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SOME MAJOR DESIGN PARAMETERS FOR THE H.T.G.C. REACTOR PROJECT

by

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SUMMARY

(a) Based on economic considerations approximate estimates of various H.T.G.C.R. parameters have been made. The paper is not an exhaustive design study but does endeavour to determine reasonable starting points. Values of these parameters prove to be -

Maximum Gas Temperature	≃	500°C - 600°C
Minimum Gas Temperature	≃	about 250°C
Fuel burnup	≃	100% - 150% (with fissile material at £5,000/Kg).
	≃	200% - 250% (with fissile material at £20,000/Kg).
Gas Pressure Ratio	≃	1.10 - 1.25

(b) There are two regions of maximum gas temperature in which it might be worthwhile to concentrate, namely, 500°C - 600°C with steam turbines or 800°C (+) with gas turbines. It appears questionable that temperatures between these two regions should be considered unless the installed cost per KW of the two types of installation are significally different.

CONTENTS

DIAGRAMS

OBJECT

In this paper an attempt has been made to evaluate, on an economic basis, the orders of magnitude which it would be reasonable to assume for the following major design parameters of the H.T.G.C. Reactor Project -

Maximum Gas Temperature

Minimum Gas Temperature

Fuel Burnup

Gas Pressure Ratio

The paper is not an exhaustive design study but merely endeavours to determine reasonable starting points.

METHOD AND ASSUMPTIONS

One given reactor has been assumed throughout the study and the following sets of calculations performed -

(a) The effect of the variation of maximum gas temperature on the cost per KWH the electrical power output and the installed cost per KW, for a given minimum gas temperature and constant mass flow.

(b) The effect of the change of minimum gas temperature on these curves, from which followed the most economic value of the minimum temperature.

(c) The effect of the increase of burnup on the cost per KWH.

(d) The effect of the variation of mass flow (and therefore gas pressure ratio) on the curves of (a). This determined the most economic value of the pressure ratio.

The thermodynamic cycle efficiencies shown in Fig. 3, were used and the following assumptions made -

(a) The system is the simple steam turbine arrangement of Fig. 1.

(b) Maximum gas temps. = up to 700°C
Minimum gas temps. = 200 - 400°C
Fuel burnup = 50% - 300%
Cost fuel/Kg. fissile material = £5000 - £20,000
Temp. approach in heat exchangers = 10°C
Load Factor = 80% - 60%
Maximum steam moisture content = 10% approx.
Gas - CO_2
Constant cost per unit area heat exchanger surface.
Constant cost per installed KW of turbo-generating plant.
Capital costs at 10%.

The method adopted was to select one basic condition and compare all other conditions with it. This was taken as the mass flow which produced an electrical power P when the gas is heated from 200°C to 300°C in the reactor. It was then found necessary to associate with this initial condition a cost per installed KW of plant and a distribution of costs between reactor, heat exchangers and turbo-generating plant. These were taken as -

(c) Cost per electrical KW of reactor, heat exchangers and turbo-generating plant = £200 - £300 at the comparison point.

(d) Distribution of costs -

Condition No.	Reactor	Heat Exchangers	Turbo-Gen.
1	70%	10%	20%
2	40%	20%	40%

It should be noted that these are the initial conditions at the comparison point. At other points the values are naturally different.

CALCULATIONS

No allowance was made for buildings or for plant other than the power producing apparatus itself. It was felt that this would obscure the picture since further (rather vague) assumptions would have to be made.

It was considered also that the assumptions of constant cost per unit of heat exchanger area and per unit of installed turbo-generator capacity were not unreasonable for this type of calculation, particularly since the actual variation of the cost of the items depends a good deal on the manufacturer. Moreover we are finally concerned with a range of maximum gas temperatures of from 700°C to 500°C corresponding (see later) to a range of electrical power of less than 2 to 1, so that linear proportionality could be a close approximation over this region.

The cycle efficiency curves, are represented typically by Fig. 3. It was found that, although the two limiting conditions, maximum steam moisture constant and temperature approach in the heat exchanger (see Fig. 2), are not connected, one being dominant to the other in different regions, the resultant maximum efficiencies fell conveniently on smooth curves. Although the calculations apply strictly to the circuit of Fig. 1, it is not anticipated that any significantly different relative results will be obtained for a reheat or a 2-pressure cycle, except perhaps that the absolute values of cost/MWH, etc. may vary.

The calculations are outlined in Appendices 1 and 2.

DISCUSSION OF RESULTS

4.1 Determination of Maximum Gas Temp.

Figs. 4 and 5 have been drawn for a wide range of the variables and show how the cost per KWH varies with maximum gas temperature for a minimum gas temperature of 200°C.

The cost does not include operating charges (see later) nor capital on plant other than the power equipment itself. The numbers 1 and 2 attached to the curves refer to the distribution of installation costs given in Para. 2 (d).

The large spread of costs is striking, although perhaps equally striking is the relatively small cost gain obtained by increasing the maximum temperature from 500°C to 700°C. There is, however, an approximate doubling of the electrical power produced by the system over the same temperature range as illustrated by the left-hand diagram of Fig. 4. This in itself would be important if there is at the same time a significant drop in the cost per installed K.W. Fig. 6 which applies to all the Condition 1 curves of Figs. 4 and 5, shows how this cost varies for the two assumed basic costs of £200 and £300/KW respectively.

The top curve, which is probably closer to reality than the other, gives a decrease in cost per installed K.W. of about 14% when the gas temperature is raised from 500°C to 700°C. Two thirds of this, however, has been contributed by the time the temperature has reached 600°C.

It would seem therefore, that on these two counts, cost/KWH and cost/KW there would not be much point in proceeding past the 600°C and because of the flatness of the curves, we might well consider the range 500°C – 600°C, the actual value finally being selected on metallurgical and chemical grounds.

4.2 Effect of Operating Costs and Load Factor.

The savings shown in Figs. 4 and 5 by increasing the maximum temperature from 500°C to 700°C should be increased to allow for operating charges. Two values of these charges at 300°C were taken, namely 0.8 pence and 0.4 pence per KWH. At 500°C these become about 0.15 and 0.08 pence/KWH.

Under these conditions, Figs. 9 (a) and 9 (b) show the order of magnitude of the total savings in pence per KWH at temperatures above 500°C up to 700°C for load factors of 60% and 80%.

From these it appears that only for low burnup (100%), high fissile cost, (£20,000/Kg) and load factors of 60% or lower would it be worth while approaching a maximum temperature of 700°C. It is doubtful if the operating cost per KWH (at 500°C) would be significantly greater than 0.15 pence/KWH. These diagrams should therefore be fairly representative of the kinds of savings to expect.

4.3 Effect of Burnup

Figs 7 and 8 are typical of the variation of cost per KWH with burnup. Other combinations of the variables give substantially the same kind of picture.

It is clear from these that if the fissile cost approaches £20,000/Kg a reasonable burnup would be in the region 200% – 250%, whereas if the fissile cost is closer to the other end of the scale, £5000/Kg, the appropriate region would be rather 100% – 150%.

4.4. Variation of Mass Flow and Pressure Ratio.

All the above calculations have been performed for a mass flow corresponding to a gas pressure ratio of 1.10. If we now take the curves of Figs. 4 and 5 and apply different mass flows we obtain very similar results except that the absolute values of the cost/KWH vary. It would be confusing to reproduce these fresh curves here. A more suitable summary of the situation is the type of diagram typified by Fig. 10. These two sets of curves cover the region in which we are interested, i.e., from £20,000/Kg fissile and 100% burnup to £5000/Kg fissile and 300% burnup. From these it is clear that the design pressure ratio could reasonably be confined to the values 1.10 - 1.25 depending on the cost of fuel (since the burnup selected will also depend on this cost as discussed under 4.3).

4.5 Variation of Minimum Gas Temperature.

All calculations so far dealt with have been based on a minimum gas temperature of 200°C. If we consider other temperatures we obtain similar diagrams to those shown in Fig. 11 for two specific cases. Obviously there is an optimum value of the minimum temperature over the maximum temperature range 500°C - 700°C.

Replotting these results in the form shown in Fig. 12 we see that a suitable value of the minimum temperature would lie between 200°C and 300°C. A convenient figure would be 250°C although it is not particularly critical.

STEAM TURBINES VERSUS GAS TURBINES

It can easily be shown that steam cycles can be envisaged which will produce thermodynamic efficiencies equal to or better than those of gas turbine cycles up to about 700°C.

Unless therefore a gas turbine plant is significantly cheaper to install than an equivalent steam plant, it would be difficult to justify the use of gas turbines at gas temperatures below about 800° C.

On the other hand if steam is to be employed it does not appear to be particularly easy to justify temperatures much above 600°C. There seem to be therefore two regions - steam turbines at 500°C - 600°C, or gas turbines at about 500°C, (or higher), with a kind of "no-man's land" in between. That is, either temperatures are kept below 600°C or we make a really big jump and adopt 500°C.

The adoption of temperatures between 600°C and 800°C would of course b be justified if it is found to be strategically important in the solution of problems at 800°C.

It might be practicable to associate a beryllium-type fuel element with a steam cycle and a graphite-type fuel element with a gas turbine plant.

CONCLUSIONS

Summarising the above results it is concluded that -

(a) Suitable values from an economic standpoint for the preliminary investigation of an H.T.G.C. project associated with steam turbines would be -

Maximum Gas Temperature = 500°C - 600°C

Minimum Gas Temperature = about 250°C

Burnup = (100% - 150% (fissile £5,000/Kg).)

(200% - 250% (fissile £20,000/Kg).)

Gas Pressure Ratio = 1.10 - 1.25

(b) There are two regions on which it might be worthwhile to concentrate -

500°C - 600°C maximum gas temperature with steam turbines and about 800°C (+) with gas turbines. It appears questionable that temperatures between these two regions should be considered unless the installed cost per KW of the two types of installation are significally different.

SYMBOLS USED IN CALCULATIONS

The following symbols have been used in the calculations -

A = Total annual costs - £

a = Time for cooling, fabrication and transport of fuel elements - Hours

B = Gas pressure ratio.

b = Burnup - fraction

C = Annual capital costs (excluding buildings) - £

c_p = Gas specific heat at constant pressure

d_R) Fractions of installation cost
)
d_H) = Attributable to reactor, heat exchanger and
)
d_T) = turbo-generatork etc., respectively.

F = Annual fuel cost - £

H = Heat from one fuel charge before removal for reprocessing - KWh

M = Gas flow - Kg/Hour.

m_1 = Total installation cost rate with $T_2 = 200^oC$ and $T_1 = 300^oC$ - £/KW electrical.

N = Number charges required per annum from point of view of processing cycle.

P = Electrical power - K.W.

Q = Quantity fissile material - grams.

S = Heat exchanger area - arbitrary units

T_1 = Maximum gas temperature - ^oC

T_2 = Gas temperature at reactor inlet - ^oC

T_3 = Gas temperature at reactor inlet - ^oC

U = Co-efficient heat transfer in heat exchanger - arbitrary units

w = Cost (fertile + fissile) per Kg. fissile material

X = Annual KWH

x = Initial cost per charge - £

y = Allowance per charge when reprocessing - £

Z = Mass fissile material in reactor - Kg.

α = Cost per KWh at $T_2 = 200^{\circ}C$, $T_1 = 300^{\circ}C$ - £

β = Load factor - fraction

γ = Reactor heat rating - KW/Kg fissile material

ε = Cost per unit turbo-generator, etc., capacity - £/KW electrical

η = Cycle efficiency - fraction

φ = Mean temperature difference in heat exchanger - oC.

ξ = Annual rate for depreciation + interest - fraction

ρ = Cost per unit area of heat exchanger - £/unit area.

APPENDIX 2

DETERMINATION OF EXPRESSION FOR POWER COST PER KWH FOR A CONSTANT MASS FLOW

ASSUMPTIONS

In the first set of calculations the following assumptions have been made -

1. A given reactor.
2. A constant mass flow of gas (CO_2).
3. Constant cost per unit area of heat exchanger surface.
4. Constant cost per installed K.W. of turbo-generator. (see later for discussion of this item).
5. The maximum load equals the installed capacity.
6. The items concerned are only the power producing plant proper.

REACTOR RATINGS

Let Z = Mass fissile material in reactor - Kg

Y = Reactor heat rating - KW/Kg fissile material

P = Electrical power - KW

η = Cycle efficiency

then - $P = \eta Z Y$ (1)

For a given initial condition 1 and any subsequent condition n,

$$\frac{P_1}{P_n} = \frac{\eta_1 Y_1}{\eta_n Y_n} \qquad (2)$$

Also from Fig. (1) -

$$c_p M (T_1 - T_3) = 860\ Z_Y \quad (1\text{KWH} = 860 \text{ Kg-Cal})$$

For constant mass flow M -

$$\frac{(T_1 - T_3)_1}{(T_1 - T_3)_n} = \frac{Y_1}{Y_n}$$

or $$Y_n = Y_1 \cdot \frac{(T_1 - T_3)n}{(T_1 - T_3)\ 1} \qquad (3)$$

COST PER KWH

Total annual costs, A, are -

$$A = \underset{(C)}{\text{Capital}} + (\text{Operating} + \text{Maintenance}) + \underset{(F)}{\text{Fuel}}$$

Within the limits of this investigation any variation (Operating + Maintenance) costs will be a second order effect. Operating and Maintenance have therefore been assumed constant.

As a result, for a given initial condition 1, and any subsequent condition, n, -

$$A_1 - A_n = (C_1 - C_n) + (F_1 - F_n) \qquad (4)$$

If β = load factor and assuming 8760 hours in one year then -

$$(\text{Cost/KWh})_n = \frac{A_n}{8760\, P_n \beta}$$

∴ from (4) -

$$(\text{Cost/KWh})_n = \frac{A_1 - (C_1 - C_n) - (F_1 - F_n)}{8760\, P_n \beta}$$

$$= \frac{\alpha P_1}{P_n} - \left[\frac{(C_1 - C_n) + (F_1 - F_n)}{8760\, P_n \beta}\right] \qquad (5)$$

$$\left(\text{Where } \alpha = \frac{A_1}{8760\, P_1\, \beta}\right)$$

HEAT EXCHANGER AREA

Let U = coefficient heat transfer in heat exchanger

φ = mean temperature difference - °C.

S = heat exchanger area

∴ from Fig. 1 -

$$c_p M (T_1 - T_2) = US\varphi$$

For constant mass flow M -

$$\frac{(T_1 - T_2)_1}{(T_1 - T_2)_n} = \frac{S_1\ \varphi_1}{S_n\ \varphi_n}$$

(assuming tube dia. increased with temp. to give constant value and therefore constant U neglecting viscosity effect).

or -

$$S_n = S_1 \cdot \frac{\varphi 1}{\varphi n} \cdot \frac{(T_1 - T_2)_n}{(T_1 - T_2)_1} \qquad (6)$$

CAPITAL CHARGES

The capital charges (C) on plant (excluding buildings) can be divided between Reactor, Heat Exchanger and Turbo-generator, etc.

Let ρ = installed cost per unit area of exchanger - £

ξ = (interest + depreciation) on capital - fraction

ε = installed cost per KW of turbo-generator etc.

then -

$$C_1 - C_n = \rho\,\xi\,(S_1 - S_n) + \varepsilon\,\xi\,(P_1 - P_n) \qquad (7)$$

Let the fraction of capital charges attributable to Reactor, Heat Exchanger and Turbo-generator be represented by $d_R + d_H + d_T$ respectively, so that -

$$d_R + d_H + d_T = 1$$

If m, is the installation cost of condition 1 in £/KW elec. then -

$$\left.\begin{aligned} \rho\,\xi\,S_1 &= d_H \cdot m_1\,P_1\,\xi \\ \varepsilon\,\xi\,P_1 &= d_T \cdot m_1\,P_1\,\xi \end{aligned}\right\}$$

or -

$$\left.\begin{aligned} \rho &= d_H \cdot \frac{m_1\,P_1}{S_1} \\ \varepsilon &= d_T \cdot m_1 \end{aligned}\right\} \qquad (8)$$

$\therefore$ from (7)

$$C_1 - C_n = d_H \cdot \frac{m_1\,P_1}{S_1} \cdot \xi\,(S_1 - S_n) + d_T \cdot m_1\,\xi\,(P_1 - P_n)$$

Substituting from (2), (3) and (6) -

$$C_1 - C_n = m_1\,P_1\,\xi\left[d_H\left\{1 - \frac{\varphi_1}{\varphi_n}\cdot\frac{(T_1 - T_2)_n}{(T_1 - T_2)_1}\right\} + d_T\left\{1 - \frac{\eta_n}{\eta_1}\cdot\frac{(T_1 - T_3)_n}{(T_1 - T_3)_1}\right\}\right] \qquad (9)$$

This expression can then be substituted for $(C_1 - C_n)$ in Equation (5).

FUEL CHARGES

Let H = maximum heat from one fuel charge - KWh

β = load factor - fraction

X = total annual KWh

N = number charges per annum consumed in power station

N_1 = number of charges in the system at any one time

x = initial cost per charge - £

y = allowance per charge when reprocessing - £

a = time for cooling, transport, fabrication - hours

Then -

$$\text{KWh elec. energy/charge} = H \times \text{cycle efficiency} = H\eta$$

$$\text{But } \beta = \frac{X}{8760P} = \frac{NH\eta}{8760P}$$

$$\therefore \quad \underline{N} = \frac{8760\beta P}{\eta H} \tag{10}$$

Also -

$$N_1 = \frac{\text{Total cycle time}}{\text{Average irradiation time}} + 1 \text{ spare}$$

$$= \frac{\text{Av. irrad. time} + (\text{cool., transp. fab.})\text{ time}}{\text{av. irrad. time.}} + 1$$

$$\text{But av. irradiation time} = \frac{8760}{N}\text{ hours}$$

$$\underline{N_1} = 2 + \frac{aN}{8760} \tag{11}$$

There will be actual fuel charges on N and interest charges on $(N_1 - N)$. If interest rate is taken as 0.06, then interest charges are -

$$\text{interest charges} = 0.06 \times (N_1 - N)$$

$$= 0.06 \times \left[2 + N \left(\frac{a}{8760} - 1 \right) \right] \tag{12}$$

If y is the allowance per charge when reprocessing, then annual fuel charges (excluding interest item of (12)) are -

$$N\ (x - y)$$

Combining this with (2), the <u>total</u> annual fuel charges become -

$$F = \text{total fuel charges}$$

$$= 0.12x + N\left(\frac{ax}{146000} + 0.94x - y\right)$$

$$= 0.12x + \frac{8760\beta P}{\eta H} \cdot \left(\frac{ax}{146000} + 0.94x - y\right)$$

$$= \text{(say) } 0.12x + \frac{P}{\eta} \cdot \phi \qquad (13)$$

Assume the worst case for allowance on fuel elements returned for reprocessing, i.e. $y = 0$, then -

$$\phi = \frac{8760\beta x}{H}\left(\frac{a}{146000} + 0.94\right)$$

Let w = cost (fertile + fissile)/Kg. fissile - £

Q = gms fissile/charge

x = cost per charge ; £

b = burnup (fraction)

$$\therefore x = \frac{Qw}{1000} \quad ; \qquad H = 24000bQ$$

and

$$\phi = \frac{8760\beta}{24 \times 10^6} \cdot \frac{w}{b}\left(\frac{a}{146000} + 0.94\right) \qquad (14)$$

From (2), (3) and (13), -

$$F_1 - F_n = \phi\left(\frac{P_1}{\eta_1} - \frac{P_n}{\eta_n}\right) = P_1\ \phi\ \left(\frac{1}{\eta_1} - \frac{P_n}{P_1} \cdot \frac{1}{\eta_n}\right)$$

$$= \frac{P_1\ \phi}{\eta_1}\left[1 - \frac{(T_1 - T_3)_n}{(T_1 - T_3)_1}\right] \qquad (15)$$

This can be substituted for $(F_1 - F_n)$ in Equation (5).

GENERAL EXPRESSION FOR COST/KWH

Let $\dfrac{m_1 \xi d_H}{8760\ \beta} \times 240 = f$ (pence).

$\dfrac{m_1 \xi d_T}{8760\ \beta} \times 240 = g$ (pence).

$\dfrac{\emptyset}{\eta_1} \times \dfrac{240}{8760\ \beta} = h$ (pence).

$\therefore$ substituting in Equation (5) –

$(\text{Cost/KWH})_n =$

$$\frac{P_1}{P_n}\Bigg[\alpha \cdot\cdot (f + g + h)\Bigg] + \Bigg[f \cdot \frac{\varphi_1}{\varphi_n} \cdot \frac{\eta_1}{\eta_n} \cdot \frac{(T_1 - T_2)_n}{(T_1 - T_2)_1} \cdot \frac{(T_1 - T_3)_1}{(T_1 - T_3)_n} + g + h + \frac{\eta_1}{\eta_n}\Bigg] \tag{16}$$

Where –

$$\frac{P_1}{P_n} = \frac{\eta_1}{\eta_n} \frac{(T_1 - T_3)_1}{(T_1 - T_3)_n}$$

VALUE OF INITIAL COST/KWH (=α)

$$\alpha = \frac{A_1}{8760 P_1 \beta} = \frac{C_1 + F_1 + (\text{Op.} + \text{Maint.})}{8760 P_1 \beta}$$

$$\doteq \frac{m_1 \xi + \dfrac{\emptyset}{\eta_1}}{8760\beta} + \frac{0.12\ x}{8760 P_1 \beta} + \frac{(\text{Op.} + \text{Maint.})}{8760 P_1 \beta}$$

$$= (\text{say})\ D + E + G \tag{17}$$

It is found that E is small compared with D, so that for comparison purposes we may neglect E when establishing a commencing point α(pence per KWH). Also since the (Op. + Maint.) has been assumed a constant the absolute value of G should not significantly affect the optimising process. We therefore assume α equal to D and do not need to give absolute values to P_1.

The effect of the (Op. + Maint.) costs are dealt with in the discussion preceding this Appendix.

VALUES OF d_H AND d_T

Two considerably different relationships between the costs of reactor, heat exchanger and turbo-generator have been taken for the initial condition. These are -

Reactor	Heat Exchanger	Turbo - gen.
70%	10%	20%
40%	20%	40%

INITIAL CONDITION 1

The initial condition with which all other conditions have been compared is -

T_1 = 300°C

T_2 = 200°C

γ_1 = γ = reactor heat rating in KW/Kg fissile.
(not necessary to specify absolute value).

P_1 = P = electrical power in KW. (not necessary to specify absolute value).

η_1 = maximum cycle efficiency = 16%
(see Fig. 3 which is drawn for a gas pressure ratio of 1.10).

The gas used throughout the calculations was CO_2.

RESULTS

The variation of cost/KWH with maximum gas temperature is shown plotted in Figs. 4 and 5.

APPENDIX 3

VARIATION OF MASS FLOW

INTRODUCTION

In this calculation the curves of Figs. 4 and 5 have been taken and the effect on them of the variation of mass flow examined.

A similar method to that used in Appendix 1 has been adopted except that the initial condition (with which subsequent conditions are compared) is each point of each base curved in turn.

Referring to the calculations of Appendix 1 we then have -

REACTOR RATINGS

As for Equation (2) -

$$\frac{P_1}{P_n} = \frac{\eta_1 \, \gamma_1}{\eta_n \, \gamma_n}$$

Also -

$$\frac{M_1}{M_n} = \frac{\gamma_1}{\gamma_n} \quad \left(\text{since } (T_1)_1 = (T_1)_2\right)$$

$$\therefore P_n = P_1 \cdot \frac{\eta_n}{\eta_1} \cdot \frac{M_n}{M_1}$$

HEAT EXCHANGER AREA

(Refer Section (5) Appendix 1).

$$\frac{M_1}{M_n} = \frac{U_1 \, S_1}{U_n \, S_n} \qquad (\text{since } \varphi_1 = \varphi_2)$$

Also -

$$\frac{U_1}{U_n} = \left(\frac{V_1}{V_n}\right)^{0.8} \left(\frac{\mu_1}{\mu_n}\right)^{0.2} \qquad (\mu = \text{viscosity})$$

$$= \left(\frac{V_1}{V_n}\right)^{0.8} \qquad (\text{since } \mu_1 = \mu_n)$$

$$= \left(\frac{M_1}{M_n}\right)^{0.8}$$

$$\therefore \frac{M_1}{M_n} = \left(\frac{M_1}{M_n}\right)^{0.8} \frac{S_1}{S_n}$$

or -

$$S_n = S_1 \cdot \left(\frac{M_n}{M_1}\right)^{0.2} \qquad (19)$$

CAPITAL CHARGES

(Refer Section (6), Appendix 1).

$$C_1 - C_n = \rho\,\xi\,S_1 \left[1 - \left(\frac{M_n}{M_1}\right)^{0.2}\right] + \varepsilon\,\xi\,P_1 \left[1 - \frac{\eta_n}{\eta_1} \cdot \frac{M_n}{M_1}\right]$$

$$= m_1\,P_1\,\xi \left[d_H \left\{1 - \left(\frac{M_n}{M_1}\right)^{0.2}\right\} + d_T \left\{1 - \frac{\eta_n}{\eta_1} \cdot \frac{M_n}{M_1}\right\} \right] \qquad (20)$$

FUEL CHARGES

(Refer Section (7), Appendix 1).

$$F_1 - F_n = \varnothing \left(\frac{P_1}{\eta_1} - \frac{P_n}{\eta_n}\right) = P_1\,\varnothing \left(\frac{1}{\eta_1} - \frac{P_n}{P_1} \cdot \frac{1}{\eta_n}\right)$$

$$= P_1\,\varnothing \left(\frac{1}{\eta_1} - \frac{1}{\eta_1} \cdot \frac{M_n}{M_1}\right)$$

$$= \frac{P_1\,\varnothing}{\eta_1} \left(1 - \frac{M_n}{M_1}\right) \qquad (21)$$

TOTAL CHARGES

(Refer Section (8) Appendix 1).

$(\text{Cost/KWH})_n$

$$\frac{P_1}{P_n}\left[\alpha_1 - f_1\left\{1 - \left(\frac{M_n}{M_1}\right)^{0.2}\right\}\right] - g_1\left(1 - \frac{\eta_n}{\eta_1}\cdot\frac{M_n}{M_1}\right) - h_1\left(1 - \frac{M_n}{M_1}\right)$$

$$= \frac{P_1}{P_n}\left[\alpha_1 - (f + g + h)_1\right] + \left[f_1 \cdot \frac{\eta_1}{\eta_1}\cdot\left(\frac{M_1}{M_n}\right)^{0.8} + g_1 + h_1 \cdot \frac{\eta_1}{\eta_n}\right] \qquad (22)$$

(Where α_1 = cost at each individual point on original curve.)

FRICTION LOSSES

The original curve was substantially for a friction loss of $0.10P_2$, i.e, $\frac{P_1}{P_2} \doteq 1.10$, since the external pipe sizes and heat exchanger tube diameters were increased to the same friction losses as the maximum gas temperatures were raised.

$$\frac{(\text{Friction Loss})_n}{(\text{Friction Loss})_1} = \left(\frac{V_n}{V_1}\right)^2 = \left(\frac{M_n}{M_1}\right)^2 \qquad (23)$$

RESULTS

On applying Equation (22) to the curves of Figs. 4 and 5 similarly shaped curves are obtained. The results can be combined in the manner illustrated by Fig. 10, which shows the variation of cost per KWH with mass flow for various maximum gas temperatures (assuming a constant minimum gas temperature.)

Since we can correlate quite closely gas pressure ratio with relative mass flow the abscissae are also approximately gas pressure ratios.

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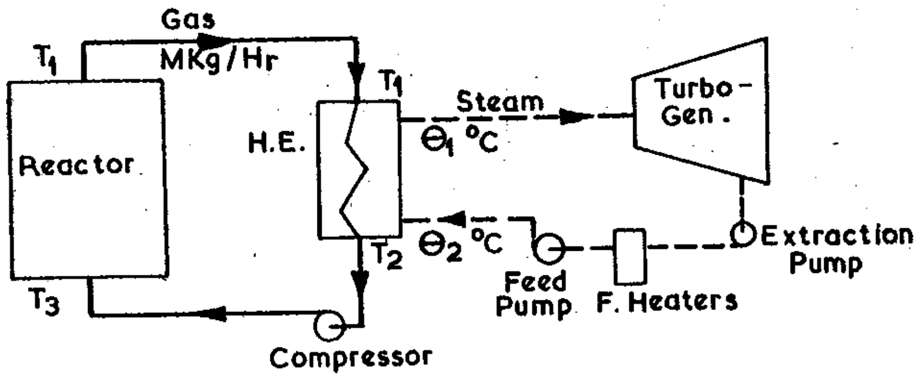

Fig. 1. Basic Steam / Gas Circuit

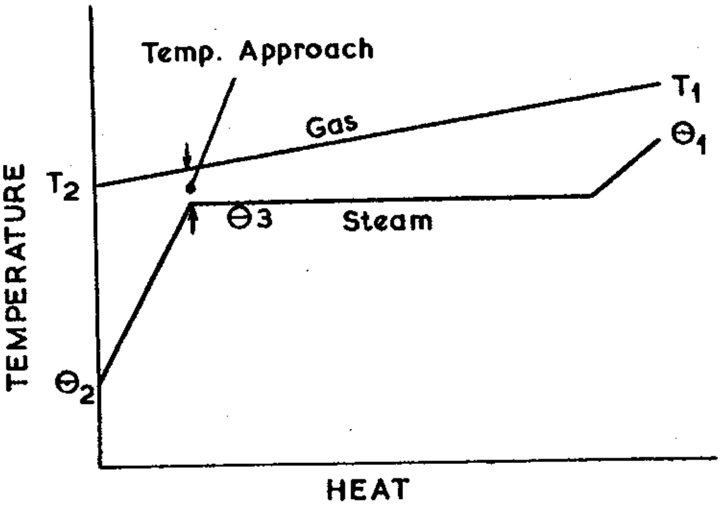

Fig. 2. Temp. Conditions in Heat Exchanger

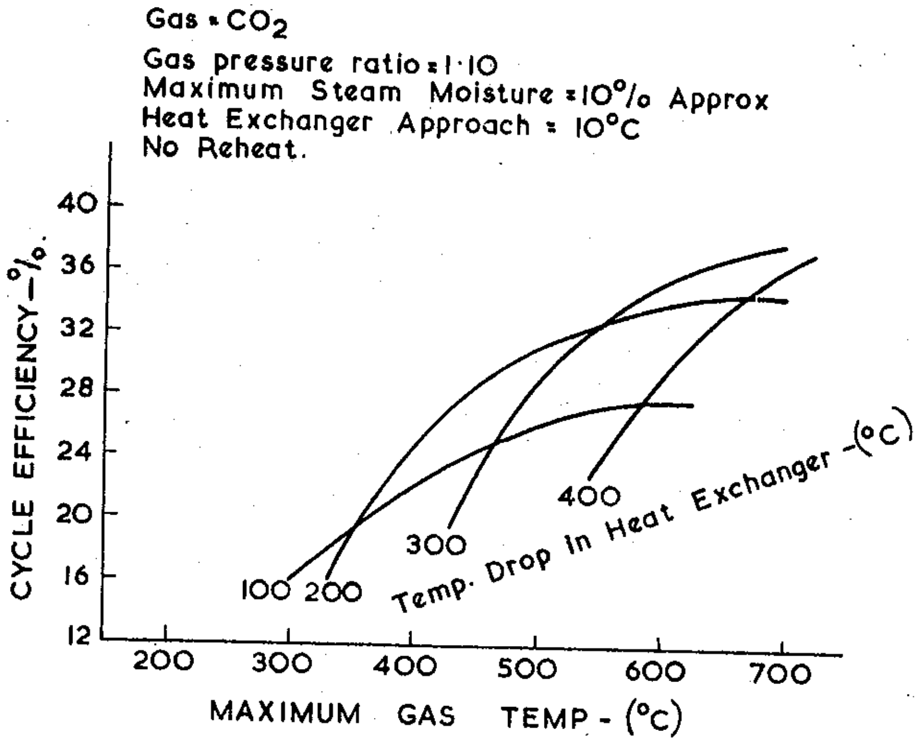

Fig.3.— Approx. Maximum Steam Cycle Efficiencies For Conditions Shown.

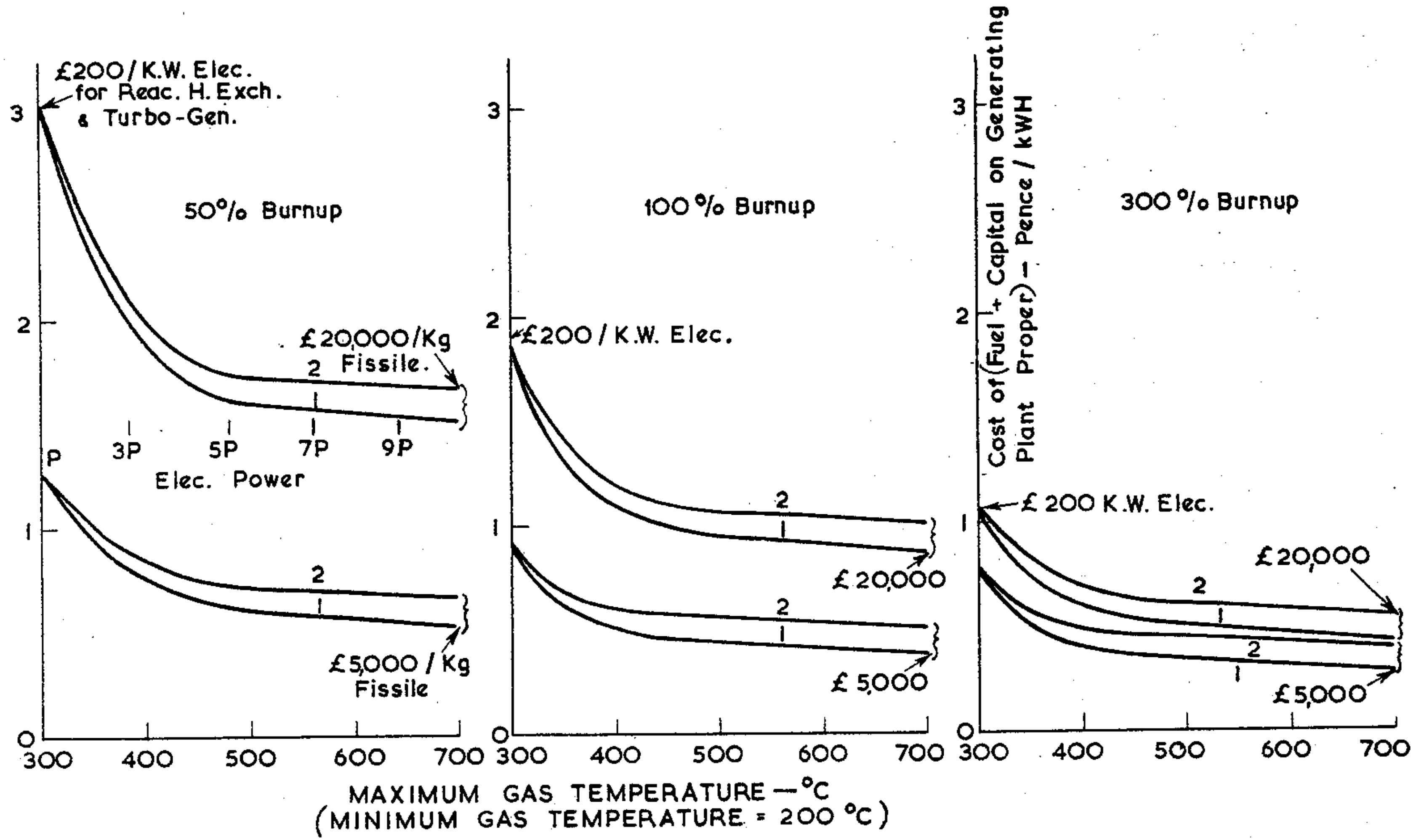

Fig. 4. — Cost per K.W.H. of (Fuel + Capital on Power Plant Proper) for Initial Cost of Power Plant at £200 / K.W.

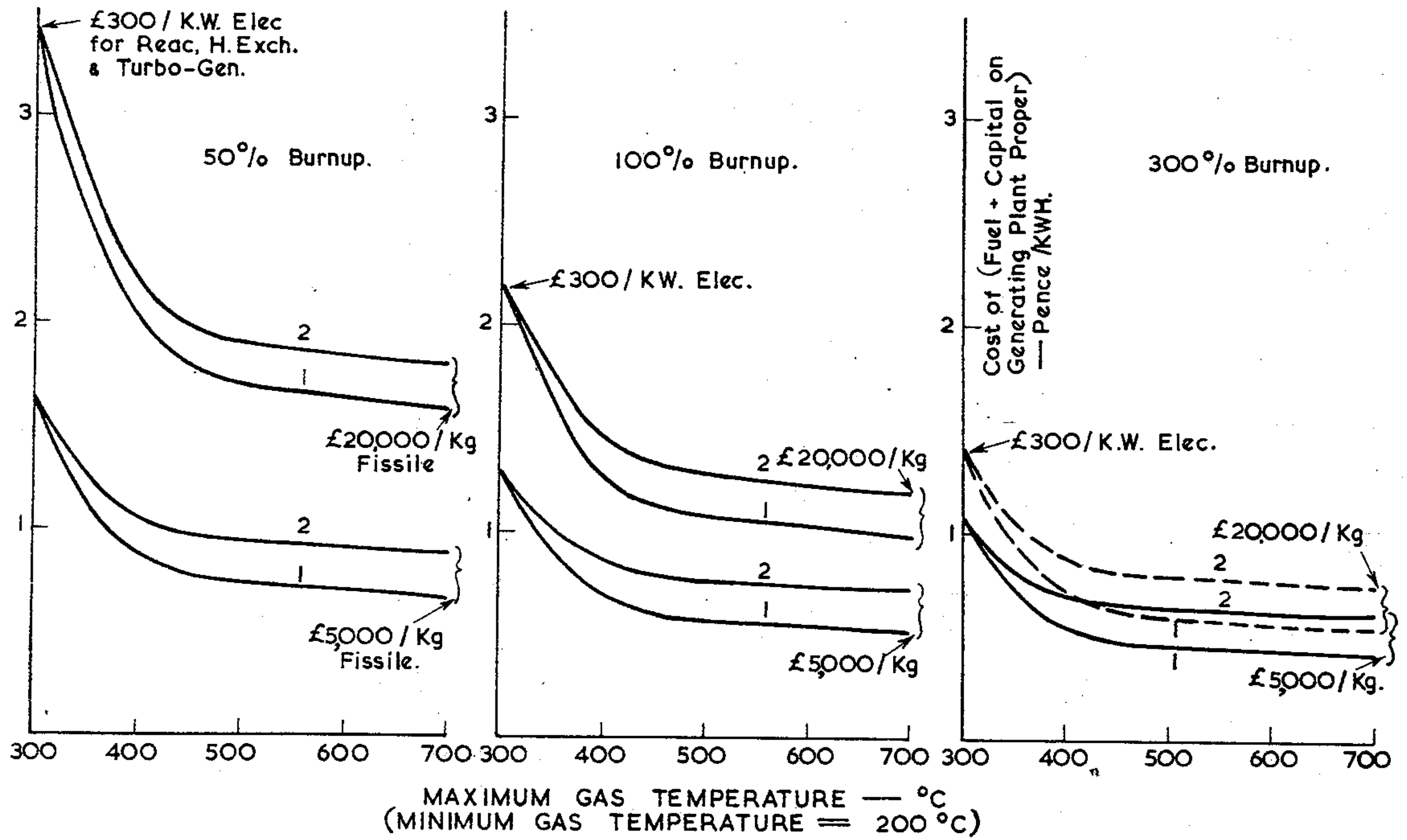

Fig.5. Cost per KWH of (Fuel + Capital on Power Plant Proper) for Initial Cost of Power Plant at £300 / KW.

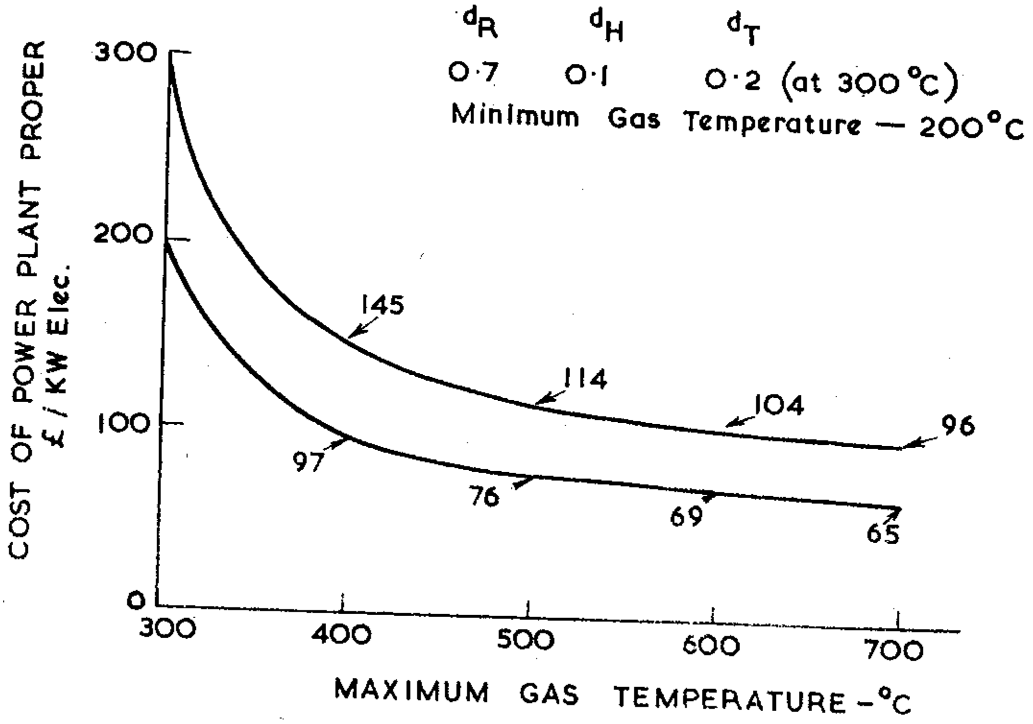

Fig. 6 – Cost per Installed KW for Given Reactor.

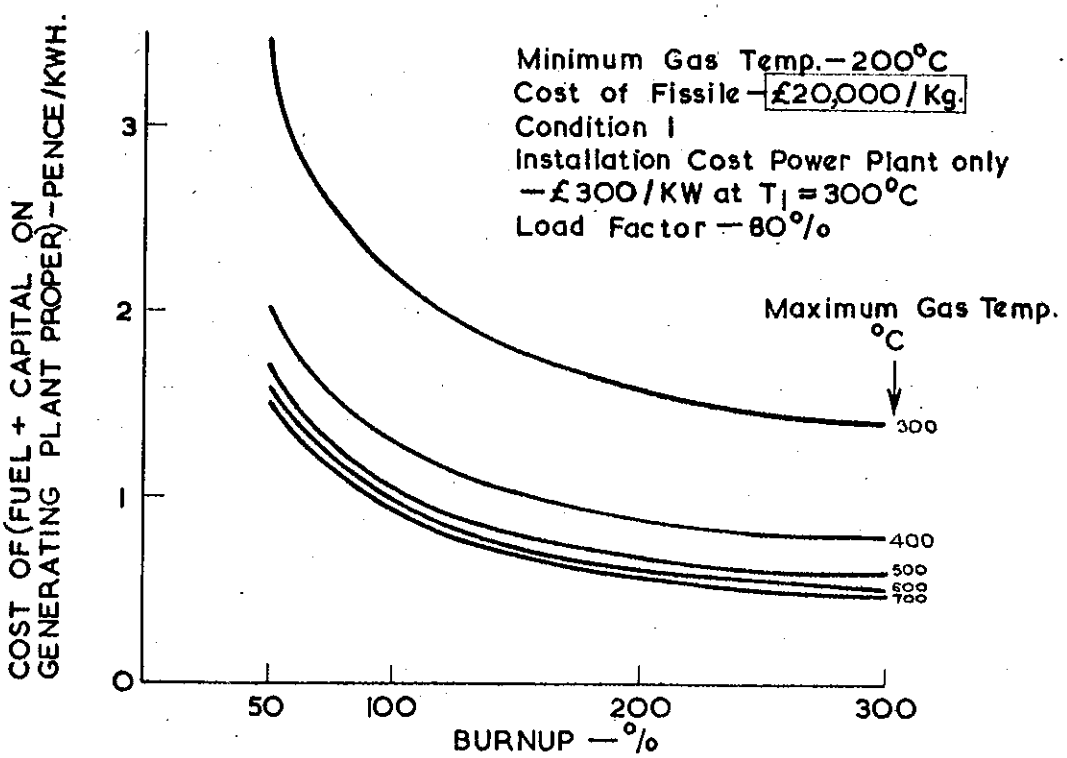

Fig. 7 — Variation of Cost / KWH with Burnup – (Fissile £20,000 / Kg)

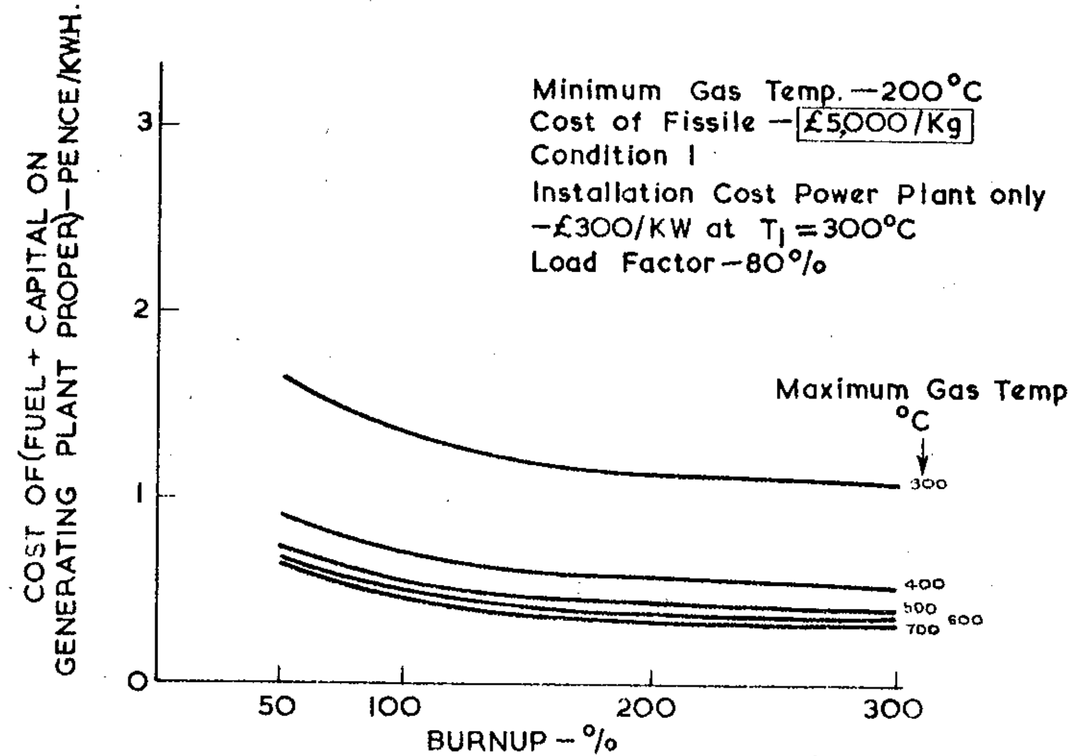

Fig. 8. Variation of Cost / KWH with Burnup – (Fissile – £5,000 / Kg)

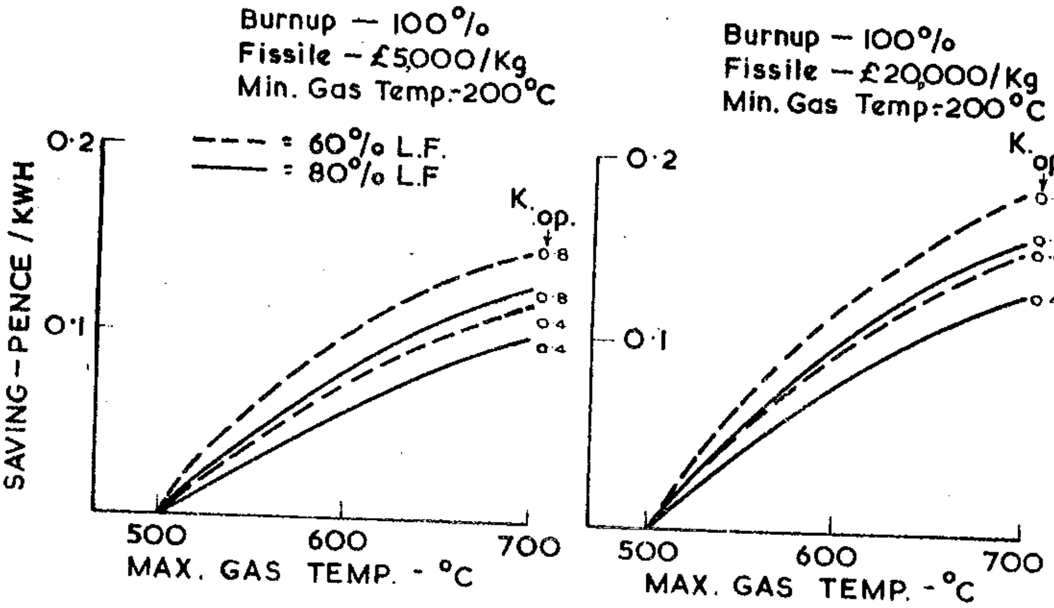

Fig. 9a.– Saving in Pence / KWH by Increasing Max. Gas Temperature above 500°C.

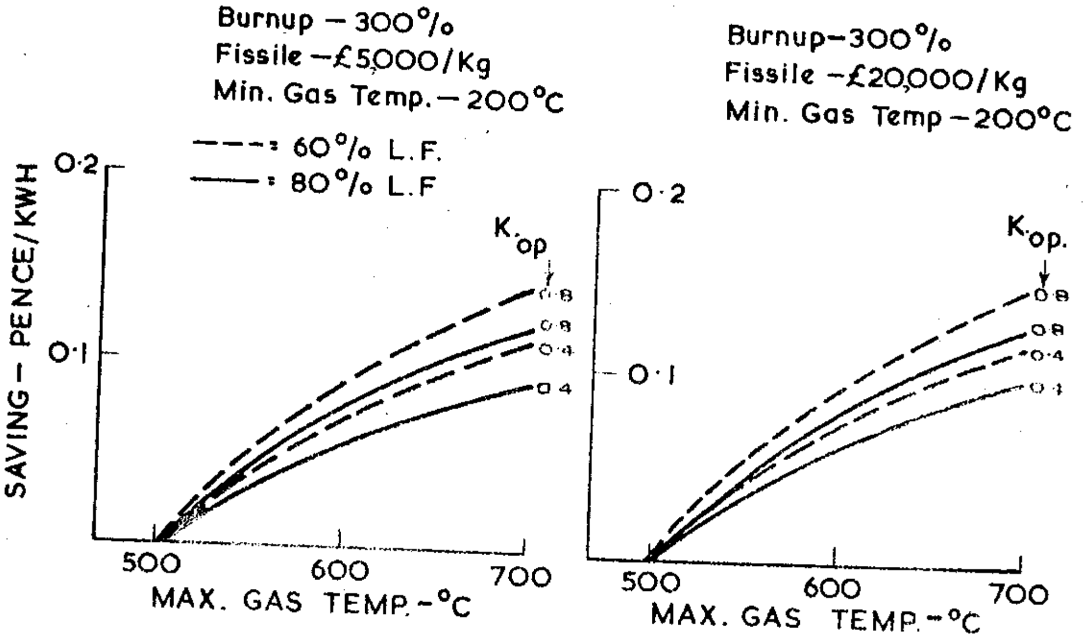

Fig. 9b– Saving in Pence / KWH by Increasing Max Gas Temperature above 500°C

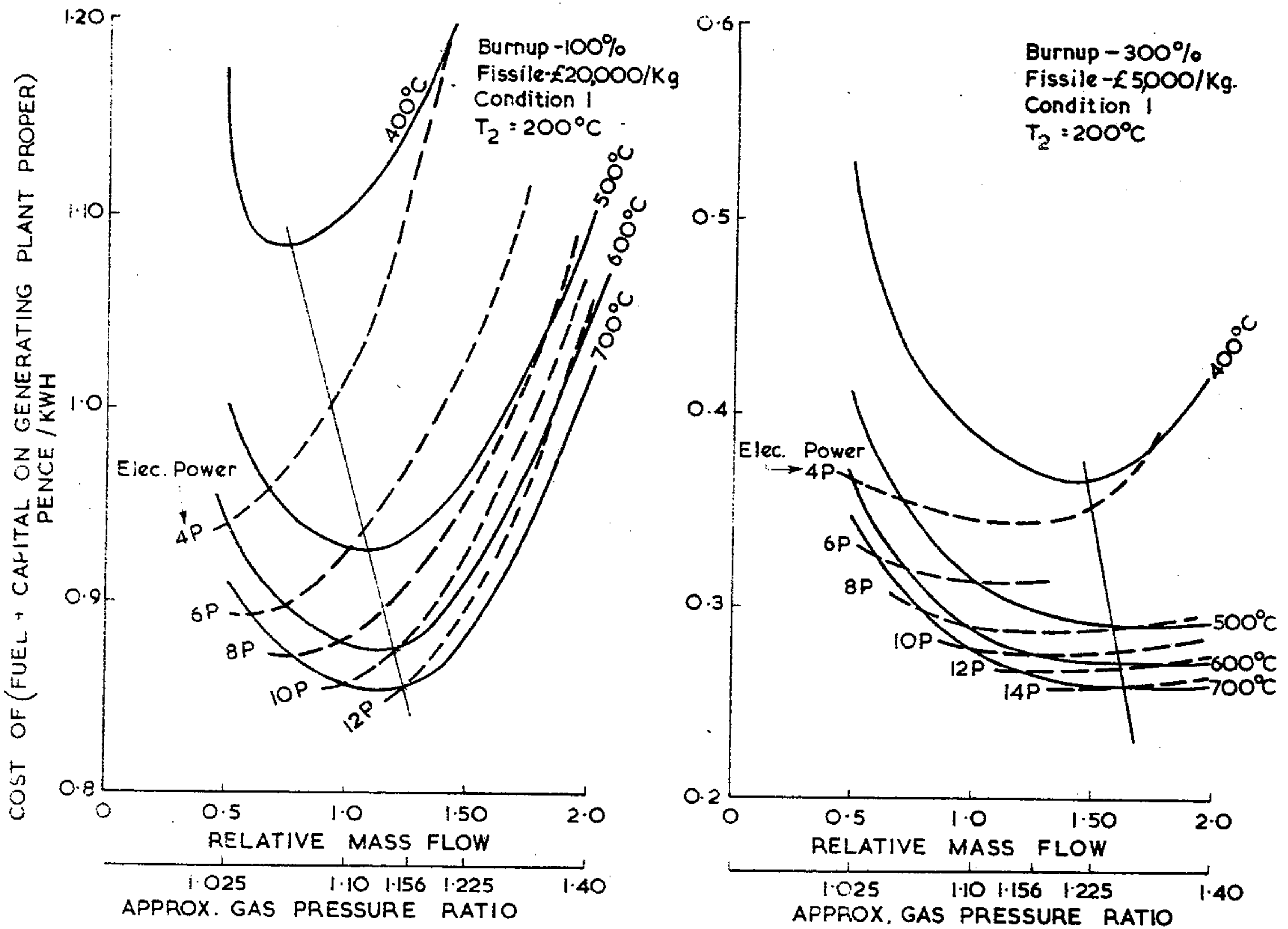

Fig. 10. — Variation of Cost / KWH with Mass Flow.

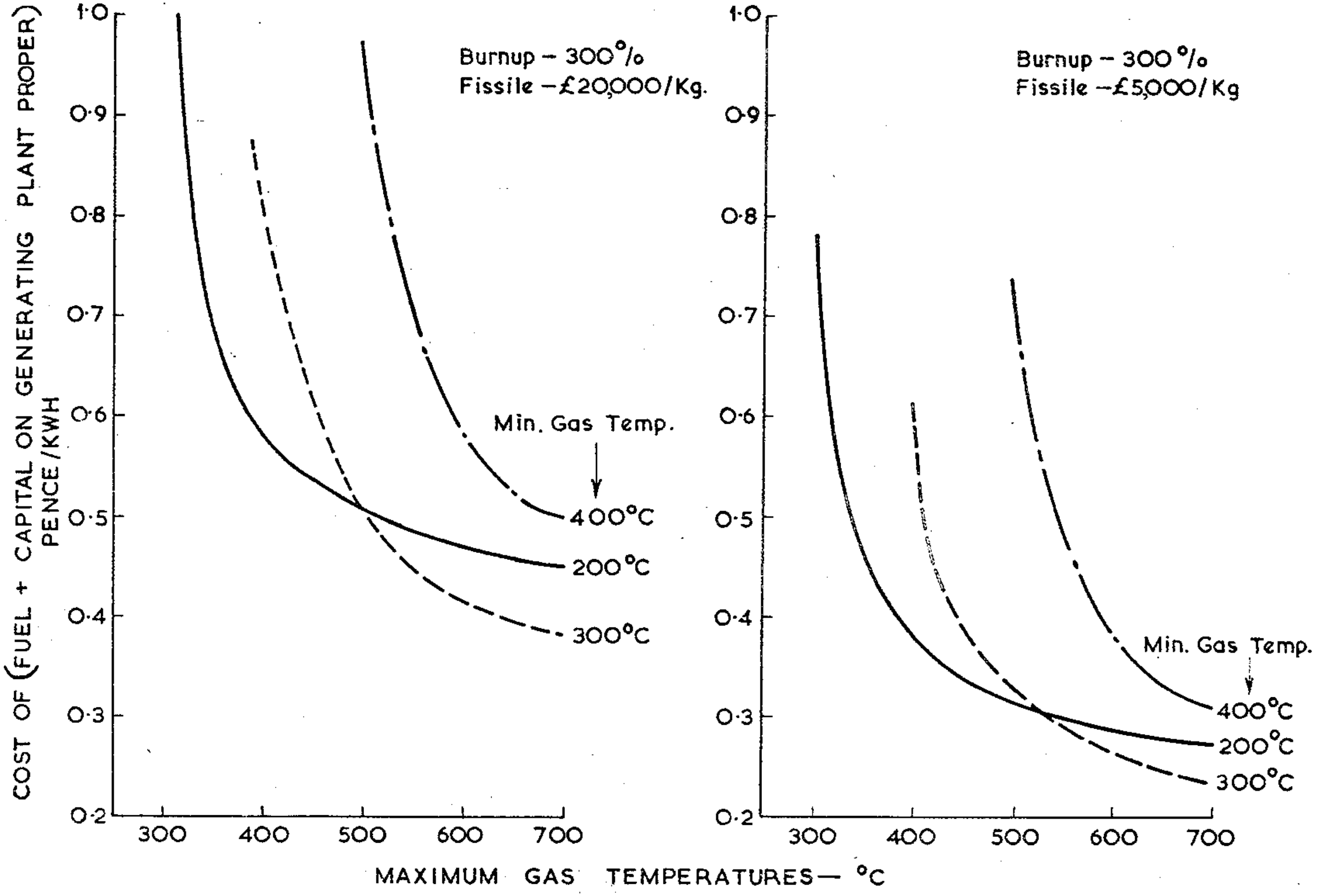

Fig. 11. Variation of Cost/KWH with Minimum Gas Temperature.

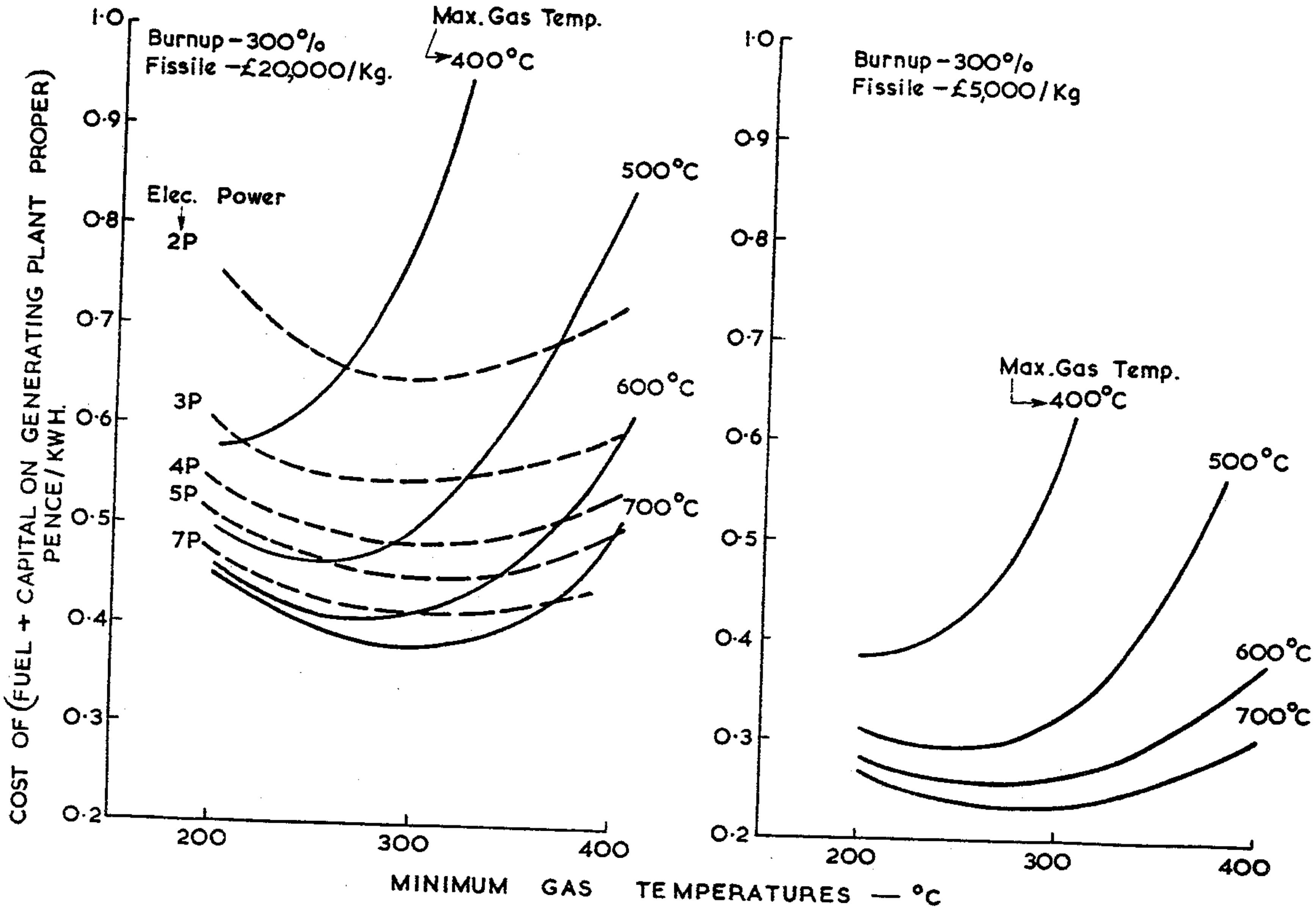

Fig. 12.—Variation of Cost/KWH with Minimum Gas Temp.