Heat Recovery Systems Vol. 5, No. 4, pp. 353–364, 1985
Printed in Great Britain.

0198-7593/85 $3.00 + .00
Pergamon Press Ltd

THE FEASIBILITY OF USING WASTE HEAT BOILERS TO RECOVER ENERGY FROM THE EXHAUST GASES OF ELECTRIC ARC FURNACES*

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Abstract—Energy can be rejected in the waste gases of an UHP electric arc furnace at rates of up to about 15 MW, accounting for 200 kWh per tonne of liquid steel. The possibility of recovering a significant proportion of this energy as steam using a waste heat boiler has been investigated. The options of using the steam to satisfy the in-works demand and generating electricity are being considered.

Extensive measurements of the conditions existing in the waste gas stream have been made throughout the steelmaking cycle for furnace practices involving oxygen blowing, continuous charging and supplementary firing with oxy-fuel burners.

Various practical implications of the use of a waste heat boiler have been studied. These include the location of the boiler, the accretion of solid matter on tubes, the effect of the presence of the boiler on gas cleaning and the control of furnace extraction to achieve optimum performance.

A case study involving a 180 tonne furnace used to produce special steels has shown that the payback of the capital involved in installing a boiler to generate sufficient steam to satisfy the works' base load would be less than two years, under the conditions prevailing during the project.

The economic appraisal of electricity generation is being evaluated, but the initial indications are that the return of capital is not attractive if generation facilities do not already exist.

1. INTRODUCTION

The proportion of steel manufactured by the electric arc process has steadily increased over the past 30 years. In 1982, it accounted for about 34% of UK liquid steel production, and there are over 250 electric arc furnaces in operation within the ECSC.

Electrical energy is a major contributor to the overall manufacturing cost, and its conservation is of prime importance. The largest single source of energy loss from an electric arc furnace is via the waste gas stream, and urgent consideration is being given to methods of reducing the quantity of energy lost in this way, and to recovering heat from the exhaust gases. Scrap preheating is potentially the most attractive method of energy recovery, but its effectiveness is often restricted because of practical considerations. In general, steelworks use considerable quantities of steam for various purposes. The objective of this study is to investigate the feasibility of using a waste heat boiler to generate steam using energy recovered from the exhaust gases of an electric arc furnace. The steam produced in this manner would replace that generated in conventional boiler plant, thereby reducing energy costs.

A case study, based on a furnace producing special steels within the British Steel Corporation, has been used to demonstrate the advantages and disadvantages of this method of energy recovery in practical and economic terms.

2. THE WASTE GASES OF THE ELECTRIC ARC FURNACE

The volume, temperature, composition, and hence the energy content, of the waste gases vary throughout the furnace cycle, and depend on such variables as the charge material, melt-down rates, oxygen practice, supplementary firing practice and the type of steel being produced. A survey of the literature was carried out at the beginning of the project and revealed a diversity in the reports of the quantity of energy contained in the waste gases. Of the total energy input to the

*Paper first presented at Conference on Energy Conservation in Industry, Dusseldorf, 1984, organised by the Commission of the European Communities and VDI.

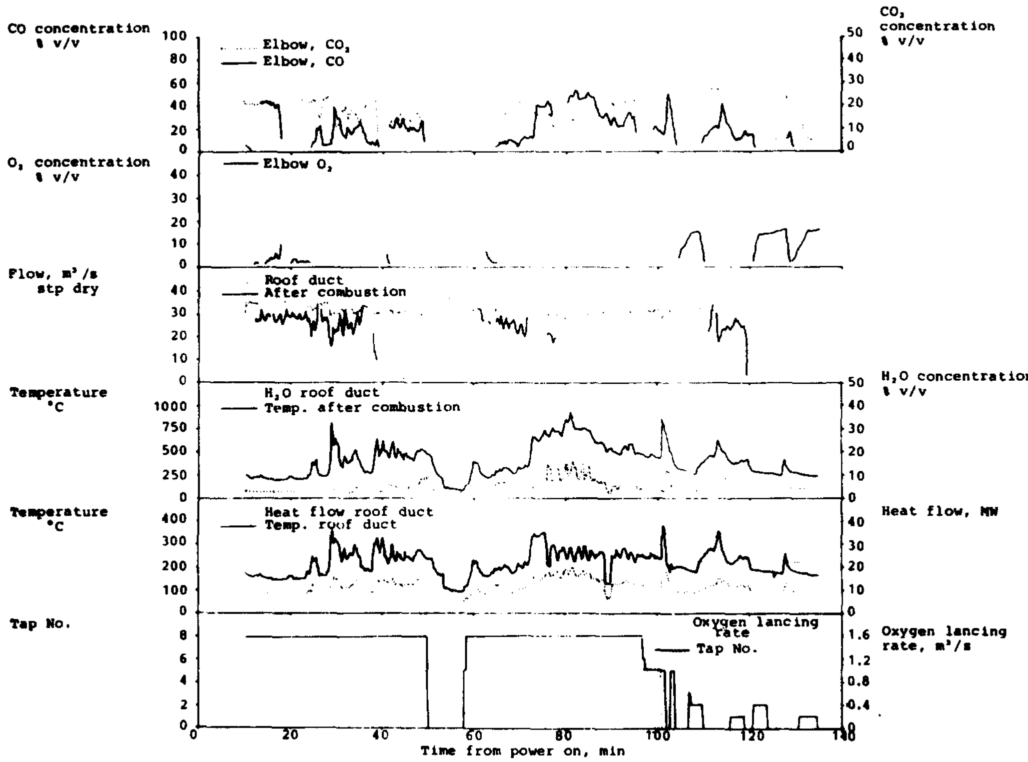

Fig. 1. Waste gas conditions—180 tonne furnace.

furnaces, fractions of between 5 and 29%, accounting for 30 to 130 kWh/tonne of liquid steel, were estimated to be lost in the exhaust gases [2, 3, 4]. In order to produce reliable information, detailed measurements were made on a number of furnaces within BSC using techniques developed specially for use in the aggressive conditions to be found in the waste gases of electric arc furnaces [5, 6]. Figure 1 shows the data obtained form a typical cast on a 180 tonne UHP electric arc furnace; an average waste heat cycle is shown in Fig. 2. When continuous charging techniques or supplementary firing with oxy-fuel burners are employed, the rate of energy rejection in the waste gases may be increased. Figure 3 is an average waste heat cycle for 180 tonne furnace with continuous feeding of granulated iron. In this case, the average rate of energy rejection is 15.5 MW, which for a charge of 180 tonne is equivalent to a loss of about 200 kWh/tonne of liquid steel.

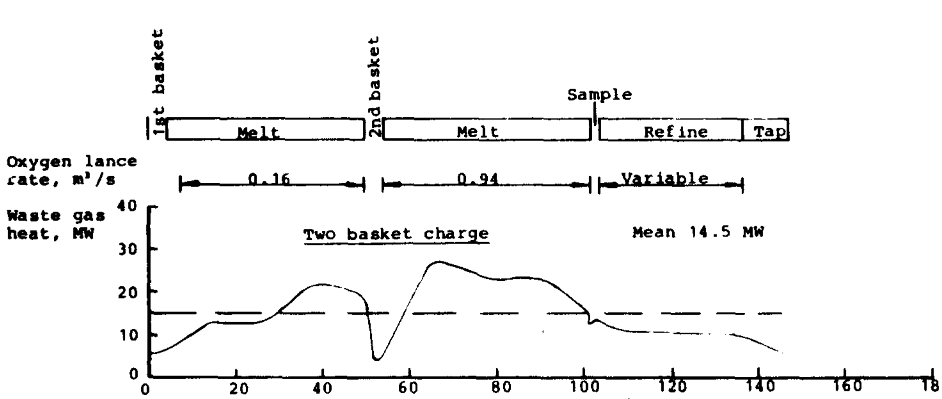

Fig. 2. Typical waste heat rejection cycle—180 tonne furnace.

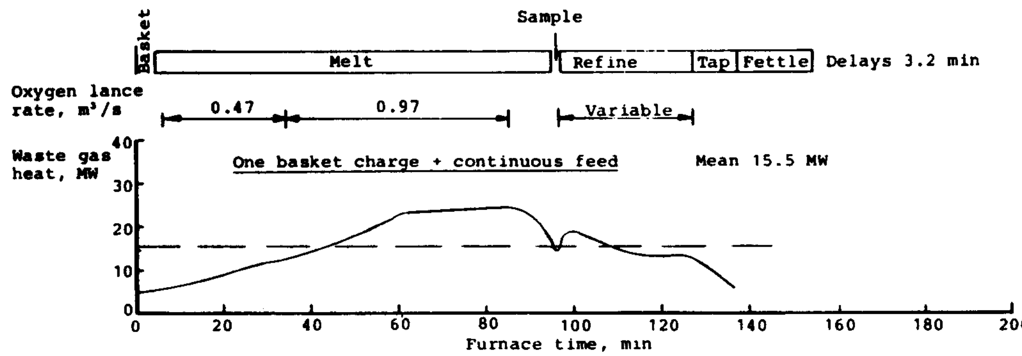

Fig. 3. Typical waste heat rejection cycle—180 tonne furnace with continuous feeding.

3. WASTE HEAT UTILISATION

In considering the practical applications of recovered waste heat from the arc furnaces, the following factors should be taken into account.

1. Changes in heat flow within the furnace cycle.
2. Forms in which the waste heat is recovered (e.g. scrap preheating, steam, electricity generation).
3. Destination and transportation of recovered energy.
4. Reliability of recovery equipment, maximisation of furnace availability and ease of maintenance.
5. Effect of the presence of the waste heat recovery unit on the operation of other items of plant.
6. Capital and operating costs.

The exhaust gas leaves the arc furnace at a high temperature and in principle should have considerable potential for energy recovery. However, its dirty condition and variable nature create significant difficulties in achieving this end. Much of the effort devoted to energy recovery has justifiably been concentrated on scrap preheating because the recovered heat is returned to the process. Some examples of the scrap heating techniques are basket preheaters, the BBC/Brusa rotary kiln process and the twin-shell method [7–14]. The first of these has been the most widely applied because of its relative simplicity and its ability to be retrofitted in an established melting shop. A number of installations are now operating successfully, but experience has shown that the quantity of energy which can be recovered is restricted by practical considerations such as the need to avoid overheating the charging basket, and to prevent welding and bridging in the charge. The reported energy savings are in the region of 20 to 50 kWh/tonne, representing 10 to 25% of the total energy in the waste gas.

The more elaborate techniques suffer from the disadvantage of high capital cost, high maintenance costs and unsuitability for incorporation into existing melting shops.

Consideration could be given to other uses for the waste heat, such as the production of hot water for boiler feeding, space heating, district heating and amenity use [15]. However, a more attractive alternative would be to provide energy for steam raising. Most steelworks require considerable quantities of steam for process and heating purposes, and its generation from waste heat would reduce the consumption of fuels in steam raising plant. The use of a waste heat boiler would be particularly advantageous either in a melting shop where practical considerations render scrap preheating uneconomic or in tandem with a preheater which removes only a small fraction of the energy in the waste gas stream.

To realise its economic potential, a waste heat boiler system must fulfil a number of requirements.

1. It should be capable of incorporation into the extraction system of the furnace with minimum re-organisation of the melting shop facilities and the existing waste gas handling equipment.

2. The steam cycle must be capable of being matched to the works demand and complemented by existing steam raising plant.
3. The boiler must be reliable and easily maintained so that production stoppages are avoided.
4. The waste gas extraction system must operate without the boiler in service, if necessary.

The various aspects of the use of a waste heat boiler have been considered in this project.

4. PRACTICAL ASPECTS INVOLVED IN THE USE OF A WASTE HEAT BOILER

4.1. *General considerations*

A number of practical aspects involved in the use of a waste heat boiler have been considered in detail involving experimentation on plant or in the laboratory where appropriate. The main factors which are discussed in Section 4.2 were:

(i) The location of the boiler within the waste gas handling system.
(ii) Maximisation of energy recovery by control of the waste gas conditions.
(iii) The effect of the accretion of solid material on boiler tubes, and its effect on heat transfer.
(iv) The effect of the presence of the boiler on gas cleaning.

4.2. *Location*

Figure 1 indicates that the gases from the furnace contain up to 55% of carbon monoxide. Furthermore, at certain parts of the furnace cycle, up to 10% H_2 may be involved. The variable composition of the gases render their collection extremely difficult. The practice adopted within BSC is to mix the gases with air and burn them in a brick-lined combustion chamber. The volume of air added is designed to ensure that the temperature of the gases after combustion is never greater than 1200°C. The combusted gases are then cooled further, either by water in a spray tower, or by mixture with large quantities of air drawn from the roof extraction hoods of the melting shop. Finally, the gases are cleaned using wet or dry electrostatic precipitators, or bag filters. An alternative method of cleaning not commonly used on the electric arc furnace plants of BSC, would be a high pressure drop Venturi scrubber.

To ensure safe operation of a boiler, it is considered necessary to retain the use of the brick-lined combustion chamber. The gases would continue to be mixed with sufficient air to ensure complete combustion, and to reduce their temperature to an acceptable level. The waste heat boiler would be situated immediately after the combustion chamber and fitted with a hot gas by-pass to avoid interruption to furnace operation in the event of boiler problems. Consideration was given to the replacement of the combustion chamber by a shell boiler but this course of action was rejected because it would not be possible to extract an acceptable amount of heat within the dimensions available. Also, a failure of the boiler could result in an interruption to furnace operation. Figure 4 indicates suggested locations for the boiler.

The most desirable site for the boiler is considered to be immediately downstream of the combustion chamber for the following reasons:

(i) The gases leaving the furnace have mixed and burned in the air indrawn at the slice gap, and hence are at their maximum temperature at the end of the combustion chamber.
(ii) Large particulates will have dropped out of the gas stream in the combustion chamber and will not reach the boiler.
(iii) The conditioning tower, if used, does not require lining to withstand high temperatures and can function as before when an emergency situation arises.
(iv) This position requires the shortest possible length of lined ductwork.

Should it be desirable to use a boiler in conjunction with a scrap preheater, it is preferable to locate the boiler upstream of the preheater, thereby presenting the gases at the highest possible temperature to the boiler and maximising its efficiency. In this case, the boiler should be designed to have an exhaust gas temperature in the region of 700°C maximum which would be adequate for the scrap preheater in which a final steel temperature in the region of 400°C is desirable.

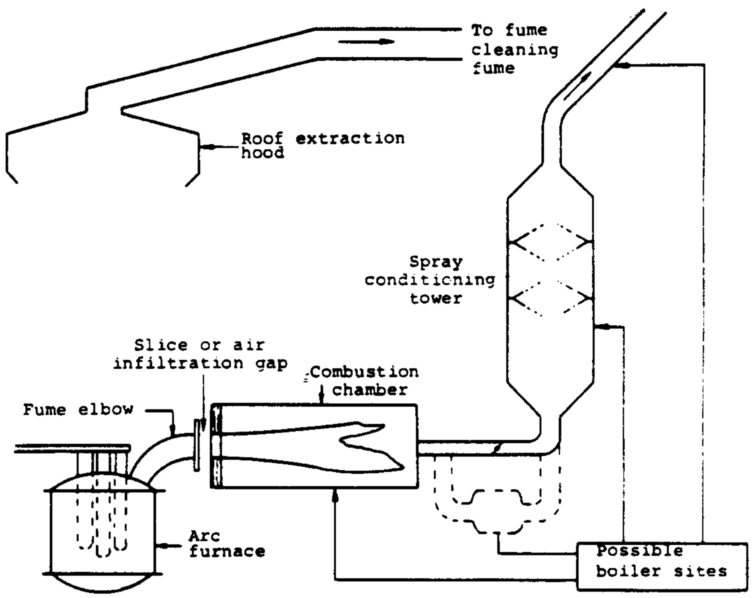

Fig. 4. General layout of electric arc furnace and associated waste gas ducting possible boiler sites.

4.3. *Control of inlet gas temperature*

Whilst the maximum temperature of the combusted waste gases is designed to be 1200°C, this figure is seldom reached in practice. During the case illustrated in Fig. 1, the maximum temperature was in the region of 800°C, and for much of the time a lower value was achieved. To obtain the maximum benefit from a waste heat recovery system, it is essential to avoid degradation of the waste gas temperature. Furthermore, to obtain the most efficient overall performance in energy terms, it is necessary to ensure that as far as possible combustion takes place within the furnace, rather than externally in the combustion chamber. A study has been made of methods of changing the geometry of the furnace offtake elbow, the air infiltration gap and the combustion chamber to effect better control of the absolute and relative rates of furnace extraction and air infiltration. An isothermal model was used to determine the most appropriate geometry and the results indicated that an increase in the diameter of the offtake from 1.0 to 1.4 m dia. would produce the best performance. The layout of the water-cooled roof panels precluded an elbow of the ideal size, and a compromise dia. of 1.3 m was found to be acceptable.

The new elbow was designed, constructed and installed on the furnace during the second half of 1983, and extensive waste gas measurements were made to assess the benefits of the new arrangement. Figure 5 shows the positions at which the various measurements were made, and Fig. 6 is an example of the experimental results. Detailed analysis of the data gained from this trial was in progress at the time of preparation of this report.

4.4. *Fouling*

The waste gases from an electric arc furnace contain large amounts of particulate matter; concentrations of up to 200 g m^{-3} have been measured. At the outlet of the combustion chamber, the material will be in solid form with the typical size range and composition shown in Fig. 7. The accretion of solid matter on the tubes of a waste heat boiler would present a maintenance problem as well as reducing its efficiency. To simulate a boiler tube, probes were constructed to the design shown in Fig. 8. The probes were constructed with concentric water passages so that they could be readily inserted into the measurement positions and removed for inspection.

To simplify the experimental procedure, the flow of water through the probe was selected to avoid boiling and the production of steam. The experimental measurements made were as follows:

(i) Heat flux intensity
(ii) Gas temperature

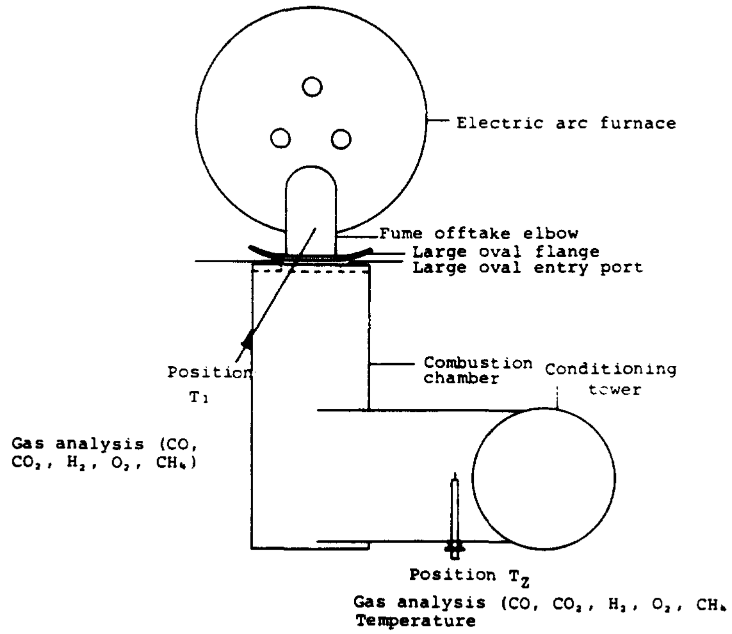

Fig. 5. Measurement positions.

(iii) Gas flow rate
(iv) Effect of accretion on heat transfer rate
(v) Accretion of solid matter and its subsequent removal.

Two probes were installed at a point between the combustion chamber and the conditioning tower in the extraction system of a 180 tonne arc furnace. This position was chosen as it is the most

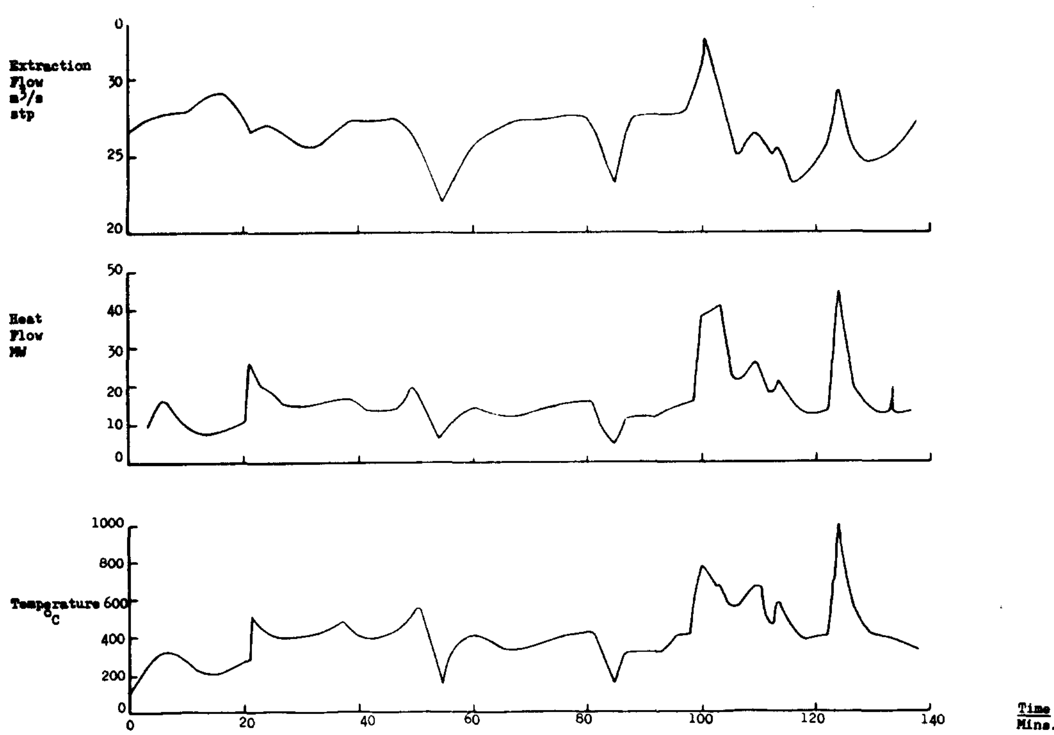

Fig. 6. Waste gas conditions—180 tonne furnace with modified offtake.

	Concentration, %		
	Sample 1	Sample 2	Sample 3
Fe_2O_3	37	46	50
Fe_3O_4	10	2	
Al_2O_3	2	3	1
CaO	16	17	9
MgO	8	6	3
MnO	5	5	5
ZnO	6	2	14
PbO	1	1	4

Fig. 7. Approximate concentrations of the main constituents of electric arc furnace fume (particle size 0.03–1 μm).

probable location for a boiler and the gas conditions would be similar to those encountered in a boiler. One probe was installed horizontally and one vertically to allow the effect of the orientation of a tube to be assessed. The position has good access to the inside of the duct to allow *in situ* examination of the probes to be made.

The probes were left in position for three months during which the furnace was in normal production. At the end of this period, there was only a thin, fairly even deposit of material on the vertical probe. The horizontal tube showed an accretion of material on the downstream segment of its surface. The deposit was fine and powdery, crusting in places and easily friable. The maximum thickness was less than 8 mm. The nature of the material suggested that it would be readily removed with conventional soot-blowing equipment.

Figure 9 shows the variation of the heat transfer rate with gas temperature, and indicates the importance of keeping the latter at the highest possible level. No significant change in this relationship was detected over the trial period.

The position of the probes had been selected to allow them to be subjected to similar gas temperatures and dust loadings to those existing in a boiler. However, the velocity of the gas at the experimental position was higher by a factor of approximately five than would exist in a boiler. Clearly this unrepresentative velocity may have an effect on the extent of fouling. Therefore, one probe was resited in the combustion chamber close to the exit where the gas velocities are more comparable with those in a boiler.

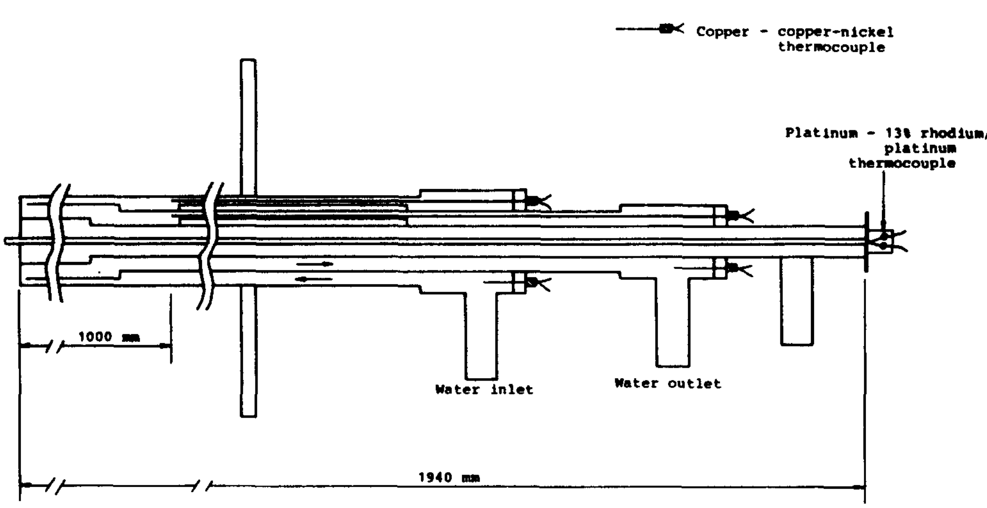

Fig. 8. Section through the probe.

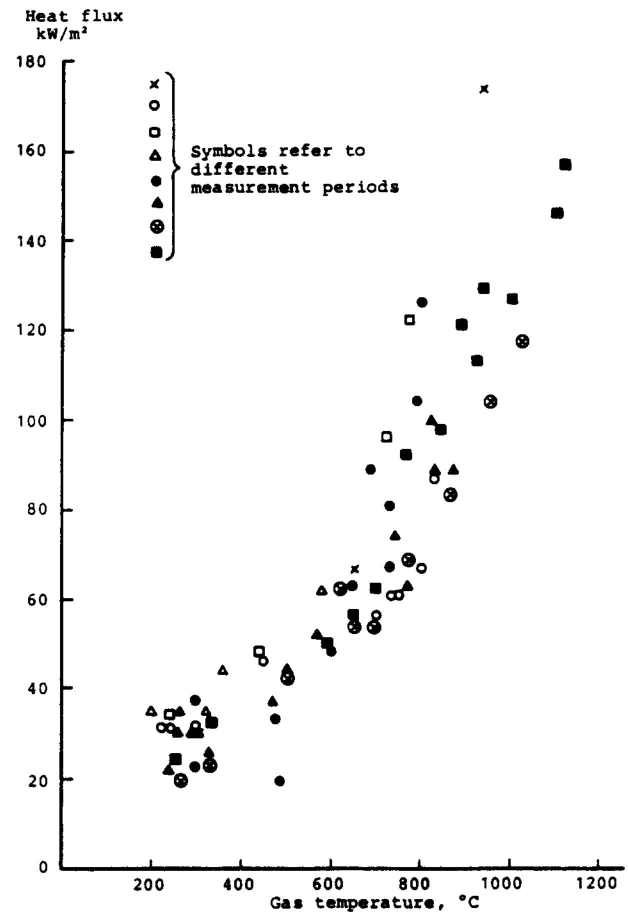

Fig. 9. Heat transfer coefficients.

It was also considered that the use of a water-cooled probe rather than a steam tube may have had an influence on the nature of the deposit owing to its lower operating temperature. Therefore, a steam tube is to be installed in the combustion chamber.

Finally, a bank of steam tubes will be inserted into the combustion chamber to check the effect on the aerodynamic behaviour of a formation of boiler tubes.

The experimental work carried out so far has been encouraging in that the extent of fouling has been less than was feared, and its influence on heat transfer rates was not serious.

4.5. *Gas cleaning*

The methods commonly used for gas cleaning are as follows:

(i) Dry electrostatic precipitator
(ii) Wet electrostatic precipitator
(iii) Bag filter
(iv) Wet scrubber.

In every case, the temperature of the gases would be reduced by the addition of air or by water sprays before entry to the gas cleaning system. The presence of the boiler would reduce substantially the cooling requirement although it would be necessary to retain the facility to cater for periods when the boiler was inoperative.

The reduction in temperature of the waste gases leaving the boiler would create a problem with the operation of dry precipitators. The efficiency of this type of plant is critically dependent on the humidity of the gases as shown in Fig. 10. Water is usually added in the spray quenching carried out in the conditioning tower. It would be impossible to achieve the desired concentration of 15%

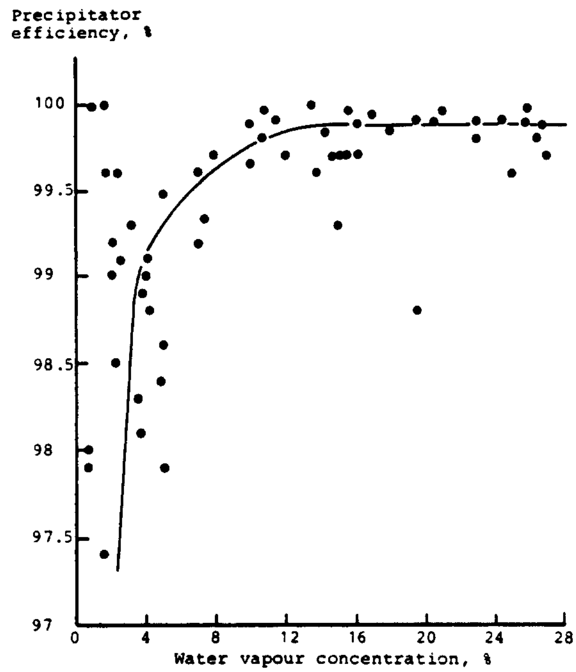

Fig. 10. Effect of water vapour on precipitator efficiency.

water vapour with gases which have left the boiler at 700°C, or less. To restore the humidity by the addition of steam, would negate the benefits of the waste heat boiler. It is concluded, therefore, that the use of a dry precipitator would be incompatible with a waste heat boiler, or other device giving a similar level of energy recovery.

With wet electrostatic precipitators, there is a danger that material deposited on the electrodes may become caked and difficult to remove should the humidity of the waste gases be low. The reduced requirement for water addition which will exist if a boiler is used could produce problems of this nature, but past experience indicates that these would not be insuperable.

The other methods of gas cleaning involve no particular problem when applied to a system which incorporates a waste heat boiler.

5. ECONOMIC EVALUATION

5.1. *Steam demand*

For a waste heat boiler to be economically viable, it is necessary that the steam generated should be as fully utilised as possible. The demand for steam will vary from works to works, and will be to some extent variable within an individual plant. A survey was carried out in the electric arc works in the Special Steels area of BSC during 1982 in order to obtain information about the extent of steam requirement.

Table 1 gives a summary of the information collected. The quantity entitled 'base load' is the lowest demand encountered under normal conditions.

The choice of the quantity of steam to be produced and hence the number and sizes of boilers

Table 1. Steam demand for electric arc works

Works	A	B	C	D
Base load, tonne h^{-1}	10	32	2.7	37
Maximum load, tonne h^{-1}	38	55	7	45
Pressure, bar	11	10–12	16	7–14.5
Temperature, °C	205	210	205	165–200
Existing capacity, tonne h^{-1}	48	110.7	14	63.5

depends on the economic viability of a number of stages of increasing steam production. These are as follows:

(i) Satisfy base load only
(ii) Increase works demand for steam
(iii) Export steam to other users, e.g. industrial users or district heating schemes
(iv) Electricity generation.

The first case study involves the simplest of these options, the use of waste heat steam to provide the base load for Works A.

5.2. *Base load production*

A number of boiler manufacturers were invited to submit proposals for waste heat boilers to operate under the typical conditions defined by the initial extraction system surveys. Detailed discussions were conducted with one manufacturer who showed a particular interest. An outline design for a boiler was prepared, and a budget cost estimated. At the same time, the cost of melting shop modifications required to integrate the boiler into the plant was estimated by BSC personnel.

The boiler was designed to reduce the temperature of 14,500 kg h^{-1} of waste gas from 1250°C to 700°C whilst keeping the draught loss to a minimum. Steam would be produced at a pressure of 1.1 MN m^{-2} from feed water at 105°C. A natural circulation boiler was proposed having an in-line plain steel tube configuration. The tubes would be arranged in two banks of 429 tubes each arranged 33 wide by 13 deep. The two-pass arrangement would allow the gases to enter and leave the boiler on the same side, thereby facilitating the provision of a by-pass and creating a convenient arrangement for incorporation into the existing plant.

The waste gases would be abstracted from the end of the existing combustion chamber and return to the main system at the base of the conditioning tower. The present transition duct would serve as the by-pass, and dampers would be located at the inlet and outlet of the boiler, and in the transition duct.

Table 2 gives a breakdown of the main items of cost. Using performance data supplied by the boiler manufacturers, a steam production cycle was calculated on the basis of the typical waste gas cycle shown in Fig. 2. The average steam production over a cast would be 9600 kg h^{-1}.

With the assumption that a boiler would be fitted to a single furnace, the annual replacement of steam generated from primary fuels by waste heat steam would be 47,000 tonne, worth £520,000. The cost of the installation is estimated to be £683,000. These figures are calculated on the marginal cost of steam production on the assumption that the existing boiler plant would need to be kept in operation.

On this very simple basis, a pay-back of capital of 1.31 yr is forecast. However, it must be remembered that the steam production cycle from the arc furnace is not consistent and there are periods such as turn-round and breakdowns when no steam will be produced. Therefore, it is necessary to retain the conventional steam raising facilities, probably operating a boiler at the lowest possible output. During periods of no production by the waste heat boiler, the steam demand would be met by the conventional plant. The boiler plant requires a finite time to increase its output from turndown to full load, and therefore accumulation facilities would be needed. Operating in this manner involves a penalty in reduced efficiency. Also, a proportion of the steam demand would be met by the conventional boiler plant, rather than the waste heat boiler. Taking

Table 2. Economics of waste heat boiler

	Costs (£)		Savings (£)	
Supply and installation of boiler		300,000	Steam make per cast tonnes	24
New services	89,500		per year tonnes	47,000
Civil engineering work and new ducting	133,000		Value	£520,000
Modifications to melting shop	42,000			
Supplies	15,000			
Control systems	50,000			
Design engineering	12,000			
Contingencies	41,500			
	383,000	383,000		
TOTAL		683,000		

Table 3. Cost balance

Costs		Savings	
Supply and installation of boiler	210,000	Steam make per cast	17.75 tonne
Modifications to melting shop	365,000	Annual steam make	34,760 tonne
Accumulator	50,000	Value	£384,000
		Less	
TOTAL	625,000	Reduced efficiency	7,000
		Maintenance	15,000
		Saving —	£362,000

Payback = $\frac{625,000}{362,000}$ yr
= 1.73 yr

these considerations into account and sizing the boiler accordingly, the simple payback of capital would be 1.73 yr. Table 3 summarises the revised cost balance.

5.3. *Further utilisation of steam*

The survey of the BSC electric arc works indicated that the maximum potential for steam generation from waste heat far exceeds the existing demand. Indeed, with the present drive for economies in energy, the use of steam has contracted rapidly in recent years and is continuing to do so. The opportunities for using additional steam within the works are therefore limited and if further applications are sought, consideration must be given to export to other works or to the generation of electricity. In the former case, the cost effectiveness can readily be calculated from a knowledge of the demand for exported steam and the expected sale price.

Three combinations of steam and power generation are being considered for the three furnace melting shop which has been used for the above case study.

(i) Generation of sufficient superheated steam by a waste heat boiler to satisfy the works base steam demand with pass-out steam. Electricity would be generated by a combination of back pressure and condensing turbines.
(ii) Similar to (i) but with saturated steam being produced by the boiler and passed through an external fired superheater before feeding the turbine sets.
(iii) Generation of electricity by using saturated steam in a single stage turbine.

The effect of using one or more furnaces to produce steam is being considered.

Items (i) and (ii) involve considerably more capital expenditure than item (iii) though the efficiency of generation is also higher.

Detailed costs and savings were not available when this report was compiled, but the use of electricity generation appears viable only when spare generating capacity already exists on the works, or when a turbine is used to consume excess steam produced by a boiler supplying the works steam base load.

6. CONCLUSIONS

The energy rejected in the waste gases of an UHP electric arc furnace has been shown to be in the region of 200 kWh tonne of steel produced.

A study of the possibility of using a waste heat boiler to recover energy indicates that the waste gases from a single arc furnace provides sufficient potential for steam generation to satisfy the base load of the Works considered. A cost-benefit analysis carried out for a BSC Works indicates that the capital cost of £525 K for the installation of a waste heat boiler on one arc furnace would have a simple pay-back period of 1.7 yr.

The economics of electricity generation are still being considered; preliminary indications are that the viability of such schemes are limited unless surplus generating capacity already exists.

Various practical factors including optimisation of efficiency, the accretion of solids on boiler tubes and the effect of the boiler on the operation of gas cleaning facilities have been considered.

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