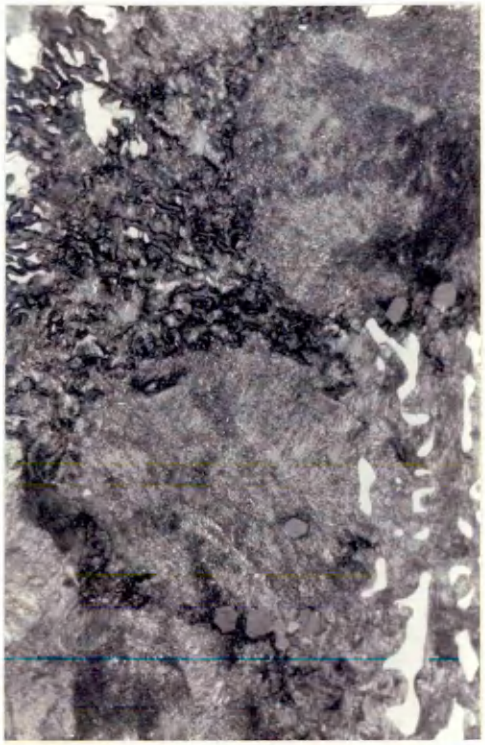
PLATE 178

D1' 63.5mm (19.05mm)

x 160

12.33°C/Min





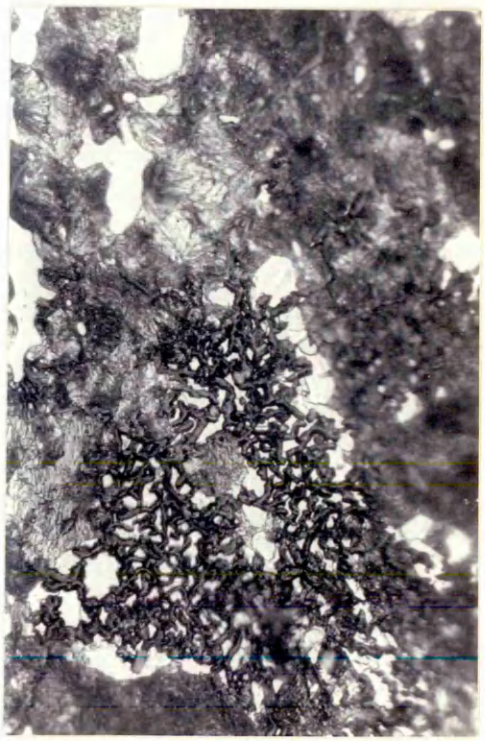


PLATE 179

D1' 89mm (15mm)

x 63

9.79°C/Min

PLATE 180

D1' 181.5mm (9.525mm)

x 160

4.32°C/Min

PLATE 181

D3' 89mm (8.5mm)

x 160

9.79°C/Min

PLATE 182

D3' 89mm (10mm)

x 160

9.79°C/Min

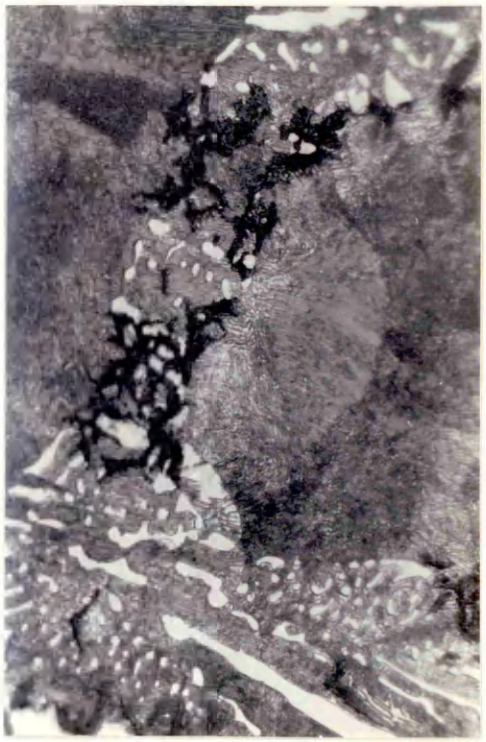


PLATE 183

D3'. 177.8mm (19.05mm)

x 16

4.43°C/Min

PLATE 184

F1'. 127.1mm (9.525mm)

x 63

6.28°C/Min

PLATE 185

F1'. 166.5mm (9.525mm)

x 160

4.76°C/Min

PLATE 186

F2'. 177.8mm (19.05mm)

x 16

4.43°C/Min

PLATE 187

F3'. 130.2mm (31.1mm)

x 160

6.14°C/Min

PLATE 188

F3'. 130.2mm (26.1mm)

x 160

6.14°C/Min

PLATE 189

F3'. 181mm (15.5mm)

x 63

4.35°C/Min

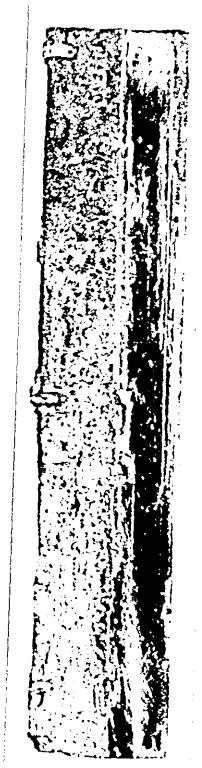
FRACTURED CASTINGS OF ADDITIONAL HIGH NITROGEN CASTS

PLATE 190

Cast B3a'

PLATE 191

Cast C2a'



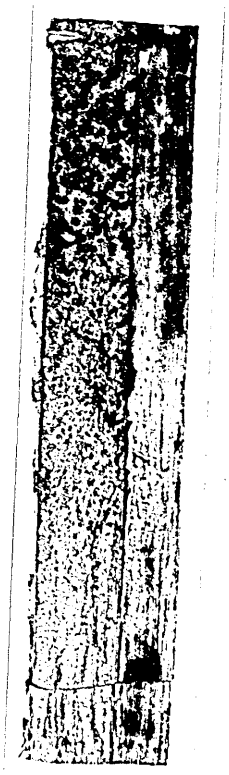


PLATE 193

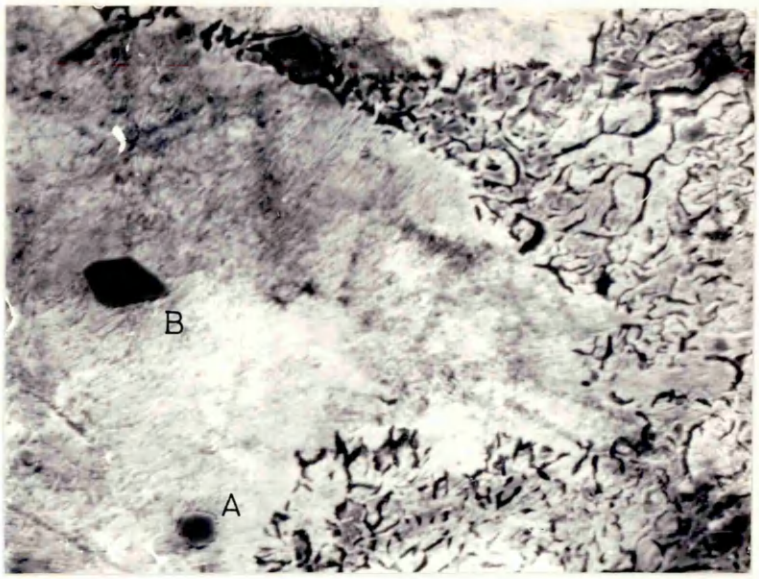
Melt G3 152.4 - 177.8mm x480

(a) Spectrum of Inclusion A shows the inclusion to be complex manganese titanium sulphide of the stoichiometry (Mn,Ti)S.

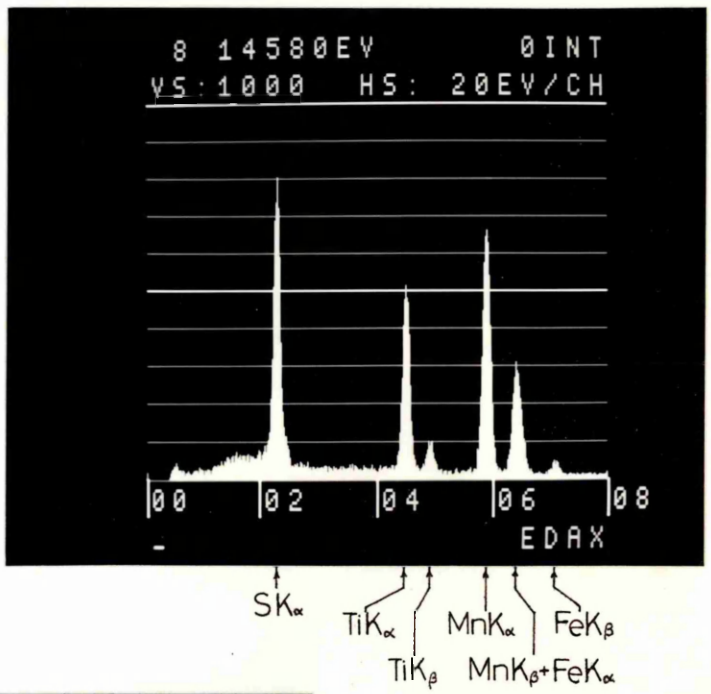
(b) Spectrum of Inclusion B shows :-

Sulphur integration peak height	6263
the background sulphur	397
	5866
Titanium integration peak height	12,120
the background titanium	340
	11,780

indicating a titanium : sulphur ratio of 2:1. Thus the stoichiometry of the titanium sulphide inclusion is Ti_2S.


B
A

(a)


8 14580EV 0INT
VS:1000 HS: 20EV/CH
00
02
04
06
08
EDAX
SKα
TiKα
TiKβ
MnKα
MnKβ+FeKα
FeKβ

(b)

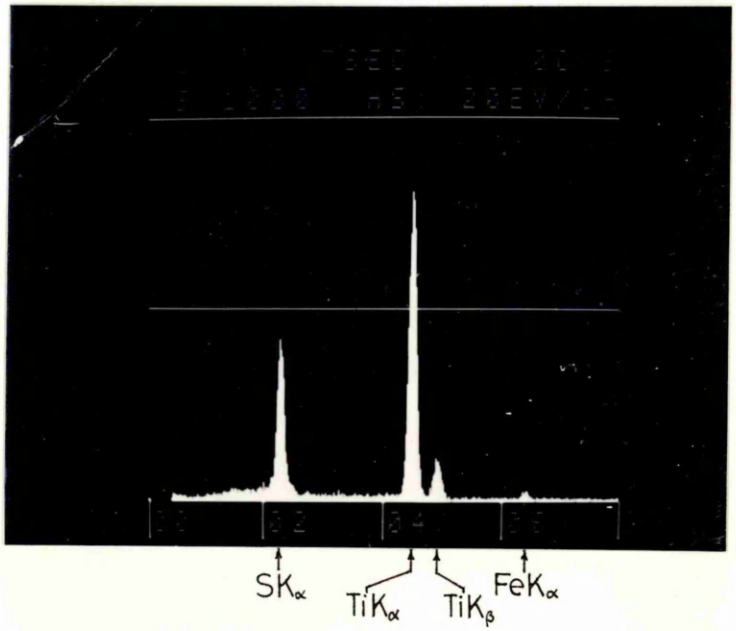
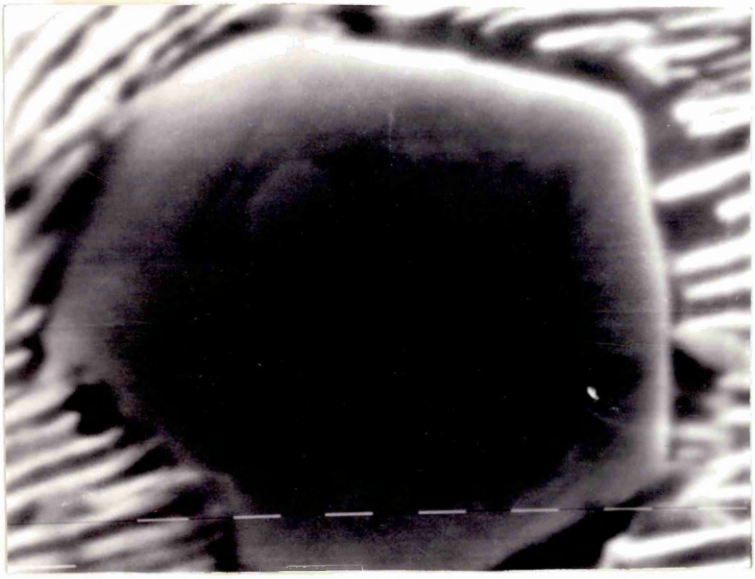

SKα
TiKα
TiKβ
FeKα

PLATE 194

Inclusion A from Plate 193. X8320



EDAX Scans for

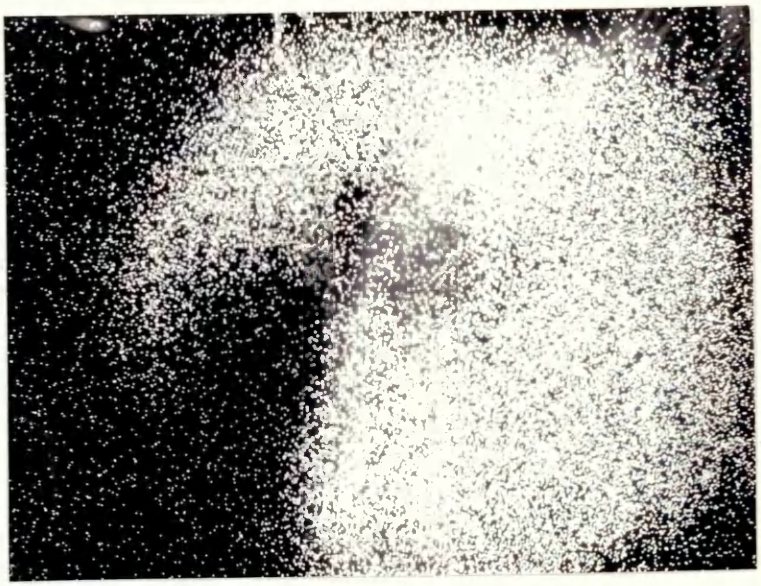
(a) Manganese

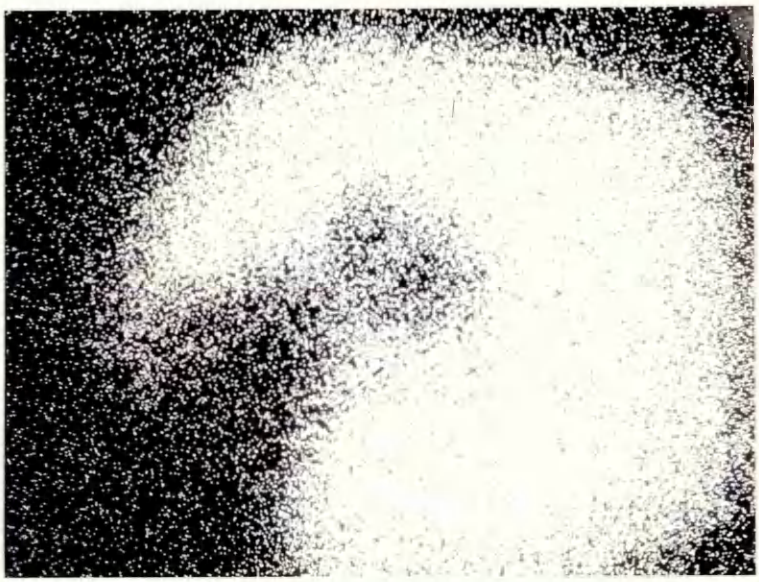
(b) Sulphur

(c) Titanium

Show the inclusion to be basically MnS with a complex titanium inclusion at the centre. This complex is both titanium sulphide and possibly titanium carbonitride, cyanonitride or carbosulphide.

(a)





(b)

(c)

PLATE 195

Inclusion B from Plate 193. X 4160

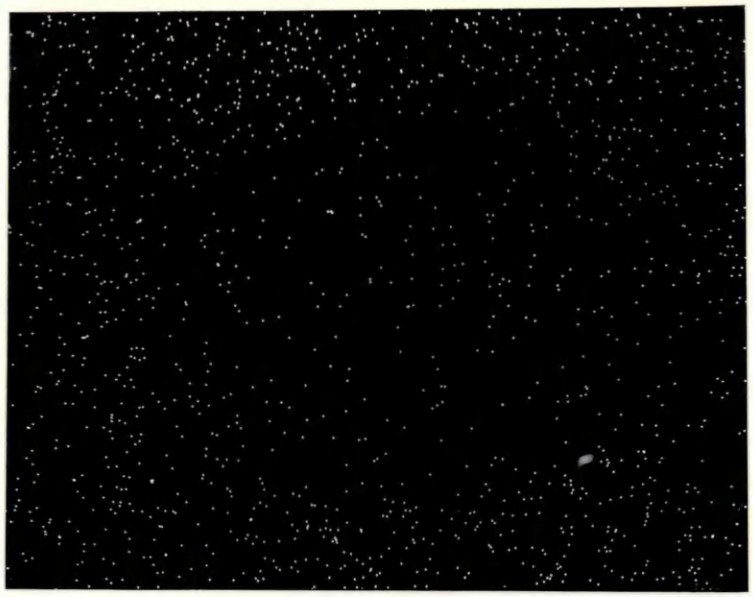
EDAX Scans for

(a) Manganese

(b) Sulphur

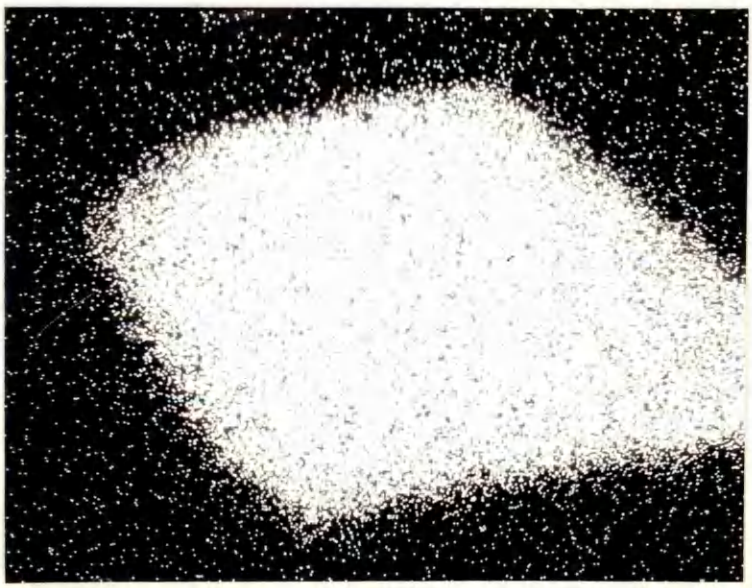
(c) Titanium

Confirm that Inclusion B is titanium sulphide of the Ti_2S configuration.



(a)

(b)



(c)

PLATE 196

G3 152.4mm - 177.8mm X 8320

EDAX scans for:

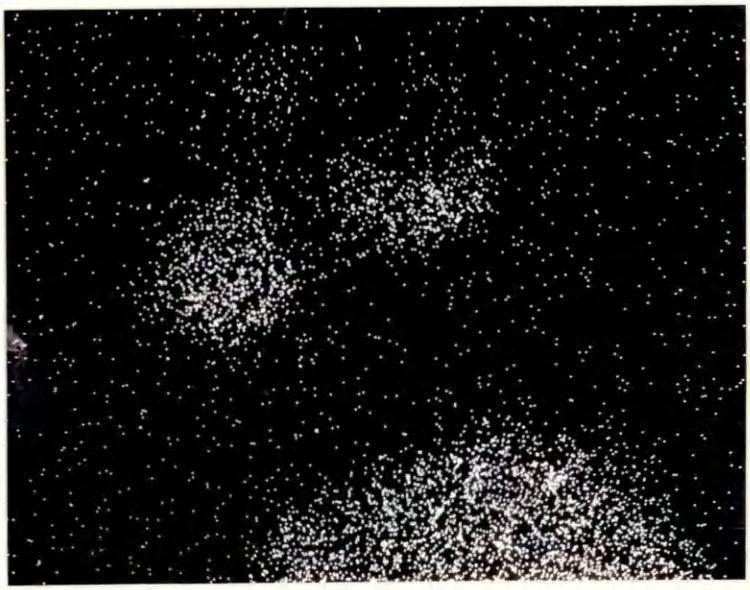
(a) Manganese

(b) Sulphur

(c) Titanium

Show three MnS, one duplexed (TiMn)S and the rest complex titanium inclusions, in a pearlitic matrix.

(a)



(b)

(c)

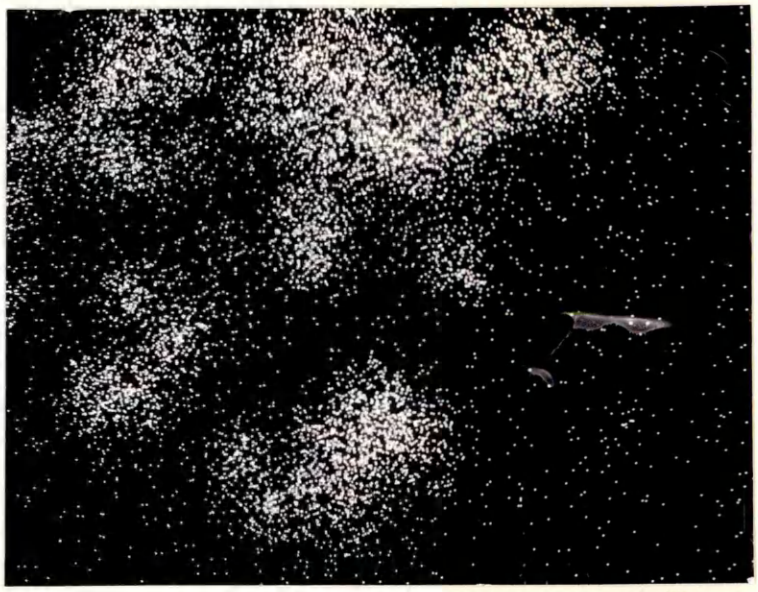


PLATE 197

G3 152.4mm - 177.8mm. X 480

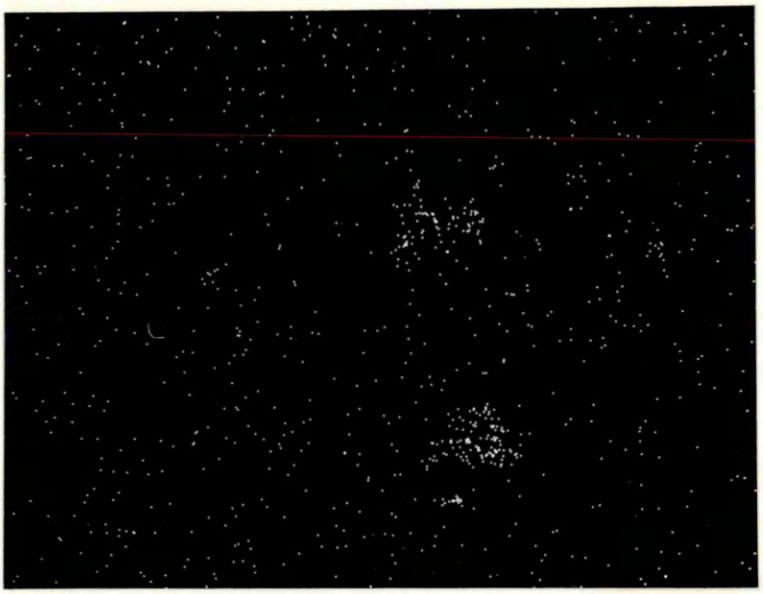
EDAX Scans for

(a) Manganese

(b) Sulphur

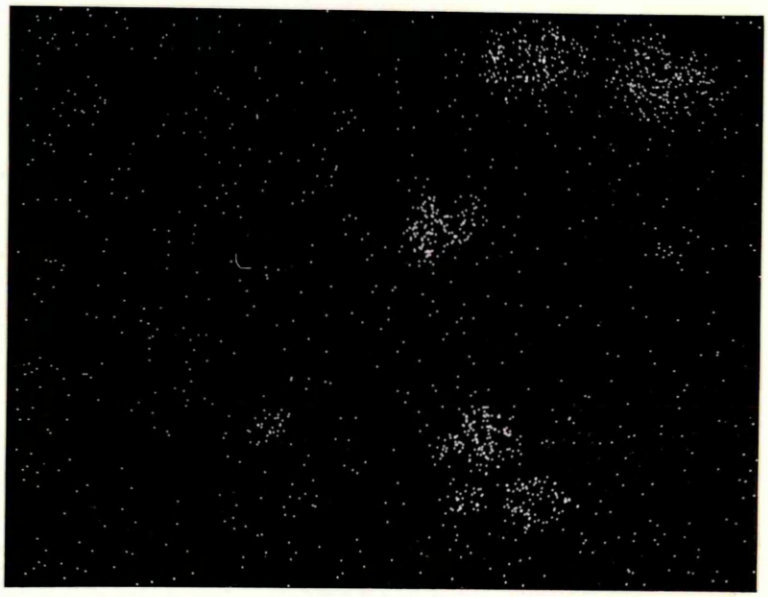
(c) Titanium

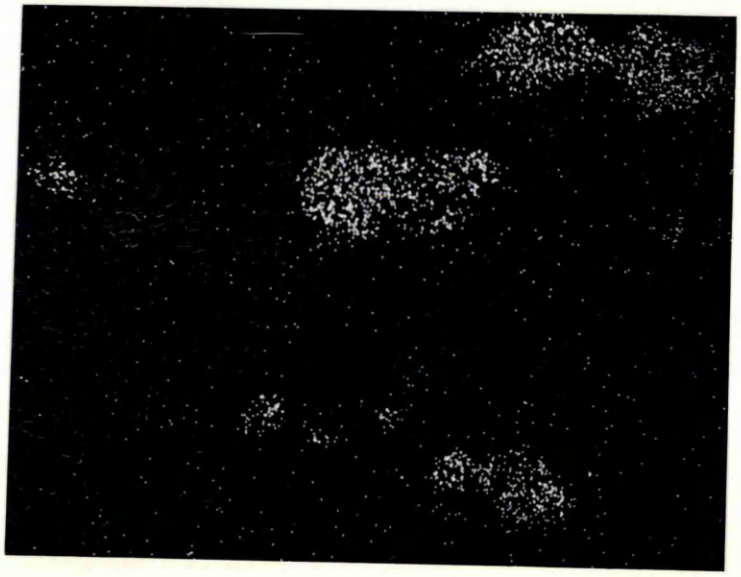
Show one MnS, one duplexed (MnTi)S, four Ti_2S and complex titanium inclusions in pearlite and associated with graphite.



(a)

(b)

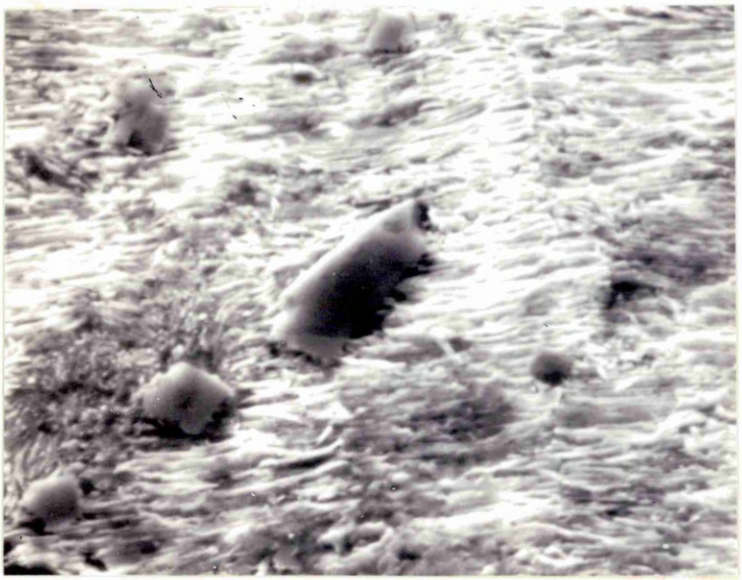




(c)

PLATE 198

G3 152.4mm - 177.8mm. X2080



EDAX Scans for

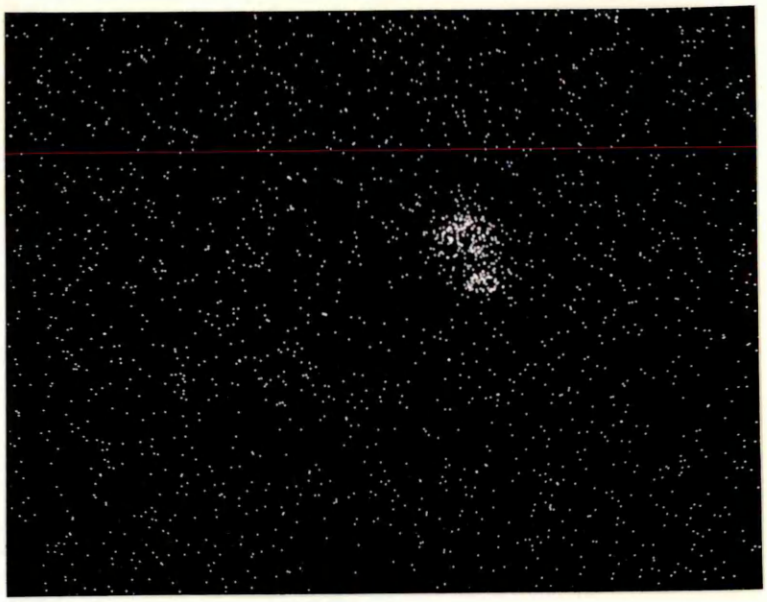
(a) Manganese

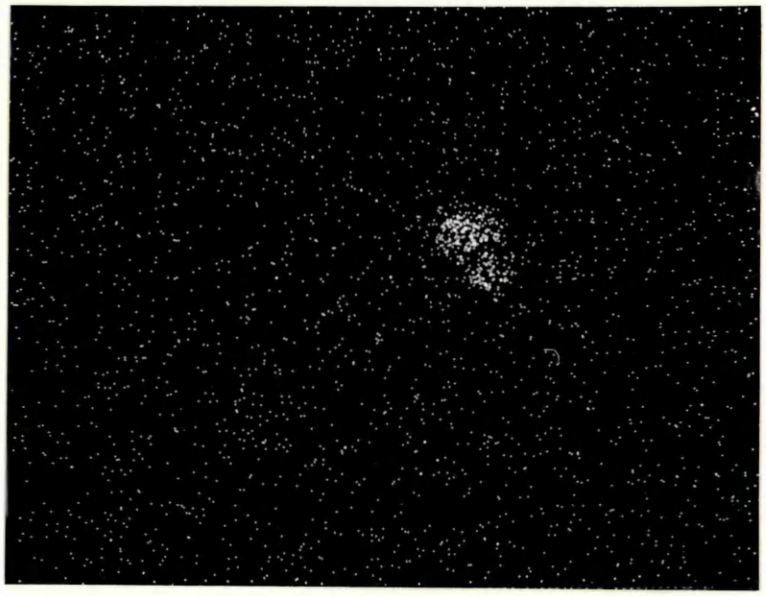
(b) Sulphur

(c) Titanium

Show one MnS and seven complex titanium inclusions in a pearlitic matrix.

(a)





(b)

(c)

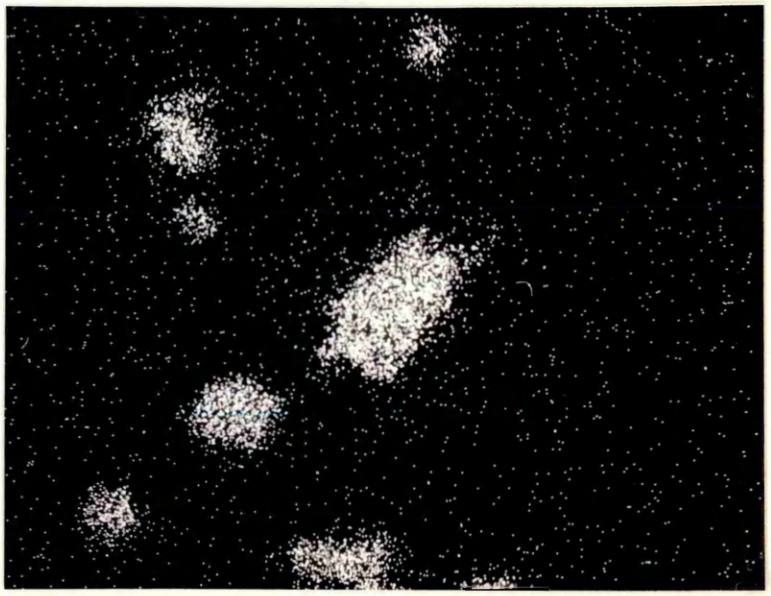
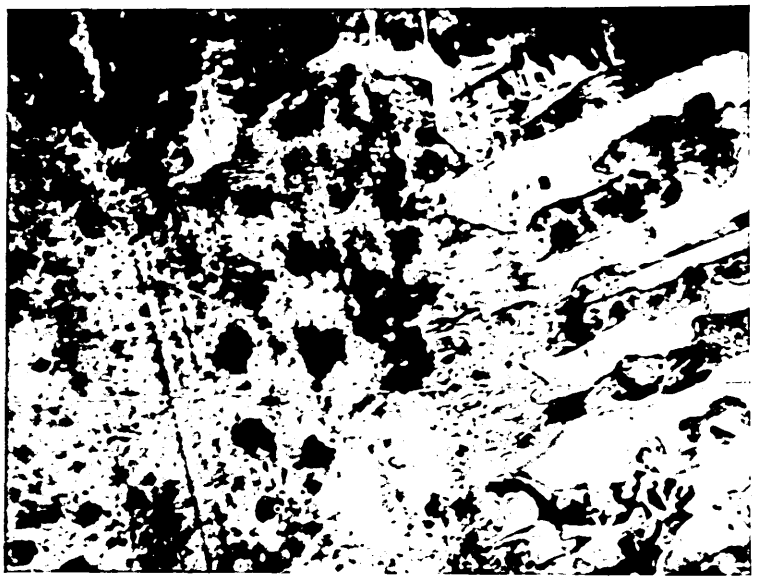


PLATE 199

F3' 177.8mm X 520



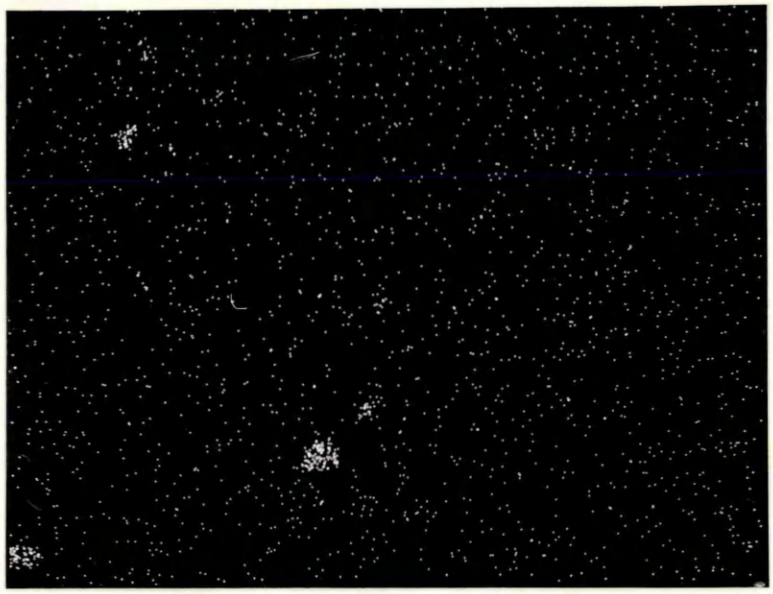
EDAX Scans for

(a) Manganese

(b) Sulphur

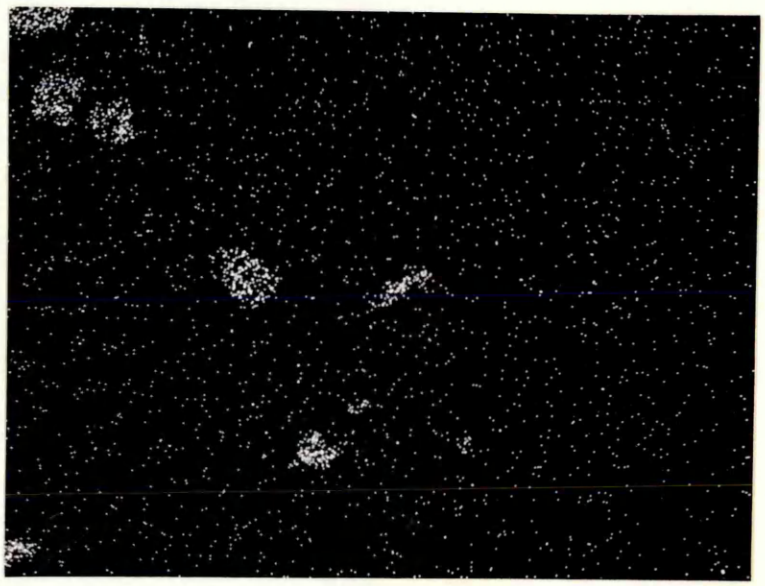
(c) Titanium

Show five Ti_2S, two duplexed (MnTi)S, one MnS and complex titanium inclusions in both pearlite and cementite with some graphite.



(a)

(b)



(c)

PLATE 200

F3' 163mm. X 520

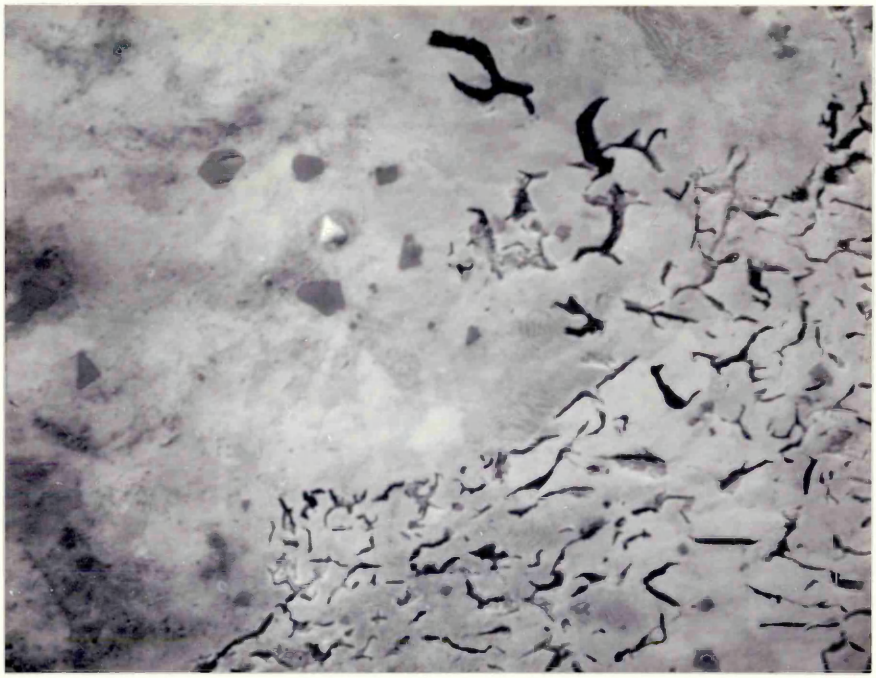
EDAX Scans for

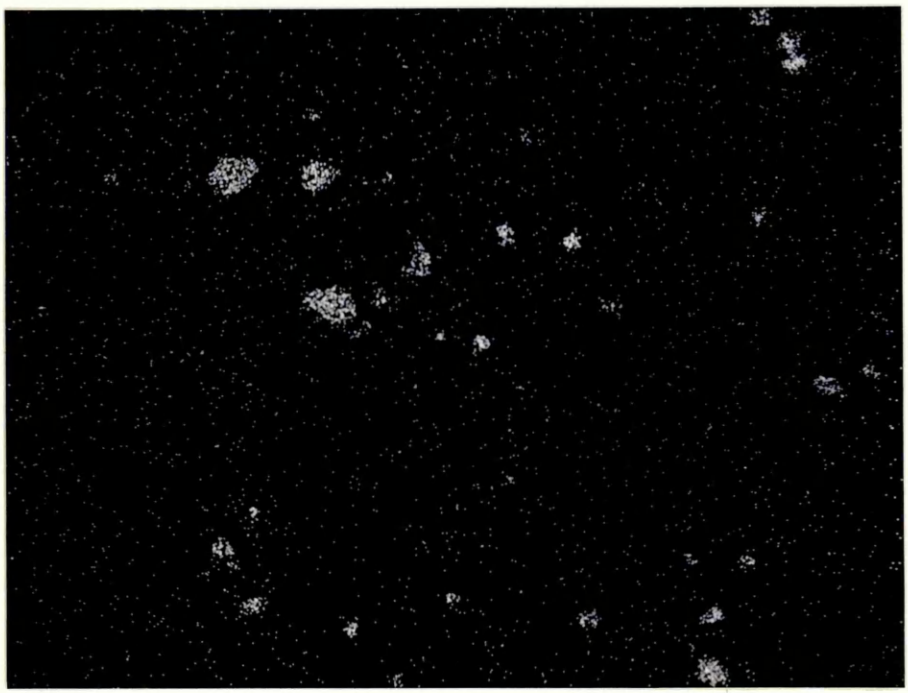
(a) Manganese

(b) Sulphur

(c) Titanium

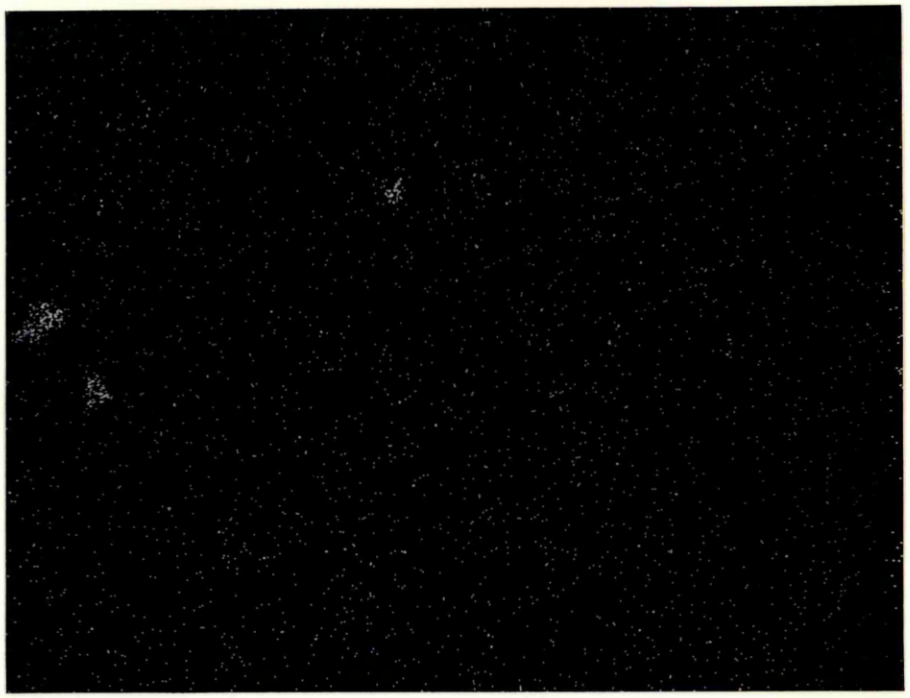
Show three MnS, four Ti_2S and thirty one complex titanium inclusions in a pearlitic matrix with 'D' type and a few compacted graphite flakes in the interdendritic spaces.

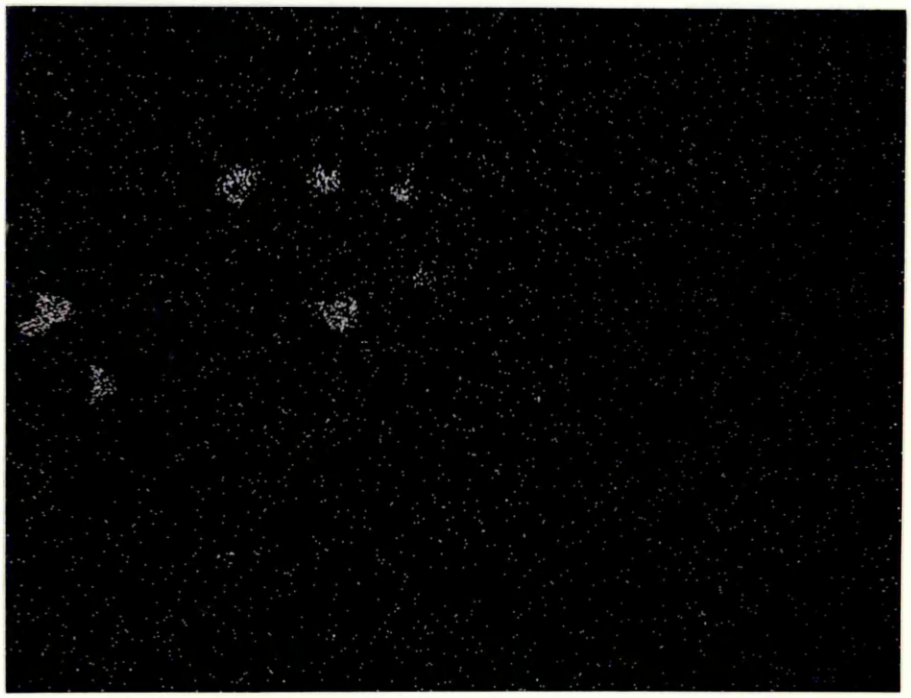




(c)

(a)





(b)

PLATE 201

F3' 163mm. X520

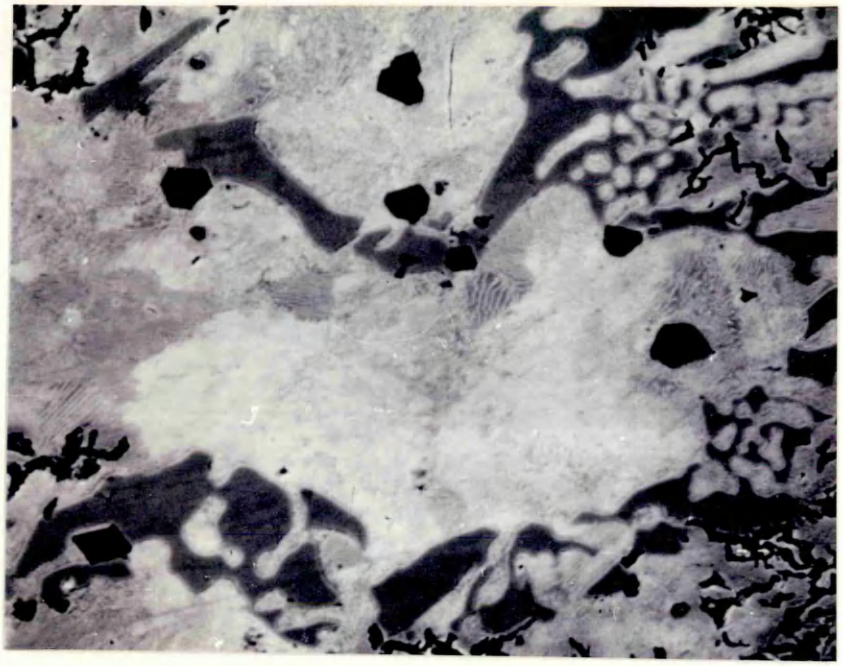
EDAX Scans for

(a) Manganese

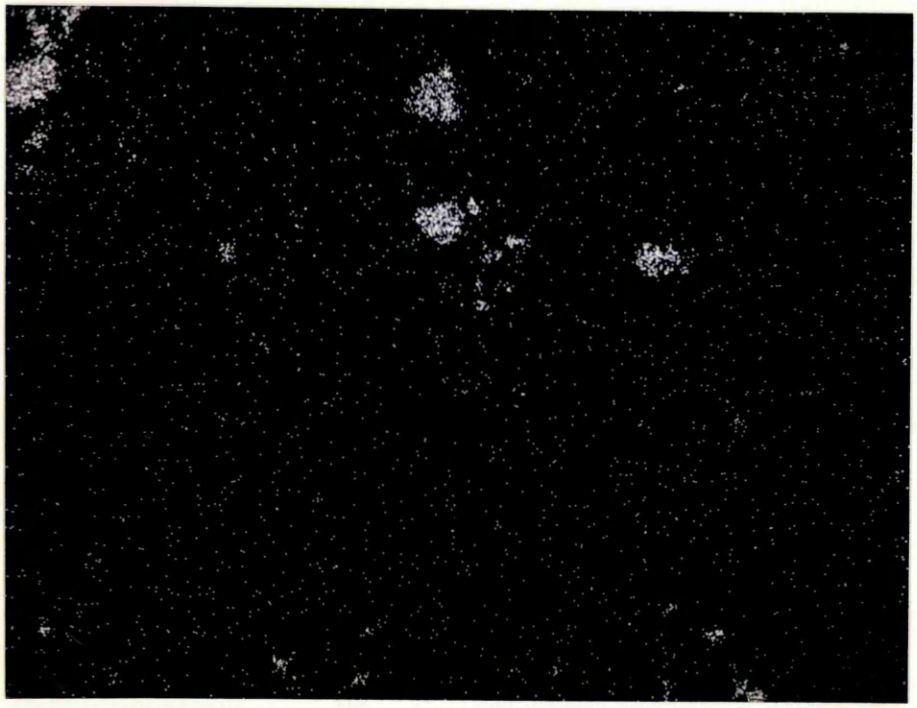
(b) Sulphur

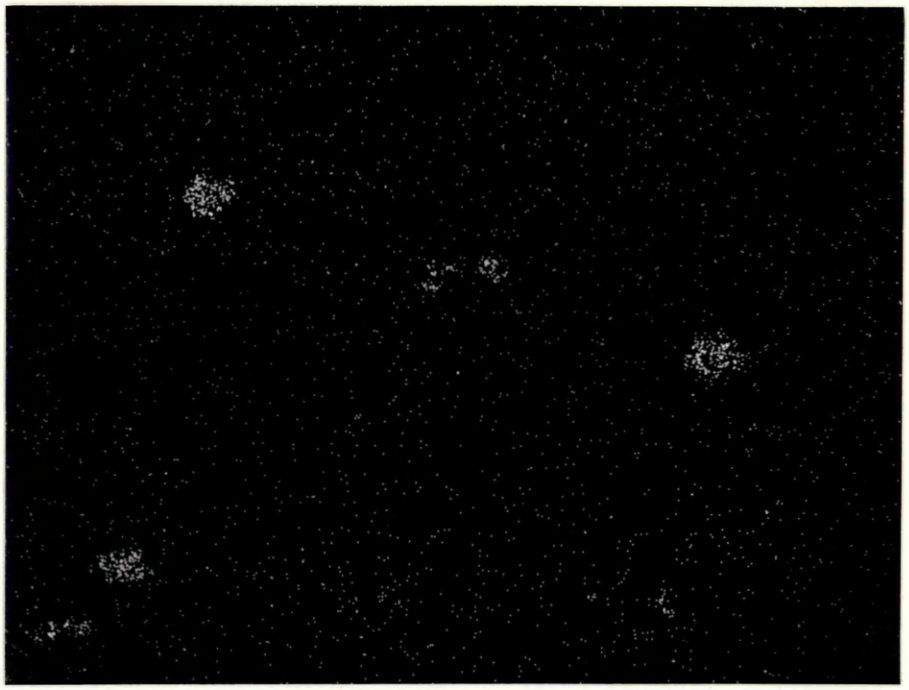
(c) Titanium

Shows seven MnS, four Ti_2S, two duplexed (TiMn)S and thirteen complex titanium inclusions in a ledeburitic matrix with 'D' type streamer graphite. The inclusions are mainly in the pearlite but some are visible in the cementite. None appear to be associated with the graphite.



(c)





(a)

(b)

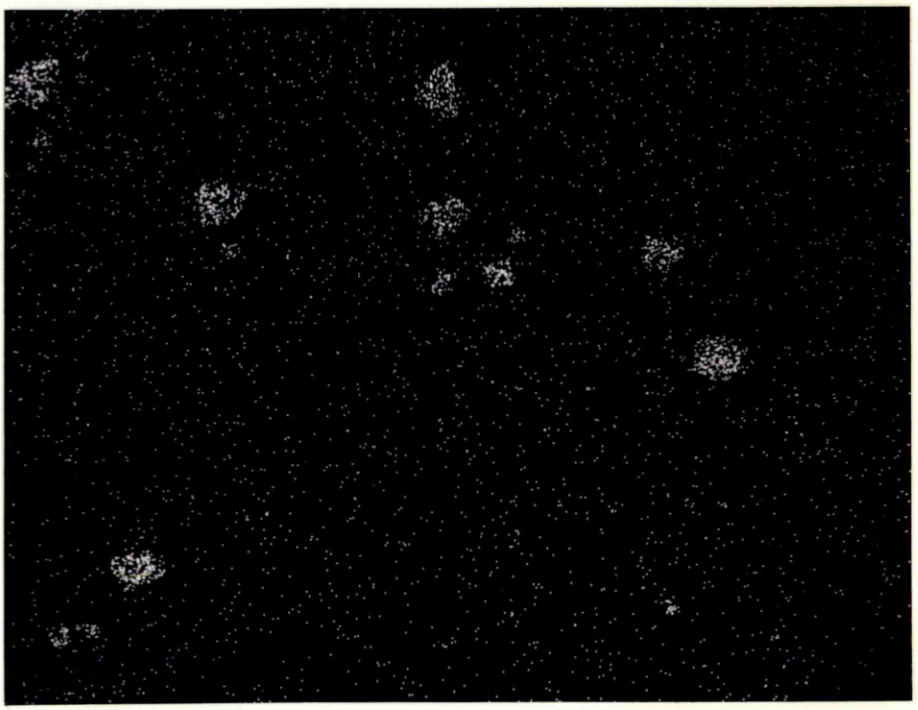


PLATE 202

F3' 127.1mm X 1040

EDAX scans for:

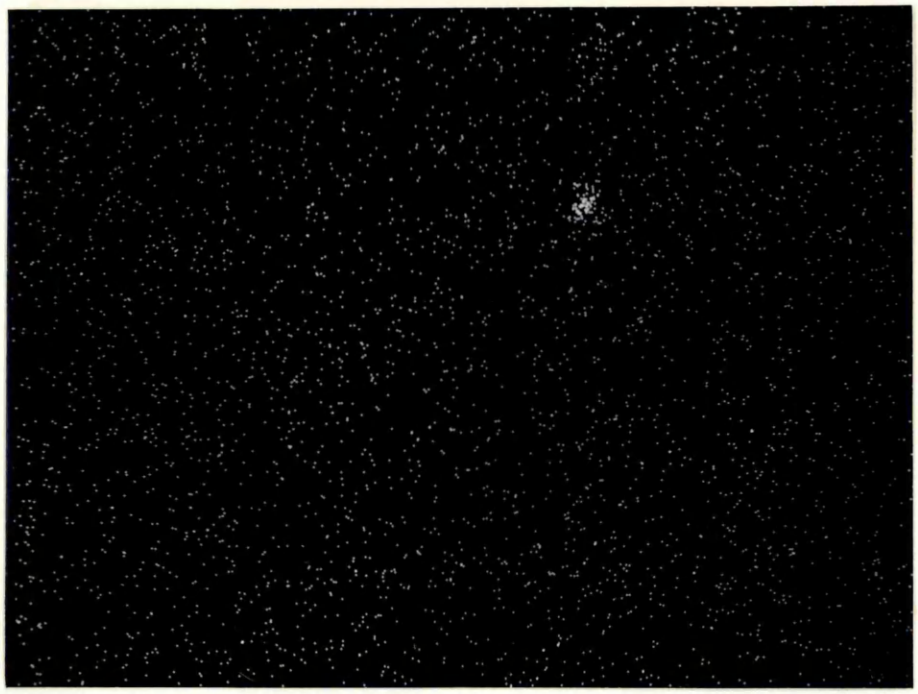
(a) Manganese

(b) Sulphur

(c) Titanium

Show one MnS and ten complex titanium inclusions both in a cementite and a pearlite matrix.

(c)



(a)

(b)

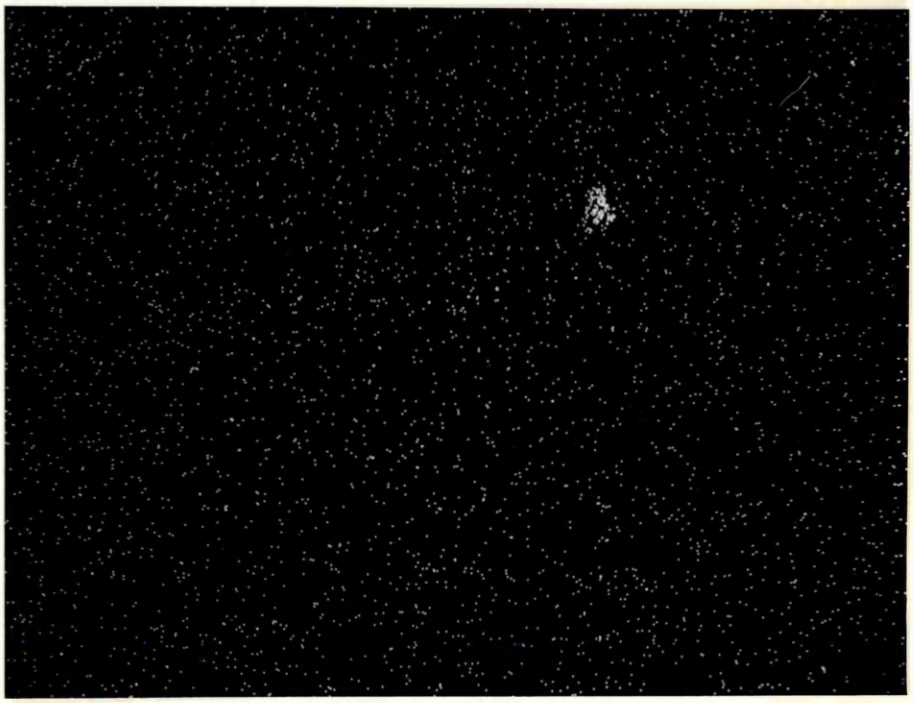


PLATE 203

B1' 166mm. X 130

This shows Ti_2S, MnS and complex titanium inclusions and represents the overall area of which a specific, central area is shown in Plate 204.

PLATE 204

Enlargement of a central region in Plate 203. X 2080

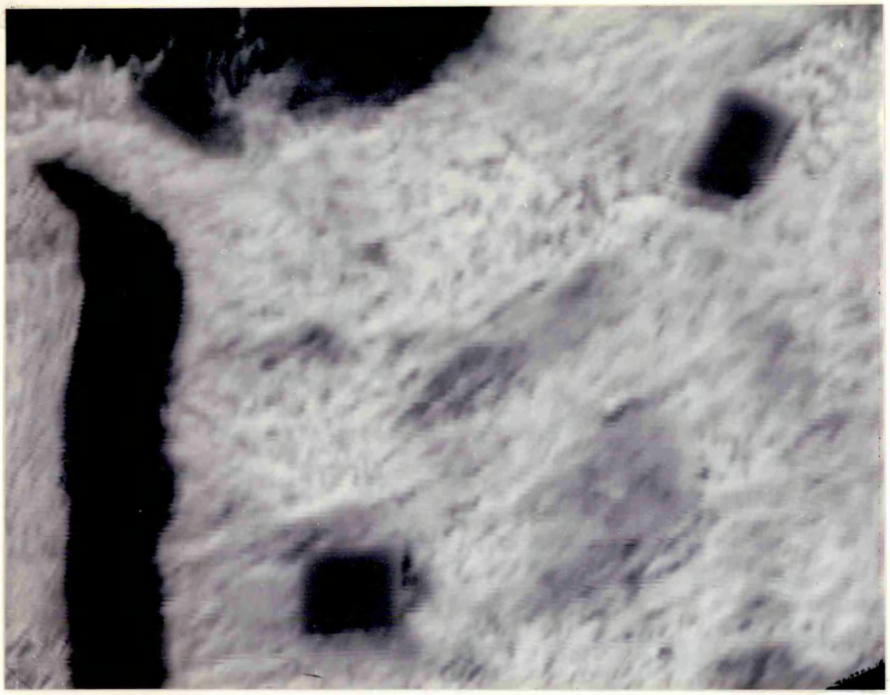
EDAX Scans for

(a) Manganese

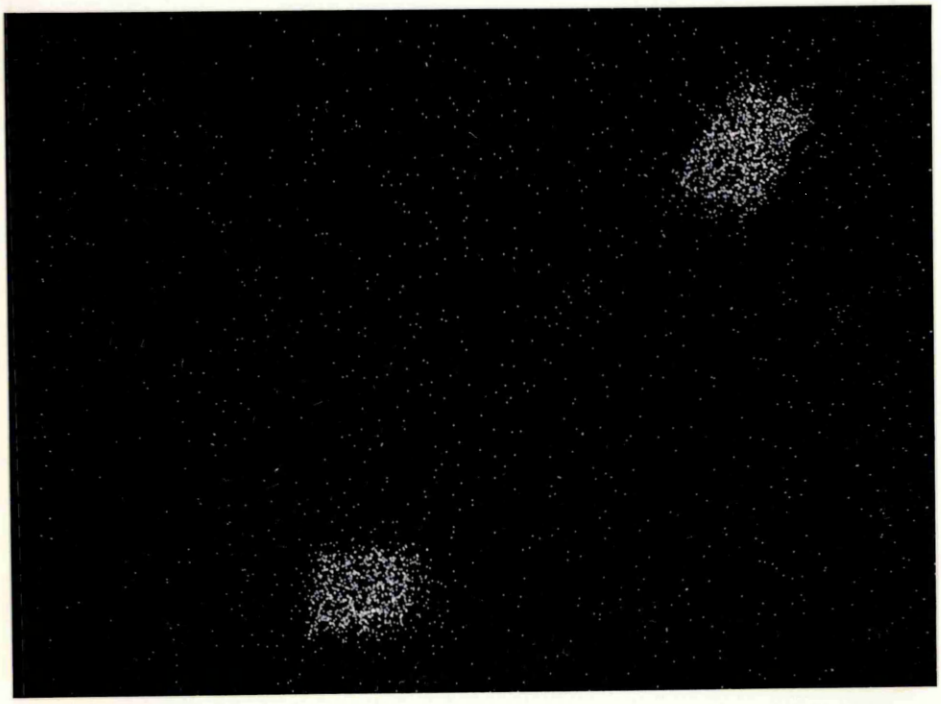
(b) Sulphur

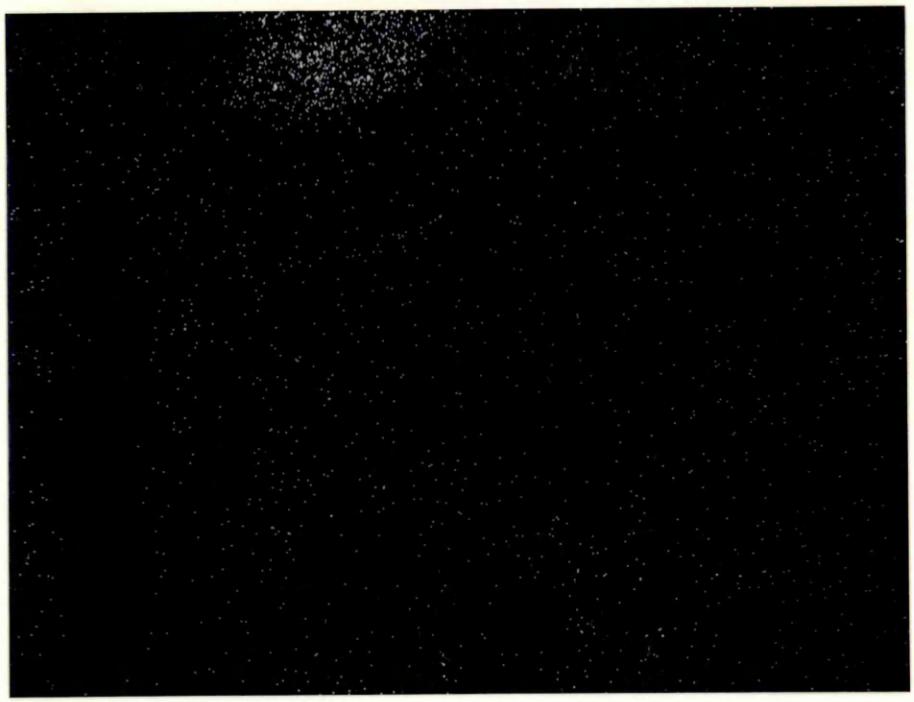
(c) Titanium

Show one MnS and two complex titanium inclusions in a pearlitic matrix.



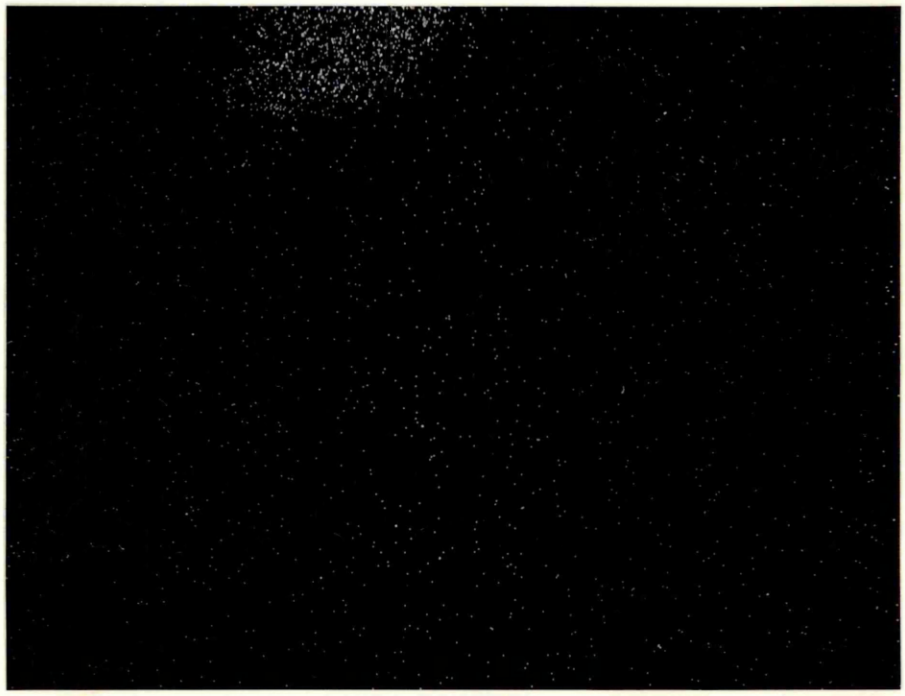
(c)





(a)

(b)



EQUIVALENT COOLING RATES (°C/MIN) FOR THE LOW NITROGEN CASTS MICROSTRUCTURAL CRITERIA GIVEN IN TABLE 20 FOR THE 1160-1100°C TEMPERATURE RANGE

Sulphur Level	Cast Groups					
	A	B	C	E	F	G
1	123.97	123.97	47.86	25.62	25.62	25.62
2	123.97	48.10	48.10	25.62	25.62	48.10
3	43.65	25.62	46.24	38.02	123.97	40.74

Table 23a Streamer Graphite Start

Sulphur Level	Cast Groups					
	A	B	C	E	F	G
1	48.10	25.62	32.36	21.88	12.33	10.96
2	48.10	18.84	25.62	11.22	11.75	25.62
3	12.33	12.33	25.62	12.33	18.20	18.20

Table 23b 'Grey' Start

Sulphur Level	Cast Groups					
	A	B	C	E	F	G
1	12.33	12.16	9.79	6.28	6.28	5.89
2	12.33	10.96	12.33	5.69	7.03	6.28
3	11.22	7.85	9.55	6.28	6.28	6.28

Table 23c Graphitic Eutectic Cell Start

EFFECT OF TITANIUM ADDITIONS ON THE SOLIDIFICATION MODE (°C/MIN)

	A	B	C	E	F	G
1	123.97	123.97	47.86	25.62	25.62	25.62
2	123.97	48.10	48.10	25.62	25.62	48.10
3	43.65	25.62	46.24	38.02	123.97	40.74
	I	II		III		

Table 24a 'Streamer' Graphite Start

	A	B	C	E	F	G
1	48.10	25.62	32.36	21.88	12.33	10.96
2	48.10	18.84	25.62	11.22	11.75	25.62
3	12.33	12.33	25.62	12.33	18.20	18.20
	I	II		III		

Table 24b 'Grey' Start

	A	B	C	E	F	G
1	12.33	12.16	9.79	6.28	6.28	5.89
2	12.33	10.96	12.33	5.69	7.03	6.28
3	11.22	7.85	9.55	6.28	6.28	6.28
	I	II		III		

Table 24c Graphitic Eutectic Cell Start

	A	B	C	E	F	G
1	A	D	A/D	D	D	D
2	A	A/D	A/D	D	D/Deg.	D/Deg.
3	A/D	A/Mesh & Dpred.	A/D	D	Dpred/A/Deg.	D/Deg.
	I	II		III		

Table 24d Graphite Type at 177.8mm

EQUIVALENT COOLING RATES (°C/MIN) FOR THE HIGH NITROGEN CASTS' MICROSTRUCTURAL CRITERIA IN TABLE 22 FOR THE 1160-1100°C TEMPERATURE RANGE

Sulphur Level	Cast Group				
	A'	B'	C'	D'	F'
1	48.10	25.62	92.26	95.50	25.62
2	48.10	48.10	123.97	-	25.62
3	40.74	100.00	63.10	48.10	41.69

Table 25a 'Streamer' Graphite Start

Sulphur Level	Cast Group				
	A'	B'	C'	D'	F'
1	23.99	9.79	25.62	25.12	-
2	22.91	25.62	25.62	-	-
3	12.33	25.62	25.62	15.14	6.17

Table 25b 'Grey' Start

Sulphur Level	Cast Group				
	A'	B'	C'	D'	F'
1	9.79	8.00	12.33	9.79	6.28
2	9.79	12.33	12.33	-	7.94
3	6.28	9.79	9.44	9.79	6.17

Table 25c Graphitic Eutectic Cell Start

TABLE 25 SUBDIVIDED INTO GENERAL GROUPS ACCORDING TO THE EFFECT OF Ti ADDITIONS ON THE SOLIDIFICATION MODE (°C/Min)

	A′	B′	C′	D′	F′
1	48.10	25.62	92.66	95.50	25.62
2	48.10	48.10	123.97	-	25.62
3	40.74	100.00	63.10	48.10	41.69
	I	II			III

Table 26a 'Streamer' Graphite Start

	A′	B′	C′	D′	F′
1	23.99	9.79	25.62	25.12	-
2	22.91	25.62	25.62	-	-
3	12.33	25.62	25.62	15.14	6.17
	I	II			III

Table 26b 'Grey' Start

	A′	B′	C′	D′	F′
1	9.79	8.00	12.33	9.79	6.28
2	9.79	12.33	12.33	-	7.94
3	6.28	9.79	9.44	9.79	6.17
	I	II			III

Table 26c Graphitic Eutectic Start

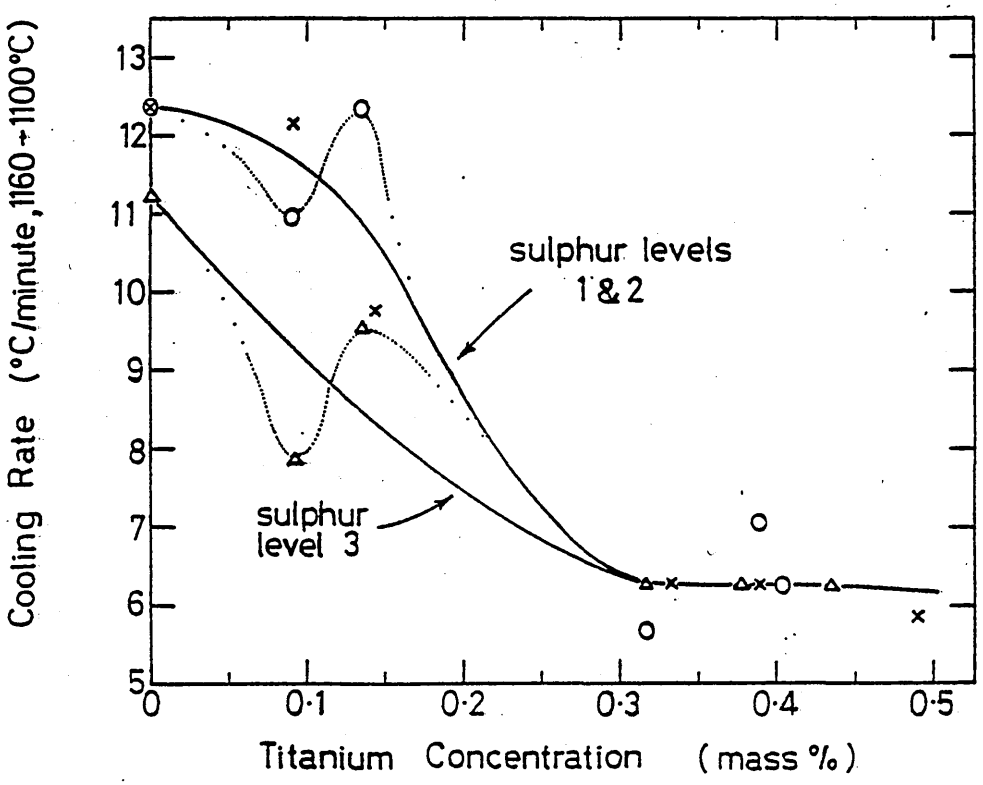
	A′	B′	C′	D′	F′
1	A	D/Deg.	Deg & A	Apred/D/ Deg.	Deg.
2	A	Apred/D	Apred/D	-	Deg./ D
3	A & Deg. Broad	A/D/Deg./ Mesh	Dpred/A	A & Broad D	Deg.
	I	II			III

Table 26d Graphite Type at 177.8mm

Figure 63 : The effect of titanium concentration on the maximum cooling rate for the formation of graphitic eutectic cells.

Sulphur Concentration :- × : level 1
o : level 2
△ : level 3

(a) 'Low' nitrogen castings :



(b) 'High' nitrogen castings :

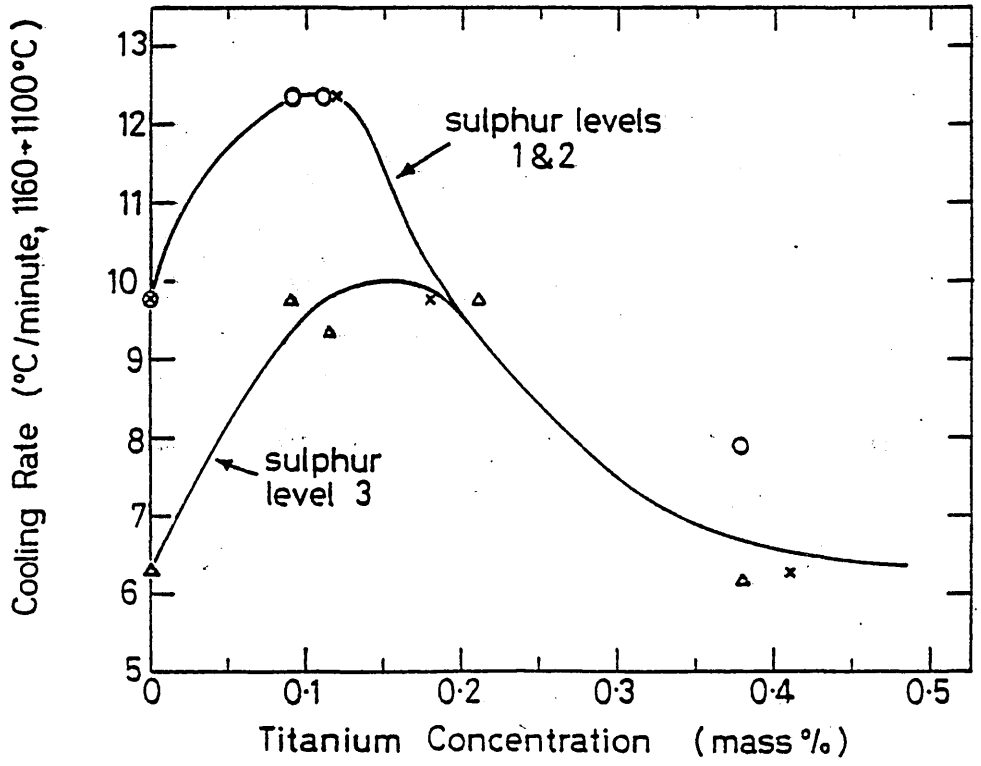
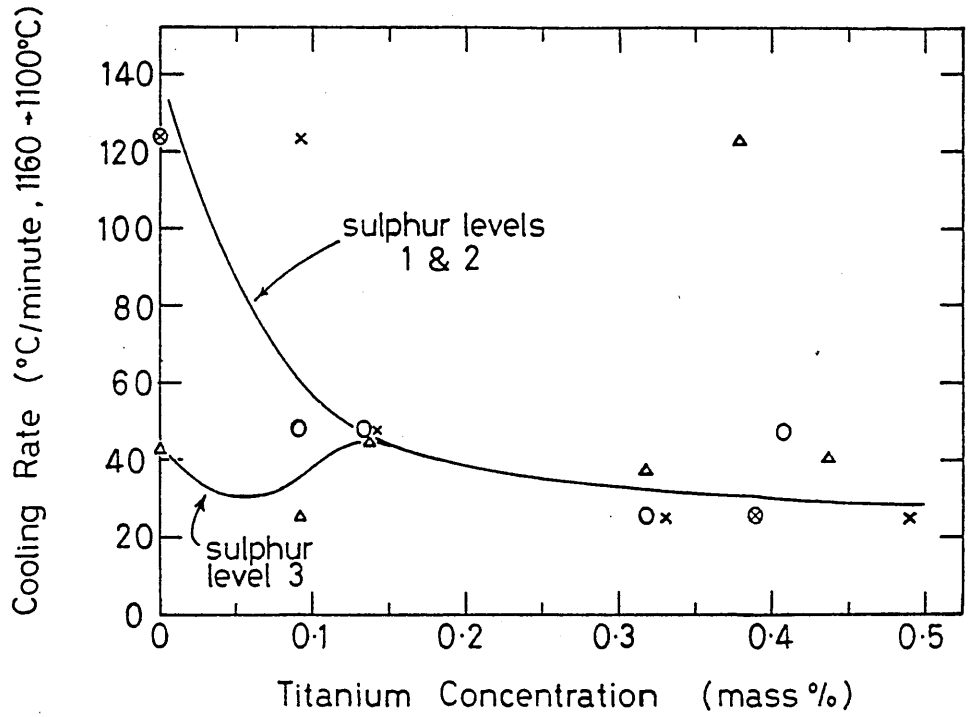


Figure 64 : The effect of titanium concentration on the maximum cooling rate for the formation of streamer graphite.

Sulphur Concentration :- x : level 1
o : level 2
Δ : level 3

(a) 'Low' nitrogen castings :



(b) 'High' nitrogen castings :

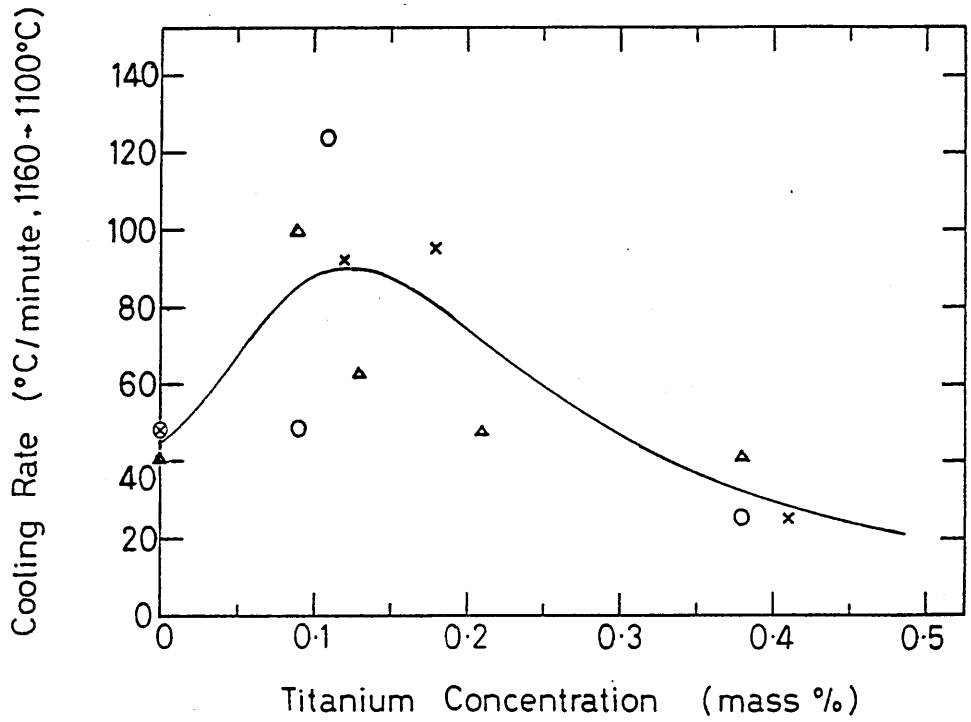
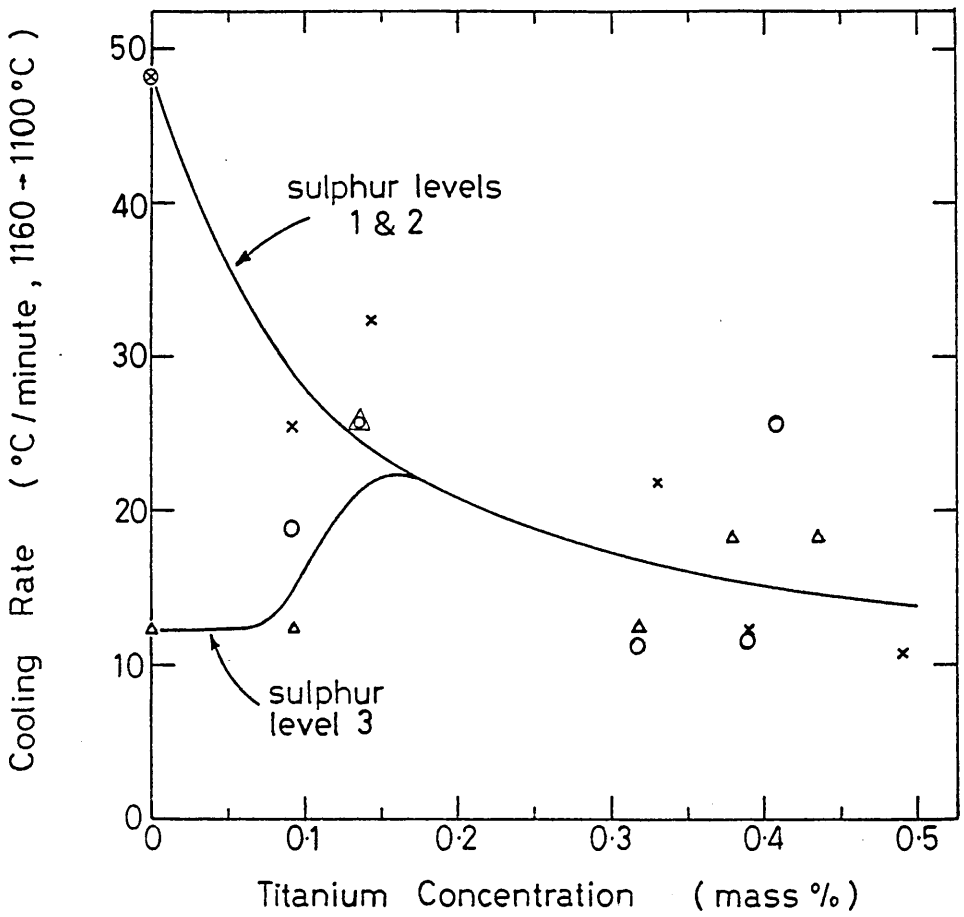


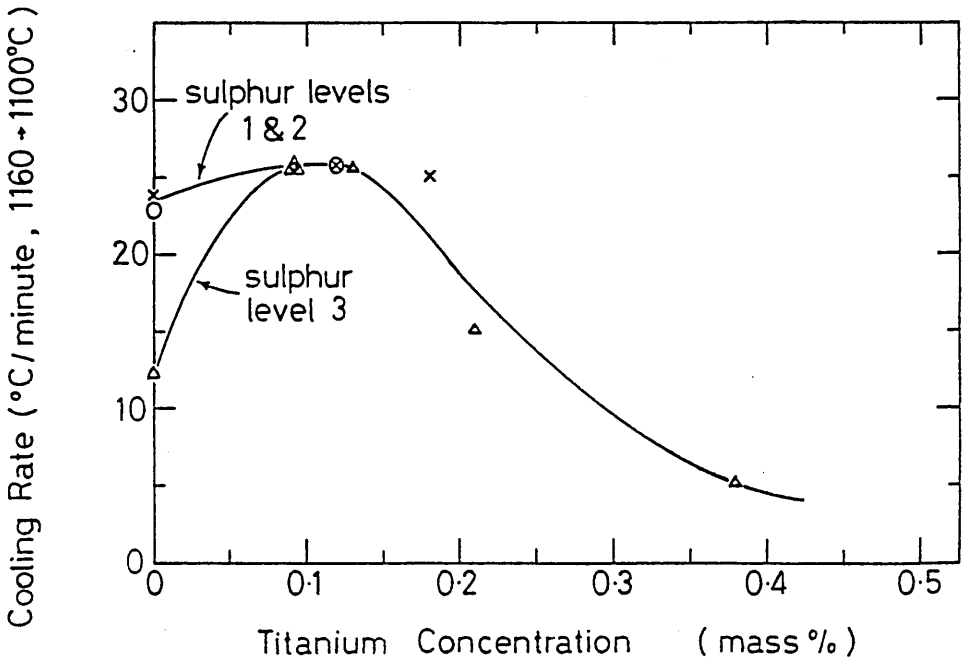
Figure 65 : The effect of titanium concentration on the maximum cooling rate for the 'grey' start.

Sulphur Concentration :- × : level 1
o : level 2
△ : level 3

(a) 'Low' nitrogen castings :



(b) 'High' nitrogen castings :



EQUIVALENT COOLING RATES (°C/Min) FOR THE MICROSTRUCTURAL CRITERIA FOR THE ADDITIONAL CASTS IN TABLE 21 FOR THE 1160-1100°C TEMPERATURE RANGE

Criteria	A1a	A1b	A1c	E1a	E3a	F2a
a) Streamer Start	91.20	<123.97>48.1	-	123.97	12.33	48.10
b) 'Grey' Start	16.03	72.44	-	12.33	4.43	16.98
c) Graphitic Cell Start	11.48	18.16	-	6.28	-	8.433
d) Graphite Type at 177.8mm	Pred D/A	Pred D/A	Large A	D & Deg	D&Deg	D

Table 27a Low Nitrogen Additional Casts

Criteria	A1a'	B3a'	C2a'
(a) Streamer Start	48.1	48.1	123.97
(b) 'Grey' Start	25.62	12.33	25.62
(c) Cell Start	4.43	6.427	6.28
(d) Graphite Type at 177.8mm	A/V.little D	A/V.little D	Fine A/Deg.D

Table 27b High Nitrogen Additional Casts

EQUIVALENT COOLING RATES (°C/Min) FOR THE MICROSTRUCTURAL CRITERIA FOR THE LOW NITROGEN CASTS IN TABLE 20 FOR THE 1160 - 700°C TEMPERATURE RANGE

	A	B	C	E	F	G
1	35.97	35.97	18.20	11.83	11.83	11.83
2	35.97	18.59	18.59	11.83	11.83	18.59
3	17.38	11.83	18.11	15.56	35.97	16.60
	I	II		III		

Table 28a 'Streamer' Graphite Start

	A	B	C	E	F	G
1	18.59	11.83	13.80	31.62	9.67	9.33
2	18.59	21.88	11.83	9.441	9.036	11.83
3	9.67	9.67	11.83	9.67	17.78	24.55
	I	II		III		

Table 28b 'Grey' Start

	A	B	C	E	F	G
1	9.67	9.55	8.81	7.78	7.78	7.586
2	9.67	9.162	9.55	7.551	8.035	7.78
3	9.33	8.299	8.71	7.78	7.78	7.78
	I	II		III		

Table 28c Graphitic Cell Start

	A	B	C	E	F	G
1	A	D	A/D	D	D	D
2	A	A/D	A/D	D	D/Deg.	D/Deg.
3	A/D	A/D Pred/ Mesh	,A/D	D	Dpred/A/ Deg.	D/Deg.
	I	II		III		

Table 28d The Graphite Type at 177.8mm

EQUIVALENT COOLING RATES (°C/Min) FOR THE MICROSTRUCTURAL CRITERIA FOR THE HIGH NITROGEN CASTS IN TABLE 22 FOR THE 1160-700°C TEMPERATURE RANGE

	A'	B'	C'	D'	F'
1	18.59	11.83	18.62	19.14	11.83
2	18.59	18.59	35.97	-	11.83
3	16.52	31.62	22.91	18.54	16.75
	I	II			III

Table 29a 'Streamer' Graphite Start

	A'	B'	C'	D'	F'
1	11.48	8.81	11.83	11.64	-
2	11.40	11.83	11.83	-	-
3	9.67	11.83	11.83	10.07	7.709
	I	II			III

Table 29b 'Grey' Start

	A'	B'	C'	D'	F'
1	8.81	8.356	9.55	8.81	7.78
2	8.81	9.67	7.78	-	8.318
3	7.78	8.81	8.71	8.81	7.709
	I	II			III

Table 29c Graphitic Cell Start

	A'	B'	C'	D'	F'
1	A	D/Deg.	Deg. & A	>A & D/Deg.	Deg.
2	A	>A & D	>A & Bit D	-	Deg. D
3	A+Deg. / Broad D	A/D/Deg. / Mesh	>D & A	A & Broad D	Deg.
	I	II			III

Table 29d The Graphite Type Present at 177.8mm

Figure 66 : The manganese-sulphur equilibria for the liquid ingot mould cast iron, from Appendix 2.