NUCLEAR ENGINEERING MONOGRAPHS

STEAM CYCLES FOR NUCLEAR POWER PLANT

BY

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Preface

The generation of power through the medium of steam, whether from the combustion of conventional fuels like coal, oil and gas, or from the fission of nuclear fuel like uranium, is well established in a range of outputs which includes the largest. A wealth of information exists in the field of application of steam in power plants using *conventional* boilers, modern practice embracing very high steam pressures and temperatures, the use of reheating and of regenerative feed-water preheating. Highest efficiencies are sought, which in turn depend directly upon the quality of the steam. Through high efficiency, the cost of fuel consumed by the plant is minimized and it often pays to build more expensive plant in order to effect savings in fuel.

With nuclear power plant, the amount of information available is much less, so new is the science. Anyway, nuclear fuels are cheaper in terms of equal calorific value and the incentive for attaining high efficiencies is less on this account. Accordingly, the study of the application of steam has tended to receive somewhat less attention than it deserves. Yet, since capital costs of nuclear power plant are currently high, the attainment of high efficiency is reflected in higher output—for a given nuclear heat input—and this helps to spread the capital cost. This, then, is the reason for analysing in detail the steam cycles that are capable of being associated with nuclear reactors.

Most of the principles used in this work are those also used in connection with conventional steam power plant but there are some major differences in their application. For instance, there is relative freedom in the selection of steam pressure in the case of conventional boiler plant but not in the case of nuclear plant. This Monograph aims to explain in an elementary way the many considerations involved in selection of steam cycles for nuclear power plant and to suggest convenient means for exploration of the several variables. Tables of the heat content of carbon dioxide are included since this gas has been selected as the coolant in commercial British reactors of the gas-cooled, graphite-moderated type. Grateful acknowledgment is made to the U.S. Department of Commerce for permission to include these Tables.

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Chapter One

STEAM CYCLES

In the foreseeable future, the large-scale harnessing of nuclear energy for the production of power would seem to be through the medium of steam. This is the outcome of the comparatively low temperatures obtainable from nuclear reactors in the present state of their development. The steam cycle offers reasonable efficiencies with modest temperatures and promises attractive efficiencies as the available temperatures rise. Figure 1* shows efficiencies that are potentially attainable with the simplest steam cycles at the higher temperatures, the adoption of the more complicated cycles, using reheat and supercritical pressure, promising still higher efficiencies.

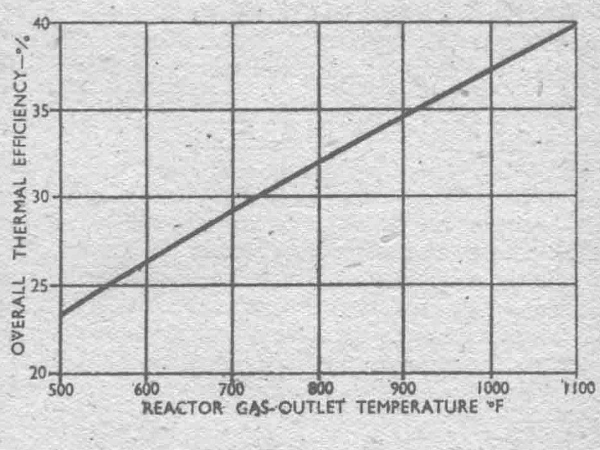


FIG. 1

Relation between reactor gas-outlet temperature and attainable steam-cycle overall thermal efficiency

The application of the steam cycle to a nuclear heat source brings with it problems of its own; yet none of these is outside the scope of orthodox thermodynamics. Resolution of the problems demands a knowledge of heat-engines, Steam Tables (Appendix Two), the Mollier Diagram (Appendix Three) and the Temperature-entropy Diagram

* *See* Appendix One (page 33) for an account of the derivation of Fig. 1.

(Appendix Four). In the following treatment, however, an attempt will be made to deal with the subject in such a way as to be of practical use to those with little prior familiarity in the field.

It is intended to emphasize reactors of the gas-cooled, graphite-moderated type and their associated steam cycles, because of the wide application of this type in Britain, and to deal, though in less detail, with reactors of the water-cooled, water-moderated type, in both boiling and non-boiling form, since these have also emerged as commercial variants. Lastly, brief reference will be made to liquid-metal-cooled reactors.

Chapter Two

GAS-COOLED, GRAPHITE-MODERATED NUCLEAR POWER PLANT

A nuclear power plant of the Calder Hall type comprises a reactor, cooled by gas circulating in a closed system through the reactor core and thence through heat exchangers, the heat being used to raise steam and drive turbines. The gas is circulated by blowers and is under pressure since it can be shown that the power consumption of these blowers varies inversely as the square of the pressure. A nuclear reactor, of whatever type, is a paradox of two conflicting factors; on the one hand, it represents a remarkable compression of heat output (in terms of volume) while, on the other, it has today to be suppressed in temperature because of severe limitations imposed by materials of construction. Together, these make the problem of transference of heat from the reactor to the steam-raising plant a difficult one. This is particularly so with gas-cooled reactors, 10 per cent of the power output of the plant being consumed by the blowers in present-day designs.

The geometry of the core of a gas-cooled, graphite-moderated reactor is established with respect to both nuclear physical and engineering considerations. It is possible then to associate with a given core a wide range of thermal outputs and yet maintain the surface temperature of the hottest fuel elements constant. For a constant gas flow through the reactor, lowering the temperature of the gas entering the reactor enables the thermal output to be increased. For a constant temperature of gas entering the reactor, increasing the gas flow has a similar effect. The characteristics of a reactor of the Calder Hall type, pressurized to 200 lb/in^2 absolute, are shown in Fig. 2 overleaf. Thermal outputs range, in this case, from 100 to 250 MW, and appropriate gas temperatures, flows and pressure losses are given which all satisfy the requirement of a maximum fuel element surface temperature of 450°C. The derivation of these characteristics is comprehensively dealt with by W. B. Hall in Chapter Two of *Reactor Heat Transfer* (Number III in this series of "*Nuclear Engineering*" *Monographs*).

It will be seen from the uppermost curves in Fig. 2 that the highest leaving-gas temperature is attained when the thermal output is least. This is to be expected, since the velocity of the gas in its passage through the reactor core is low; the gas spends more time in contact with the fuel element and thus more closely approaches the temperature of the

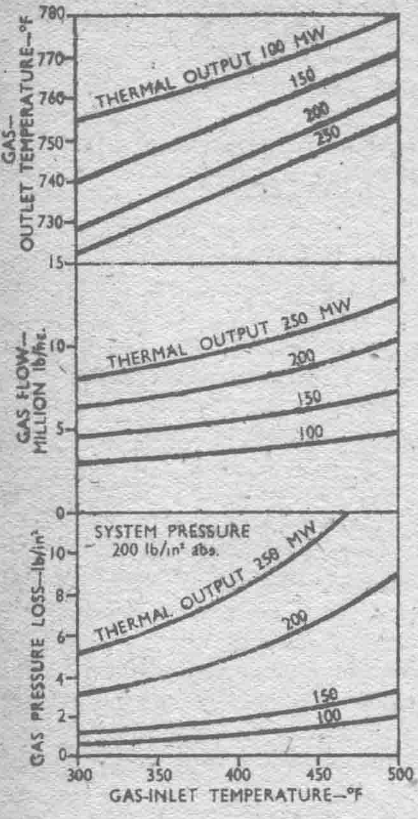


FIG. 2
Characteristics of typical gas-cooled graphite-moderated reactor

latter. It will be seen from the lowermost curves that the pressure loss across the reactor is least when the thermal output is least, again because of the low velocity of the gas. Under these conditions, then, the corresponding steam-cycle thermal efficiency would be the highest, not only because of temperature (high thermal efficiencies invariably being associated with high temperature), but also because the power consumed by the coolant circulators is least. On the other hand, the lowest leaving-gas temperature prevails when the thermal output is greatest and, at the same time, the pressure loss across the reactor is the highest. The corresponding steam-cycle thermal efficiency would be the least; nevertheless, the net electrical output of the plant would, of course, be considerably higher than in the reactor operating at a thermal output of only 100 MW. Since the capital cost of the given reactor is almost independent of the thermal rating and is an appreciable fraction of the total cost of the nuclear power plant as a whole, the higher electrical outputs would be expected to be associated with the lowest capital costs per net kW installed and the least cost of production of the units sent out, the latter despite the poorer thermal efficiency of the plant.

It is one of the primary aims of steam-cycle analysis to assist in the most advantageous selection of the design and operating conditions of a given reactor core. In particular, detailed consideration is given to

(*a*) the thermal rating of the reactor,
(*b*) the effect of varying the gas temperature entering the reactor,
(*c*) the use of single- or multiple-pressure steam cycles,
(*d*) the application of reheating and feed-heating,
(*e*) the apportioning of gas pressure loss in the reactor and in the heat exchangers and ducting, and
(*f*) the temperature approach at the "pinch-points" in the heat exchangers.

THE SINGLE-PRESSURE STEAM CYCLE

In the single-pressure steam cycle, Fig. 3, the steam pressures attainable (for any given gas temperatures entering and leaving the reactor) depend upon the feed temperature and upon the temperature approach between gas and water at the gas outlet from the evaporating section of the heat exchanger, point *A*. The highest steam pressures are associated with minimum temperature approaches and no feed heating. The former, however, are associated with extensive heating surfaces in the heat exchangers which not only add to the capital cost but also to the gas system pressure loss and, therefore, blower power consumption. Feed heating would be expected to have the usual beneficial effect on steam-

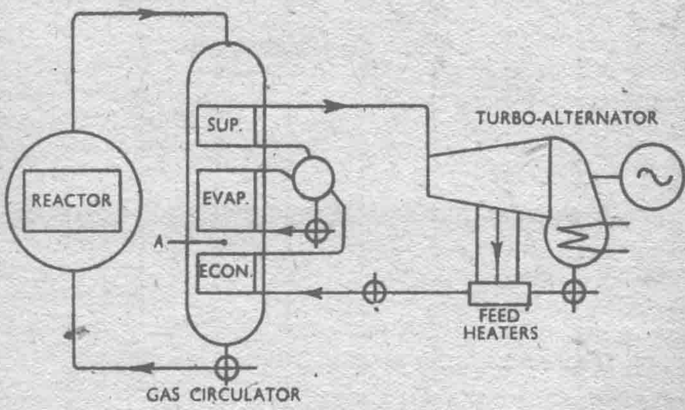


FIG. 3
Single-pressure steam cycle

cycle efficiency if it were not for the lower associated steam pressure. Figure 4(*a*) is a temperature-heat diagram for a typical heat exchanger; gas is shown entering at 750°F and leaving at 350°F. Feed water enters at 100°F, is raised to saturation temperature in the economizer section and at this point—the *pinch-point*—is within 30°F of the gas temperature. Evaporation takes place at a constant pressure of 340 lb/in^2 abs. and a temperature of 429°F, and the steam is then superheated to within 30°F of that of the incoming gas. It is obvious from this diagram that the steam pressure can be only that which corresponds to a saturation temperature defined as being, in this case, 30°F below the gas temperature at the pinch-point. Figure 4(*b*) is a temperature-heat diagram for the same gas conditions but with feed water entering at 300°F. Since much less heat is now required to be added in the economizer, the pinch-point occurs at a lower gas temperature. In turn, the saturation temperature at which evaporation takes place is lower and so, therefore, is the steam pressure.

Since there is a definite relation between the gas temperatures, the temperature approach, the feed temperature and the attainable steam pressure, a series of graphs may be plotted to facilitate correlation of

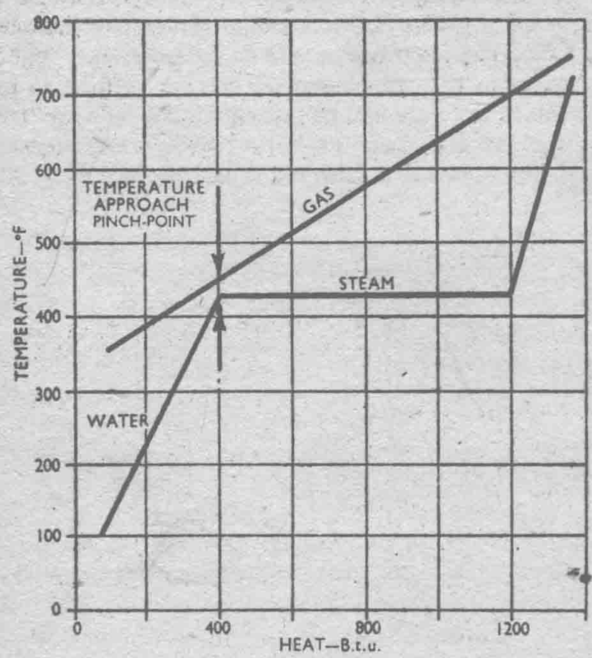


FIG. 4(*a*)

Typical temperature-heat diagram: single-pressure cycle without feed-heating these. Figure 5(*a*) is a typical example, drawn for an incoming gas temperature of 700°F and a temperature approach of 30°F (both at the pinch-point referred to above and at the superheater outlet). The gas is assumed to be carbon dioxide. From this it may be seen that if, for example, gas leaves the heat exchangers at 350°F, it would be possible to produce steam at 260 lb/in² abs. from feed water at 100°F, or at only 165 lb/in² abs. from feed water at 200°F. Figure 5(*b*) is another typical graph of the same kind, drawn for an incoming gas temperature of 750°F and the same temperature approach. Now, with gas leaving at 350°F, it would be possible to produce steam at 320 lb/in² abs. from feed water at 100°F, or at 195 lb/in² abs. from water at 200°F.

In this series of graphs, preparation of which involves little time or effort, the purpose of suggesting the incorporation of various temperature approaches is to determine the most advantageous from the point of view of heat-exchanger design. Obviously this is related to the type of heating surface envisaged and its configuration. Discussion of this subject is outside the scope of this Monograph and it should suffice to say that an approach of 20° to 30°F should be economically feasible for the purpose of steam-cycle analyses.

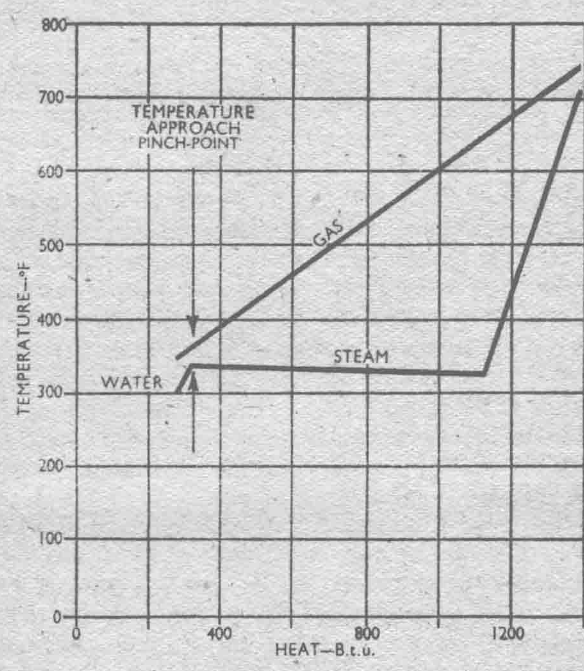


FIG. 4(*b*)

Typical temperature-heat diagram: single-pressure cycle with feed-heating

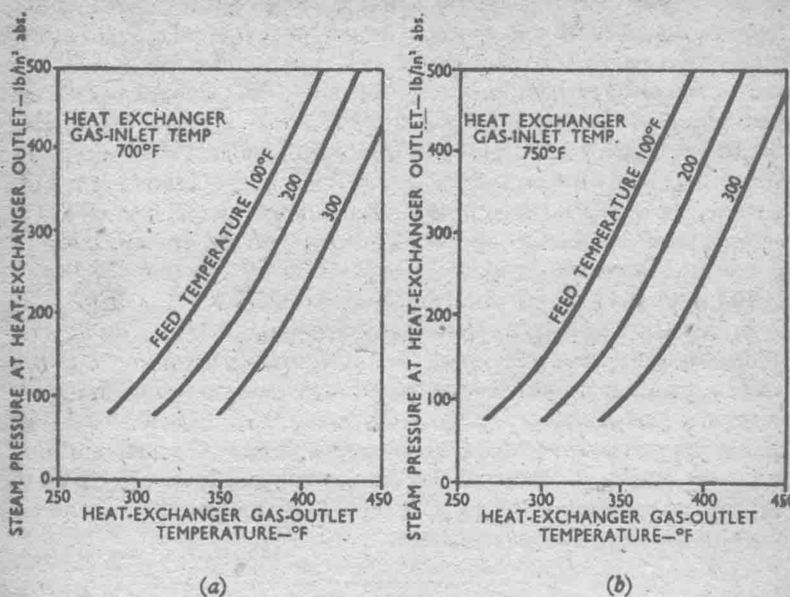
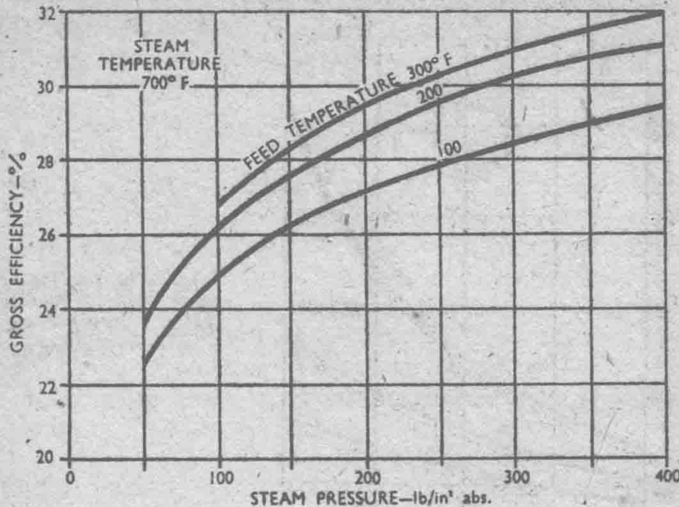


FIG. 5

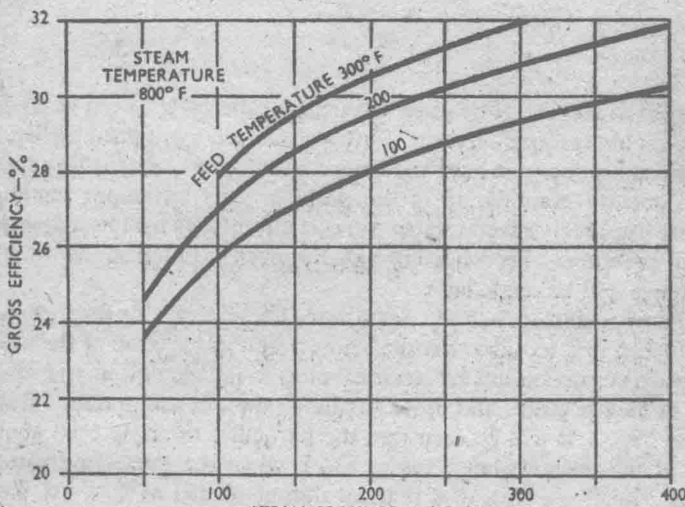
Typical relation between H.E. gas-inlet and -outlet temperature, feed temperature and attainable steam pressure: single-pressure cycle

A second series of graphs may be plotted now to facilitate interpretation of the attainable steam conditions, associated with any given reactor inlet and outlet gas temperatures, in terms of steam-cycle gross efficiency. Figures 6(*a*) and 6(*b*) are typical examples, drawn for steam temperatures of 700°F and 800°F. In these graphs, the assumption has been made that the condenser vacuum is 29 in. Hg, the dry stage efficiency ratio of the turbine is 86 per cent, the wet stage ratios (which, of course, decline as the steam pressure rises, due to increasing moisture content at the turbine exhaust) are varied as described in Appendix Three dealing with the Mollier Diagram, and the mechanical, electrical and other losses aggregate 5 per cent.

Having Figs. 5 and 6 to hand, it is possible, for example, to consider the case of a reactor giving a gas temperature of 730°F which is cooled in the heat exchangers to 340°F. By interpolation between Figs. 5(*a*) and 5(*b*), the steam pressure attainable is 260 lb/in² abs. when feed water is supplied at 100°F. From Fig. 6(*a*) the gross efficiency of the steam cycle—allowing a small drop in pressure in the steam pipes connecting the heat exchangers to the turbine—is 27·8 per cent. Alternatively, the steam pressure could be 150 lb/in² abs. if feed water were



(*a*)



(*b*)

FIG. 6

Typical relation between steam pressure, feed temperature and steam-cycle gross efficiency

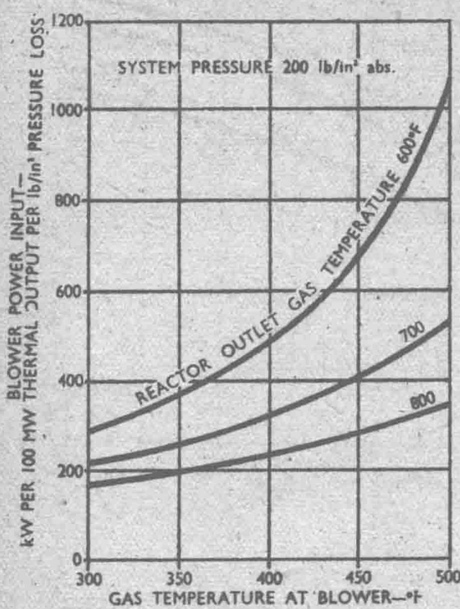


FIG. 7
Relation between blower power consumption and reactor gas-inlet and -outlet temperatures

supplied at 200°F. The gross efficiency of the cycle would be 27·7 per cent. This example serves to illustrate the fact, mentioned earlier, that feed-heating does not have the beneficial effect that might be expected from cursory examination of the problem; any advantage tending to accrue from higher feed temperatures is nullified by the lower associated steam pressure. Feed-heating has, however, a practical use to which reference will be made later.

The *gross* efficiency of the steam cycle obtained in this manner means little when it is recalled that the primary aim in selection of the cycle is to obtain the maximum *net* electrical output, i.e. the output after deduction of blower power and other auxiliary power consumption. Reverting to Fig. 2, it will be seen that the particular example used above—that of the reactor giving gas at 730°F when the inlet temperature is about 350°F*—relates to a thermal output of 250 MW, a gas flow of 8·8 million lb/hr and a gas pressure drop of 6·2 lb/in² in the reactor. Tentatively assuming an apportionment of gas pressure loss in the reactor of 60 per cent and in the external circuit (including the heat exchangers) of 40 per cent, the total pressure loss in the system is

* This is 10° higher than the heat-exchanger outlet temperature because of work of compression in the blowers.

10·3 lb/in². From these data, the power consumption of the blowers can be calculated, for the small pressure ratios involved, as follows:

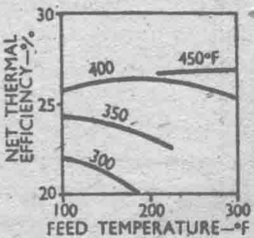
$$8{\cdot}8\times10^6\times10{\cdot}3\times0{\cdot}985\times\frac{144\times0{\cdot}746}{1{\cdot}98\times10^6\times0{\cdot}80}=6100\text{ kW}$$

This is simply the product of volume flow and pressure drop, the specific volume of the gas at the reactor inlet (where the blowers would normally be located) being 0·985 ft³/lb. The remaining constants are involved in taking account of the overall blower efficiency (assumed here to be 80 per cent) and in bringing the product to kilowatts. The power consumption of the blowers can be conveniently read off graphs such as Fig. 7, the bases of which are an overall blower efficiency (including motor losses) of 80 per cent and a system pressure of 200 lb/in² abs. The bulk of the blower power consumption appears as heat in the gas and must be added to the reactor thermal output to obtain the total heat input to the steam cycle. The net electrical output in this particular example can now be found as follows:

Reactor thermal output (MW)	250
Heat added by blowers at 95 per cent (MW)	5·8
Heat input to steam cycle (MW)	255·8
Gross electrical output at 27·8 per cent (MW)	71
Blower power input (MW)	6·1
	64·9
Other auxiliaries at 5 per cent (MW)	3·3
Net electrical output (MW)	61·6
Net thermal efficiency (per cent)	*24·6*

The effect of feed-heating in any particular case can be ascertained by the above method, and Fig. 8 is a typical result, that for the reactor having a thermal output of 250 MW. As the gas temperature at the reactor inlet is raised, so there is a slight advantage in raising the feed

FIG. 8
Effect of feed-heating on steam-cycle efficiency: see text



temperature; when the gas temperature is 350°F or less, the non-feed-heating cycle is more efficient; at 400°F, a feed temperature of 200°F is advantageous and at 450°F, the feed temperature may be 300°F.

Taking the effect of feed-heating into account, exploration of the most appropriate steam cycle for any given reactor output and gas-inlet temperature gives the result shown in Fig. 9. Although the gross electrical output of the turbo-alternators increases steadily as the reactor gas-inlet temperature is raised, the net output does not, because of the steeply-rising power consumption of the blowers. The curves show that interest in the selection of the most advantageous steam cycle would centre in the range of reactor gas-inlet temperatures of 400 to 450°F, probably towards the lower temperature because the rising capital cost at higher temperatures is hardly offset by the increase in electrical output. It is not within the scope of this monograph to describe the subsequent steps of cost appraisal involved in overall economic optimization. The purpose of steam-cycle analysis is to present to the plant designer a "short-list" of the most suitable steam conditions; he in turn offers his designs to the estimator. The conclusions are tempered by many practical considerations before the final selection is made. Among these, for example, is the investigation of the effect of apportionment of gas-pressure loss in the reactor relative to that in the external circuit, tentatively assumed so far to be 60 : 40.

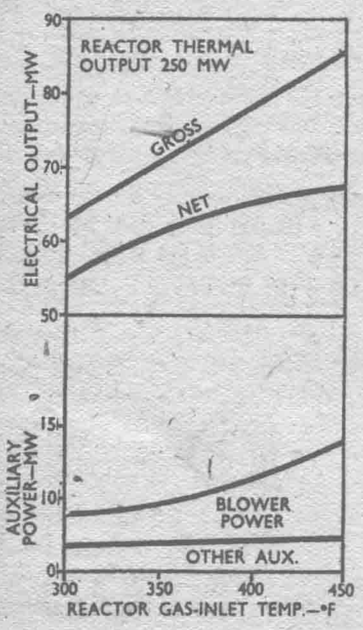


FIG. 9

Typical relation between reactor gas-inlet temperature and net electrical output