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A history of the development of the steam boiler, with particular reference to its use in the electricity supply industry

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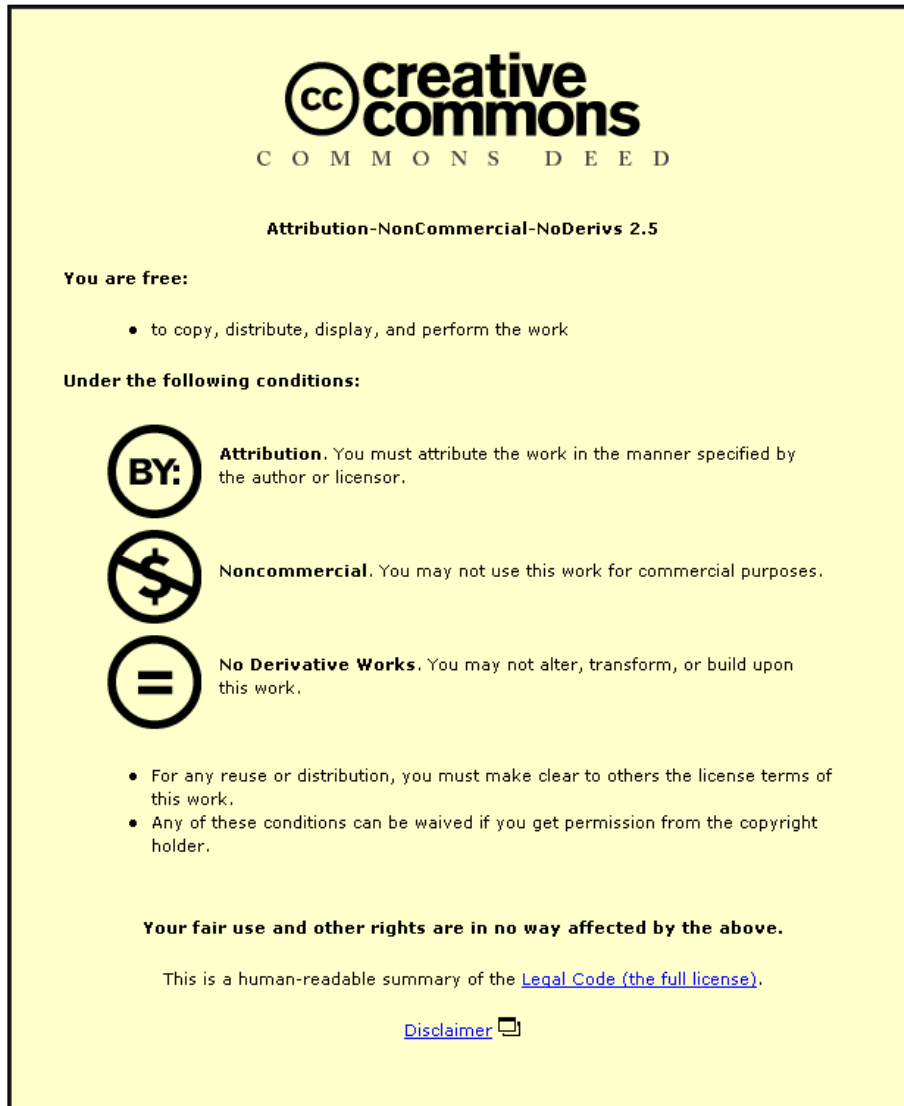
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
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A HISTORY OF THE DEVELOPMENT OF
THE STEAM BOILER, WITH PARTICULAR
REFERENCE TO ITS USE IN THE

ELECTRICITY SUPPLY INDUSTRY

by

RAYMOND WARBURTON

A MASTER'S THESIS

Submitted in partial fulfilment of the
requirements for the award of

MASTER OF PHILOSOPHY

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1981

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GLOSSARY OF TERMS & ABBREVIATIONS

A.S.M.E.	American Society of Mechanical Engineers
Air heater	A device installed in the path of boiler gases, usually after the economiser in which the air for combustion absorbs heat from the gases before they enter the chimney.
Atmospheric pressure	Pressure caused by the weight of the air in the atmosphere above the surface of the earth.
Austenitic steel	A non-magnetic steel which has a particular crystal structure distinct from the normal ferritic steel.
Automatic boiler control	A system which automatically controls the fuel and air supplies to a boiler, adjusting for the required steam output while preserving the best practicable combustion efficiency.
Availability	The capacity of a plant available for use expressed as a percentage of the plant installed, it may be related to a particular time period, e.g. 24 hours.
B & W	Babcock & Wilcox, a manufacturer of boiler and ancillary plant, who were pioneers of water tube boiler manufacture.
B.E.A.	British Electricity Authority, a body formed on nationalisation to be responsible for the supply industry, it assumed direct responsibility for the generation and transmission of electricity while maintaining overall control of the area distribution boards.
B.t.u.	British thermal unit, the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit, previously written BThU.
Base Load Station	A power station with low generating costs that consequently runs at high loads for long periods.
Blow down	The removal of concentrations of solids from boiler water by blowing a pre-determined quantity to waste, previously known as blow off.
Boiler drum	A vessel, previously rivetted or solid forged, now usually fabricated by fusion welding which forms a focal point for water tubes in a modern boiler. The steam drum normally provides a reserve of water for the tubes and a space in which the steam generated can separate out from the water. Multi drum boilers may include water drums set at a lower level than the steam drum and a mud drum set at the lowest possible in which solids are allowed to settle before being blown down to waste.

C E A	Central Electricity Authority, a change of title of the B E A, brought about in 1955 as a result of the removal of Scotland from the control of the electricity authority.
C E B	Central Electricity Board, a Board formed as a result of the 1926 Electricity Act to direct, own and operate the Grid on behalf of the state - See Appendix III.
C E G B	Central Electricity Generating Board is the board responsible for the generation of electricity since January 1958, when the Electricity Council was formed to have overall responsibility for the supply industry.
Calorific value	A measure of the total heating power of a fuel usually expressed in Btu's.
Capacity	The output usually in megawatts that a power station can give.
Capital charges	Expenditure or charges which are spread over a longer period than that in which they arise.
Caustic cracking	Cracking in steel under stress in the presence of high concentrations of caustic soda.
Chain grate stoker	A fire grate formed by a moving continuous chain of cast iron links, built in various widths to suit the boiler.
Commissioning Date	The date when an item of plant is first available for use.
Corrosion fatigue	The occurrence of cracks in steam pipes, boiler drums and other parts caused by repeated thermal and mechanical stressing.
Condenser	A vessel in which exhaust steam from an engine or turbine is converted back to water by passing cold water through a tube nest in the vessel.
Creep	The gradual stretching of metal under stress. For a given stress the rate of creep increases with temperature.
Critical pressure	The pressure below which latent heat is required to convert a liquid into vapour.
Cut off	The point at which the steam inlet valve shuts on a reciprocating steam engine, usually quoted as a percentage of stroke.

Deposits	The collection of fine ash on boiler and superheater tubes which prevents heat transfer and restricts the passage of gases.
Downcomer.	External boiler pipework used to convey water from the boiler drum to bottom water wall headers.
Downtime	Periods during which an item of plant is shut down for overhaul or repair.
E S I	Electricity supply industry.
Economic loading	The distribution of load between a number of items of plant to ensure that each one runs at the highest level of efficiency.
Economiser	A device consisting of banks of tubes through which water passes before entering the boiler proper, the water is heated as it passes through these tubes by exhaust gas from the boiler.
Electrostatic Precipitator	By applying high voltage direct current to a wire grid within a separation chamber the dust is ionised and abstracted from the gas passing through the precipitator.
Energy	The capacity for doing work.
Exhauster Fan	Paddle type fans used to draw pulverised fuel and the carrying air from suction type mills.
Furnace rating	The heat input to the furnace; usually expressed in Btu/hr/cu.ft of volume.
Grid	An interconnecting network (grid iron), which operated at 132 kV to transfer supplies between power stations and was originally controlled by the CEB; the section of this system which work at higher voltages is known as the super grid.
Header	Usually a square section tube used for water distribution in a water tube boiler; normally water enters via downcomers and leaves via rising water wall tubes, hand holes with sealing caps are included for clearing internal deposits.

I C L	International Combustion Ltd, manufacturer of boilers and ancillary plant who did extensive early work on the use of pulverised fuel in power stations.
I C E	Institution of Civil Engineers.
I E E	Institution of Electrical Engineers
I M E	Institution of Mechanical Engineers
I M E A	Incorporated Municipal Electrical Association
kW	Kilowatt: 1000 watts, practical unit of rate of consumption of electricity.
kWh	Kilowatt hour; a measure of electrical quantity when one kilowatt flows continuously for one hour.
Load factor	The ratio of the amount of electricity produced in a given period to the amount that would have been produced if the maximum demand had been maintained throughout the period.
M S U A	Manchester Steam Users' Association
MW	Megawatt : 1 million watts, a large unit of electricity convenient for use in power-station practice.
N D T	None destructive testing. A method of testing plant parts for soundness by means of gamma rays, ultrasonics, or magnetism without necessarily dismantling the parts concerned.
p s i	Pressure in pounds/square inch, sometimes qualified by a (absolute) or g (gauge) when the pressure of the atmosphere is considered. Throughout this thesis psi is used as the small difference in pressure due to the atmosphere only needs to be considered in technical calculations.
Peak load	The system's highest demand for electric power during a given period.

Pounds of steam per pound of coal	The number of pounds of steam generated from every pound of coal burned. This figure is a useful check on boiler efficiency providing a consistent coal is burned.
Primary air	The air for combustion which first comes in contact with the fuel.
Primary air fan	A P.A. fan is fitted with pressure type mills. It draws air from the air heater to pressurise the mill and act as a carrying medium for the pulverised coal.
Pulverised fuel	Coal finely ground so that it burns in suspension in a furnace, usually known as P.F.
Pulverised fuel burners	Various designs all mix and eject P F and air through nozzles in such a way that the mixture will light instantly and continuously so long as fuel is supplied.
Range plant	Turbine and boiler plant connected by a common steam main which enables a turbine to draw steam from two or more boilers, and the steam from any boiler to be taken to two or more generating sets.
Regenerative feed heating	The use of steam bled from the turbine to heat the feed water for the boiler.
Re heat	The exhaust steam from the high pressure cylinder of a turbine is passed through the re heater section of the boiler. It is thereby re heated, usually to its original temperature before entering the intermediate pressure cylinder of the turbine for further work.
Spinning Reserve	The difference between the actual load on the electrical system and the output capacity of the generating units connected to the system.
Scale formation	Calcium and magnesium salts tend to form a hard scale on the water side of boiler tubes, the higher the working temperature the faster the scale forms. Chemical or other treatment of the feed water is designed to remove or change the chemical structure of the salts.
Secondary air	Air introduced into a combustion chamber to promote turbulence and complete combustion.
Sootblowers	Devices used for cleaning boilers. Jets of steam or air are blown at the gas sides of heating surfaces to remove dust deposits while the boiler is on load.
Stays	Long bolts used as internal supports for large flat areas of plate in a boiler.

Steam tables	Published tables giving agreed values for total heat, volume, and entropy of steam and water at various temperatures and pressures.
Steam turbine	A heat engine used to convert the heat energy in steam to mechanical energy, its mechanism consists of fixed and moving blades against which the steam acts to rotate the shaft.
Tangential PF burner	In this arrangement the burners are positioned at the four corners of the furnace, and are adjusted to fire tangentially to an imaginary circle at the centre of the combustion chamber.
Tertiary air	A third supply of air sometimes introduced along the path of a flame, after the secondary air inlets to assist with the complete combustion of long flame or slow burning coals.
Thermal efficiency	Calculated by dividing Heat output by Heat input. This calculation may be applied to individual items of plant or may give the overall efficiency of the power station, heat units used in the calculation must be compatible, normally Btu's.
Undertaker	Company or Local Authority who undertakes to provide a supply of electricity.
Unit generator	A boiler and turbine without interconnection to other boilers and turbines, normally controlled from a central point.
Vertical PF Burner	Used for low volatile coals which burn with a long flame where turbulence is not required.
Volatile matter	Hydrocarbons in coal are given the collective name of volatile matter.
Volt	The unit of electrical pressure.
Water walls	The walls of boiler tubes surrounding the combustion chamber, replacing the firebrick of early water tube boilers.
Wetness loss	Loss caused by moisture in wet steam impinging on turbine blades, minimised by high steam temperature or reheating.

INTRODUCTION

I

This thesis traces the development of coal fired boiler plant from the experimental installations of the early 18th century to the 1965 design at Drax power station, this being the largest coal fired boiler at present installed in Britain. From 1875 the main line of boiler development has been for use on power stations, so from this period I have confined my studies to boiler development and its relationships within the Electricity Supply Industry. The study is not intended to be an economic history although economic factors have been considered at various stages, rather it is a history of developments in boiler technology. The main question under examination is, "What factors affected these developments?" and the answers to this question have provided the underlying structure of this thesis. The thesis shows how the electrical needs of the economy, widespread developments in technology, and financial considerations have enabled the coal fired boiler to remain the most important way of generating power.

II

The approach to the subject has been mainly chronological and the body of the thesis is divided into four parts, subdivided into chapters to separate specific areas, although some degree of overlap has been necessary. Part 1 covers the invention of the steam boiler and its development to the end of the 19th century; Part 2 continues to 1940. As safety is an important subject, although of limited scope, I have departed from strict chronology and covered this subject through to modern times in Part 1, also in the period 1900 to 1940 there were a number of parallel but inter-linked themes advancing together that made it necessary to follow a thematic system to avoid unnecessary complication. The rapid advance in boiler plant technology brought about by increasing demand and full nationalisation is followed through in Part 3 and brings the history up to 1970. Part 4 draws together the various themes researched and explains

the effects of the inter-relationship between various items of plant within a power station and the effect of these relationships on boiler development.

As a result of the many developments in boiler design, the thermal efficiency has increased from about 30% in 1800 to over 90% in a modern boiler. Some of the advances that contributed to the production of low cost steam that are researched in this thesis include manpower utilisation and the efficient combustion of a gradually deteriorating quality of coal, low production costs soon became necessary in early generating stations where electricity was in competition with an established gas industry. Limitations on the use of high pressure, high temperature steam are cited as copper gave way to iron and eventually to complex austenitic steels, plant sizing and siting are also investigated and the reasons for the development of large power plants on remote sites.

III

This study of the development of the steam boiler was undertaken because of the fragmented nature of any information on the subject, previous work has tended to be on the development of the steam engine, the supply of steam being relegated to an odd chapter¹. Farey's treatise is an exception and I have relied heavily on this book for information on the early development of boilers.² John Farey (1791 - 1851) was a practising engineer who began collecting information at the commencement of his professional studies in 1806 and was personally acquainted with Watt, Woolf and other engineers of that era.

¹ Instances of this can be seen in the following books :

T Tredgold, The Steam Engine (1838), H W Dickinson, A Short History of the Steam Engine (1963), R J Law, The Steam Engine (1965), G Watkins, The Textile Mill Engine Newton Abbot (1970).

² J S Farey, A Treatise on the Steam Engine (Historical Practical & Descriptive) (1827) Reprinted Newton Abbot 1971.

Another engineer and boiler maker, William Fairbairn (1789 - 1874), provided extensive information on the development of materials and methods of his lifetime. Contemporary encyclopedias are a valuable source even though the contributors are frequently anonymous, but engineers of some repute were invited to contribute articles: Fairbairn for instance provided the section on Iron in the 1861 edition of the Encyclopedia Britannica.

Studies related to the electricity supply industry have tended to concern themselves with the organisation of the industry rather than the plant installed, and this is true even of Hannah's substantial work Electricity Before Nationalisation.¹ The only extensive survey of power station development is Parsons book, The Early Days of the Power Station Industry which effectively stops at the turn of the century.² There is, therefore, a need for a more technical treatment of the industry and this thesis meets part of this need. My most important sources have been engineering journals and institution papers which have provided a mass of useful information; the engineering journals were on some occasions selective in their approach to new installations, but the number available ensured that the field was adequately covered. Technical papers to various institutions and societies provided a reliable source of information on contemporary experience, but papers of this nature are often prepared by people who have made a success of an installation so that questions and comments from the audience often gave a wider and more realistic view of the situation. Contemporary text books deal more with the authors ideas of best practice than with actual experience, Boiler House Practice by J N Williams being an important exception.³ Reports of plant tests, electricity commissioners data, and newspaper reports provided supplementary

1 H H Ballin, The Organisation of Electricity Supply in Great Britain (1947)

H Self & E M Watson, Electricity Supply in Great Britain - Its Development & Organisation (1952)

L Hannah, Electricity Before Nationalisation (1979).

2 R H Parsons, The Early Days of the Power Station Industry (Cambridge 1939).

3 J N Williams, Boiler House Practice (1956).

sources while various lines of investigation were suggested by my own experience and that of colleagues within the supply industry.

IV

In order to understand the aims of power engineers some of the theories and requirements of steam engineering are quoted below, these theories will be expanded as necessary in the body of the thesis.

Power production costs are very much affected by the quality of the steam used in the engine or turbine and are at a minimum when steam is introduced into the engine at the highest pressure and temperature the system is designed to handle, and exhausted at the lowest. Theoretically the efficiency of a heat engine is based on the relationship¹ :-

$$\frac{\text{Heat input} - \text{Heat output}}{\text{Heat input}} \times 100 \text{ quoted as a percentage}$$

and the range 'heat input - heat output' has expanded as metals able to withstand the higher temperatures and pressures have become available.

The same criterion of efficiency is applied to the boiler, the heat input is based on the quantity of coal burned and its heating value. Heat loss from the boiler is kept to a minimum by reducing the temperature of the flue gases to the lowest possible level and keeping the air flow through the boiler at the optimum level necessary for complete combustion of the coal.²

Since steam was first used commercially as a source of power, there has been a continued search to improve the efficiency of production and utilisation of steam within the constraints imposed by the availability of material and the return on capital cost. Expensive material cannot always be economically justified, as the reduced fuel costs obtained by using advanced steam conditions may not counterbalance additional maintenance costs and high capital investment.

1 E H Lewitt, Thermodynamics Applied to Heat Engines (1953), p.213

2 Ibid p.370 - 2

Steam as a working medium proved to be a lucky choice that has been able to cope conveniently with every engineering advance that has been made, any disadvantage that steam (water vapour) has as a working fluid is more than compensated for by the cheapness of water and its availability compared with any other material.

V

Such an apparently simple machine as the steam engine, requiring only coal and water, which were readily available in most areas, would appear to be a suitable vehicle for entrepreneurial activity, but in fact this activity was limited for a variety of reasons.¹ Manufacturers with skills of a suitably high standard to produce engine cylinders were loyal to Watt who held the master patent, and engine erectors trained by Watt had to be tempted away before a pirate could start in opposition. Watts' much extended patent on the external condenser, with its consequent control of the steam engine and his subsequent litigation to maintain this control, squeezed out competitors for many years.² Activities of the Manchester Steam Users Association³ and similar bodies continued the controls in an attempt to prevent boiler explosions, while later governmental action in the form of the Boiler Explosion and the Electricity Acts of 1882 and later left little scope for direct entrepreneurial activity, by imposing strict controls on technical practice and by providing monopoly powers, both of which obstructed entry into the industry.

- 1 D S Landes, The Unbound Prometheus (1969)
P L Payne, British Entrepreneurship in the Nineteenth Century (1974)
D H Aldcroft & H W Richardson, The British Economy 1870 - 1939 (1969)
cover much of the field of entrepreneurial activity in the 19th century.
- 2 E Robinson & A E Musson, James Watt & the Steam Revolution (1969)
covers the activities of Boulton & Watt & their numerous legal forays.
- 3 W Pole ed. The Life of Sir William Fairbairn (1877) Reprinted Newton Abbot (1970) contains an extensive section on the formation & activities of the M S U A.

Development of boiler plant has been a continuous process in Britain for almost 200 years, and it was anticipated that the next stage would have been to build a 1000 MW Unit by 1980: both International Combustion and Babcock & Wilcox anticipated few problems in meeting this requirement. As a result of the complete upset in the fuel industries in the 1970s, electrical demand for the first time ceased to expand at its average $7\frac{1}{2}\%$ per annum, and consequently expansion of the supply industry is now in a state of suspended animation.

This check in the growth of demand and the almost complete suspension of power station construction brought the era of continuous boiler development to an end with the design of Drax power station, and a convenient point to end this thesis.

PART ONE

DEVELOPMENTS TO 1900

The first part of this thesis considers the need for the development of a source of industrial power and in five chapters shows how the boiler developed by the end of the 19th century into an important and safe link in the chain supplying energy in a useable form to industry.

The subject of power is considered in Chapter I, and how the early atmospheric engines, supplied from simple boilers, provided a source of back-up power to water wheels. Theoretical aspects of steam utilisation are explained later in the chapter and some of the experimental physicists who worked in this field are mentioned. In the second chapter the high pressure boiler is introduced, with the consequent dangers of explosion, the necessary safety requirements, inspection techniques and government legislation needed to control this danger through to the present day are discussed. Further development of boiler plant during the 19th century, including the smoke tube and water tube boiler, are discussed in Chapter II. Various items of ancillary plant were developed in the latter part of the century and their effect on improving boiler efficiency are also discussed in this chapter. In Chapter IV the various types of boiler used in the early electric light stations are described and the reasons for their selection are discussed and some comparison of cost is made; the effects of the Electricity Acts of 1882 & 1888 are also noted. Deptford, the first super power station, is described in this chapter and the advantages of automatic stoking and superheated steam in the larger power station are also investigated. Chapter V summarises the development of boiler materials and manufacturing techniques to the end of the 19th century and notes that all the necessary elements for an efficient boiler design, capable of considerable expansion, were available to service an expanding electricity supply industry.

I

Before the 18th century industrial power depended on four basic sources of power: human, animal, wind, and water. The use of human and animal power was reaching its limit by the beginning of the 19th century.

Expansion of the use of wind power was limited; the erratic nature of air currents and the fact that wind could not be stored meant that this type of power was unsuitable where paid employees working regular hours were involved.

Water power, however, showed greater possibilities of development, initially the speed of water flowing in hill streams was used to drive horizontal or vertical water wheels by striking the paddles.¹ Users of water power realised that by building dams upstream of the factory water could be stored and controlled. This store of available energy could be converted into velocity energy and used in the older type water wheel. The improved over type water wheel, where the weight of water provided the driving force, and later the water pressure engine, where the water was used to drive a piston, made more power available.

Storage of water by the use of dams evened out daily cycles and water could be stored overnight, but excess or flood water could not be stored against drought in the summer without heavy expenditure on a large water collection system. Mine owners had further problems, their main power requirement was for pumping water from the workings, therefore, mine engines could not be placed below the lowest natural drainage point. The power had to be taken to lower levels by wooden pump rods with consequent high friction losses at support points.

¹ R A Buchanan, Industrial Archaeology in Britain (1972), p.240

In order to have a more compact source of energy under the complete control of management and free from interference by rivals, or dissatisfied workers, natural philosophers and inventors began to look at the possibility of using the pressure of the atmosphere. Toricelli, a pupil of Galileo, had proved in 1643 that atmospheric pressure existed and ways of obtaining vacuum to utilise this pressure were investigated. An internal combustion engine, in which the explosion of gunpowder was used to create a vacuum, was tried by Papin¹, but this was abandoned, due to lack of a control system. Both alcohol and carbolic were tried as fuels before Otto² produced a gas fired internal combustion engine in 1876.

Combustion external to the engine had been used by the Greeks in the 1st century AD, when the hot air produced by fires on an enclosed altar was used to displace water. Later experiments by such people as the Marquis of Worcester³ (circa 1650) and Thomas Savery⁴ in 1698 used steam as a more convenient operating medium as dry steam occupies more than 1500 times the volume of water from which it is formed.

The earliest type of boiler used commercially supplied the atmospheric engines of Savery and Newcomen⁵ and was a development of the under-fired brewing copper. The working pressure was barely above atmospheric and a lead or wood cover to exclude the air was all that was required. A more advanced form for a working pressure of 2 to 3 lb/in² gauge, was the "Haystack Boiler".⁶ See illustration overleaf.

1 Denis Papin. French Scientist (1647 - 1712)

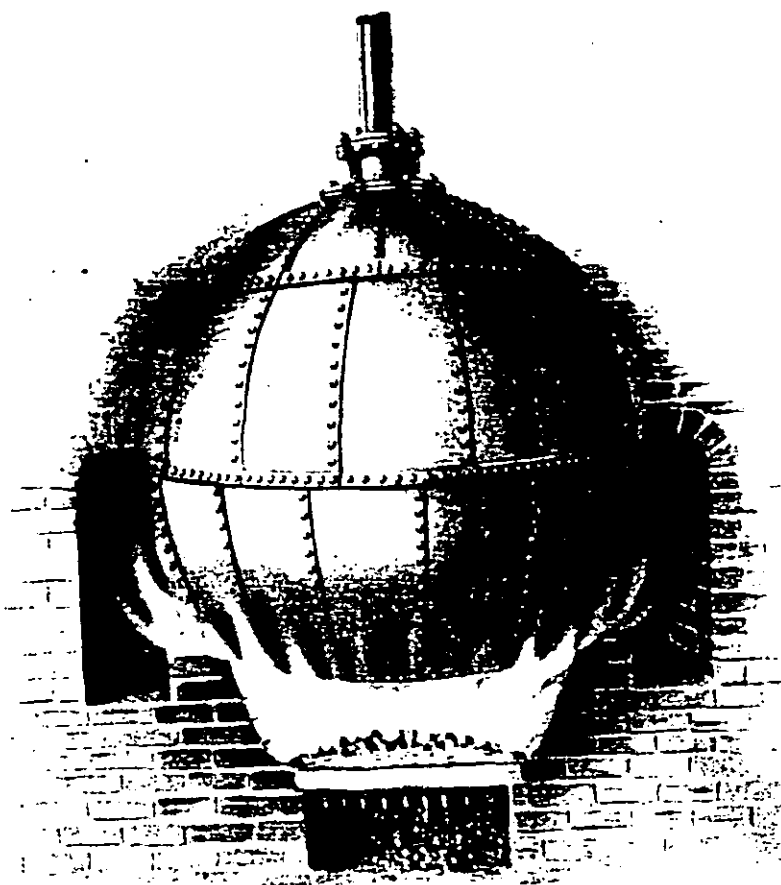
2 Nicholas Otto. A German amateur scientist & inventor

3 Marquis of Worcester. Natural philosopher & experimenter

4 Thomas Savery. Cornish mining engineer

5 Thomas Newcomen. Ironmonger of Dartmouth who introduced the atmospheric engine in 1712

6 R J Law, 'A Survey of Tank Boilers down to 1850' Transactions of the Newcomen Society XLVIII (1976/77), 25 - 37



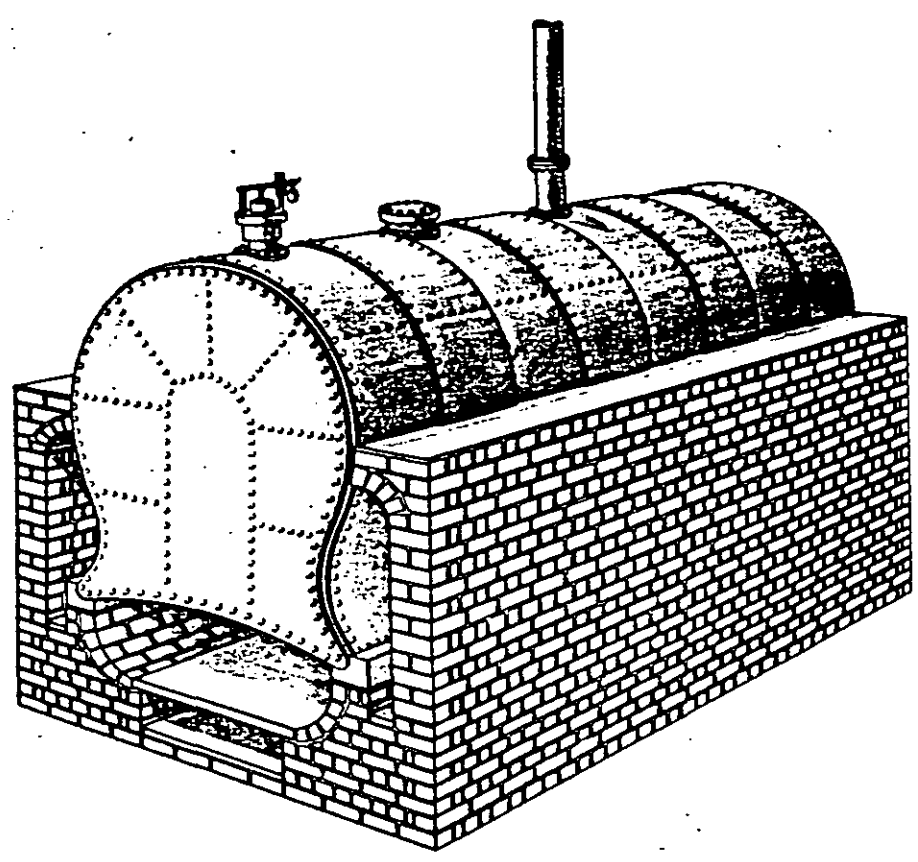
The boiler illustrated is a typical example of that used in 1725, made of riveted wrought iron plates instead of the copper sheets which had been used before this date.¹ The hot gases from the fire passed round the lower half of the boiler before reaching the chimney.

With the coming of Watt's engine, steam was required in greater volume and this meant increased boiler heating surfaces. As a result the 'Haystack' boiler became elongated and finally developed into the 'Wagon Boiler'.² This type remained in extensive use for 50 years despite being unable to withstand a working pressure of more than 5 lb/in² gauge. The weakness of this shape at higher pressures became only too evident and Trevithick in this country and Evans in the USA decided that the only practical shape of boiler for higher pressures was circular. Thus around 1795, when rolled iron plates were available, construction became more similar to the 'egg' or 'dish' ended cylindrical boiler, this boiler

¹ M B Rowlands, 'Stonier Parrott & the Newcomen Engine' Transactions of the Newcomen Society, XLI (1968/69), 49 - 64.

² see illustration overleaf.

WAGON BOILER



generated about 3 to 4 pounds of steam per pound of coal, an approximate efficiency of 2½%.¹

Steam continued to be the most suitable working medium to convey heat in a useable form from an external heat source to an engine. Other substances such as mercury and methyl have been used, but water for steam generation is universally available, although its quality and cost may be widely variable. Water is not in any way toxic and in the form of steam can hold a large quantity of heat per unit volume.

¹ Sir Warrington W Smyth, Coal & Coal Mining (1899), p.203
Manchester Steam Users Association - A Sketch (Manchester 1905), p.61
 The MSUA took exception to this design of boiler and considered no amount of careful inspection could make them safe.

If water at 32°F is heated at constant atmospheric pressure its temperature will increase until boiling point is reached at 212°F. The heat absorbed by the water in reaching boiling point is known as sensible heat, as the effect can be sensed by a thermometer.

Should the heating be continued after boiling point is reached, there is no increase in temperature, the heat absorbed is utilised in converting the water into steam and is known as latent heat.¹ During this process of conversion the steam contains water in suspension and is known as wet steam; the ratio of the weight of actual dry steam to the total weight of steam is called the dryness fraction. When the whole of the moisture is evaporated it becomes dry saturated steam and is still at 212°F if it is at atmospheric pressure. In changing its state one pound (.0161 cubic feet) of water makes 26.79 cubic feet of dry steam.

Once this condition is reached the addition of further heat causes the temperature to rise again and the steam becomes superheated, the limiting temperature of superheated steam is a metallurgical problem and 1100°F final temperature is the highest commercially used. At a temperature of 1100°F the pipework is at a dull red heat and is reaching the point at which the combination of temperature and load is such as to shorten the safe life of the superheater and pipework.²

1 S H Moorfield & H H Winstanley, Heat Engines (3rd edn 1947), pp.73 - 77

2 Babcock Pipework Babcock & Wilcox Publication 1564 (c1955), p.3

The higher the temperature the more energy the steam contains. If the pressure in the heating vessel is increased, the temperature at which the water boils rises, conversely at lower pressure it boils at a lower temperature. All the changes in temperature, pressure, and volume are tabulated in steam tables so that the energy levels available in steam at the various conditions is readily obtained.

Early work on the properties of steam was done both by Beighton and Payne, but it was not widely known and James Watt found it necessary to carry out a number of experiments in 1764 to obtain the latent heat and specific volume of steam.¹ This work was a preliminary to Watt's invention of the separate condenser in 1765, he carried out further experiments in 1774 and 1781 working at pressures up to 43.5 psig. The first publication of experiments on steam was made by Bettencourt in France in 1790 giving a series relating pressures of steam at different temperatures, the more wide ranging experiments of Watt were not published until 1821.² H V Regnault in the 1840s made the first systematic series of measurements on the heat properties of steam at the higher pressures in use after the expiration of Watt's patent. Professor H L Callender published the result of many years work on the properties of steam in 1900 and producing therefrom a set of steam tables.³ Since then much work has been done by many eminent workers and by 1930 satisfactory practical agreement had been reached for most of the properties over a wide range. Although the precise values of steam tables are useful when exact figures are required for thermodynamic calculations, the practical application of high pressure steam frequently ran in front of published values until the Keenan steam tables were issued in 1930.

1. J. Fairey, A Treatise on the Steam Engine (1827), .1, p.313

2 Ibid, p.405 .

3 Efficient use of Steam (HMSO 1968), p.820

The earliest steam engines utilised the vacuum created by the sudden condensation of steam, either to draw water into the cylinder as in the Savery engine, or to pull down a weighted beam as in Newcomen's engine.¹ Vacuum is still used in modern steam practice, so that steam, over a range from 3,659 lbs/sq.in and 1100°F, down to a vacuum of 29" of mercury is used in a modern steam turbine. Steam at a pressure of 200 psig and 800°F allowed to expand naturally to a vacuum of 28" Hg would require a heat input of 1356.4 Btu's/lb of steam, and the heat rejected to the condenser would be 916.016 Btu's/lb steam. The theoretical efficiency obtainable using steam over this range would be :

$$\frac{1356.4 - 916.016}{1356.4} \times 100 = 32.46\%$$

Using steam at the most advanced conditions a theoretical efficiency of :

$$\frac{1444.2 - 765.8}{1444.2} \times 100 = 46.97\%$$

is obtainable. If used over this range, the moisture in the exhaust steam is likely to cause damage to the engine and so it is necessary to reheat the steam at some point. Re heating of steam improves the theoretical efficiency of a heat engine, but it is not always economically advantageous because of the cost of additional plant; this point will be discussed in a later section.

1 H W Dickinson, Thomas Newcomen Engineer (2nd Edn Dartmouth 1952), p.3

II

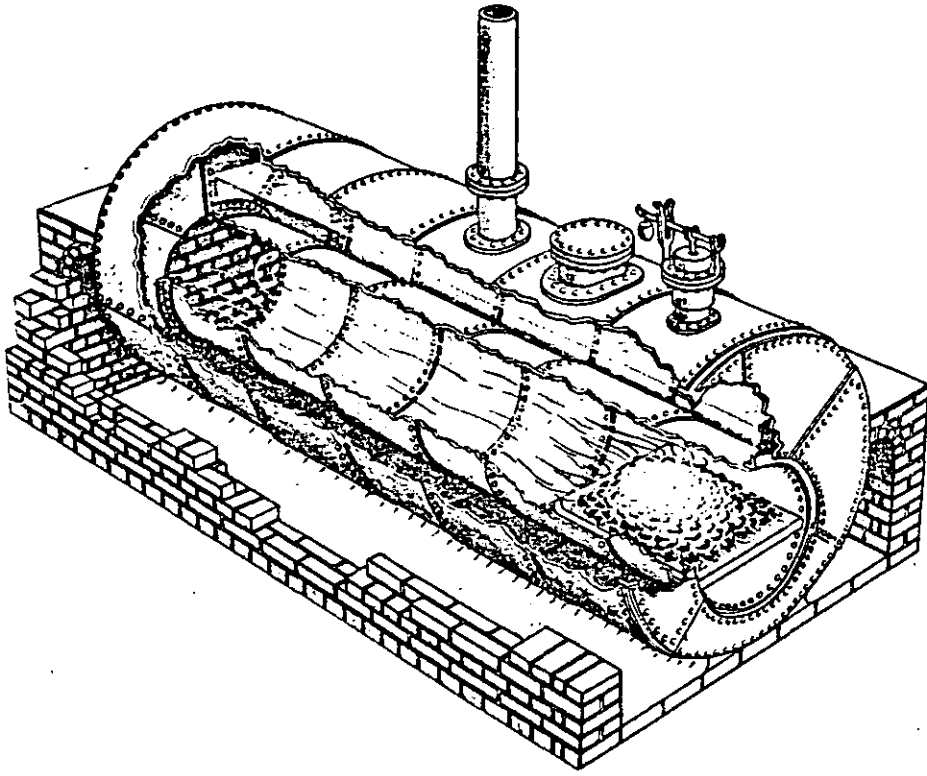
The first steam boilers were more likely to implode than explode as steam was drawn from the boiler by the suction of the piston. As operating pressures increased and internally fired boilers were introduced, disastrous boiler explosions became more common. Trevithick's Cornish boiler, introduced in 1804, was the fore-runner of modern boiler practice; being of cylindrical form with a large fire tube running through the centre, it had the best shape to resist the internal forces.¹ Unfortunately the necessarily large fire tube (diagram over) limited the steam space in the top of the boiler and left a shallow depth of water above the hottest part of the fire so that even this design was likely to explode if the water level was allowed to fall below normal working level.

Various forms of weight-loaded safety valves were in use at this time, the first being attributed to Papin and used on his digester (pressure cooker) in 1682.² The safety valve was, however, easily tampered with, or wedged shut by the stoker who often did not appreciate the danger of this practice.

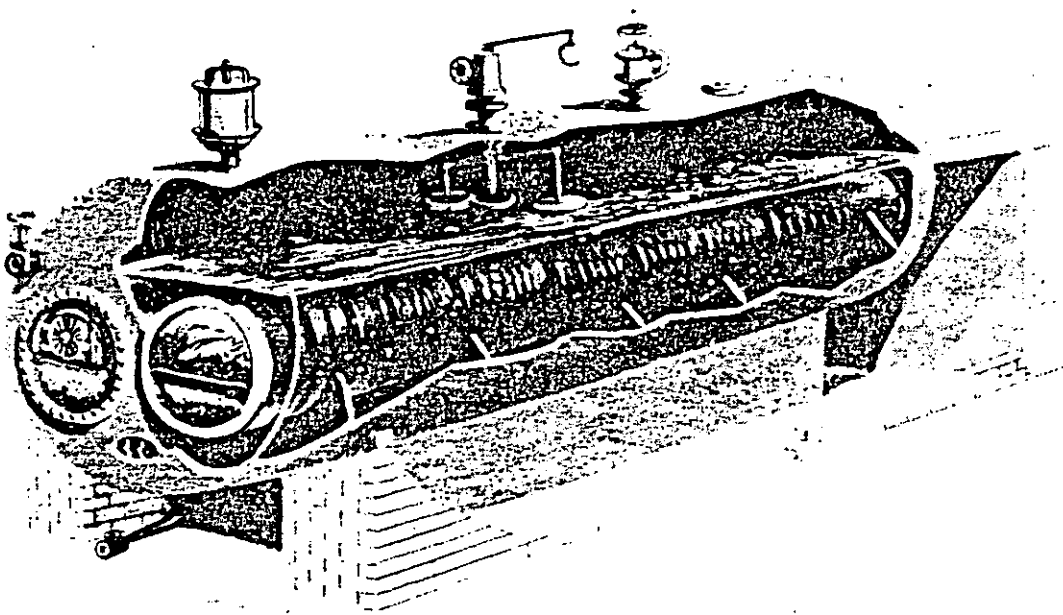
Wm. Fairbairn, a Manchester engineer and boiler manufacturer, with a strong interest in materials testing, realised from the number of boiler explosions that were occurring, that a programme of research and training was necessary to provide the information required by both manufacturers and users. As a result of this programme the Lancashire boiler was patented by Fairbairn on April 30th 1844 (No. 10166), this design had two smaller fire tubes instead of the one large tube of the Cornish boiler. These smaller tubes were subject to less strain, while allowing an increased fire grate and heating surface, it also meant a much greater depth of water could be maintained over the fire tube.

1 L T C Rolt, Victorian Engineering (1970), p.63

2 J Fairey, A Treatise, 1, p.108



CORNISH BOILER



LANCASHIRE BOILER

The expansion of manufacturing industry and the subsequent large demand for steam boilers, led to the making of inferior boilers by inexperienced manufacturers, and boiler explosions became a common occurrence. Many fanciful theories were put forward at the resulting inquests and Wm. Fairbairn was often called as an expert witness. In November 1845 at Bolton the inquest jury recommended that his report should be forwarded to the Secretary of State for the Home Department, with a view to bringing in legislation on steam boilers, but no action was taken by the Department. Boiler explosions continued to take their toll of life and property and in late 1854 Fairbairn convened a number of meetings which culminated in the formal establishment on January 23rd 1855 of the Manchester Steam Users Association, with an initial enrolment of 271. The objects and constitution of the Association were quoted in *The Life of Sir William Fairbairn* (see Appendix 1).

After the first eight years of its existence the Association was inspecting some 1600 boilers, and only 3 accidents with the loss of 2 lives had occurred on the premises of members. By 1874 the number of boilers under regular inspection had reached 2,689, and government interest had been aroused. A bill to place all boilers under government inspection was put before Parliament in 1869 by Henry B Sheriden MP, but it did not reach the statute book. In 1870 the bill was re-introduced and was strongly objected to by Fairbairn and the Manchester Association who preferred the government not to interfere in such matters. These objections were successful and a select committee was appointed under Mr John Hick to investigate the question.¹ The report, issued in June 1871, recommended that the responsibility for explosion should remain on the steam users and that the efficiency of coroners' enquiries should be somewhat improved.

1 John Hick - an engineer from Bolton, a prominent member of the MSUA and the British Association

One frequent topic of discussion at the time the Manchester Steam Users Association was founded was the provision of boiler insurance, the majority of the Association's management were against this as they considered it would lead to carelessness. Mr R B Longridge, however, was in favour of providing this facility.¹ Because of this difference of approach, Mr Longridge resigned in 1859 to form the Steam Boiler Assurance Company, now known as the Vulcan Boiler & General Insurance Company. The formation of a second specialist company, the National Boiler Insurance Company in 1864, which the MSUA's assistant engineer joined, caused the association to review their attitude so that by December 1864 they also were providing insurance.²

Attitudes to government interference slowly changed and in 1882, Mr H Mason, the association's President, introduced a Bill in Parliament which eventually became the Boiler Explosions Act 1882. This Act made it compulsory to report all explosions of boilers to the Board of Trade within twenty four hours, and gave the board powers to instigate an enquiry, the costs being chargeable against any person responsible for the explosion.

A second Act in 1890 extended the provisions to cover steam ships other than those in the service of the crown. These Acts had the effect of placing the responsibility for explosions on the owners where the boilers were found to be at fault, and so it became advisable, for their own protection, that the boiler should be known to be in sound condition. Certificates of inspection from a boiler insurance company provided the necessary proof of the fitness of boilers for the duty they were to perform.

1 C A Smith, 'The Growth of Boiler Assurance', The Heating & Air Conditioning Journal; (February 1979), 52

2 MSUA - A Sketch (Manchester 1905), p.67

Clauses in the Factory and Workshop Act 1901, applied to steam boilers and included the following :

- (a) The boiler should have attached to it a proper safety valve and a proper steam gauge and water gauge to show the pressure of steam and the height of water in the boiler; and
- (b) be examined thoroughly by a competent person at least once in every fourteen months.

The Act required that the boiler and fittings should be maintained in good condition and a copy of the inspection report should be attached to the general register of the factory.

Photographic evidence shows that new boilers in the 1890s were already fitted with the required gauges. However, the requirements brought older boilers up to the necessary standard, and prevented neglect of equipment where already installed. The provision that the boiler be inspected every fourteen months made compulsory the annual examination required by boiler insurance companies, whilst allowing two months leeway to fit in with the load requirements. Having a boiler out of service for cleaning and inspection in power stations was not a major problem as the lighter summer loading left spare plant capacity. In industrial plants which often ran without spare capacity, the inspections had to be fitted into short holiday breaks and this Act helped the insurers to gain the co-operation of their clients.

The 1901 Act proved to be generally satisfactory and it was not materially altered before its repeal in 1937. Basic boiler design was little changed in this period and the clauses in the Act were adequate to deal with such changes as were made. The Factories Act of 1937 combined the provisions of the previous Act with that of others to provide a comprehensive Act with a wider scope.

Boiler inspection from the earliest days included an overpressure hydraulic test, visual inspection for cracks, particularly in known trouble spots, and the use of hammer testing at riveted joints. Forged drums for water tube boilers made from a single billet were introduced in the late 1920s, followed shortly afterwards by drums of welded construction. Many older water tube boilers continued in use throughout the country and as a result of differential expansion strains these drums tended to leak along the seams as they got older. Minor leaks were often left for some time before being repaired by caulking along the seams. The development of water treatment chemistry in the 1920s included a technique of dosing the water with caustic soda to make it slightly alkaline. This was an advantage in that it overcame the natural acidity of the water and of any acids that were formed from the carbon dioxide and oxygen absorbed from the atmosphere. If a minor leak occurred, the water changed to steam and left the caustic soda behind in the joint, this strong caustic soda solution attacked and weakened the metal.

Where this condition was suspected the boiler inspector could have rivets removed and use a penetrating dye to detect any crack formation round the holes. Unfortunately undetected caustic cracking led to the explosion of a 200 psig boiler drum in October 1949 at York (Foss Island) showing that the hydraulic and hammer tests were inadequate in certain circumstances.² This explosion was so intense as to throw a large section of boiler drum a distance of 150 ft. after passing through the boiler house roof.

¹ Caustic Cracking in Steam Boilers British Engine Technical Report, New Series 1, (1952), 9

² HMSO. Report of Preliminary Enquiry (3355). Explosion of a Water Tube Boiler at the Foss Island Power Station, York. (1950)

The high voltage X ray machines in use at manufacturers' works were too large for site use and the British Electricity Authority began to search for suitable equipment for routine testing of riveted seams and welded joints. Experimental work in the Authority's North Eastern Division, in conjunction with consultants Merz & McLellan, on the use of sound wave beams resulted in the production of the Kelvin & Hughes 2B ultrasonic equipment. Ultrasonic probes are a sophisticated version of the wheeltapper's hammer, which gives a ring if the metal is sound and a cracked note if any discontinuities are present, Hughes had previously worked on sonic crack detection in armour plate in 1942, with limited success. With the sonic device the frequencies are beyond the range of human hearing and a suitably scaled cathode ray tube is used to receive the signal, any abnormal blips being due to faults in the metal.¹ This device was also found useful for checking thinning of metal in areas where corrosion or erosion was taking place. When cracking was found to be present in any riveted vessel the full extent could be found by removing a number of rivets, dusting with iron powder and applying a strong magnetic field which caused the powder to concentrate round any cracks in the metal.

By 1953 non destructive testing (NDT) teams were formed in all divisions of the BEA and investigational work went ahead on what proved to be a long job. For instance the Southern Division's inspection programme of ultrasonic testing, combined with the removal of 10% of all rivets for magnetic inspection, took 10 years (to 1960) before all riveted vessels had been inspected.

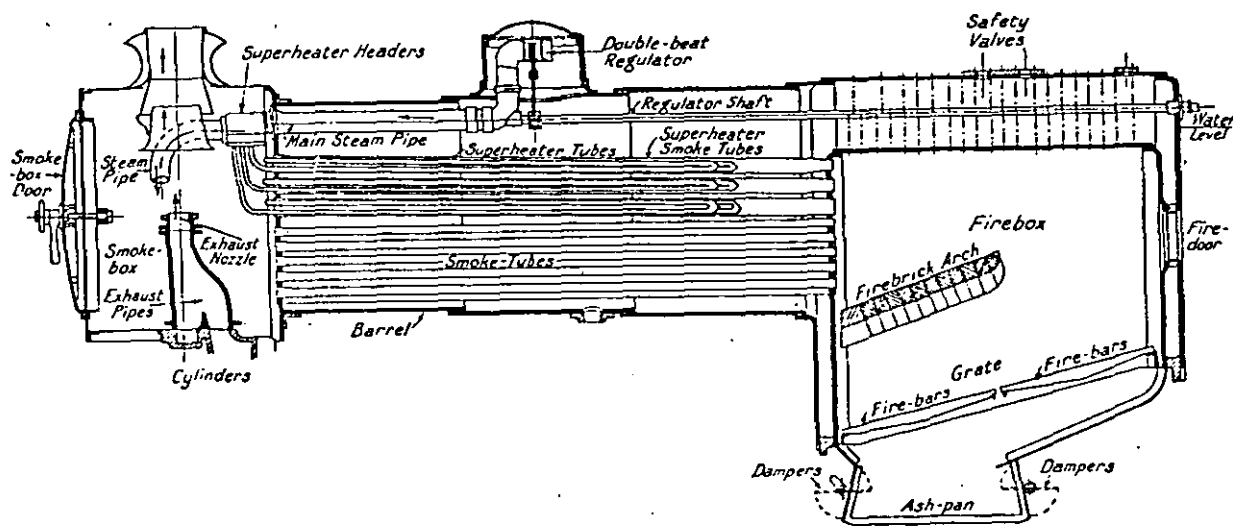
¹ Technical Guide to Ultrasonic Flow Detection (Kelvin & Hughes Ltd, 1953), Section A/2.

Increased steam pressures and temperatures, the use of welded pipe work, and the introduction of stainless steels, extended the scope of their work. As welding and NDT techniques improved it was recognised that modern designs of steam raising plant could, with safety, run for longer periods without examination, allowing expensive plant to spend less time out of service; as a result regulations under the Factories Act were amended. The interval between inspections now extends to twenty six months, until the boiler is 21 years old for water tube boilers with fusion welded or solid forged drums and headers, having an evaporative capacity of not less than 50,000 lb. of steam per hour. This amendment was effective from 27th June 1964 and has applied to every boiler built for the ESI since this date, all boilers being much larger than the minimum laid down as this size is barely adequate for a 6 megawatt turbine.

III

Many early lighting plants used at exhibitions and agricultural shows were supplied with steam from easily transportable locomotive type boilers, as was Brighton's first power station in 1882 and that at Eastbourne built in the same year. Locomotive boilers consist of a water cooled furnace and a large number of smoke tubes passing through the cylindrical main boiler, a design suggested by Henry Booth (Liverpool & Manchester Railway Company Treasurer) ¹ to Stephenson in 1828.

The semi-portable locomotive boiler was ideal for the first small power stations, being comparatively light and rapidly installed; it could be quickly brought up to pressure and could cope with rapid changes of load. Men experienced in this type of boiler and its associated small engine could be poached from the railways. As stations became larger, boilers also needed to be of greater capacity and so the locomotive boiler was soon superseded.



Semi-portable Boiler

¹ Edward Knight, American Mechanical Dictionary (New York 1874), p.2328

The Lancashire boiler, introduced in 1844, became the most widely used industrial boiler in Britain; it was often used in the early lighting stations.¹ Initially it consisted of a cylindrical shell, 12 feet long and 6 feet diameter, made from some 40 plates; it was pierced by two internal cylindrical flues, each containing a fire grate. External side and base flues built into a brick setting caused the hot gases to travel three times the length of the boiler before being released to the atmosphere. Alternating stresses caused by heating and cooling often led to cracking of the drum over the riveted flange of the fire tube; the tube was also liable to collapse under pressure if it was in any way out of true. Crude boiler makers forcing cheap small plates into line added to the minor design faults and so the early Lancashire boilers did not live up to the expectations of its designer, William Fairbairn.

The addition of various patent reinforcing rings to the fire tube and the development by manufacturers of methods of producing large steel plates of consistent quality allowed the boiler not only to grow in size, but also to work safely at much higher pressures.

A number of variations on the basic Lancashire boiler were tried, the most important was the Galloway modification introduced in 1851.² In the Galloway variation the two tubes were joined into one from about the halfway mark and conical cross tubes were fitted into this section, increasing the heating surface while still being easy to clean. The Economic and Scotch boilers were other variations on the Lancashire boiler, with added smoke tubes, these types were initially used in small power stations and eventually became successful in marine and light industrial fields.³

¹ See illustration on page 16

² E Matheson, *Aid Book to Engineering Enterprise* (1889), p.522

³ G E Foxwell, ed. The Efficient Use of Fuel (HMSO 2nd edn.1957), pp.325-327

These various developments in Lancashire boiler design show something of the improvements in manufacturing techniques over a period of some sixty years.¹ The fact that riveted joints were a source of weakness was soon realised and efforts were made to increase plate size, and steel was introduced as soon as it became a consistent, reliable product. Variations on the Lancashire boiler were introduced to improve the output from a given physical size as the sites into which boilers had to be fitted were often very cramped. The end result was a cheaper, more efficient boiler, able to work at the higher pressures demanded in the late nineteenth century.²

More rapid steam raising was possible with the Economic and Scotch boilers and this gave some improvement in efficiency as it was possible to allow fires to go out overnight, but because of the large amount of brickwork and quantity of water in a Lancashire boiler it required regular boosting to maintain the temperature.

Although the developed Lancashire Boiler needed little maintenance of the parts under steam pressure, the brickwork flues required regular repair. Differential expansion between the boiler metal and the brickwork led to cracking of mortar and bricks, this allowed flue gas to by-pass some of the heating surface and reduced the efficiency of the boiler. The more expensive Economic and Scotch type boilers did not suffer from this problem, but they were more difficult to clean on both the water and gas side, so that total maintenance costs were almost as high and fouling of the tubes caused a similar loss of heat to the chimney.

¹ W D Wansborough, Modern Steam Boilers (1913), pp.7 - 20

² J D French, Modern Power Generators (1908), p.7

A design that proved to be of the greatest importance to the supply industry was that of the Water Tube boiler, the principle behind this boiler is that of separating the water into numerous tubes of small section so that each one is subject to the maximum amount of heat; bronze water heating vessels embodying this principle were found in the ruins of Pompeii. Early steam generating boilers employing water tubes were devised by Count Rumford (1796) and Woolf (1803), the first practical attempt to make a high pressure boiler was that of Jacob Perkins (1824) who worked a tubular boiler for two and a half years at pressures between 500 and 800 lb.per sq.in.¹ This water tube boiler consisted of a number of cast iron tubes arranged in three tiers in the furnace, a pump was used to force water through the tubes and it had no boiler drum. It would appear that this boiler was ahead of its time as it was very similar to the once-through supercritical boiler introduced by Benson in 1922.

Joseph Eaves followed in 1825 with a design having 100 tubes in the furnace, connected 10 at a time, via tee pieces to top and bottom drums, large diameter downcomers external to the furnace were used to ensure good circulation. In 1849 the Belleville water tube boiler was introduced in France; it consisted of a number of flattened spirals surrounding the furnace, formed by screwing the ends of straight tubes into junction caps of malleable cast iron or steel; this feature meant the boiler could be opened in sections for scale to be removed from the tubes. The boiler was little used in land practice, but became popular with the French navy because of the ease with which the tubes could be cleaned.

Stephen Wilcox patented his water tube boiler in the USA in 1856; this design used inclined water tubes extending over the fire between water legs placed at front and back with a 'D' shaped steam and water drum running parallel to the tubes. Wilcox was trying to produce a safety boiler by using a number of parallel water tubes in which the steam was generated,

¹ S J Thompson, 'Boilers Past & Present' Proceedings I Mech E CXLVIII (1942), 137 - 40.

but in doing this he introduced weakness by using large flat areas for the water legs and a flat base to the 'D' shaped drum which had to be stayed to prevent bulging.¹ Although this boiler had some unsafe features it nevertheless provided a good basic design which was developed and refined as the years went by. Another sound basic design was produced in the Rowan Tri-drum boiler, introduced in 1858 as the predecessor of the Stirling bent tube multi-drum boiler, patented in 1889 in the USA.

In 1867 the now world famous names of Babcock & Wilcox appeared for the first time with the introduction of the sectional water tube boiler with free circulation of water in one continuous circuit.² The joint design was based on that of Stephen Wilcox, but the steam generating tubes were connected to a further nest of tubes which replaced the drum, and the square section of the steam legs produced the ultimate in safety boilers at that time. See illustration on p.29.

Interest in the safety of boilers against explosion can be appreciated when the estimates of the energy confined within a boiler are seen.³ Working at 100 psi, a cylindrical boiler contains sufficient energy to project it to a height of over three and a half miles; a Lancashire boiler at the same pressure would project to two and a half miles, and a Locomotive boiler to half a mile. A further calculation showed that a cubic foot of water at 60 psi and heated to saturation temperature had about the same energy as one pound of gunpowder. The destructive energy available in any boiler is dependent on the amount of water it contains, the working pressure, and the speed with which it is released. With a shell boiler any failure was a calamity - the whole of the energy was released immediately as the seam split assunder. The boiler house was usually wrecked and often other boilers alongside were damaged.

¹ S J Thompson, 'Boilers - Past & Present' Proceedings I Mech E CXLVIII (1942), 139

² Steam, its generation & use (Babcock & Wilcox Ltd, 3rd British Edition, 1902), p.35

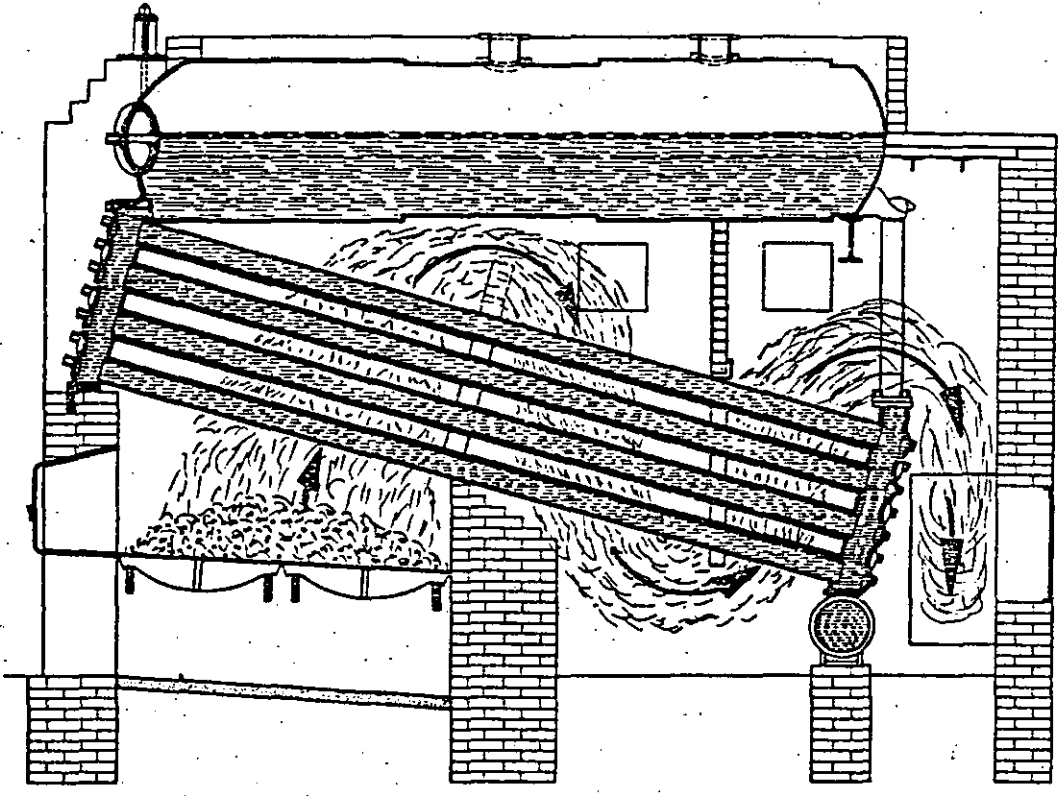
³ Ibid p.15

A tube failure was usually contained within the furnace as only a limited amount of water could flash off from within the tube. The ultra safe Babcock & Wilcox boiler did not become popular as it was unsuitable for carrying variable industrial loads. The steam and water tubes did not provide an adequate separation surface for the steam bubbles, which meant that a large quantity of water was often entrained in the steam when the boiler output was high. Steam leaks at the various joints meant that the maintenance costs were high and shut-down time was excessive. Design improvements continued, by model No.4 the drum had returned, various types of vertical headers in cast and wrought iron were used to supply water to the tubes until model No.18 was reached to provide the standard basic model supplied to power stations for many years.

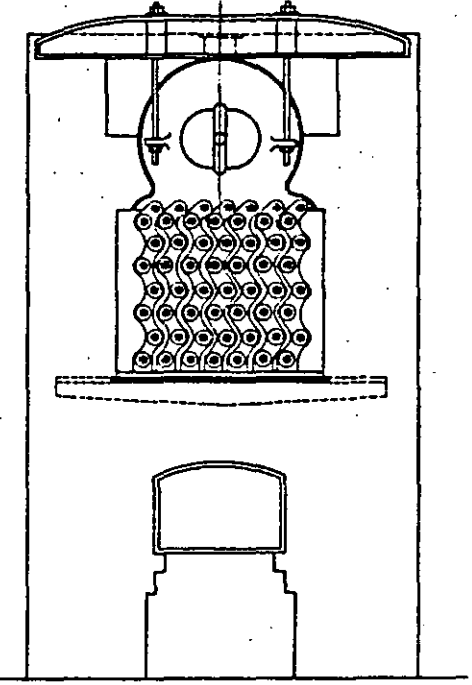
Requirements for a safe and efficient Water Tube boiler were listed by Babcock & Wilcox as follows :¹

1. Sinuous headers from the drum, two for each vertical row of tubes.
2. A separate and independent connection with the drum front and rear for each vertical row of tubes.
3. All joints between the parts of the boiler proper to be made without bolts or screw threads.
4. No surfaces to be used which require to be stayed.
5. The boiler supported independently of the brickwork so as to be free to expand and contract as it heated and cooled.
6. The drum to be not less than 30" diameter.
7. Every part accessible for cleaning and repair.

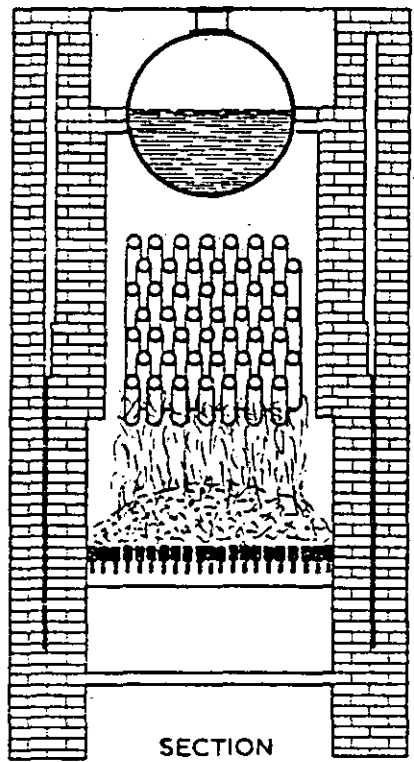
¹ Steam, its generation and use (Babcock & Wilcox Ltd, 3rd British Edition, 1902), p.39



SECTION
SIDE ELEVATION



FRONT ELEVATION



SECTION
FRONT ELEVATION

EARLY WATER TUBE BOILER

The boilers so far described boil water to produce steam, but do it very inefficiently and the quality (i.e. dryness) of the steam is variable; additional components are necessary to remedy this situation. To improve the efficiency of a boiler it is essential to have close control of the amount of air passing through the boiler, limiting it to that necessary for complete combustion. With hand firing, control is lost every time the furnace door is opened to add fuel to the fire. Any air or flue gas passing through the boiler must be cooled as much as possible before being released to the atmosphere, with the proviso that where fans are not used, the temperature must be high enough to cause the gas to rise up the chimney. To obtain the most efficient use of steam once it has left the boiler, the steam must contain the greatest possible amount of heat. As early as 1830, Trevithick realised that superheating the steam would have the advantage of reducing condensation as steam entered the cylinder of the steam engine; cylinder lubrication and gland packing problems prevented its development at the time. Later, in 1857, Hirn in Germany made some further investigation, but little progress was made until the end of the century. Wilhelm Schmidt successfully used superheated steam on the Prussian State Railways in 1897, and Wm. Patchell of the Charing Cross and Strand Power Company did some work at Maiden Lane Power Station between 1893 - 95.¹

Reducing the exhaust gas temperature was the aim of Edward Green in designing his economiser (patent number 10986, 1845), it consisted of a number of tubes through which the cold boiler feedwater was passed and it was placed in the path of the gases leaving the boiler. A similar device to pre-heat the combustion air while reducing the final gas temperature was patented by Hall in 1842, but its use tended to burn out the grate and its development was delayed, pending the introduction of improved grate materials.

¹ W H Patchell, 'Notes on Steam Superheating' Proceedings I Mech E (1896),
134 - 56

It is normally assumed that with the addition of a Greens Economiser each 10 degree F rise in temperature of the feed water passing through the economiser gives a reduction in coal consumption of 1%. A very good result was obtained by the Bleachers Association having a trial carried out on a battery of four Lancashire boilers, fitted with Greens Economisers.¹

These economisers reduced the temperature of the exhaust gases from 800°F to 330°F, raising the temperature of the water to the boiler from 110°F to 345°F, and resulted in 23.5% reduction in coal consumption. Calculations based on coal savings showed a reduction of costs of £1,750 per annum, a more than adequate return on the capital invested.

A similar test, carried out at Dalmarnock power station, showed a feed temperature rise of 133°F when an economiser was fitted to a water tube boiler, and an annual saving of about £2,400 was achieved on a boiler of twice the capacity. A much greater improvement in efficiency was achieved with the Lancashire boiler because the basic design of the two types of boiler is completely different.

Lancashire boilers in early power stations were often not fitted with economisers as the number of running hours per annum of a power station boiler supplying a lighting load was far less than that of boilers supplying industrial power plant. With reduced running, which on some boilers, may have been as little as two hours per day during the summer months, depreciation and interest charges would have been greater than the saving on fuel charges. As the station load and running hours increased, the demand for steam would rise and the installation of a common economiser for a range of, say, four Lancashire boilers, would increase the output and improve the efficiency at a lower capital cost than adding a fifth boiler.

1 A. Regnauld, Modern Power Engineering (c1920), IV, p.123

From the early days of steam boilers it was realised by Watt and others that correct firing was most important, instructions were provided by Watt as to how it should be done.

Despite this, engine owners often provided men of brawn, but little brain, as stokers and (to try to improve the situation) various mechanical stokers were introduced.¹ The first mechanical stoker, patented by Brunton in 1819 was a circular rotating grate, as it emerged from the boiler casing dead ash was scraped off and fresh coal was added from the hopper by a toothed roller. This was only suitable for externally fired waggon and cylindrical boilers and was little used.

Shortly afterwards Holmes developed a means of oscillating the grate bars so that coal was carried forward the length of the furnace, finally falling off the end as ash and clinker. This type of automatic stoker was suitable for internally fired boilers such as the Lancashire & Cornish and is still used in small industrial boilers.

In 1822 Stanley patented the sprinkler stoker which imitated the action of the fireman in spreading the coal over the grate, however, with this system it was still necessary to clean the fires by hand.

Bodmer was the first to introduce a travelling grate stoker in 1834, followed in 1841 by Jukes patent chain grate stoker, this formed the basis of the most widely used method of firing power stations in the first 70 years of the electrical supply industry.² The Jukes system used a simple flat link chain fitted with rollers, the number of chains used depended on the width

1 W R L Kent & D C Gunn, Boiler Plant Instrumentation (1956), p.24-32

2 C Flick, 'The Movement for Smoke Abatement in 19th Century Britain' Technology & Culture XXI (1980), 43

of the grate. These driving chains were connected to each other by transverse bars to which short lengths of grate were attached and coal was carried through the furnace as in the Holmes stoker.

The Vicars self feeding mechanical fire grate was also introduced about this time; in this design a regular supply of coal was pushed forward onto the fire grate by the alternate action of a pair of feeding plungers. Intermittent reciprocating motion of the fire bars carried the fire forward in a similar manner to that of the Holmes system and was the basic idea from which the Taylor retort stoker was developed.

John Daglish compared the effectiveness and efficiency of these various methods of mechanical firing and presented a paper incorporating his results to the I.Mech.E in 1869.¹ In discussing the paper the consensus of opinion appeared to be that mechanical stoking had little advantage over hand firing, except that a greater steam output could be produced per boiler and the production of black smoke was eliminated. Where adequate boiler capacity was already installed, automatic stoking was, at this time, no advantage, but on a large new installation the cost of a boiler could possibly have been saved.

Mr T R Crampton's contribution to the discussion included an extensive discourse on the use of low grade pulverised coal, which when finely ground and blown into the furnace produced extremely good results when used to fire a reverberatory furnace at Longhedge Works, Battersea. Crampton also reported results of his experiments on firing a locomotive type boiler with pulverised fuel in which he used a separate zig-zag combustion chamber lined with firebrick, to give the necessary time and temperature for complete

¹ J Daglish, 'On the Mechanical Firing of Steam Boilers'
Proceedings I Mech E (1869), 172 - 81

combustion to take place. He also made sure that adequate, but not excessive, air was supplied so ensuring the best practicable conditions were obtained for burning the coal. This system, ideal from a combustion viewpoint, but expensive in plant and power, was later to become the only way to burn sufficient low grade coal to fire a large capacity boiler. See Part 2, Chapter II.

IV

Britain's first public lighting installation was at West India Docks in 1875 and it caused a great deal of interest, not only in London, but around the country. Various installations of a public nature were tried out in the next few years, often using portable engines, with locomotive type boilers manufactured by various agricultural and road engine makers. The first municipal generating plant was installed at Billingsgate by the City Corporation Markets Committee in November 1878, using a Robey engine, a Robey was also used to light Holborn viaduct, while a Ransome, Sims & Head semi-portable drove a generator lighting the Embankment. The Holborn system lasted a mere six months until May 1879 and was shut down due to high running costs, and while the Embankment collected a few other customers, including the Gaiety Theatre, it only survived until July 1884, when its contract was not renewed because of the high charges. During the period 1878/79 there were a number of installations outside London, including Pullars of Perth, Trafalgar Colliery in the Forest of Dean, Liverpool Pierhead, Blackpool's first illuminations, using a Marshall engine, and street lighting at Westgate-on-Sea, where a Garret portable engine was installed. The locomotive type boilers used were of the simplest kind, usually working at about 60 lbs/sq.in, hand fired, fitted with a pressure gauge, a water level gauge glass, and a spring loaded safety valve.

The first steam power station to start life with the intention of being a central public supply station was Edison's Holborn Viaduct Works.¹ He offered the City of London Authorities three months free electric lighting for the viaduct and certain nearby streets, the City readily accepted and raised no objection to him supplying private consumers as well.

¹ E B Watton, Holborn Viaduct to Calder Hall (Babcock & Wilcox 1957), p.7

Current was first supplied from the station on the 12th January 1882, and the opening ceremony was on the 12th of April. The three month free lighting dated from the 24th of April, indicating that the supply could not be guaranteed before then, however, once under way current was supplied as contracted until 1886, when the station was shut down. Edison's station was completely American in design, using his own "Jumbo" 110 volt dynamos driven directly by a Porter Allen engine and supplied with steam from Babcock & Wilcox boilers.

Brighton's supply undertaking developed from a demonstration by Robert Hammond of the Brush arc lighting system, driven by a 12 h.p. Robey engine, with a Locomotive type boiler, in December 1881. He was asked by the local shop keepers to afford them a supply and this he agreed to do. Unfortunately for the Hammond Electric Light Company, he was unable to do this before January 21st, and so lost first place to Edison. A second engine was in service by the 27th February and a permanent supply was made available between dusk and 11.00pm. Business expanded and by the following year a 40 Lamp Marshall set was added. By 1885 the Hammond Company became the Brighton Electric Light Company with a new power station in Gloucester Road containing Brush dynamos with a semi-portable under the front end of a locomotive boiler.¹ This philosophy of light engines and locomotive boilers was followed throughout the life of the company until it was forced out of business by Corporation competition and eventual take-over in 1894.

Earl Street power station in Hastings was also in service in 1882.² A group of local tradesmen had formed an electric light committee in January, by May they were inviting tenders for the erection of the works. By the beginning of October the station was in operation, showing the rapidity with which a simple station using Locomotive boilers, semi-portable engines and belt driven generators could be erected.

¹ R H Parsons, Early Days of the Power Station Industry (CUP 1939), p.12

² J Boyd, 'Early Days at Hastings' Seeboard 138 (1971), 2

The equipment was supplied by Robert Hammond of the Brighton Company and for a number of years this pattern was followed wherever he was appointed as a consultant. Eastbourne, the fourth pioneer company supplying electricity in 1882, followed the Brighton and Hastings companies in building a station quickly, using light semi-portable engines and Locomotive type boilers.

Not only were the earliest power stations in the country for public supply built in 1882, but also the initial Parliamentary legislation was passed and the first IEE wiring regulations were published.¹ One of the earliest opportunities for the public to see electric incandescent lighting occurred at the Crystal Palace electrical exhibition. The Electric Lighting Act 1882 enabled the Board of Trade to authorise any local authority or company to supply electricity in an area. This authorisation permitted the installation of a system of supply, including breaking open the streets as necessary. However, the Act also gave local authorities the right to take over the assets of companies after a period of 21 years. The Act had the immediate effect of discouraging private enterprise, whilst local authorities were not particularly interested in taking the risk. Included in the Act was the right for any individual to demand a supply of electricity if he was within an area of supply. Limited development took place by avoiding the Act, e.g. by obtaining the consent of the local authority for the use of overhead lines, following railway tracks, or using culverts already in existence.

In the Electric Lighting Act 1888 the period prior to the possible exercise of the reversionary purchase right was extended to forty two years, with further optional stages of ten years. With this change a new impetus was given to the establishment of electricity supply undertakings, although the upturn in the economy in the 1890s may also have had some influence.

1 Electricity Council, Electricity Supply in Great Britain a chronology. (1973) p.4

In 1883 two further lighting companies took their first steps, starting by supplying their own premises, and within a few weeks giving supplies to neighbours; the Grosvenor gallery used Marshall semi-portables, but Gatti's restaurant had a more unorthodox approach. Stefano Gatti and his brother, proprietors of the Adelaide restaurant in the Strand, installed a generating plant and 330 lamps, for the amusement of their guests, and steam was supplied from two vertical boilers, fitted with Field tubes.¹ This type of boiler consisted of a vertical cylinder with an internal fireplace and steam generating tubes closed at one end, hanging down into the furnace, as steam bubbles formed on the tube and rose within the boiler fresh water was supplied from the body of the boiler, via an inner pipe which almost reached the bottom of the boiler tube.² Field tube boilers were frequently used on fire engines where their small water capacity and the rapidity with which they could be brought up to pressure made them ideal. Boilers of this type with rapid response characteristics could be lit up as required and attendance would be unnecessary when not generating electricity.

Unfortunately these boilers had a number of characteristics which made them unsuitable for general power station use. Any sludge within the boiler water tended to collect at the blind end of the tubes, and it could not be removed by blowing off, this meant that mechanical means had to be used with the boiler off-load, so maintenance costs were generally high. If the sludge developed sufficiently during a running period, or the boiler was overloaded, the flow pattern within the tube would be disrupted, insufficient cold water would be supplied, and violent eruptions of steam would carry water over into the engine. Should sufficient sludge or scale be formed within the inner tube, the outer one would be starved of water eventually overheat, and then rupture. The disadvantages of the Field tube outweighed the advantages of rapid steam generation, and consequently these boilers were rarely used in power stations.

¹ R H Parsons, Early days p.107

² J W French, Modern Power Generators (1908), p.11

However, a Niclausse boiler was installed at Upper Boat (Cardiff) in 1904, this boiler was similar to a Babcock & Wilcox but fitted with Field tubes. The next boiler to appear on the scene was a Marine boiler, manufactured by Hick Hargreaves & Co. of Bolton. Three double furnace boilers were installed at Whitehall Court, dated 1888, and were still in service into the 1940s no economisers were installed, but some of the exhaust steam was used to pre-heat the boiler water in a Berryman tubular feed heater, and the remainder was used to supply a heating system to the houses in Whitehall Court. The condensed steam from both systems was available for re-use in the boiler. Using exhaust or bled steam from public supply stations for heating purposes is economically sound, but has rarely been used in this country, only two such stations exist at present: Spondon H supplying steam to a nearby process plant, and Battersea supplying heat to a large domestic development across the Thames.

Bolton Road works in Bradford was the first municipal power station to be built, supply commenced in September 1889. It appears to have been the first to install Lancashire boilers and also an economiser.¹

Looking at the installations so far surveyed, the possible reason for the selection of a particular boiler type at any one site can be considered. Edison as an American and a professional inventor would tend to go for an advanced American design of boiler, following the pattern of the Pearl Street station in New York, which was already being built. In contrast Hammond, who was an entrepreneur rather than an engineer, would tend to go for a simple British design, well tried on the steam side, requiring little site preparation, and easily removed at the end of the demonstration if it should be necessary. Installation costs would be minimal, requiring almost no pipework, and fixings would be limited to a few bolts grouted in to steady the machine. Little protection would be required as can be seen

¹ T H Carr, 'The first Municipal Power Station', Electrical Power Engineer XXXII (1950), 58

with the first Grosvenor Gallery installation which was in the yard behind the building. It was inevitable in the absence of any other strong influence that Hastings and Eastbourne should follow the precedent set by their neighbouring coastal resort of Brighton. The situation of Gatti's restaurant was such that ground space would almost certainly be at a premium making a vertical boiler the obvious solution, with the addition of the Field tubes, to give rapid pressure raising characteristics it was the best choice in the circumstances. Choosing a wet back marine for the Whitehall Court station is more difficult to justify, however, once the basic foundation is built, the boiler can be installed almost in one piece, with no further brickwork or flues etc. being necessary. It is possible that site constructional and other difficulties may have had some influence on the boiler selected in this case, as the Marine can be installed in very cramped conditions. However, the Marine boiler requires frequent repair and long term costs may be high.

Bradford's supply station was not only the first to be built by a municipality, but also the first to be built in a major industrial area. With almost every textile mill in Lancashire and Yorkshire fitted with a Lancashire boiler it would have been impossible to think of fitting anything else. The Lancashire is an economical boiler, needs few repairs, can be run on poor water, and at that time a local manufacturer could be found in most industrial areas.

As the various power stations were extended different types of boiler were often installed, the requirements of capacity, flexibility and running costs varied as the undertaking grew, eventually settling on a water tube boiler. C H Wordingham in 1901 quoted boiler cost per 1000 lbs of water evaporated at economic continuous rating, based on a working pressure of 150 lbs./sq.in. and a boiler evaporation of 7,500 lbs./hour.

TABLE I COST & SPACE REQUIREMENTS OF BOILER TYPES

	Cost at Works £	Delivered & Erected £	Floor Space Square feet
Lancashire	63	75	408
Galloway	79	89	371
Babcock & Wilcox Water Tube	62	72	200
Marine (Wet Back)	87	-	120
Economic	59	77	210

Source: C H Wordingham, Central Electrical Stations (1901), pp.69 & 71

It can be seen from the table that the water tube boiler is the cheapest available. Although in this capacity it takes more floor space than the wet back Marine, in larger sizes the floor space required/thousand pounds of steam reduces rapidly.

The Grosvenor Gallery station expanded rapidly in response to a demand from outside consumers, and in 1886 Sebastian de Ferranti, a brilliant young engineer, was called in to advise the company. In 1887 the London Electricity Supply Company was formed to take over the Grosvenor Gallery Station, with Ferranti as Chief Engineer, and the undertaking grew rapidly. To cope with the actual and anticipated demand, Ferranti selected a large Thames-side site at Deptford on which to build a super power station of 120,000 horse power. This cheap out of town site had the adequate cooling water supplies and cooling facilities necessary for a large power station. Alternating current was generated at Deptford station so that it was easily transformable to the 10,000 volts necessary for the transmission system Ferranti had designed to convey the power from Deptford to the Gallery. The plan included 80 Babcock & Wilcox boilers with economisers working at 200 lbs/sq.in;² two Corliss engines each of 1,250 horse power, and the

¹ W L Randell, S Z De Ferranti. His influence upon electrical development (1946) pp.3-11.

² 'The London Electricity Supply Corporation Central Station at Deptford' The Engineer LXVI; (1888), 355

remainder to be of 10,000 horse power, made by Hick Hargreaves & Co. Despite the large area available at Deptford, it was decided to build the boilers on two stories with a coal bunker above supplying the coal by chutes to the operating floors. The ground area required by the boiler house at that time was much greater than that of the engine room; by building a two storey boiler house the length of pipe runs could be kept to a minimum and coal distribution to the bunkers made easier. This station with its high voltage trunk feeders to a central distribution point and the intention to build 10,000 horse power reciprocating engines was designed to be the most advanced in the world.

As a result of a disastrous fire and consequent loss of supplies from the Grosvenor Gallery distribution switchboard in November 1890, many customers lost confidence in the alternating current system and transferred to competing direct current suppliers. This loss of confidence caused the directors to stop construction of the Deptford station and the large engines were never completed.¹

By maintaining Grosvenor Gallery as a generating station and using the two small engines and 24 boilers already installed at Deptford, the LES Co. were able to supply the more limited undertaking. The decision of the Directors to stop further construction work at Deptford was commercially sound because of the limitations on sales. Ferranti, disappointed by the decision, left shortly afterwards. Once the difficulties with the 10,000 volt transmission system had been cleared the only other technical problem to be overcome was the scaling and eventual blockage of the boiler tubes; a problem aggravated by the high working pressure of 200 lbs/sq.in. Thames water had been used for boiler feed and proved to be totally unsuitable because of the large amount of dissolved solid matter in the water.

¹ A Ridding, S Z De Ferranti Pioneer of Electric Power (1964), p.23

A 6" bore hole was sunk on site to give a source of more suitable water, the use of this water greatly reduced the scaling problem. Deptford was only one of many stations to suffer scaling problems due to poor water being used in water tube boilers, it was often found easier and quicker to cut out and replace boiler tubes rather than to clear out the scale from an almost blocked tube. Tubes which had become badly scaled tended to overheat and blister so that they were in any case likely to burst within a short time. Weir's improved evaporator of 1886 and Wm. Baby's Detartriser as they became more widely used, helped the situation by mechanically removing the hardness salts before the water was offered to the boiler.

After the initial demand for electricity was satisfied, the novelty aspect was not sufficient to encourage further growth, price had to be reduced to be competitive with gas, and building more efficient large stations on the lines of Deptford was one way of reducing costs. Engineers began to investigate other ways of reducing costs, one way that looked particularly attractive was to generate steam by burning rubbish. Town refuse had been burned as a hygienic method of disposal since the 1870s, and some places had used this heat for a variety of municipal purposes, often for public baths and wash houses. A number of studies were made in the 1880s on the use of waste to generate electricity and the first demonstration of this took place in Halifax in late 1893.

A contemporary report in Electrical Engineering said "An interesting exhibition is now being shown in Halifax for the purpose of generating steam for electric lighting etc. with ashbin refuse as the only fuel.¹ The installation consists of a Livet expanding flue steam generator (two furnaced) capable of giving 300 horse power when town refuse is burned. The electric plant comprises a Parsons turboelectric generator which energises a searchlight of 25,000 candle power and a full complement

¹ 'Town Refuse & Electric Lighting' Electrical Engineering, XII (1893), 548

of arc lamps..... This exhibition will prove not only interesting, but also that it is possible to produce in any city the electric light at low cost by simply burning rubbish".

Cheltenham was the first town to use refuse on a regular basis when in May 1895 it opened its electricity station adjacent to the town's destructor and took a lot of its steam from this source.¹ Oldham built a similar arrangement the following year and a combined scheme designed as such from the beginning opened in June 1897 at Shoreditch. There were over 40 such stations by 1905 and with only a short break electricity generation from rubbish continues to the present day, although generation is for private rather than public supply, as at I M I Kynoch or the Nottingham Council district heating scheme.²

Main-stream generating stations continued to rely on coal fired boilers, but with increasing boiler size, handling the necessary quantity of coal became a problem. Hand firing is limited to small boilers since one man cannot fire and trim more than 2000 lbs. of coal per hour, so that a 500 horse power boiler at 100% rating would be the maximum size that one man could look after. Some boilers were built with additional firing doors at the side to increase the available grate area for emergency overloads, but this was not satisfactory as even with additional staff the firing was uneven and the stokers were working at the limit to which they could throw the coal. Improved mechanical stokers became available in the 1890s, these increased the boiler economy, effected a saving in labour, and allowed cheap small coal to be used; they also often increased the output from a boiler unit because of the improved efficiency of combustion.³

1 D G Tucker, 'Electricity from Town Refuse - Three quarters of a Century Ago' Electronics & Power XXII (1976), 17, 18

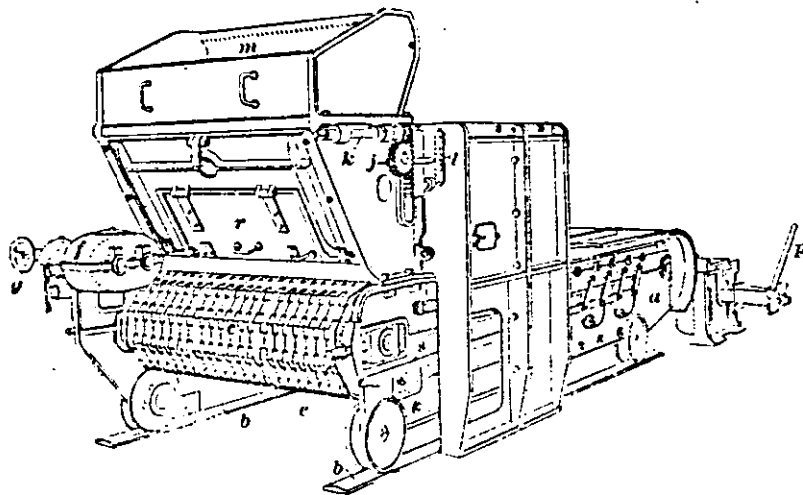
2 J J Crawford, 'Total Energy & District Heating', Electronics & Power XXI (1975), 621 - 624

3 G M Bailes, Modern Mining Practice V (Sheffield c1905), 12

Although good hand firing can be as good as mechanical firing, it needs constant attention to fill any holes that appear in the fire bed and to remove clinker as soon as it interferes with the air supply to the fire. Little and often is recommended as the best way to supply coal, but an unsupervised fireman is more likely to put a large quantity of coal on at each firing to allow longer rest periods. When coal is supplied in this way it cools the furnace and chokes the air supply so that carbon escapes from the furnace without being burned.

The advantages of automatic stoking were used in different ways at different power stations. At the Spa Road electricity works in Bolton, normally unsaleable coke breeze from the nearby gas works was mixed with coal to reduce fuel costs. The nearby town of Farnworth fitted mechanical stokers to the new boiler plant, but left the original boilers hand fired, so that the firemen would be kept fully occupied.

Some difficulty was experienced by Babcock & Wilcox in developing a suitable mechanical stoker for use with their water tube boiler, almost every kind was tried until the simplest chain grate was made for an installation at the Bankside station of the City of London Company.¹



Babcock & Wilcox chain grate stoker

¹ James Kennal, 'A Review of the Introduction of the Babcock & Wilcox Boiler for Electricity Supply' Proc. IEE LX (1922), 76

The Babcock & Wilcox engineers, assisted by the station staff, adapted and modified the chainrate stoker until adequate rates of combustion per square foot of grate area were achieved. Further development work by the manufacturers and the addition of mechanical draught systems steadily increased the rates of combustion. The development of mechanical stoking meant that larger size boilers could be built, this was easily done in the case of the Babcock & Wilcox boiler by putting two or more boilers in parallel within one outer casing, and using a common combustion chamber of a suitable size, for run-of-the-mine coal volumes of 1 to $1\frac{1}{2}$ cubic feet per brake horse power were usually allowed.

Superheated steam was first used about 1828 and its use increased gradually until 1870, but fibrous gland packings and low grade engine oil could not stand high temperatures, so the emphasis moved to two cylinder engines with steam jackets to reduce condensation.

When metallic packings became available for piston rod and valve stem packing, a little development became possible. Selected crude mineral oils specially treated were later developed and steam at over 600°F could be used in reciprocating engines without breakdown of the oil.¹

One further limiting factor in the use of high superheat temperature is its effect on materials; the strength of metal decreases as its temperature rises, so the rise in pressure and temperature necessary for improved efficiency depended on metallurgical improvements. Early power station boilers were limited to about 150 lbs/sq.in. using wrought iron plates, cast iron drum ends, and lap welded iron tubes with no superheat. Increases in pressure and temperature were not possible until steel of consistent quality could be obtained. Each improvement in steel was followed by an advance in steam conditions, and often boiler makers were waiting for a suitable steel to be produced, in later years joint research accelerated progress.

1 G M Bailes, Modern Mining Practice V (Sheffield c1905), 87

The superheating experiments by Patchell were carried out on one Babcock & Wilcox boiler at the company's Maiden Lane station, it was fitted with a McPhail & Simpson superheater, consisting of a bank of hairpin tubes arranged beneath the drum.¹ Steam, on leaving the drum, passed through the superheater and was then passed through a further set of tubes, immersed in the water in the boiler drum, before continuing to the engine. The tubes within the drum eliminated most of the superheat, giving a final temperature of about 10 degrees above saturation, but it ensured the steam reached the engine in a dry condition, and an economy of 5% was recorded on the year's working.

In 1896 Mr Patchell reviewed the development of superheating before the Institute of Mechanical Engineers, and a good deal of interest was shown in the McPhail & Simpson system. Passing the steam through the drum was considered most important by the inventors, as it prevented excessive superheat and also eliminated any possibility of the superheater becoming a condenser at times when the temperature of the flue gases was low. Although this system prevented excessive superheat, passing the steam through tubes in the water space could never raise the temperature above that of the water. Professor Unwin was scornful of the idea and he suggested that if the apparatus delivered superheated steam, it was more by accident than design, and what it really did was to act as an economiser by absorbing some waste heat from the gases and returning it to the boiler.

James Kemnal of the British Babcock & Wilcox Company had designed an integral superheater in 1887 for use in the Imperial Continental Gas Association's station in Vienna, to replace a separately fired superheater, made by the German engineer, Shoerer. Dixon's patent superheater was first manufactured by Hick Hargreaves in 1895, and described in their literature as 'A number of 'U' shaped tubes of small diameter, and great thickness,

¹ R H Parsons, Early Days p.108

made of a special grade of steel, being cold solid drawn without a weld. These tubes hang vertically from a heavy wrought steel tube plate into which they are expanded. This tube plate is heavily bolted to a cast iron box, provided with inlet and outlet branches and divided longitudinally by a diaphragm so arranged as to cause the steam to pass in parallel down one leg of each tube and up the other".

In a Lancashire boiler, the Dixon superheater was suspended in the gas pass at the outlet from the fire tubes, and if added to a water tube boiler, was installed at one side of the boiler tubes.

In the early superheater installations, it was found difficult to estimate the exact amount of superheat obtainable from any given installation, much depended on method of operation. A temperature of 500°F at the engine was usually aimed for, but it was considered that for a Corliss engine, as manufactured by Hick Hargreaves the acceptable maximum was 700°F.

A series of tests run on a Corliss engine supplied with steam at about 81 lbs/sq.in.gauge, saturation temperature 325°F gave the following results, using different levels of superheat.

TABLE II FUEL SAVING AT VARIOUS LEVELS OF SUPERHEAT

Steam Pressure p.s.i.g.	81.08	81.36	79.51	81.36
Total Superheat Temp. leaving Boiler	325° Dry	432°F	510°F	545°F
Total Superheat Temp. at Engine	325°F 98.6% Dry	402°F	477°F	506°F
Indicated Horse Power High Pressure Cylinder	309.6	335.9	362	376.5
Indicated Horse Power Low Pressure Cylinder	440.5	409.3	385.6	388.8
Indicated Horse Power Total	750.1	745.2	747.6	765.3
No. of Boilers in use	6	5	4	3
Pounds of Coal burnt/sq.ft. grate	10.9	11.9	14.1	15.8
Pounds of Coal/IHP/Hr.	2.171	1.994	1.941	1.641
% Coal Saved		8.15	10.59	24.41

Source: Patent Superheater Hick Hargreaves catalogue (Bolton c1902), p.10

It can be seen from the table (see previous page) that a considerable saving in fuel cost can be made by using superheated steam, providing due limits are observed so that maintenance costs are not increased there can be an overall improvement in running costs. This improvement was obtained with a decreasing number of boilers in use, showing that a saving in capital expenditure and staffing, could also be obtained. Precise information on the extent to which superheating was applied in power stations by the end of the nineteenth century is not available, but superheaters had been installed in Edinburgh and Cheltenham, while Bolton installed superheaters throughout in 1899. The Edinburgh installation used steam at 160 psi from six mechanically fired dry back marine boilers, fitted with superheaters but not economisers, a superheat of 60 to 80°F was reached and this was considered to be highly satisfactory. These superheaters consisted of coils of wrought iron pipe, fastened into cast iron headers and were installed in brick chambers on top of the boilers; the superheater was traversed by the flue gases after they had passed through the boiler tubes. Boiler efficiencies of 73.4% were claimed, giving an improvement of approximately 10%.

Leeds Corporation had two Dixon superheaters fitted to Lancashire boilers and a letter from their manager to Hick Hargreaves, dated July 1901, claims to have had two years trouble free operation and quotes test figures showing an economy of 12% with 70°F of superheat.¹

¹ Patent Superheater, Hick Hargreaves Catalogue (Bolton c1902), p.12

V

From the earliest use of steam in the time of Hero of Alexandria (150 AD) there was a long period of near stagnation in its use until the seventeenth century. Della Porta in 1606 described an apparatus for displacing water by steam pressure; the boiler in this case seems to have been an ordinary wine flask.¹ However, later experimenters such as the Marquis of Worcester (c 1660) and Savery (1698) were using copper, as had the ancient Greeks. Copper was the only material which could be made up into suitable plates and stand up to the direct heat of the fire; wooden lids covered with sheets of lead were used as boiler tops. Boilers made of wood were built at Watt's suggestion and proved successful for low pressures as steam at 6 psig is produced at a temperature of 230°F which wood can easily withstand.² Such a boiler was used successfully at Greenwich for a number of years and although the copper fire tube was re-newed several times, the wooden parts were unchanged throughout the life of the boiler.³ Wrought iron, a cheaper material than copper and more suitable for boiler manufacture, was introduced by Stonier Parrott (of Coventry) before 1720.⁴ These wrought iron boilers were made by riveting hammered iron plates together as wrought iron was a most suitable material for boiler making, being stronger than copper and highly resistant to corrosion.⁵ Small hammered wrought iron plates were available by 1725, but the advantages of the improved material were diminished to some extent by the large number of riveted joints which tended to leak.

1 R J Glynn & E B Watton, 'The Development of Boilers', Heaton Works Journal, (Summer 1953), 397

2 H W Dickinson, A Short History of the Steam Engine (Cambridge 1938), p.119

3 Hoyt - Engineers Pocket Companion (Hoyt Metal Co. c1940), p.161

4 Letter - William Cotesworth to George Liddell, 12.12.1717, Cotesworth Manuscript CM2/754, Gateshead Public Library

5 J Farey, A Treatise on the Steam Engine (David & Charles reprint, 1971) 1, p.230

Blacksmiths did much of the original work on boilers, but by 1790 boiler making was becoming a separate specialist trade and rolled iron sheets of about 3/8" thick were available¹. The combination of these two factors reduced the number of joints necessary, while the improved specialist skills reduced the leakage from whatever joints were made, but the shapes were still often made by hammering the plates in a concave hole in the ground. Cast iron was introduced into boiler-making by Smeaton in 1770, but this material was not very trustworthy under shock loads and at high temperatures, although it was still used circumspectly for many years. Neither of these two materials were immediately used to their full potential due to Watts' personal prejudice against the use of high pressure steam, however, when his patent expired in 1800 the way was open for Trevithick to produce a high pressure engine.

The use of iron now became essential and improved manufacturing techniques accelerated the rate of development and the introduction of steel into boiler-making in 1865 continued the development.² As steel was a more uniform material, thinner plates were permitted by the Board of Trade for marine boilers, allowing the possibility of further pressure increases and superheating, but this was delayed to some extent by engine limitations.³ When superheating was finally tried, the mechanics of it were obviously not fully understood, or information was not sufficiently dispersed, as can be seen in the specification for the McPhail & Simpson superheater, where steam tubes were allowed to make contact with water in the drum, losing much of the hard won superheat.

1 Dickinson, Short History p.118

2 R J Glinn & E B Watton, 'The Development of Boilers', p.399 & H F Reeman 'Some Notes on the Development of Steam Boilers' Proceedings I Mech E CXLVII (1942), 173

3 The Board of Trade at this time was responsible for the administration of regulations applicable to the Merchant Navy, hence its control of marine boiler design

Cast Iron was still in use during the 1880's by Babcock & Wilcox, despite the recommendation of Lavington E Fletcher (Chief Engineer MSUA) who proved, after an extensive series of tests, that the material was not suitable for use in steam boilers.¹ Improved forging techniques saw the substitution of wrought steel for cast iron headers, and bending machines able to deal with larger and thicker boiler plates were introduced so that pressures of 125 psi were possible.

Construction of boiler drums by welding was feasible but was frowned on by inspecting bodies as satisfactory non-destructive testing was not available and the technique was not developed till a more favourable time.

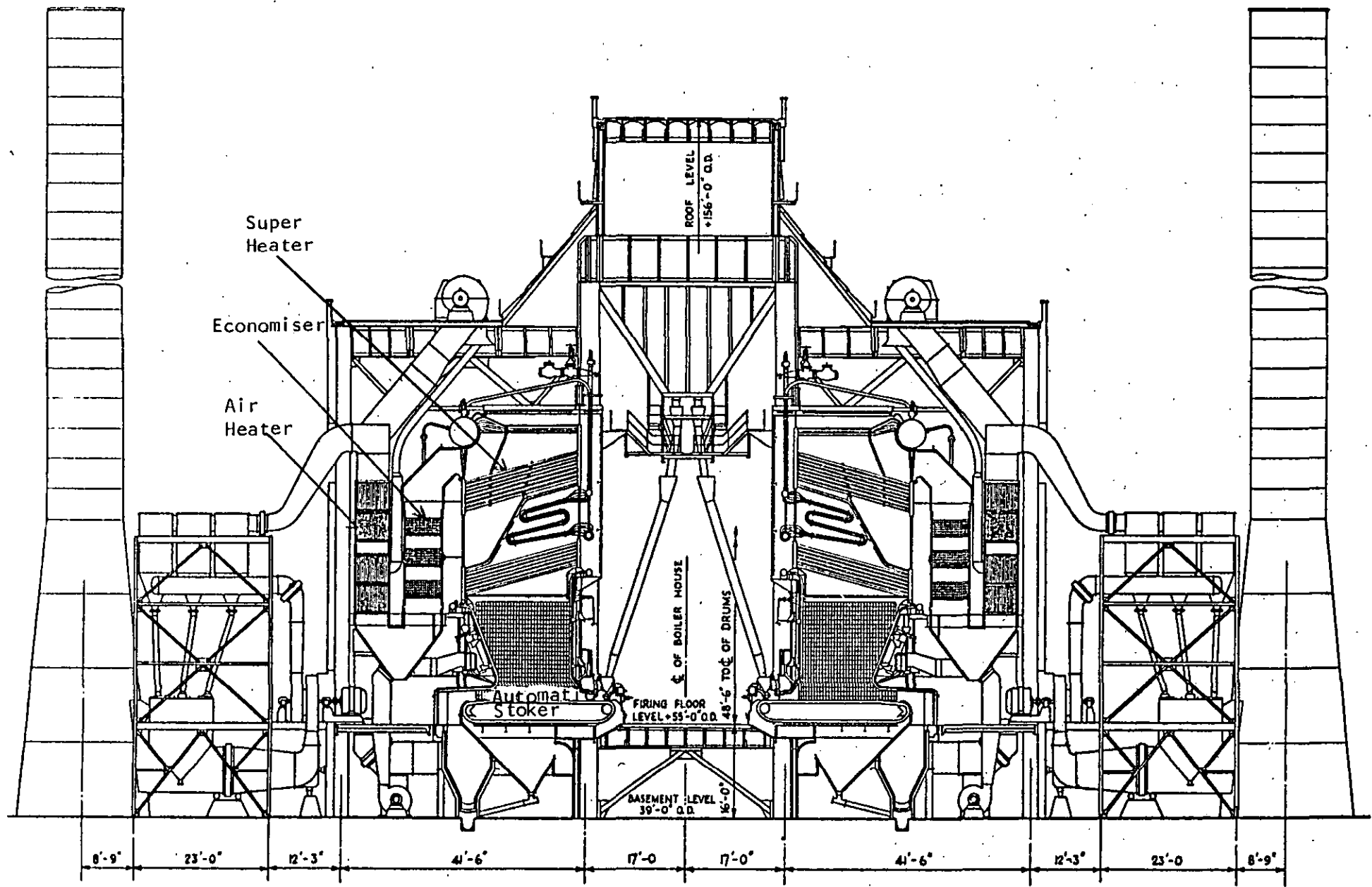
Demand for electricity was expanding as its use for power became more common, so that boilers by the end of the nineteenth century were of such a capacity that it was essential to have automatic stokers. With hand firing the large amount of coal on the firing floor and the large numbers of men required to handle the coal would have created complete chaos.

Coal costs were not of great importance to manufacturers in the early years of steam power, the availability of power was the important factor, similarly when electric lighting was first introduced its use for floodlighting or advertising was happily paid for. Undertakers realised that with a wider market, selling electricity at a cheaper rate would increase the return on the investment in underground distribution mains and the search for more efficient steam energy production began. The newly developed water tube boiler was eminently suitable for a further advance in steam pressure, but this was not possible without improvements in steam engine design. Rapid growth of the electricity supply industry forced the necessary development of the engines and encouraged the use of the turbine so that superheated

¹ MSUA - Historical Sketch, p.47. These tests took place from 1874-76 and resulted in the prohibition of the use of cast iron in boilers built under the association's supervision

steam could be used, increased load required growth in boiler size beyond the limits of Lancashire boiler development and encouraged improvements in automatic boiler firing.

By the end of the nineteenth century all the items necessary for the rapid advancement in boiler design were available (see diagram overleaf). Economisers, air heaters, superheaters and automatic stokers were all past the experimental stage; the dissemination of information on design and operation was much better on well tried techniques, but was still sparse on new development. Decisions on steam conditions and design could now be based on overall economic considerations, reliability, efficiency, capital and maintenance costs all could have a bearing on the final decision.



**PERCIVAL LANE POWER STATION – RUNCORN
TYPICAL SECTION THROUGH BOILER HOUSE**

PART TWO

DEVELOPMENT FROM 1900 to 1939

During the period from 1900 to 1939 the electricity supply industry consolidated its position as an important public service, but to achieve this position it had to pass through an extensive period of development. At the turn of the century the industry was highly fragmented and was unsure in which direction it was to progress; the three main avenues of technical development are explored in this section.

In order to avoid confusion each parallel path is followed through in a separate chapter and the overall effect is considered in Chapter IV. The first effect considered is the necessary growth in boiler size needed to cope with increasing demand, this in turn required improved combustion techniques and the development of the automatic stoker. The development of the automatic stoker and its ancillary apparatus in competition with pulverised fuel is traced through in this chapter. In Chapter II the main alternative method of firing coal as pulverised fuel is investigated, the reasons for its limited development and its effect on boiler design are traced.

Steam at increasing temperature and pressure was used in the period up to 1939; reheated steam was also used experimentally in a number of stations, the reason for these advances and the necessary technical developments in manufacturing methods and materials are investigated in Chapter III.

I

Water Tube and Lancashire boiler designers responded to the requirements of the expanding electricity supply industry; in the 1890s, saturated steam at 120 psi was common, by 1905, 160 psi & 600^oF was the requirement and by 1910, pressure had risen to 200 psi. This surge in development was brought about by a number of factors, the first being the introduction of the steam turbine to power station work in 1890 at Forth Banks (Newcastle). Engine makers fought back by introducing the four cylinder triple expansion, this was the limit to which a reciprocating engine could be designed while the turbine, which was still in an early stage of development, soon matched the reciprocating engine in steam consumption, with plenty in hand for further design improvements. In 1904 a comparison test was run by Merz & McLellan consulting engineers at Neptune Bank power station, a 800 kW triple expansion engine showed a steam consumption of approximately 24 pounds of steam per kWh generated, whilst a 1500 kW steam turbine returned figures better than 20 pounds per kWh except at very low loads.¹

Electric light stations were rapidly becoming power stations with the expansion of electric tramways and the general upsurge in the economy, bringing with it the increasing use of electric motors in industry. Bolton Corporation, in a 1902 handbook, listed 118 motors totalling 676 horse power, ranging from one of 3/4 horse power used by a dentist, to a 20 horse power motor driving a planing machine; seven years before when supplies were introduced no motors were connected to the system. This expansion of daytime load required a flexible system which could cope with the comparatively light day load, the normal lighting load, and short term overloads when both lighting and power loads were on together.

¹ H W Dickinson, A Short History of the Steam Engine (CUP 1938), p.228

Steam turbines seemed to be ideally suited for this work, they were also more compact than large slow speed reciprocating engines. The growing electrical system loads required increasing quantities of steam despite improved utilisation and the Lancashire boiler reached its ultimate capacity limit of 12000 lbs/hour. As three Lancashire boilers of this size would be required to supply a 1500 kW turbine, the eventual size of the boiler house, combined with long and complicated pipe runs for even a moderate 10 MW power station, forced the power engineer to install water tube boilers. The water tube boiler of comparable capacity was about one third the physical size of a Lancashire boiler, it also could respond more rapidly to changes in demand whilst still maintaining designed steam pressure, also like the turbine the design could be expanded to meet future requirements. By 1905 turbines of 5000 kW capacity and boilers producing 20,000 lbs/hour, were being built; the following year boilers of twice the size were commissioned.¹

Main stream boiler plant design can be seen to have been advancing rapidly in terms of water tube boiler capacity; pressure and temperature was, however, not advancing at the same rate after an initial boost to 200 psi and 600°F. Most water tube boilers at the time were made by Babcock & Wilcox, but there were others such as the Hornsby which was installed at the Bow power station of the Charing Cross Company in 1904. They were of the "Upright" type with groups of almost vertical tubes expanded above and below into steam and water boxes. Two boilers were combined to form a single unit, the largest in the world at the time producing 66,000 lbs of steam at 160 psi and slightly superheated. Surprisingly these boilers were hand fired from front and side and in emergencies could produce 100,000 lbs/hour. Stirling boilers were used in a number of power stations in the south of England; in its original form the Stirling had four inter-connected drums, the two upper front drums and the

¹ Sir Leonard Pearce, 'Review of forty years development in Mechanical Engineering Plant for Power Stations'.

lower drum forming a triangular water and steam circuit.¹ The incoming feed water entering via the upper rear drum and flowing into the bottom drum cooled the gases down before they left the main boiler. Variations on this design having 3, 5 & 6 drums were used at various times; major development eventually settled for either a single or a three drum design.²

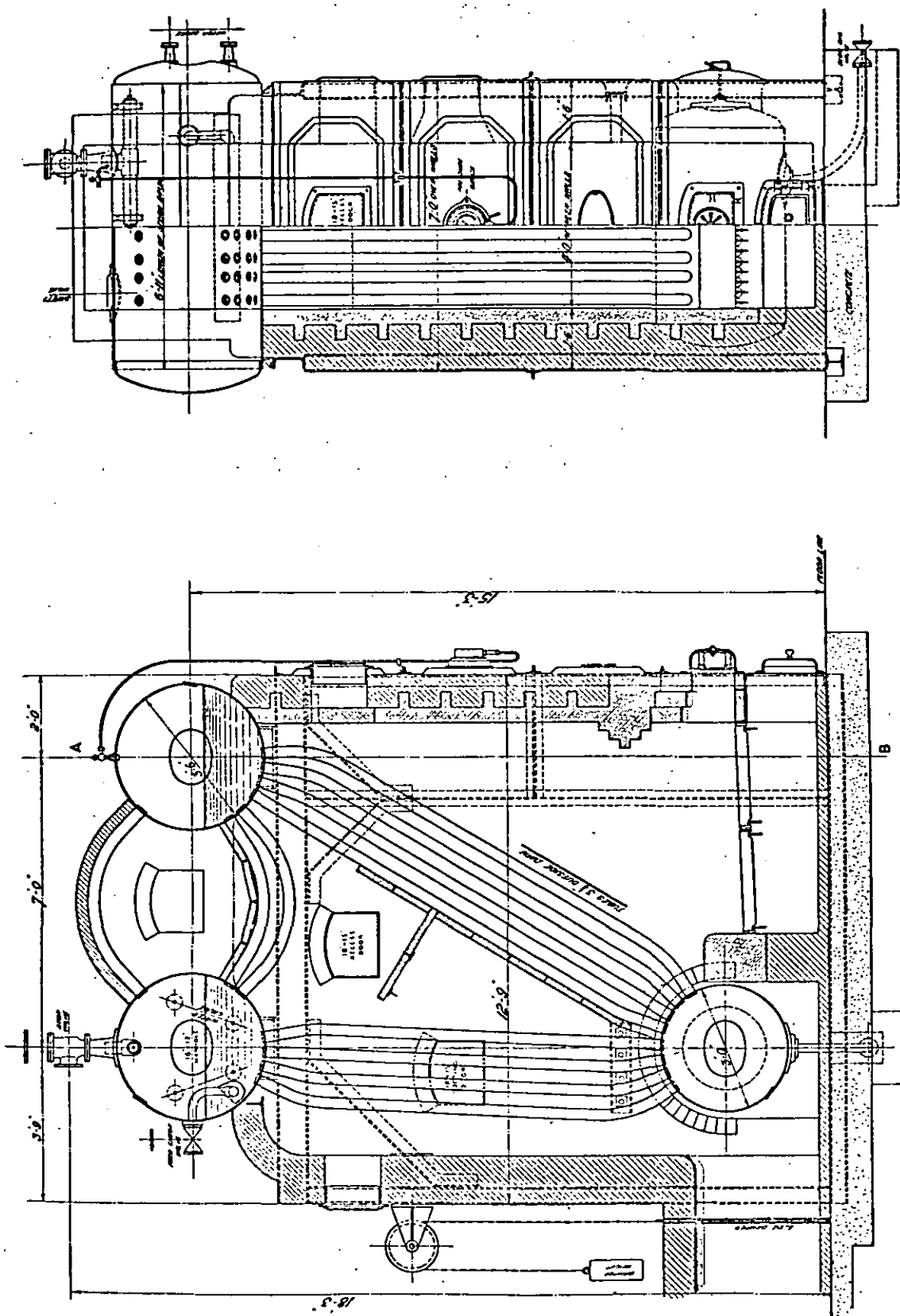
Some engineers preferred boilers with vertical or nearly vertical tubes, this type of boiler was praised by J W Jackson in a paper before the I E E³ (10th November 1913) and in the ensuing discussion several members agreed. Points made in favour suggested that the higher furnace improves combustion and there is less chance of soot and other deposits forming on the tube surface. The water sides of the tubes were said to allow the steam bubbles to rise more freely in the vertical tubes while the scale forming salts tended to fall into the mud drum from where they could be blown out via the blow-off or blow-down valve.

A large percentage of the heat generated in a boiler furnace can be wasted, some losses are unavoidable, but others are due to bad management or poor boiler design. Incomplete combustion of the carbon in coal, due to lack of air, produces dark smoke and wastes fuel, conversely excessive air passing through the furnace, or entering the flues through leaks, wastes heat by warming air only to throw it away. The air flow through a boiler originally depended solely on the resistance to air flow of the fire bed and the boiler, and the draught created by the chimney, control being obtained by a throttling valve or damper at the chimney base. This draught depends entirely on the difference in density between the gases within the chimney and the air surrounding the chimney, the heat required to produce this difference in density is not available for the generation of steam. Generally natural draught is adequate when exhaust gases are allowed to escape at 500°F, but anything in excess of this is wasteful.

1 R Kennedy, Modern Engines & Power Generators, (1905), VI, p.63

2 Illustration of 3 drum boiler, see overleaf

3 J W Jackson, 'Steam Boiler Working in Electrical Power Stations'
IEE Journal LI (1914) 481 - 489



Three-Drum Stirring Water-Tube Boiler.

Like any other condition dependant on nature, natural draught can be erratic, such things as wind force, humidity, and ambient temperature can all have an effect. In order to make the draught independent of these conditions, mechanical draught was introduced and this made it possible to create a stronger draught available as required. Early attempts at improving the draught concentrated on forcing air through the fuel bed by means of steam jets below the fire so that the chimney suction only had to overcome the resistance of the boiler and flues. Steam jets were an efficient method providing they were renewed regularly, but if they became worn they consumed more steam than their assistance produced.

The Meldrum forced draught system was the best known steam jet installation,¹ it was fitted in a number of electricity supply stations in the 1890s. Shortly afterwards Howdens introduced forced draught, using a fan to supply pressurised air, via a common duct to a group of boilers.

Where a number of boilers were discharging to the same chimney, a supplementary induced draught fan was installed at the chimney base to provide additional furnace suction. Using a mechanical draught system meant that a small electric motor or steam engine was needed to drive the fan, but the energy used could be compensated for by reducing the temperature of the exhaust to the chimney. The Ellis & Eaves induced draught system was one method of reducing the final gas temperature. An air economiser or box was fitted in the flues before the fan and the air for combustion could be raised to 300°F as it passed through the heater and the waste gases reduced to 400°F as they passed over the outside. Cooling the waste gases reduced the volume to be handled and also reduced fan maintenance costs. With an induced draught system, there is no tendency for dust to be blown out through cracks and fire doors can be opened without the danger of flames being blown out into the boiler house.

¹ P Dawson, The Engineering & Electric Traction Pocket Book (3rd edition 1903)

To use a mechanical draught system successfully it is necessary to have both forced and induced draught systems, in association with some form of automatic stoking, the installation of these items would only become economically viable on boilers burning more than 2000 lbs of coal per hour.

Combining the continuous flow of coal possible with an automatic stoker and the more precise control of air or gas flow obtainable with a mechanical draught system, correct combustion conditions could be maintained for long periods. It had been determined that when the carbon in coal was completely burned with the correct amount of air, the percentage carbon dioxide (CO_2) in the flue gases was 19%.¹ This value could not be obtained in practice as some atoms of air did not meet some atoms of carbon and consequently, due to incomplete combustion, some carbon monoxide (CO) was produced. From extended trials it was found that between 14 & 15% CO_2 in the flue gases provided the best results that could be obtained under practical conditions. If less air was supplied to the boiler the percentage CO_2 would increase, but unburned carbon or CO was released to the atmosphere. If more was supplied the percentage CO_2 would decrease and air was heated in its passage through the boiler only to be released up the chimney. Various instruments were devised for boiler house use which recorded the amount of CO_2 in the flue gases. These indicators passed a measured quantity of flue gas through a solution of caustic potash at regular intervals. As the gas bubbled through the solution, CO_2 was absorbed by the potash and the outlet gas volume measured, comparison of the two volumes was usually recorded on a chart for the benefit of both the operator and the engineer in charge. The development of these various devices meant that by the end of the 19th century the production of steam could be a much more controlled and efficient process. With the continued growth in boiler size induced draught fans and automatic stokers became an essential part of any water tube boiler installation after 1905, as it became impossible to operate the boilers without these mechanical aids.

¹ W Francis, Boiler House & Power Station Chemistry, (2nd edition 1947), pp.75-77

The problem of black smoke recurred frequently with different boilers despite the use of automatic stokers, it was brought about when designers tried to increase the output of a boiler by adding to the bottom of the tube bank. This addition brought the tubes too near to the fire and cooled the flames before combustion was complete. Smoke problems were also brought about by trying to burn in too thick a fire bed and so preventing the flow of air through the fuel. To overcome this problem Babcock & Wilcox put two or three small boilers within one casing and inter-connected the water and steam sides, this allowed the use of twin grates and reduced heat losses.

When automatic stokers were first introduced, the coal was often shovelled from the floor into a small hopper at the boiler front, so that the physical effort necessary to handle the coal was just as great as that necessary to fire the boiler. With increasing quantities of coal being used, improved methods became necessary, one system used an elevated rail track with small side tipping trucks running the length of the boiler house. These trucks were filled from a large bunker at the end of the boiler house and pushed to individual boilers by the trimming gang as required. Deptford's system of installing large bunkers above the boiler house, capable of holding a 12 hour supply of coal, became the standard method still used in modern power stations. Coal was lifted to the bunkers by skip hoists or bucket elevators and allowed to fall to the grate via a fan tail chute as required.

Coal used in power stations varied in quality, but usually at this time contained between 10% & 20% incombustible material, so that for every ton of coal brought into the power station, between 2 and 4 cwt. of ash had to be removed. ¹ With hand fired boilers the large ash had to be cleaned out of the fire at intervals and with the small ash drawn from beneath the grate, it was dropped at the boiler front, sprayed with water, and wheeled away in barrows.

¹ Calculated from Bolton (Spa Rd. Works), Cost Sheet June 1902
854 Tons of Coal, 151 Tons of Ash. Percentage Ash 17.6%

Ashing by hand was probably one of the most uncomfortable and dangerous of a stoker's routine jobs, there was always the possibility of being burned by hot ash, or the firing tools, and the sulphurous smells produced by the hot ash when quenched could make the surrounding area almost uninhabitable. Dilute sulphuric acid was produced by the wet ash and this tended to corrode the floor plates and the boiler front, which in the Lancashire boiler was not a separate casing, but part of the boiler plate. With the increase in coal consumption and the use of automatic stokers, "Ash Wheeler" became a separate occupation and a training ground for future boiler operators. Where chain grate stokers were fitted, the ash and any unburned coal ran off the back of the grate into ash hoppers where the coal finally burnt out and the ash was allowed to cool. At suitable intervals the hopper outlet doors were opened by the ash man, allowing the ash to fall into "jubilee trucks" on a narrow gauge rail track, ready to be wheeled away. Improved methods of ash handling were introduced once the complete combustion of the coal on the grate could be obtained. This was achieved by an improved short grate link, and the use of a dumping bar which provided a slight check to burn out the fuel before releasing it to a continuously running water sluice, and on to an ash pond which could be cleared as necessary.

An improved vacuum system for ash removal was introduced about 1912, in which the ash was removed to storage hoppers ready for removal by road or rail without any manual labour whatsoever.¹ Where a large number of boilers were installed, ashing systems like this were economically viable, one man being able to look after the whole of the ashing, the escape of dust and fumes into the station was prevented and the environment outside the works was improved. Following on from the new ash removal systems, improved seals were developed to prevent large quantities of air being drawn into the furnace through the dead coal at the back of the grate.

¹ County Borough of Bolton Souvenir Booklet (Bolton 1935), p.2

Improvements were made from time to time in the design of grate links to prevent overheating, improved driving methods, variable speed gearboxes, twin and triple grates to increase the grate area etc. The maximum width of grate built in the 1920s was a single 24ft wide, triples were not successful as the bearings on the centre grate regularly overheated and eventually standard designs for power station boilers tended to be twin grate L type by ICL, or style 28 Babcock & Wilcox. Firebrick arches were used to reflect heat onto the raw coal and for many years grate width was limited to 12ft as this was the limit to which a self supporting arch could be built.

The use of pulverised fuel expanded rapidly in the 1920s and with no apparent limitation on the size of boiler it could fire it provided an additional spur to stoker manufacturers to improve and expand their designs. The introduction of the Liptak fire arch removed one of the major limitations so that by 1938 ICL grates with an area of 756 sq.ft were fitted to a boiler, with a maximum continuous output of 200,000 pounds of steam per hour¹. Steam output for a given boiler design could be increased by making the boiler taller, without increasing floor area, provided sufficient coal could be burned within that given ground area. To obtain this increased coal burn per square foot of grate area, stoker manufacturers enclosed the grate completely (making the forced draught fan a necessity) and supplied hot air to cause the coal to burn more fiercely. The area beneath the grate was later compartmentised, each section being fitted with separate dampers to control air distribution over the fuel bed.

Developments in one section of a power station often had an effect in another; for instance, feed water heaters supplied with partly used steam from the turbine, were introduced in 1916 at Blaydon Burn power station; the result was the Economiser had less work to do². As the Economiser was now taking

¹ China Light & Power Company Souvenir (1939), p.11

² Electricity Council Electricity Supply in Great Britain a Chronology (1973), p.8

less heat away from the flue gas it was necessary to find a way to recoup this loss and development work on the combustion air pre-heater went ahead rapidly. By using better grade materials and improving construction techniques, the grates could be run at a much higher temperature than previously and so the final stage of heat removal from the flue gases became the air heater. The continued improvement in the design and capacity of the chain grate stoker slowed down the change to pulverised fuel among the more conservative Chief Engineers, and the ultimate was not reached until 1950,

when a 285,000 lb/hr boiler was installed at Kingston on Thames power station.

II

During the nineteenth century good quality coal was comparatively cheap and it has been estimated¹ that between 15 and 30% of the coal worked in a seam was left behind in the form of unsaleable fines². Of the coal actually brought to the surface, a proportion of this was considered unsuitable, as can still be seen in the form of waste dumps in the older mining areas. Although the advancement in design of automatic stokers was allowing coal to be burnt more efficiently, combustion engineers were interested in the possibility of using these waste fines by pulverising the coal into a fine powder and burning it in suspension. Although patented by John Samuel Dawes in 1831, for use in iron smelting, the first apparent mention of pulverised fuel in boiler house practice was in John Bourne's Treatise on the Steam Engine, published in 1861, but practical application made very little progress for some years.

Coal in lump form burns under very different conditions to that of pulverised coal, as combustion can only take place when the material is in contact with air, the surface area of the coal piece affects the rate of burning. An inch cube of coal has an outer surface area of six square inches, until the outer layer has burned and the ash has fallen away the inner layer cannot start to burn. Coal burned in this form has to stay in the furnace up to 20 minutes before combustion is complete, the seven cubic feet of air necessary being controlled over this period.

If the same one inch cube of coal was ground into smaller cubes, each of .01 inches each side, the total surface area exposed would be 600 square inches. In this form the coal would still require the same

1 A Regnauld, Modern Power Engineering (c 1922), IV, p.221

2 In modern practice a maximum of 5% is left behind and all coal brought to the surface is sold after any necessary cleaning.

amount of air and if the coal particles were evenly distributed in this air, conditions for complete and rapid combustion would be far more favourable. The comminution of coal in a PF installation is carried much further so that 80% will pass through a sieve with 200 meshes to the linear inch.

Reduction of coal to the near consistency of a fluid mixing it with the correct quantity of air, plus a small excess to ensure complete combustion, and injecting the mixture into the furnace so that distillation of the volatiles and burn-out is almost instantaneous, is the essence of PF firing.¹

The first successful method of firing a boiler with suspended coal was that of the Swartzkopff syndicate². Coal fines were pulverised in an enclosed mill, very similar to that used in Mediterranean countries since the middle ages to crush olive stones for oil. This early crushing mill consisted of two heavy rollers, one at each end of a short horizontal axle, the axle was rotated by a vertical drive shaft and the coal was crushed between the rollers and the bed of the machine. This was a batch process, the ground coal being emptied via a hatch in the side of the mill into a storage bunker after a suitable grinding time had elapsed. When required to be burnt, the pulverised coal was carried by a screw conveyor to the boiler front and then catapulted into the furnace by a rotating wire brush.

Sufficient air was blown into the furnace beneath the jet of coal dust to burn it out while it was still in suspension. This method of burning coal resulted in a flame very similar to that obtainable from a gas jet.

1 J N Williams, Boiler House Practice (1956), p 386

2 Rankin Kennedy, Modern Engines & Power Generators (1905), VI, p.99

It was claimed that using the very worst slack on the market, the Swartzkopff system showed better results than by hand stoking, and only a small quantity of white dust was left behind in the bottom of the furnace.

Willesden power station (Acton Lane) was the first to try pulverised fuel, a 10,000 lb/hour Scotch Boiler, manufactured by John Fraser was adapted in 1903 to burn PF.¹ The makers of the PF system guaranteed an evaporation of 10 lbs of water per lb. of coal - which would correspond to a boiler efficiency of 86% with the type of coal used. It was agreed that if this figure was not achieved, the system would be removed, as the equipment was only in use for a short time before removal it must be assumed that the guarantee was not met. This failure to meet the guarantee set back the use of PF in British power stations for some years, and although there is an unconfirmed mention of its use at Trafford in 1911,² the first permanent installation was that at Hammersmith in 1919.

Use of pulverised fuel was advancing rapidly in the USA and the following items were put forward as advantages of PF firing, but these claims still had to be proved using British coal.³

1. Increased efficiency due to :-
 - (a) Higher temperature of combustion
 - (b) Less excess air and therefore higher CO₂ content of flue gases
 - (c) Complete combustion and so no carbon loss in ash
2. Ability to use any class of coal whatever without smoke production
3. Increased flexibility of operation so that fuel supply can immediately be adjusted to the load, while still maintaining very high thermal efficiency
4. No stand-by losses, i.e. it does not need regular addition of fuel to maintain banked fires
5. Reduced labour and maintenance costs with cleaner working conditions

1 London Generation (House magazine) October 1949. See p.33 for earlier experiments

2 IEE Journal LXVIII, (1930), 513. H L Guy in discussion

3 T H Carr, Electric Power Stations (3rd edition 1947), 1, p.216

Although these statements were broadly true they could prove to be self-cancelling, for instance if very high ash coal was used, wear of mills increased and consequently so did maintenance costs. With the complete combustion obtained there was no smoke, but as larger boilers were made the quantity of very fine dust emitted from the stacks increased and caused a new problem of dust deposits on the surrounding area.

Differences between British and American coal raised a number of unexpected problems initially, nevertheless there has been continuous development in pulverised fuel firing since 1919, and despite the deterioration in coal quality, each problem has been overcome as it has arisen.¹

Hammersmith Corporation in November 1918 agreed to accept the tender of the Erith Engineering Company for the supply of a mechanical stoker for the new Stirling Boiler for the sum of £1,350.² Erith Engineering declined to proceed due to rapidly rising costs between July and the date of acceptance. In considering firing arrangements for the new boiler, the Electrical Engineer (G G Bell) reported his dissatisfaction with mechanical stokers and brought to the notice of the Electricity Committee the new system of firing by powdered fuel recently introduced to metallurgical and cement plants in the United Kingdom. After viewing the powdered fuel plant at the Raynham Cement Works it was decided in February 1919 to accept a tender from the Powdered Fuel Company. The tender was divided into three sections, part A provided an initial installation for £15,870, which would supply sufficient equipment for the new boiler (No.16) which could easily be extended under part B at a cost of £7,615 to supply boilers 14 and 15. If the system proved successful, it was proposed that further necessary standby plant be installed at a cost of £9,740.

1 Imports of American coal during the shortage of 1957 created many problems when burned as PF at Ince & other power stations.

2 Hammersmith Electricity Committee Minutes, 12.2.1919, p.52

In support of their tender the company guaranteed a saving of £7,000 per annum if all boilers were PF fired. If full normal rating with smokeless combustion and absence of nuisance to the surrounding district was not obtained, the company also guaranteed to put it right within 45 days, or remove all the plant free of cost to the council. These guarantees by the Powdered Fuel Company, plus a clause providing that no part of the fees under proposal A should be paid until the guarantees were met, no doubt influenced the committee in their decision to install the plant. This clause would be inserted by the company to try to get an opening into power station work so as to expand their field of operation.

Despite this offer the only other power station contract they obtained was from Hammersmith Corporation in 1922¹ to supply firing equipment for two new 30,000 lb/hour boilers, supplied by Stirling² the original proposal to extend the system to supply the other boilers was not proceeded with.

The central or bin and feeder system of firing offered by the Powdered Fuel Company was that of Holbeck, designed in the United States in 1915. A primary circuit consisting of a separately fired rotary coal drier, a Bonnot horizontal roller mill with an expansion chamber separator at the outlet to return oversize particles for re-grinding and a powdered coal storage bin. A separate ring circuit carried powdered fuel to the burners, any surplus being returned to the storage bin. To transport the pulverised coal between the mill and the storage bin and also round the ring main motor driven exhausters fans were used.

The burner used was of simple design consisting of a short horizontal tube set into the side of the boiler furnace, teed into the burner tube

¹ Hammersmith Electricity Committee Minutes, 24th May 1922

² Ibid,

26th January 1921

was the fuel supply pipe. Additional air necessary for complete combustion was blown through the incoming fuel to accelerate it into the furnace. This burner was not very successful as insufficient turbulence was obtained, consequently some coal particles did not receive sufficient oxygen to burn completely before leaving the furnace. Despite this loss, due to incomplete combustion, the boilers were in use for over 20 years.

The cost of coal during and immediately after the first world war had risen rapidly, pricing was based on size rather than the heat content (calorific value) of the coal so that cheap smalls and slack suitable for PF firing was often readily available, while grades suitable for automatic stokers were in great demand and comparatively expensive. Despite the possibility of using cheaper fuel, the number 16 boiler at Hammersmith was the sole PF boiler until numbers 17 & 18 were ordered in 1922, followed almost immediately by an order from Peterborough Corporation to Simon-Carves for PF equipment.¹ The decision to fit pulverised fuel firing to two of the four Vickers-Spearing boilers being installed at Peterborough was taken after construction was under way. A unit or direct fired system was installed by Simon-Carves in which the coal was ground on demand; combustion efficiency with this design was also below optimum, due to the cramped nature of the combustion chamber, which was designed for use with a travelling grate stoker.

Although the boilers were designed to produce 25,000 pounds of steam per hour, they frequently ran up to 20% overload, and in one emergency period produced double normal output for a short time. Experience with damaged firebrick in the combustion chamber led to the design and installation in 1925 of a special water-cooled furnace for one of the boilers; it was claimed to be the first water-cooled combustion chamber in this country.

¹ 'The Peterborough Power Station' Electrical Review CV(1929), 53

In December 1923 a company was formed which was to have a catalytic effect on the extension of pulverised fuel installations in this country, it was first registered as Vickers & International Combustion Engineering Ltd, with a share capital of £500,000.¹ The company was formed to exploit pulverised fuel firing of power station boilers; the shares were equally divided between Vickers, who provided factory space and plant at Barrow-in-Furness, while International Combustion Engineering of New York were to provide all Lopulco designs for the new company. In April 1924 engineers of the new company, accompanied by R A Chattock (Birmingham) C G Bell (Hammersmith) and Messrs. Cockshott & Millen (Metropolitan District Railway) visited ICE (N Y). Chattock was so impressed by what he saw that he cabled Birmingham Corporation to stop all work at Nechells power station until his return so that the Lopulco bin and feeder system could be installed instead of travelling grates.

The six Vickers-Spearing boilers installed at Nechells (Princes Station) were fitted with convection superheaters, four had Foster Economisers and the remaining two had Thermix air heaters to provide hot air for combustion. Coal having a nett calorific value of 9,500 B Th U/lb. with an ash content of 25% was supplied for the boilers and was of a much cheaper quality than any previously used by Birmingham Corporation.

Raymond bowl mills were used in the early Lopulco installations, the deep grinding bowl is stationary and it has a hardened grinding surface (bull-ring) against which the coal is ground by a roller. A vertical drive shaft enters the bowl at the bottom; this shaft supports and rotates a spider from which a pivoted arm and heavy roller is suspended. As the spider rotates, centrifugal force causes the rollers to fly out, trapping and crushing the coal between the rolls and the bullring. The ground

¹ International Combustion Papers. Archives, Derby Works

coal was drawn from the mill and transported to the PF bunkers by means of an exhaustor fan. From these bunkers, to small PF bins at the boiler, the coal was carried forward by Fuller-Kinyon screw pumps, using the minimum of air. Outfall from the boiler bins to the burner pipes was regulated as necessary, the coal flowed down to fishtail burners set into an arch over the front boiler wall. Primary air was supplied at the burner, secondary air to complete the combustion process, provide the necessary turbulence, and control the flame shape was provided via slots in the rear wall. High flame temperatures and impingement on the firebrick had led to this use of secondary air; by passing air through cavities between the refractory lining and the outer casing, the air was pre-heated and the brickwork was kept cool. An innovation in furnace cooling was tried to protect the rear wall, the first section of each superheater tube was carried across close to the firebrick before being led into the gas outlet passage, where the superheater was normally placed at this time. This design of boiler had many features that over years have been refined to form important parts of modern boiler design.

Other contracts for PF firing equipment followed during 1924, including Brimsdown, Willesden, St Pancras, and Derby, while Poplar Borough Council appointed Vickers & International Combustion Engineering as main contractors for their extension, but further development was needed.¹

Although the use of secondary air helped to prevent refractory being damaged, furnace ratings were kept low and smoke was frequently produced until the brickwork reached red heat. To cure the smoke problem a much higher furnace rating was required, with large areas of firebrick high furnace ratings could not be achieved.

¹ See table overleaf for growth in use of PF to 1932

TABLE III BRITISH CENTRAL POWER STATIONS : PF INSTALLATIONS BY MARCH 1932

STATION	BOILERS INSTALLED	CAPACITY klbs/hr. NORMAL/ OVERLOAD	FIRING SYSTEM
NECHELLS BIRMINGHAM	6 SPEARING 4 SIMON-CARVES	35/40 150/180	LOPULCO SIMON-CARVES
HAMS HALL BIRMINGHAM	5 B & W	200/240	LOPULCO/ATTRITOR
SOUTHWICK BRIGHTON	2 WOOD (ICL)	100/120	LOPULCO
BARKING LONDON	10 B & W	135/187	LOPULCO
DERBY	3 B & W 2 CSG (ICL)	60/80 60/80	LOPULCO LOPULCO
HAMMERSMITH	2 STIRLING	40/40	HOLBECK
HAYLE	1 B & W	20/20	UNKNOWN
KIRKSTALL LEEDS	3 STIRLING	160/184	LOPULCO
LEICESTER	2 CSG (ICL) 1 LOPULCO (ICL)	150/180 150/180	LOPULCO
LIVERPOOL	3 B & W 3 B & W	160/184 125/156	ATTRITOR ATTRITOR
LUTON	2 CLARKE CHAPMAN 2 WOODSON	120/120 45/45	CLARKE CHAPMAN WOODSON
BARTON MANCHESTER	1 B & W	130/170	FULLER LEHIGH
METROPOLITAN RAILWAY	6 LOPULCO (ICL) 2 B & W	80/100 9.6/10	LOPULCO LOPULCO
NORTHMET BRIMSDOWN	5 B & W 4 CSG (ICL) 1 B & W	100/130 175/200 6/9	LOPULCO LOPULCO FULLER LEHIGH
NORTHMET WILLESDEN	1 CLAYTON 2 B & W	80/100 75/90	LOPULCO FULLER LEHIGH
NESSCO DUNSTON	2 B & W 4 B & W	30/37.5 125/156	FULLER LEHIGH CLARKE CHAPMAN
PETERBOROUGH	2 VICKERS SPEARING 2 SPEARING 3 SPEARING	25/40 80/100 50/70	SIMON-CARVES SIMON-CARVES LOPULCO
POPLAR	3 SPEARING	70/85	LOPULCO
STEPNEY	3 SPEARING	75/75	CLARKE CHAPMAN
ST PANCRAS	2 B & W 2 SPEARING	45/75 55/75	LOPULCO LOPULCO
STRETFORD	1 B & W 1 B & W	18/18 20/20	HOWDEN BUELL HOWDEN BUELL
WALLASEY	2 SIMON-CARVES	52.5/70	SIMON-CARVES
WEST BROMWICH	3 B & W	30/30	FRAZER & CHALMERS BETTINGTON MILLS
WEST MIDLANDS WALSALL	3 THOMPSON	40/75	LOPULCO
WEST MIDLANDS IRONBRIDGE	3 STIRLING	225/270	FULLER LEHIGH
WORCESTER	1 STIRLING	90/90	ATTRITOR

SOURCE: S B Jackson 'PF Firing With Special Reference to Power Station Practice'
TRANS INSTITUTE OF MARINE ENGINEERS XXLIV (1932), 3

Attempts were made by Claude Bettington, a South African, to overcome this problem, due to his accidental death in 1912 development was discontinued. Bettington's design consisted of a vertical firebrick lined combustion chamber surrounded by a close fitting jacket of water tubes with a second row of tubes a short distance away.¹ The burner fired upwards in the chamber, the burning coal and gases fell down and left the chamber at the bottom before passing between the rows of tubes. This boiler design incorporated two important features, the firebrick was cooled to some extent by a water jacket, and a long flame path was obtained without it impinging on the refractory.

Early pulverised fuel boilers were modified versions of automatic stoker designs, the first boiler designed for PF was installed at the steelworks of Taylor Brothers, Trafford Park.² W R Wood, a director of Usco, an associate company of International, designed the boiler, its main features being the elimination of brickwork from the combustion chamber, and the use of corner firing. Known variously as the "Wood", "Manchester" or "Combustion" steam generator, the boiler had a furnace lined completely with boiler tubes (patented as the Murray fin tube) and the fuel burners were fitted in each corner.

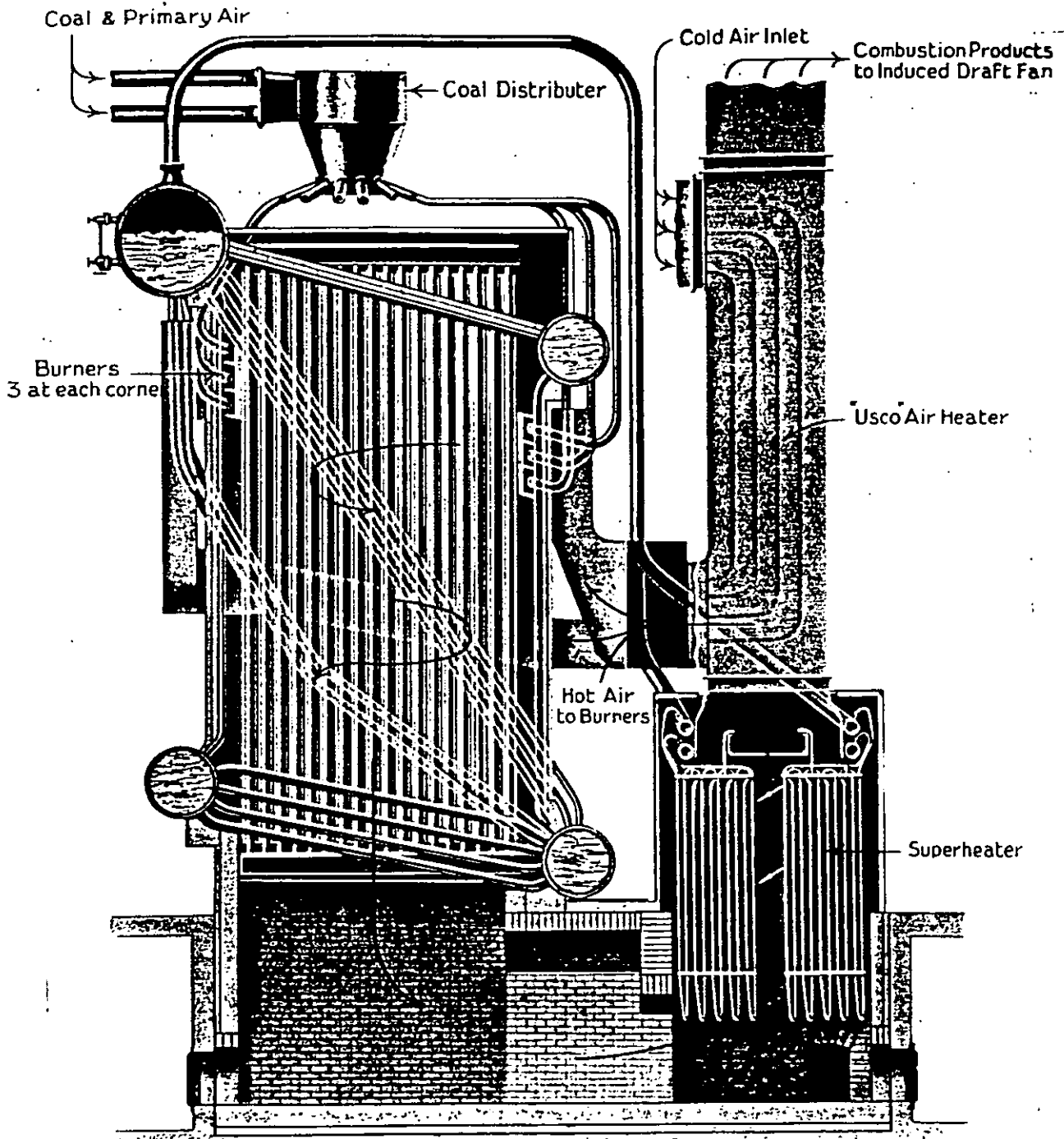
The boiler installed at Taylor Bros had three burners in each corner of the furnace, set to fire tangentially to a circle at the core, this gave a long flame, each burner setting up turbulence within the fire.³ Flames corkscrewed down within the combustion chamber, and burning was complete before the coal particles escaped from the high temperature area.

1 W F Goodrich, Pulverised Fuel a Practical Handbook, (1924), p.12

2 Underfeed Stoker Company

3 E Watson-Smyth, 'Pulverised Fuel firing as applied to modern combustion methods' Salford Engineering Society 9.3.1929 p.14

See illustration overleaf for layout of boiler.



The original 'Wood Steam Generator'

Commissioned towards the end of 1925 Wood's patent system proved to be an immediate success and engineers came from all parts of the world to see this boiler, included amongst them was Kreisinger, the father of American PF systems.

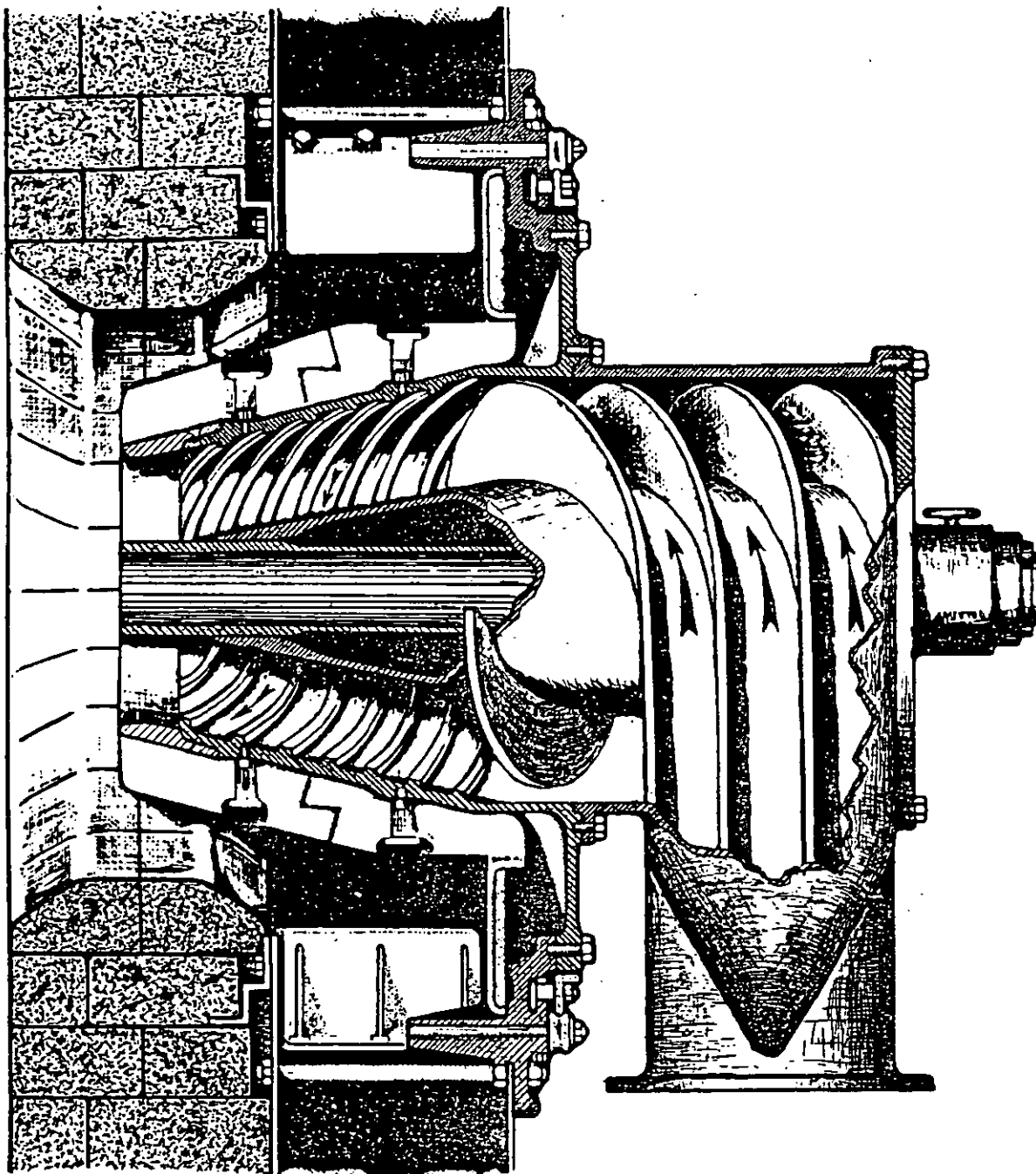
Christie (Chief Engineer, Brighton) inspected the Manchester plant and was so impressed by its flexibility, ease of operation and improved efficiency that he immediately ordered two for installation at Brighton. In 1925 Vickers withdrew from the company and the name was changed to International Combustion Ltd.; the American influence was very strong at this period, Rosencrantz and Wood became important figures in the new ¹ company.

Further development work on burners continued, resulting in the introduction of the R type burner, patented by Rosencrantz in 1927. Walsall power station was the first to use the R type short flame turbulent burner which introduced a rapid swirl to the coal dust as it left the burner nozzle. Additional air was supplied round the outside of the tube forming a ball of fire at each burner. Attempts were made to design a volcano burner based on the R type; two boilers at Derby were fitted with this type of burner in 1929². All the coal necessary to produce 80,000 lbs. of steam/hour was passed through this one burner, despite many modifications the carbon loss remained excessive and the design was never repeated, these boilers however, remained in service until the 1960s.

Although ICL did the bulk of the early PF work, Clarke Chapman and Simon-Carves were also concerned in a number of installations; work done by Simon-Carves led to the first boiler plant to be fired solely by anthracite duff as pulverised fuel. Although Simons had done limited work in power

¹ ICL Papers

² Commemorative Booklet Derby Corporation Electricity Department Extensions 1929/30



TURBULENT FLOW BURNER

stations, it had installed over twenty plants in European collieries and four in this country so that their interest in burning colliery waste was natural.

Anthracite has a high flame temperature, and in consequence the risk of damage to combustion chamber brickwork is greater, but it was argued that with this low volatile coal the use of water tube walls would extinguish the flame during periods of low load. The plant installed at Aberpergwm Colliery in 1929 showed that such limitations on the use of pulverised anthracite did not apply; the results proved that water walls could be used with confidence, provided that a bituminous coal was used during start up. Two Simon-Carves boilers rated at 25000 lb/hr were installed with a unit pulverising system, using high speed mills. ICL quickly realised the opportunities in this market and contracted to supply a pulverised anthracite system to Cefn Coed Colliery and work was completed in 1932.²

The success of these two colliery installations enlivened the interest of Swansea Electricity Department who were anxious to use this locally available cheap coal but found it could not be easily burned on the chain grates available at the time; they ordered 4 x 240 Klb/hr boilers from International Combustion. To burn anthracite in such a large boiler, ICL reverted to a downward firing system, with a fishtail burner. A reflective wall of firebrick was built behind the burners where flame impingement was unlikely, while the remainder of the combustion chamber was lined with water tubes where refractory damage was more likely. For the first time a "Hardinge" ball mill was used in an ICL installation, although it had been invented early in the century, it consisted of a horizontal rotating conical drum in which the coal and a charge of iron balls were rotated. The new 2" diameter balls crushed the large coal at the greater diameter of the mill, smaller and worn balls tended to work their way up the taper and continue

1 'Pulverised Fuel Plant for Anthracite Duff' Engineering CXXX (1930), 705

2 'Boiler Equipment at the New Swansea Power Station' Engineering & Boiler House Review XLVII (1933), 214

to grind the coal finer before it is exhausted to the storage bin. A ball mill was used for this installation despite its greater power consumption, as the maintenance costs and out of service time would have been excessive using any other type of mill grinding this hard coal.

Once tests had proved the plant to be satisfactory Swansea Corporation signed a 19 year fixed price contract for the supply of anthracite duff, and eventually extended the station until eight boilers were installed. These boilers had forced and induced draught fans, plate type air heaters and economisers, they also had auxiliary oil burners for start up and light load conditions. Washing sprays at the chimney base had been used at Derby to clean the exhaust flue gases, but with the much bigger station envisaged at Swansea, the Howden-ICI flue gas scrubbers were used to remove dust and sulphur. Flue gas washing never became very popular, the only other large installations being at Battersea and Fulham; the major objection to gas washing is its cooling effect which tends to cause a low cloud in the vicinity of the power station. Electrostatic precipitators, first used by Oliver Lodge at a lead works in 1884, clean the gas by ionising the dust particles with a high negative voltage which causes it to be attracted to a discharge plate.¹ Northmet carried out the first power station installation at Willesden in 1929, and the Birmingham stations followed.

Installation of PF fired plants continued during the 1930s, the consumption of coal in power stations during 1925/26 was just over 6 million tons, of which 21 thousand tons (0.35%) was pulverised, by 1938/39 coal consumed was 13.3 million tons, 2.2 million tons (16.5%) being P F.² The pioneering days of P F were given a temporary boost by the rapid rise of fuel costs, when attempts were already being made to reduce the cost of

1 Keith Blackman Ltd. History & Fundamentals, Electrical Precipitation
2-ATC-1 p.7

2 Electricity Council Handbook of Electricity Supply Statistics (1972) Table 17

electricity generation. In the early stage of development PF was considered to be an ideal way of burning unsaleable coal. It was claimed that small size, high ash coals of low volatile content could be obtained very cheaply for use as P F and these claims turned out to be true. Once it was shown that these coals could be burned with relative efficiency, prices rose and it was realised that a better quality coal could in fact provide cheaper steam. When better coal was used there was a reduction in ancillary costs, with lower ash content, ash handling and disposal costs were lower, less coal was used and this reduced maintenance costs on pulverising equipment.

Bell's suggestion to his committee that powdered fuel be used to fire the boilers for the proposed new extension at Hammersmith was based rather more on dissatisfaction with chain grate stokers than on a burning desire to pioneer a new combustion system. The Powdered Fuel Company submitted the sole tender for the job, previous work by this company had been limited to small installations and their Holbeck system of American design had only been in use since 1915.

I have found no evidence of the use of P F in British power stations pre 1919 other than that at Willesden and an unsubstantiated comment about its use at Trafford Park. The first American power station installation was at Milwaukee in 1917, and on the continent of Europe the French Vitry power station claimed the honour in 1923.¹

Pulverised coal as a fuel for cement works and steel plants had progressed more rapidly than its use in steam because of differing requirements and geographical location. The coal is burned in a combustion chamber separate from the production unit and the hot gases are passed over the steel or limestone/clay mixture when combustion is complete, the ash in the case of cement becomes part of the mix.

¹ J N Williams, Boiler House Practice, (2nd edition 1956), p.382

Cement and steel plants requiring large quantities of heat were usually situated in coal producing areas so that transport costs of ash into and out of the production unit were not excessive and cheaper coals could be burned economically. This aspect of costing can be illustrated as follows : -

Good quality coal with 10% ash, transported 30 miles, then 100 tons of coal would cost $30 \times 10 = 300$ ton miles to bring ash into the site and with an ash dump 5 miles away a further cost of 50 ton miles would be incurred.

In an industrial/mining area 30% ash may only travel 10 miles, costing $10 \times 30 = 300$ ton miles, with an ash dump one mile away outgoing costs would be $30 \times 1 = 30$ ton miles.

Comparing the two total costs of 350 ton miles with 330 ton miles means that transporting the high ash coal could be a viable proposition.

Supplying high ash coal 30 miles would cost $(30 \times 30) + (5 \times 30) = 1050$ ton miles and probably completely nullify the advantage of buying cheap coal.

Power station growth in size in the early years of the 20th century was balanced by the reduction in fuel consumption per unit of electricity generated. Derby power station in 1904 used 10 lbs of coal/unit and improved boiler design had halved the fuel consumption by 1915; these figures are fairly representative of stations burning a normal range of coals.¹ From these figures it can be seen that if twice as much electricity could be produced per lb. of coal, little development of the automatic stoker of 1900/1905 was necessary to service a boiler of twice the capacity in 1910. As these figures were obtained despite the deterioration in the quality of available coal, there was little encouragement to use other types of firing, although the Hammersmith Engineer considered automatic stokers unreliable.

¹ Commemorative Booklet Derby Corporation Electricity Department Extensions 1929/30. Table 1.

While the advantages of pulverised fuel were many, there were disadvantages that had to be considered, coal in powdered form like many other combustible materials, when mixed with air is a highly explosive material and even the controlled ignition of a boiler was a minor explosion. Stoppage of coal flow means an immediate loss of ignition on a P F boiler with a rapid drop in steam production and hence generation, without the back-up of an inter-connected system serious disturbance of electrical supplies was possible. An even more serious possibility is the loss of coal, followed by a rapid restoration and re-ignition from hot refractory, the consequent explosion could be of sufficient violence to wreck the boiler, or the pulverising equipment and pipe work. Authoritative information on the subject does not appear to have been widespread, the first book I have traced on the subject of Pulverised and Colloidal Fuel was not published until 1924 and the first paper to the I Mech E was published the previous year.¹ With such a dearth of information engineers were unlikely to seriously consider its use.

The first rush to install plant to make up for wartime shortages was over before any useful information of P F was available, a period of industrial depression slowed the expected expansion in demand for electricity, and the consequent demand for new boiler plant also slowed. A substantial reduction in the cost of coal, a fall in the cost of plant and materials and a reduction in wages meant that where extensions did become necessary, plant of known design would be preferred.² This change in conditions probably caused a revision of the original Hammersmith decision to convert the older boilers to pulverised fuel, this would have required an expensive reconstruction job on the furnaces of boilers whose actual running time would be reduced when the two new boilers were

¹ W F Goodrich, Pulverised Fuel a Practical Handbook (1924), p.382

& H W Hollands, 'Powdered Coal Firing for Water Tube Boilers' Proc I Mech E CXXV (1923), 1143

² Electricity Commissioners 3rd Annual Report 1922/23 p.5, Sec.2

commissioned in 1922. New boilers numbers 17 & 18 were however, required to carry a large portion of the load for extended periods, major capital expenditure had already been incurred for the initial installation so that the use of pulverised fuel for the extension would be economically viable.

Between 1924 & 1939 decisions whether to install chain grate or pulverised fuel firing were often balanced on a fine edge; cheap coal availability, transport and maintenance costs, return on capital by improved plant efficiency or availability, all had a bearing on the ultimate decision. The decision to use pulverised fuel at Neshells was based on a known availability of suitable cheap coal from the Warwickshire coalfield, once the maximum quantity available was being burned in the Birmingham power stations a decision was made to fit chain grates in any further new plant. Christie's coal supplies for Brighton are not known, but as transport costs to this station would be high, the efficient burning of high grade coal would be important, but the prime consideration from the Chief Engineer's remark is flexibility. Brighton undertaking with little industry and no backing from a grid system would be prone to numerous peaks, such as sea mists creating sudden lighting loads for short term, hotel loads are also very unpredictable, so that a boiler which could be rapidly brought up to full load and just as rapidly shut down was very useful operationally.

What was a correct decision at any one time or place could prove to be the wrong decision at a different time as developments were made in various directions. Economic appraisals were difficult to make as figures were often biased, direct comparison was almost impossible. To overcome this difficulty Lamb of Manchester Corporation had two similar boilers¹ installed at Barton, one with chain grates and the other fitted for P F.

¹ H L Guy & H C Lamb, Operating Results Barton Power Station
MV Electrical Pub 7485/2-1 (Manchester 1930)

In order to get boilers of the requisite size (100,000 lbs/hour) in 1920 Lamb found it necessary to build a boiler with two furnaces back to back and using four automatic stokers: by the time of the 1926 extension a standard type of boiler could be built to produce 130,000 lbs of steam/hour.

Number 10 boiler was built for pulverised fuel, while 11 and 12 were each fitted with twin stokers, after a number of modifications were made an extended test was carried out on both Nos. 10 and 11 to obtain a standard of comparison, using a normal Lancashire slack of 11,500 BthU/lb.

Although the gross efficiency of the PF boiler reached 84.2% and was $\frac{1}{2}\%$ higher than that fired by chain grate, when due allowance was made for the extra power used to grind the coal the figures were 79.6% and 80.9% respectively. From these results, burning the local coal, there was no economic advantage in using coal in pulverised form, it was however, found that with the design of combustion chamber used there was less boiler fouling and consequently a higher availability. This comparative test shows that the nett efficiency of a pulverised fuel boiler is not always higher than that of a chain grate; another advantage of pulverised fuel, its flexibility began to lose its importance with the spread of the national grid, which had a cushioning effect on individual systems.

Although coal costs, technical improvements and changes in requirements all had an important bearing on the development of pulverised fuel, it is interesting to note some of the contacts and personal links that affected progress. Inspection of Table III (p.74) of P F fired boilers in power station practice brings out a number of groupings, there were 40 boilers installed in the London area, 13 were installed by the Northmet Co. and 10 by the County of London Co. Almost 53% of the P F boilers in the London area were installed by these two British controlled companies who tended to go for advanced designs in any plant they built. An installation

at the Metropolitan Railway Company had a further 8 boilers (19%) a decision probably influenced by the visit of two of their directors to America with International Combustion. The remaining small installations belonged to four local authorities, including Hammersmith who no doubt influenced the nearby councils.

The group in the Midlands would be strongly influenced by Chattock at Birmingham and by the proximity of the ICL works at Derby, while the installation at Taylors steelworks would have had some influence in the north west. An ex Hammersmith engineer, J F Savent, was associated with the installation of P F at Dunston power station and was later Superintendent of Kirkstall (Leeds) when it was installed there. G R T Taylor of Taylor Bros gave ICL the opportunity to build a large boiler, he was associated with the formation of Vickers and International in 1923 and held a minor share in the company. Two successive Chief Electrical Engineers left Derby, G H Lake to Nottingham and F Nicholls to Leeds, very soon after their appointments they started to install PF equipment at stations under their control. There were other similar examples of this and it seems that whenever PF was used, engineers associated with it became firm believers and advocated its use wherever possible.

III

At the beginning of this section increases in steam temperature were discussed, however, the first limited advances in pressure were not made until 1917 when North Tees power station was designed to work at 475 psi and the standard riveted boiler drum was found to be no longer adequate.¹ For many years the technique had been to build a riveted drum and where leaks were found the metal edges were forced into the joints until the leakage was stopped; at this high pressure the method was not successful. Welding had been tried for boiler manufacture at the turn of the century, but it had not achieved the necessary standard to satisfy the insurance companies. However, welding added to normal riveting was accepted and made a successful seal. This pressure of 475 psi was higher than most engineers were prepared to accept and pressure settled at 350 psi for a few years. Barton and Nechells are examples of stations where this pressure was used.

An increase in pressure without an increase in temperature would mean that the point at which moisture droplets were formed in the turbine would be nearer the high pressure end, this would tend to accelerate blade erosion in the lower pressure stages and reduce the efficiency of the turbine. To control this problem the temperature of the steam must be increased to at least 700°F and preferably 750°F. As this was beyond the temperatures at which the available steels could be safely worked, the initial temperature at North Tees was limited to 675°F and after doing some work and consequently losing some heat, it was then re heated to 520°F. As a result of the problems experienced with the leaking riveted seams at North Tees, experimental work on the production of solid forged drums was accelerated and in the early 1920s such drums were produced by the forge masters of Sheffield.

¹ H F Reeman, 'Some Notes on the Development of Steam Boilers'
Proc I Mech E, CXLVII (1942), 173

The difficulty of reaching the necessary high steam temperature, brought about by material limitations, was temporarily by-passed by re heating the steam after it had done some work in the turbine; this was not the way British engineers wished to progress. Higher pressures and superheats through stress action and the weakening influence of temperature increased the severity of conditions at temperatures above 675^oF and development of new materials was thought to be necessary before further progress could be made.

Nickel-chrome steels and alloys provided the necessary material, but development was necessary to improve its "creep"¹ properties before it could be used commercially.² Materials necessarily pass through a number of phases from evolution, through the development of the necessary fabrication processes and eventually into the final design and operational stages of a commercial plant. By 1923 power stations were being built with steam conditions of 375 psi and 750^oF and these became conditions at a good modern power station for the next 10 years.

In many of these boilers mild steel superheaters were installed; provided steam velocities were kept high and even distribution was obtained it was found that mild steel could cope with these temperatures and so the use of more expensive steels or the use of re heat was avoided.

The early 1930s saw steam pressures and temperatures moving up again to about 600 psi and 825^oF with increased experience with the new materials and the introduction of larger capacity turbines. A larger size turbine was necessary before higher pressure steam could be used, with a smaller

1 "Creep" Where a metal is subject to stress over a period of time at a temperature above some moderate and characteristic limit it will fail by creep at some much lower stress than that indicated by a straightforward break after heating.

2 A L Mellanby & W Kerr, 'The Use & Economy of High Pressure Steam Plants', Journal I Mech E Vol CXXIX, (1926), 63

turbine the blading would have been too short to gain any thermodynamic advantage. However, the use of steam above 800°F led to expansion problems, on the turbine side the connecting pipework had to have additional bends built in to accommodate the greater expansion, and a more precise control of steam temperature was necessary to maintain differential expansion within the turbine. If a sudden change of steam temperature from say 800°F to 850°F took place, the shaft and moving blades of the turbine would expand rapidly, the heavier casing and fixed blading would expand more slowly and there would be the possibility of a rub or even major damage to the turbine. To maintain a constant steam temperature over a wide range of loads, the correct positioning of the superheater within the boiler casing was necessary and fine control of the steam temperature was obtained by using cooling sprays or by-pass dampers.

Development of the water tube boiler was markedly influenced by the progress in superheater design; the demand for higher steam temperatures necessary to improve the thermal efficiency could only be satisfied if the location of the superheater was given precedence over that of the steam generating surface.¹ Early superheaters were built up from ten or twenty rows of hairpin tubes hung vertically in a space at the outlet from the boiler; these gave only a low degree of superheat and were difficult to drain when starting up. As superheaters became bigger, the cooler sections (primary) were made horizontal to improve the drainage and the high temperature section (secondary) was moved nearer the furnace to absorb some radiant heat.

It was found that a radiant superheater had a drooping temperature characteristic; that is as the boiler load increased, the superheated steam temperature was reduced. A convection superheater heated solely by the high temperature flue gas was found to have a rising characteristic so that by suitably proportioning the two types, a constant steam temperature could be maintained over a wide range of loads.²

¹ T H Carr, Electric Power Stations (3rd edition 1947), I, p.251

² Ibid, p.254

The adoption of higher working pressures, final steam temperatures, and feed water temperatures resulted in a greater proportion of the heat supplied being absorbed in superheating the steam as shown in the table below.

TABLE IV SELECTED EXTRACT FROM STEAM TABLES

Steam Pressure lbs/sq.in gauge	150	180	250	350	600
Final Steam Temperature °F	366	500	650	750	850
Saturated Steam Temperature °F	366	380	406	436	489
Feed Water Temperature °F	60	100	180	250	340
Total Heat in Superheated Steam BThU/lb	1196.8	1268.8	1343.6	1391.3	1434.9
Heat already in Feedwater	28.1	68.0	148.0	218.6	311.2
Heat supplied by Boiler	1168.7	1200.8	1195.6	1172.7	1123.7
Sensible Heat	310.3	285.0	233.4	195.5	163.4
Latent Heat	858.4	846.3	821.8	791.4	729.4
Superheat	-	69.5	140.4	185.8	230.9

Calculated from J H Keenan & F G Keyes, Thermodynamic Properties of Steam (New York 1966)

This change in relationship between the steam generating and the steam heating requirements meant a large reduction in the number of tubes actually generating, while the conflicting requirement of a large combustion chamber required far more tubes in the water walls. One result of this change in emphasis was the reduction in the number of tubes screening the superheater from the furnace, allowing the secondary superheater to absorb more radiant heat. Development of the water wall was brought about by the use of pulverised fuel which tended to erode refractory bricks; to overcome this problem the walls were lined with water tubes which eventually became part of the boiler circuit.

Advances in steam temperature however, were not made without some setbacks, a Parsons turbine on test in August 1900 was badly damaged when supplied with steam at too high a temperature.¹ On investigation it was found that the brass blades in the turbine contained a trace of lead which gave the metal a brittle point at 460°F, this caused the blades to snap off under load when running at high temperature. Brass was used for turbine blades because of limitations in manufacturing technique, but despite improvements in blade materials the accident created some prejudice against high steam temperature which slowed the advance in steam conditions for some years. The turbine under test was a two cylinder 1.0 MW machine² and it was decided as an experiment to add further heat to the steam between leaving the first cylinder and entering the second. Steam was exhausted from the first cylinder at 10.4 psi and 198°F, it then passed through a locomotive type boiler where it was re heated to 260°F. Test results showed no reduction in steam consumption, due mainly to the additional losses brought about by the resistance to flow in re heater pipe work. Although the tests were of limited value, it showed that with higher initial pressures and a greater degree of re heat in a better design of re heater, the theoretically possible reductions in steam consumption would be obtained.

Blaydon Burn power station of the Priestman Power Company was the scene of further re heating experiments in 1916.³ A two cylinder 3 MW turbine had been built and fitted with bled steam feed heating to improve the efficiency of the power station, and because of its suitability for experimental work a further attempt was made to find a viable re heat design.

1 R H Parsons, Development of the Parsons Steam Turbine (1936), p.42

2 1.0 MW = 1000 kW

The biggest turbine made at the time & because of limitations in manufacturing technique it was made as two separate 500 kW turbines with shafts mechanically connected & exhaust steam from number one turbine being piped to the second.

3 R H Parsons. Op.Cit. p.151

Steam was supplied at 600°F and after partial expansion was re heated to 400°F but the experiment was discontinued; data on the improvement in efficiency is not available.¹

Re heating trials at Carville B were the first to show proof of a definite advantage, using steam as a re heating agent. With an increase in temperature between the high pressure exhaust and the low pressure inlet of 89° a theoretical improvement in efficiency of 0.6% was possible. Actual test figures showed that with a loss of pressure through the re heater of 0.25 lbs/sq.in. there was an improvement in efficiency of 0.515%.

Some experimental work was also carried out before 1914 by Ferranti, at the Sheffield works of Vickers where he installed a 3 MW turbine, supplied with steam at 200 psi and 750°F with re heating after partial expansion to 750°F. Ferranti claimed at a meeting of the IMEA in 1927 that he had obtained some remarkable results, but they were not as good as they should have been. The trials were abandoned and because of the disappointing results, reports were not published, it was only found out some years later that a serious steam leakage in the casing had affected results.²

A serious attempt to build a commercially viable re-heat power station was made by NESCO at their North Tees station, when five standard and five re heat boilers were commissioned in 1920.³ The steam was supplied at 500 psi and 675°F, after partial expansion the steam was re heated to 520°F.

1 R H Parsons Development of the Parsons Steam Turbine, p.139 & Discussion in IEE Journal LXXIII (1933) Newcastle Section Meeting

2 S Z DeFerranti, 'Power Plant Design' Incorporated Municipal Electrical Association 1927 Conference Report, 170

3 Ibid, 172

Although some degree of success was achieved, good results were not quickly obtained due to a number of failures of plant not connected with the re-heat system and impetus was lost. The consulting engineer to NESCO and driving force behind the re heating experiments in the North East was Charles Merz, who was later appointed consultant to the County of London Electric Supply Co. for the construction of Barking power station. He convinced his new masters that steam re heating was a viable proposition and one of the 40 MW machines built for the 1922 extension was fitted with the necessary equipment to use re heated steam. At Barking each re heat boiler had both a superheater and a re heater, so that although more than one boiler supplied steam to the turbine, on low loads an individual boiler could do all the work. Re heating was proved to be a technical success in British practice as a result of the Barking installation, but the balance between thermodynamic gain, the higher capital cost and operational complication, was a point of dispute for some years.

Thomas Roles (Bradford) in a paper to the 1927 IMEA Convention, commented on the complication of pipework necessary with re heating, R A Chattock (Birmingham) an equally eminent engineer, agreed on this point.¹ W H Duffett (Rotherham) pointed out the difficulties of calculating the relative importance that capital cost and efficiency bore to overall cost, with the varying price of coal, also large capital projects in the past had become obsolete before the expiration of the funding period.

Re heating requires additional expensive control equipment and release valves to ensure turbine safety in fault conditions, without it the additional steam in the re heater pipe work beyond the control of the turbine stop valve could cause the turbine to run to excessive speeds.

¹ T Roles, 'Power Plant Design' IMEA 1927, 118

As more than one boiler was necessary to supply a turbine, at this time uneven re-heater steam flows between boilers made control of the re heated steam temperature difficult. Savings could be made on other items of plant to partially compensate for these additional costs, a smaller and cheaper condenser could be used and consequently the amount of cooling water was reduced. The quantity of feed water to be pumped to the boiler was also reduced, but maintenance costs were higher and breakdowns with unusual designs tended to be more frequent. However, the advance in steam conditions on the straight cycle, and the consequent improvements in efficiency, were generally sufficient to discourage undertakers from installing re-heat plant.

Many of the technical advances mentioned in this part of the thesis were only applied to a limited extent because of the organisation of the supply industry. Most undertakings had only a small area under their control supplied from one power station and with no back-up from an external source, because of this engineers generally tended to favour a simple design of proven reliability and less prone to breakdown due to overstressing or maloperation. Larger undertakings such as NESCO or Manchester Corporation with a number of interconnected power stations could afford to take some degree of risk and install plant of more advanced design.¹ The 1926 Electricity Act created the National Grid and provided a much greater degree of interconnection, but also temporarily reduced the rate of power station expansion: By 1935 the reliability of the Grid had been proved and from this time a greater tendency to use more advanced designs can be seen.

¹ A practice that was followed in USA, see I V Robinson, 'Power Stations & Their Equipment, A Review of Progress' Journal IEE LXX (1931), pp.129-14

IV

Growth of electricity demand in the established areas of supply and extension into new ones progressed rapidly so that by 1921 there were 665 power stations in Great Britain¹. Efficiency of operation varied widely from the very modern power stations at the top of the league, such as Barton which averaged 19.8% efficiency from 1924 to 1928, to Hinckley where second hand Willans engines were installed, or Melbourne where an engine from a Nile paddle steamer was fitted, both working with steam at 80 psig. The concentration of generation brought about by the 1926 Act began to achieve cheap and efficient generation nationwide, while the gradually increasing capacity of individual boilers and the size of power stations meant that manpower per Megawatt was steadily reducing. As the number of connections to the Grid increased, small high cost power stations were shut down so that by 1939 the number of power stations had been reduced to less than 450, and many of these ran for only a limited number of hours per year.²

Power station development advanced from the basic design available at the turn of the century, improvement in metals and manufacturing techniques were used to full advantage by both boiler and turbine makers; new ideas such as re-heated steam, regenerative air heaters and bled steam feed water heaters were introduced and developed where economically viable. Combustion became more of a science and less of an art; the Institute of Fuel was formed in 1927 shortly after pulverised fuel was first developed as a boiler firing system. The advanced techniques such as re-heating and pulverised fuel firing did not advance as rapidly as one would have expected as the old established methods fought back by increasing the temperature of the straight superheating cycle and increasing chain grate size as necessary.

¹ Garckes Manual 1935/36 Edition p.21

² The Grid system was constructed by the C E B as a result of the 1926 Electricity Act. See Appendix V for duties and responsibilities

By 1939 average fuel consumption per unit of electricity sent out had fallen to 1.43 lbs of coal compared with up to 25 lbs/unit forty years before.

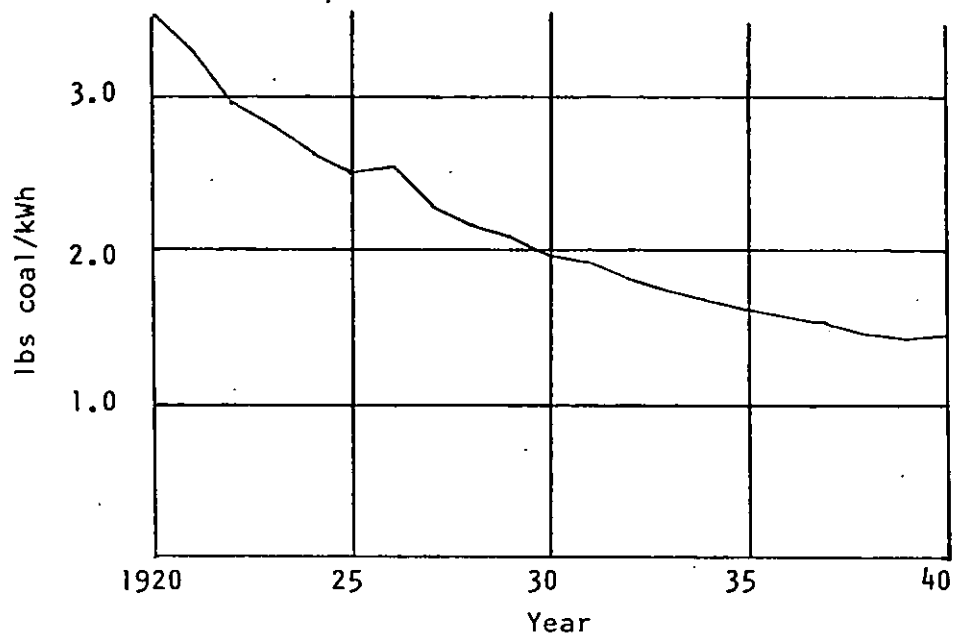


TABLE V. CONSUMPTION OF COAL lbs/kWh SENT OUT 1920 - 40

Year	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930
lbs Coal/ kWh	3.55	3.3	2.95	2.8	2.63	2.5	2.52	2.27	2.16	2.07	1.98
Year	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	
lbs Coal/ kWh	1.91	1.83	1.75	1.67	1.62	1.56	1.51	1.44	1.43	1.44	

NOTE : This figure is not a good standard of comparison as it varies with heat content of coal.

SOURCE : L Hannah Electricity Before Nationalisation (1979) Table A.3 p.432

Power stations were still being built near the load centres and some very advanced designs were produced; the largest turbine in Europe, with a capacity of 105 MWs was built at Battersea in 1935, four boilers were necessary to supply steam to this machine. In 1938 the Northmet Company at Brimsdown were running with the most advanced steam conditions in the country with a pressure of 2000 psi at 940°F indicating the possibility of further advances, these, however, were special cases and most power stations were designed as simple reliable systems to deal with rapid changes in demand.

PART THREE

THE MODERN PERIOD - POST 1940

This part concerns itself with the effect of wartime and post war conditions, and also with the results of the 1947 Electricity Act which took into public ownership the generation, transmission and distribution of electricity. Part three also follows through the development of the large modern boiler and the reasons for the particular form of this development. The first chapter covers a period of approximately 20 years from 1940, during which period the use of pulverised fuel expanded and most of the problems of super-heating and re heating steam to over 1000° were overcome. Boiler reliability was much improved during this period and the concept of one boiler supplying one turbine was developed; bulk transmission of electricity at extra high voltage allowed the generating authority to consider the building of large power stations at sites near the coal and remote from the load point.

Chapter II follows the development through to 1970, during which period boiler capacity expanding rapidly from 120 MWs in 1960 to 600 MWs by the end of the era. The final chapter provides a summary of the highlights of this period and indicates the effects of the various developments on the cost and efficiency of boiler plant.

I

The disturbance to the national economy brought about by the declaration of war soon caused the government to curtail, and later to completely veto, the routine expansion of generating capacity. Plant already being manufactured was completed, but not always on the site for which it was originally planned; for instance, the boiler designed to be built as Bolton number 5 was actually erected at Trafford power station, to supply more directly to the heavy industry in Trafford Park. Certain essential war requirements caused power stations such as Earley (Reading) and Castle Meads (Gloucester) to be constructed in the shortest possible time and to do this existing proved designs were used. Control of power station extensions had little effect on plant commissioned during the war years, but lack of forward planning meant that by the end of the war, construction was falling off rapidly.

The introduction of the Grid system, a result of the 1926 Electricity Act, had reduced the amount of spare capacity available by 1939, and despite the installation of some new plant, during the war, increased running time and a higher percentage of plant over 20 years of age, meant that breakdowns were more frequent, and that the spare margin was very slim. It was obvious that serious plant shortages would ensue in the years following the war, and strict control of expansion of non-essential consumption was maintained during the war, and for some time afterwards. Shortage of generating capacity was aggravated by lack of labour and materials and in December 1946 the amount of plant out of service, due to breakdown, was 13.1% of the total capacity installed.

¹ Sir Johnstone Wright, 'Some Aspects of Generating Station Development' Proceedings I Mech.E CLVII (1947), 208

This was more than twice the pre-war figure. By this time 17.3% of the plant was more than 20 years old and such frequent failures were to be expected. At Bolton power station eight boilers, running at 200 psig, were used to supply steam for a 12.5 MW turbine, it was not unusual for eight boilers to come on line at 07.30 and by 08.00 for three of these boilers to be shut down with tube leaks. Another restriction was brought about by deterioration in the quality of coal which made it impossible for many boilers to achieve their full rated output; boiler fouling increased and off load periods for essential cleaning became more frequent.

The fuel crises of February 1947 brought home the seriousness of the situation to both the domestic and the industrial consumer, but the long time lag between concept and completion of a power station brought little prospect of immediate relief. At the end of the war, the Central Electricity Board had initiated a construction programme to complete the installation of 6 million kW of new generating plant, by 1950, the first one million kW to be built in 1946. Owing to material and labour shortages, only 26% of this target was achieved.¹

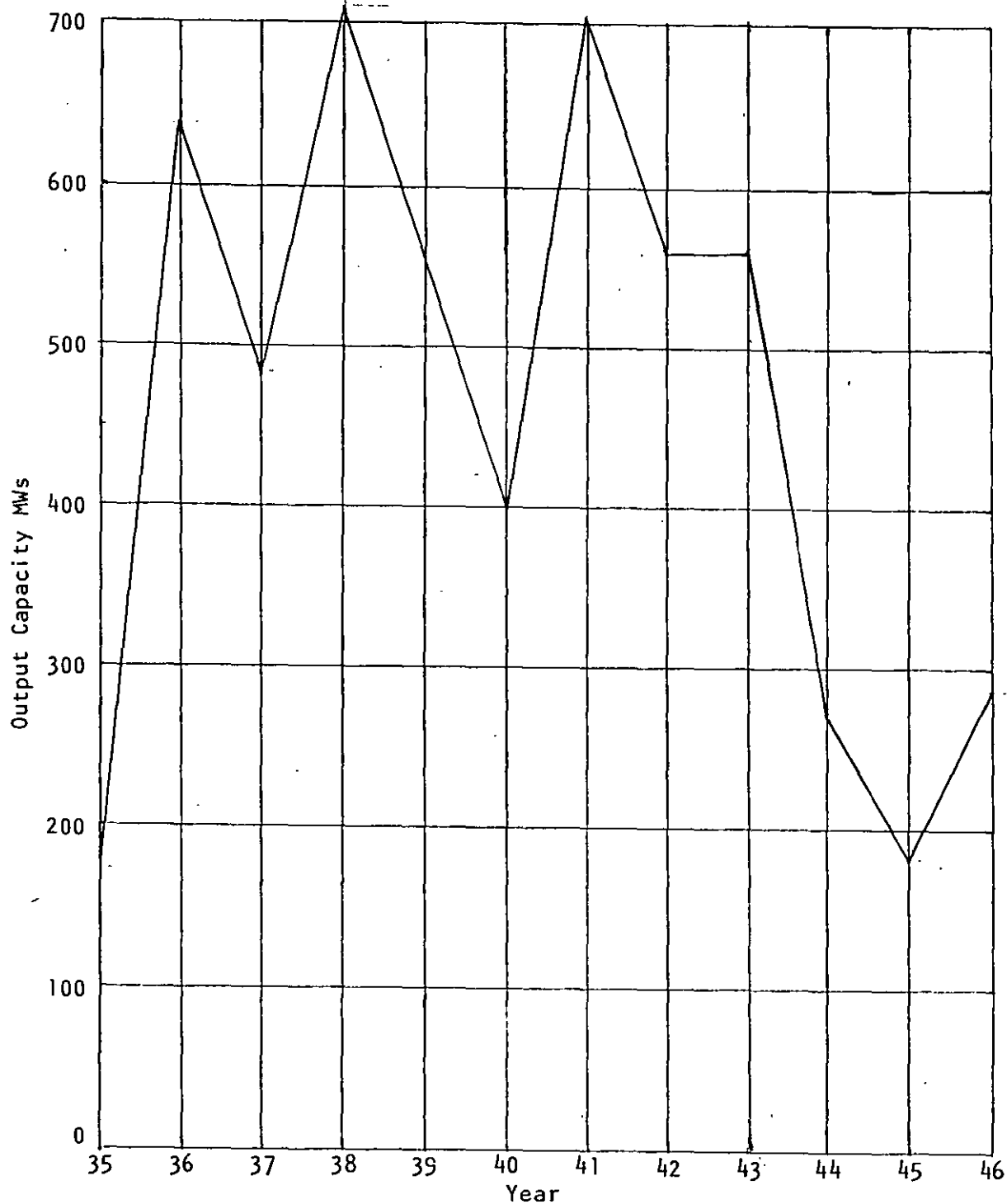
Planning national plant requirements through the CEB meant that the best use could be made of manufacturing capacity and available sites, reinforcing weak parts of the system as necessary to keep each area self supporting. Co-ordination of national plant requirements allowed the largest practicable measure of standardisation in plant design, it was at last becoming possible for a manufacturer to turn out a standard design, without making numerous modifications to satisfy individual specifications required by the various undertakings. In order to avoid stereotyped development, the CEB technical committee had agreed that the local undertakers should be responsible for designing and constructing power stations; this had however, led to these

¹ L Hannah, Electricity Before Nationalisation (1979), p.134

TABLE VI PLANT INSTALLED PER YEAR 1935 - 1946

Year	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946
Capacity Installed	174	640	486	712	440	400	708	560	560	271	181	288

SOURCE : Handbook of Electricity Supply Statistics (1972)



Plant Installed per Year 1935 - 46

unnecessary variations from basic design. It was, however, still necessary to produce some non-standard designs to complete existing stations working in the 300 to 415 psi range, with temperatures between 750°F and 825°F, so as to take advantage of the inter-connecting steam ranges, which were still commonly used.

Non-standard plant built to existing designs provided about 7.5% of the total newly installed capacity, a further 87.5% was built to comply with the Control of Turbo Alternators (No.1) Order SR & O 1947(No.2386). This order prescribed 30 MW turbines operating at 600 psi and 800°F, it also permitted 60 MW turbines using steam at 900 psi and 900°F. Two boilers per turbine were usually supplied with adequate overload capacity, so that any three of four boilers could supply the full load steam requirements of two turbines if necessary, as boilers were still considered to be less reliable than turbines. Although the existing situation necessitated this high level of standardisation design studies were carried out in preparation for the time when advances would again be possible.

Extensions to older stations were usually duplicates of original plant, but all new designs of boiler supplying more than 300 k.lb/hour were PF fired and the consumption of pulverised coal increased fivefold between 1940 and 1950. The development of water walls for PF boilers proved to be a boon to boiler designers generally, allowing greatly increased furnace ratings.² When, however, chain grate fired boilers were operated at consistently high loads, heavy fouling occurred and frequent shut down periods were required for cleaning. This problem had begun to appear in 1937 and the following year many boilers were downrated by as much as 15%; by early 1939 a committee had been formed to investigate the problem.³ Once the reason for fouling was found to be due to certain 'sticky' constituents in the ash, improved on-load

1 Electricity Council, Electricity Supply in Great Britain - A Chronology (1973) p.29

2 Furnace Rating; Steam production per unit of furnace volume.

3 Boiler Availability Committee. Chairman M H Adams

and off-load cleaning techniques and slightly lower outputs gave much better availability of the boilers. Pulverised fuel boilers did not suffer the same problems with deposits, due to the higher furnace temperatures, but these same high temperatures tended to melt the ash into slag, which built up on the boiler heating surface and eventually ran like lava into the ash hopper. International Combustion had found a partial solution to the problem by the introduction of the tilting burner in the early 1940s.¹ These corner burners were adjusted externally for tilt, with the object of obtaining the best position to avoid excessive slag deposits, the optimum tilt varying with the type of coal used. East Midlands coal, with its high chlorine content (up to 1 per cent) proved to be the worst for producing slag deposits and this was to cause considerable difficulty for a few years when generation began to be concentrated in the Trent Valley. The slagging problem in pulverised fuel boilers was controlled in a similar manner to that used to reduce bonded deposits in stoker fired boilers, that is increasing the water cooling of the furnace, division walls were used in some designs to provide extra cooling. Tilting burners were not, however, dispensed with as they were found to vary the temperature of the superheated steam and were eventually incorporated into the automatic control system of the boiler.

The first standard post war boilers, mainly built to ICL and B & W designs, were constructed on previously ear-marked sites near to load centres in order to keep transmission losses to a minimum, a practice followed by the C E B since its inauguration.

Although the Central Electricity Board was divided into seven areas, it had run with all sections inter-connected since 1939, but inter-area load flows were kept to a minimum. The principle of minimal inter-area flow meant that each area had to be self supporting and consequently the future requirements of each area had to be estimated and the relative merits of

¹ R H Gummer, 'Thirty Years Advance in Steam Generation' Journal of the Institute of Fuel, XXIX (1956), 200.

alternative programmes had to be examined. The anticipated incidence of load, capacity of the grid transmission system, room available for expansion on existing sites, or availability of new sites and the cost including transport of suitable coal, all affected the installation of power plant in a particular area. The economies of new plant extensions had also to be determined in relation to their effect on the costs of the whole area, since the introduction of new highly efficient plant resulted in decreased generation at the older stations. With the increasing capacity of individual power stations arrangements for transporting coal became of major importance, coal was transported to estuary and coastal stations by 1250 and 4000 ton colliers, 100 and 300 ton barges for river and canal side stations, and in 10 and 20 ton trucks for railborne supplies. Large areas of land became necessary to hold coal in transit, apart from that necessary for a coal storage area. A station of 240 MWs using approximately 2000 tons of coal per day (2 trains of 60 wagons) would require sufficient siding accommodation for 4 trains of full wagons, two trains of empties, plus two run-round tracks for manoeuvring locomotives round the trains. The area of land required for coal handling and storage was frequently as large as that required for the station buildings, building power stations near the load centres proved to be expensive as land costs were high and the transport of power station quality coal was also expensive when carried to stations remote from the coalfield. As a result of the continued growth of electricity demand, increasing coal transport costs and the concentration of coal production in the East Midlands and South Yorkshire coalfields, the newly nationalised electricity supply industry had to consider the possibility of bulk transfer of electricity rather than coal for the next phase of its development.

To transfer electricity with minimum loss it is necessary to keep the current to a minimum, as any loss in a transmission line depends on the electrical resistance of the line and the square of the current flowing. Electrical power is measured in watts, a watt being the product of the

current flowing and the voltage applied to the line, so that to keep the current to a minimum a high transmission voltage is necessary. By increasing the operating voltage from the original grid voltage of 132 kV to 275 kV it became possible to transmit six times the power over a given line. The decision to build a superimposed grid working at 275 kV was taken in 1950 and the first section was commissioned in July 1952 between Newark and Sheffield, to allow bulk transmission of power from the Trent Valley to the industrial centres of Yorkshire.¹ The system proved an immediate success and it was rapidly extended to form a ring round the North and Midlands, a necessary pre-requisite to the extension of power generation in the Midland and East Midland Divisions of the recently established British Electricity Authority.

The first post war station to be completed on a green site was that at Meaford near Stoke on Trent, officially opened on October 20th 1947, by the Rt.Hon. E.Shinwell, who was Minister of Fuel & Power.² It had been decided in 1938 that a large new generating station should be built in the North West Midlands and considerable project design work was carried out before the declaration of war so that when the final decision to construct the plant was made, work could proceed rapidly. In February 1945 work was started on the site, in July of the same year the foundation stone was laid and by January 1948 the first generator was in commercial operation. Meaford A, as the station eventually became, was designed as a self-contained unit and as such was not capable of extension. This became the standard procedure after nationalisation, although three or more stations were built on one site they were separate entities, usually designated A, B, and C.

1 L C Butterley, 'Fuel & Power - Pattern of Generation' Summaries of Lectures (Electricity Council 1974), p.14

2 F Favell & H Nielson, 'Meaford Power Station' GEC Journal, XV (1948),
1 - 4

The plant installed at Meaford consisted of four turbines, each with a maximum rating of 30 MW, with six boilers supplying steam at 600 psig and 825°F, having an economic rating of 192 klb and a maximum rating of 240 klb, this meant that five boilers could carry the load without distress in case of one being out of service, but the work could be done more efficiently with six running at their economic load. Designed to burn North Staffordshire coal as pulverised fuel, the station had the advantage of low transport costs for coal, but the proximity of coal seams had complicated the actual siting of the station. Later stations in Yorkshire and the East Midlands were built over coal deposits and compensation was paid to the Coal Board to leave these seams unworked as the increasing weight of power station plant limited the alternative sites with suitable load bearing strata.

As a result of the work done by the Availability Committee boiler reliability was improved and further consideration was given to the building of Boiler/Turbine units with no cross connection of the water or steam pipework. The first plant to be built on the unit principle was installed at Stockport power station as a wartime emergency measure, a 30 MW turbine working at a higher steam pressure than the rest of the station was installed in 1943.¹ To fit the necessary boiler plant in the space available on the site it was decided to build one boiler with a generously dimensioned combustion chamber to reduce the incidence of fouling, using pulverised coal as fuel which was less likely to cause bonded deposits. The advantages of unitised plant was a capital saving on inter-connecting pipework and steam receivers, it also was ideal for use with re-heated steam as the steam returning to the boiler was a known proportion of the steam supplied to the turbine.

¹ F C Garrett, ed. Garckes Manual of Electricity Supply L (1954), A - 112

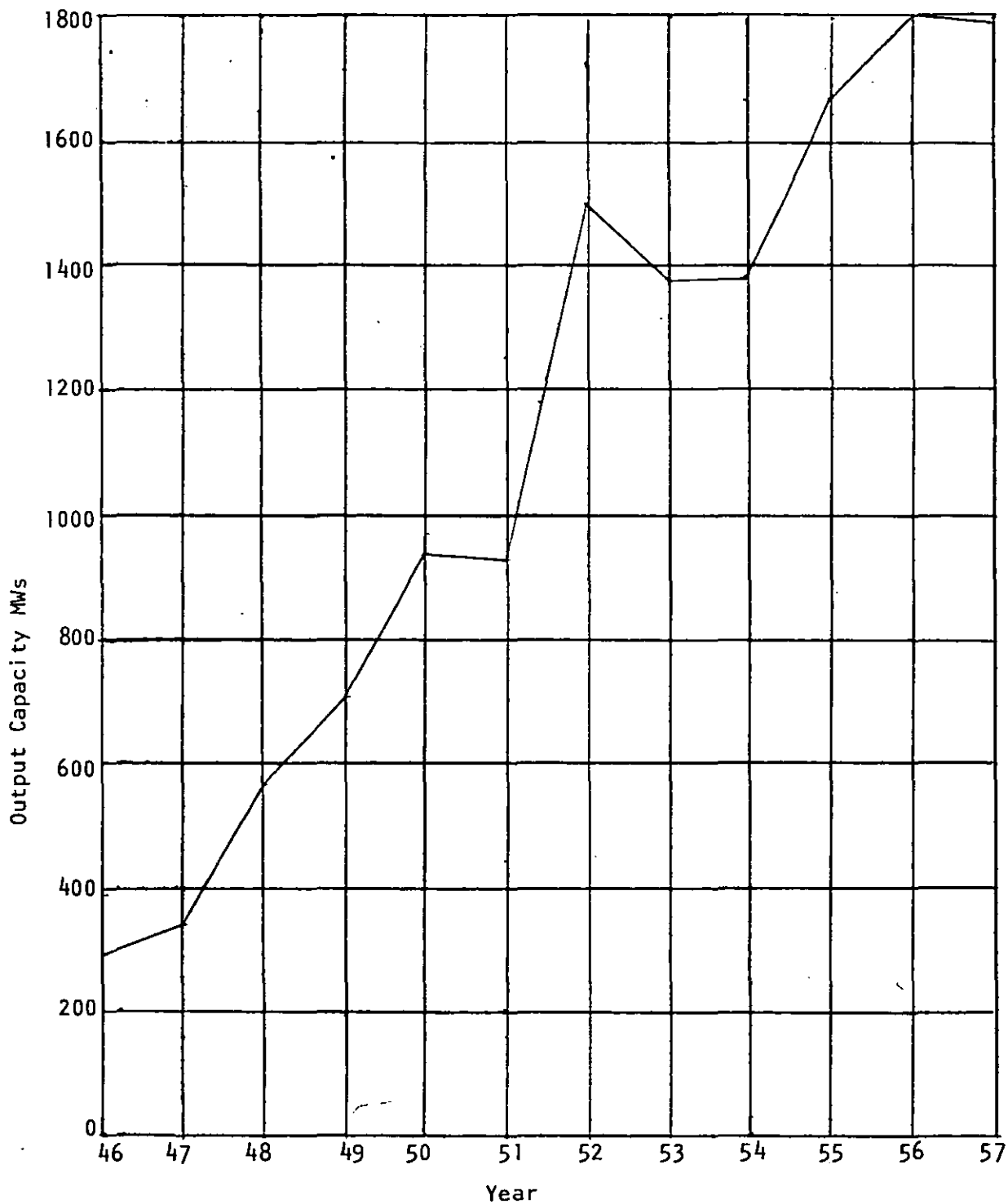
The first large scale application in this country of the unit boiler was at Dunston B II, where two 50 MW re-heat turbines were installed.¹ In October 1949 the first of two Babcock & Wilcox boilers was commissioned, it supplied 410 klbs of steam/hour at 600 psi and 849°F, with re-heat to 849°F, this was not, however, an indication of immediate future development but a continuation of the long standing interest of NESCO in re heating, since long before the industry was nationalised.

A number of stations built towards the end of the standard series such as Bold, Blackwall Point, Huncoat, & Rye House had a matching number of boilers and turbines, with the minimum amount of inter-connection; Bold normally ran fully inter-connected while Rye House ran as separate units, only inter-connecting in emergencies. The first complete station designed on unit principle was built at Keadby, where in April 1952 the first boiler by the Stirling Company was put into service.² At this time it was the largest in service in the United Kingdom, supplying sufficient steam to run a 60 MW turbine.

Babcock & Wilcox supplied the boiler plant for Meaford power station, but many other companies normally not involved in power station work were invited to participate in the expansion programme. John Brown Land Boilers, Yarrow, Clarke-Chapman, and Simon-Carves were among those building to the post war standards and even Daniel Adamson, a company who normally built boilers for industrial plants, had a contract to build two boilers of 135 klb/hour for Cowes power station extension, where 2 x 12.5 MW turbines were installed. By spreading the work among a large number of boiler contractors and applying a similar technique to other parts of the power station, construction was again accelerated.

¹ A Howell & J B Jackson, 'The Design & Operation of Dunston B II' Proc. I Mech E CLXVII (1952), 81

² Keadby Generating Station Babcock & Wilcox pubn. 1626 (1955), p.1



Plant Installed per Year 1946 - 1957

TABLE VII - PLANT INSTALLED PER YEAR 1946 - 1957

Year	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957
Capacity Installed	288	340	566	703	937	935	1492	1366	1375	1665	1797	1788

SOURCE : Handbook of Electricity Supply Statistics (1972) Table 3

The revocation of the Control of Turbo Alternators Order in August 1950, allied with the easing of control on capital expenditure and the clearing of the back-log of installation necessary to maintain a stable system, allowed the Electricity Authority to consider the building of more advanced designs of plant.¹ At about the same time a report was published by the Anglo American Council on Productivity on a visit to the USA of productivity teams representing the British electricity supply industry. It was recommended in the report that the construction of 120 MW units should be considered as the time of manufacture and erection of a 120 MW unit was no greater than that of a 60 MW one, and, as technology and transport could cope with the largest pieces of equipment required, 120 MWs became the standard size for a little while.

Another suggestion by the Productivity Council was that to speed construction and to conserve building material, there would be considerable advantage in constructing a semi-outdoor boiler. The concept of outdoor and semi-outdoor plant was not new, many early egg-ended and Lancashire boilers were built outdoors, the idea being later developed by the oil industry in both the United States and Great Britain. The superstructure of a power station is a basic steel framework to support the generating plant and its auxiliaries, the weatherproof cladding being applied later. As the weatherproofing is not load bearing the costs do not form as large a proportion of the overall costs as may be expected, but any possible saving is worthy of consideration.

Capital costs are not the sole criteria, the complete power station must operate reliably, efficiently, and cheaply; to evaluate the various factors in the notoriously fickle British climate it was decided to build a semi-outdoor boiler plant at Ince on the Wirral Peninsula, the installation

1 A decision that would have been difficult to implement without a national authority.

2 F H S Brown, 'Design Features of the Semi-outdoor Power Station at Ince' Proceedings of the Institution of Electrical Engineers CLXVII (1953) 103

was a standard one of 4 x 60 MW boiler/turbine units, working at 900 psi and 900°F. When the station was completed it was estimated that a saving of about £1 per kW installed was made, but extra heat loss from the boiler, due to its outdoor construction, was capitalised at £45,000 and this reduced the saving by 20%. Additional complications were introduced into the pipework of the station where such items as pressure gauge lines and safety valve drains had to be protected from frost, operation and maintenance were also affected to some degree, the discomfort of working outdoors in winter cold generally being greater than that of working in an enclosed boiler house in summer heat. With the shortage of materials and skilled bricklayers that existed at the time, it was expedient to use this technique for a short time, but with the introduction of plastic coated steel sheets, the operational advantages of an enclosed boiler house overcame the slight saving in capital expenditure.

Once the decision was taken to build a semi-outdoor station it was comparatively easy to implement, but before building the new standard 120 MW unit, it was thought advisable to build some high pressure plant of intermediate sizes. Three stations were built with 60 MW units, working with the new advanced steam conditions of 1500 psi and 1050°F, followed shortly afterwards by two more stations with 100 MW units. Drakelow 'A' was the first new station to be designed after the 'Control of Turbo Alternators Order' was revoked in August 1950, and No.1 turbine was first put on load in December 1954, shortly after the single machine installed at Stourport 'B'.

The four boilers supplied to Drakelow 'A' were manufactured by I C L, to their Lopulco three drum radiant design, with corner firing, each being capable of producing 515,000 pounds of steam per hour.¹ Low grade East

¹ Engineering & Boiler House Review Dec. 1955 Drakelow 'A'
ICL Reprint W 562, p.3

Midlands coal having a gross calorific value of 8,770 B Th U/lb. with an ash content of 21.5% and 14% moisture was to be supplied to the station and the furnace was designed to accommodate this poor fuel. An additional complication was the low melting point (2070°F minimum) of the ash in the fuel and the high steam outlet temperature, this meant that unless the furnace was correctly designed, it would not be possible to achieve the specified requirements for continuous operation over long periods with only on-load cleaning.

The combustion chambers were designed to be completely water-cooled by close pitched bare tubes on the side walls and finned tubes on the front and rear walls and roof. Gas lanes between the superheater tubes were wide to reduce the possibility of dust build-up. A deflecting nose was built into the furnace wall tubes to protect the high temperature section of the superheater from direct radiation from the fire, but to obtain the high superheater temperature required, no water screen tubes were fitted. Omitting the screen tubes proved to be a mistake as these boilers continually suffered from high superheat temperature as soon as the furnace walls became slightly fouled, and after a few years' operation additional screen tubes were fitted in the furnace to improve steam temperature control.

Although the pressure parts of a boiler can be designed accurately, the heat transfer in different parts of the furnace cannot be precisely predicted as it is often based on extrapolation from previous experience and so modifications such as this occasionally prove necessary.

After careful consideration it became clear that only two steels offered reasonable promise of satisfactory service working at 1500 psig and 1050°F, these were :-

1 H Greenwood, 4½ Years Operating Experience At Drakelow
CEGB East Midlands Division (Nottingham 1959)

111

(a) Firth Vickers FCB (T) austenitic stainless steel, having 18% chromium, 12% nickel and 1% niobium content.

(b) A ferritic steel having 2.1/4% chromium and 1% molybdenum content.

The main differences being that austenitic steel is non-magnetic, it has a 50% greater thermal coefficient of expansion and a much higher creep strength than the alternative. With this superior creep strength thinner pipes could be used, which gave a much more flexible piping system and less weight to support. Electrodes suitable for welding this particular steel were readily available and a considerable amount of piping made from 18/12/1 steel had been installed in the United States and in 1949 when it was decided to use this material, it was believed to be trouble free. The alternative ferritic steel was rejected as little information was available on its creep strength; British made welding electrodes were not available and the pipework etc. would have to be made almost twice as thick as that of austenitic steel. The decision to introduce austenitic steel into British power stations was based on American published experience, it must be presumed that problems and failures had been kept quiet and the possible difficulties had not been fully investigated by British engineers.

The use of austenitic material with Nicrex and Armex welding rod was eventually agreed on by the B E A, Steelmakers, Manufacturers and Insurance Companies. It was decided that austenitic should be used in the knowledge that while new ferritic steels might eventually become available for these conditions, any further advance would almost certainly require the use of austenitic materials and experience should be obtained in the use of such material.

At Drakelow the main steam piping to the turbine was made from the 18/12/1 steel with welded joints using Nicrex for the starting and finishing runs and Armex GT for the main body of the weld. The second half of the superheater and its inter-connecting headers were made from 18/11 steel, with a slightly lower nickel content.

Prior to the commissioning of No.4 boiler at Drakelow, a gamma ray inspection of welded joints in the main steam lines revealed that cracks were present in the parent metal alongside some welds, as a result of this No.3 was shut down and further cracks were found. In view of this situation the remaining two units at Drakelow and the Stourport B2 unit were shut down for a full survey to be carried out. Minor cracks were found during this further investigation and were repaired by grinding out and re-welding.

A programme of regular inspection was initiated by the B E A and an investigation was carried out to find ways of eliminating the cracking. It was eventually found that welding with Armex without a preliminary run of Nicrex gave the best results, providing post welding heat treatment was carried out.

By using the new methods of post weld heat treatment, inaugurated at Drakelow and Stourport, much less trouble was experienced at Willington, the third station to use austenitic steel, only Armex GT welding rods were used from the start and higher temperatures were used for the heat treatment.

This excursion by the B E A into the comparatively unknown field of austenitic steel proved to be somewhat costly, over a period of about 5 years from July 1954 to October 1959 plant was out of commission for 20% of the possible operating hours. The cost of repairs, additional fuel costs in running replacement plant and capital charges accruing while the plant was out of commission totalled over £2,000,000, although some of these costs were borne by the manufacturers.

see over for table

TABLE VIII PLANT OUTAGE & COSTS ATTRIBUTED TO AUSTENITIC DEFECTS
JULY 1954 - OCTOBER 1959

Station	Additional Fuel	Repair Costs	Capital Charge lost capacity ¹	Aggregate Loss
	£	£	£	£
Drakelow	1,187,250	50,315	104,000	1,341,565
Stourport	113,385	14,814	15,600	143,799
Willington	549,975	5,778	43,800	599,553
				2,084,917

¹

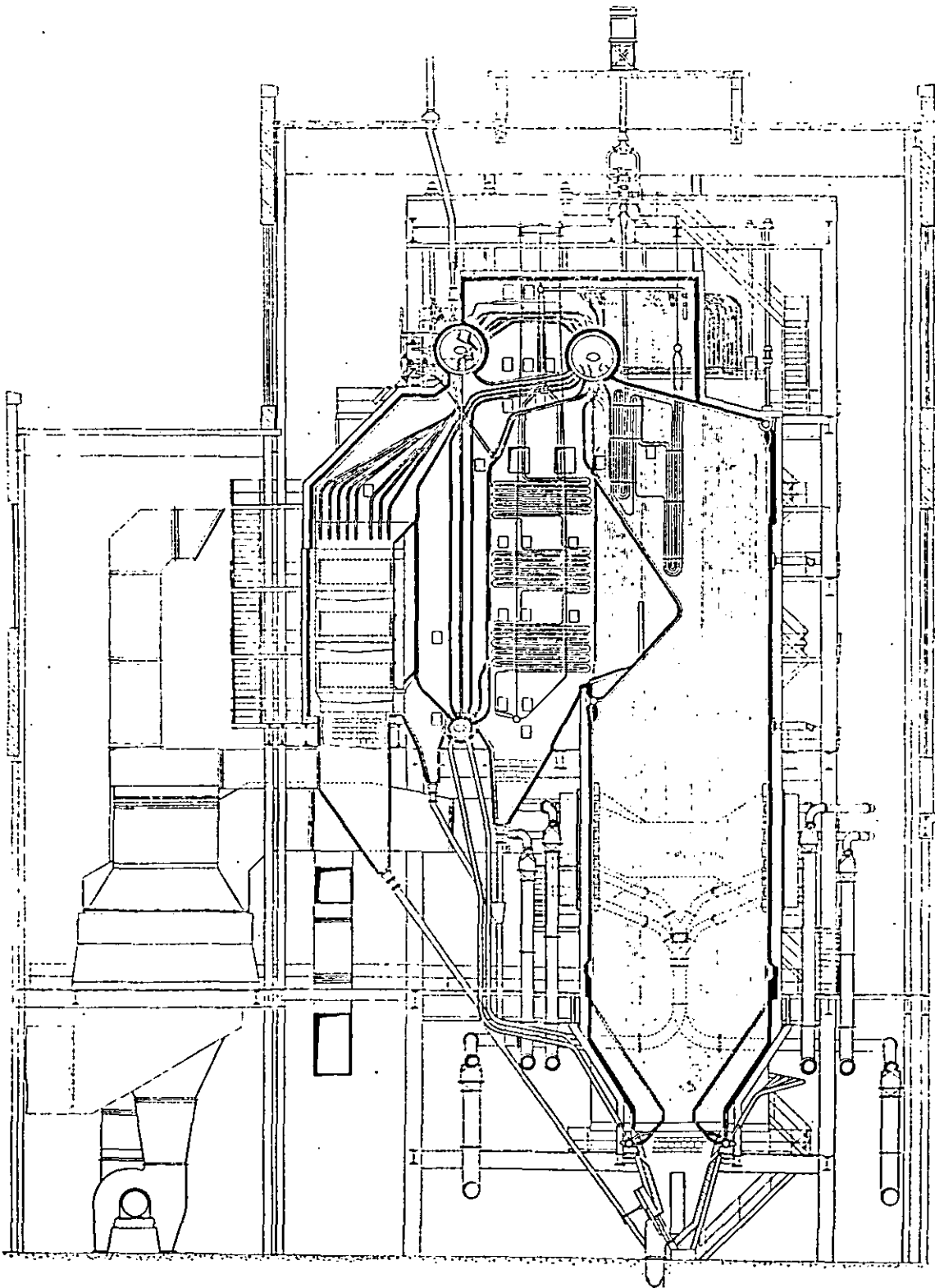
Capital charges on the plant for the period when it was not available due to austenitic defects; Based on plant cost £60/kW, Interest Rate 5½% .

Source : Operating experience with Austenitic Materials, (Appendix 1).

As a result of these excess costs, the use of austenitic materials was suspended for a time, and in some cases new designs were produced, using slightly lower steam temperatures until more suitable austenitic steels were produced. When new materials became available the B E A belatedly organised a series of test programmes with varied heating and cooling cycles to assess their suitability.

Despite the metallurgical problems brought about by the use of new materials and the aggravation of this problem by the difficulties experienced in controlling steam temperature, Drakelow 'A' proved to be a very successful station, achieving gross boiler efficiencies of 86% and overall station efficiencies of 30.7%; unfortunately it never became top station as the long periods out of service in its early life allowed it to be overtaken by later designs. Apart from control of water level, no automatic equipment was fitted to the boilers and a high degree of skill was attained by operating engineers and stokers who carried their skills to the later generating stations in the Trent valley and elsewhere.

DRAKELOW 'A' POWER STATION
Central Electricity Authority, East Midlands Division



Four boiler Units, each evaporating 515,000 lbs steam per hour, steam pressure 1550 psi and final steam temperature 1060°F, fired with pulverised fuel. These were the last large tri-drum boilers to be designed by ICL, all later designs were produced with a single drum to reduce manufacturing costs.

In 1950 the Authority obtained competitive tenders for 30, 60 & 100 MW units, these tenders showed that it would be economic to move to a larger size.¹ With the increased steam pressures being considered, turbine blade sizing presented a complication, the length of low pressure blading for a 60 MW turbine, running at 3000 rpm (blade tip speed 1,250 fps) could easily be designed with adequate strength, but the small high pressure inlet blading had to be built to very close tolerances to maintain efficiency. Once improved material and designs were available for the necessarily longer low pressure blading in a 100 MW turbine, the high pressure blading could be made correspondingly longer with greater tolerances, the advantage moved further towards the larger units. This improvement was another step towards the 120 MW re heat units advised by the Productivity Council and Willington and Castle Donnington were designed with units of 400 MW capacity, the first one being commissioned in 1956.

Although the Board had committed themselves to a small number of units using steam at 1050°F, with austenitic steam pipes, it was fortunate, in view of the problems with this new material, that the designers of the first re heat units had reverted to improved ferritic steam piping. A steam temperature limitation of 1000°F was considered to be advisable, due to problems with materials and the first re heat machines were actually designed for a steam temperature of 975°F, with re heating to 950°F.

With units of 100 MWs and over one stage of re heating became both technically and economically viable, two stations were built with 100 MW boiler/turbine units, working at 1500 psi and 975°F/950°F, to give an equivalent efficiency to that of the non re heat units running at 1050°F.

¹ L Lamb, 'Trends in design of large power station boilers',
Journal of the Institute of Fuel XLV(1972), 443

It became evident during the design stage that it would not be difficult to use initial and re heat steam temperatures of 1000°F using a limited amount of austenitic steel for the high temperature section of the super-heater.¹ Thirty nine 120 MW units at 1500 psi 1000°F/1000°F were built; the first ones being commissioned in 1958 and for a few years this became the new standard size.

Boilers big enough to supply these 120 MW turbines were reaching their limits without radical re-design and some manufacturers introduced changes in anticipation of the next increase in size. The nearly square section furnace required by International Combustion for corner firing reached a limiting point at 120 MWs and all larger designs were built with two separate furnaces connected to a common boiler drum, the tri-drum design was also abandoned at this stage, due to the high cost of boiler drums and the changed heat absorbing relationship in re heat boilers. Front fired designs as used by Babcock & Wilcox and Foster Wheeler were also finding problems and in order to install sufficient heat absorbing surface, extra division walls of water tubes were fitted in the furnace. Division walls provided extra steam generating surface and were introduced as a limit of 72ft was placed on the width of the furnace by length of available sootblowers (36 ft), which were necessary to clean the heating surfaces at the furnace outlet. Unfortunately the introduction of division walls upset the relationship between steam generating and superheating surface areas, and it became necessary to install some of the primary superheating tubes in the front wall of the furnace, which added to the complications of starting a re heat steam generator from cold, it did however, leave more space between the superheater sections to fit the re heater. Another innovation introduced with the 120 MW units was the platen superheater,

¹ F Dransfield, 'Development of Large Turbine/Boiler Units'
Electrical Review CLXIX, (1961), 952

this section of the superheater consisted of a number of closely pitched tubes hung from the furnace roof like a curtain. The position of these platens and the number installed could be readily altered at the design stage and proved a useful adjunct, particularly when furnace size limitations affected a particular boiler design, the relationship of superheat to re heat used in different steam cycles can be seen in the diagram below. To reduce design complications it was decided, as a deliberate policy, that the re heater would not be steam cooled during pressure raising, the tube metal was kept within temperature limits by selective use of coal burners until steam flow was established.¹

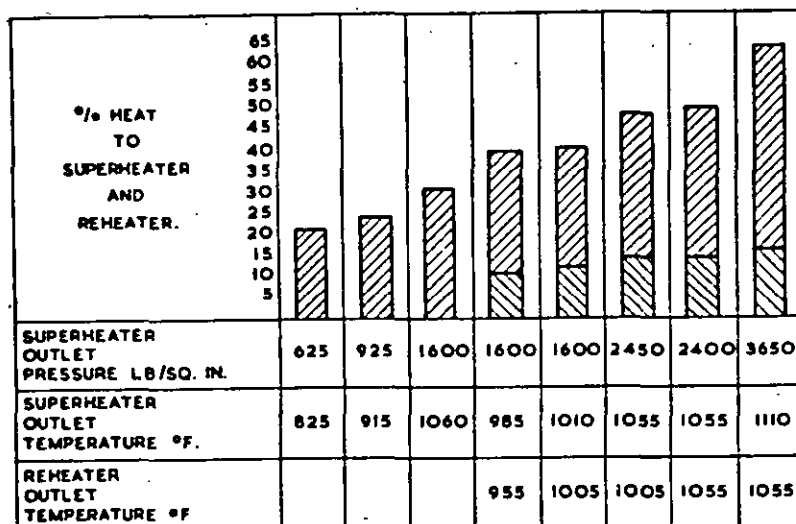


TABLE IX HEAT REQUIRED FOR SUPERHEATING AND REHEATING IN VARIOUS STANDARD STEAM CYCLES

Source : R Bagley, Progress in Modern High Pressure Boilers, Babcock & Wilcox, Pub.No. 1813, (1964), p.5

By this time the Electricity Authority's policy of building power stations near the source of cheap coal and transmitting power via the 275 kV super-grid had proved successful and design of a 400 kV grid was already under way. The decision to concentrate power production in the Trent valley

¹ F Dransfield, 'Electrical Power Generation from Fossil Fuels' Journal of the Institute of Fuel XXXV (1962), 134

was based on the fact that the flow of water in the River Trent was such that it could supply a large power station every 10 miles along its length downstream from Drakelow, supported by the National Coal Board's first long term Plan for Coal published in 1950. At this time the national average mining costs stood at £2.5s.5d. per ton, Leicestershire being lowest at £1.13s.5d. and Neath the highest at £3.15s.5d.¹

If mining costs alone were considered for investment purposes then the obvious place to build up production was in areas where there were large reserves and production costs were low, this the N C B did. Apart from some investment in the South Western and Northern Divisions for the production of special coal, the bulk of investment was made in the East Midland and Yorkshire Divisions. Coal shortages caused some re-assessment of the situation so that a second Plan for Coal was issued in 1956, which stepped up the proposed rate of investment in areas where a rapid return could be expected, this particularly applied to the South Derbyshire and Nottinghamshire coalfields.

During 1955 the Ministry of Fuel & Power became disturbed about possible future coal production and costs and decided on a programme of nuclear power development. To be economically viable a nuclear power station must have a high load factor, for safety reasons they are normally situated in sparsely populated areas, and because of the large quantities of cooling water required it is an advantage to site them on the coast. These requirements had a direct effect on coal fired stations in that coastal sites were reserved for nuclear stations, consequently cheap sea transport was no longer available for coal. It also meant that all coal fired plant had to be designed so that it could be shut down for periods

¹ E S Simpson, Coal & Power Industries in Postwar Britain (1966), p.5

of three or four hours and brought back on load without difficulty in less than an hour so that they would be available for morning load while allowing nuclear stations to generate the night load. The decision to construct the first 1000 MW power station near the expanding coal field at High Marnham and the construction of the 400 kV grid system necessarily went together to transmit the power from the prototype rural power station to the point of use. The successful conclusion of this exercise made it possible to carry on with the expansion of power production down the valley of the River Trent, with even larger generating units.

The capacity limitation at 120 MW per unit was held for a little time because of weight and physical size limitations in transporting plant from the manufacturer's works to the power station site. Research to overcome this problem was carried out in a number of different directions. Experience and theory had shown that up to the point at which a major technical design change became necessary, the cost of plant declined as size increased, a reduction of 20% in cost per kW installed for each 100% increase in output was achieved between 1950 and 1960. An important limitation at each stage has been the size and weight of a generator that could provide suitably stable electrical conditions and still be transported from factory to site in this country. The use of hydrogen at gradually increasing pressures for cooling the windings up to 120 MW proved very successful. Turbine and boiler designs were usually matched to the largest available generator although a certain degree of compromise or complication had to be accepted, such as the narrowing of the upper part of the boiler, or building two furnace outlets to overcome the limitation caused by maximum sootblow length.¹ Improved site welding techniques developed for building pressure vessels at nuclear power stations were modified so that boiler drums could be transported in two or three sections and welded together on site before erection.²

Designs were produced to comply with the maximum transport weight of 150 tons including vehicle which applied on British roads. However, the Ministry of Transport, after investigation, permitted certain routes between manufacturers' works and power station sites, to carry loads of up to 200 tons and in the case of two sites, loads of 240 tons were allowed.

1 R Bagley, Progress in Modern High Pressure Boilers
Babcock & Wilcox, Pub.No.1813/1 (1964) p.3

2 Ibid. p.3

Rail transport could not be used as an alternative as although the dead weight could usually be safely carried gauge and height limitations often applied.

The specialist transport department of the Electricity Authority initiated a number of projects designed to improve the transport of large loads in this country. ¹ A low load trailer incorporating hovercraft principles was produced so that axle loading could be greatly reduced, this was particularly useful in spreading the load when bridges had to be crossed. Two shallow draught roll-on, roll-off ships were produced to the Authority's specification on which they had first call; heavy plant could thus be moved from Tyneside, Manchester etc. to a suitable point on the coast near the power station site. A special rail vehicle was built whose main frame was moveable off centre so that short rail journeys could be made despite its gauge limitations.

Within the power station building the four main items, boiler, condenser, turbine and alternator have to be installed in such a way as to allow for maintenance to be carried out, adequate space must be left between units for replacement of parts. This is a complex problem requiring sufficient space to remove the alternator rotor endways from within the stator windings, condenser tubes required transverse clearance for renewal, and boiler spacings sufficient to allow full retraction of 36ft lance type sootblowers. Above or below these clearance areas, or taking up as little extra space as possible it is necessary to fit coal bunkers, milling plant and many other items.

High speed coal milling plant could not be developed to adequate size to be compatible with space requirements and the already high maintenance costs of these mills would have been exorbitant with the poor grades of power station coal now being mined.

¹ R Farrall, Development of Special Transport for Power Station Construction

International Combustion extrapolated their 'L' type mill design to a maximum of 14 tons/hour to supply a 120 MW boiler with 4 mills in service and one on overhaul, the Babcock 'E' type medium speed mill was similarly stretched, but both companies were working on new designs. Both John Thompson and Foster Wheeler concentrated on a large tumbling ball mill, which although it had the heaviest power consumption of any mill type, could run with no maintenance other than lubrication from one boiler inspection to the next. Three ball type mills with 6 fuel conveying fans (exhausters) were adequate to supply a 120 MW boiler with one exhauster out of service for maintenance.

Balancing capital expenditure, running, and maintenance costs between the three different types showed very little difference in the long term so that boiler manufacturers were usually allowed to fit milling plant of their own choice.

With the increased size and complexity of the 120 MW re heat plant, methods of operation and grades of staff on operation were changed. Plant control rooms were developed, from which most of the operation of two units could be carried out, remote control of valves, dampers etc. was possible from within this control room, temperature and pressure indication with alarm systems were also displayed within the room. The problem of controlling the large quantity of steam in the turbine and re heating system had been overcome in the first re heat stations by the use of an intercepting valve which could be shut in emergencies by the same control system as the main turbine stop valve.

The problem of turbine control was becoming evident even with non re heat turbines of 100 MW's capacity and it was necessary to develop an anticipatory device to prevent dangerous overspeeds. By continuous measurement of speed, electrical load, and steam pressure within the turbine it was possible to predict an overspeed, shutting all steam valves and

putting out the boiler fire before a dangerous condition was reached.

A typical staffing arrangement on a pair of 120 MW units consisted of an operations engineer designated Plant Control Engineer, a Unit Operator and two assistants who were trained in both boiler and turbine operation, with 3 or 4 Auxiliary Plant Attendants who look after lubrication, routine checking of mills, pumps etc. and local operation where necessary.¹

The operational complexity of these units made automatic boiler control essential and with such equipment optimum combustion condition could be maintained with greater safety and less operator fatigue. Control of combustion, of mill output, steam temperatures, and water level for instance were all inter-related and during start-up conditions, 3 men were often required to look after these items until the automatic boiler control could be put into service. Staffing on operation of an immediate post war station with 4 x 30 MW turbines and associated boiler plant, with semi-automatic control required a Leading Stoker, with 4 Stokers, a similar number of staff in the turbine room, plus about 10 Auxiliary Plant Attendants, so that approximately 60% fewer operators were required on the larger unitised plant.

Power stations in 1948/49 employed on average 2.8 men/MW sent out, by 1962 this figure had fallen to 1.3 and the newer stations at this time were down to 0.7 employees/MW.²

Progress in alternator design was necessary before a larger generating unit could be made, Metropolitan Vickers developed their direct water cooled stator winding, in addition to hydrogen cooling, while English Electric introduced a high speed fan to circulate hydrogen coolant at a much faster rate.

¹ A E Powell & E Forth, 'Design, Commissioning, & Operation of Blyth A Power Station' Proceedings I Mech E CLXXV, (1961), 448

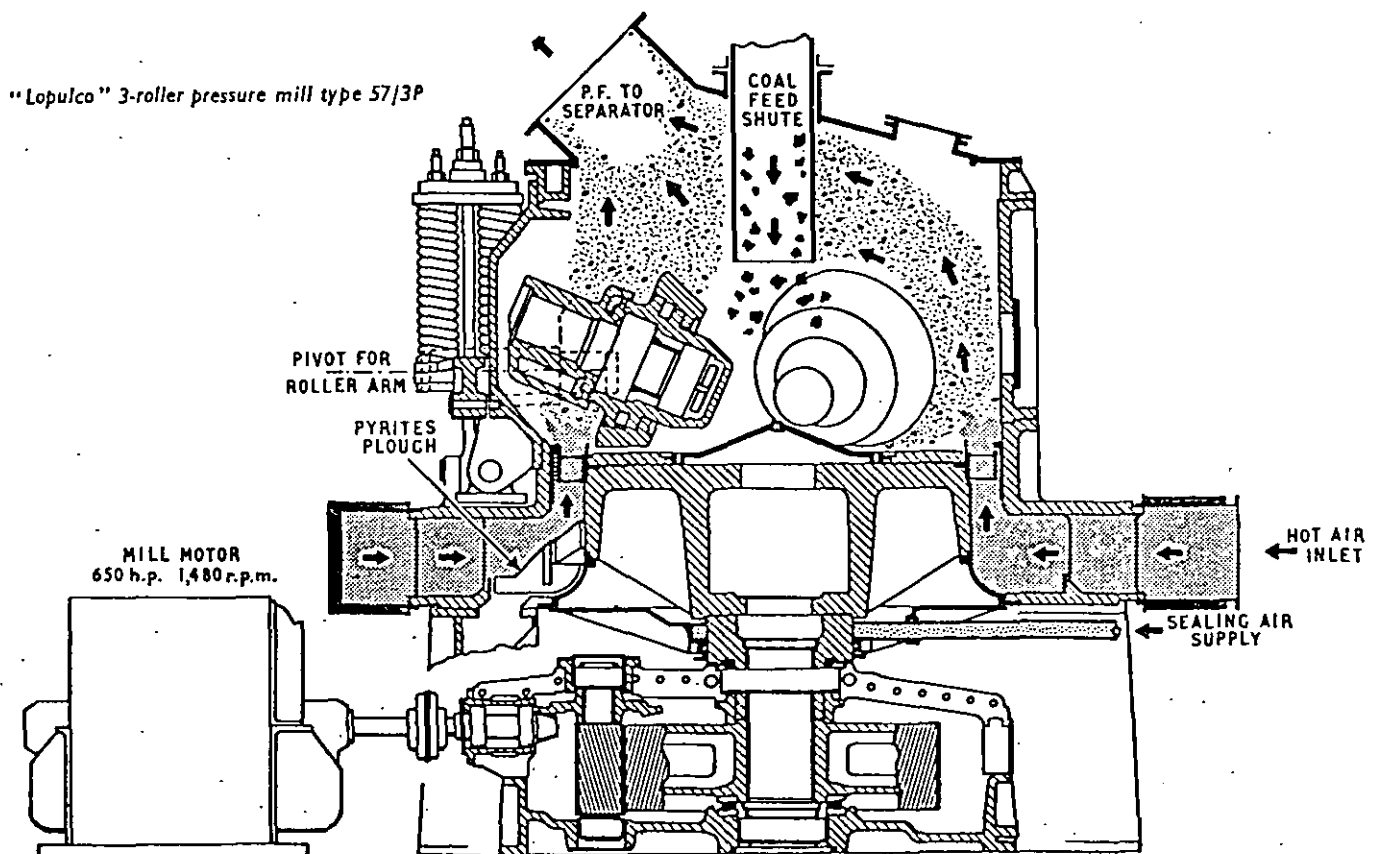
² Sir Ronald Edwards, The Expansion of Electricity Supply (Electricity Council 1963), p.6

With both these systems the coolant passed directly through the copper of the windings, so eliminating the heat barrier of the electrical insulation. These developments allowed the stator windings to carry a greater current within a given casing size, also by increasing the generating voltage to about 16 kV the amount of current flowing for a given power output was kept down. Once these improvements in alternator design had been proved by application to some 100 MW and 120 MW alternators, the production of larger generating units could be considered and 200 MW was chosen as a staging point.

With the possibility of rapid advances in size from 200 MW a further step in temperature and pressure could be envisaged. It was expected that a considerable increase in pressure would be economical but the supercritical region was avoided as there was no experience in Europe of large supercritical machines. It was decided to fix on a pressure of 2300 psi at the turbine stop valve, this required a pressure of 2650 psi in the boiler drum, and safety valve setting of 2750 psi. Critical pressure is about 3200 psi; at this point the density of steam and water is the same and no latent heat is required for water to change into steam. Natural circulation of the boiler water was still possible at 2750 psi as there was sufficient difference in density between steam bubbles and water for the steam bubbles to rise within the tubes and be replaced by water from the external downcomers; International Combustion however, decided to introduce assisted circulation. Electric motor driven pumps were installed in the boiler water circuit, increasing the electricity consumption of the boiler by about 0.15%, but a compensating saving in capital costs was made by the use of smaller diameter and consequently thinner boiler tube. Steam temperature at the boiler stop valve on these 200 MW units was fixed at 1060°F, but austenitic steel was avoided except in the final section of the superheater by using the newly developed chromium, molybdenum, vanadium alloy ferritic steels.

High Marnham power station, near Lincoln, was the first installation of 200 MW units, the boiler contract going to International Combustion, who supplied the five boilers to this the first 1000 MW station. Shortly afterwards two contracts for Willington and West Thurrock were awarded to Babcock & Wilcox to supply two 200 MW boilers for each station. The South of Scotland Electricity Board also ordered two similar Babcock & Wilcox boilers for Kincardine; by the time construction was started on these contracts, designers were already looking for further advances so that only eleven boilers of this size were built in Great Britain.

To provide the large milling capacity required for High Marnham, the three roll pressurised mill was introduced by ICL, this mill was designed to grind 28 tons of coal per hour, with 10% moisture and it could still handle 23.7 tons per hour when coal with 23.0% moisture was supplied. The three roll mill could handle a much larger quantity of coal within a given physical size than could the two roll design, the consequent reduction in mill numbers allowed a deep narrow bunker to be used, giving improved space utilisation within the boiler house.



In order to continue using their well established corner fired system ICL found it necessary to introduce a twin furnace design so that they were able to use eight corners, and with sixteen burners in each, were in effect using 2 x 100 MW furnaces connected to a common boiler drum.¹

By increasing the height of the combustion chamber, the use of division walls, and superheater platens Babcocks found they could provide a suitable 200 MW boiler.² The designers of the Babcock boiler decided to stick with natural circulation so that no modification of operating techniques were necessary and they avoided some of the problems with vapour formation in the pumps during an emergency shut down.

To obtain the necessary coal input Babcocks mill designers also produced an improved medium speed mill ready for the 200 MW unit boilers.³ With this much improved mill design, maintaining optimum pressure between the ball and track became more important and continuous automatic setting was provided by means of pneumatic cylinders. Numerous experiments were made to find optimum conditions and the resulting mill could be produced in sizes grinding up to 40 tons/hr of coal with 25% moisture and 40% ash with grinding rings of the newly developed Ni-hard (4½% Ni-iron) a hard wearing material used extensively by other manufacturers once its properties were known.

Both types of boiler proved successful and apart from teething problems during commissioning went ahead with very little trouble.

Although the first 120 MW units did not come into service until 1958, 200 MW units had been ordered three years before, similarly the few 275 MW units were not commissioned until 1962, but 500 MW units were ordered in 1961.

1 Anon The 1000MW High Marnham Power Station ICL Pub.No. WP5816, p.7

2 FHS Brown & JW Dore, 'Re Heat Practice in British Power Stations' Proceedings I Mech E, CLXXII (1958), 590

3 E C McKenzie, Recent Advances in Ring & Ball Pulverisers, Babcock & Wilcox Pub.No. 1884/1 (1967) p.4

There were at this time still six boiler makers tendering to the CEA, with the advantage that design competition was stimulated, but it also increased the number of minor design faults, this however, did not prove to be very serious in the long term. One advance however, did not succeed; this was the introduction of super-critical boiler plants as part of Drakelow 'C', a Benson type was built by Babcocks and a Sulzer design was produced by ICL. These boilers were designed to produce steam at 3500 psi in an unusual type of steam generator that did not have a boiler drum, they were based on original ideas from the late 1920 s that had not been fully developed, unfortunately these designs have been dogged by troubles since they were first built.

At the time of its conception in 1959, Drakelow 'C' was planned to contain four of the largest size of unit with a single shaft turbine that was feasible and economically justifiable, these were either 350 or 375 MW units.¹ Initially tenders were accepted from John Thompson of Wolverhampton for 2 x 350 MW boilers working at 2300 psi. Tenders were later invited for two further units of 375 MW's to complete the station, working at the super-critical pressure of 3500 psi, the object being to demonstrate the feasibility of such plant for application in the future. Calculations based on an annual load factor of 77.5% for the first five years gave an expected efficiency of 38.0%, a figure that has never been achieved in practice, due mainly to the low availability of the boilers. Supercritical boilers were calculated to be potentially most profitable using double re heat at 1050°F. The operating problems of a double re heat system added to the more complex super critical boiler were such that its use was unwarranted, instead temperatures of 1100°F superheat and 1050°F re heat were decided upon, with the extensive use of improved austenitic steels costing some six times as much as a simple ferritic alloy steel. An economic comparison of subcritical and supercritical boiler tender costs showed that the thermal gains only just balanced the extra investment but the decision to go ahead was based on the need to stimulate

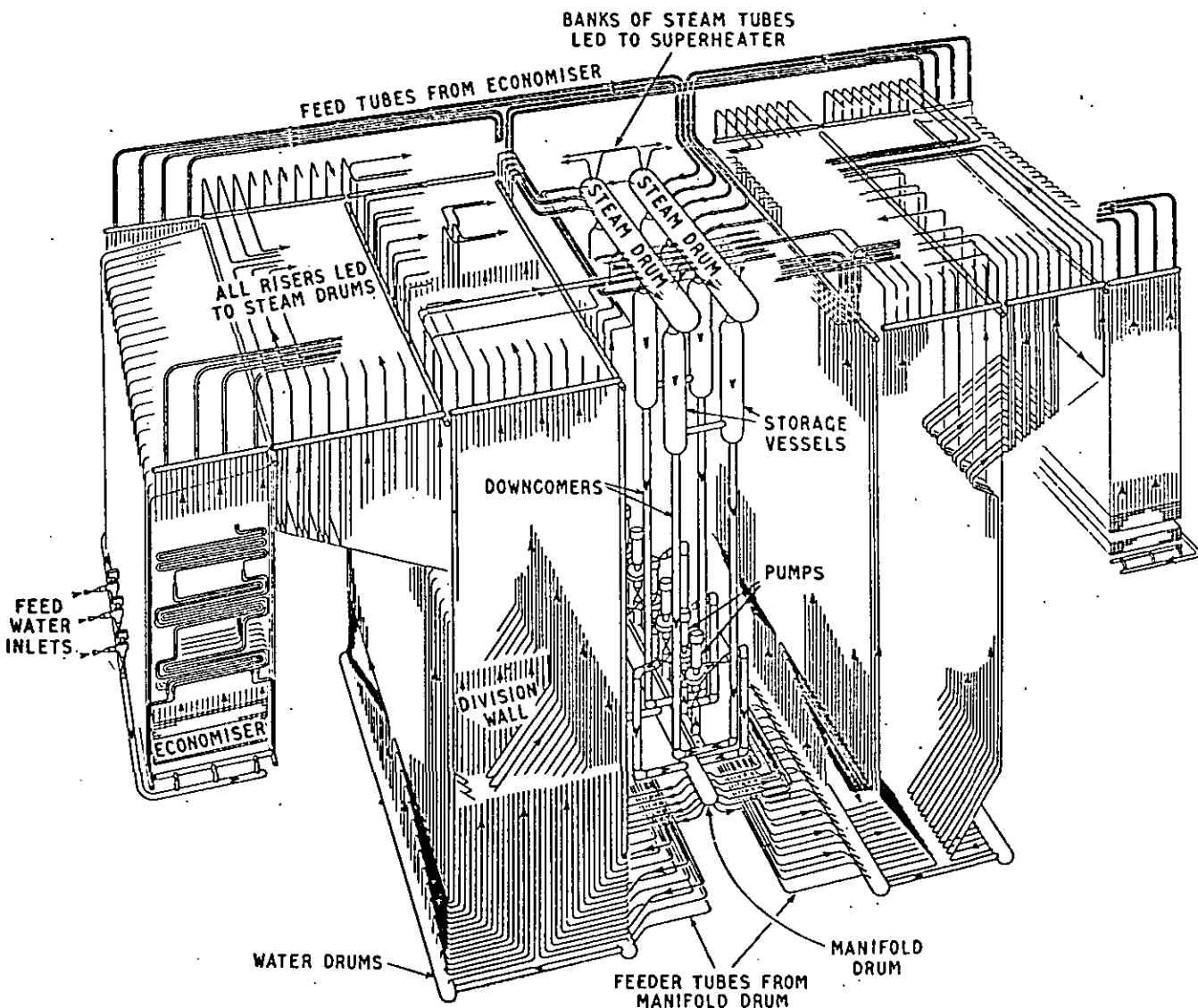
design development and the production of low cost high temperature steels in the hope that such development would eventually prove economic. There were many problems with these supercritical boilers, particularly with leaks caused mainly by overheating and corrosion; it took nearly ten years to overcome these difficulties and no further supercritical boilers have been ordered in Britain.

Before inviting manufacturers to tender for Drakelow C power station, a number of 275 MW boilers were built as a direct development of the 200 MW designs, when the tenders were received the CEGB decided it would be possible to build a 550 MW turbine and avoid limitations in turbo-alternator design by re-introducing the technique of cross-compounding in which two turbines are built side by side, each with its own alternator. The first contracts were placed in February 1958, the turbine, built by Parsons had an 'A' line consisting of one high, one intermediate and two low pressure cylinders, whilst the 'B' line had two intermediate and two low pressure cylinders; at the time of commissioning it was the largest generating set in Europe. International Combustion were awarded the boiler contract which at the time was for the largest boiler in the world, having a maximum continuous evaporating capacity of 3,750,000 lb/hr at a pressure of 2400 psi.¹ (see diagram overleaf)

To make this gigantic step forward ICL decided to build two 275 MW boilers back to back (see diagram) and although fully interconnected on the steam and water side it had two separate furnaces each with a division wall allowing firing from eight corners in each furnace. Due to the wide variety of coals supplied to the station the coal input to the boiler varied from 200 to 220 tons per hour and adequate milling capacity was supplied to allow for a variation in ash content from 6% to 40%. Eight Lopulco three roll mills were installed, six being used for normal operation although

¹ 'The 550 MW Twin Furnace Reheat Boiler for Thorpe March Power Station' Electrical Review Nov 21st 1958 (ICL Reprint WP 5820), p.3

Circulation diagram for International Combustion 550 MW reheat boiler



when in good condition each mill could grind 50 tons per hour so that ideally the boiler could produce full load from four mills.

It was some little while before the second contract was placed, AEI were to supply the turbo-alternator and Babcock & Wilcox the boiler. The original design was for a twin furnace with division walls, but the delay in placing the contract allowed time for second thoughts, by increasing the rate of heat release/cubic foot and bringing the platens forward into the furnace a single furnace front wall fired boiler design was eventually produced by Babcocks, so saving the expense of a second boiler drum.¹ It had 54 burners

¹ R Bagley, Progress in Modern High Pressure Boilers
Babcock & Wilcox Pub No. 1813/1 (1964) p.4

and a single boiler drum 130ft long, 5ft 6ins in diameter. The furnace was 120ft wide and in order to overcome the limitation of sootblower length, the furnace was built with two outlets each 50ft wide, with a 20ft gap, 36ft long sootblowers entered the outer side walls and 14ft blowers in the inner walls.

The suspension of large boilers weighing some 10,000 tons requires large sections of steelwork fixed at heights up to 200 ft and because of the great number and the complex arrangement of tubes to be fitted up to this level, prefabrication techniques were developed. When large panels and assemblies could be delivered from the works prepared ready for welding to the next section, erection times for a 550MW boiler was reduced to that necessary to build a 100MW boiler. The Babcock boiler drum weighed 264 tons and with its length of 136ft it meant that it could not be transported complete from the works, and consequently it was built on site. Site welding to this extent was a result of the extensive research work by both the CEGB and manufacturers since the value of welding in pressure vessel work had been proved in the early post war standard boilers.

Experience of building these two very large boilers stood the manufacturers in good stead when the next standard series of 500MW units was put out to tender. Although the demand for electricity and the size of individual boilers continued to grow, the number of contracts available to individual boiler manufacturers were being reduced; as a result some of the manufacturers began to look at the possibility of mergers, or putting in joint tenders for contracts.¹

When tenders were invited for the 500MW series in 1961, Foster Wheeler/John Brown submitted a joint contract as did John Thompson/Clarke Chapman in order to keep design costs to a minimum, and so have a better chance of a share in the programme, these consortiums were encouraged by the CEGB to

¹ Sir Francis Tombs 'Economies of Scale' Proc I Mech E CXCI, (1978), 389

produce more concentrated and competent companies. International Combustion produced their standard corner fired design with a twin furnace and a single boiler drum, the remaining tenders were all for front fired boilers whose dimensions varied slightly as did the number of burners and the distribution of the heating surfaces, but not radically different from each other.

Although there were many minor problems with the 500MW units, in turbines and alternators as well as boilers there were no major design faults and they continued to pay their way with improved efficiency, lower staffing levels, and keeping capital costs to the minimum in the face of rising inflation.

Still looking to the future the CEGB obtained planning permission in August 1964 to build a 3000MW power station at Drax near Selby in Yorkshire. If the supercritical boilers installed at Drakelow had proved successful a similar type would have been built at Drax to supply the 660MW turbines to be installed there; the pressure would have been about 3650 psi and a second stage of re-heat was a strong possibility. As both designs of boiler had been unsuccessful, despite expensive modifications, a subcritical boiler supplying 4450 klbs of steam per hour at 2400 psi and 1055⁰F with re-heat was installed. This design of boiler gave a further slight improvement in efficiency, 90.0% of the heat in the coal being converted to steam, and it was expected that the next series of coal fired boilers would be of this size. Due to expansion in nuclear generation and a check in the phenomenal rate of growth of electricity demand (7½% per annum until 1974) further power stations of this size have not been built.

To produce this quantity of steam requires an input of 262 tons of coal per hour, 10 mills are provided, each capable of pulverising 35.5 tons of coal per hour, normally 8 mills and 48 out of the 60 coal burners are in service to maintain full load.¹ In order to fit 60 burners into the combustion chamber

1 R Bagley, B Powell & R J Weeks. Design, Commissioning & Operation of Three Hard Coal Fired 660 MW Boilers at Drax Power Station (Babcock & Wilcox 1979), p.11

the designers (Babcock & Wilcox) had to install burners in both the front and rear walls. To obtain combustion under these conditions it was necessary to alter the proportions of the furnace, making it narrower and deeper, the dimensions being 80ft and 40ft with a central division wall compared with their 500MW design which had a furnace 96ft x 30ft. This change meant that after about 50 years of PF development the two types of boiler firing, i.e. long flame corner firing and the short flame turbulent burner were being used in almost identical furnaces. The change in proportions of the boiler allowed a change in the position of the related turbine which at Drax is placed diagonally across the engine room, a convenient space saver in this particular station.

Apart from the unsuccessful supercritical units there has been little thermodynamic advance since the 200MW units were introduced at High Marnham with steam at 2300 psi at a temperature of 1050° and re heated to 1000°F. Continued advances in capacity and physical sizes have however, reduced the heat and friction losses, cost per kW installed is still lower with the larger machines, while utilisation of staff and output per unit volume continued to improve as boilers became larger.

III

National control of power station development, tentatively applied by the CEB from 1926 onward, became more positive as a result of the 1947 Control of Turbo Alternators Act and the eventual nationalisation of the supply industry in 1948. Nationalisation put firm control of design effort into the hands of the British Electricity Authority and eliminated the dispersal of effort despite the necessity to continue using consultants during its early years.

Concentration of control in this manner gave more power to the consumer, and an organisation large enough to employ its own specialist boiler engineers who could evaluate tenders and point manufacturers in the direction the supply industry wished to progress. Information on construction and operation could be tabulated, design faults and solutions to maintenance problems could be collated and distributed to power stations and design offices much more quickly than had previously been possible. This centralisation of design and information allowed far more rapid development of boiler plant than would have been the case had development been left in the hands of local undertakers, design development was pushed to the economic and technical limits and maximum co-ordination was achieved between the designers of the various component parts of the power station.

Apparent limits on growth were met with on a number of occasions, such as the weight limit on transport of boiler drums or the strength of material available for turbine blades, but these limits were overcome or by passed by co-ordinated research of users and manufacturers. An initial backlog of installation was made up by building plant little different from that installed during the war but to cope with the pent up demand, larger units were necessary; the increase in size gave an improvement in efficiency, while the cost per kW installed and the space required was reduced. (see diagrams overleaf)

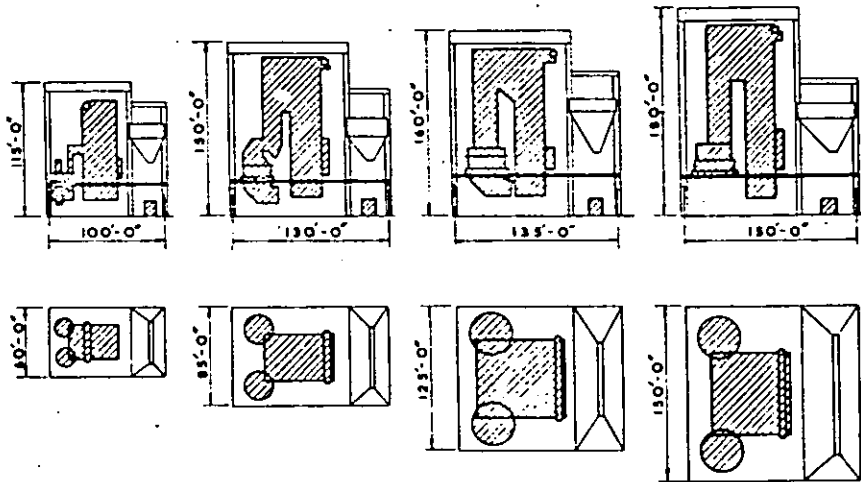
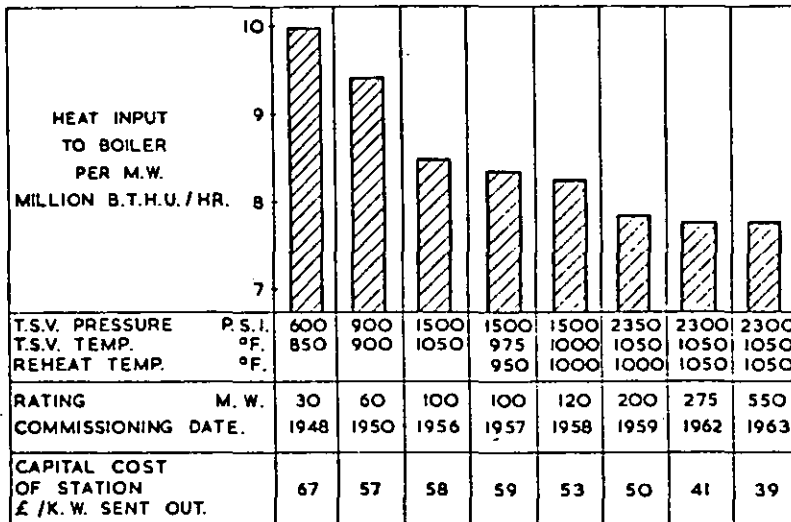


TABLE X BOILER HOUSE VOLUMES/KW

22.1 CU. FT./K.W.	13.35 CU. FT./K.W.	12.72 CU. FT./K.W.	10.3 CU. FT./K.W.
30 M.W.	120 M.W.	200 M.W.	350 M.W.

SOURCE : R Bagley, Progress in Modern High Pressure Boilers (1964), p.2



TSV = Turbine Stop Valve

TABLE XI STEAM CONDITIONS, SIZES, CAPITAL COSTS

SOURCE : R Bagley, Progress in Modern High Pressure Boilers (1964), p.1

Growth in size brought many necessary changes and developments in its wake, some, such as the siting of power stations, or the use of extra high voltage, were a necessary concomitant of larger units whilst others were only feasible in the larger power stations. Re heat for example, became economically and technically feasible as the limits of the straight cycle were approaching and the operational complications had to be accepted. Because of the more complicated operational requirements a better qualified operator was needed and automatic boiler control had to be developed as a complete system, a development that has assisted the expansion of electronics and computers in other industries. By eliminating the interconnecting steam ranges, boilers and turbines lost much of their operationally separate identity and although made by different manufacturers they were subsequently operated as generating units with Unit Operators controlling the complete plant from a central point.

The period covered by this section has seen a continuation of the growth of the supply industry at an ever increasing rate, while the cost to the consumer has been reduced when due account is taken of the rate of inflation. Control of costs to the consumer has been possible by continuing and expanding practices from the earliest years of using the heat in the coal as efficiently as possible, using the highest quality of steam that the available materials permit, while keeping capital and maintenance costs to a minimum.

PART FOUR

MAJOR INFLUENCES & CONCLUSIONS

In the previous sections the main features of boiler development have been described. It is now necessary to consider the major factors influencing these developments, and why they took place at any particular time; this final part will attempt to answer these and other questions.

Some factors were important for only a brief period but others were of significance throughout the period studied. I will look first at those that have been consistently important and then consider a number of factors whose influence was vital only at particular times.

The major consistent feature during most of the period under review was to keep to a minimum the cost of producing steam and in turn the cost of producing electricity. The simple way to minimise steam production costs is to convert the potential heat in the fuel into high quality steam as efficiently as possible, but external constraints and costs have had considerable influence on the achievement of this goal. An estimate of the efficiency of combustion made in the early 19th century produced a figure of 3%, the latest test figure of 94.8% for a boiler at Drax power station shows the technical evolution over this period of time.

Another underlying factor influencing technical change has been the rapid and continuous rise in the demand for power; a simple rule of thumb used for estimation gave an approximate increase in demand of $7\frac{1}{2}\%$ per annum until the early 1970s. The desire to keep costs to a minimum and the continuously rising demands for power were frequently in conflict as obsolete plants were often run beyond their normal life to cover peak demands on the system. A result of this is that annual average efficiencies of plant throughout the

supply system are much lower than the maximum because of the lower efficiencies of old plant, and also because newer plant was often unable to run at its optimum efficiency due to system load variations.

Boiler efficiency in itself is a complicated subject with many different facets, the difficulties are added to by relationships within the power station complex and external problems such as siting and the environment, all of which have affected boiler development in the long term. High combustion efficiency, however, is not necessarily highly cost efficient and low cost is most important for power production. There are three major and inter-related factors to be considered, (I) running costs, (II) capital costs and (III) technical advancement, each item is treated in a separate chapter.

Running costs can be subdivided further into (I(a) wages, cost of fuel and the power necessary to supply station auxiliary plant, (I(b) maintenance costs including cost of replacement generation, i.e. stand by plant.

Technical advancement (III) depends on internal and external stimulus, any advancement made affects both capital and running costs and the effect of such an advancement on each of these costs needs to be considered separately.

The impact of these different forces varied considerably over time, in the earliest years electric lighting was a luxury item, costs were less important than continuity, but loss of supply could lead to the customer changing to another source of illumination. By the mid 1930s electricity was a major power source and although continuity was still important, the back-up of the Grid was widely available and cost of supply was usually of prime importance, even so old rivalries occasionally overrode financial considerations and despite incurring additional costs undertakers refused to co-operate. An example of this can be seen in Fulham Corporation's refusal to accept the suggestion made by the CEB that they should operate barges jointly with a power company.¹

¹ L Hannah, Electricity Before Nationalisation, (1979), p.139

In addition to these difficulties there were problems of feedback and interrelationships between sectors. Development in one section was often awaited before advances could be made elsewhere; because of the complex inter-relation between the various items of plant it may be extremely difficult to correctly ascribe the initial causality. For this reason although the significant factors listed above will be considered in turn, there will often be considerable overlap, this is inevitable in a topic of this nature.

A number of minor but still important factors are considered in Chapter IV, while the final chapter reiterates the aims of boiler engineers and highlights the work of specialist groups whose research provide the necessary information and materials to enable the manufacturer to achieve this high level of technology.

I (a)

The importance of the cost of fuel was realised at an early stage, this can be seen in the utilisation of normally unsaleable coal for coal pit winding engines when it was not worth the cost of transportation. Bright or dry steam coals were used at places remote from the pits and for marine use; in cases of this nature the high cost of good quality coal was more than balanced by the reduction in transport costs per unit of heat. Power stations initially worked in a broad band between the two extremes although during the last 30 years the available quality has deteriorated considerably; the effect of this poor coal and its transport costs on power station siting was discussed and illustrated in Part III The Modern Period.¹ Further comments on firing methods will be made later. (see pages 148-150)

In the early electric lighting stations the better quality large sized coals were used for the hand fired boilers, but as chain grate type automatic stokers became more widely used it was found that cheaper "smalls" were more effectively burned; an unexpected bonus. The mode of combustion on a chain grate stoker is that of a flat bed of fuel passing through the furnace, large lumps of coal allowed air to pass through the interstices between pieces, creating hot spots and uneven burning, allowing unburnt coal to be thrown away with the ash.² Large coal was in great demand for railways and domestic use so that this coal was always dearer, but as the demand for cheaper smalls expanded with the growth of power stations, the cost tended to increase. The increase in demand for fine coals, however, allowed the collieries to introduce some automation.

¹ E M Rawstron, 'Changes in the Geography of Electricity Production in Great Britain' Geography XL (1955), 92

² Combustion & the Chain Grate Stoker Babcock & Wilcox pubn. 1446 (c1949), p.19

As power loading machinery produces a greater percentage of small coal, whilst increasing the productivity of the pit, some degree of balance was obtained and the cost of power station coal did not rise unduly.¹ The capital cost involved with the initial installation of automatic firing equipment and the running cost of the necessary electric motors, as against any saving of fuel costs or staff, would initially affect the decision to install automatic stokers. The growth in physical size of boiler plant was such that by 1905 almost all new boilers were fitted with chain grate stokers, similar forces of increasing demand, growth in plant size and the limited availability of medium quality coal caused the change-over to pulverised fuel in stations built after 1950. It is impossible to compare capital costs of methods of firing as although some figures are available of various contract prices for firing equipment, differences of time and place allow only a limited comparison to be made.² With increasing boiler size and extensive automation the costs of operating staff as a percentage of total costs were small; unions did not resist change as operators were usually paid on plant capacity and there were no redundancies within the industry to create resentment.

1 A R Griffin, The British Coal Mining Industry Retrospect & Prospect (Hartington Derbyshire, 1977), p.116

2 See Appendix VI for comment by H C Lamb on tests at Barton Power Station

I (b)

Boiler maintenance times and costs are kept to a minimum by using a simple basic design, whether it be a plain tank boiler, a Lancashire boiler, or a Water Tube boiler, and the same principles apply to the ancillary and auxiliary apparatus of the boiler, this is particularly important when extended breakdown could cause loss of power to the consumer. Until the nationalisation of the supply industry the majority of plant installed was built to moderate standards, technical advance being left in the hands of the larger corporations and companies. The cost of maintenance of the more technically advanced equipment is not necessarily greater than that of the more conventional plant, but the reliability is generally lower on new designs, and consequently they require more frequent attention. There are additional costs incurred during a breakdown in running replacement plant of lower efficiency if the repairs cannot be carried out at periods of reduced load. With larger or higher pressure plant, cooling time and time necessary to get back to normal running conditions are much greater so that the stand by plant may run twice as long in these circumstances. The replacement generation costs or cost of stand by plant was spread over a larger number of power stations once the 132 kV Grid lines were installed and minimising shut down time was less important. As the time of local maximum demands varied the introduction of the Grid had a levelling effect on the area peak, so reducing the amount of plant on load at any one time and also the amount of spinning reserve.¹ Despite this reduction in spare running plant at any one time emergency breakdowns could be more easily dealt with by a slight change in the output from a number of stations, this gave better response times and an opportunity to try high risk and experimental plant.

1. Spinning Reserve. The difference between the actual load on the system and the output capacity of the generating plant is reserved in the system.

II

Capital investment in early industrial steam plant was usually made by mine owners or lease-holders in order to maintain a return on previously invested capital. As coal mines went deeper drainage became a problem, initially winding water out in tubs was feasible, but while lifting water, coal could not be wound from the mine, profitability was reduced and other methods were sought. Drainage soughs were used where a suitable low level outfall could be obtained, but this non-productive tunnelling was often expensive, depending on the geological conditions. Edward Smith of Houghton paid 3s.10d. per yard in 1750 for a drainage sough driven through stone, for a mile long tunnel this would cost £340 and in poor ground conditions it could cost three times this figure.¹ Newcomen's earliest known engine was installed at a colliery near Dudley Castle in 1711 and a second at Griff Colliery shortly afterwards; costs of these engines are not available, but as prototypes their costs would probably not be representative.

An early engine installed in Scotland is reputed to have cost just over £1000 in 1725, if we take this to be a 6.0 horse power engine, which most of the early engines appear to have been, it was equivalent to 4.5 kW output at a cost of £222 per kilowatt.² Taking the £ in 1750 as being 30 times its 1975 value, the equivalent's cost would be almost £6,700 per kW; it was, however, an essential expenditure if the mine was to be kept in business and a sough could not be constructed. Sir Francis Tombs confirmed this estimate in his 1978 Parsons Memorial Lecture,³ and continued the figures to recent times. (see graph over page)

1 A R Griffin, The British Coal Mining Industry retrospect & prospect (Hartington Derbyshire, 1977) p.43

2 Ibid, p.46

3 Sir Francis Tombs, 'Economies of Scale' Proceedings I Mech.E CLXXXII (1978), 387.

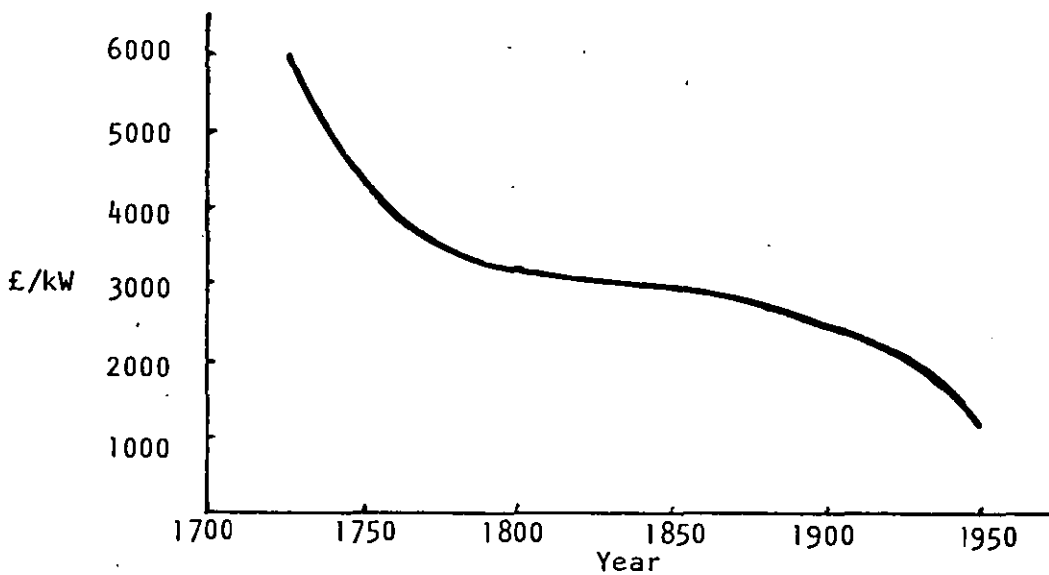


TABLE XII COST/kW OF STEAM POWER PLANT

Year	1725	1739	1953	1775	1850	1900	1923	1950
£/kW	6100	5000	4000	3500	3000	2500	2000	1100

Based on the 1975 value of the pound

SOURCE : Sir Francis Tombs 'Economies of Scale' Proc I Mech E
CLXXXII (1978). 387

The fall in cost was mainly due to economies of scale, but improved materials and manufacturing techniques also had a direct effect on cost and were the main reason for the reduction in cost per kWh between 1725 and 1750 before engines started to grow in size.

Such a large scale reduction in cost was necessary to encourage the development of steam on a commercial scale so that it was not a last resort but a useful tool to allow penetration to greater depths. Development of larger and cheaper engines encouraged the utilisation of steam in other industries where expensive animal power, or unreliable wind and water power had previously been used.

Rough costing of pumping power was undertaken, comparing cost of animals and their necessary feed, with that of the coal supplied, or comparing the amount of water pumped by different engines. ¹ Depreciation was, however, not costed and for many years was not considered necessary, due to the long working life

¹ W W Smith, Coal & Coal Mining, (1899), pp.224 - 240

of the slow speed pumping engines, the Elsecar engine for instance ran almost continuously for 128 years, and the Moira engine now in the Ford museum had a working life of 100 years.¹ More recently textile mill engines shut down in the 1960s were built when the early power stations were being constructed, many boilers had similarly long lives, low pressure boilers over 100 years old were still in use in the Black Country at the end of World War I.

Industrial or pumping plant was, however, built for a known load and rapid development of suitable plant was not expected nor was the load expected to increase. Power stations when first built were attempting to satisfy an unknown load at a time when technical development was starting to accelerate, there was no information available on which to base rates of depreciation, if indeed it was considered.

Early electrical development in Bolton provides an illustration of this unknown quantity, the Spa Road Works was opened in October 1894 with two alternators each of 100 kW and one 50 kW and extensions were made each year until 1912 when the economic limit of the site was reached at 7,600 kW.² Work commenced on a new site at Back-o'th-Bank so that by September 1914 the first of two 4,000 kW turbines were commissioned, operating costs at the new station were so low that the electrical distribution was rapidly converted to accommodate the new supply system and Spa Road was shut down in January 1916. Although economically justified by the low running costs at Back-o'th-Bank, the closure of the Spa Road works meant that plant less than 4 years old was being scrapped because of the rapid development of the water tube boiler and the steam turbine. Compared with this short life, Back-o'th-Bank number one machine ran for 25 years, and number six was available for 56 years, although for the last 20 years of its life was rarely used. Although reduction in costs, due to technical development, were often the

¹ N Cossons, The BP Book of Industrial Archaeology, (1975), p.84

² County Borough of Bolton, Extensions to Back-o'th-Bank Generating Station (Bolton 1935)

main reasons for a short running life, site restrictions meant that low capacity equipment was often replaced before the end of its planned life by plant with three or four times the original capacity, due to growth of local demand. Wide variation in actual plant life made estimation of a suitable rate of depreciation difficult and eventually a period of 25 years was reached by consensus of opinion, loans were repaid over this period and any residual life after this was looked on as a bonus.

Although some knowledge of how to calculate the profitability of a new or modified installation was available,¹ the general level of skill in engineering economics was low and Gill in his inaugural address as president of the IEE in 1923 claimed that he could not remember an instance of a student being familiar with the economic aspect of engineering studies.² Engineering economics began to be introduced into technical studies in the twenties and the requirements of the CEB developed the techniques, but often costs were subordinate to a sound engineering job even in recent years. Such attitudes often led to major modifications which could not have been financially justified had a proper economic appraisal been carried out.

During the life of a power station the two major costs are those of fuel supply to the station and the repayment of capital and interest charges. Keeping fuel costs to a minimum by means of good design, operation and maintenance is a normal function appreciated by engineers, but the techniques of value engineering developed very slowly until the nationalisation of the supply industry, when teams of economists and engineers were formed to ensure adequate return was achieved on any investment.

1 Appendix IV

2 F Gill, Inaugural Address IEE Journal, LXI (1923), 1

III

Without technical advancement in power plant in general, the ever increasing demand for power could not have been met and there has been a continuous requirement for improved materials and techniques. Initially boiler makers took advantage of improvements as they were developed, eventually manufacturers and the supply industry could point steelmakers etc. in the direction they wished them to go and even produce materials or equipment in their own research departments.

One of the early users' initiatives came from Austria where the use of cast iron in boilers was prohibited, forcing Babcock and Wilcox into using steel for the sinuous front wall headers, these headers were initially formed by fire welding as were the boiler tubes¹. Fire welding was a blacksmiths technique and not particularly suitable for use in pressure vessels, but this technique was discontinued once a forged header had been developed by Babcocks own staff.

The eventual development of solid drawn tube in long lengths by specialist manufacturers allowed the introduction of the "high head" type boiler similar to the Battersea 1929 design. Tubemaking, forging and eventually electric arc welding were the keys to boiler making development, eliminating rivetting and bolted joints which were prime sources of leakage as working pressures increased. As electric arc welding development continued, almost limitless growth in boiler size became possible and production line type construction techniques were introduced in the 1950s, maximum use of economy of scale being made at each stage of development. Unfortunately some of the designs produced in the 1930s had furnaces that were too small for the amount

¹ James Kennal, 'A Review of the Introduction of the Babcock & Wilcox Boiler for Electricity Supply' Proc. IEE LX, (1922), 76.

of coal burned, consequently tubes tended to overheat and burn out, especially when unsuitable grades of coal were used; the poor coal also tended to foul up the boiler heating surfaces causing frequent shut down periods for cleaning. These two problems were more related to chemistry rather than to engineering, the overheating of boiler tubes often being due to a build up of a non-conducting scale on the water side of the tube, while the furnace side fouling was due to alkali salts in the coal and mode of combustion. Extensive research was necessary to overcome these problems which had reduced the reliability of boilers and slowed up the rate of development.¹ These are just two examples of the many items that reduced the availability of boilers compared with that of a turbine, so preventing the development of the Unitised system (one boiler, one turbine) and a Unit system is essential to the full utilisation of re-heated steam.

The Economiser, patented in 1845, may be considered to be an early technical development, adding what was initially a piece of ancillary equipment to the basic boiler; as steam power became essential for industrial development the economiser was considered to be an important part of the boiler and yet it was often omitted in many early power stations. These power stations were built to supply a lighting load for a limited number of hours per day, and consequently the reduction in coal costs, brought about by the installation of an economiser, was not sufficient to repay the capital charges for an economiser, as the load factor improved the economiser once again became worthwhile. The economiser was one of the first items of boiler plant to be affected by developments on the turbine side, bled steam feed water heaters were introduced in 1916 to improve the station efficiency but they had the effect of reducing the boiler efficiency. To reduce the boiler exhaust temperatures again it was necessary to install combustion air pre-

1 See reports of Boiler Availability Committee

heaters which recovered the loss in boiler efficiency and increased the rate of combustion¹. The introduction of the bled steam feed heater demonstrated the inter-relatedness of plant within the power station and other developments have often had to be delayed until related plant was modified.

Electrical engineering developments were also essential to the growth of the industry and the size of individual items of plant, from the cooling of generators by air flow caused by its own movement, to the present method of cooling the necessarily large alternators by a complicated system of hydrogen and distilled water which provides the first stage of boiler feed water heating. High voltage transmission from Ferranti's 10,000 volt system at Deptford in 1888, to the 400 kV of the present British Grid, were necessary developments for the siting of power stations away from the load centre at points where coal, water, or land, was more conveniently available. The construction of the 400 kV system was essential to the concentration of large scale generation in the coal producing areas, without it any gains made would have been dissipated in transmission losses.

Design developments, whether electrical or mechanical, usually increased some costs by using additional or more expensive items, but they normally reduced costs/kW installed or generation costs. Money was, however, saved by improved manufacturing techniques and electric arc welding was particularly of cost benefit as it could be used extensively for construction and repair work, replacing damaged boiler tubes, re-building worn or broken parts, and putting a hard facing on parts liable to erosion.

Pulverised coal and its development to the stage where it is the main source of power station heat is a good example of the sporadic nature of technical

1 A contributory factor to the over-rating & consequent boiler fouling previously mentioned in this section.

development and the effect of external influences. This method of burning coal was feasible in the earliest days of power, but its reliability was even more in doubt than that of the chain grate stoker, and acceptance was initially slow. Adoption of PF was spasmodic in the years between the wars, as economic conditions, fuel availability and technical development in relation to the chain grate stoker varied. Over most of the period from 1920 to 1940 high cost was against PF installation on three major counts¹ :-

1. Capital costs were high due to the additional equipment required and the limited number built, with a continuous flow of orders manufacturers could have reduced costs.
2. Maintenance costs of PF plant were higher than on the others as the abrasive nature of powdered coal caused heavy wear of pulverising plant and pipework. Improved hard surface materials were required to overcome this problem.
3. Running costs were higher on pulverised fuel plant due to the large power requirements of pulverising mills which require about 6% of the station output, compared with about 2% on stoker fired boilers.

With the growth of electrical demand between the wars, increasingly larger boilers were required, development of the chain grate stoker kept pace with these size increases as the comparative cheapness of the chain grate allowed it to absorb development costs.

The estimated post 1945 growth of electrical demand was such that much larger boilers would be required in the foreseeable future, the chain grate boiler was having difficulty burning available coals and it appeared to be approaching its final limiting size; these factors caused the decision to be taken that all

¹ J N Williams, Boiler House Practice, (2nd Edition 1956) p.411

new coal fired stations would burn it as PF. This decision in itself reduced the capital costs by the continuous flow of large, more standardised orders to manufacturers, while improved hard wearing metals and better designs reduced maintenance costs. Milling costs were still comparatively high, but with increased mill sizes and the higher efficiency of large boilers, the effect was less severe.

Boiler house staffing in the smaller plants was little different whether PF or chain grate was used, but with the larger sizes and increased automation found possible with PF, the ratio of men/megawatt dropped rapidly.

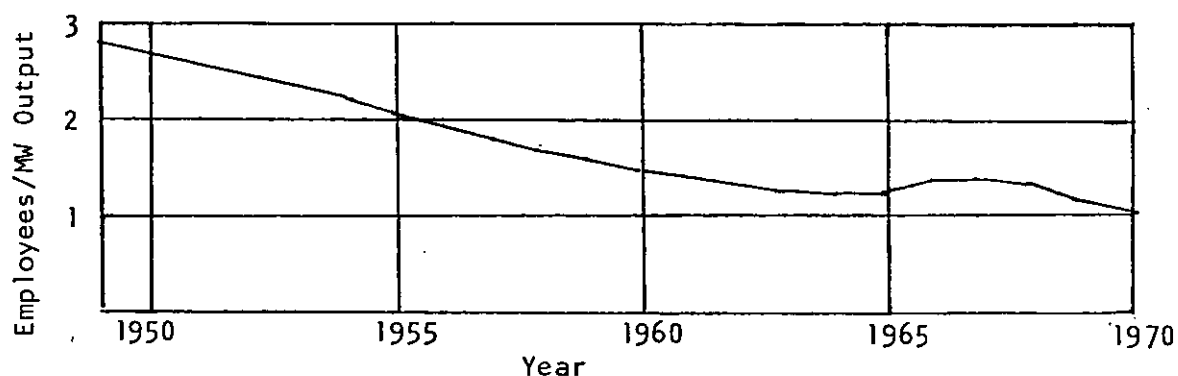


TABLE XIII GENERATION EMPLOYEES/MW OUTPUT 1949/70

1949	1954	1955	1956	1957	1958	1959	1960	1961
2.78	2.24	2.05	1.93	1.85	1.75	1.60	1.48	1.41
1962	1963	1964	1965	1966	1967	1968	1969	1970
1.35	1.3	1.28	1.26	1.38	1.42	1.35	1.20	1.06

The increased number of employees/MW in the years 1966-8 was caused by staff being trained to operate new plant prior to commissioning.

SOURCE : CEGB Statistical Year Books 1964 & 1970, table 12

In the growth of the use of pulverised fuel from an occasional installation suitable for certain special cases to almost universal use, with continuously improving efficiency in larger units and increasing cost effectiveness, while keeping necessary staff to a minimum, we have in microcosm the development of power plant.

IV

Minor factors often not directly concerned with the hardware of engineering have influenced the development of plant at different periods, delay in expected legislation in the early 1920s restricted development in some areas until the final form of such legislation was known. When legislation finally appeared in the 1926 Electricity Act it not only inaugurated the Grid system, but also in effect, made the CEB electricity wholesalers and introduced a complicated method of payment, using a complex schedule which included a hypothetical efficiency clause. This clause was based on an efficiency that could have been obtained had the undertaker been allowed free choice of plant installed and the CEB paid out on many outrageous claims to maintain good relations.¹ Occasionally the Board insisted that these hypothetical efficiencies be proved and the extra high pressure plant installed at Brimsdown was built as a result of this insistence, forcing development that otherwise would not have occurred.²

The development of such high pressure plant required increasingly pure water supplies to prevent scale formation within the tube, as the rate at which scale forms increases with pressure. Research into methods of water treatment to deal with this problem produced certain techniques and in order to apply such new techniques it became necessary to employ chemists or specialist boiler house engineers with training in water treatment.³ The formation of the Institution of Fuel Economy Engineers for qualified fuel technologists in September 1925 followed by the Institution of Fuel Technology in March 1926 indicates that a

1. L Hannah, Electricity Before Nationalisation (1979) p.144

2. Discussion with R W Clauston Archivist Babcock & Wilcox March 1980

3. P Chilvers, 'Thirty eight years of power station chemistry' EPEA Journal XXXXVI, (1964), 205

closer interest was being taken in fuel economy; these two bodies combined to form the Institute of Fuel in 1927 and since this date fuel technologists had a steadily increasing influence in power station work.¹ Development of education in fuel technology by the Institution widened the knowledge of the mechanical and electrical specialists to some degree, and eventually provided a qualification in its own right.

Smoke abatement was a feature of public discussion in the 1920s, encouraging the formation of the Smoke Abatement Society and the eventual legislation covering the emission of smoke, (soot, ash and gritty particles) with the appointment of smoke and alkali inspectors.² As a result of the work done by the Institute of Fuel and others on improving combustion techniques, and the closing of older power stations brought about by the 1926 Electricity Act, the effect of clean air legislation has been minimal, except on pulverised fuel plant where lack of good dust precipitators had a retarding effect on early development. The fine dust deposited over the surrounding area by PF boilers presented an unexpected problem; as a result investigations into dust collecting plant was accelerated and the electrostatic precipitator was commercially developed, without this or some similar device pulverised fuel would not have become a major boiler firing system.

Early electrostatic precipitators used mechanical rectifiers to obtain the necessary high voltage direct current and control of this voltage was difficult, also internal design of the precipitator collector was arbitrary and consequently they were of low efficiency. By 1948 when the use of pulverised fuel was expanding rapidly, improvements in internal design had brought collecting efficiencies up to 98%, but further improvements were necessary as power

¹ R Hayman, The First 50 Years (Institute of Fuel 1977), p.9

² Electricity Commission Report on Emission of Soot, Ash, Grit, and Gritty Particles from Chimneys, 1932

stations grew larger and the quantity of coal burned increased. With the introduction of solid state rectifiers standards improved and the 500 MW units were fitted with precipitators having a guaranteed efficiency of 99.3%.¹ In 1974 the Alkali & Clean Air Inspectorate increased the standard so that for all new installations an efficiency of 99.5% is now required, although this does not appear to be a great change, a reduction of 30% in dust emission is necessary to achieve this new standard. Without this improvement in precipitator performance the practice of installing 2000 MWs of plant on one site would not have been allowed with the present attitude to atmospheric pollution.

¹ A A Barrett, 'Electrostatic Precipitators in the Power Generation Industry' Filtration & Separation XVIII (1980), 389

V

The continuous aim of the boiler maker and operator has been to produce a source of power as safely and cheaply as possible within the various limiting parameters mentioned in this chapter. Every effort has been made by British manufacturers to work to these limits since industrial steam power was first introduced and this effort has been more productive since 1948 when the supply industry was nationalised and development work was co-ordinated through the various regional project groups. Apart from the obvious developments in mechanical and electrical engineering that were necessary to produce the large modern boiler there were many other professions involved in specialised aspects of the work. Metallurgists were soon required to produce metals able to work at high temperatures and in an abrasive environment, as a result of their work, boilers were designed to produce high temperature steam, which in turn introduced problems of calcium and magnesium scale within the boiler and so initiated research into water treatment chemistry.

At one period steam conditions were advancing at such a rate that boilers were built working to a higher pressure than that to which steam tables had been calculated, encouraging further research, while much early work on automatic control systems was triggered by the requirements of boiler manufacturers. These developments and many others were necessary so that the target of a cheap and efficient supply of steam could be provided, this I consider has been achieved by the boiler manufacturers and their major customer, the electricity supply industry. If any period of time is considered during the years of industrial boiler development, the steam boiler can be seen to have been a leader in the field of heavy engineering progress, either by the efforts of individual manufacturers or by pushing forward research and development in associated fields. This past performance of the boiler industry gives confidence that design progress will continue and that future technical problems will be overcome.

As a result of the rapid increase in unit size and technological advancement, there were many technical and organisational problems to be overcome. Despite this the specific aim of minimising the cost of electricity to the consumer that was written into the nationalisation act has been achieved in the face of the rising costs of primary fuel, labour, and engineering materials. Problems such as those experienced with the early austenitic steels or with the supercritical boilers, although comparatively minor when related to the size of the industry, were nevertheless expensive and if problems on a similar scale had been experienced with the 500 MW units efforts in other directions would have been nullified and the losses would have been enormous. The difficulty of achieving a balance in technical development is well illustrated by the problems quoted above, but the success of the 500 MW units shows that the designers were not generally over-reaching themselves whilst approaching the limiting parameters laid down by the transmission system. Heavy investment in plant has been necessary to provide the standards of supply required by the consumer and to make a rough comparison, the capital invested in ICI is about equal to that invested in the North Western Region of the CEBB.¹ Without the resources of a national authority and its elimination of the early parochial attitudes of local undertakings I consider it would have been impossible to achieve such advances as have been made since 1948.

¹ W F Cusworth, 'The Organisation & Management of a Region'
Summaries of Lectures (Electricity Council 1974), p.16

APPENDICES

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APPENDIX I

THE MANCHESTER STEAM USERS' ASSOCIATION, FOR THE PREVENTION OF STEAM BOILER EXPLOSIONS AND FOR THE ATTAINMENT OF ECONOMY IN THE APPLICATION OF STEAM.

Objects & Constitution, January 23rd 1855.

This association undertakes the periodical inspection of steam boilers and gives a pecuniary guarantee of the integrity and efficiency of its inspections to the amount of £300 on each boiler enrolled, so that in the event of the explosion of an approved boiler, whether that explosion arise from collapse of the furnace tubes or rupture of the shell, or failure of any part of the boiler whatever, all damage done thereby, other than by fire whether to the boiler itself, or to the surrounding property, will be made good to the extent of £300.

The association also assists its members by taking indicator diagrams when requested, as well as by affording competent engineering advice with regard to the working of boilers and engines, the prevention of smoke, the economy of fuel, and any other points calculated to prove of value to the association as steam users.

Its system of inspection is voluntary, and permissive on the part of its members. Its reports are suggestive and recommendatory on the part of its officers. Its benefits are mutually shared by all enrolled. There are no shareholders to whom dividends are paid out of the members' subscriptions, but the funds are devoted solely to promote the direct objects of the association. The executive committee are appointed by the general voice of the members of the association. They receive no remuneration for their services. They employ a considerable amount of steam power themselves, and are thus interested in everything that affects its use.

The object of the guarantee is not so much to ensure the members against pecuniary loss in case of explosion as to give a pledge of bona fide intention of the association to prevent the occurrence of explosions by efficient supervision and careful periodical boiler inspection.

SOURCE : W Pole ed. The Life of Sir William Fairbairn, Bart. (Newton Abbot 1970), p.268

SUMMARY OF BOILER EXPLOSIONS ACTS

The Boiler Explosions Acts 1882 and 1890 provide for enquiries to be held with respect to explosions from boilers in the United Kingdom and in British ships. The term 'boiler' is defined as meaning any closed vessel used for generating steam, or for heating water, or for heating other liquids, or into which steam is admitted for heating, steaming, boiling or other similar purposes. Boilers used in the Government service and domestic boilers are excluded from the scope of the Acts and explosions from boilers in railway locomotives (except those used in private sidings) are not dealt with under the Boiler Explosions Acts by the Department of Trade and Industry. Subject to these exceptions, the owner of any boiler from which an explosion occurs must report the fact to the Department of Trade and Industry who thereupon arrange for an engineer surveyor to inquire into the cause of the explosion.

In serious cases a preliminary inquiry may be held, or, if they consider it necessary, the Department may order a formal investigation to be held by a court consisting normally of two commissioners, one an engineer and one a lawyer. In such inquiries and investigations the reports are published. The reports of minor explosions are not published, but the cause of the explosion as ascertained by the Department's surveyors, together with the Engineer Surveyor-in-Chief's comments are communicated to the owner and other interests.

EXPLOSIONS DEALT WITH SINCE THE PASSING OF THE BOILERS ACT 1882

Period	No. of explosions	No. of lives lost	No. of persons injured	Total
1882-3 to 1914-5 Average, 33 years	2,389 72.4	864 26.2	1,932 58.5	2,796 84.7
1915 to 1918 Average, 3½ years	100 28.6*	51 14.6	124 35.4	175 50.0
1919 to 1939 Average, 21 years	1,270 60.5	227 10.8	881 42.0	1,108 52.8
1940 to 1959 Average, 20 years	747 37.4	94 4.7	362 18.1	456 22.8
1960	42	2	10	12
1961	45	2	7	9
1962	55	7	41	48
1963	38	4	23	27
1964	53	7	16	23
1965	47	3	8	11
1966	47	1	9	10
1967	52	3	8	11
1968	45	3	44	47
1969	36	1	11	12
1970	47	0	10	10
1971	48	2	27	29
TOTALS Average, 89½ years	5,061 56.5	1,271 14.2	3,513 39.3	4,784 53.5

* Because of the war, inquiries were not held in all cases in these years; in 1917-18 only very serious and important cases could be dealt with.

APPENDIX III

SUMMARY OF REQUIREMENTS OF 1961 FACTORIES ACT RELATING TO STEAM BOILERS

Section 32. Every steam boiler shall be fitted with :-

- (a) A suitable safety valve fitted directly to the boiler, so adjusted to prevent the boiler being worked above its permissible working pressure.
- (b) A suitable stop valve at the connection to the steam pipe.
- (c) A correct steam pressure gauge marked in a distinctive colour with the maximum permissible working pressure, the gauge to be easily visible to the attendant.
- (d) At least one water level gauge of transparent material.
- (e) A distinctive number easily visible where there are two or more boilers.

All boilers shall be provided with means for attaching a test pressure gauge and unless externally fired shall be provided with a suitable plug or an efficient low water alarm.

Every part of every steam boiler shall be of good construction, sound material and adequate strength.

Section 33. Every steam boiler, its fittings and attachments shall be properly maintained.

A steam boiler shall not be used unless it has been examined as the Minister may prescribe and re-examined at intervals as required.

A report of the result of every examination shall be made on the prescribed form and signed by the person making the inspection, the report shall then

be attached to the general register of the factory.

No new boiler shall be taken into use unless it has a certificate from the boiler manufacturer or a boiler inspecting company specifying its maximum working pressure and the nature of the tests to which it has been submitted.

Where the report of any examination specifies a reduction in permissible working pressure or any other condition for securing the safe working of the boiler, the person making the report must send a copy to the factory inspector of the district.

If the person employed to make such examination makes a report which is false or deficient in any material respect, he shall be guilty of an offence and liable to a fine not exceeding one hundred pounds. If the chief inspector is not satisfied as to the competency of the person employed to make the examination, or as to the thoroughness of the examination, he may require the boiler to be re-examined by a person nominated by him. Where such a re-examination shows that the report was inadequate or inaccurate in any material particular, the cost of the re-examination shall be recoverable from the occupier.

SOURCE : Factories Act 1961, Sections 32 - 34

APPENDIX IV

ECONOMIC COMPARISON OF STEAM BOILERS

(Based on 1915 Costs)

Approximate estimates of cost of power plant for a power station consisting of three 20 MW turbines complete with boiler plant, they do not include the cost of items not materially affected by changes in boiler design, e.g. buildings and switchboards.

	200 psig 700° F	475 psig 700° F
Capital Cost		
Boiler plant (including 30% spare plant)	£187,000	£235,000
Turbines, alternators & condensers	261,000	266,000
	<u>£448,000</u>	<u>£501,000</u>
Annual Charges @ 15% (Interest, depreciation & repairs)	£ 67,200	£ 75,150
Annual charges per kWh generated based on 175,000,000 kWh per annum	<u>.0921d</u>	<u>.1030d</u>
Avg Steam Consumption/kWh	12.08 lb	10.9 lb
Coal Consumption/kWh (6 lb coal = 1 lb steam)	20.1 lb	18.2 lb
Coal Cost /Annum @ £.5 per ton	£ 78,500	£ 71,000
Coal Cost/kWh	<u>.1077d</u>	<u>.0974d</u>
Total Cost/kWh		
Capital Charges	.0921d	.1030d
Coal Cost	<u>.1077d</u>	<u>.0974d</u>
	<u>.1998d</u>	<u>.2004d</u>

Under these conditions it is not economically viable to install the higher pressure plant.

SOURCE : J H Shaw 'The Use of High Pressure & High Temperature Steam in Large Power Stations' IEE Journal LVII (1916), 6

Variations in basic conditions can affect the costing as illustrated below, using Shaw's method to provide a comparison.

Increase in the cost of coal to £0.75 per ton would give the following :-

Capital Charges	.921d	.1030d
Coal Cost	.1615d	.1461d
Total Cost/kWh	<u>.2536</u>	<u>.2491</u>

Under these conditions the advantage swings in favour of the high pressure plant.

If as a result of increased demand for high pressure plant the price falls by 10%, other conditions remaining unchanged from the basic calculation, the costing would be :

Capital Charges	.0921d	.0927d
Coal Cost	.1077d	.0974d
Total Cost/kWh	<u>.1998d</u>	<u>.1901d</u>

The advantage is again with the high pressure plant.

Using the original calculation, but with an increase of 1% in annual charges would produce the following results :

Capital Charges	.10131d	.1133d
Coal Cost	.1077d	.0974d
Total Cost/kWh	<u>.20901d</u>	<u>.2107d</u>

This condition keeps the balance in favour of the low pressure plant.

APPENDIX V

DEVELOPMENT OF THE GRID SYSTEM

The Grid system resulted from the Electricity (Supply) Act, 1926, under which the Central Electricity Board was established and given the following main duties :-

- (a) To concentrate the output of electricity for public supply systems in a limited number of power stations ("selected stations") chosen for their efficiency and low operating costs, and to control the output of these stations as regards quantity, time and rate. The stations remained in their existing ownership.
- (b) To connect the selected stations with each other and with the system of local electricity undertakings by constructing or acquiring main transmission lines (known as the Grid).
- (c) To arrange for extensions and alterations of selected stations and for the construction of new selected stations as and when necessary.
- (d) To standardise alternating current frequency throughout the country, so that effective interconnection could be established.
- (e) To supply, either directly or indirectly, local undertakings which required electricity for distribution, and for this purpose to purchase the output of the selected stations and sell it to the local undertakings.

SOURCE : Electricity Supply, Historical Review (BEA 1948), p.7

APPENDIX VI

Résumé of contribution by H C Lamb to
discussion on the economics of PF boilers

The capital charges on the experimental PF boiler recently installed at Barton power station are £600 p.a. greater than the comparable chain grate boiler, while the improvement in nett test efficiency is nil.

By making due allowance for the auxiliary electrical supplies there is an improvement in the nett working efficiency of 2%. When burning coal of a calorific value of 11,500 Btu/lb at 15/- per ton, a 2% improvement saves £500 per annum and the nett loss is £100.

When burning a coal with calorific value of 10,000 Btu/lb costing 10/- per ton gives a working efficiency of a PF boiler 5% or 6% better than an automatic stoker, this gives a saving of £900 per annum on coal costs and a nett saving of £300 per annum, but there is only a limited quantity of this cheap fuel available.

SOURCE : IEE Journal LXVIII (1930), 512

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The collection noted below were consulted for background information, any specific items used are noted in main text footnotes. ICL documents are not filed systemically and consequently precise reference is not possible.

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