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by

EXTRACTION METALLURGY DIVISION

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SUMMARY

The combined shaft-electric furnace being developed in these laboratories has been found to be well suited for the melting of iron pellets produced by the SL-RN process. The pellets can be rapidly and efficiently preheated in the shaft, then injected into the furnace at controlled feed rates by hydraulically-operated rams.

When an excess of coke was present in the furnace the metal produced contained about 2.8% carbon. Attempts to produce low-carbon iron on a continuous basis were unsuccessful because of severe erosion of refractories.

In a 17.5 hr run in which the pellets were preheated in the shaft to about 490°C by combustion of natural gas, the total energy required was 843 kWh per ton of pellets. Of this total, 705 kWh was supplied as electrical energy in the furnace, the balance (138 kWh) represented the energy derived from the gas.

The rate of heat loss from the furnace was found to be 100 kWh/hr at 1380°C. Using this figure, projections indicate that SL-RN pellets could be melted in this furnace at a total energy requirement of about 725 kWh per ton, of which about 50% would be supplied in the shaft by combustion of natural gas, the balance would be supplied electrically in the furnace.

The above projection method, when applied to the experiment described in this report, indicated that the heat loss would be 348 kWh per ton. The observed heat loss was 352 kWh per ton. This close agreement strongly supports the validity of the projections made regarding the potential performance of this shaft-electric furnace for melting SL-RN pellets.

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BACKGROUND

A program to improve both the thermal and economic efficiency of electric arc furnaces has been in progress in these laboratories for several years. Thermodynamic and heat balance calculations suggested that preheating, and where applicable, prereducing the charge in the solid state offered the greatest hope of reducing the consumption of electrical energy. This is particularly true for those processes, such as the smelting of oxide ores, in which the off-gases produced contain substantial quantities of energy, provided this energy can be efficiently utilized for the preheating and/or prereduction of the ore. In other processes in which little off-gas is produced, it might often be economically desirable to utilize energy from fossil fuel for preheating and prereduction. In most locations fossil fuel energy is much cheaper than electrical energy.

A shaft furnace was chosen as the preheating and/or prereducing unit for two reasons. 1) This style of furnace is noted for its high efficiency in transferring heat from a gas to a solid. 2) The fact that the solids travel through this furnace by gravity makes it comparatively simple to attach to another unit, in this case an electric arc furnace.

It was realized that the solid burden must be free-flowing and relatively closely sized for the shaft to operate successfully but it was believed that modern pelletizing techniques which are being used on an ever increasing scale in the iron ore industry would produce a satisfactory feed for this type of equipment.

The early work was directed mainly toward developing the combined shaft-electric furnace for the smelting of oxide ores. In the autumn of 1964 the Steel Company of Canada requested that the experimental program be enlarged to include an investigation of the melting of SL-RN pellets. The Department agreed to include this investigation, the major objectives of which were to be as follows:

1. To determine whether SL-RN pellets could be successfully melted by this process, with particular reference to the flow of materials through the equipment, and heat transfer problems.

2. To determine what grades of iron, from high-carbon to low-carbon, could be made.

3. To obtain as much quantitative information as possible about the operation, particularly regarding the energy requirements.

EXPERIMENTAL

The shaft-electric furnace underwent some modification during this investigation. Most of these modifications were connected with the achievement of the first objective and will be discussed in more detail under that heading. The arrangement in use at the end of the tests is shown in Figure 1. The pellets were fed down the shaft, past the preheat combustion box, and were pushed into the furnace by the rams. The hot gases from the burner were drawn up through the downcoming pellets by suction applied to the exhaust line. The rate of feed of hot pellets to the furnace was controlled by the frequency of the ram strokes.

In most experiments coke was fed with the pellets to reduce the small amount of iron oxide present in the pellets and to provide carbon to be dissolved in the iron. Since the pellets contained small quantities of predominantly siliceous gangue, some limestone was fed to adjust the slag composition. The analyses of the three lots of pellets and one lot of chips are shown in Table 1. The limestone was high-grade (97.6% $CaCO_3$).

TABLE 1

Chemical Analyses of Pellets (%)

Constituent	Pellets			Chips
	Lot 1	Lot 2	Lot 3	
Total Fe	90.3	90.4	91.7	92.1
Metallic Fe	83.7	82.5	90.6	90.9
CaO	0.54	3.26	3.52	0.43
MgO	1.78	0.14	< 0.1	1.21
SiO_2	2.89	2.35	2.61	2.42
Al_2O_3	0.16	0.09	0.26	0.25
S	0.014	0.013	0.01	0.019
P	< 0.003	0.009	0.003	< 0.002
C	0.03	--	0.06	0.04

First Objective. Determination of the suitability of the combined shaft-electric furnace for melting SL-RN pellets.

The first experiments consisted of a series of short tests, (about 8 hr each) devoted to studying the behaviour of the pellets in the combined shaft-electric furnace, particularly the control of the feed rate, and the preheating. Because a slight negative pressure was required at the top of the shaft to draw the hot gases up through the bed, the pellets were fed into the top of the shaft through two bells, each operated by a pneumatic cylinder. The rate of feed of hot pellets from the bottom of the shaft into the furnace was controlled by a ram, and the bells had to be operated at a commensurate rate to keep the shaft full of pellets at all times. Considerable mechanical difficulty was encountered with the bell system and it was later abandoned in favour of a feed inlet pipe (No. 6 in Figure 1). This pipe, 3 1/2 in. ID by about 4 ft long, when full of pellets, provided sufficient resistance to air flow to reduce to a tolerable level the amount of air drawn in at this point.

In early experiments a single pneumatically operated ram was used to inject the hot pellets from the bottom of the shaft into the furnace. On a few occasions some sticking and fusion of the pellets occurred due to overheating, and the ram would not operate. It was later replaced by four stronger hydraulically operated rams that were able to move the pellets even when some sticking and fusion occurred.

In the early experiments a gas burner firing into the arc furnace crucible was used to provide hot gases needed for the preheating of the pellets in the shaft. A number of experiments were performed using this arrangement which demonstrated the excellent efficiency of heat transfer between the ascending hot gases and the descending colder pellets. However this system was found to be undesirable because of the difficulty of controlling the burner to provide exactly the quantity of hot gas required for the preheating, and because the burner gases caused severe oxidation of the furnace electrodes. In addition, considerable fly ash from the coke was entrained in the gas stream, and on several occasions this fly ash built up in the exhaust lines to such an extent that the experiment had to be terminated. For the later experiments the shaft furnace was modified by installing the gas burner in a combustion chamber about half way up the shaft, as shown in Figure 1. Using this arrangement, it was found that the process was much easier to control, the fly ash problem was greatly diminished, and the electrode oxidation problem disappeared.

Heat transfer from the hot gases to the incoming pellets was very rapid. In the longest run (17.5 hr) when the pellets were heated from room temperature at the top of the shaft to about 500°C at the combustion box, the rate of temperature rise of the pellets was about 50°C/min, when the linear rate of descent of pellets was about 3.3 in/min. The exhaust gases left the top of the shaft at about room temperature. In a few experiments, temperatures in the centres of some pellets were measured by cementing a fine thermocouple into the centre of a pellet, and allowing it to be fed down the shaft in a normal manner with the other pellets, while recording the temperature. In these experiments the rate of rise of temperature in the vertical portion of the shaft was in order of 50°C/min, but because hot gas (> 1300°C) was being drawn from the furnace, the rate of rise of temperature in the horizontal zone just before the pellet entered the furnace was very much higher, e.g. about 370°C/min. These tests demonstrated that heat could be transferred very rapidly into the pellets when sufficient driving force (hot gas) was applied.

<u>Second Objective</u>. Determination of the grades of metal that could be produced.

In most experiments, the coke was mixed with the pellets before they were fed down the shaft, the amount used varying from about 3 to 9 lb of coke per 100 lb pellets. In these cases the carbon content of the metal varied from about 0.1% to about 2.5%. Numerous short experiments using ratios of 7 lb coke/100 lb pellets yielded metal containing about 2% carbon.

In one of the longer experiments, (17.5 hr) the coke/pellet ratio used was 7/100 and in this case the carbon content of the metal was about 3%. In the latter hours of this experiment it was noted that the furnace contained excess coke, but the experiment ended before the coke/pellet ratio could be adjusted to eliminate this excess.

Attempts were made to produce low-carbon iron by melting the pellets with little or no coke present. Several short experiments (8 hr) using coke/pellet ratios of 3/100 yielded metal containing less than 0.8% C. A longer experiment (18 hr) then was performed using no coke. The carbon content of the metal was less than 0.1%, but the FeO content of the slag was over 25%. Because of the low carbon content and hence high melting point of the metal, the bath temperature had to be kept very high (about 1600°C). The combination of high furnace temperature and high FeO slag caused serious erosion of the refractories, particularly around the mouth of the tunnel connecting the bottom of the shaft with the furnace crucible, and the run had to be stopped. In spite of the fact that low-carbon iron had been successfully made a number of times in earlier short runs, the longer run demonstrated that in a sustained operation the attack on refractories was so severe as to make this mode of operation unpractical.

<u>Third Objective</u>. Acquisition of quantitative information.

After the shaft-electric furnace had been developed to the stage illustrated in Figure 1, a longer run was made to obtain as much quantitative information as possible on all aspects of the operation, particularly the amounts of electrical energy and gas required, and the efficiency of their utilization. Although not all the measuring equipment and procedures had been completely developed at the time, a reasonably complete record of the more significant items was obtained. In this test, coke (7 lb/100) was mixed with the pellets before they entered the shaft. A small amount of carbon monoxide was generated in the furnace by reduction of the iron oxide, but most of the preheating of the pellets was done by hot gases from the burner installed in the combustion box. The furnace was operated at about 200 kW, because the pellet feed rate was limited by the material-handling facilities. For this feed rate the burner in the combustion box was over-size and had to be operated intermittently and manually rather than automatically as had been hoped. This resulted in less effective control of the temperature in the shaft and on one occasion the pellets become overheated and fused. To prevent a recurrence, the temperature was kept at about 500°C from then on.

Because it was suspected that if the pellets were heated in the shaft to a very high temperature under oxidizing conditions, the metallic iron in the pellets might be oxidized to iron oxide, the attempt was made to operate the burner with a deficiency of air. The ratio of primary air to gas being supplied to the burner was kept at about 6/1, but unfortunately a very considerable amount of secondary air was drawn in around the burner port, since Orsat analyses of the gases in the combustion box showed that their oxygen content ranged from 5 to 10%.

Attempts were made to measure the flow rates of the air being sucked down the 3 1/2 inch feed pipe, and the exhaust gases from the top of the shaft, but the records obtained were inaccurate due to faulty performance of measuring instruments. The exhaust gas was analyzed with a gas chromatograph, and it was found that except for one or two brief periods, it contained almost no CO, the CO_2 content ranged from 5 to 7%, and the oxygen from 7 to 11%. The high oxygen content was believed due to the large amount of secondary air being drawn in around the burner, augmented by that sucked down the feed pipe.

Although the amount of sensible heat in the exhaust gas could not be accurately evaluated because of the faulty flow record, it was estimated to be very low because the temperature of the gas was only 60°C at the top of the shaft. Similarly the latent heat was estimated to be low because the gas contained virtually no CO, and hence probably only small amounts of other combustibles.

The results of the test are summarized in Table 2. In this summary, the heat supplied to the shaft by the burner in the combustion box was calculated by assuming that the gas was completely burned, and the amount of heat was expressed in kWh.

The temperatures at the base of the shaft and at several locations higher in the shaft are shown in Figure 2, the average temperatures at several different locations in the shaft are shown in Figure 3, and the temperatures of the metal bath and furnace roof are shown in Figure 4.

TABLE 2

Results of Test

Duration (hr)		17.5
Feed rate of pellets (average (lb/hr)		577
Coke/pellet ratio		7/100
Heat supplied by burner in shaft (kWh/hr)*		40
Preheat temperature at base of shaft (average) (°C)		490
Electrical energy supplied to furnace (kWh/hr)		204
Temperature of metal bath (average) (°C)		1380
Carbon content of metal (average) (%)		2.8
Energy supplied per ton (2000 lb) of pellets, (kWh):		
	Electrical	705
	By gas burner	138
	Total	843

* Burning natural gas (1025 BTU/cu. ft.)

It will be noted in Figure 2 that the temperatures in the shaft cycled frequently during the run. This was due to the fact that the burner in the combustion box had to be operated intermittently. Also it is shown in Figure 3 that the temperature at T_4, 44 inches above the base of the shaft, was higher than T_1, T_2 or T_3, all of which were closer to the base of the shaft. T_4 was located very close to the combustion box and was reflecting the flame temperature of the burner more than the temperature of the pellets at that point.

It will be noted in Figure 4 that the metal bath temperature decreased slowly from about 1525°C in the early hours of the run to about 1350°C, and remained fairly steady throughout, while the roof temperature rose steadily in the latter half of the run, finally reaching about 1650°C. This rise in roof temperature is believed due to the accumulation of excess coke in the furnace in the latter hours of the run, with attendant increase in arc length and hence more heat being radiated to the roof. Unfortunately time did not permit decreasing the coke/ore ratio to the optimum level.

DISCUSSION AND CONCLUSIONS

Using the analyses of the feed materials and the relevant heat capacity data, the amounts of heat required in the shaft and in the furnace to accomplish the heating and melting were calculated and compared with the quantities used. The results are summarized in Table 3.

TABLE 3

Process Heat, and Heat Losses

Basis: One ton (2000 lb) pellets plus associated coke and flux

A. Shaft	
Heat supplied by natural gas	138 kWh
Heat required to heat charge to 490°C	83 "
Difference (heat losses)	55 "
B. Furnace	
Heat supplied electrically	705 kWh
Heat required to heat charge from 490°C to 1380°C, complete melting, etc.	353 "
Difference (heat losses)	352 "

In this run, a relatively modest amount of preheating was accomplished in the shaft, (preheat temperature (490°C), because the burner was not ideally suited for the job, and the electrical energy input to the furnace had to be restricted to about 200 kW because faster feed rates could not be obtained. It is obvious that if more preheating was done in the shaft, less heat would be required in the furnace to complete the melting and more electrical energy could be saved, at the expense of some additional gas energy. Also, at any steady furnace temperature, the furnace heat losses would be expected to be relatively constant and independent of the throughput, hence if the furnace was operated at 250 kW input while maintaining a constant bath temperature, the throughput could be increased, and the amount of heat lost per unit of throughput would decrease. Calculations were performed to give an indication of what performance might be expected from this shaft-furnace unit, if the charge was preheated in the shaft to 1000°C, and the furnace was operated at 250 kW. As an aid for making these projections, the heat loss of the furnace at a bath temperature of 1380°C was measured by maintaining this temperature constant for an extended period of time, with about 1000 lb of molten metal in the furnace. The heat loss was found to be about 100 kWh/hr. The projection is summarized in Table 4.

These calculations indicate that the amount of electrical energy required may be greatly reduced (from 705 to 357 kWh/ton) if the preheat temperature can be raised from 490 to 1000°C, and if the furnace is operated at its maximum capability. Additional small improvements may be possible if the heat losses from the shaft and the furnace can be decreased with improved insulation.

TABLE 4

Projected Energy Requirements for Shaft-Electric Furnace

Basis: One ton (2000 lb) pellets plus associated coke and flux

A. Shaft	
Heat required to heat charge to 1000°C	222 kWh
Thermal efficiency (based on present work)	60%
Projected energy required in shaft	368 kWh
B. Furnace	
Heat required to bring charge from 1000°C to 1380°C, complete melting, etc.	214 kWh
Heat losses	143 "
Projected energy required in furnace	357 "

The projected heat loss from the furnace shown in Table 4 (143 kWh per ton) is based on the assumption that the rate of heat loss will be mainly a function of furnace temperature, and independent of throughput. When the measured value of 100 kWh/hr for a temperature of 1380°C is substituted in the energy balance calculations for this particular run, the calculated heat loss is found to be 348 kWh per ton. The actual heat loss, shown in Table 3, was 352 kWh per ton. This close agreement strongly supports the validity of this method of projecting the energy requirements.

1. Electric Furnace
2. Furnace Roof
3. Furnace Electrodes
4. Tap Hole Runner
5. Furnace Shaft
6. Feed Inlet
7. Preheat Gas Burner
8. Preheat Combustion Box
9. Rams
10. Sight Glass
11. Pressure Probe for Exhaust Control
12. Orifice Plate
13. Gas Sampling Tube
14. Sand Seal
15. Thermocouple Tube
16. Pressure Probes to Measure Induced Air
17. Clean Out
18. Inlet for Immersion Thermocouple
19. Radiamatic Temperature Indicator
20. Coke Inlet
21. Exhaust

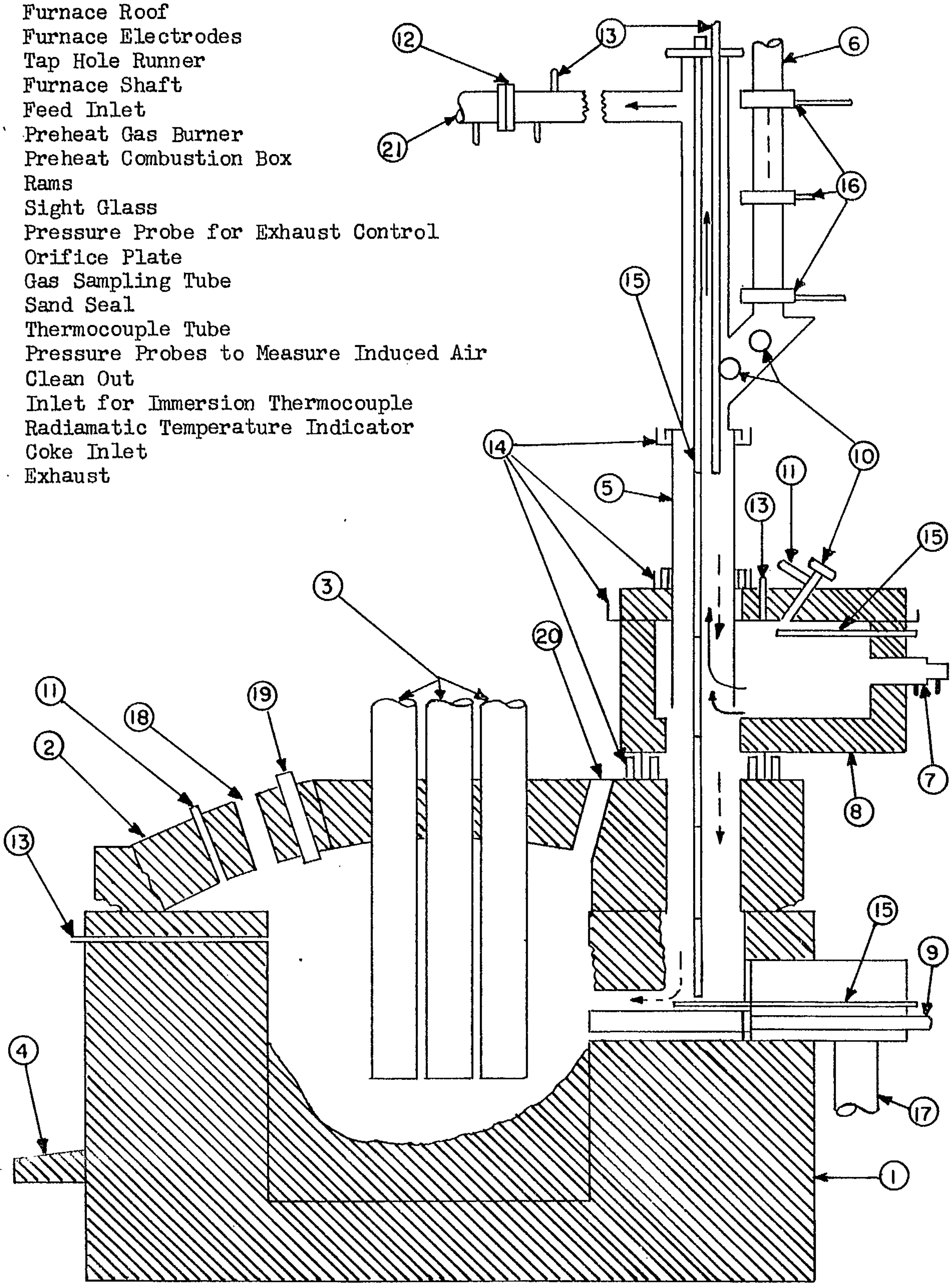

Figure I Diagram of
Shaft-Electric Furnace

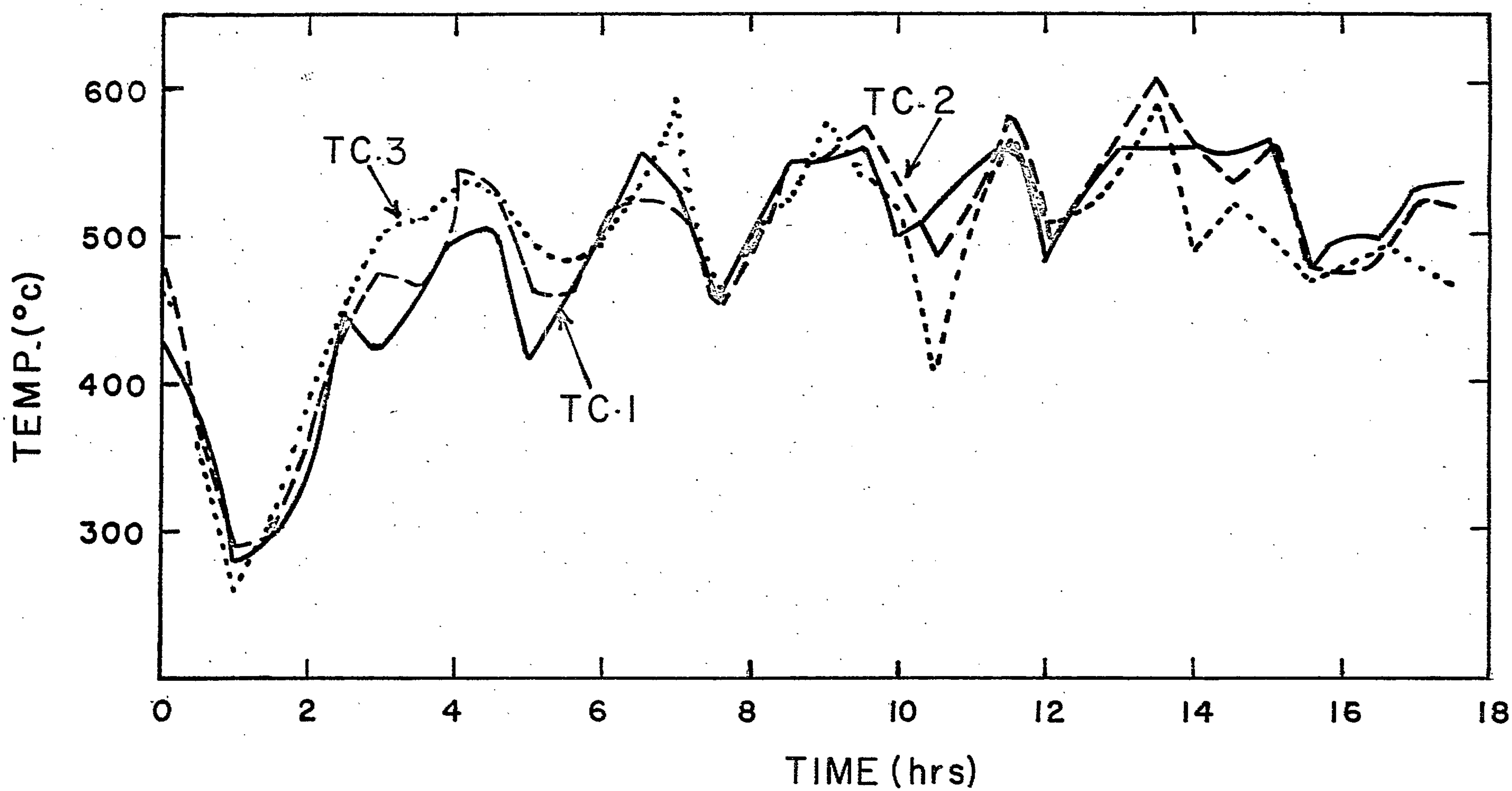

Figure 2. Temperatures at Several Elevations in the Shaft

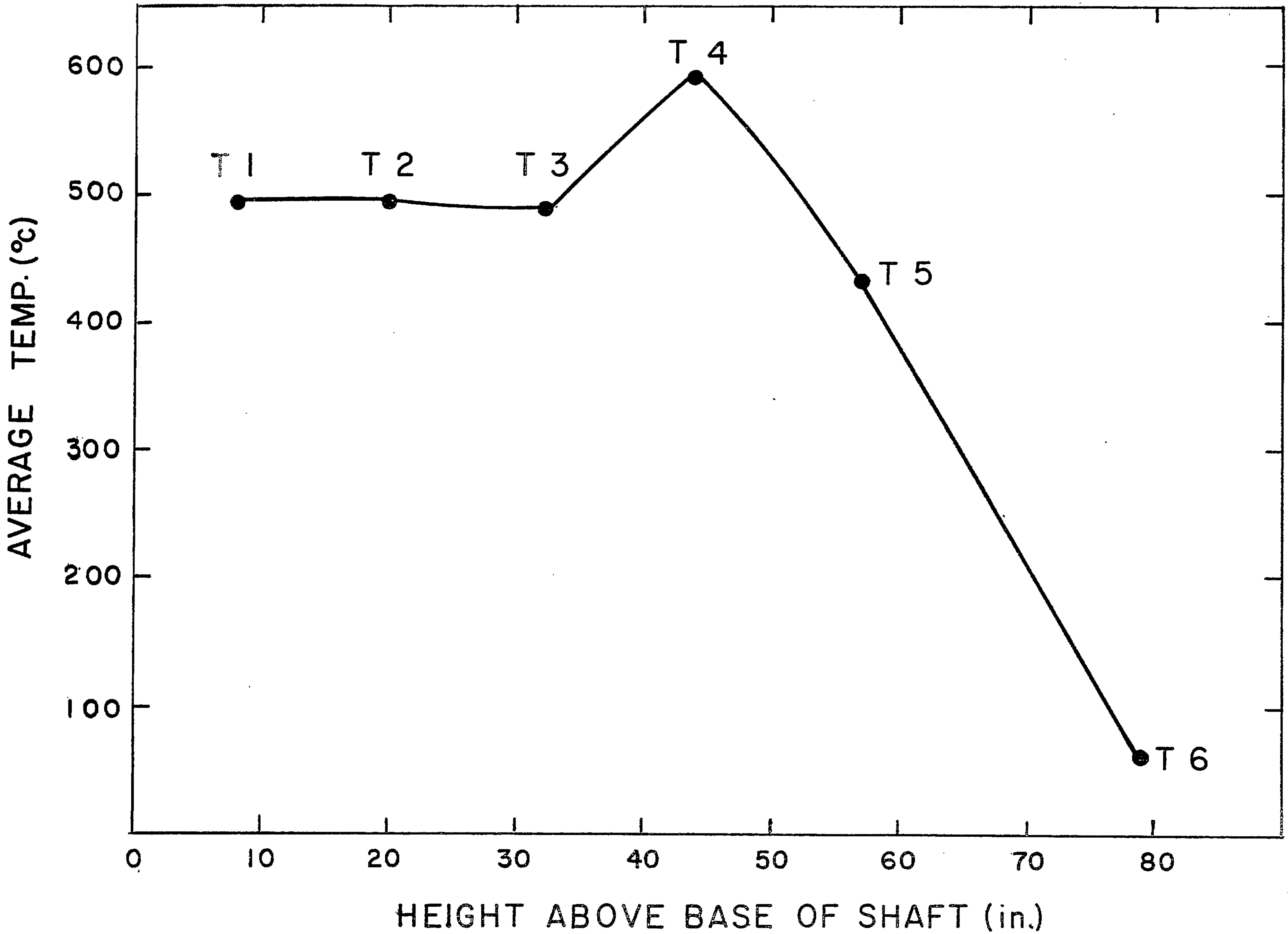

Figure 3. Average Temperatures at Several Elevations in the Shaft

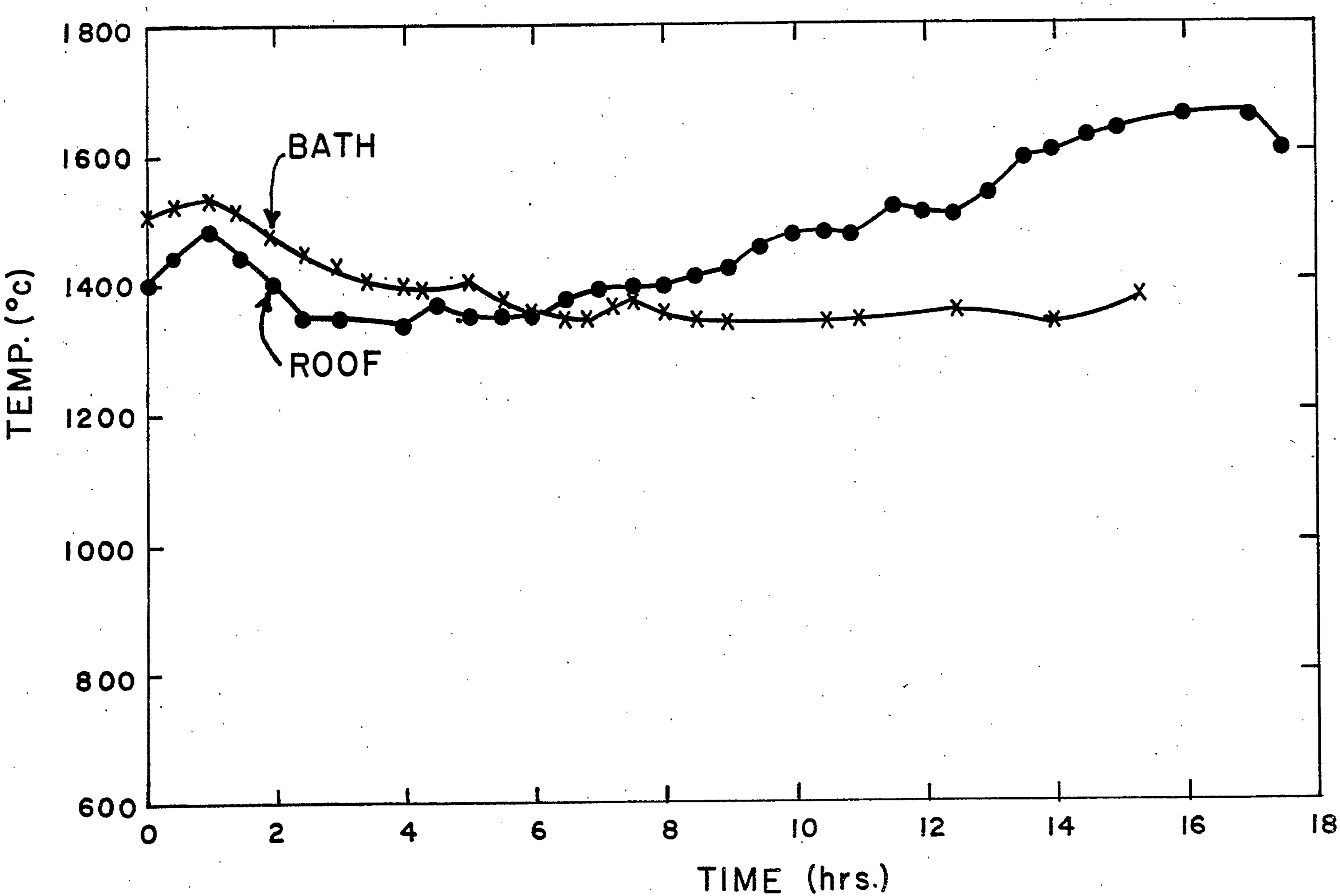

Figure 4. Bath and Roof Temperatures